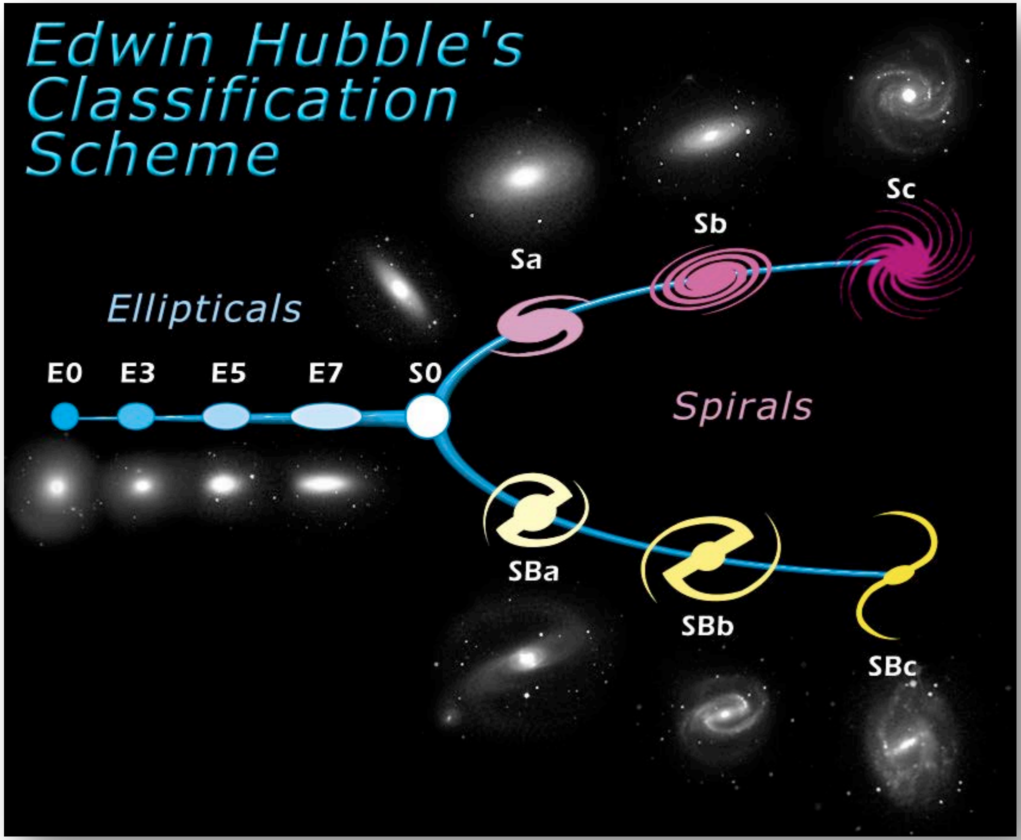
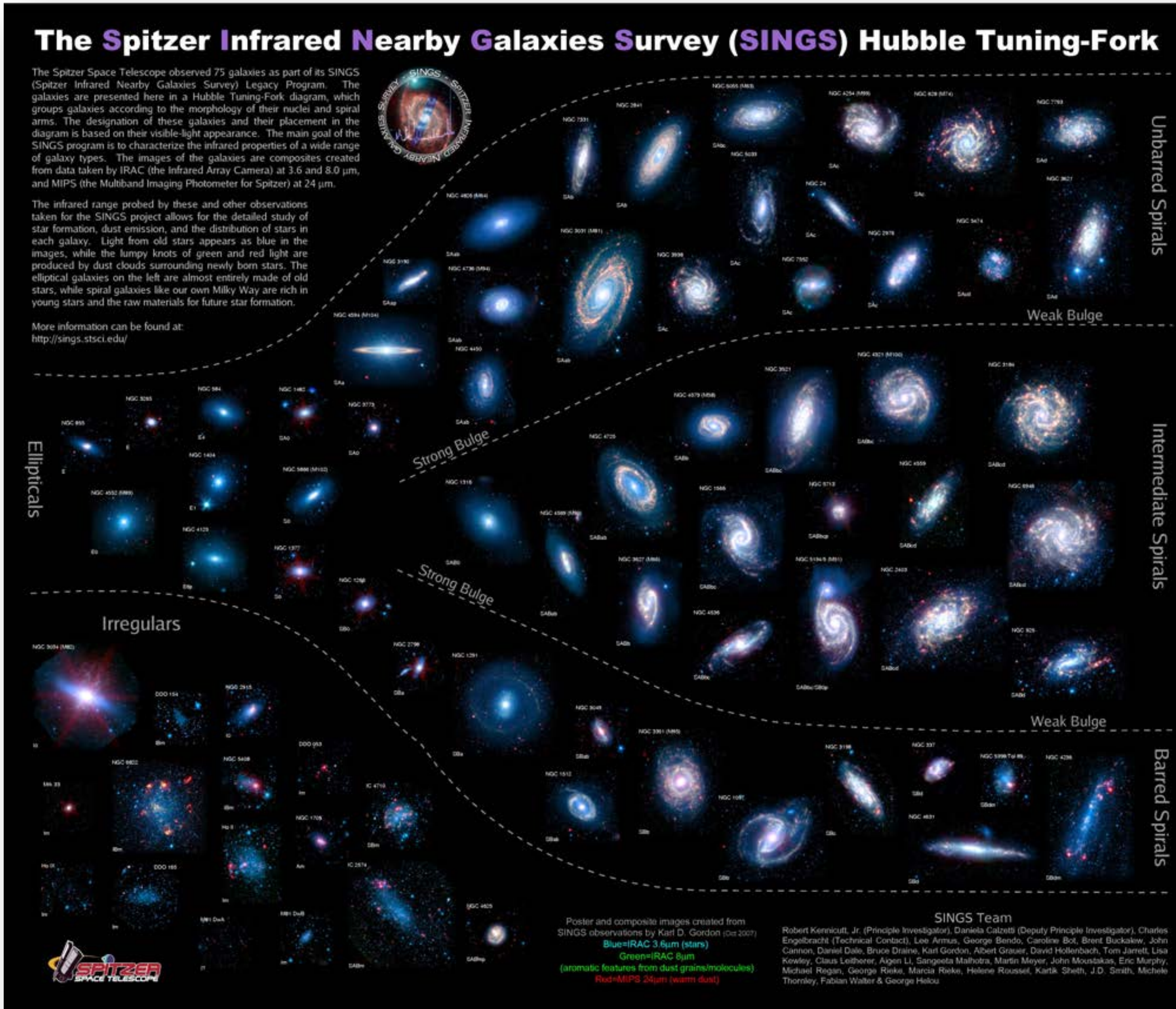
Galactic & Extragalactic Astronomy

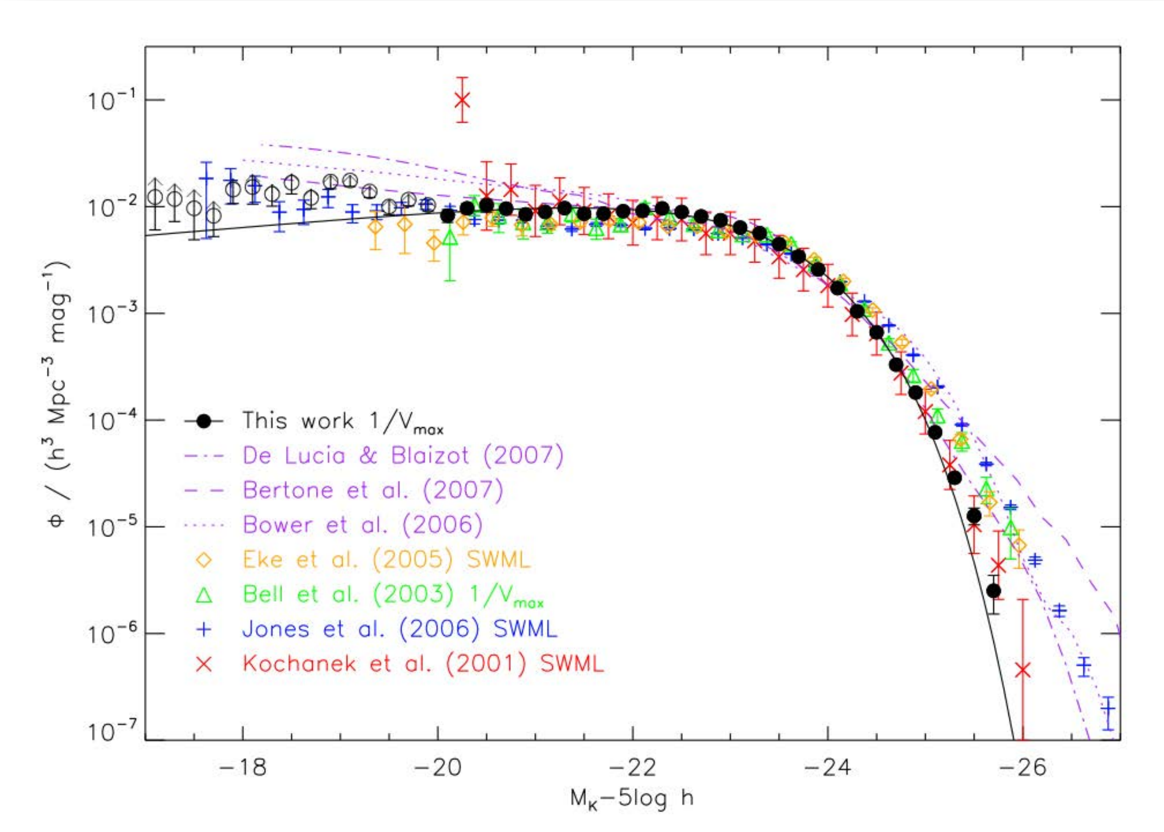
Course 1: Introduction

Morphological types

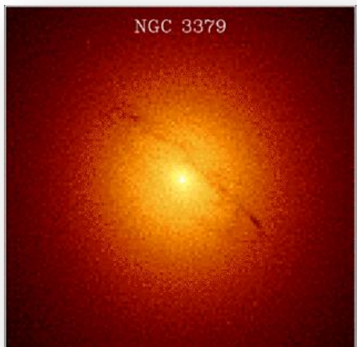


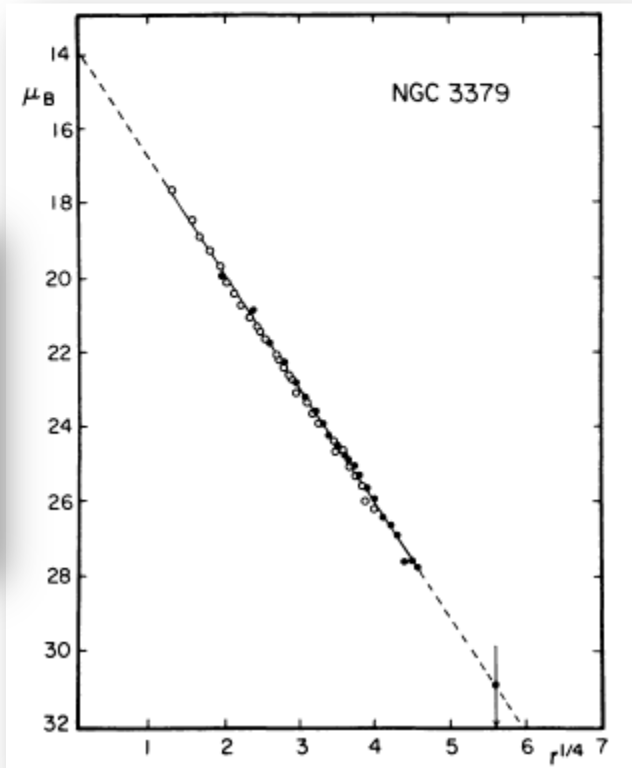

The Spitzer Infrared Nearby Galaxies Survey (SINGS) Hubble Tuning-Fork
The Spitzer Space Telescope observed 75 galaxies as part of its SINGS (Spitzer Infrared Nearby Galaxies Survey) Legacy Program. The galaxies are presented here in a Hubble Tuning-Fork diagram, which groups galaxies according to the morphology of their nuclei and spiral arms. The designation of these galaxies and their placement in the diagram is based on their visible-light appearance. The main goal of the SINGS program is to characterize the infrared properties of a wide range of galaxy types. The images of the galaxies are composites created from data taken by IRAC (the Infrared Array Camera) at 3.6 and 8.0 µm, and MIPS (the Multiband Imaging Photometer for Spitzer) at 24 µm.
The infrared range probed by these and other observations taken for the SINGS project allows for the detailed study of star formation, dust emission, and the distribution of stars in each galaxy. Light from old stars appears as blue in the images, while the lumpy knots of green and red light are produced by dust clouds surrounding newly born stars. The elliptical galaxies on the left are almost entirely made of old stars, while spiral galaxies like our own Milky Way are rich in young stars and the raw materials for future star formation.
More information can be found at:
http://sings.stsci.edu/
Ellipticals
Irregulars
Strong Bulge
Strong Bulge
Unbarred Spirals
Weak Bulge
Intermediate Spirals
Weak Bulge
Barred Spirals
Poster and composite images created from SINGS observations by Karl D. Gordon (Oct 2007)
Blue=IRAC 3.6µm (stars)
Green=IRAC 8µm
(aromatic features from dust grains/molecules)
Red=MIPS 24µm (warm dust)
SINGS Team
Robert Kennicutt, Jr. (Principle Investigator), Daniela Calzetti (Deputy Principle Investigator), Charles Engelbracht (Technical Contact), Lee Armus, George Bendo, Caroline Bot, Brent Buckalew, John Cannon, Daniel Dale, Bruce Draine, Karl Gordon, Albert Grauer, David Hollenbach, Tom Jarrett, Lisa Kewley, Claus Leitherer, Aigen Li, Sangeeta Malhotra, Martin Meyer, John Moustakas, Eric Murphy, Michael Regan, George Rieke, Marcia Rieke, Helene Roussel, Kartik Sheth, J.D. Smith, Michele Thornley, Fabian Walter & George Helou
SPITZER SPACE TELESCOPE

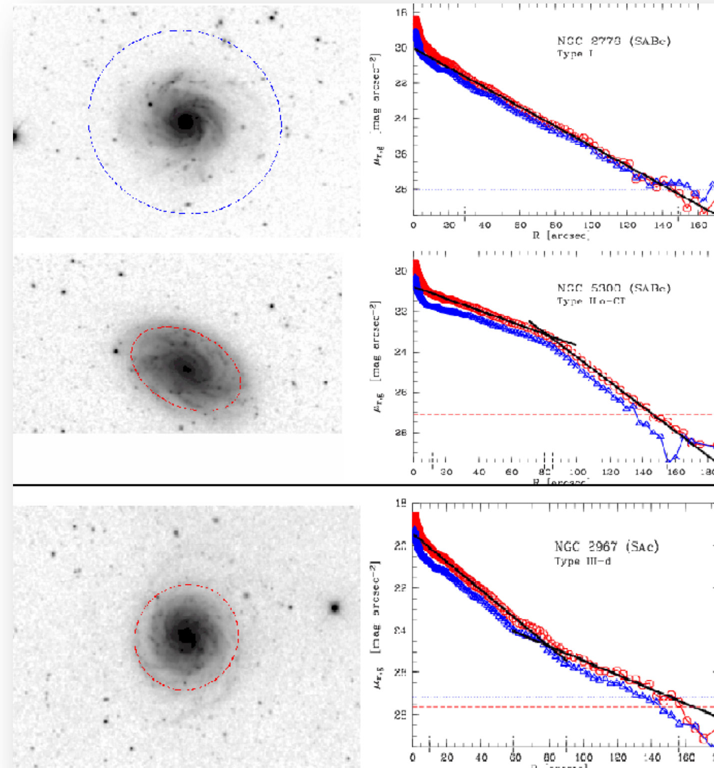
Luminosity function



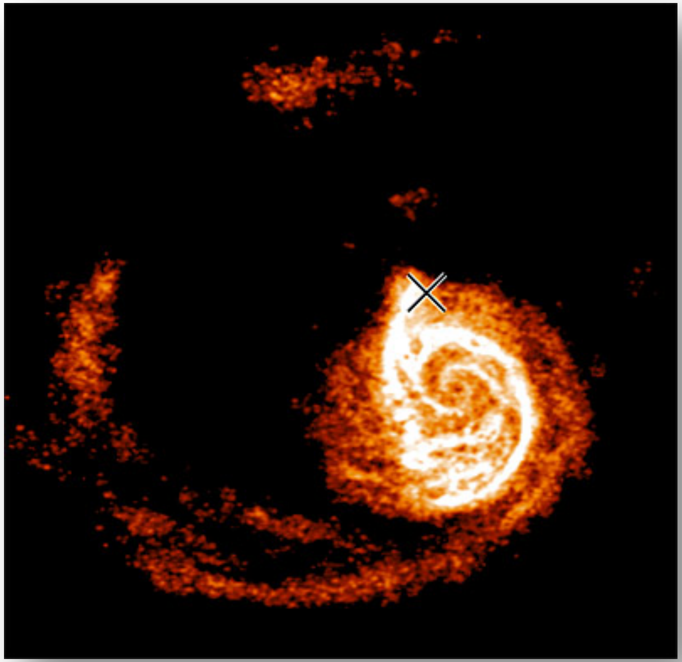
Luminosity profiles





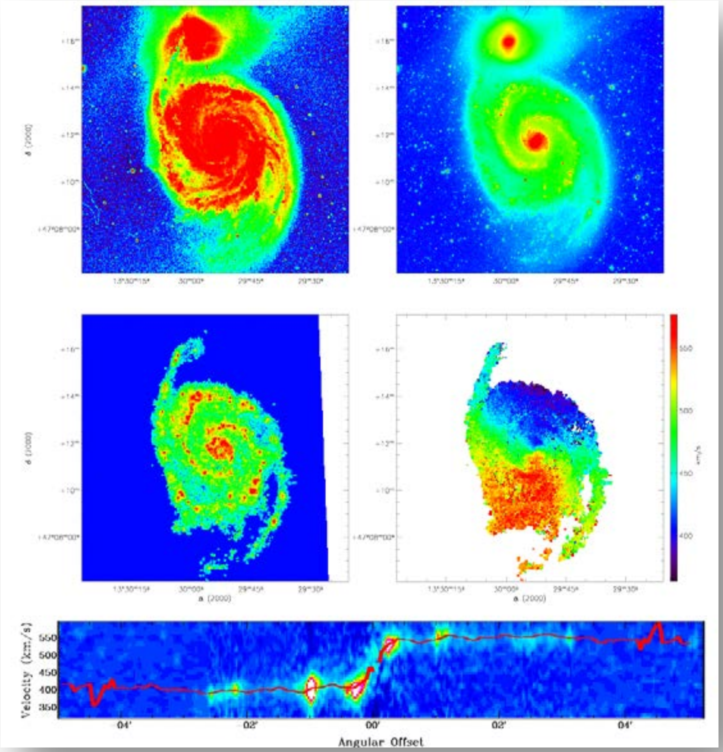


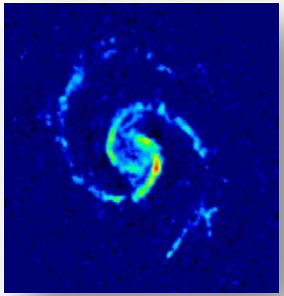
ISM (HI, HII, H_2)



