Probing the Geography, History and Chemistry of Nearby Galaxies with Future Telescopes

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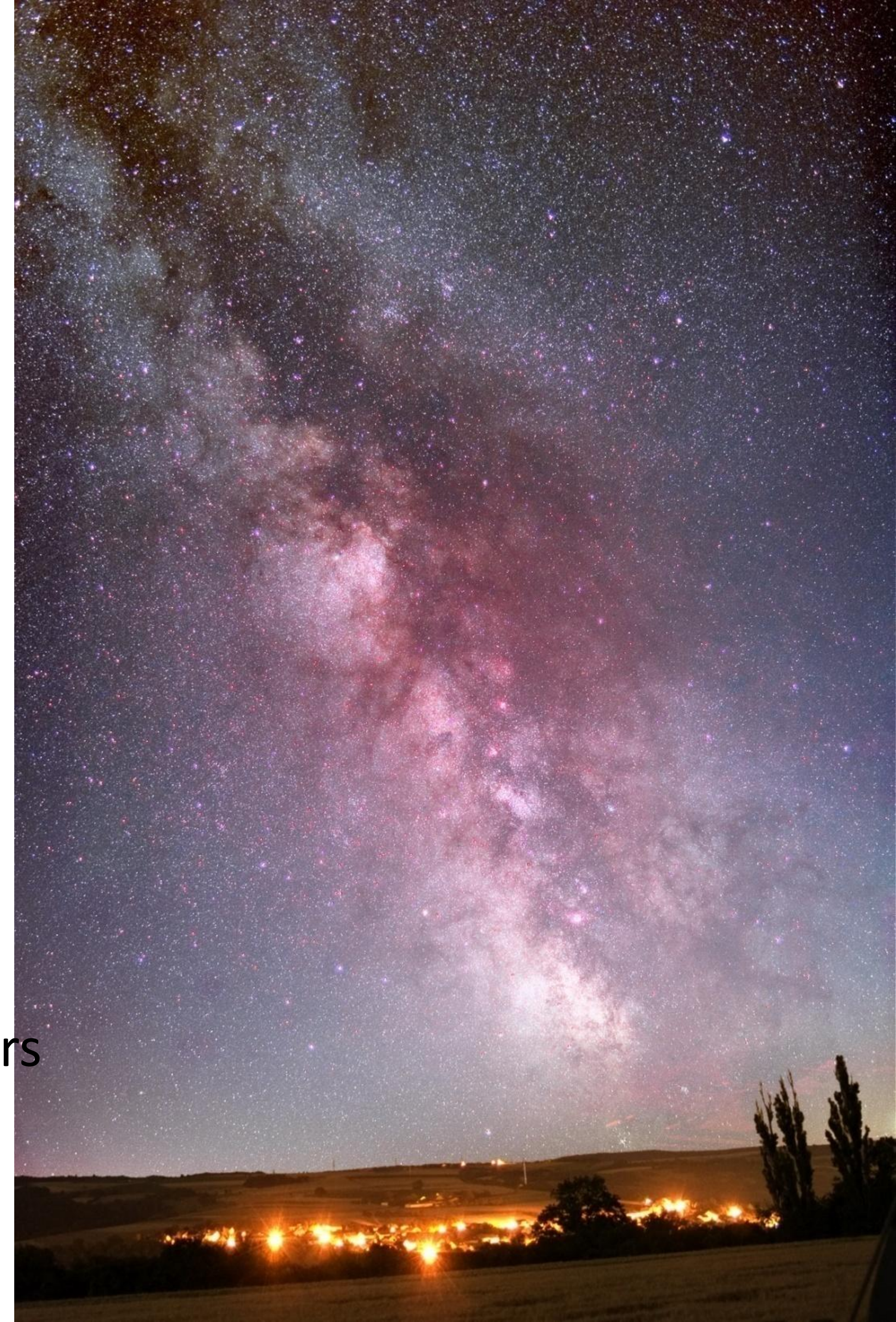
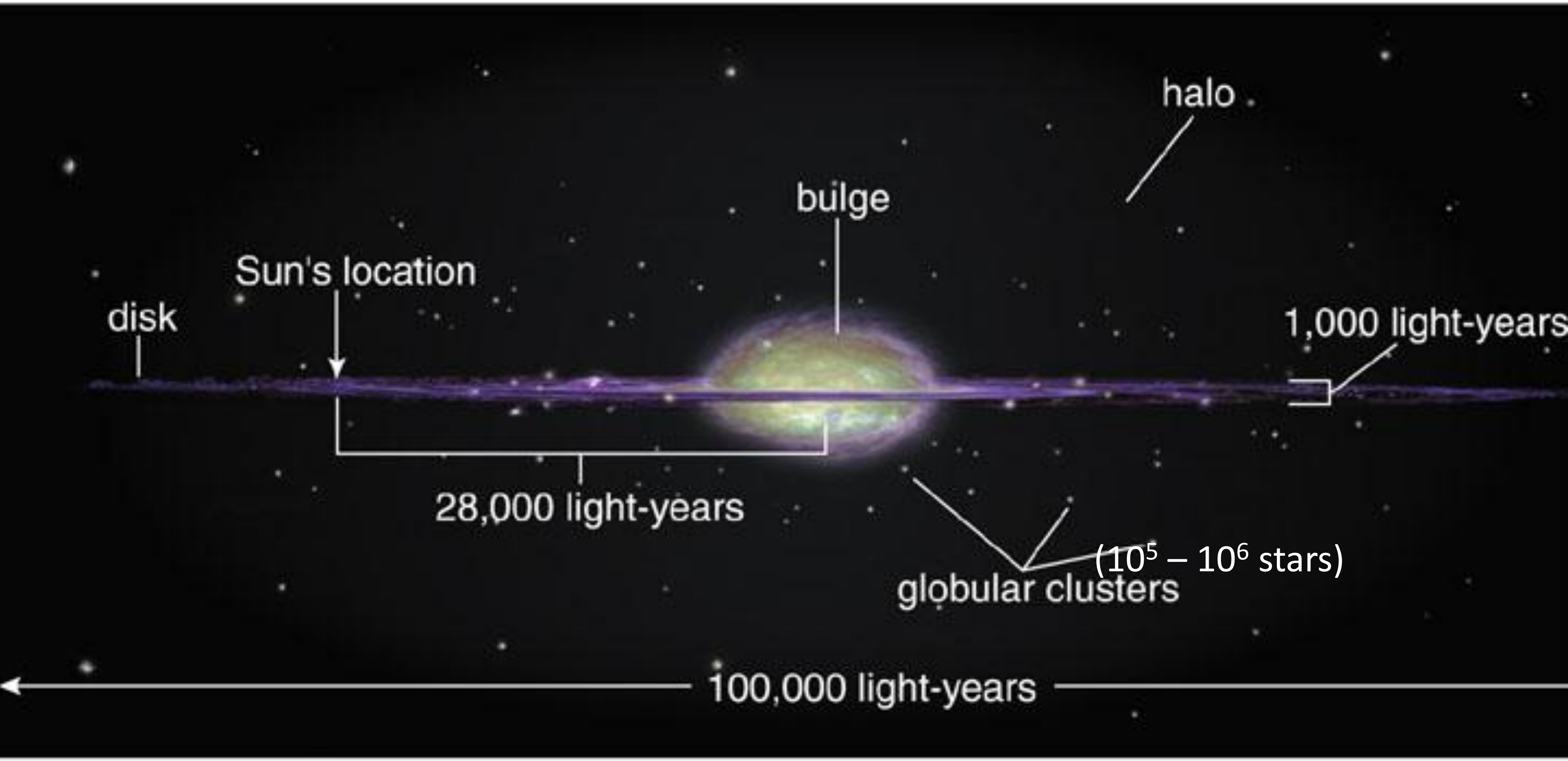
JSPS-DST ASIA ACADEMIC SEMINAR –
CPS 8th International school of Planetary Sciences

Galactic Astronomy

- Content
  - Stars
  - Gas, Dust
- Structure & Kinematics
- Dynamics & Ecology
- Formation & Evolution
  - Star formation
  - Chemical evolution
  - Dynamic evolution
  - Interaction with neighbours
- Galactic Centre



Galactic Structure

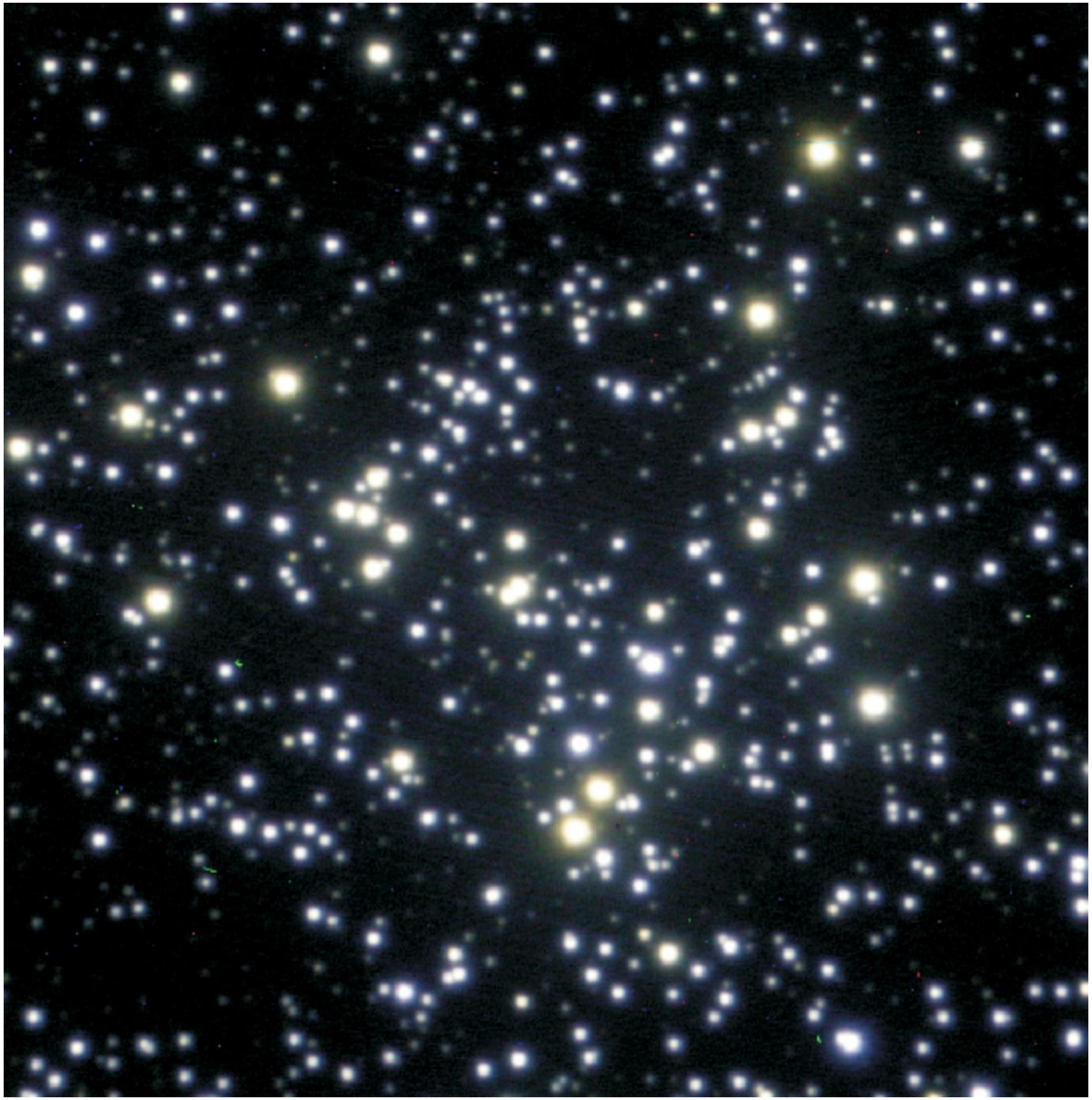


Harlow Shapley (1920s): Size from globular clusters

Halo is metal poor and > 10 billion years old

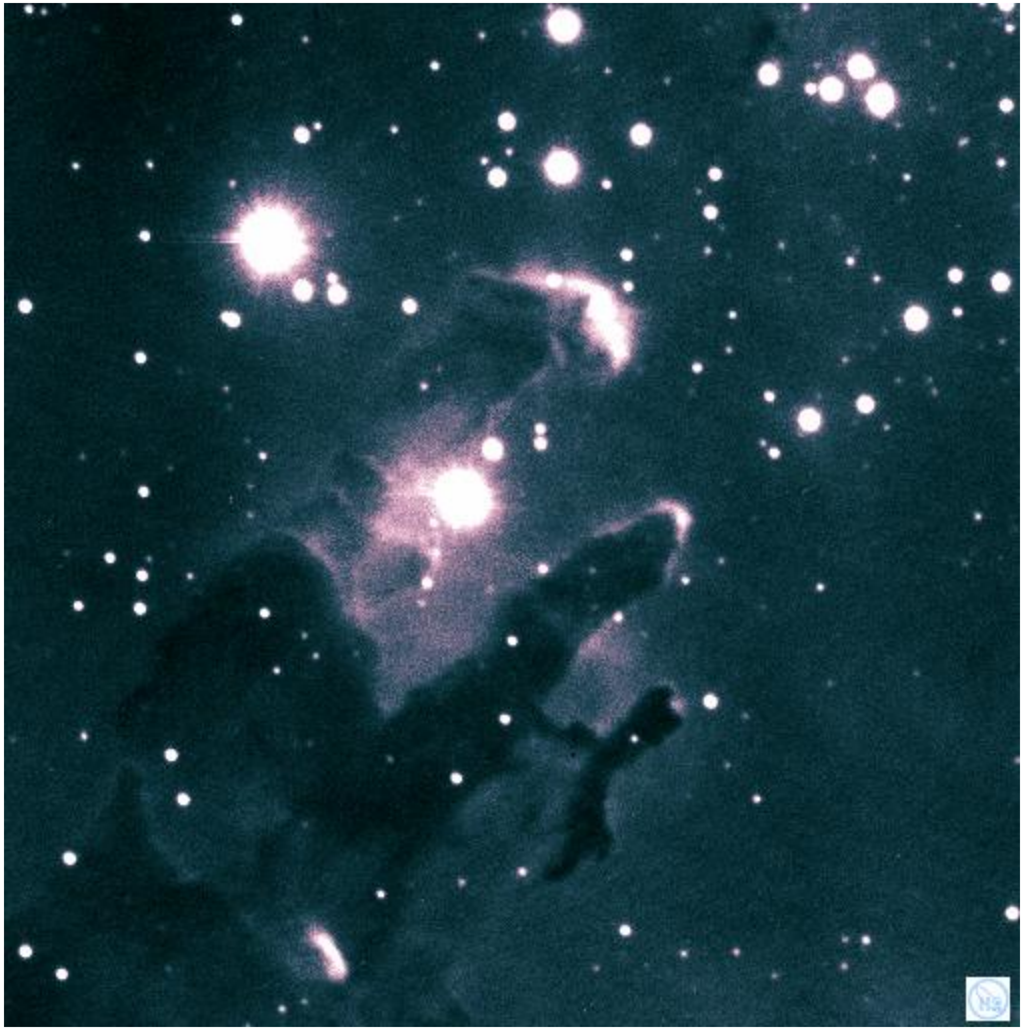
Galactic Disk

- Stars
  - Single
  - Binary
  - multiple
  - Associations
  - Open Clusters
    - A few 100 stars
  - less than a few billion year old
  - Metal rich

