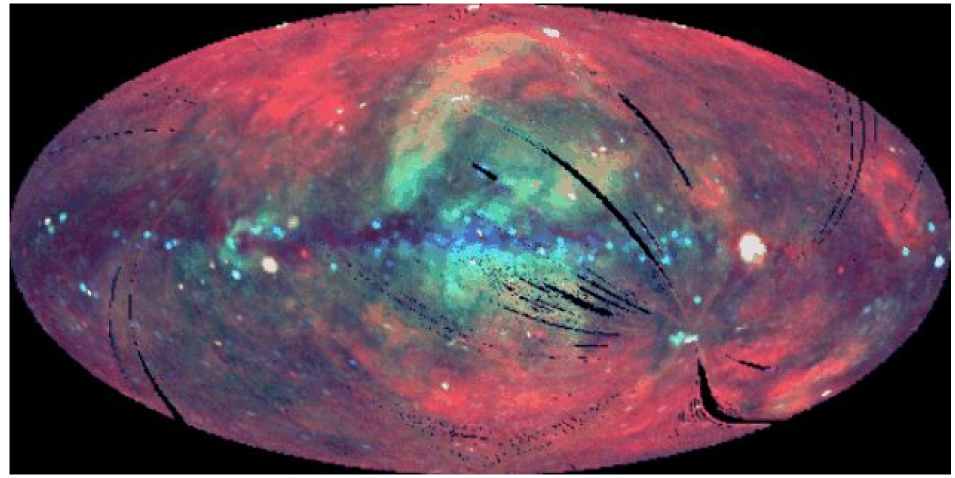
dusty news from todays astro-ph

- The Crab Nebula has condensed most of the relevant refractory elements into dust, suggesting the formation of dust in core-collapse supernova ejecta is efficient.
- arXiv:1209.5677 A Cool Dust Factory in the Crab Nebula: A Herschel Study of the Filaments