HI

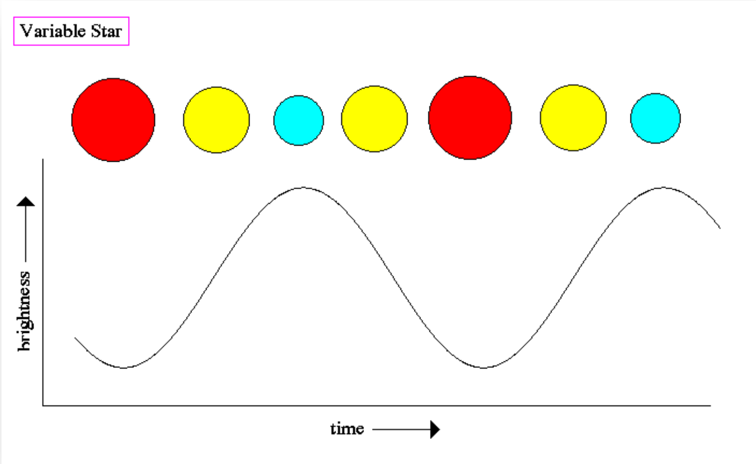
HII

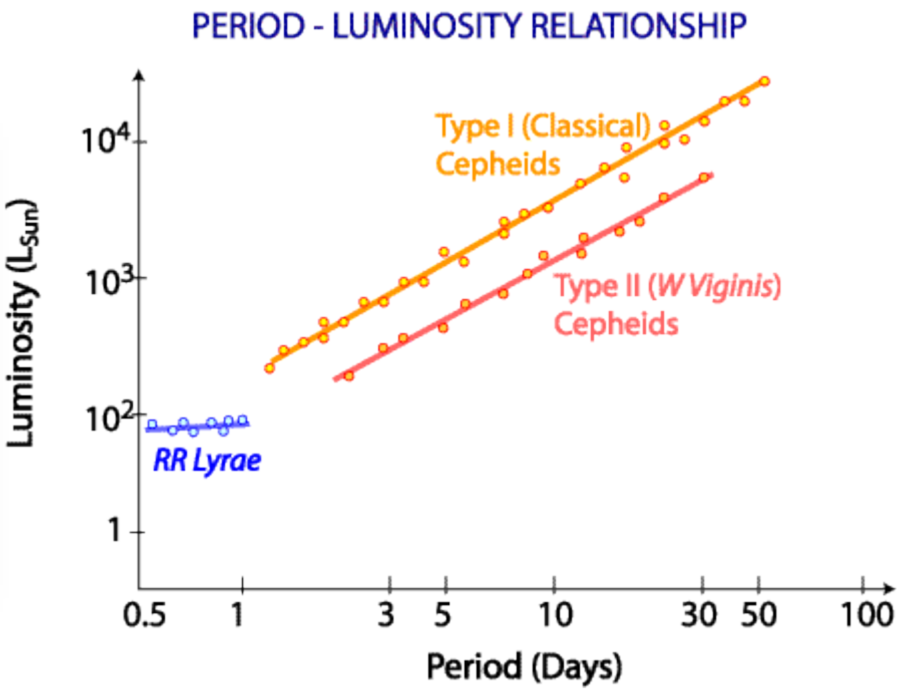




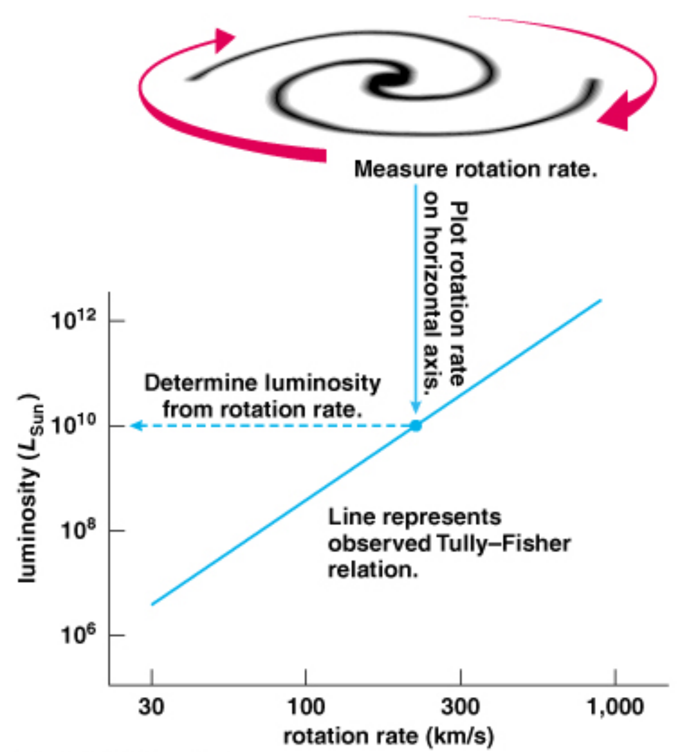
H_2

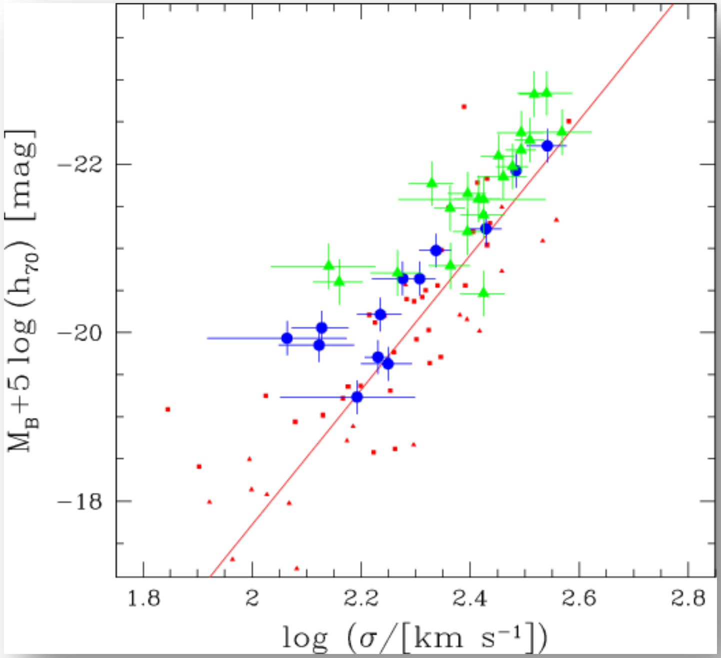
Distance scale



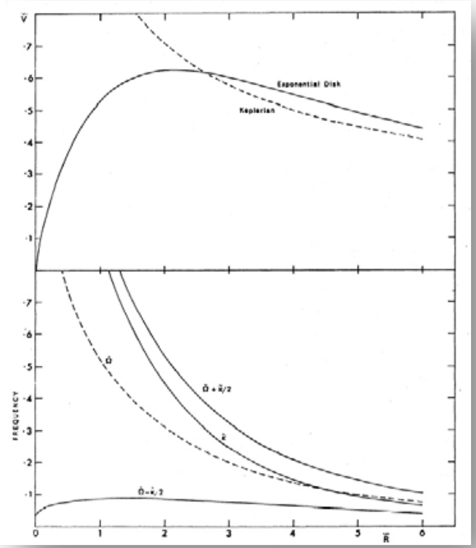


Distance scale

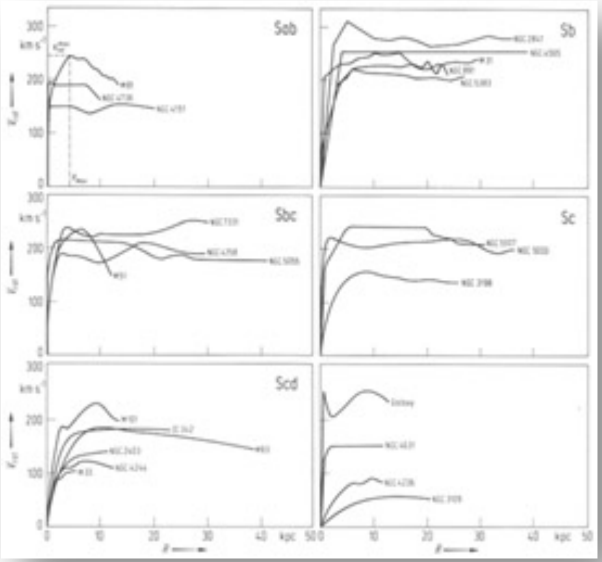




Kinematics & rotation curves

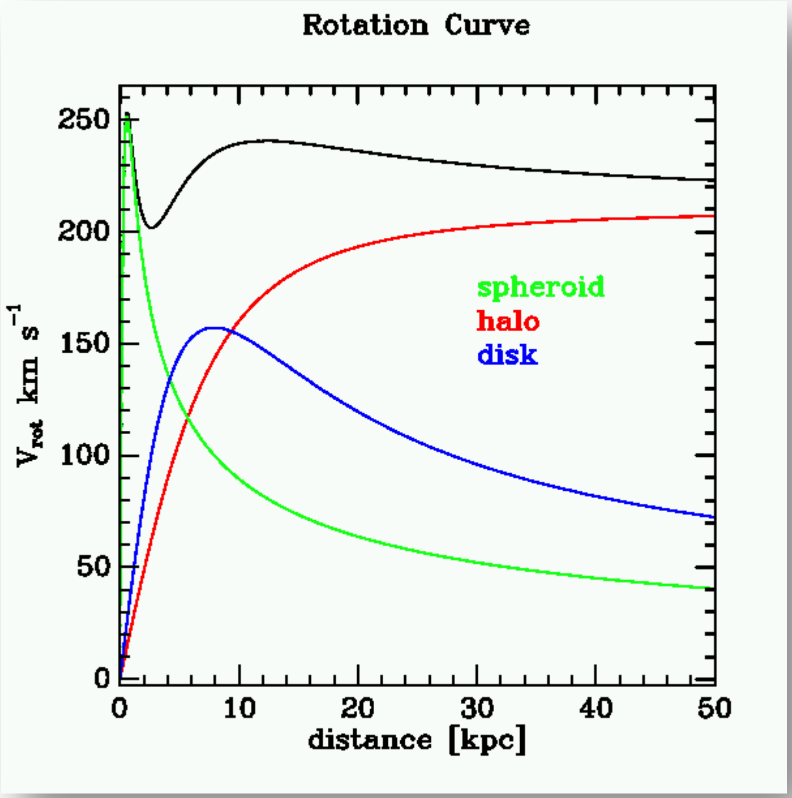


(Freeman 1970)

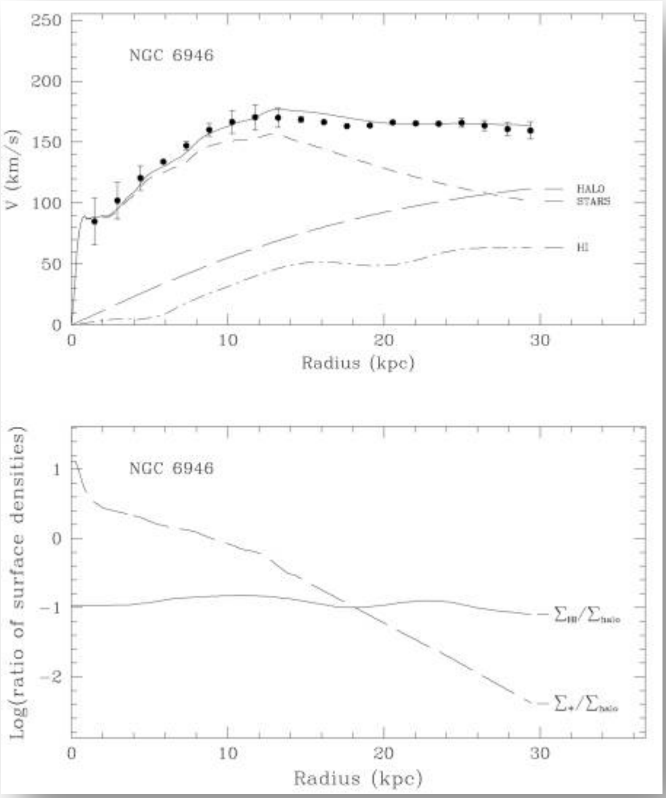


(Bosma 1976)

Mass models

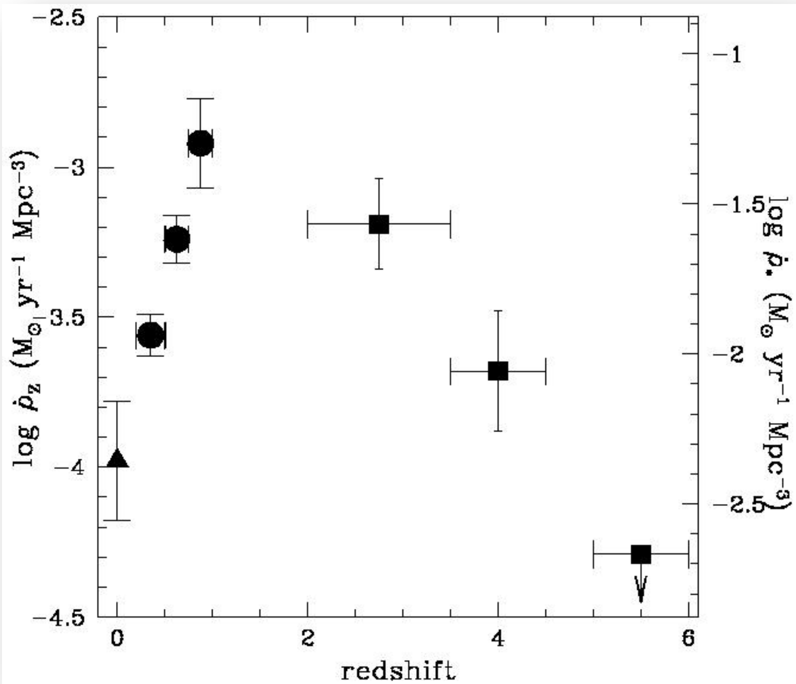


Rotation Curve
spheroid
halo
disk
V_{rot} km s^{-1}
distance [kpc]
0
50
100
150
200
250
0
10
20
30
40
50

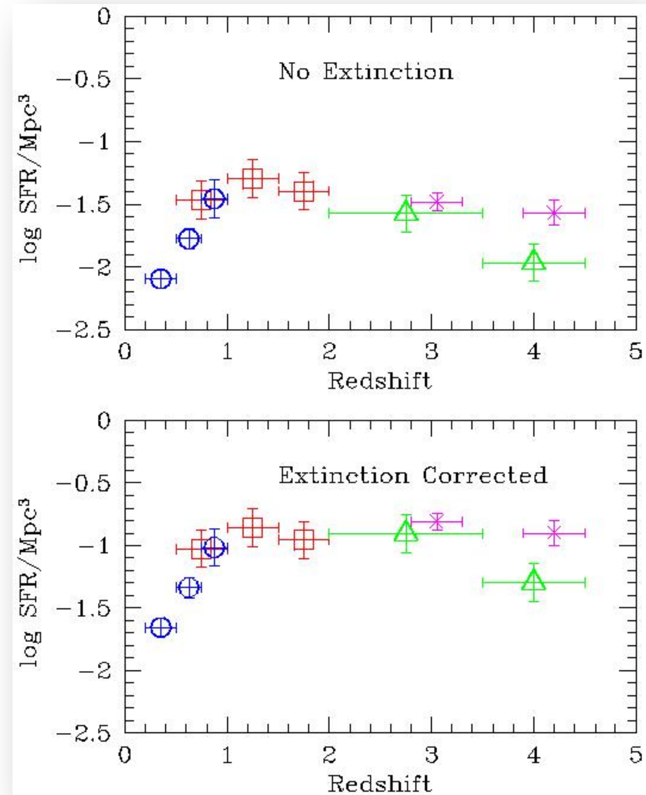


NGC 6946
V (km/s)
Radius (kpc)
HALO
STARS
HI
0
50
100
150
200
250
0
10
20
30
NGC 6946
Log(ratio of surface densities)
Radius (kpc)
$\Sigma_{HI}/\Sigma_{halo}$
Σ_{*}/Σ_{halo}
1
0
−1
−2
0
10
20
30

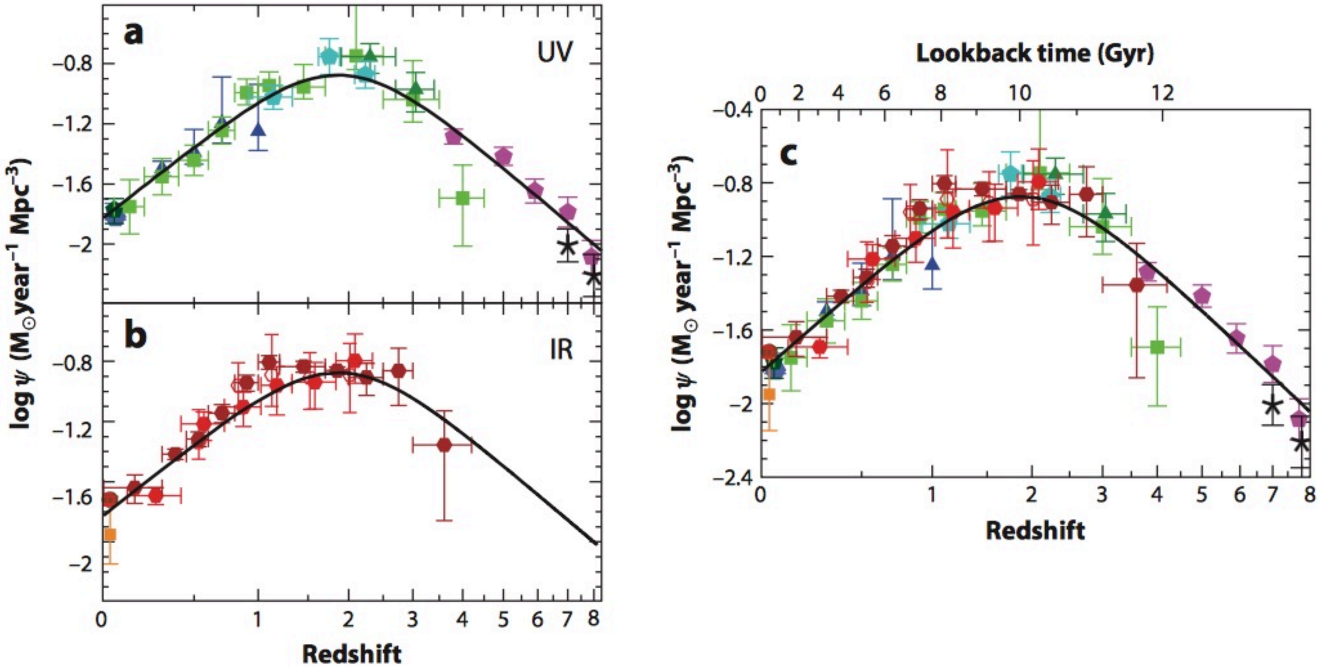
STAR FORMATION (SFR) vs z



Original paper (Madau plot)

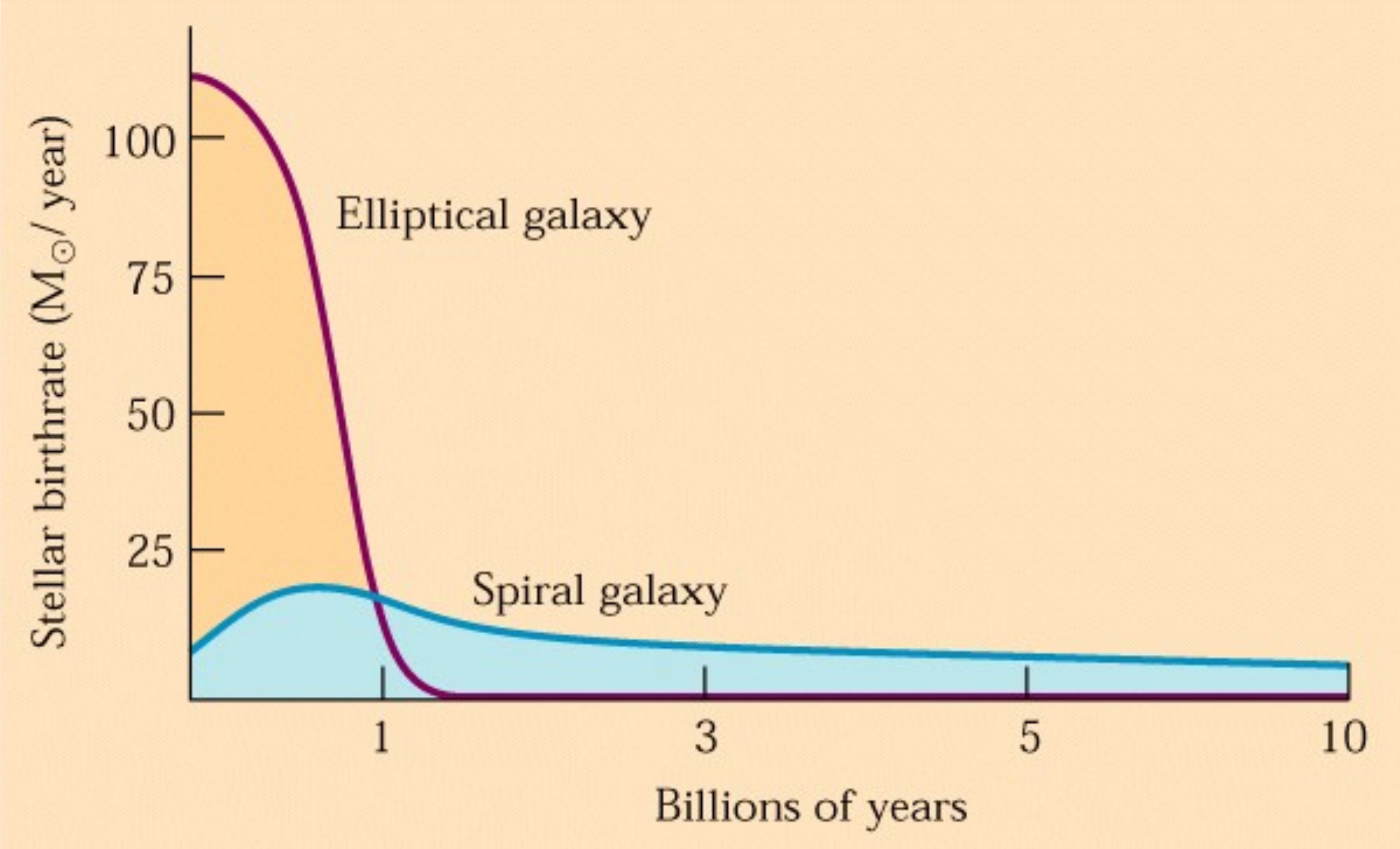


STAR FORMATION (SFR) vs z

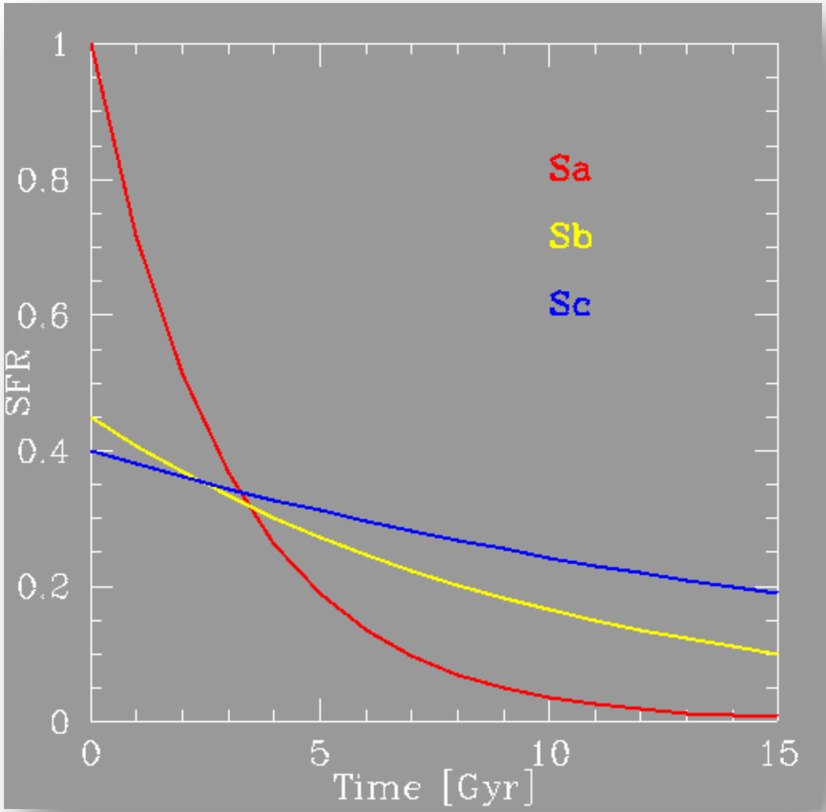


(Madau & Dickinson 2014)