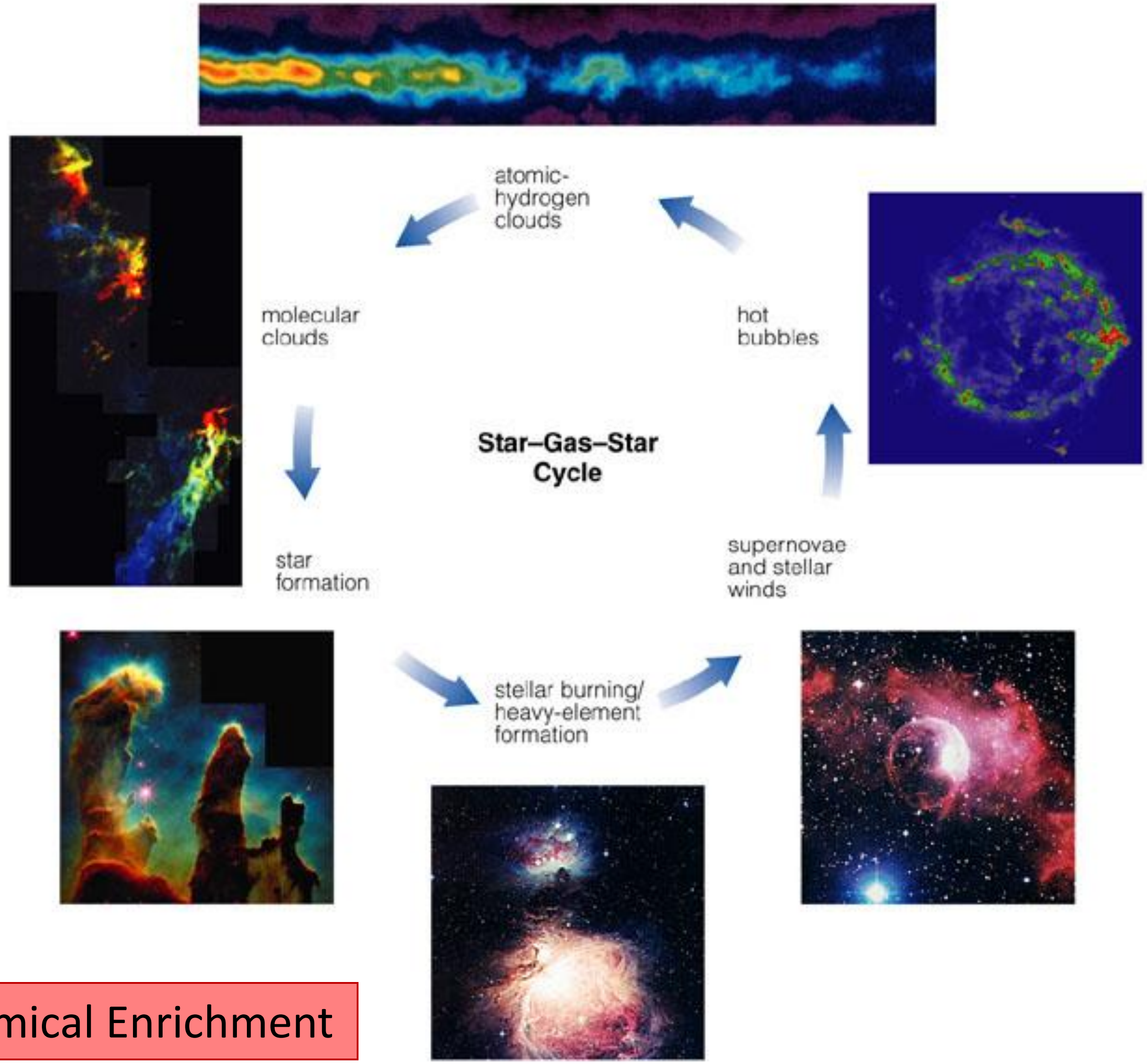


Galactic Disk

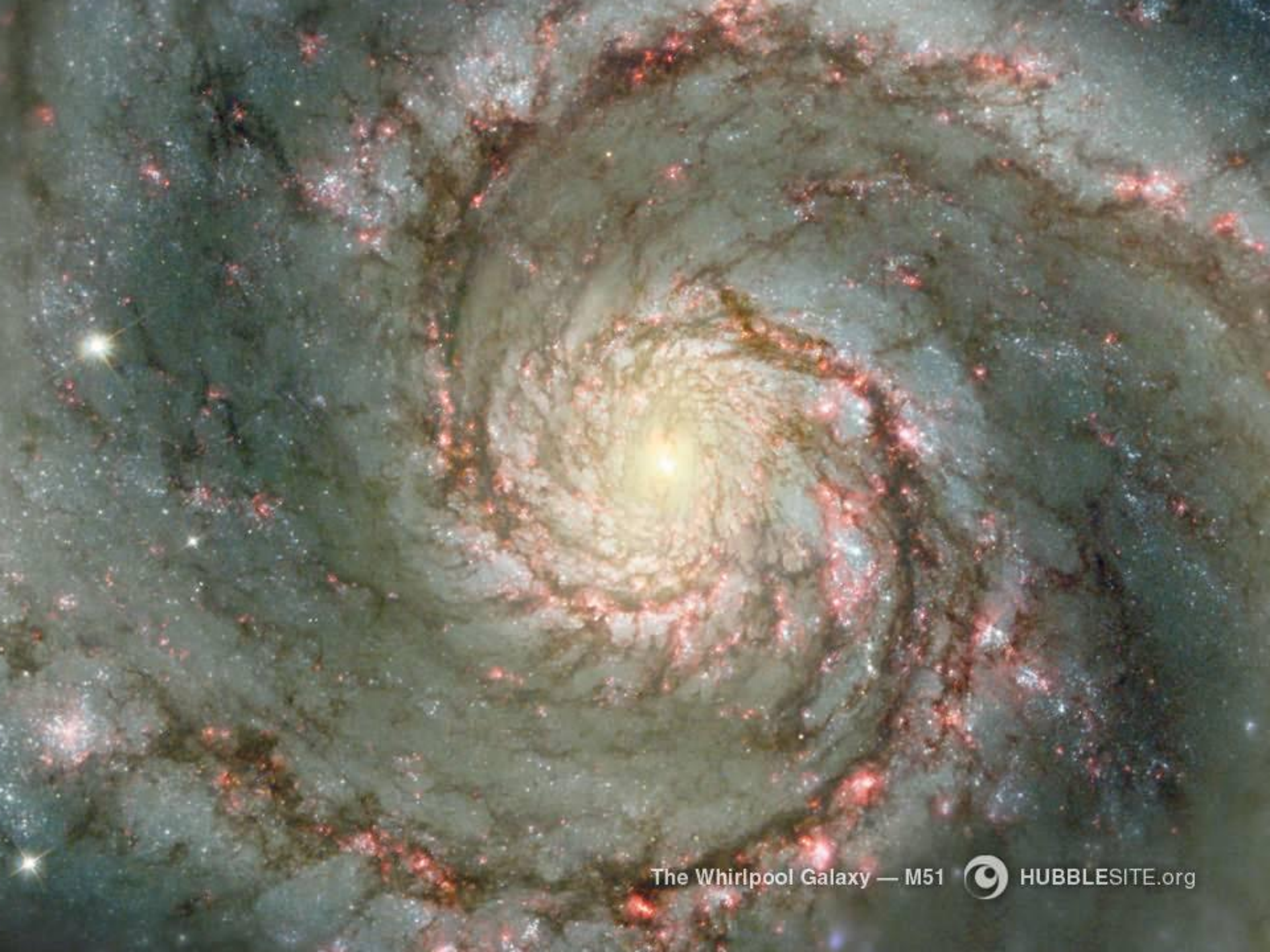
- Gas and dust
  - Diffuse
  - Clouds of different density and size
    - Globules (~1 $M_\odot$)
    - ….
    - Giant Molecular Clouds (~$10^6 M_\odot$)
  - Absorbing
  - Polarizing
  - Reflecting
  - Ionized
  - Emitting in the IR