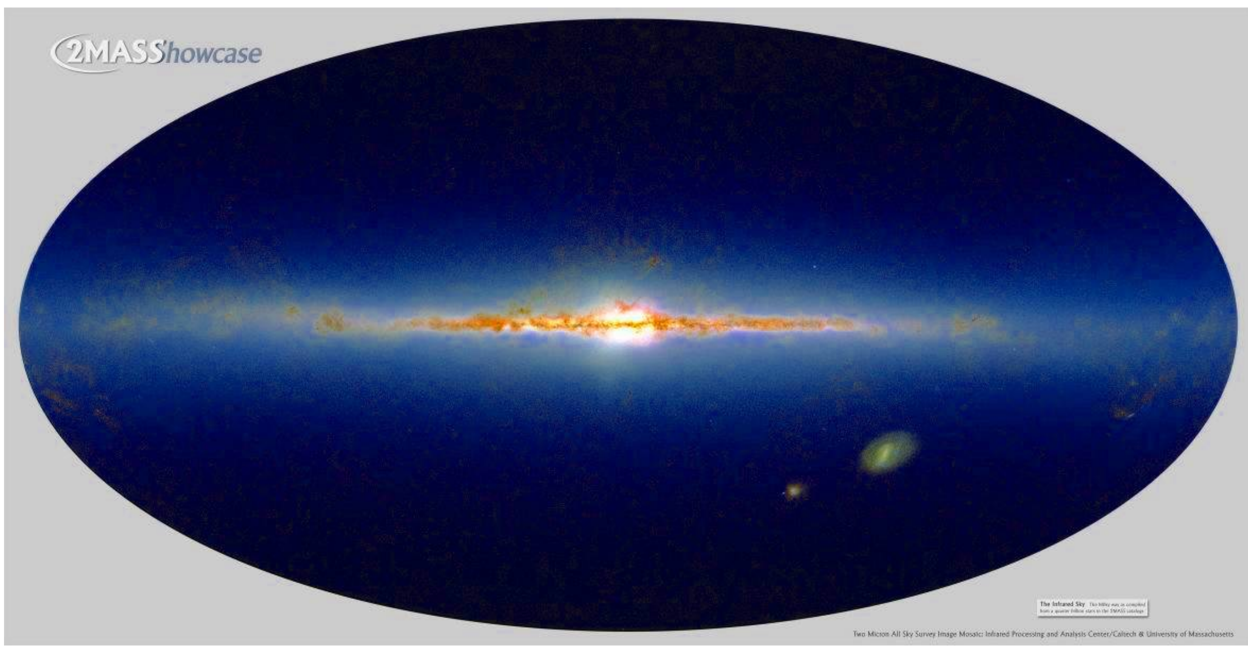
H. L. Gomez, et al

Milkyway

- Why study the MW?
  - its big, bright,close
  - Allows detailed studies of stellar kinematics, stellar evolution. star formation, direct detection of dark matter??
- Problems
  - We are in it
  - Distances are hard to determine
  - Dust is a serious issue