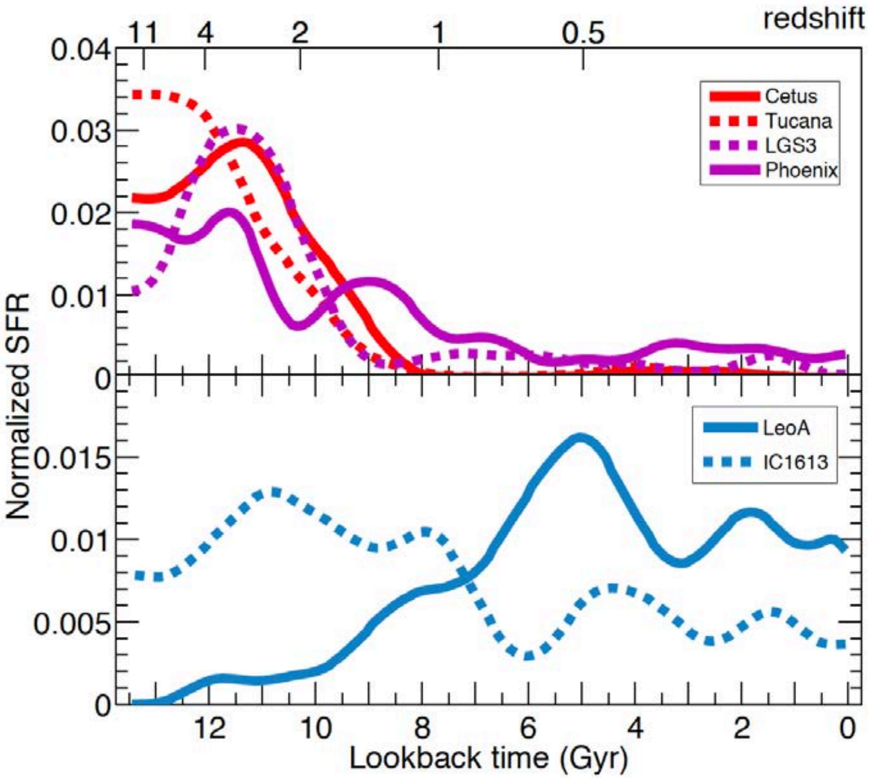
Star formation (SFR) vs type

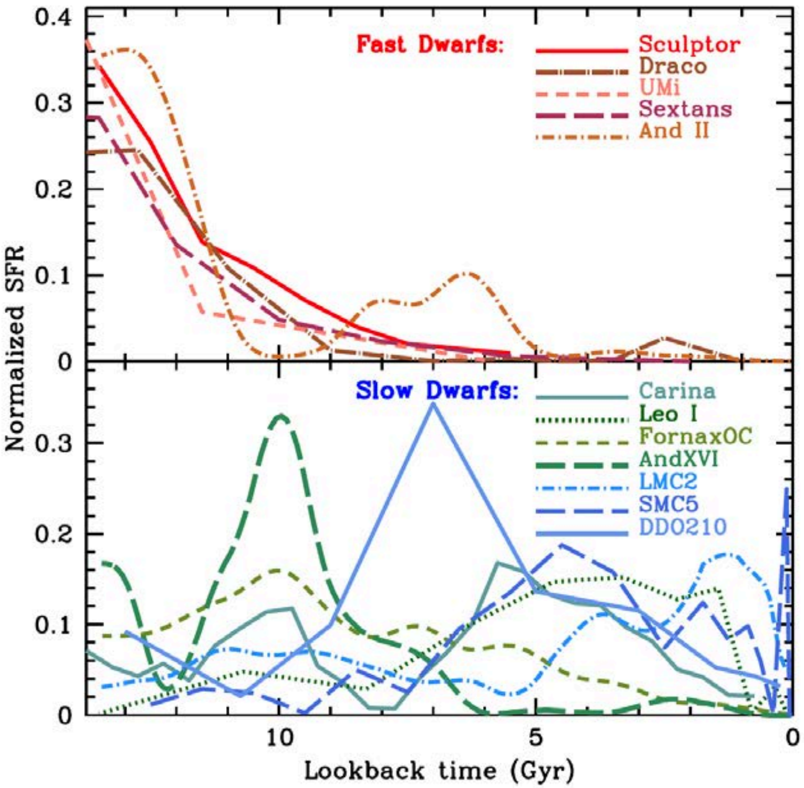


Star formation (SFR) vs type



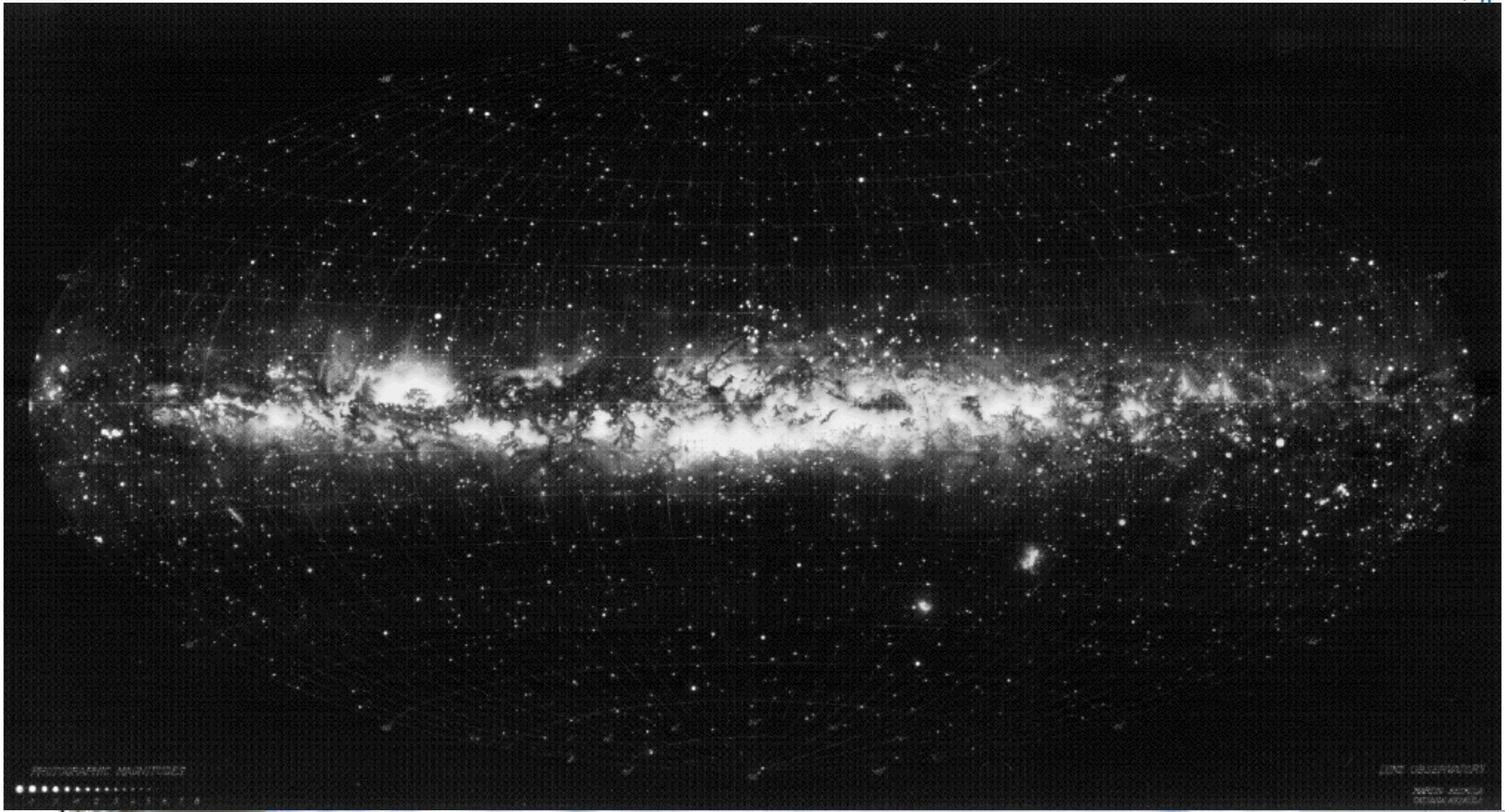
Star formation (SFR) vs type





Milky Way (1)

Milky Way (2)



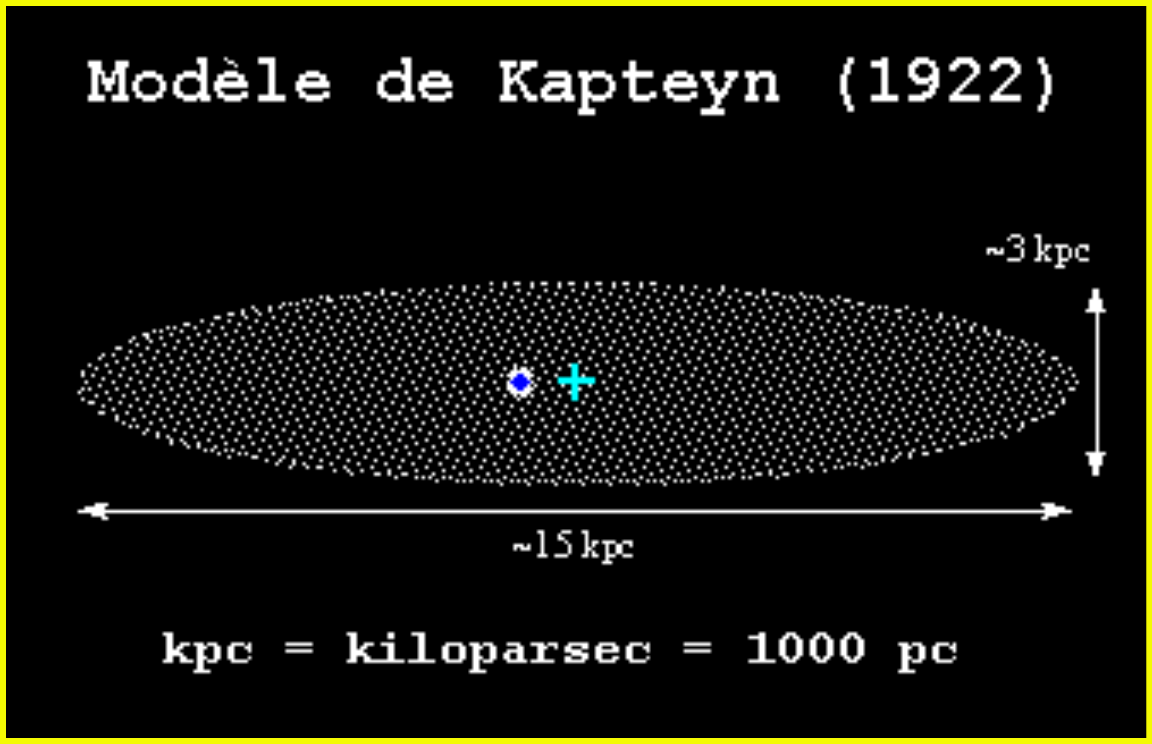
Center in the visible

$A_V \sim 30$ mag.!

From COBE

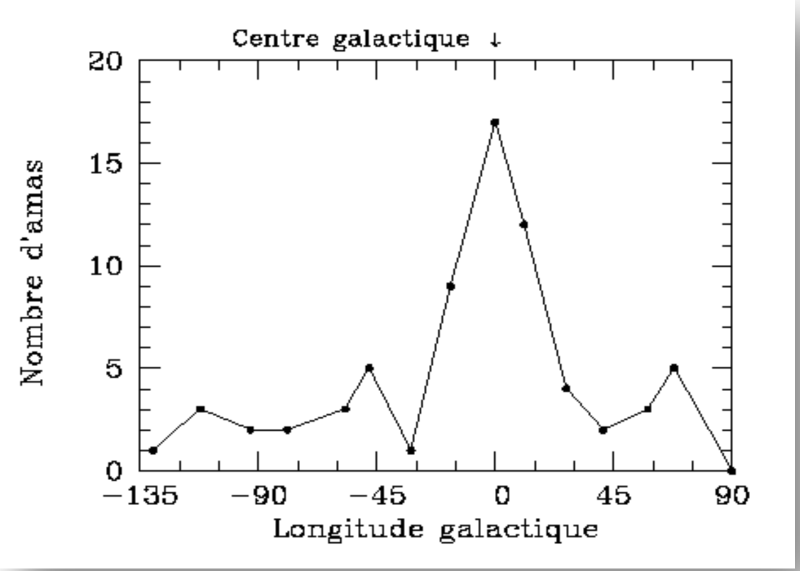
In the IR

Kapteyn's Model



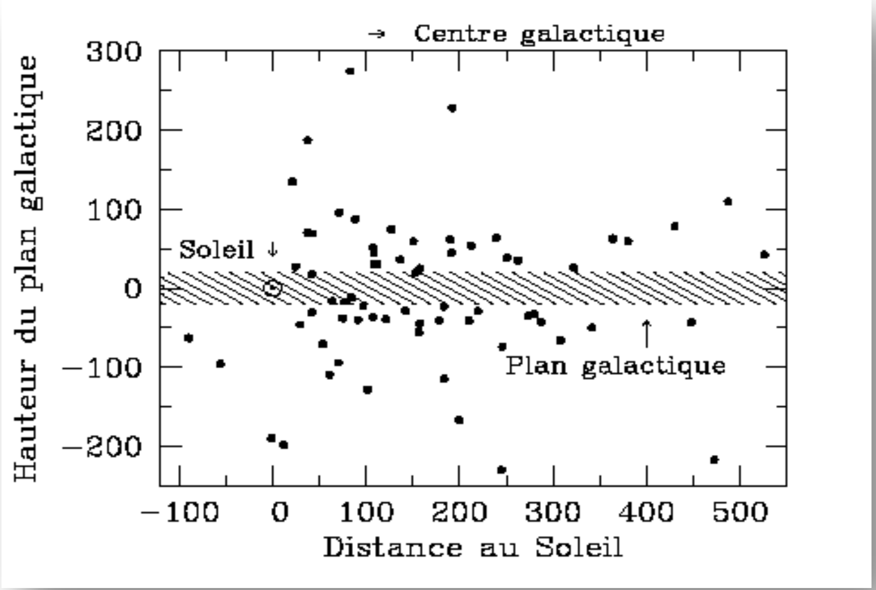
Shapley's Model (1918)

- The globular clusters are not distributed uniformly in <u>longitude</u> but there is a strong concentration in **Sagittarius**

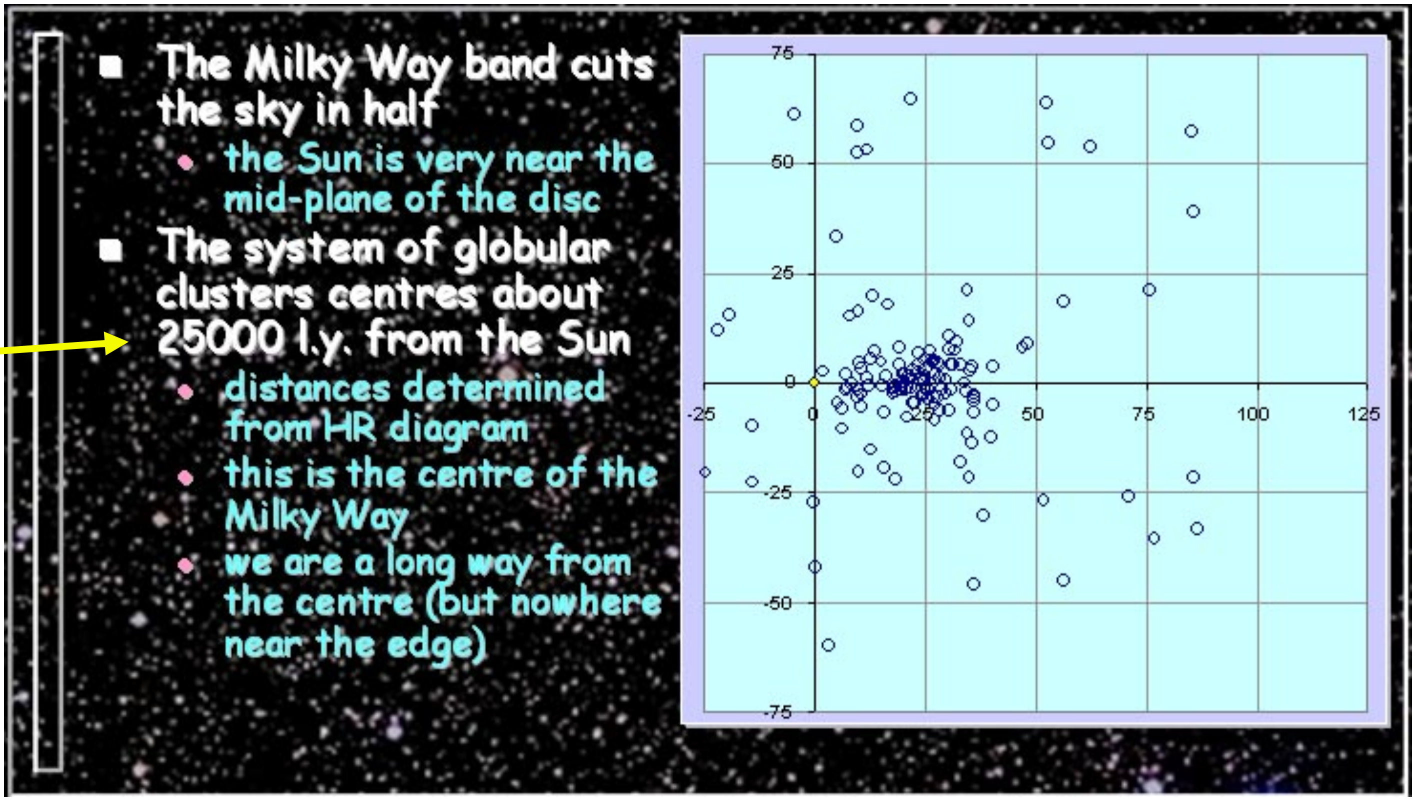


Shapley's Model (1918)

- Clusters are distributed uniformly in *latitude*, on each side of the Galactic plane