Galactic Disk: Ecology

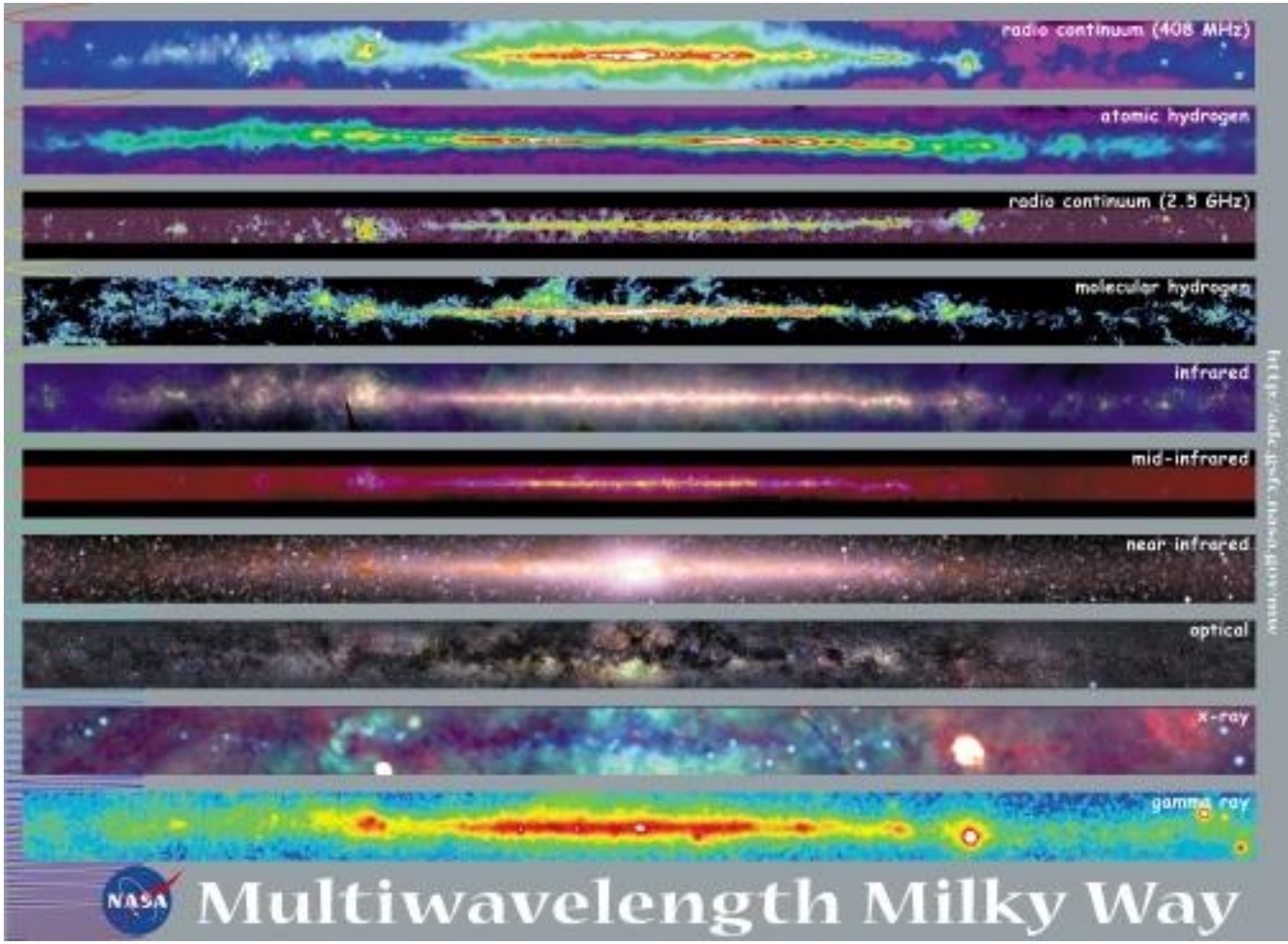


Leads to Chemical Enrichment

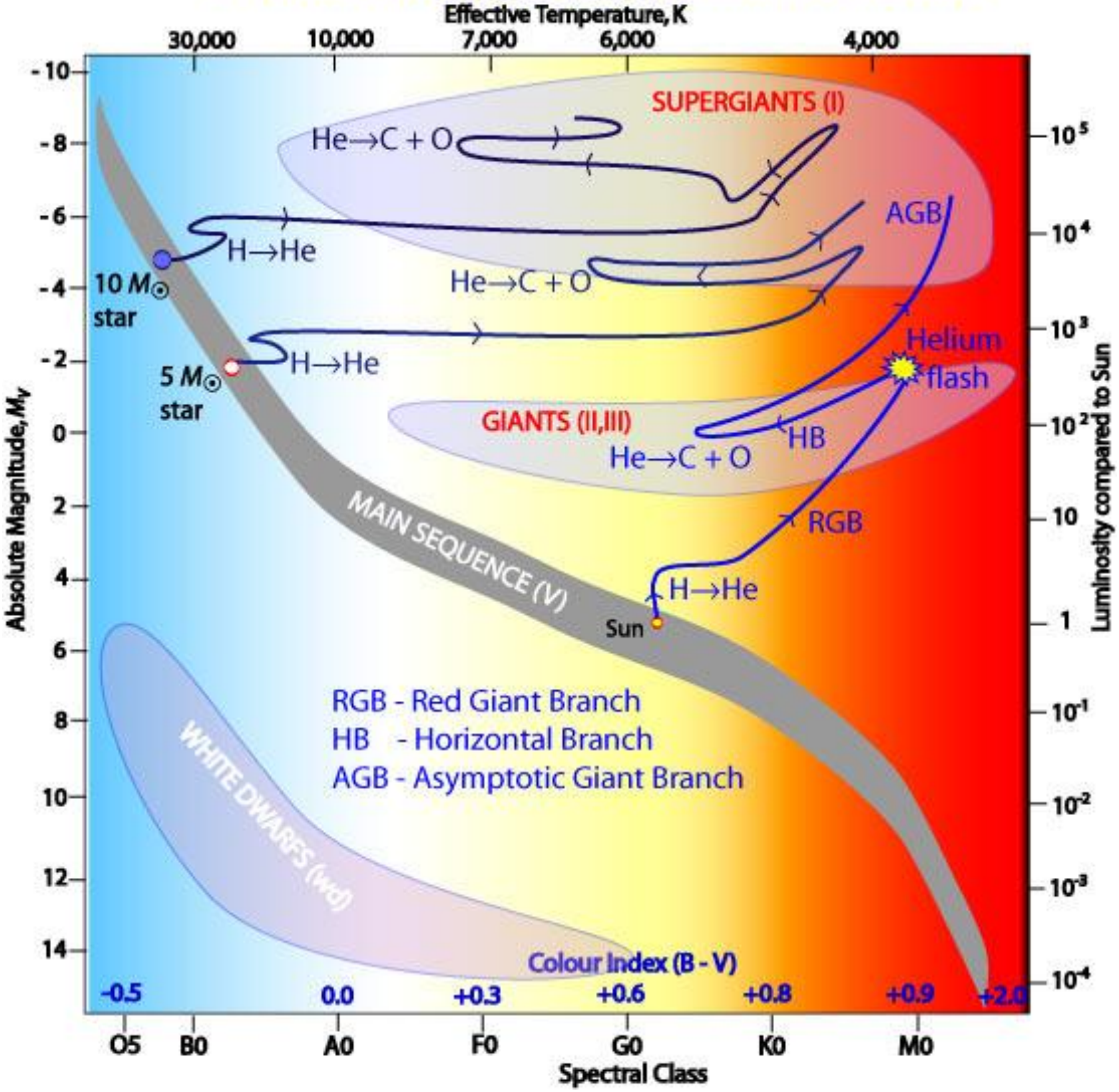

The Whirlpool Galaxy — M51
HUBBLESITE.org

Multiwavelength View

- Infrared
    - Emission from warm dust, hot dust, stars
- Radio
    - 21 cm H I line
    - Synchrotron radiation from charged particles in magnetic field
- X-rays and gamma-rays
    - supernova remnants
    - Pulsars
    - starforming regions



Evolutionary Tracks off the Main Sequence



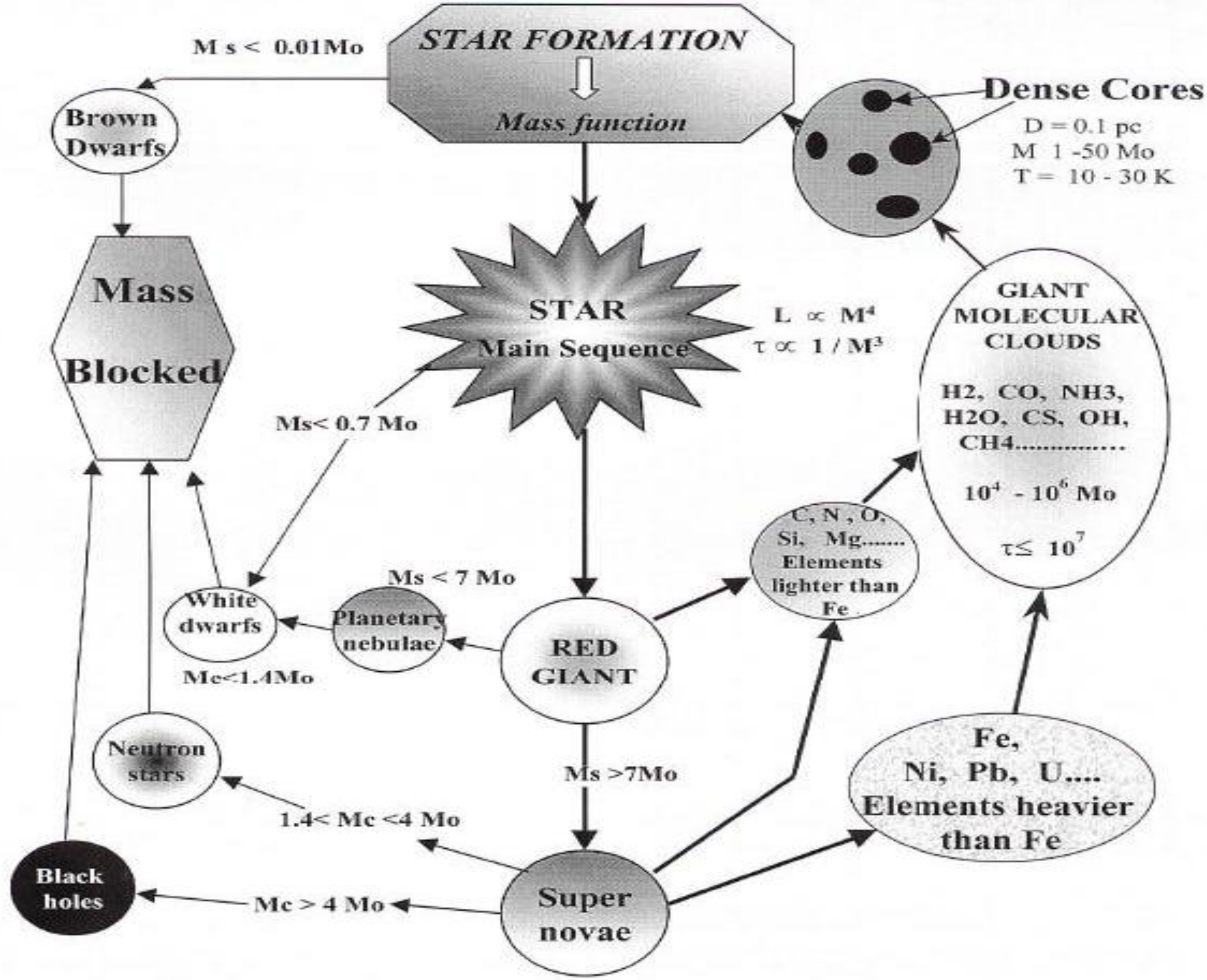
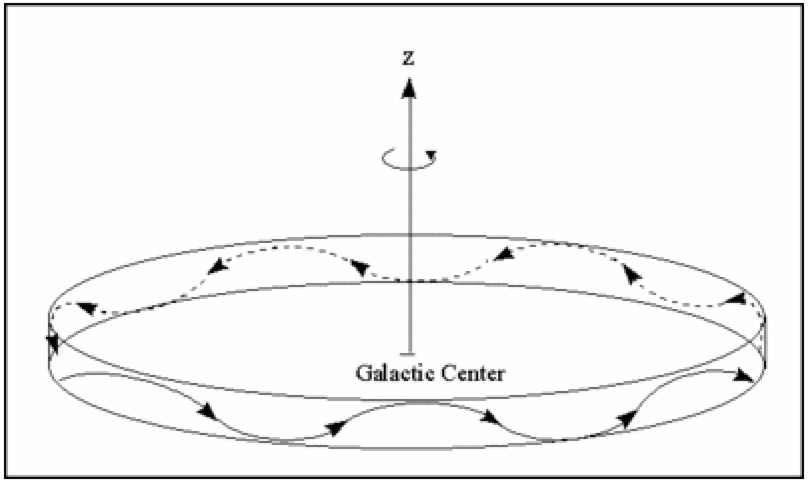


Figure shows schematically, right part of the figure, the cycle that matter follows since the origin of the universe, enriching at each cycle the interstellar medium of heavier elements. Ms indicate the original mass of the star and Mc the residual mass after the mass loss

- About 1/3 of the local disk is in gas and about 2/3 is in stars.
- About 1 star in 500 near the Sun comes from the stellar halo (spheroid), the rest coming from the disk.
- About 5-10 percent of the local stars belong to the young disk, the rest to the old disk.

- **Stellar "Population Types"**
- Moving away from the solar neighbourhood, the properties of stars begin to change. A useful characterisation of these changes is called the **population concept**. Stars are found to broadly belong to two population types. The concept was proposed by Walter Baade in 1944. Baade noticed in studies of the nearby spiral galaxy M31 that the disk stars in M31 were like nearby disk stars in young associations in the Galaxy, while the bulge stars mere nearly resembled those of the Galaxy's globular clusters. Young, metal rich stars rotating with the disk of the Galaxy are termed **Population I,** while old, metal weak stars are termed **Population II**. The fundamental difference between these two types relates to when and how they were formed.

- **Population I**
- The disk of the Galaxy is thought to be about 10 Gyr old. It presently contains about 20% gas by mass, and along spiral arms and in giant molecular clouds new stars are forming at a rate of about a solar mass per year. This rate is just about right to build up the disk mass over its lifetime of 10 Gyr.



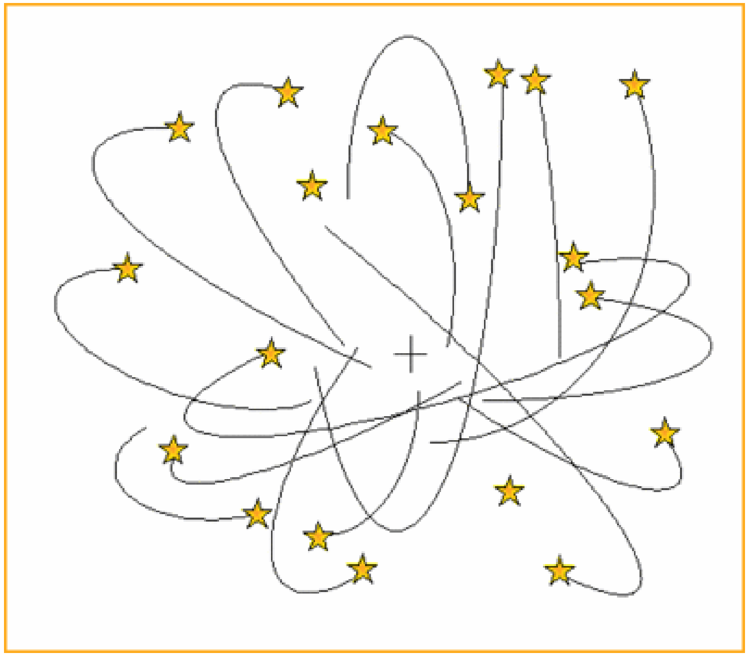
The Young Disk

The very youngest stars are of type O and B, and are found in associations and clusters, often still containing the protostellar gas (gas from which stars will form). Hot stars of this type light up the gas clouds around them by ultra-violet photo-ionisation, causing the clouds to glow conspicously in the light of Hydrogen emission lines --- these are called HII regions. Cold gas clouds, which are in the process of collapsing under gravity before stars begin to form, can be detected via emission from molecules such as CO.