Components of the Galaxy

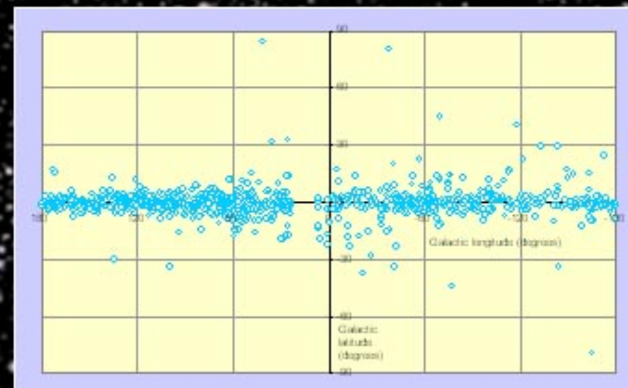


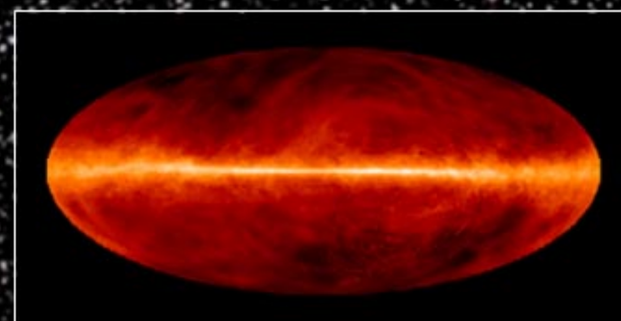
~ 8 kpc

Components of the Galaxy

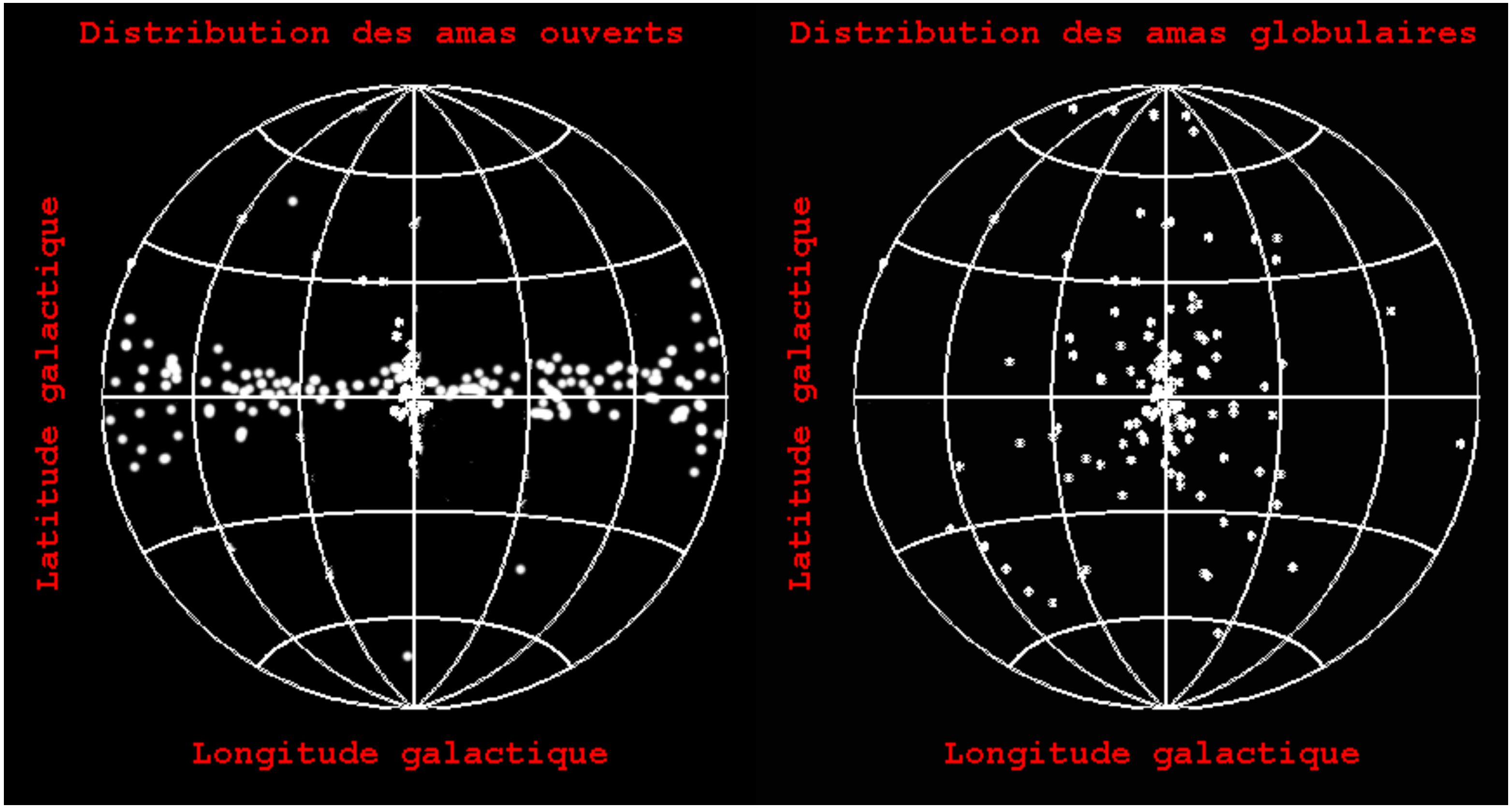
- Open clusters are found close to the Milky Way on the sky
  - they belong to the disc
- Globular clusters aren't
  - they form a spherical "halo" around the disc
- Hydrogen gas is very concentrated in the mid-plane of the disc
  - new star formation confined to disc

→ The disc contains younger stars than the halo





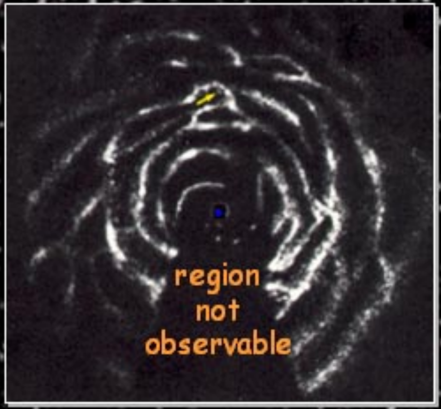
Components of the Galaxy

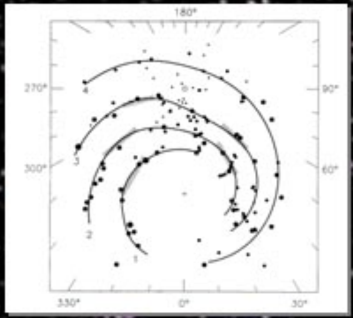


Components of the Galaxy

- We can use the rotation of the disc to map the Milky Way in hydrogen gas
  - neutral hydrogen emits a radio spectral line at 21 cm
  - orbital motion produces Doppler shift
  - use geometry to work out location of cloud

➔ The Milky Way appears to be a rather untidy spiral
  - similar results from mapping the ionised hydrogen associated with hot (massive, young) stars





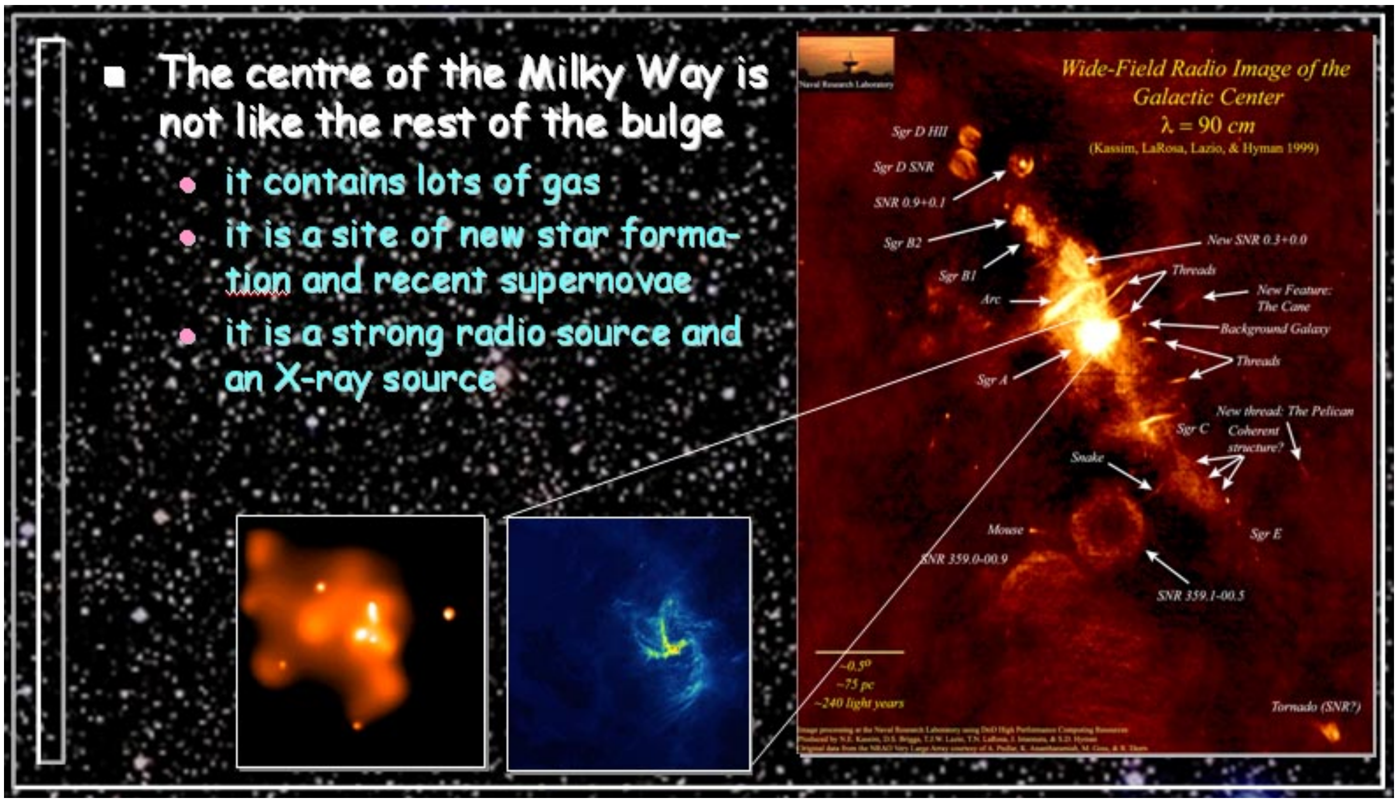
Components of the Galaxy

Components of the Galaxy

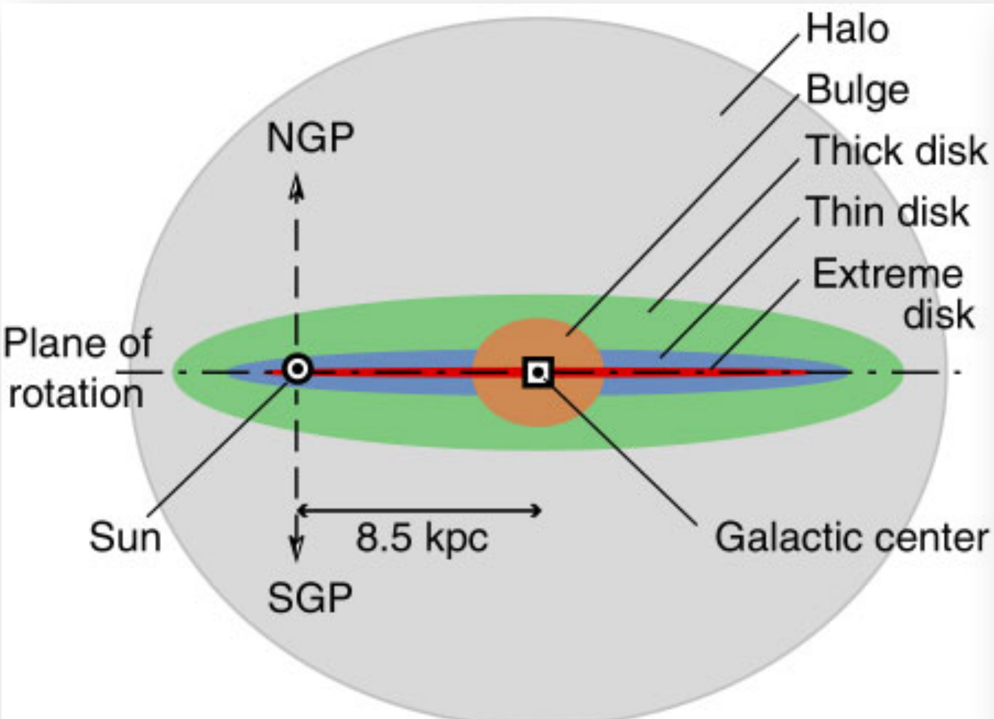
- By looking in the infra-red we can see through the dust
  - the Milky Way looks remarkably like NGC891
- By looking in radio we have mapped out spiral arms
  - the Milky Way resembles galaxies such as M61

➔ The Milky Way is a typical large spiral galaxy
  - (like the Sun, larger than most, but not a champion!)

Components of the Galaxy



Components of the Galaxy



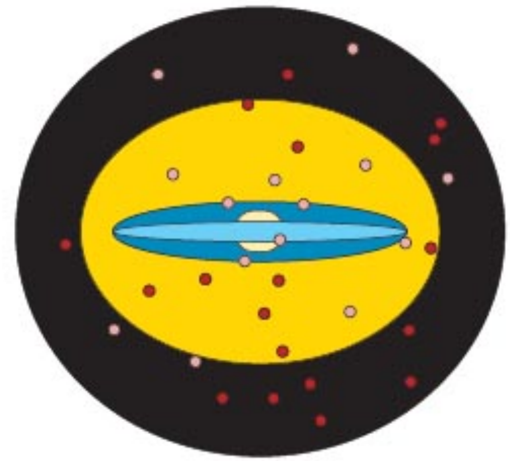
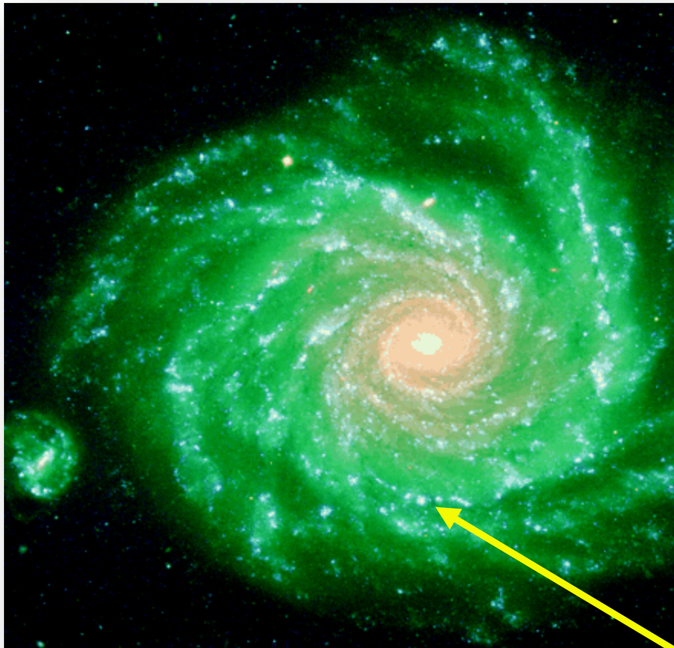
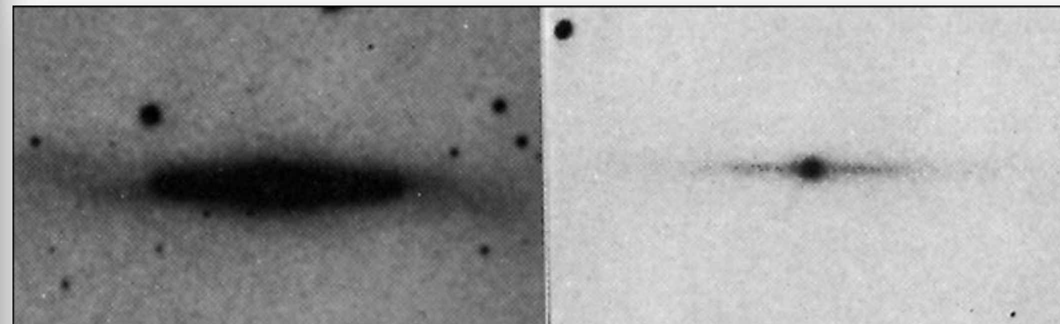


Fig. 1. Schematic of Milky Way showing the stellar disk (light blue), the thick disk (dark blue), stellar bulge (yellow), stellar halo (mustard yellow), dark halo (black), and globular cluster system (filled circles). The stellar disk is about 30 kpc (100,000 light years) in diameter. The baryon and dark halos extend to a radius of at least 100 kpc.

Components of the Galaxy





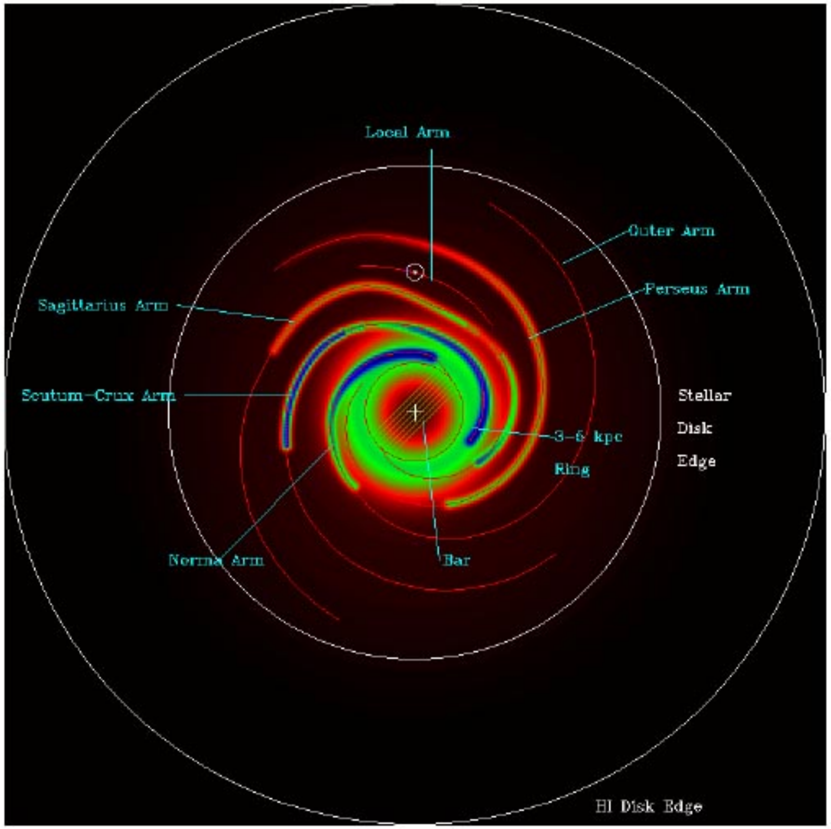
Thick disk

Thin disk

Position of the Sun

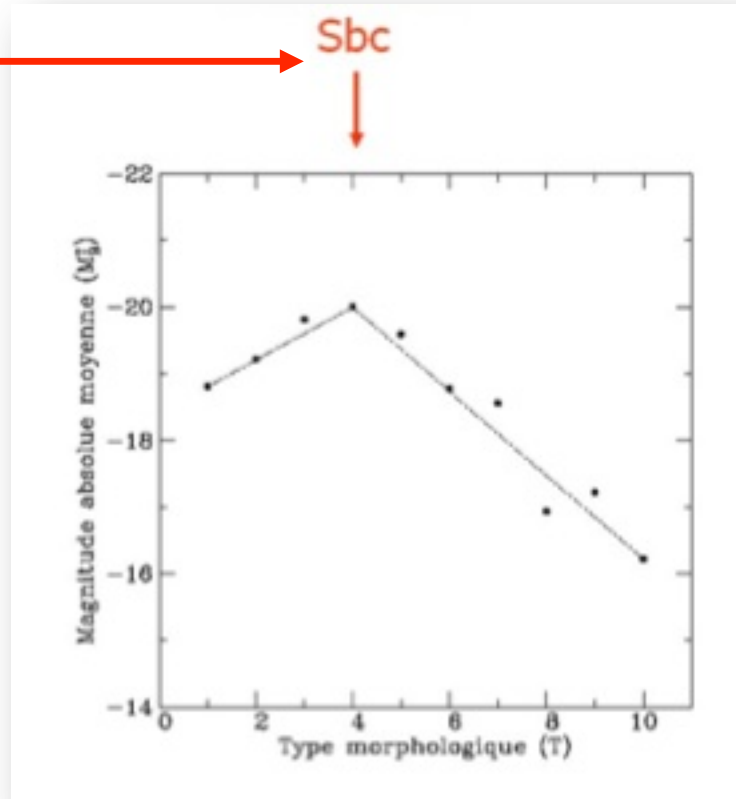
Components of the Galaxy

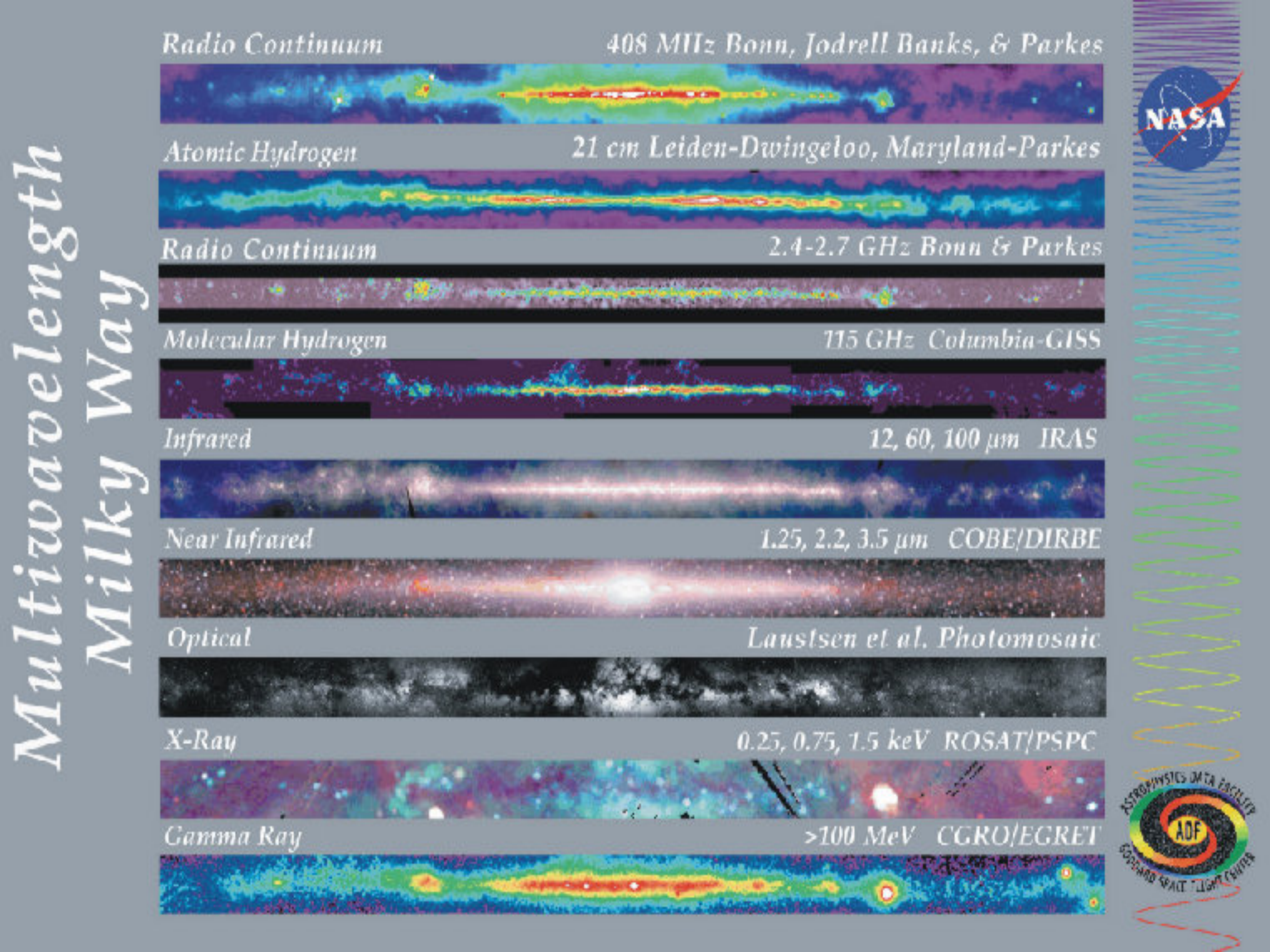
- ‘top’ view
  - are we a grand design spiral?
  - probably an Sb to Sc type
  - more than just a pair of arms
  - we’re in a ‘spur’ off an arm



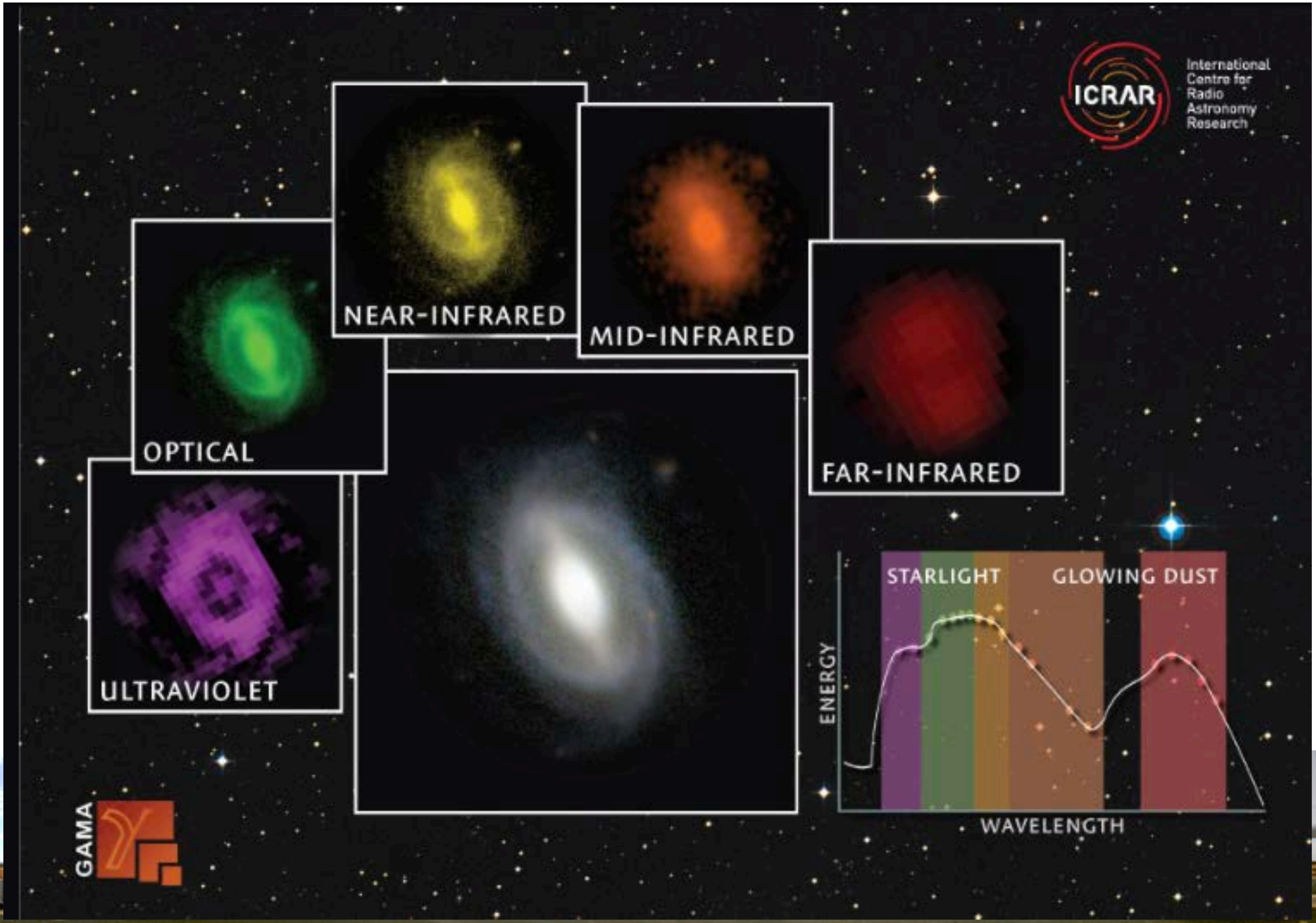
Components of the Galaxy

Milky Way
Andromeda

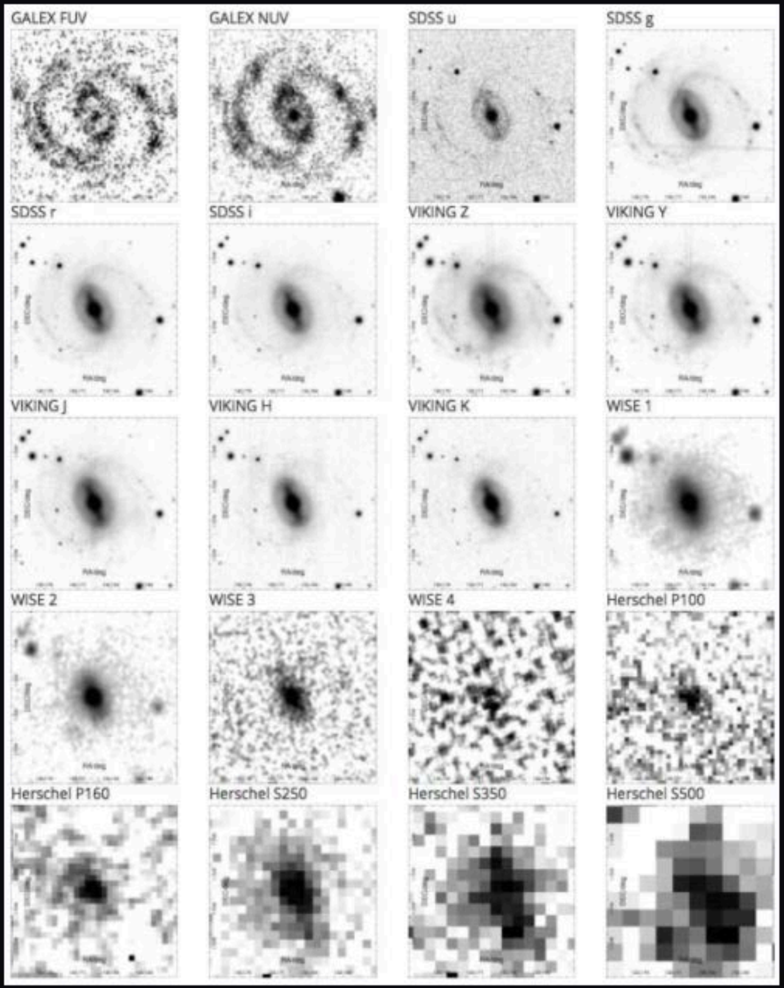



Multiwavelength Milky Way
Radio Continuum
408 MHz Bonn, Jodrell Banks, & Parkes
Atomic Hydrogen
21 cm Leiden-Dwingeloo, Maryland-Parkes
Radio Continuum
2.4-2.7 GHz Bonn & Parkes
Molecular Hydrogen
115 GHz Columbia-GISS
Infrared
12, 60, 100 μm IRAS
Near Infrared
1.25, 2.2, 3.5 μm COBE/DIRBE
Optical
Laustsen et al. Photomosaic
X-Ray
0.25, 0.75, 1.5 keV ROSAT/PSPC
Gamma Ray
>100 MeV CGRO/EGRET
NASA
Astrophysics Data Facility
ADF
Goddard Space Flight Center

Multi-Wavelength Imaging



Multi-Wavelength Imaging



A galaxy from the GAMA survey observed at 20 different wavelengths from the far ultraviolet to the far infrared. Credit: ICRAR / GAMA.

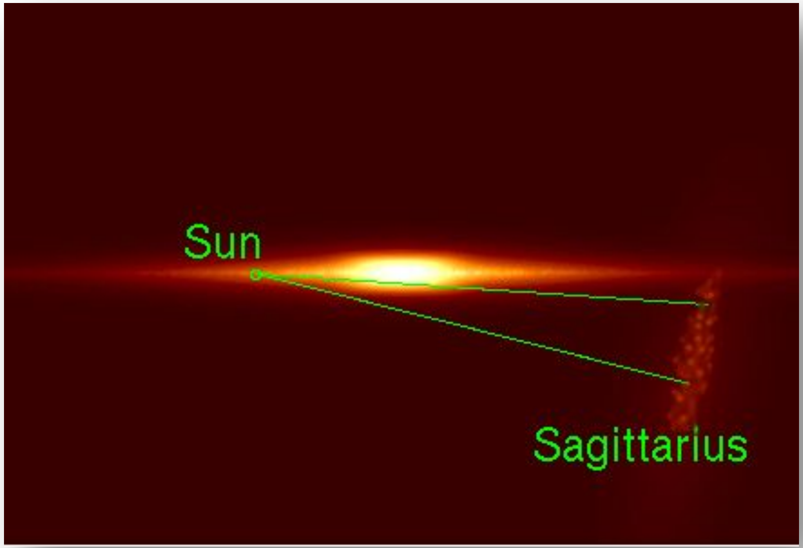
Formation & evolution of the Galaxy

- Recent observation suggest that the MW formed by the aggregation of stars and gas originating from a reservoir of small galaxies formed previously (**hierarchical clustering)**
- This model replaced the model of the rapid **monolithic collapse** (10^8 a.) (Eggen, Lynden-Bell & Sandage 1962)

- Start of the process ~12×10^9 years
- 2 evolution tracks:
  1) One in the halo and the bulge which are slowly rotating
  2) One in the disc which has a rapid rotation
- Age of the disk ~ 10×10^9 years

Formation & evolution of the Galaxy

- Existence of a thin and a thick disk shows that satellites'mergers is a continuous process since the formation of the MW
- Ex: Sagittarius



Formation & evolution of the Galaxy

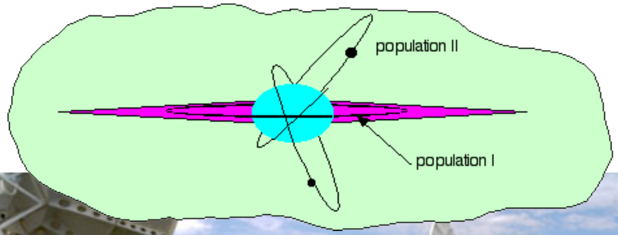
- A large part of Galactic and Extragalactic Astronomy in the last 20 years is devoted at the study of this hierarchy of structures
- See: Hartwick 1996, *Unsolved Problems of the Milky Way*, IAU Symp. 169

- Stars belonging to the different components are sorted by their kinematics
- Thin disk: $\sigma < 20$ km/s & thick./diam. ~ 1/10
- Thick disk: $\sigma > 20$ km/s & thick./diam. ~ 1/3
- Halo $v_x \sim v_y \sim v_z$

Concept of Stellar Populations

- In 1940, Walter Baade observed M31 and realized that the bright stars in the bulge and the halo have redder colors than those of the disk.

- The color-magnitude (HR) diagrams and the spatial distributions show the existence of two distinct groups of stars (concept of populations: I & II).



Components of the Galaxy

➢ **DISK:**

1. flat, D ~ 30-40 kpc
2. young * (pop I)
   Z ~ 400 pc

   +

3. gas & dust
   Z ~ 100 pc

   +

4. younger * in the spiral arms

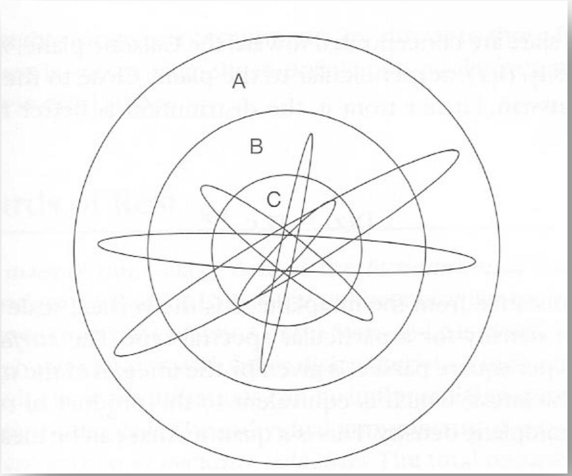
➢ **BULGE:**

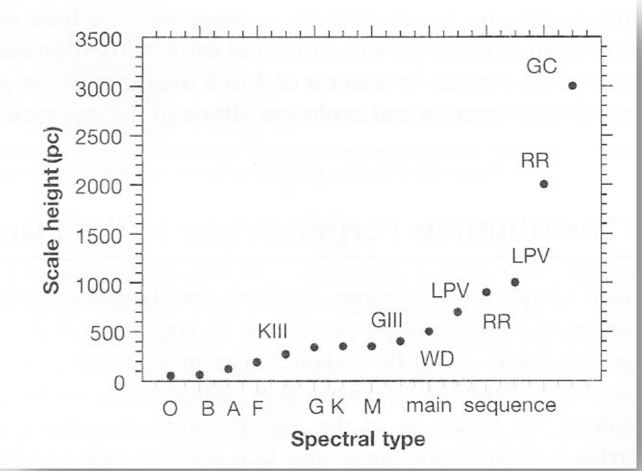
1. +/- spherical
2. old * (pop II)

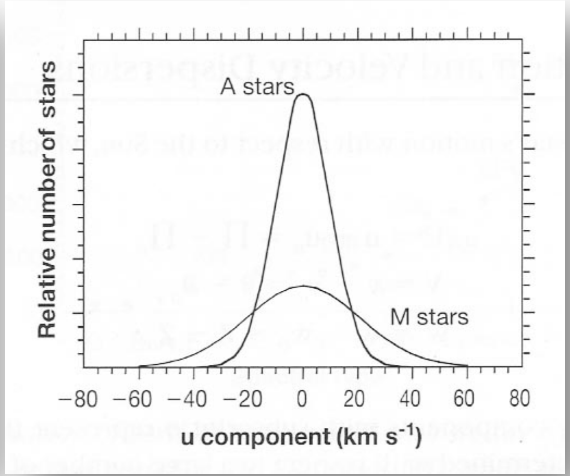
➢ **HALO:**

1. +/- spherical
2. old * (pop II)
3. Globular clusters:
   10^5-10^7 M_{sun}

Components of the Galaxy



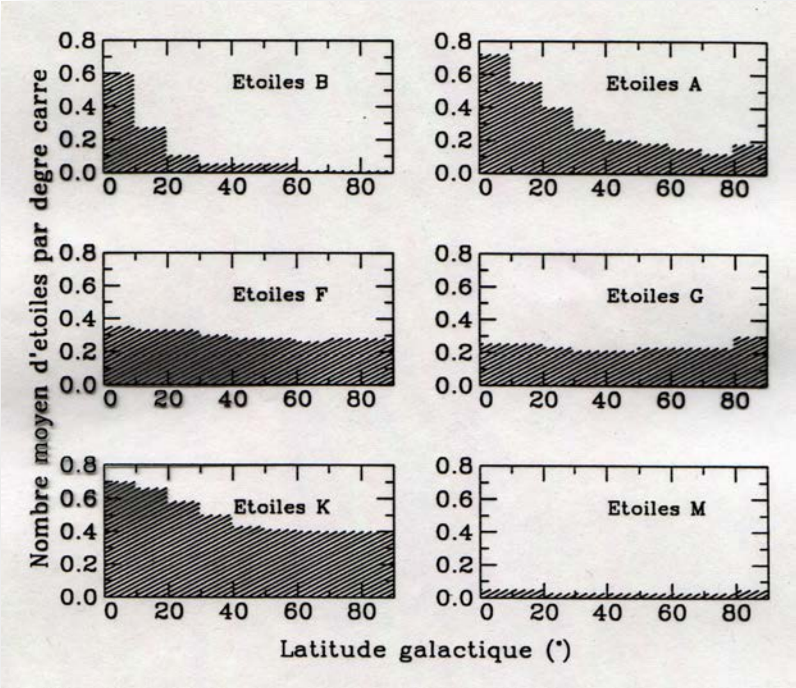




- population II objects move on orbits in all directions
- Mean metallicity is C > B > A
- σ increases with spectral type

Stellar Populations

- Pop I is not homogeneous
  1. Young stars close to the plane
  2. Old stars in a thicker disk



Galactic Structure

Flat disk:

•10^{11} stars (Pop.I)

• ISM (gas, dust)

• 5% of the Galaxy mass, 90% of the visible light

• Active star formation since 10 Gyr.

Central bulge:

• moderately old stars with low specific angular momentum.