All of these objects, as well as much of the gas layer, are concentrated very close to the galactic plane, with a **scale height** of about 100 pc. Scale height *hz*is defined as the exponential falloff in density (ρ) of the stars or gas as a function of height *z* above the Galactic plane: $\rho(z) = \rho(0)\, e(-|z|/hz)$

http://casswww.ucsd.edu/archive/public/tutorial/Galaxies.html

http://ircamera.as.arizona.edu/NatSci102/NatSci102/lectures/milkywayparts.htm



http://casswww.ucsd.edu/archive/public/tutorial/Galaxies.html

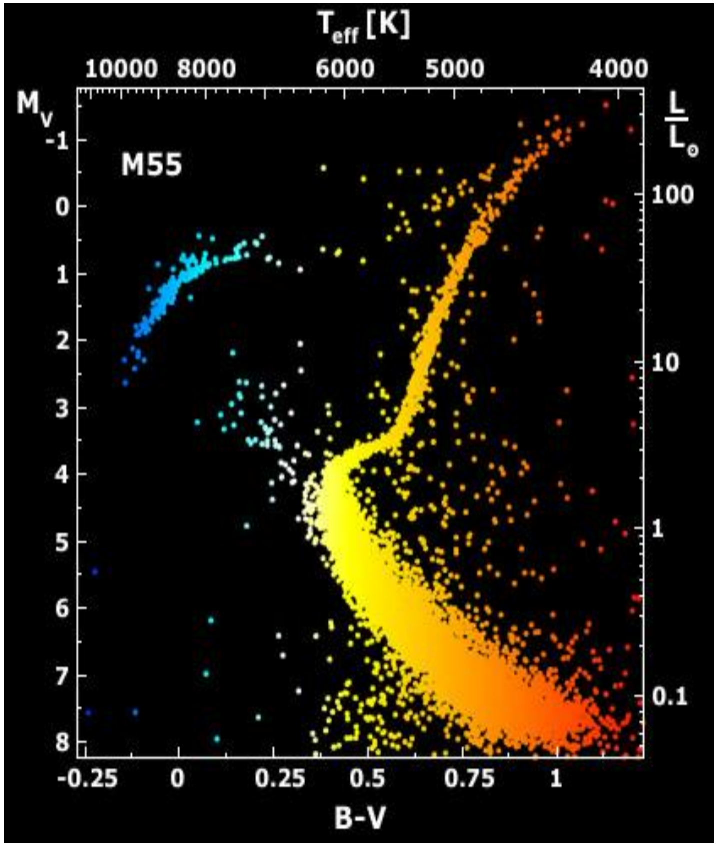
http://ircamera.as.arizona.edu/NatSci102/NatSci102/lectures/milkywayparts.htm

- Population II stars are old.
- The physical distribution of Population II is spheroidal, unlike Population I objects of the disk. Population II therefore includes both the **stellar halo** and the **bulge.** The stellar halo and bulge differ in their metallicities --- the halo is metal weak ([Fe/H] < -1) while the bulge is generally metal rich (with a metallicity distribution quite like the disk). Both the bulge and halo are centrally concentrated --- that is most of their mass and light is within the **solar circle** (the orbit of the Sun around the center of the Galaxy at R = 8 kpc).
- Typical stellar halo objects are **globular clusters**, **subdwarf stars**, certain kinds of **RR Lyrae** stars

- **Population II**

- **The stellar halo is old, with ages for typical objects known to lie in the range 12-14 Gyr. This has been determined from the colour magnitude diagrams of globular clusters and nearby subdwarfs. It would seem that the halo stars were the very first to form as the Galaxy was collapsing from a gas cloud in the early universe. As a consequence they retain information about this early time.**

- **Neither the halo or bulge rotate very much. The halo rotates very little, with a systemic velcity around the Galactic center of about 20 +/- 20 km/s, (compare to the disk rotation of 220 km/s). This means that the halo is pressure supported, unlike the disk which is rotation supported. Halo stars have a large velocity dispersion (in all three components) of about 120 km/s and this is what keeps them in their spheroidal configuration. The bulge rotates slowly at about 100 km/s and has a velocity dispersion of about 100 km/s. Hence it is somewhat intermediate between the disk and the halo in these respects.**



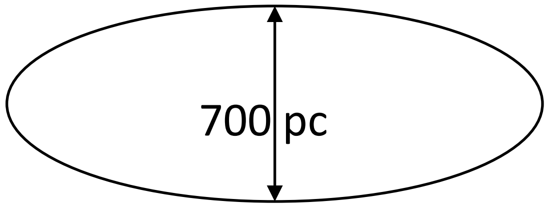
http://apod.nasa.gov/apod/ap010223.html

Galactic Halo

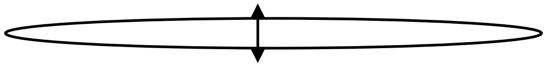
- Individual stars
  - RR Lyrae stars are distance indicators ($M_V \approx +0.6$)
- Globular clusters
  - About 150 known
  - Metal poor ones in spherical halo (25 kpc radius)
  - Slightly metal rich ones in thick disc (a few kpc thick)
- Halo density decreases as r^{-3}
  - Total mass estimate: $10^8\ M_\odot$
  - Highly eccentric orbits
  - seen as high velocity stars when pass through the disc

Initial Conditions?

Fat Disc



- Early Galaxy



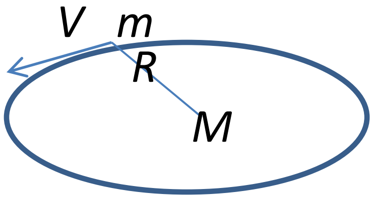
Thin Disc

100 pc

- Today

- Stars keep forming as disc collapses:
  - Stars form from gas
  - Gas cools rapidly to a thin disc

Stellar Dynamics

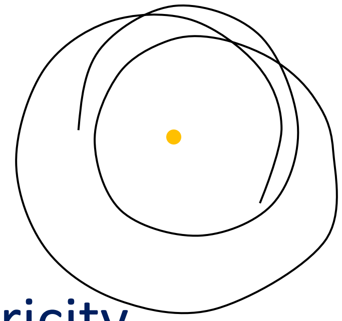


- Circular orbit around a point mass

  $F_G = GMm/R^2 = mV^2/R$
- Virial Mass: $M = V^2R/G$
- Sun: $V = 220$ km/s, $R = 8.5$ kpc ⇨ $M = 1\text{x}10^{11}\ M_\odot$

  Orbital period: $P = 2\pi R/V = 2.5\text{x}10^8$ years
- Distributed mass: Orbit may not close

  $$\frac{V^2}{R_C} = \frac{GM(R)}{R^2}$$



- Disk stars: nearly circular orbits
- Halo stars: plunging orbits of high eccentricity

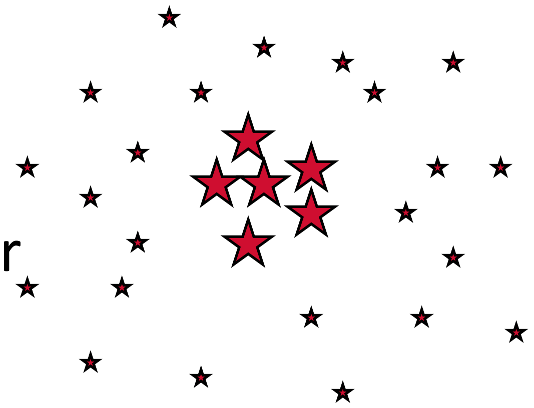
Equipartition

- Define Kinetic Temperature For stars:

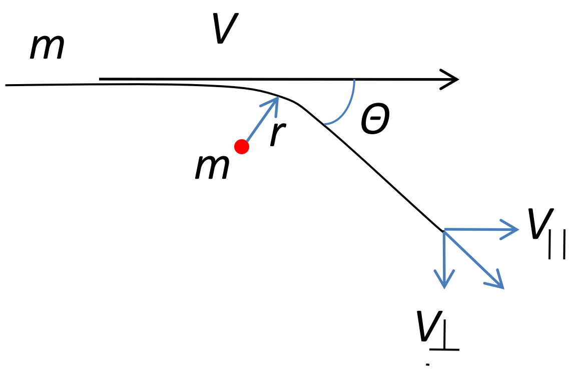
$$kT \approx mv^2$$

- Like thermal equilibrium of molecules in a gas

- Globular Clusters
  - Equipartition drives mass segregation
  - High mass stars sink to centre
  - Low mass stars evaporate from cluster
  - Or to outer regions of cluster



Stellar Encounters



- Interaction time scale: $\Delta t = r/V$
- Change in velocity: $V_{\perp} = \frac{F}{m} \Delta t$

$$= \frac{Gm}{r^2} \frac{r}{V} = \frac{Gm}{rV}$$

- For significant encounter, $\Theta \geq 1$ radian

$$r \leq \frac{Gm}{V^2} \approx 0.005\ (m/M_{\odot})(V_{\mathrm{km/s}})^{-2}\ \mathrm{pc}$$

Mean distance between stars is 1 pc. Hence encounters are rare.

- **Dark Matter**
- We have divided the galaxies stars and gas (i.e. its visible mass) broadly into young disk, old disk, stellar halo and bulge, but there is a further aspect to Galactic dynamics which we have hardly considered yet, the issue of dark matter. It was discovered in the 1970's that galaxies rotate in a peculiar way, in that the outer parts of galaxies seem to be moving too fast. Too fast here means that the visible matter doesn't appear to have enough gravitational attraction to retain the material in the outer parts. A great deal of work has gone into this issue over the last 30 years and has led to the conclusion that the *visible parts of galaxies represent only a small part of the total mass of the galaxy.* Most of the mass in galaxies seems to be in a dark form, the composition of which still remains completely uncertain.
- The main evidence for **dark matter** comes from **rotation curves** of disk galaxies. A rotation curve measures the rate at which stars and/or gas move in their *circular orbits around the center of the galaxy*.
- The rotation curve of the milky way is much harder to measure than for external galaxies, since the gas and stars beyond the solar circle are moving mostly transverse to the line-of-sight rather than along it. However, so many rotation curves have been measured for other disk galaxies there is no reason to suppose that the Milky Way would be particularly different, so even if the flattness of the rotation of the outer Galaxy is poorly measured it is thought to be flat nevertheless. Improved astrometric space missions within a decade or two will resolve this observational difficulty.
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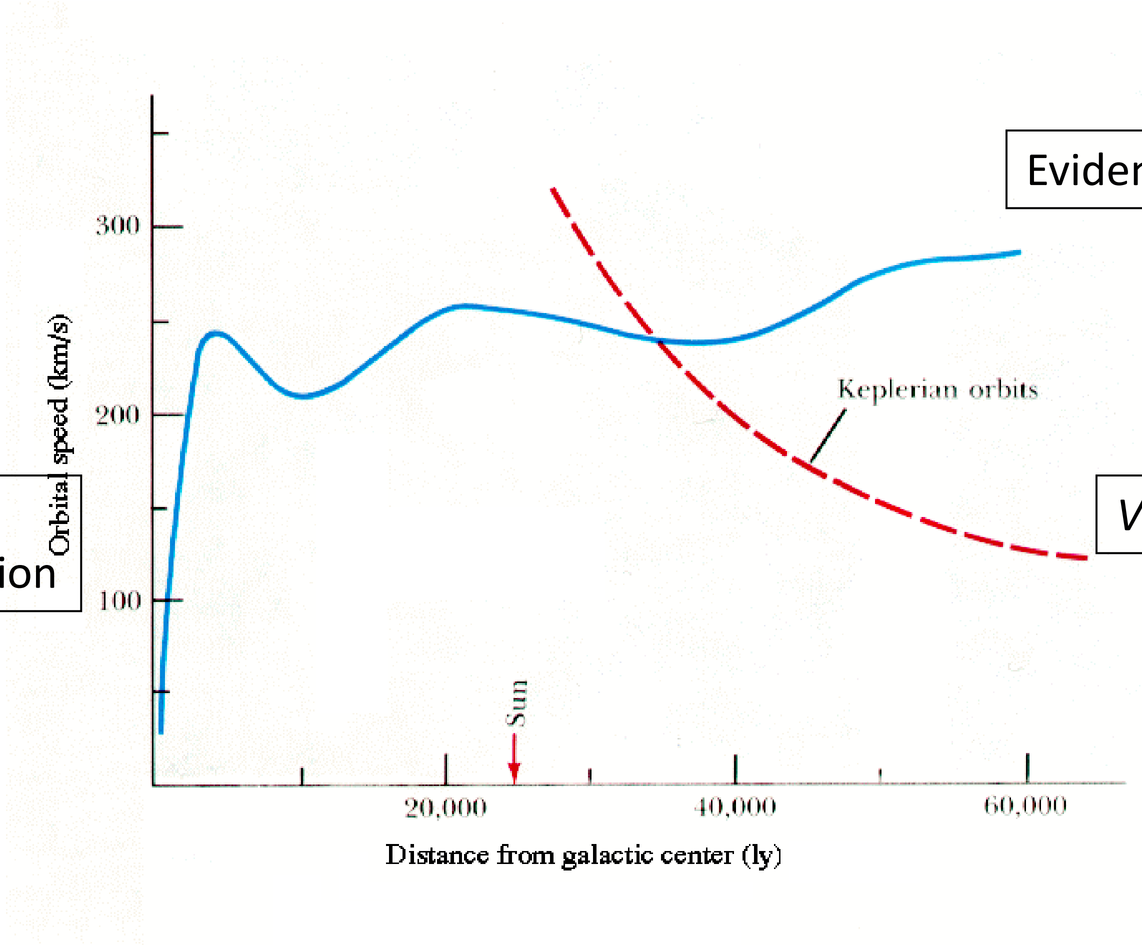
Galaxy's Rotation Curve