• Wide range of metallicity

• Triaxial shape (central bar)

• Central supermassive BH

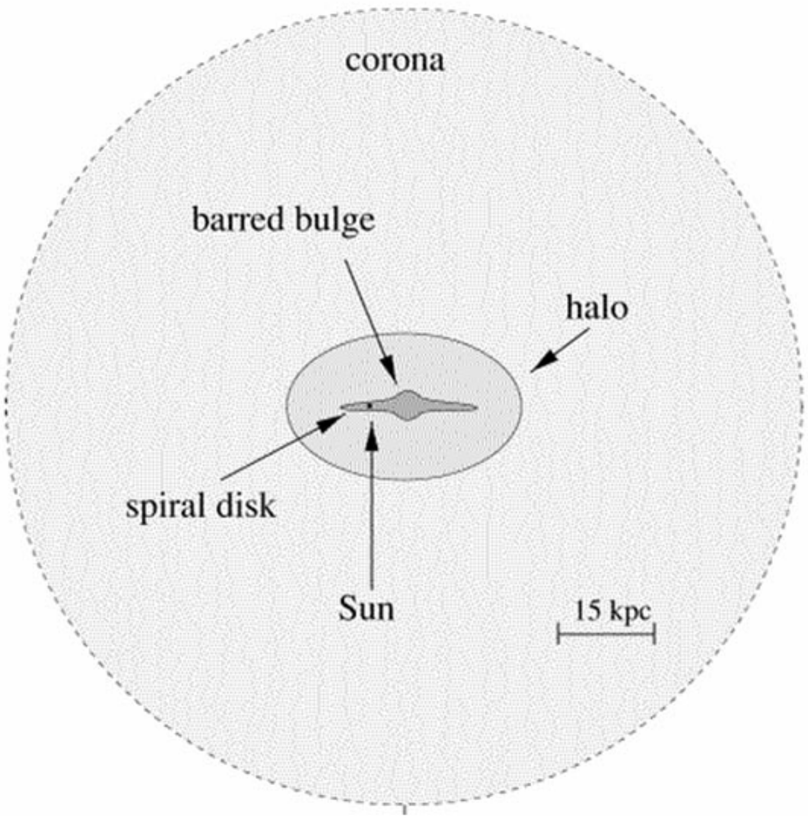
Stellar Halo

• 10^9 old and metal poor stars (Pop.II)

• 150 globular clusters (13 Gyr)

• <0.2% Galaxy mass, 2% of the light

•**Dark Halo**



Interstellar Matter (ISM)

- gas & dust

not distributed uniformly

dense clouds at different T

- 4 types of regions

1. **Molecular clouds**
2. **HI clouds**
3. **HII regions**
4. **Super-bubbles**

Interstellar Matter (ISM)
Molecular Clouds

- temp. ~ 10 K
- cold and dense regions of dust & gas
- many molecules: H_2, OH, CO, H_2O, CH_3CH_2OH (ethhyl alcohol) > 50 types of molecules
- dense star formation

*O,B heat the molecular clouds

HII regions

The "Black Cloud" B68
(VLT ANTU + FORS1)

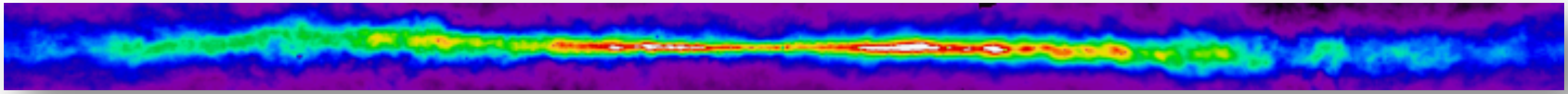
ESO PR Photo 20a/99 (30 April 1999)

Interstellar Matter (ISM) Molecular Clouds

- Dust acts as a catalyst in the formation of molecules:
  - the different elements assemble at the surface of the grains
  - the grains protect the molecules against UV radiation from hot stars which would dissociate the molecules
- The more a region is dense and cold (no thermal excitation), the easiest it is for those stars to form by gravitational collap.

Interstellar Matter (ISM)
HI clouds

- temp. ~ 100 K
- neutral hydrogen HI
- the most abundant gas component



Interstellar Matter (ISM) HI clouds

- As in external galaxies (e.g.: UGC 7170), the disc of the MW is *warped* and thickens in the outer parts.

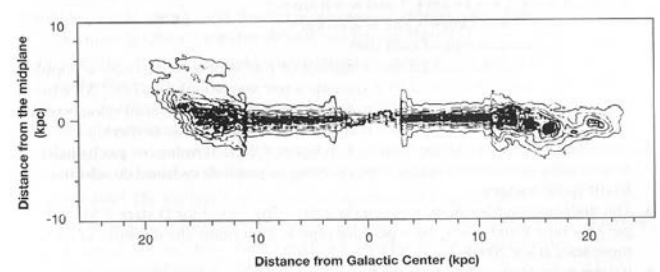


FIGURE 8.26 *H I distribution along the plane of the Milky Way, based on observations at galactic longitudes 75° (left side) and 255° (right side). (Figure from Burton 1992.)*

The warped edge-on galaxy ESO 510-13

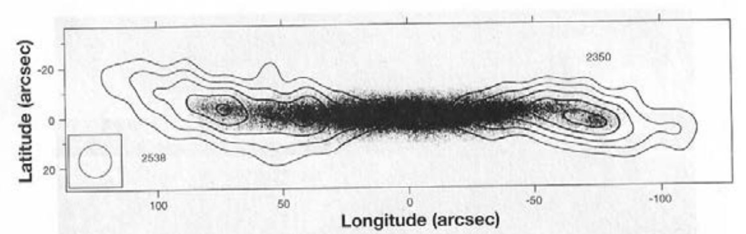
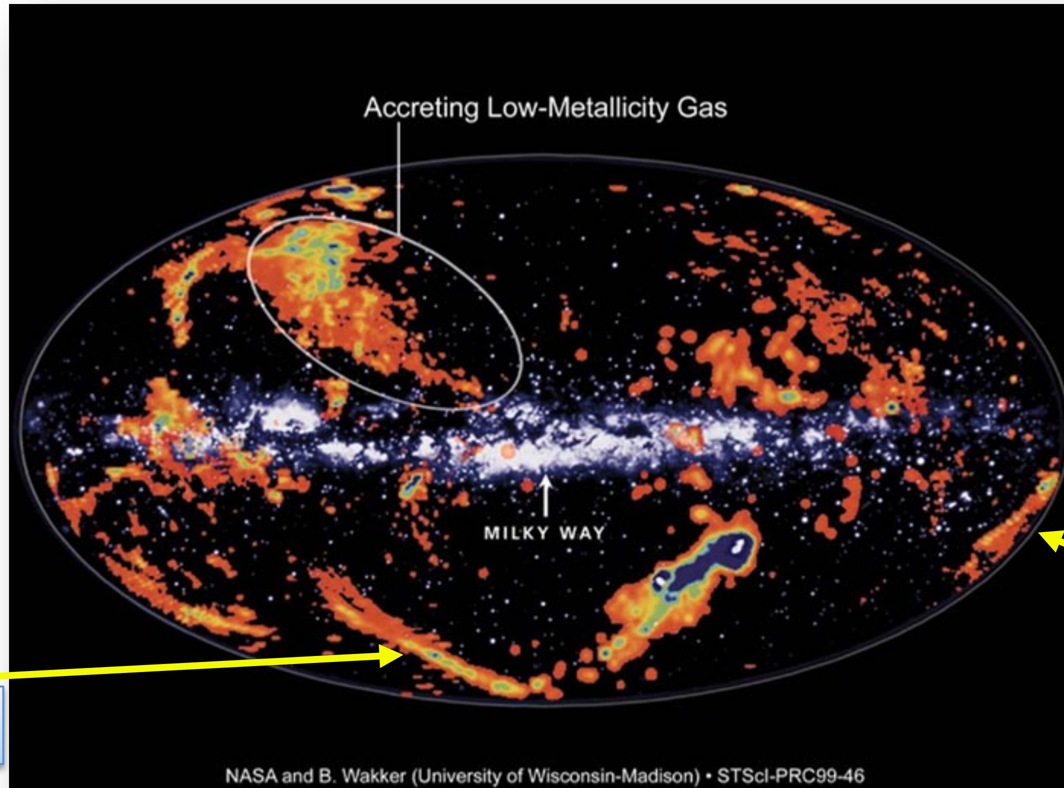


FIGURE 8.27 *H I velocity channel contours overlaid on a B band image of UGC 7170, showing the gas warp. (Figure from Cox et al. 1996.)*

Interstellar Matter (ISM)
HI clouds

HVCs



Magellanic Stream

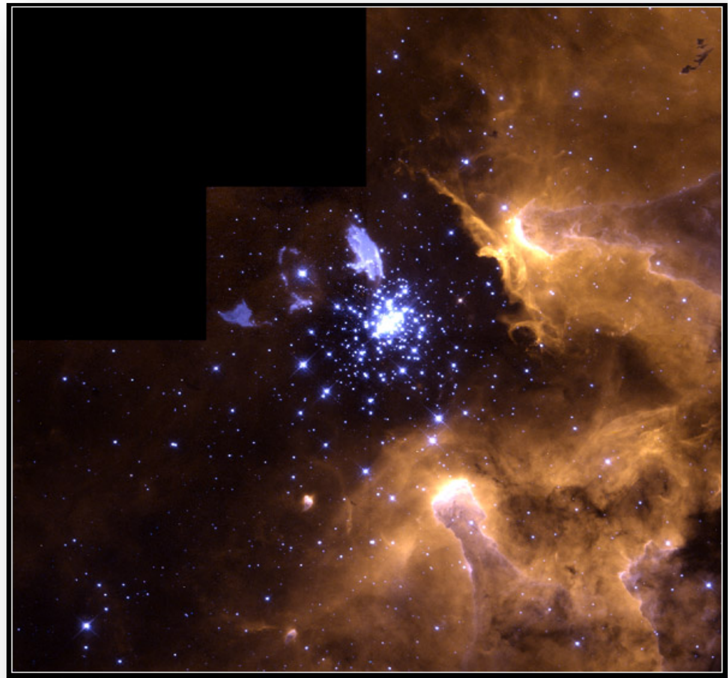
Sagittarius dSph

Interstellar Matter (ISM)
HII regions

- temp.: 10 000 K
- surround the O & B hot *
- UV photons from the OB * ionize the hydrogen
- diameters

  *O 10-100 pc

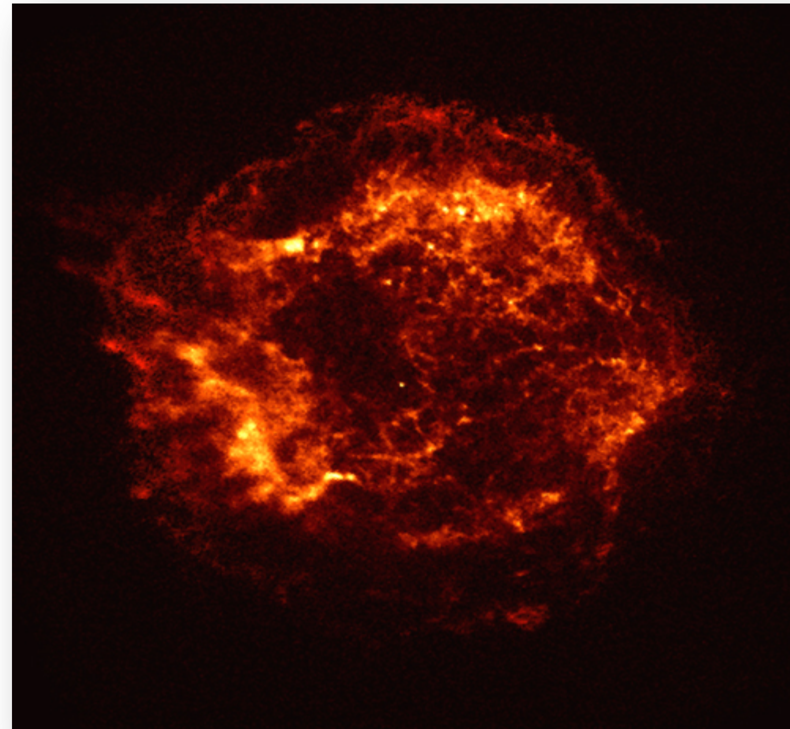
  *B 1-10 pc



NGC 3603 HST • WFPC2
PRC99-20 • STScI OPO • June 1, 1999
Wolfgang Brandner (JPL/IPAC), Eva K. Grebel (Univ. Washington), You-Hua Chu (Univ. Illinois, Urbana-Champaign) and NASA

Interstellar Matter (ISM) Super-bubbles

- temp. ~ 10^6 K (X-rays)
- produce by SNs



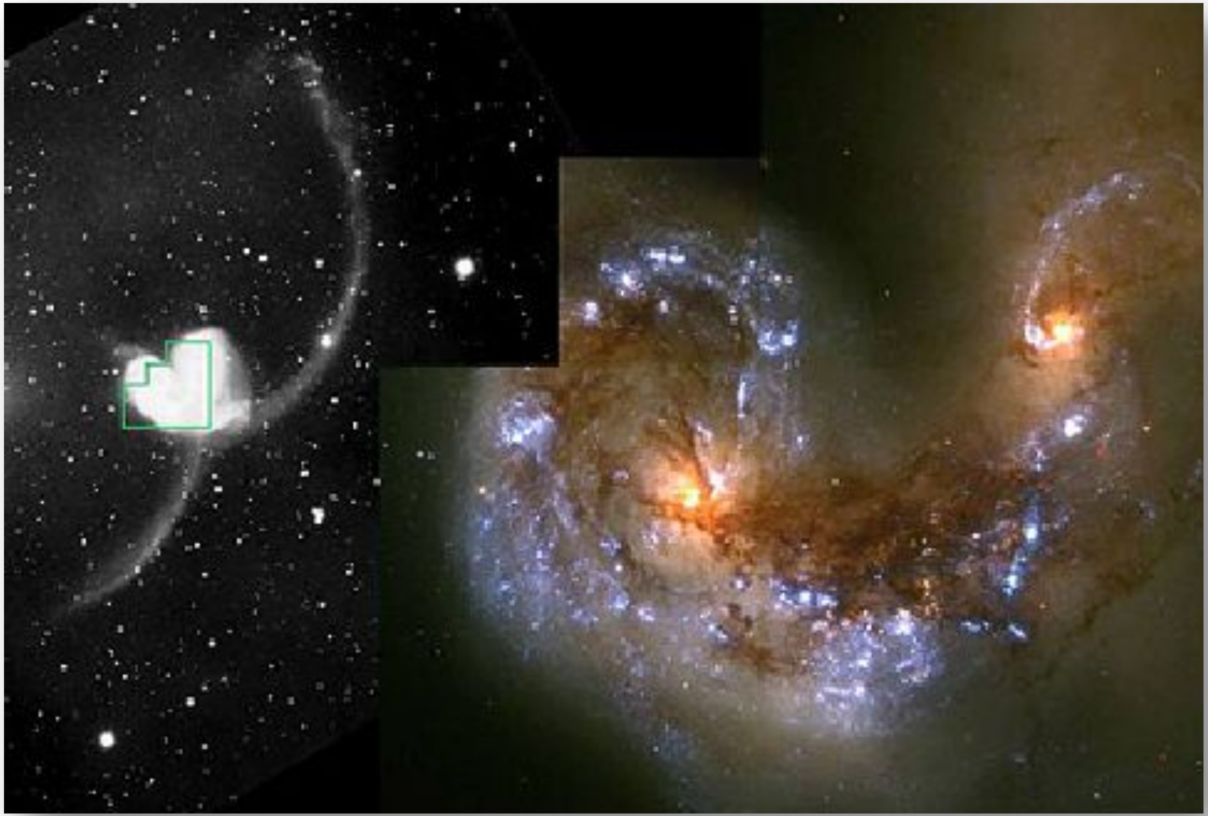
Canadian Galactic Plane Survey (CGPS)

Interstellar Matter (ISM)

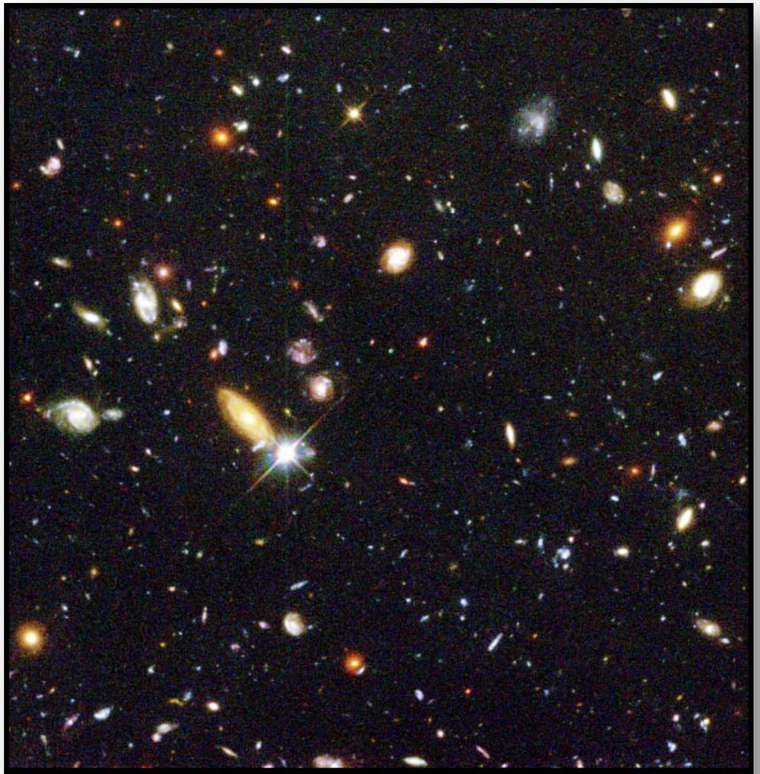
- $M_{gas}/M_{*} \sim 10\%$
- $M_{dust}/M_{gas} \sim 1\%$
- $M_{gas} \sim 10^{10}\ M_{sun}$
- $M_{dust} \sim 10^{8}\ M_{sun}$

Back to external galaxies

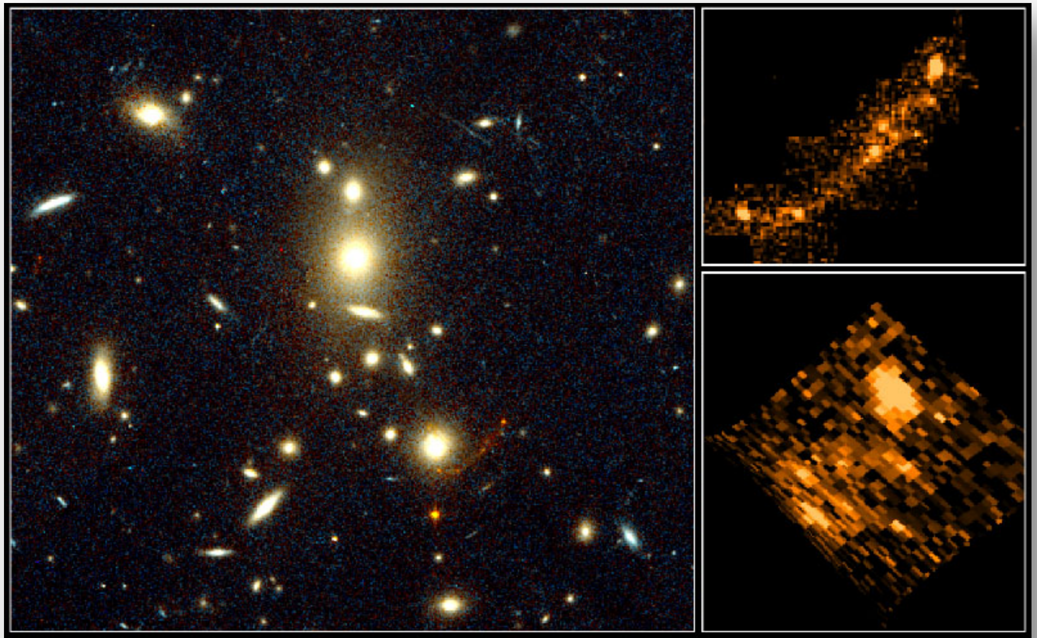
Mergers (Antennae)