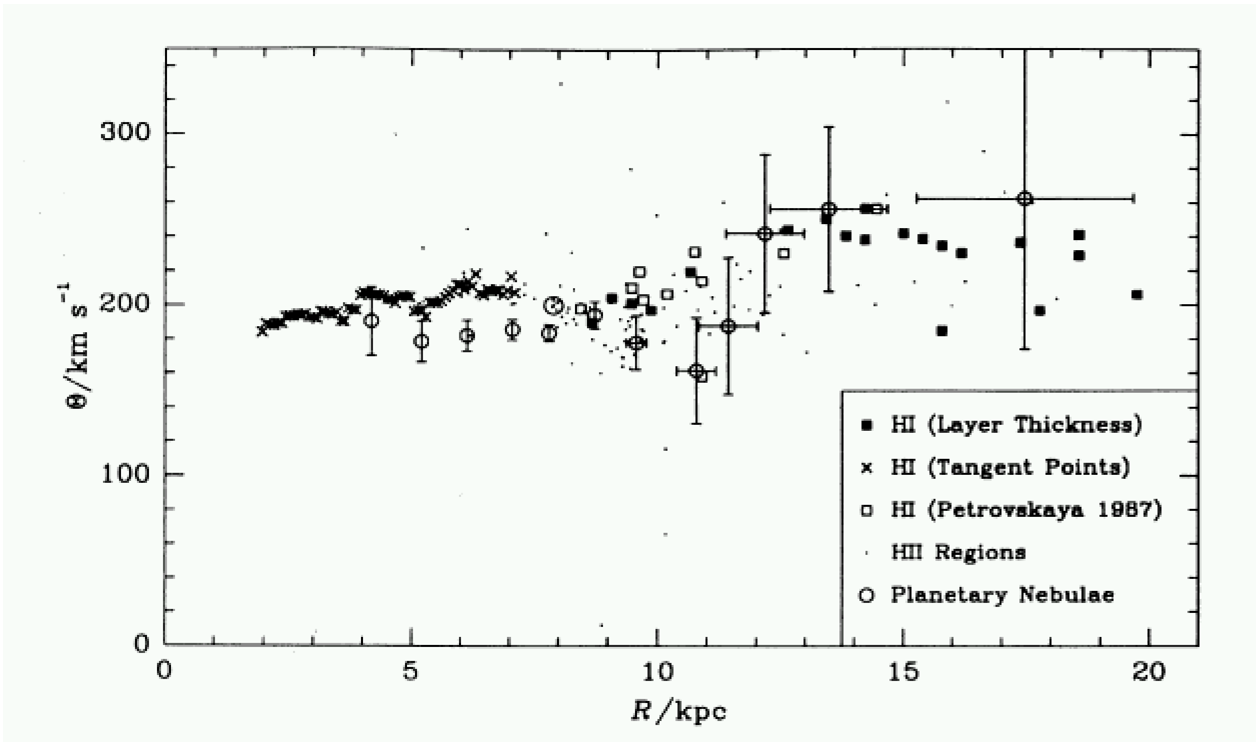
Evidence for dark matter



$V = \omega R$:
solid body roation

$V = [GM/R]^{½}$

http://abyss.uoregon.edu/~js/ast123/lectures/lec16.html

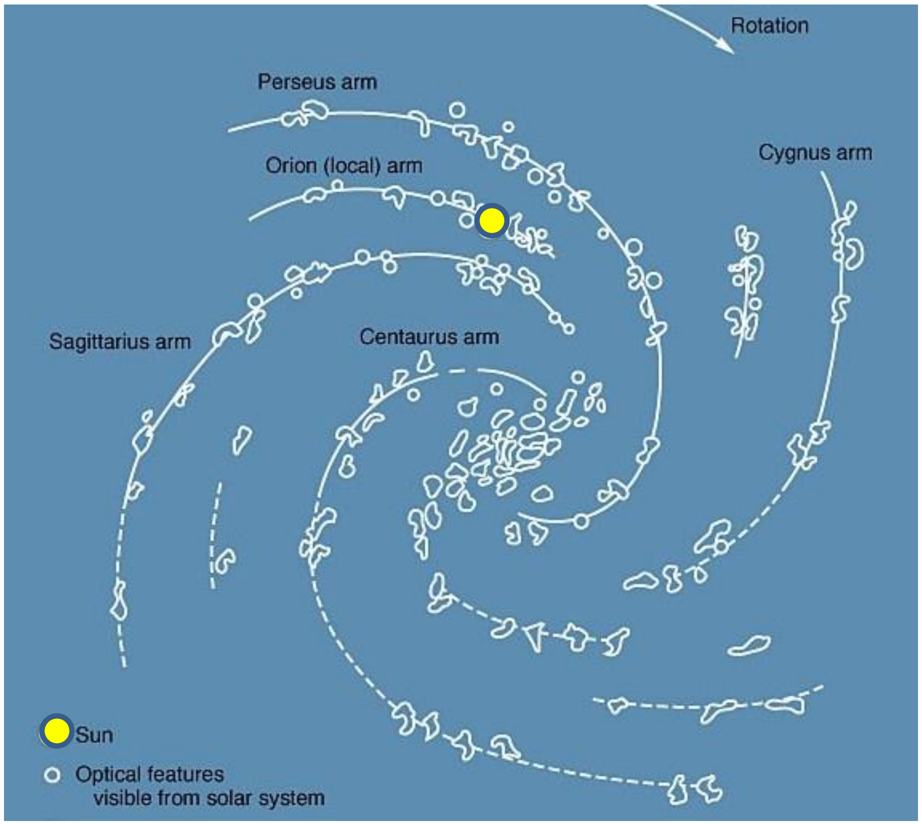


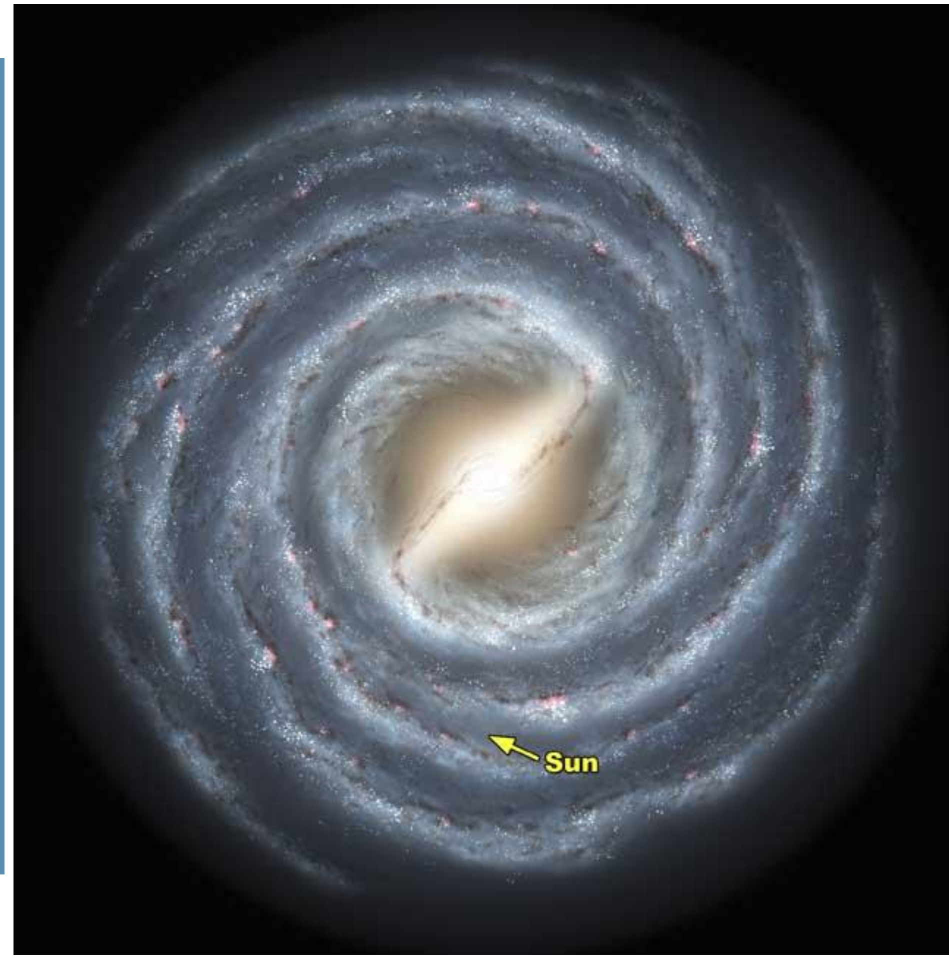
Merrifield,1992:AJ....103.1552M

Dark Matter in Galaxy

- Estimated mass in stars, remnants, gas: $< 4 \times 10^{10}\ M_\odot$
- Dynamical mass: $20 \times 10^{10}\ M_\odot$
- Flat Rotation Curve: $M(R)/R = \text{const}$
- Dark matter halo: density $\rho = \rho_0 (R/R_0)^{-2}$
- Density near sun: $0.01\ M_\odot\ \text{pc}^{-3}$
- Candidates for dark matter:
  - MACHOS (Massive Compact Halo Objects)
    - Black Holes
    - Neutron Stars
    - White Dwarfs
    - Planets
  - WIMPS (Weakly Interacting Massive Particles)
    - Neutrinos
    - Super-symmetric particles

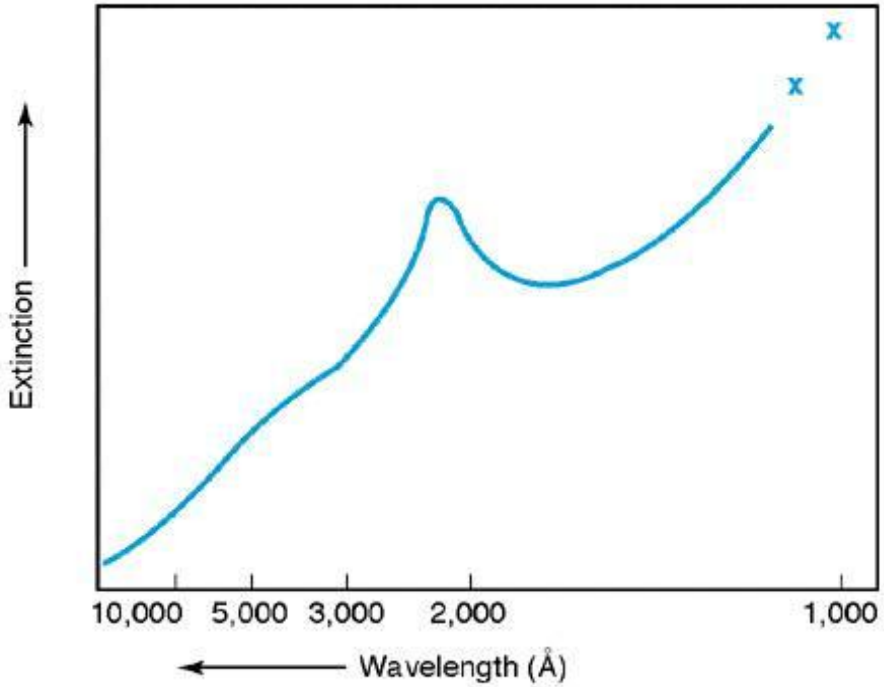
Outsider view of Galaxy





Interstellar Extinction

The amount of extinction varies as a function of wavelength such that it is highest at short wavelengths and lowest at longer wavelengths. There are approximately 30 magnitudes of visual extinction towards the centre of our galaxy. Such regions of high extinction are investigated at infrared and radio wavelengths for obvious reasons!



Note the 2200 Angstrom bump possibly due to the presence of carbon in the form of spherical graphite grains in the ISM.

Interstellar Extinction

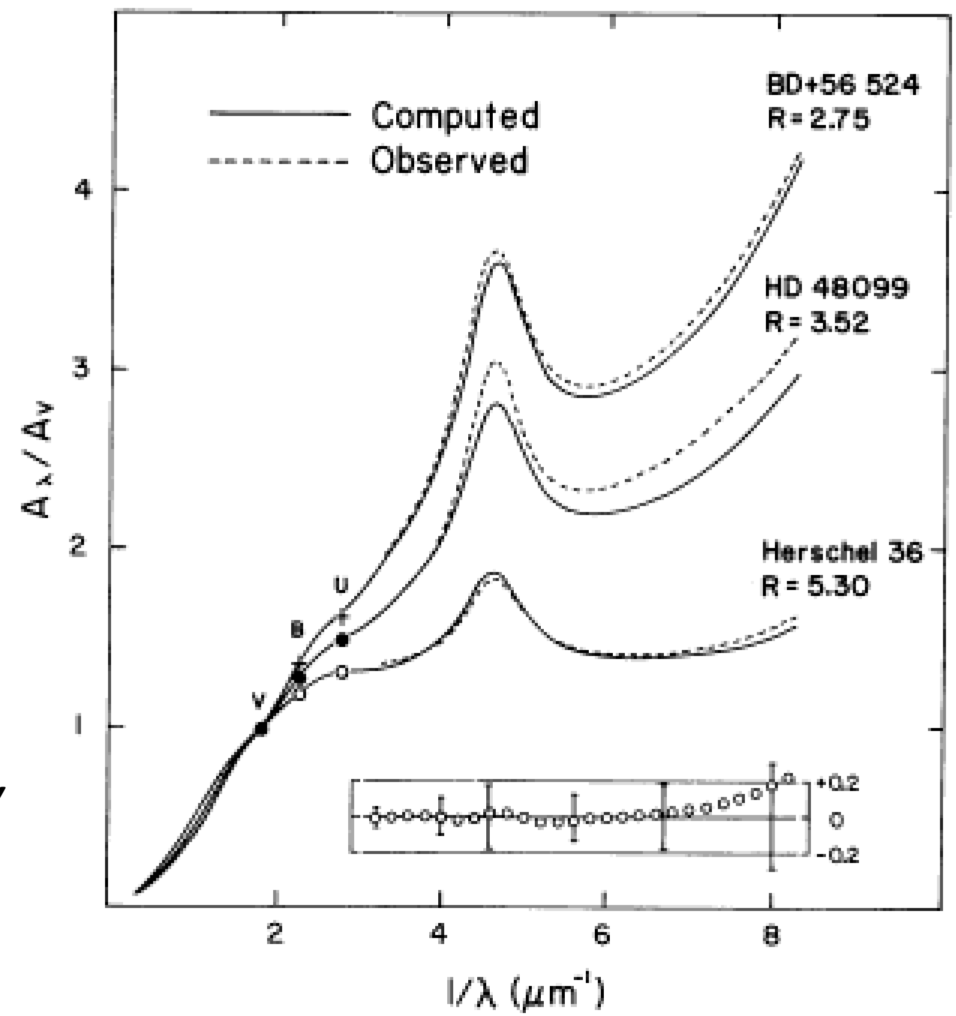
- $m_\lambda = M_\lambda + 5\log d + A_\lambda$
- $E(\lambda_1\text{-}\lambda_2) = A_{\lambda_1} - A_{\lambda_2}$
- $R = A_\lambda / E(\lambda_1\text{-}\lambda_2)$

Dust scatters blue light more than red

Know intrinsic colours, compare with observed colours, and determine extinction

Mean extinction: 1 mag/kpc in *V*

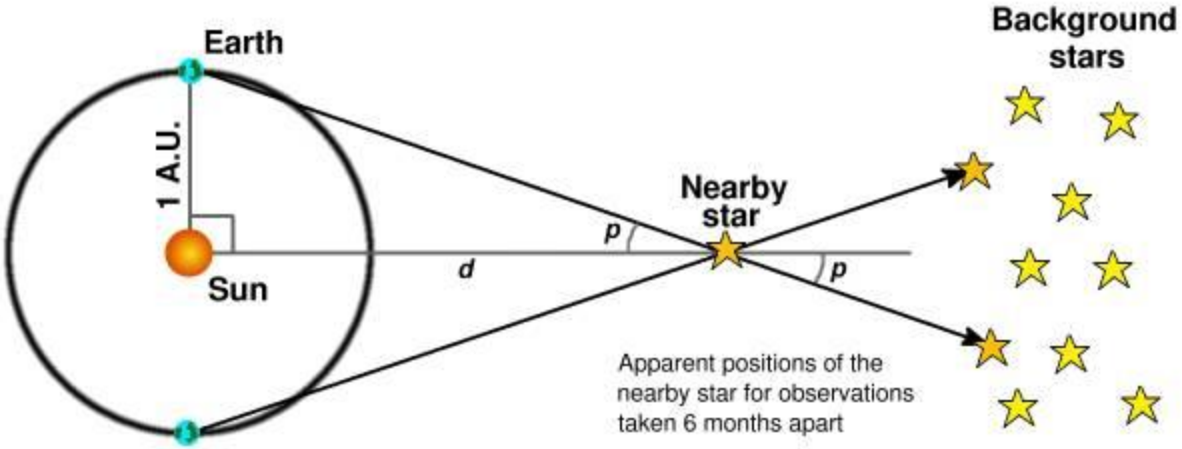
Dust layer: 1 kpc thick



John. S. Mathis, 1990: Annu. Rev. Astron. Astrophys. 28: 37–70

Distance Determination

- Trigonometric Parallax



- Photometric Distances

$$m_\lambda = M_\lambda + 5\log d + A_\lambda$$

  – Cluster HR Diagram

Star Formation History: Formalism

- Star Formation Rate: mass converted to per year
  - Local surface density: 8 $M_\odot$ pc^{-2}
  - In 10 kpc radius: 2.5×10^9 $M_\odot$
  - Age of disk: 1.5×10^{10} years
  - SFR: 0.2 $M_\odot$ /yr
- Initial Mass Function
  - Normalized distribution function of stars born with different masses

Initial Mass Function

- Total Luminosity Function

$$dN = \phi_t(M_v)dM$$

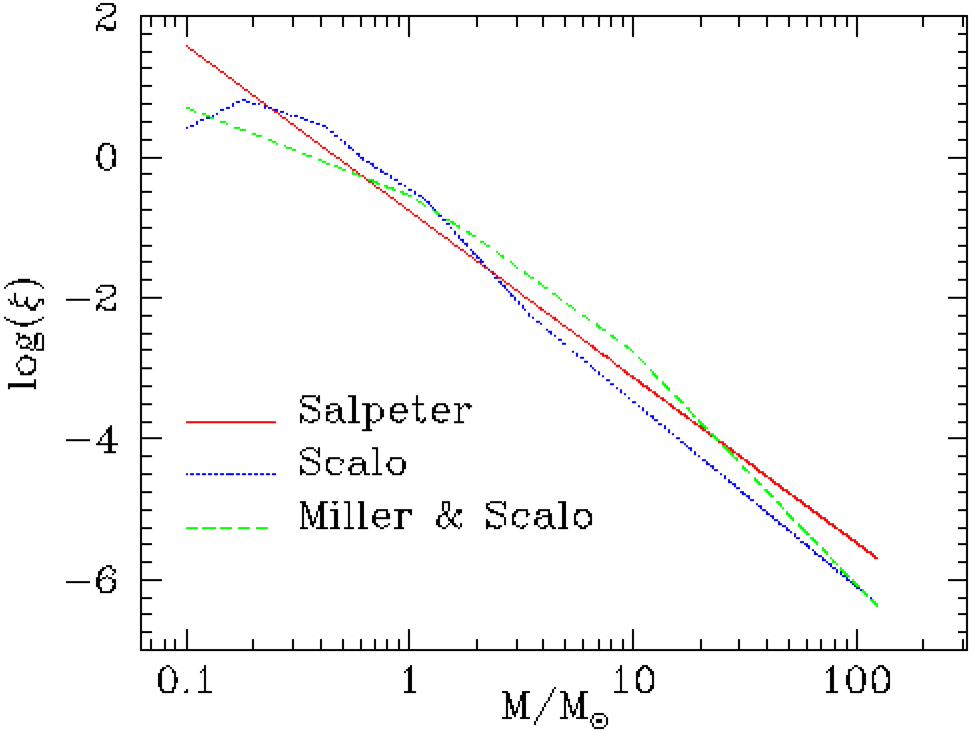
- Initial Mass Function

$$dN = \xi(m)d(\log_{10} m)\frac{dt}{T_0}$$

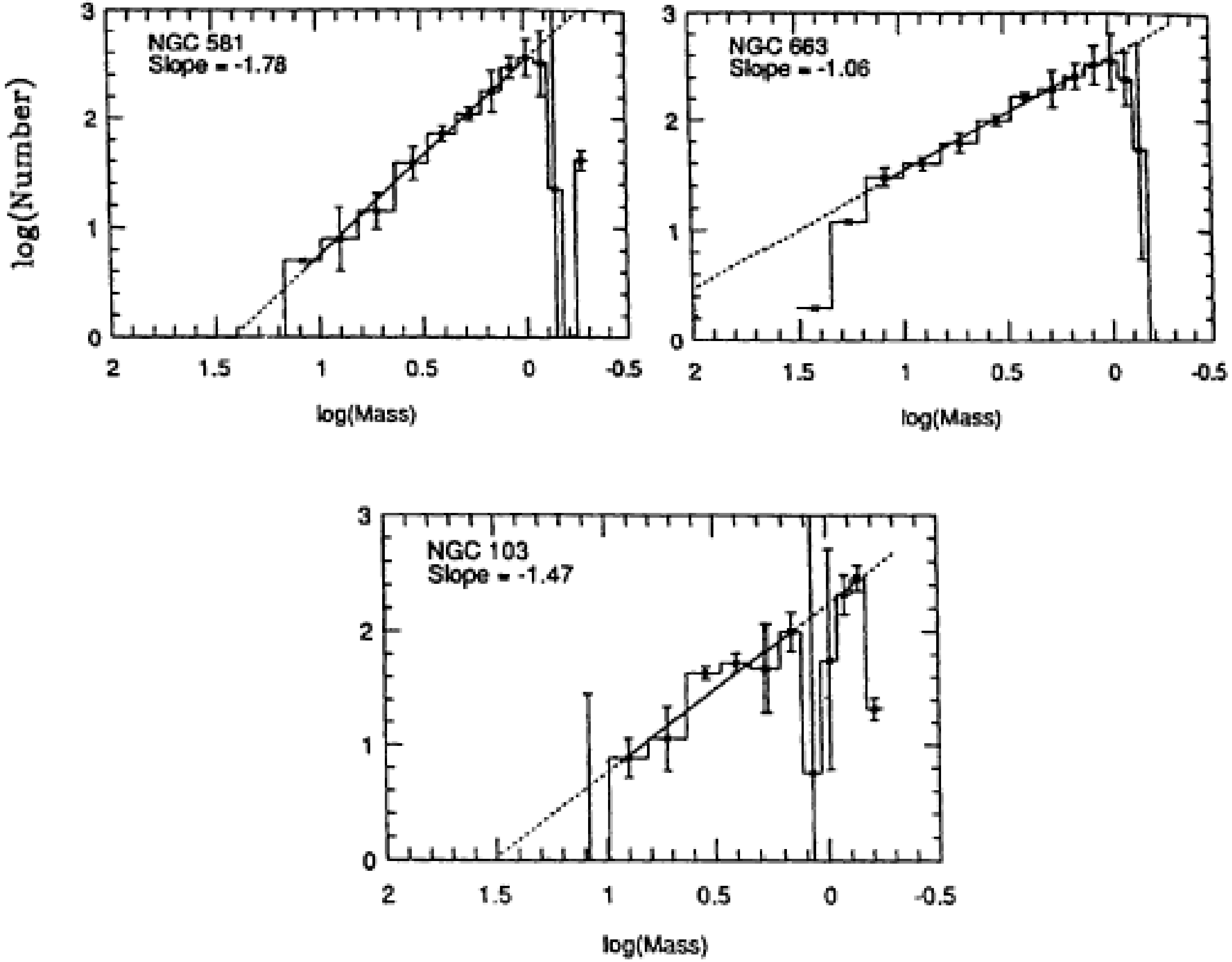
- $dN(m) \sim m^{-\gamma}dm$

Salpeter:

$\gamma = 2.35$



IMF from open clusters



Phelps, R. L. & Janes, K. A.,1993:AJ....106.1870P

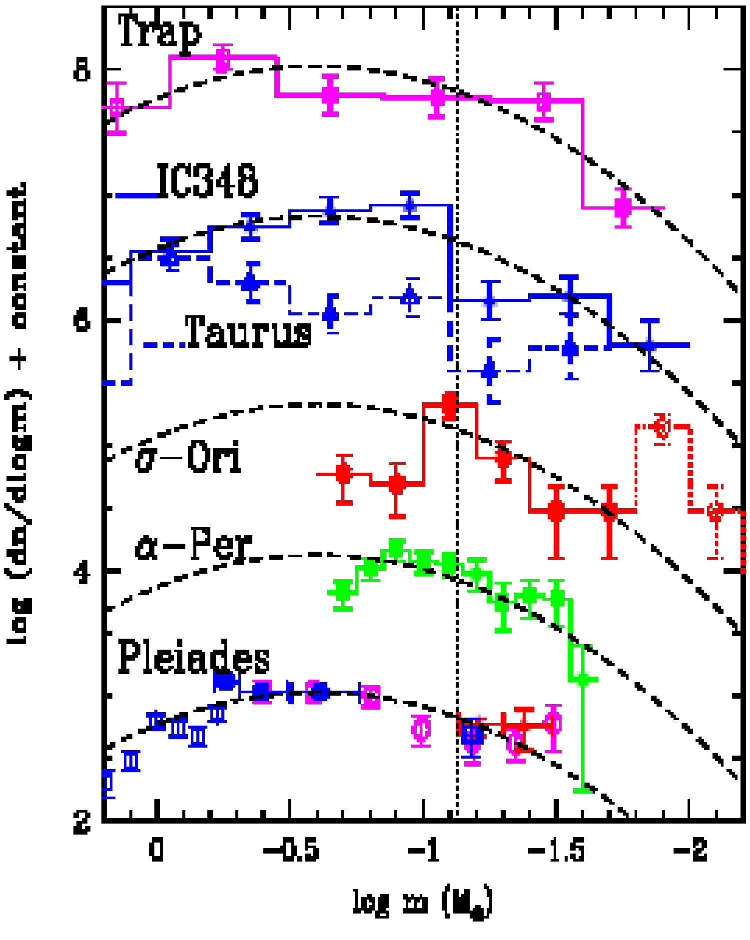


Figure 6. IMF for young clusters. Dash-line: field system IMF (2). Vertical dotted line: H-burning limit.