Distant Galaxies

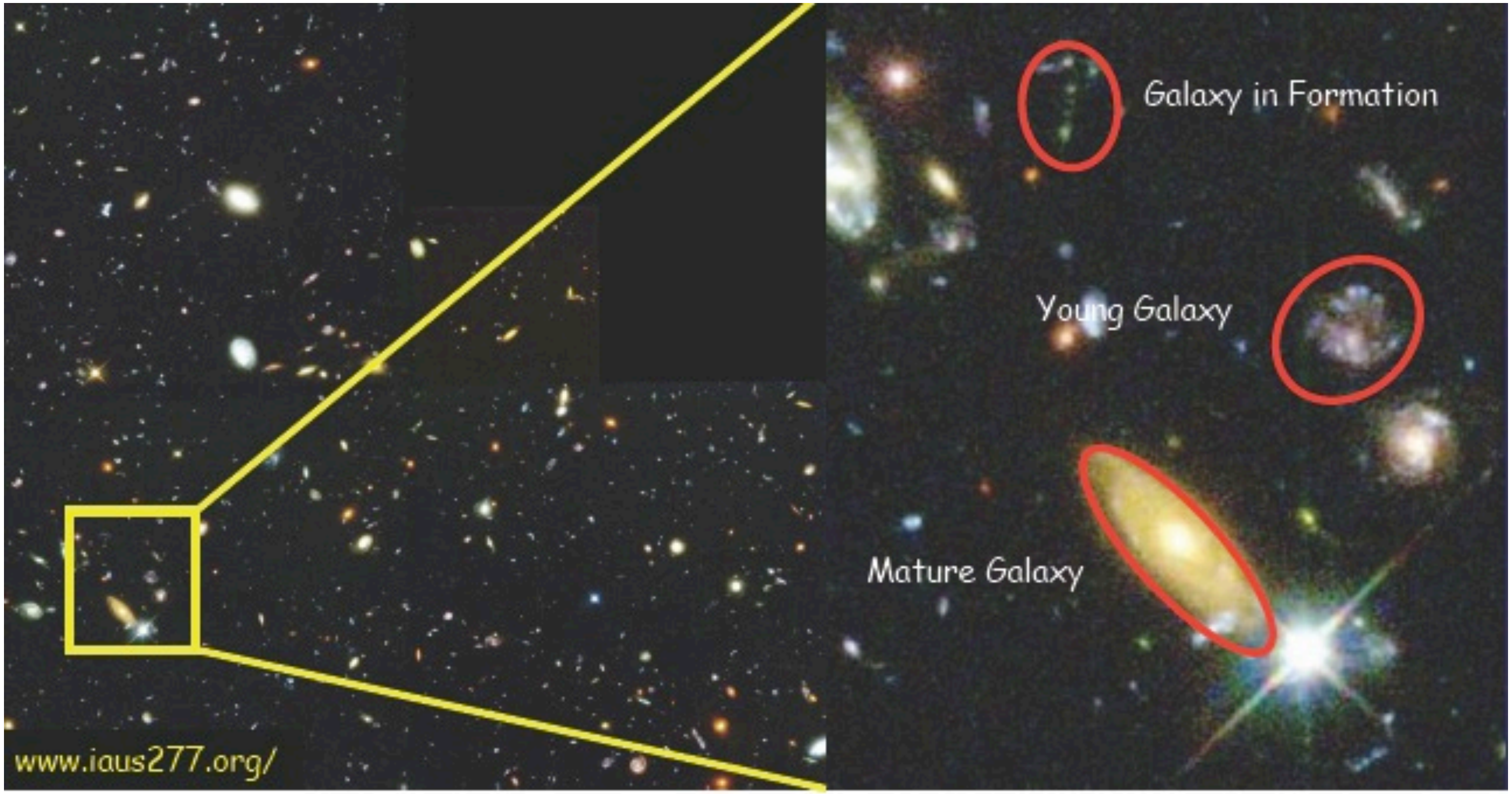


Hubble Deep Field HST • WFPC2
PRC96-01a • ST ScI OPO • January 15, 1996 • R. Williams (ST ScI), NASA

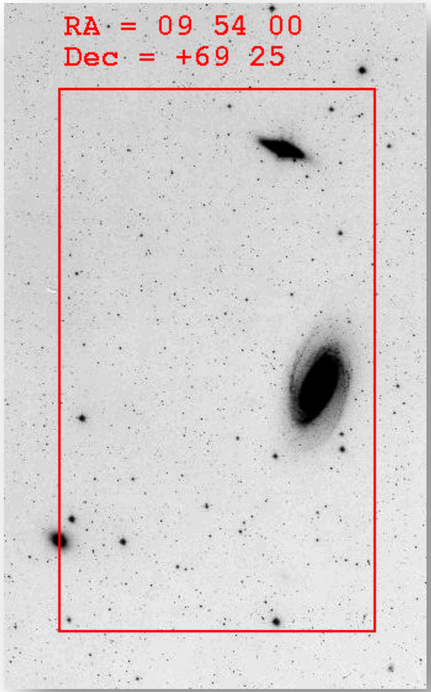


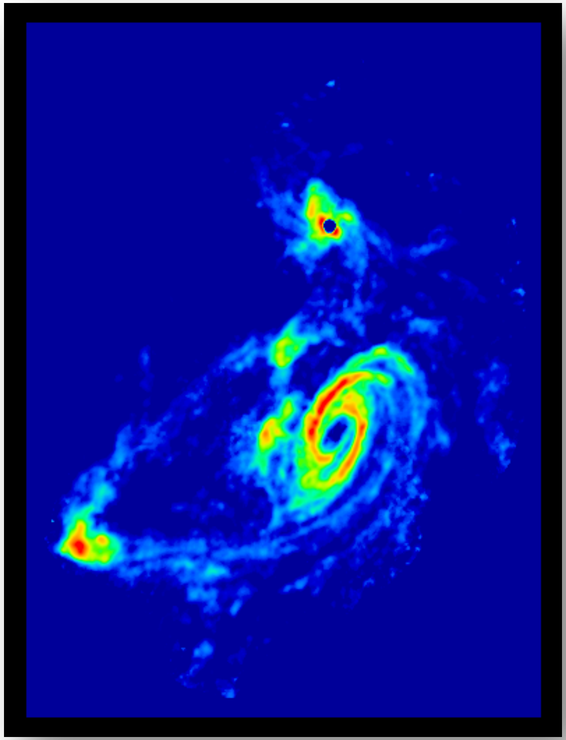
Gravitationally Lensed Image of Highest Redshift Galaxy HST WFPC2
PRC97-25 • ST ScI OPO • July 30, 1997
M. Franx (Kapteyn Astronomical Institute), G. Illingworth (Lick Observatory) and NASA

Distant Galaxies



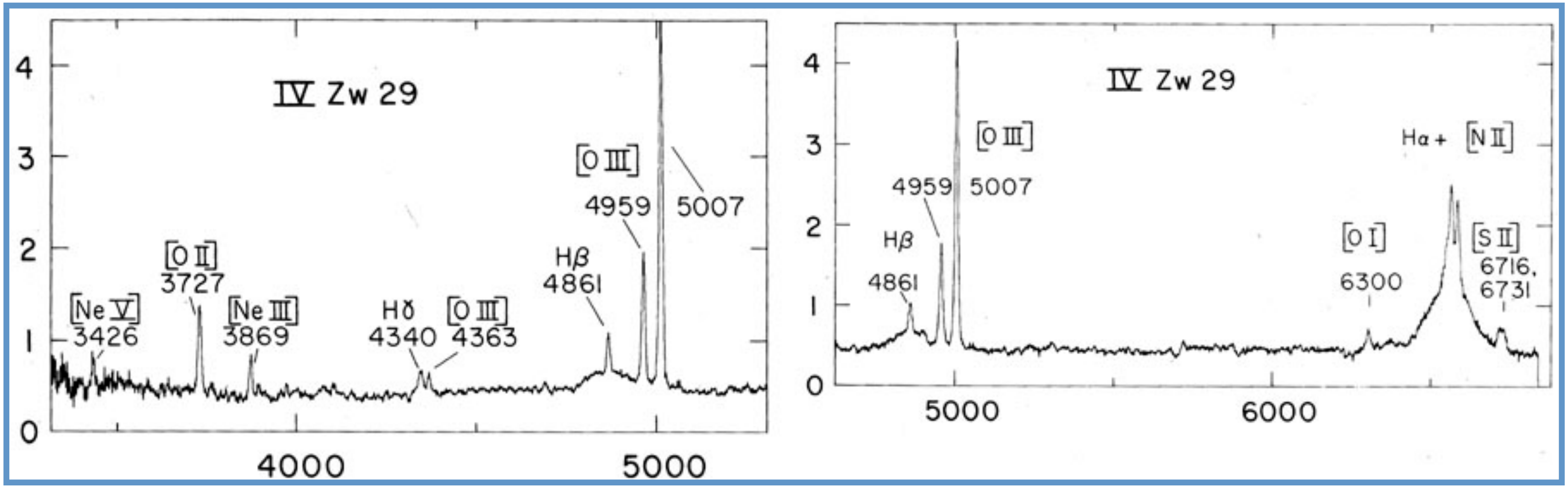
Starburst





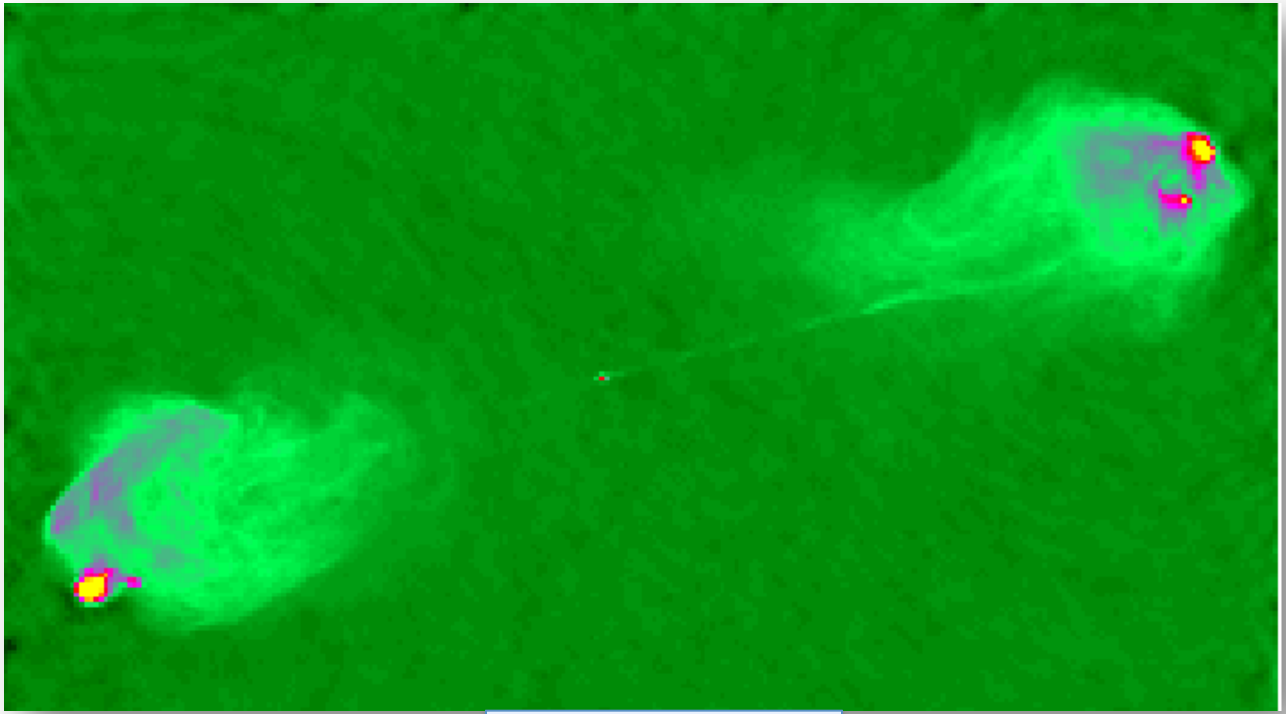
M81 & M82

Active Galactic Nuclei (AGN)



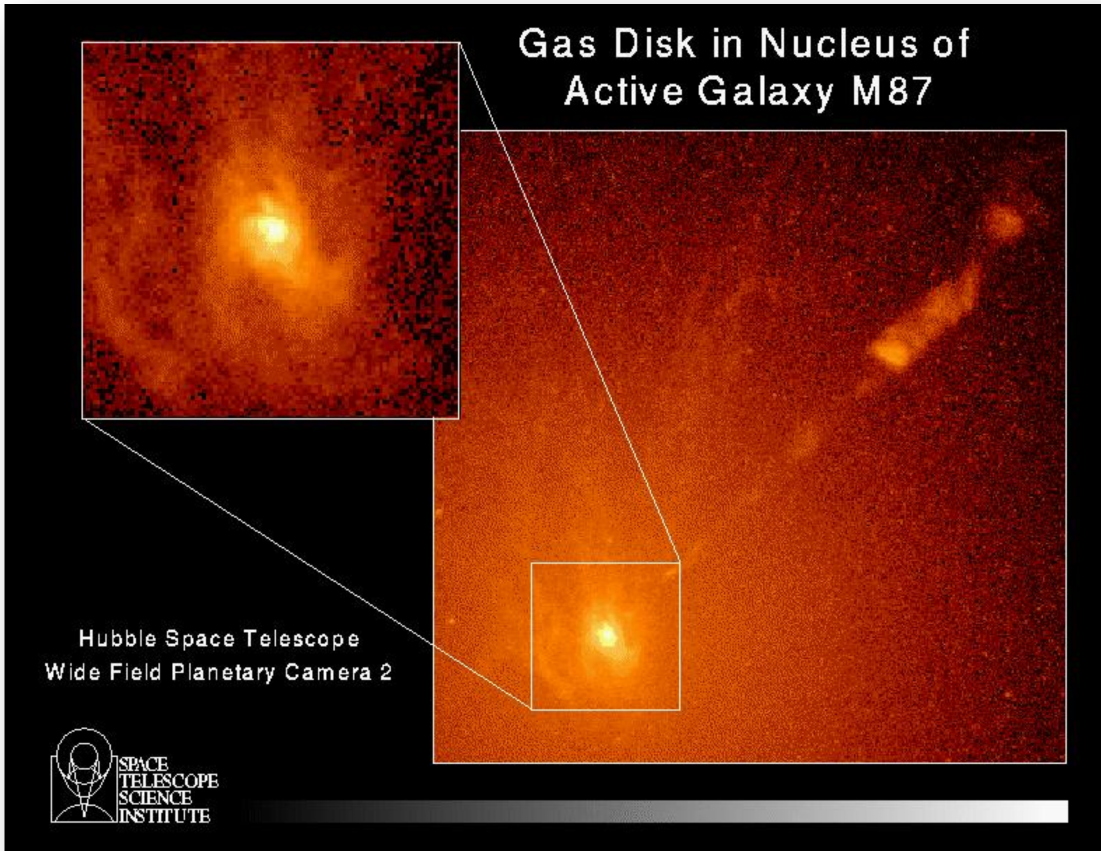
Seyfert I

Active Galactic Nuclei (AGN)

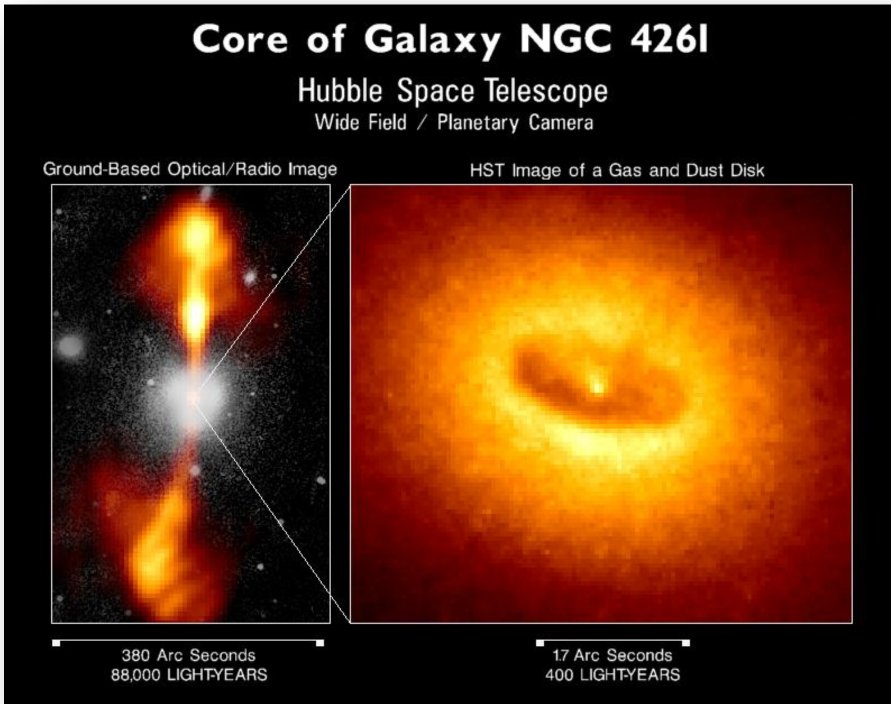


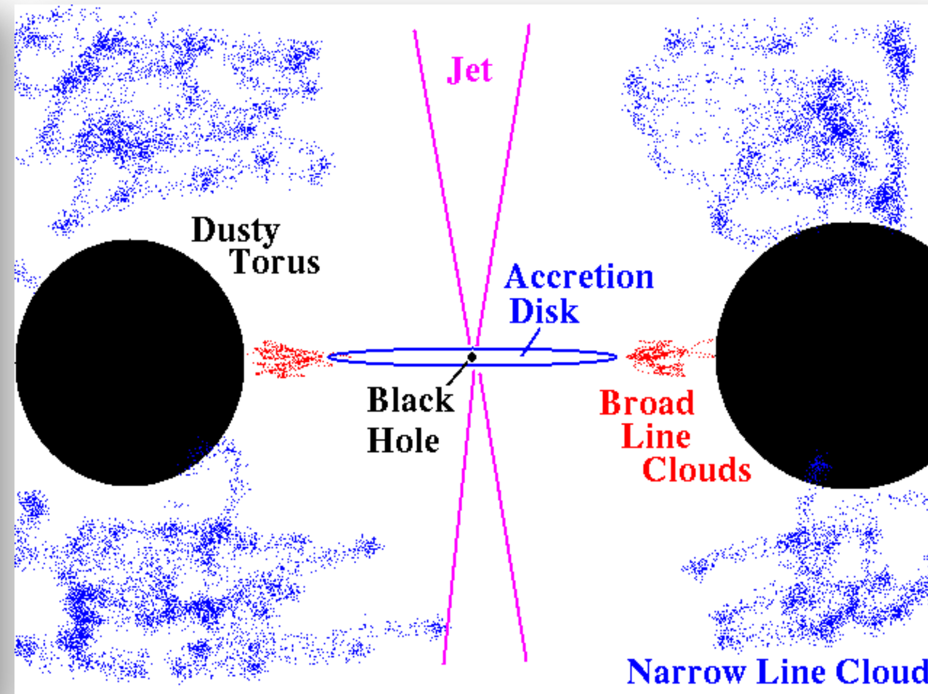
Cygnus A

Active Galactic Nuclei (AGN)



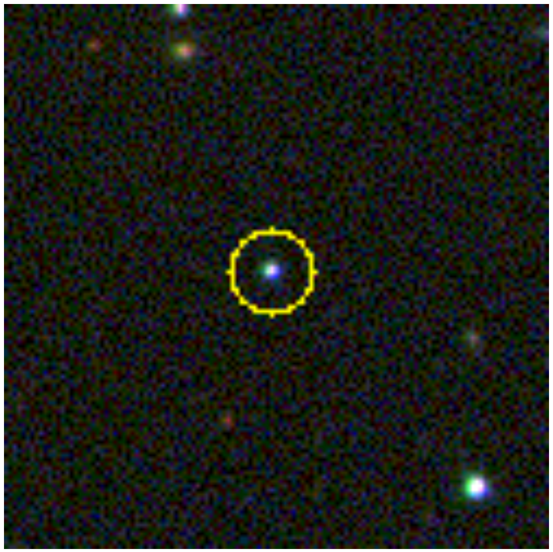
Active Galactic Nuclei (AGN)