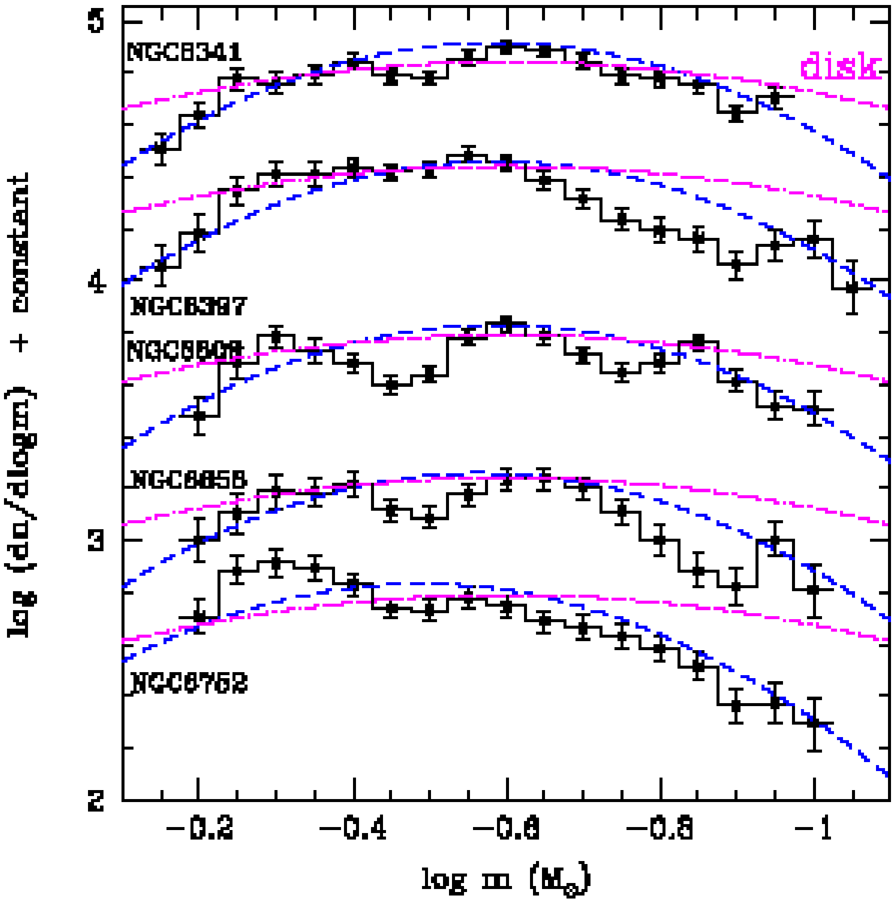


Figure 7. IMF for several globular clusters. Dot-dash line: disk system IMF (2)

Chabrier, 2003:Publ.Astron.Soc.Pac.115:763-796

Chabrier 2004

Galactic Centre

- Central bulge is hard to see due to dust extinction
  - Exception: Baade's window
    - Bulge contains old and young stars (Population I & II, variety of metallicities)
- Central Bar: stars and gas: aligned 20^{o} to the line of sight
- Galactic Nucleus: observed in the radio, infrared, X-ray and gamma-ray regions
  - Central surface density: $4x10^{12}\ M_{\odot}\ pc^{-2}$
  - Evidence for supermassive black hole

Galactic Centre

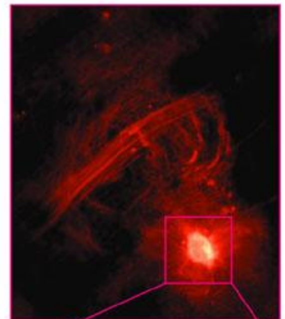
Optical Region

Inner 70 parsecs

1.4 GHz radio Continuum

0.5^{o} x 0.5^{o}

Filaments perpendicular to Galactic plane; trace magnetic fields



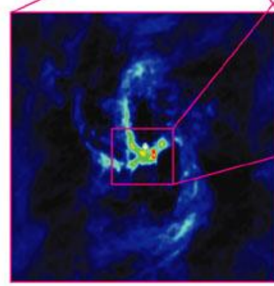
Sagittarius A*

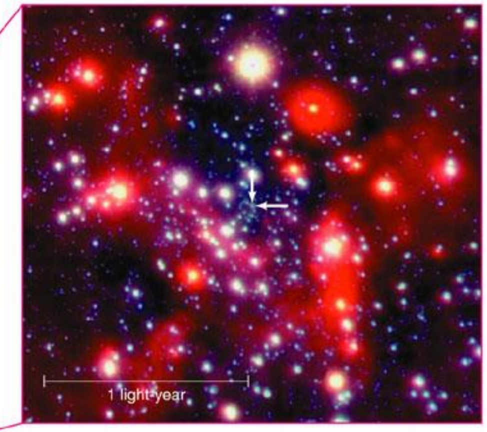
Radio: 4 pc x 4pc

Spiral of ionized gas

IR star clusters

Molecular ring: 2 pc dia





The inner parsec in IR

Central star cluster: 10^{6} stars pc^{-3} compared to 0.1 pc^{-3} near sun

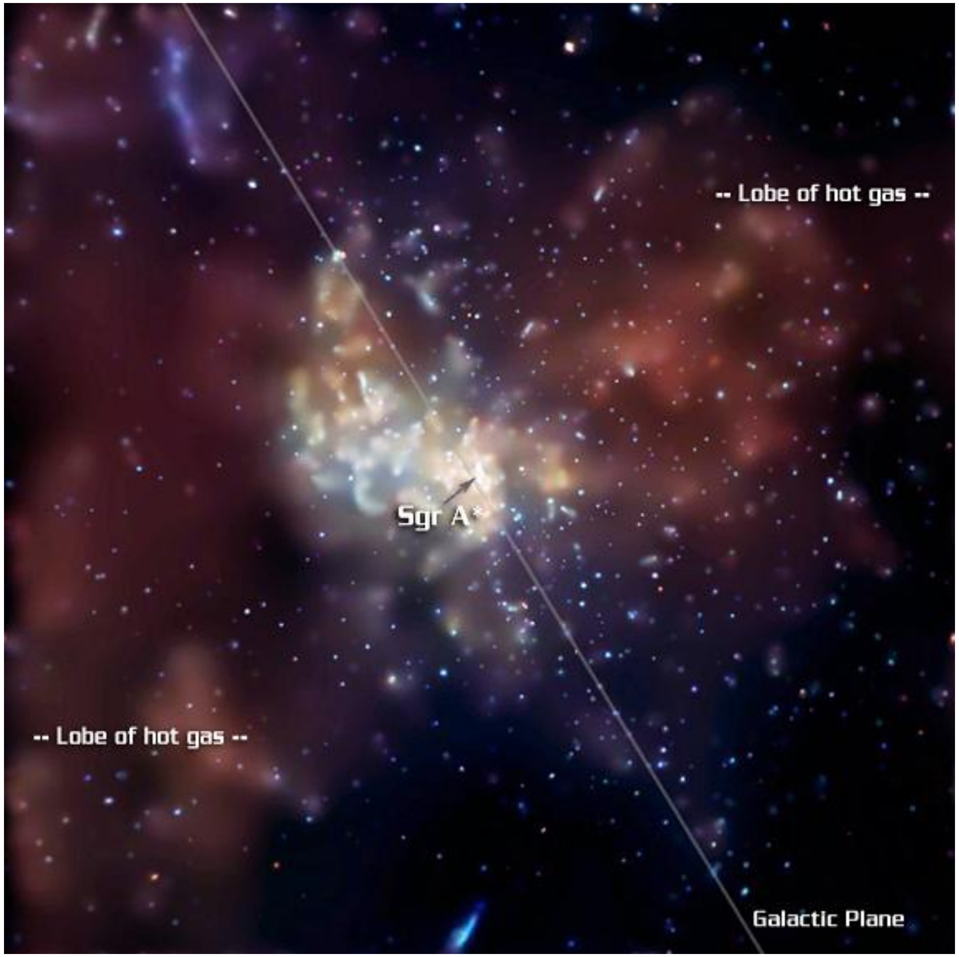
Total mass $3 \times 10^{7}\ M_{\odot}$ at 10 pc radius

Repeated star formation, the most recent 10^{7} years ago.

Radio source: Sagittarius A*

- Radio source in the centre of nucleus
- A torus of molecular gas rotates around it
- Star cluster is centred around it
- Variable nonthermal source: $L < 10^5 L_\odot$
- Size: 0.3 mas = 2.4 AU

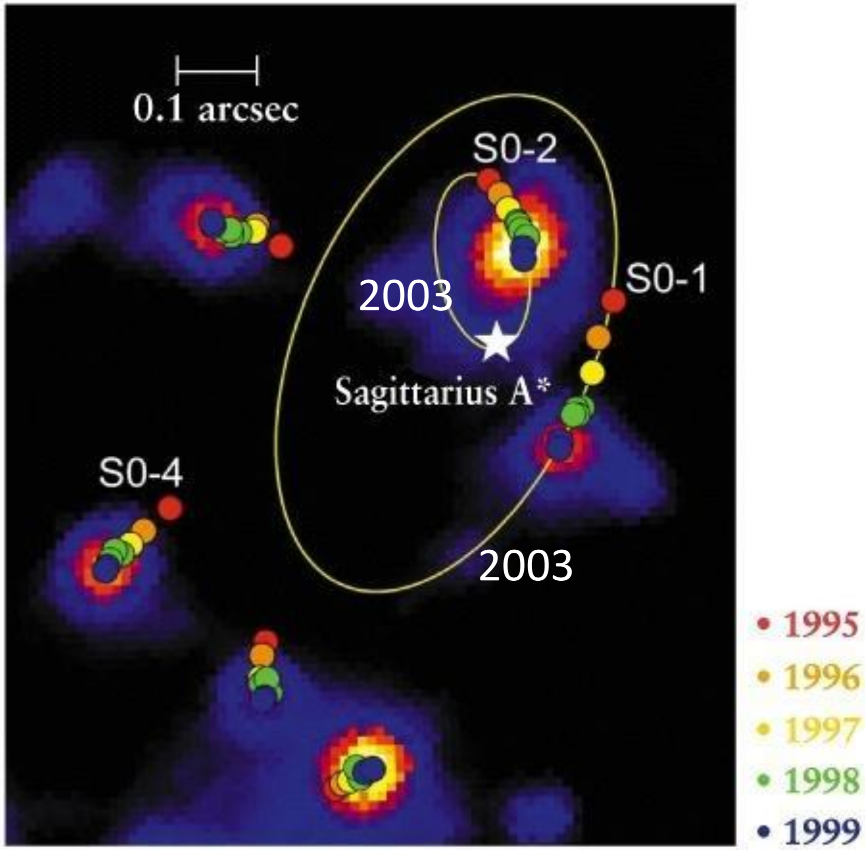
Galactic Centre in X-rays



Proper motions of stars

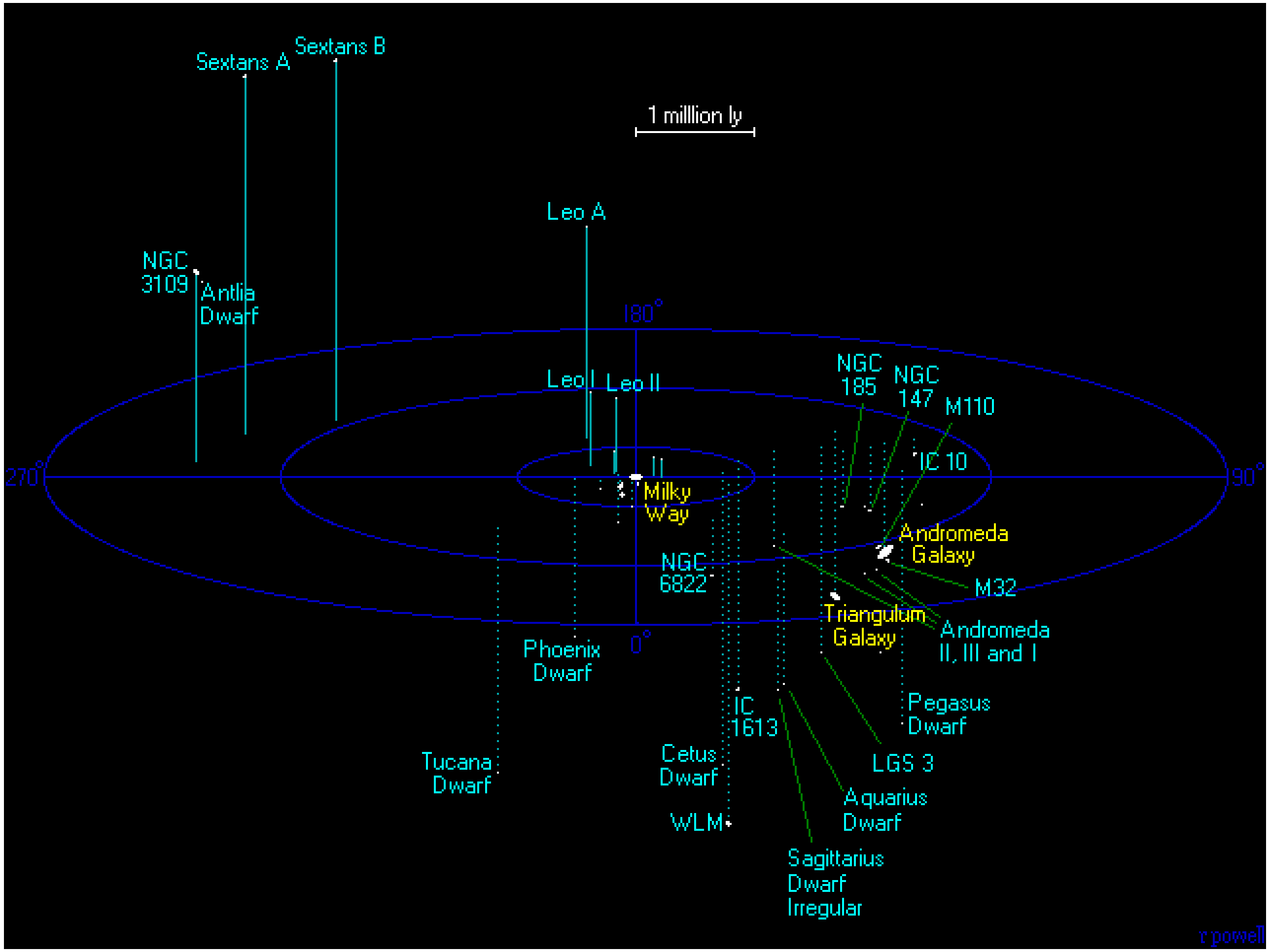
0.1 arcsec = 850 AU
0.04 pc: V = 500 km/s
0.01 pc: V = 1000 km/s
$V^2 R$ = constant
Constant mass up to 0.5 pc
Mass within 0.01 pc
= $3 \times 10^6 M_\odot$

Size of black hole at the galactic centre
Swarzschild Radius: GM/c^2
A few $R_\odot$



http://blackholes.stardate.org/directory/image.php?o=milky-way-sagittarius-a&p=Milky-Way-diagram

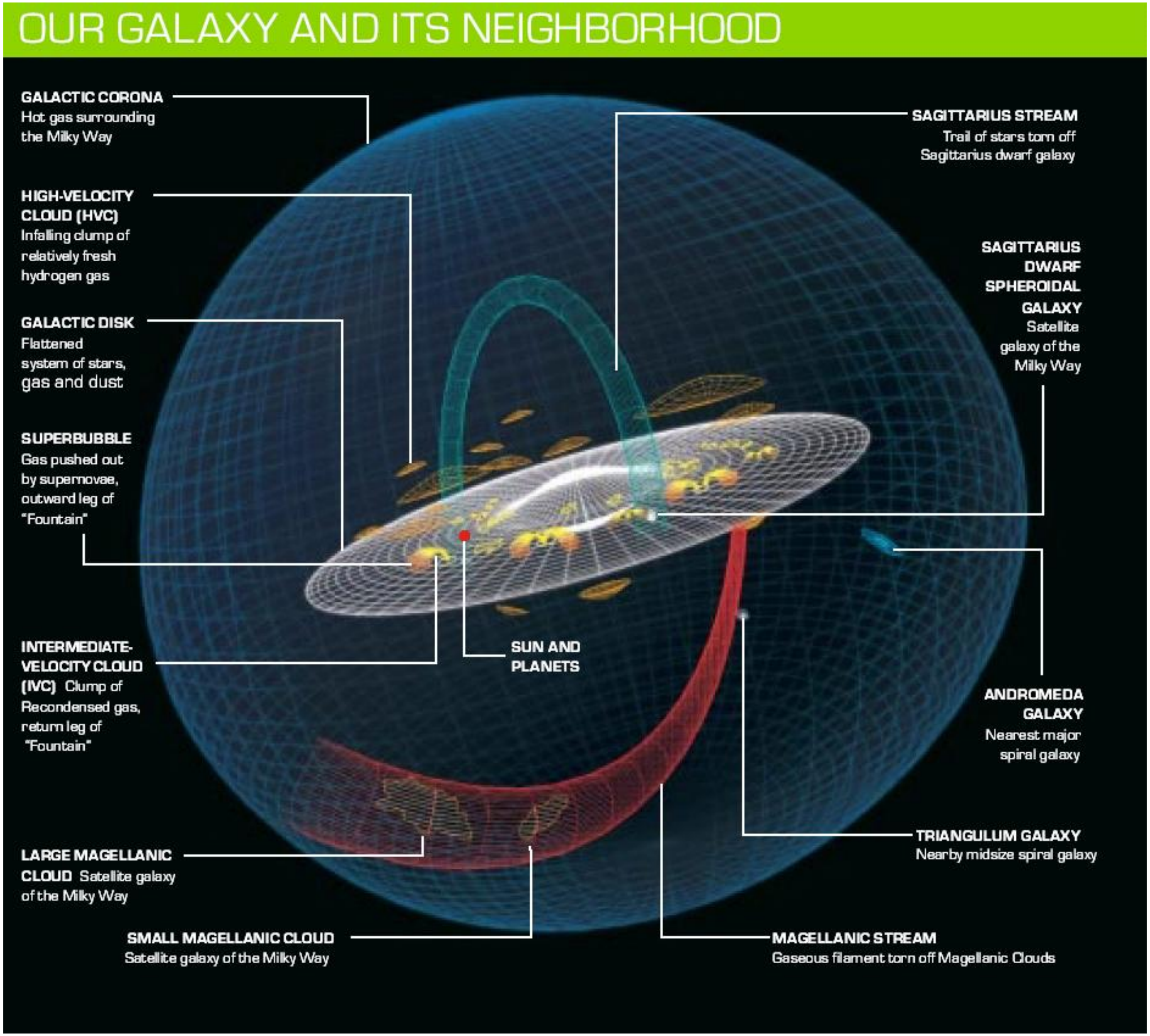
Local Group of galaxies



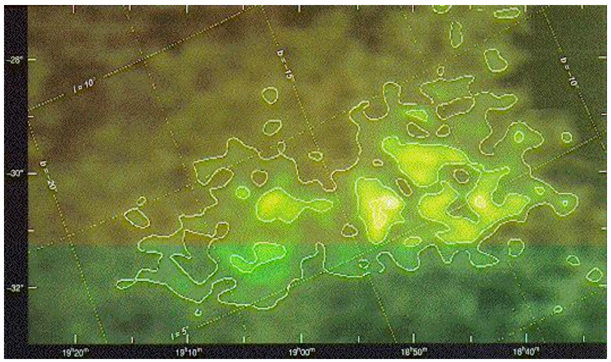
Summary

- Our Galaxy
- Structure, stellar population
- Stellar evolution and chemical evolution
- Kinematics of halo, bulge and disk
- Distance, Extinction
- Star formation history, Initial mass function
- End of Part-1

Galactic Environment

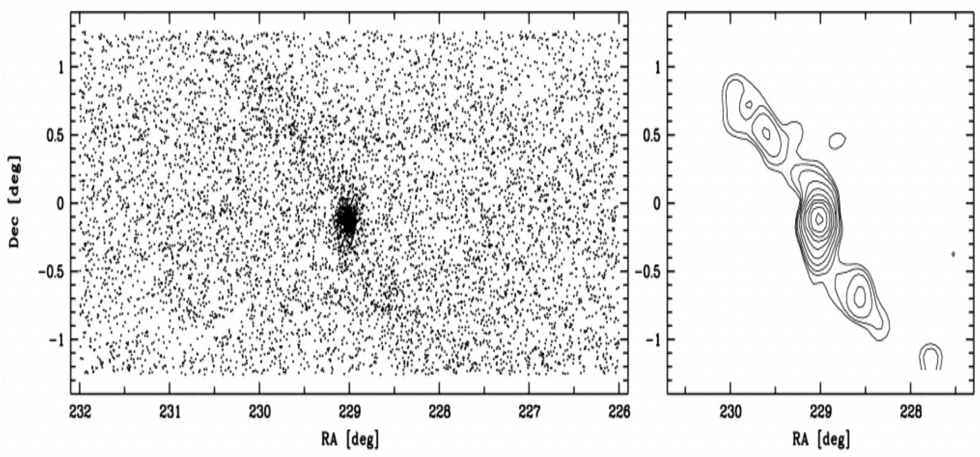


There be fragments yet...

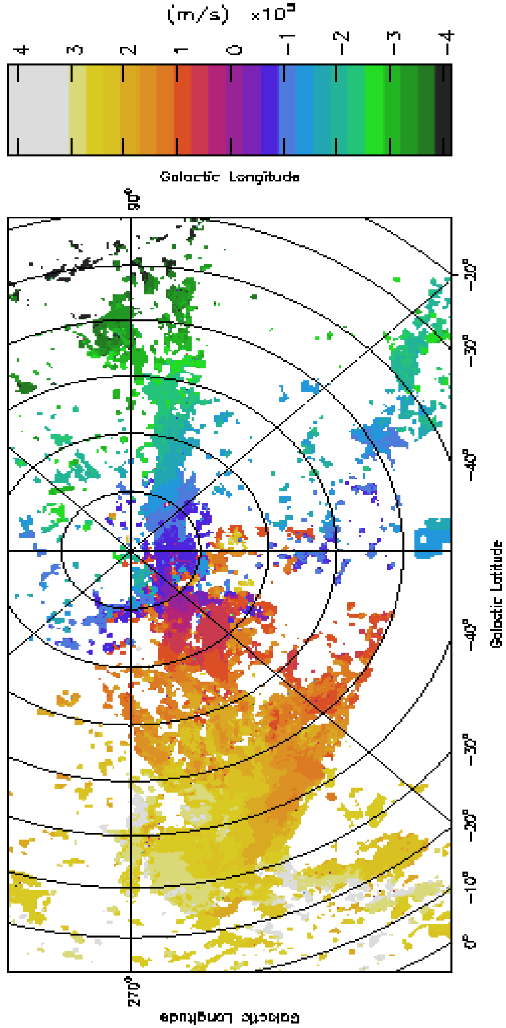


Sagittarius Dwarf

Canis Major Dwarf



Globular cluster tidal tails



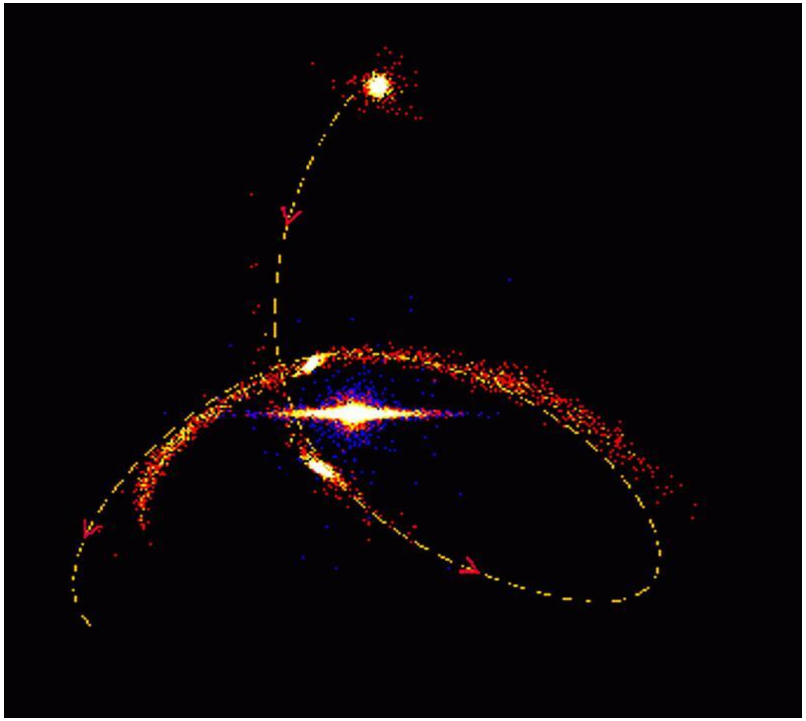
The Magellanic stream

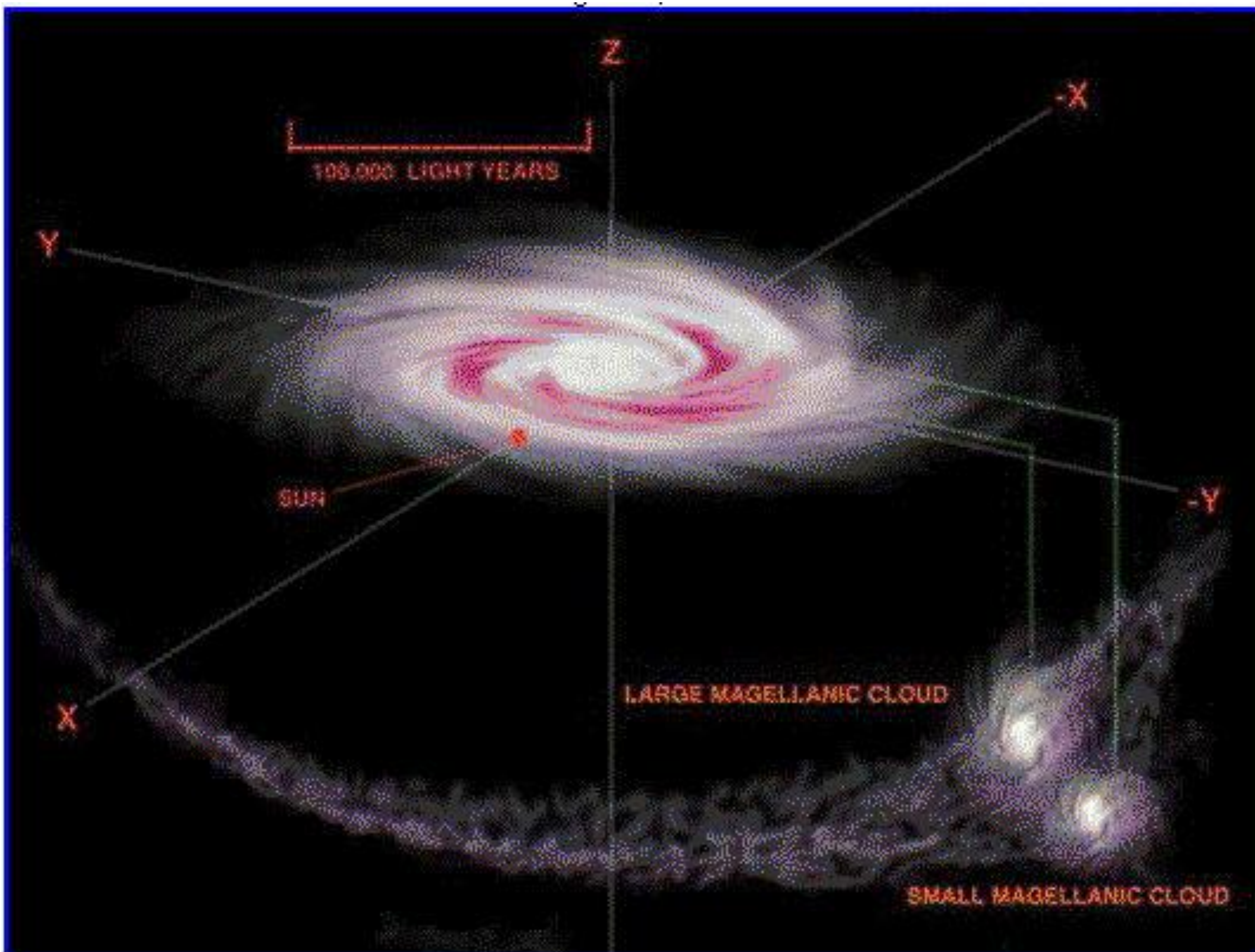
The Galactic Mixmaster

The stellar halo

Inner regions :
probably nicely mixed.

Outer regions :
probably still a little lumpy.




Z
-X
100,000 LIGHT YEARS
Y
SUN
-Y
X
LARGE MAGELLANIC CLOUD
SMALL MAGELLANIC CLOUD

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