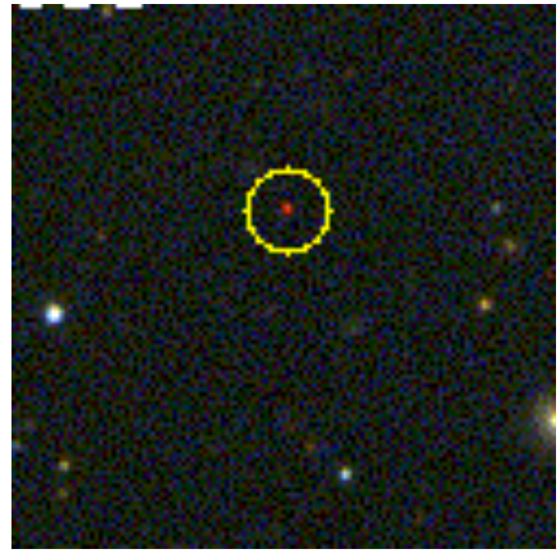




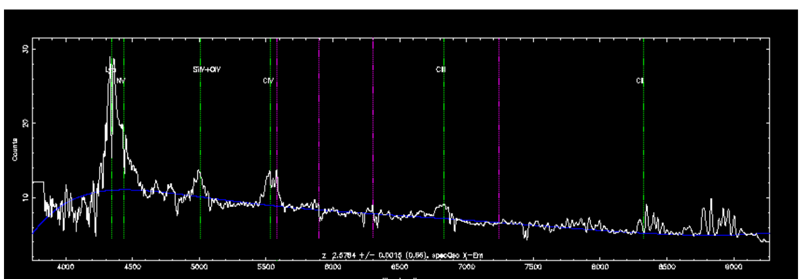
QSO = cosmological probe

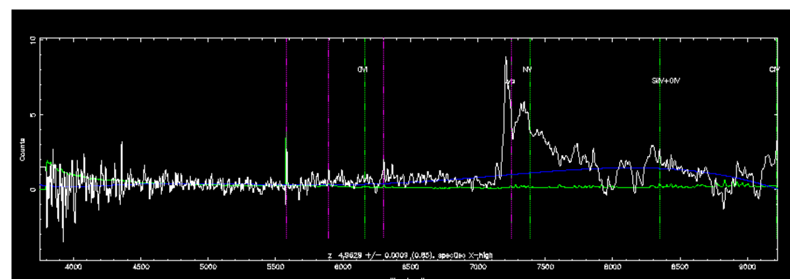
Z = 2.6



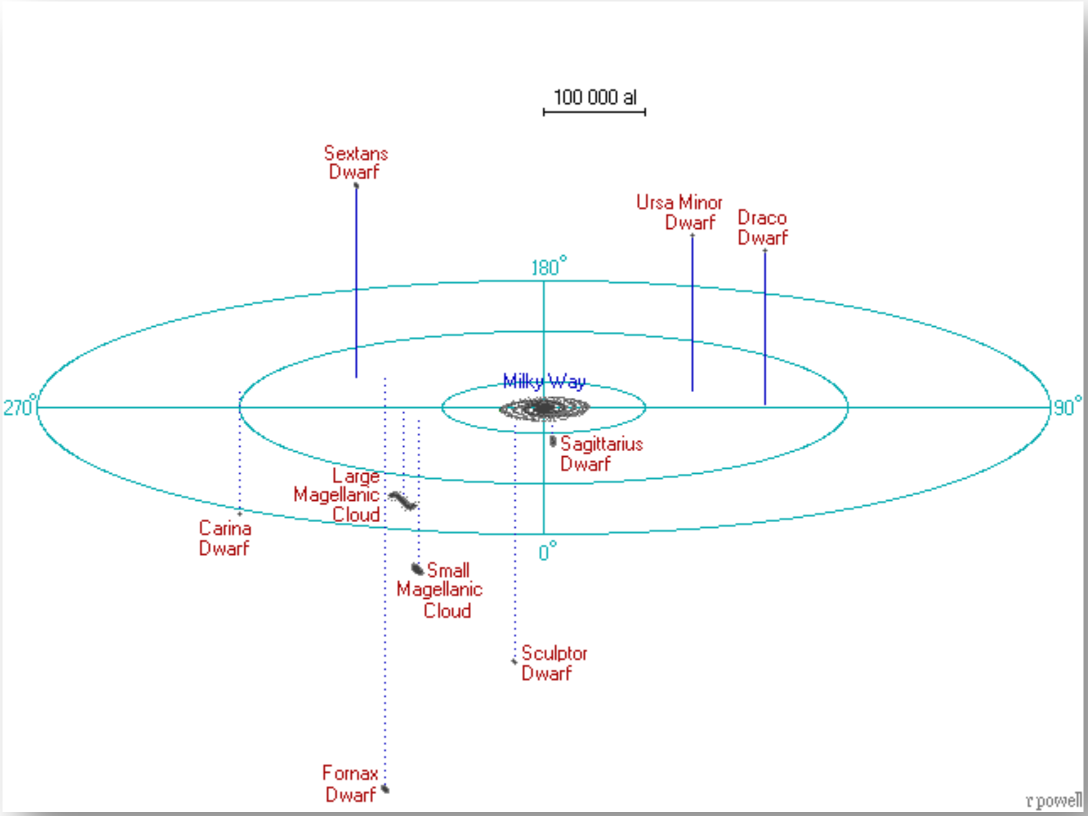


Z = 5.0





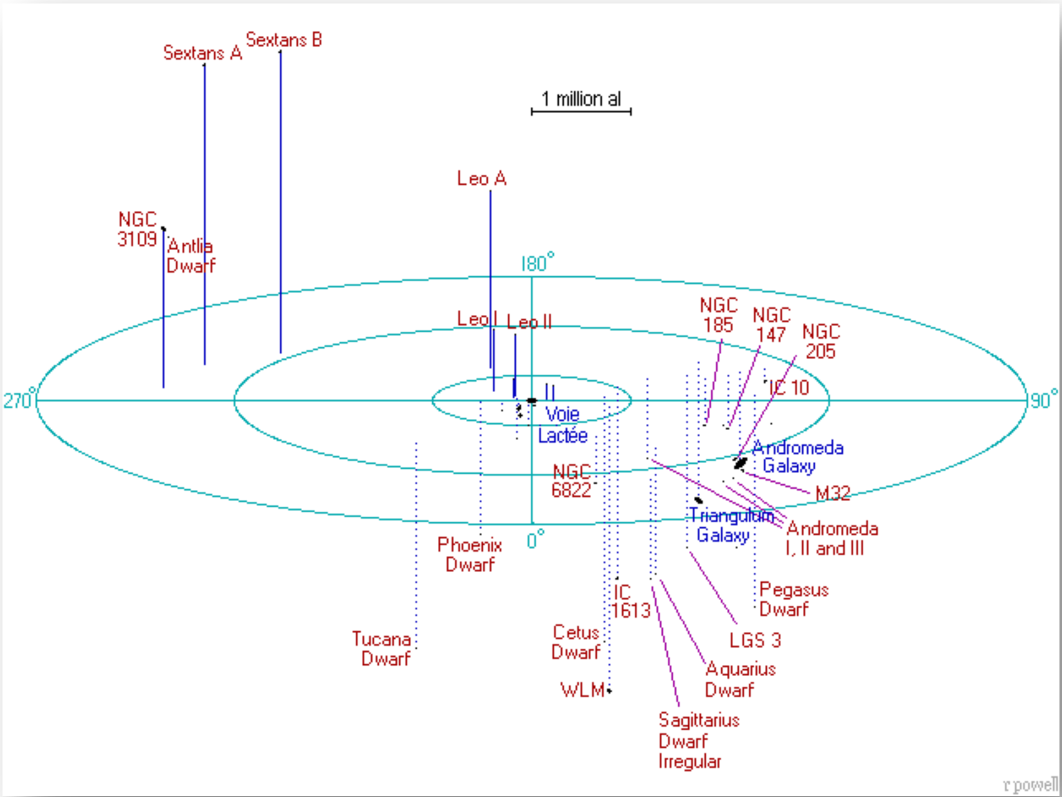
MW's satellites
(Universe out to 150 kpc)



Number of galaxies out to 150 kpc = 1
Number of dwarf galaxies out to 150 kpc = 9
Number of stars out to 150 kpc = 200 x 10^9

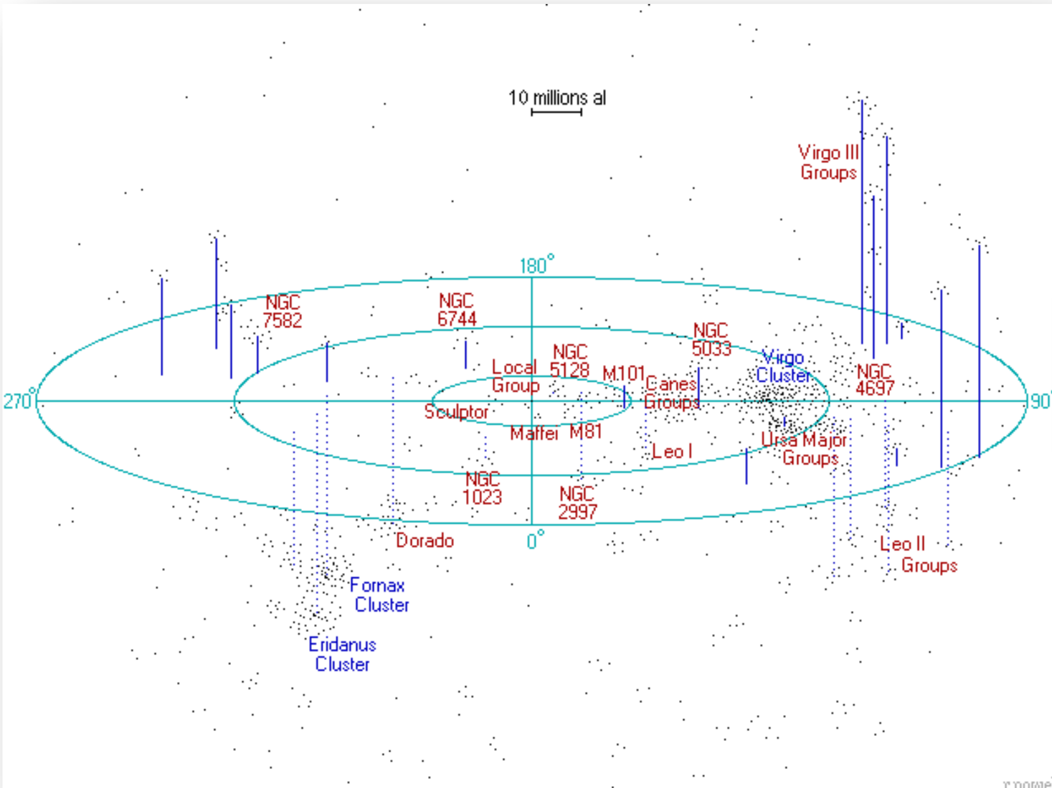
Local Group of Galaxies

(Universe out to 1.5 Mpc)



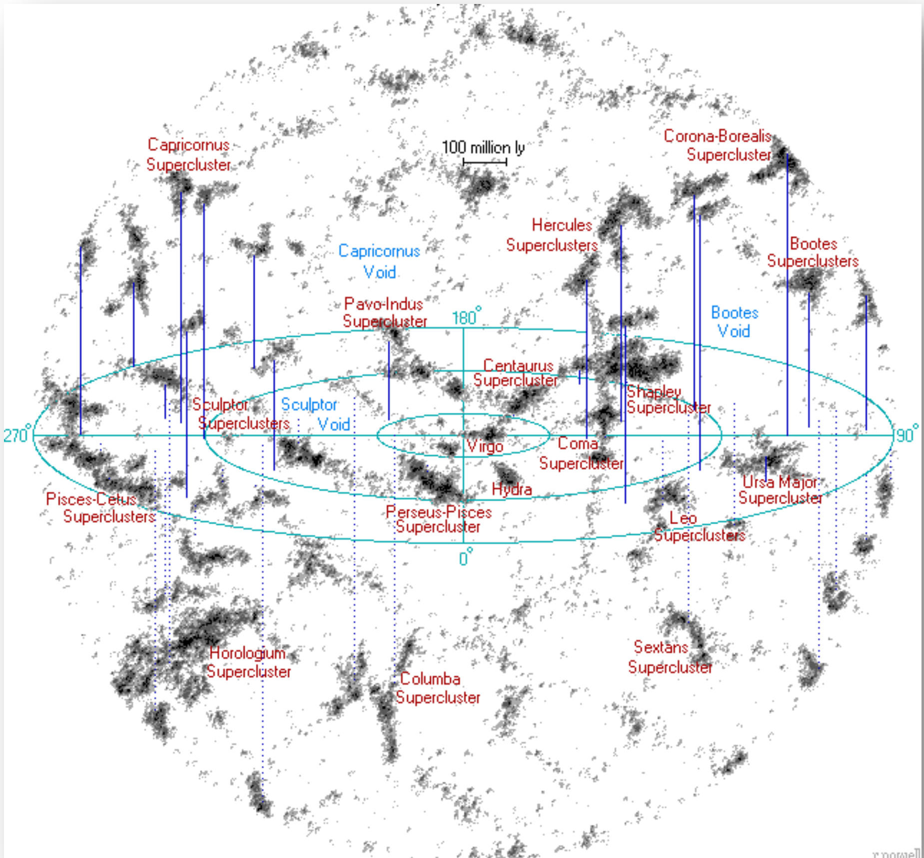
Number of galaxies out to 150 kpc = 3
Number of dwarf galaxies out to 150 kpc = 36
Number of stars out to 150 kpc = 700 x 10^9

Virgo Supercluster
(Universe out to 30 Mpc)



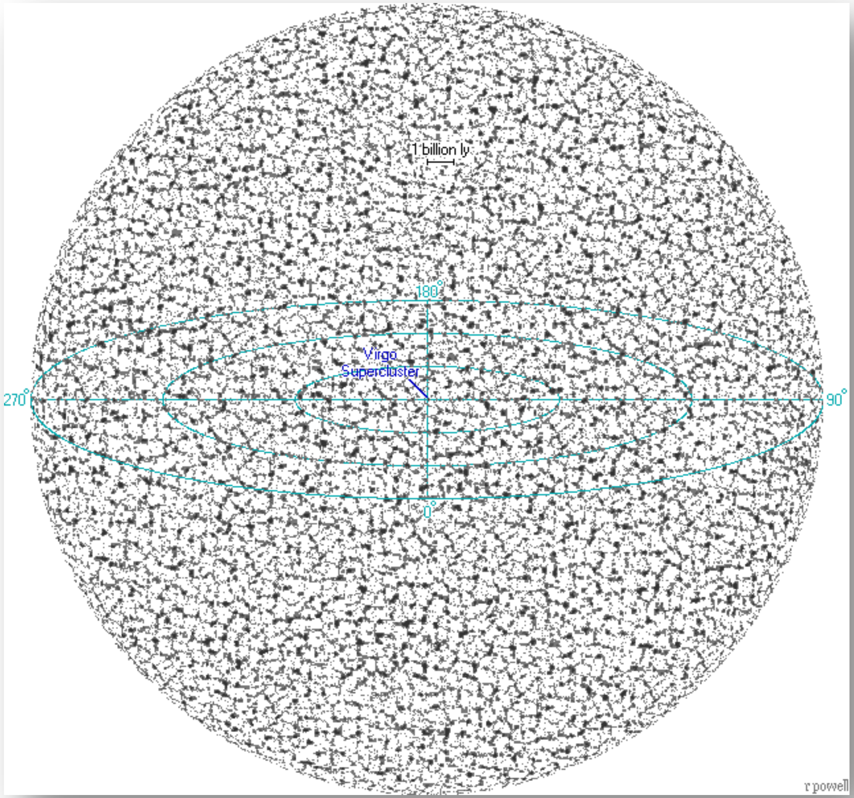
Number of groups of galaxies out to 30 Mpc = 160
Number of large galaxies out to 30 Mpc = 2500
Number of dwarf galaxies out to 30 Mpc = 25000

Nearby Superclusters
(Universe out to 300 Mpc)



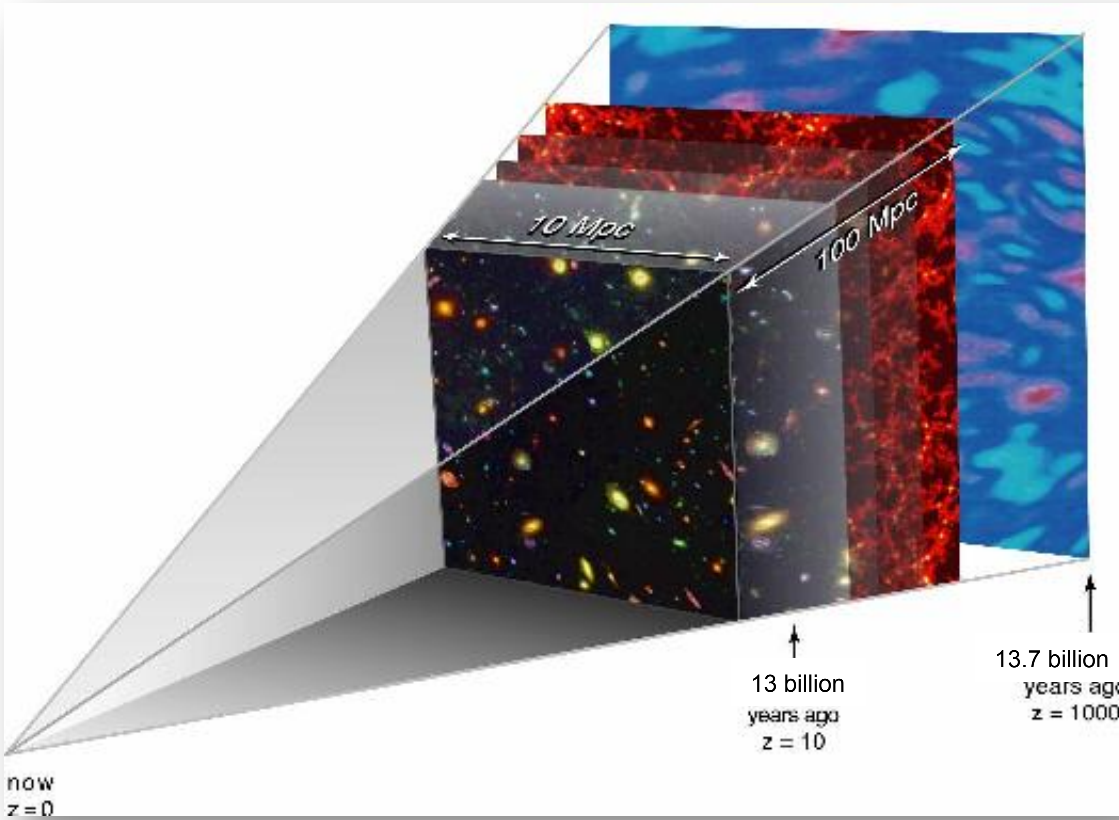
Number of superclusters out to 300 Mpc = 80
Number of groups of galaxies out to 300 Mpc = 160 000
Number of large galaxies out to 300 Mpc = 3 millions

Visible Universe
(Universe out to ~14 x 10^9 l.y.)

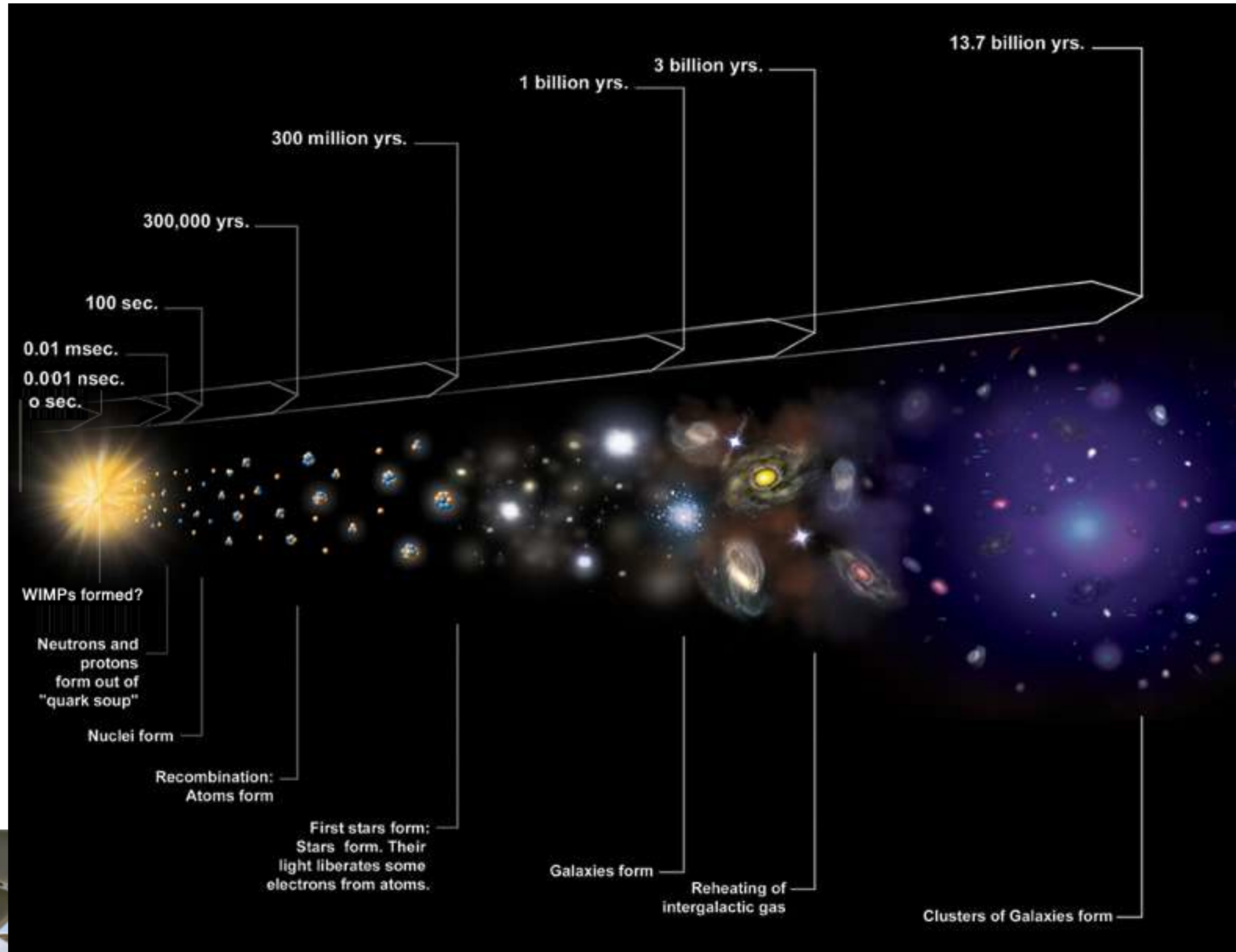


Number of superclusters in the visible Universe ~ 270 000
Number of groups in the visible Universe = 500 millions
Number of large galaxies in the visible Universe = 10 billions

Dark Ages


10 Mpc
100 Mpc
13 billion
years ago
z = 10
13.7 billion
years ago
z = 1000
now
z = 0

Universe History



Composition of the Universe