Milky Way in X-rays- Image of the Hot ISM



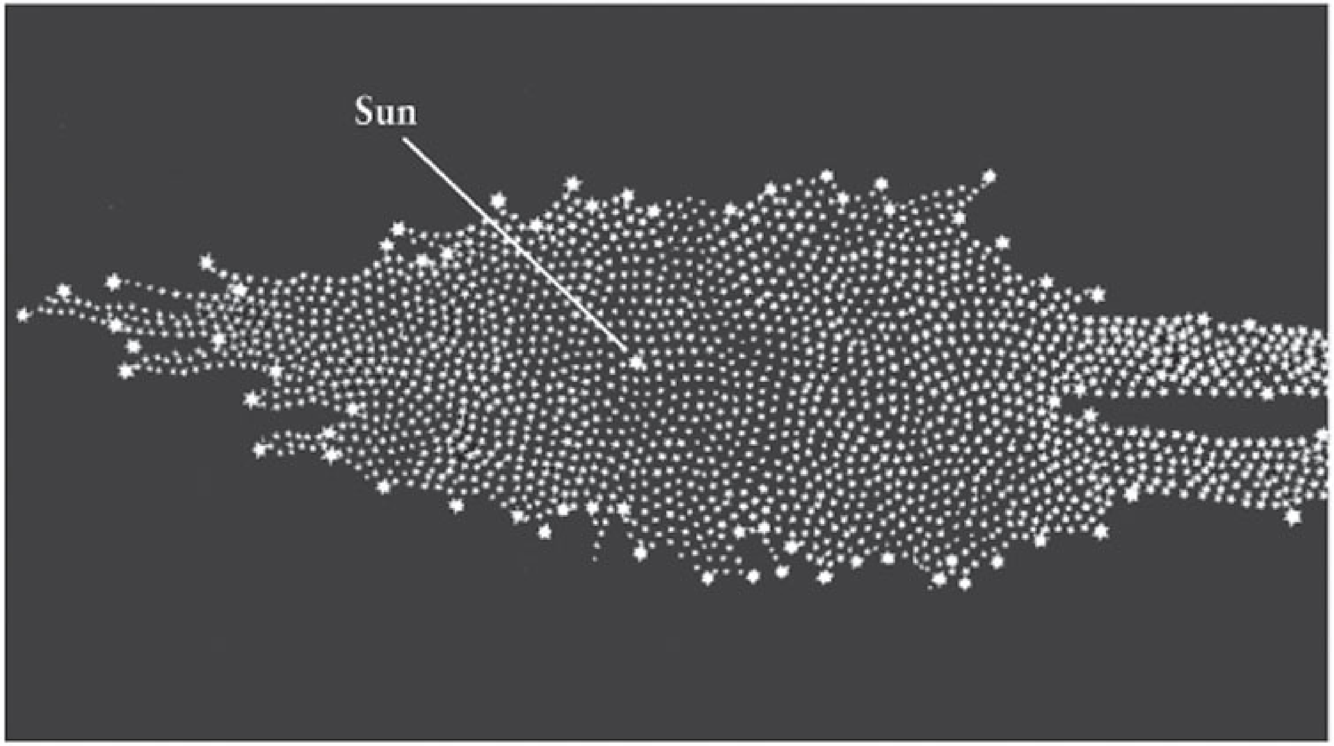
Milky Way in IR
www.milkywaproject.org

Chapter 2 in S+G

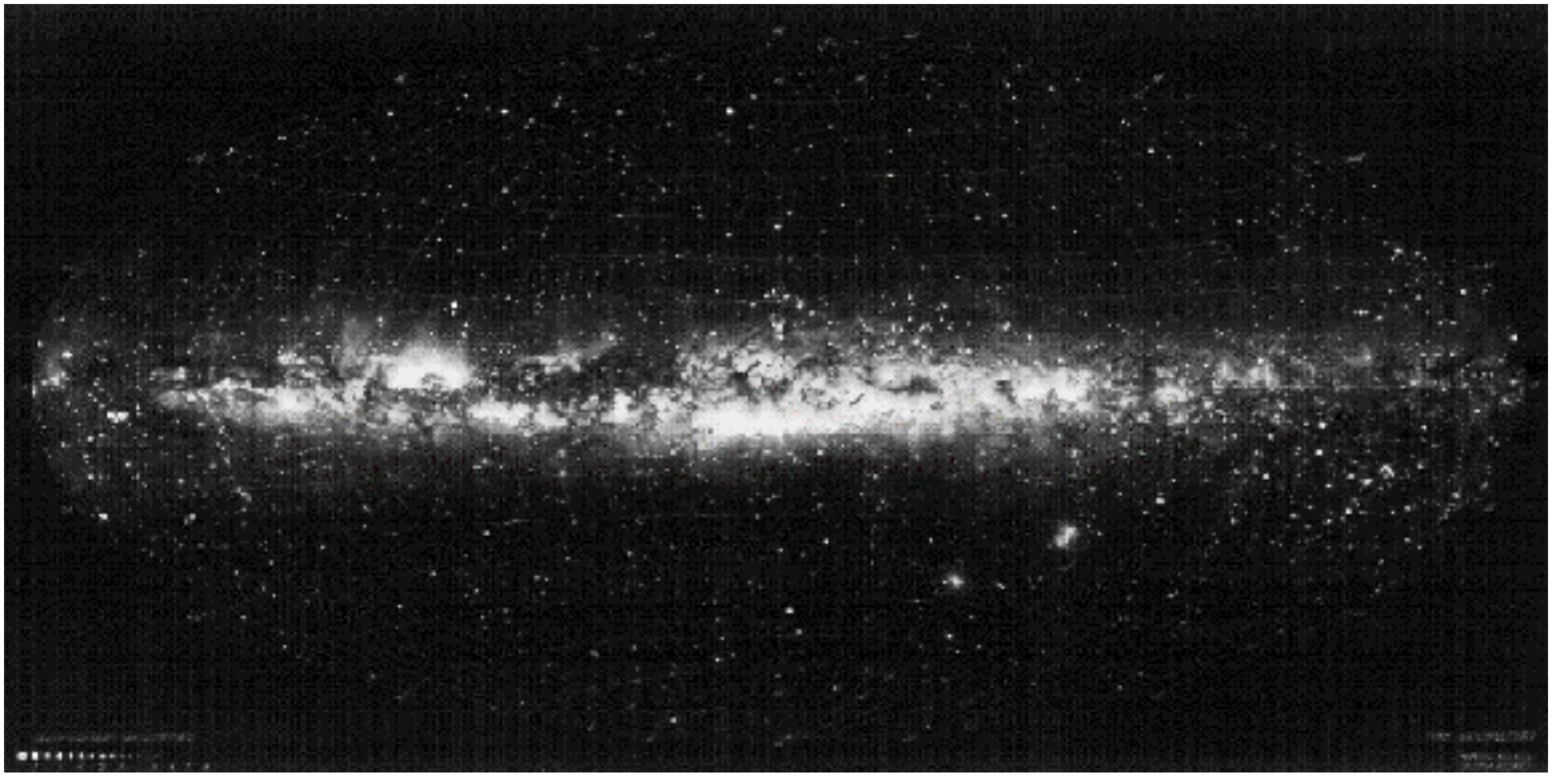
- We have covered most of the material in chapter 2 but organized in different way.
- Please re-read ch 2.
- We will cover some more material about the MW now

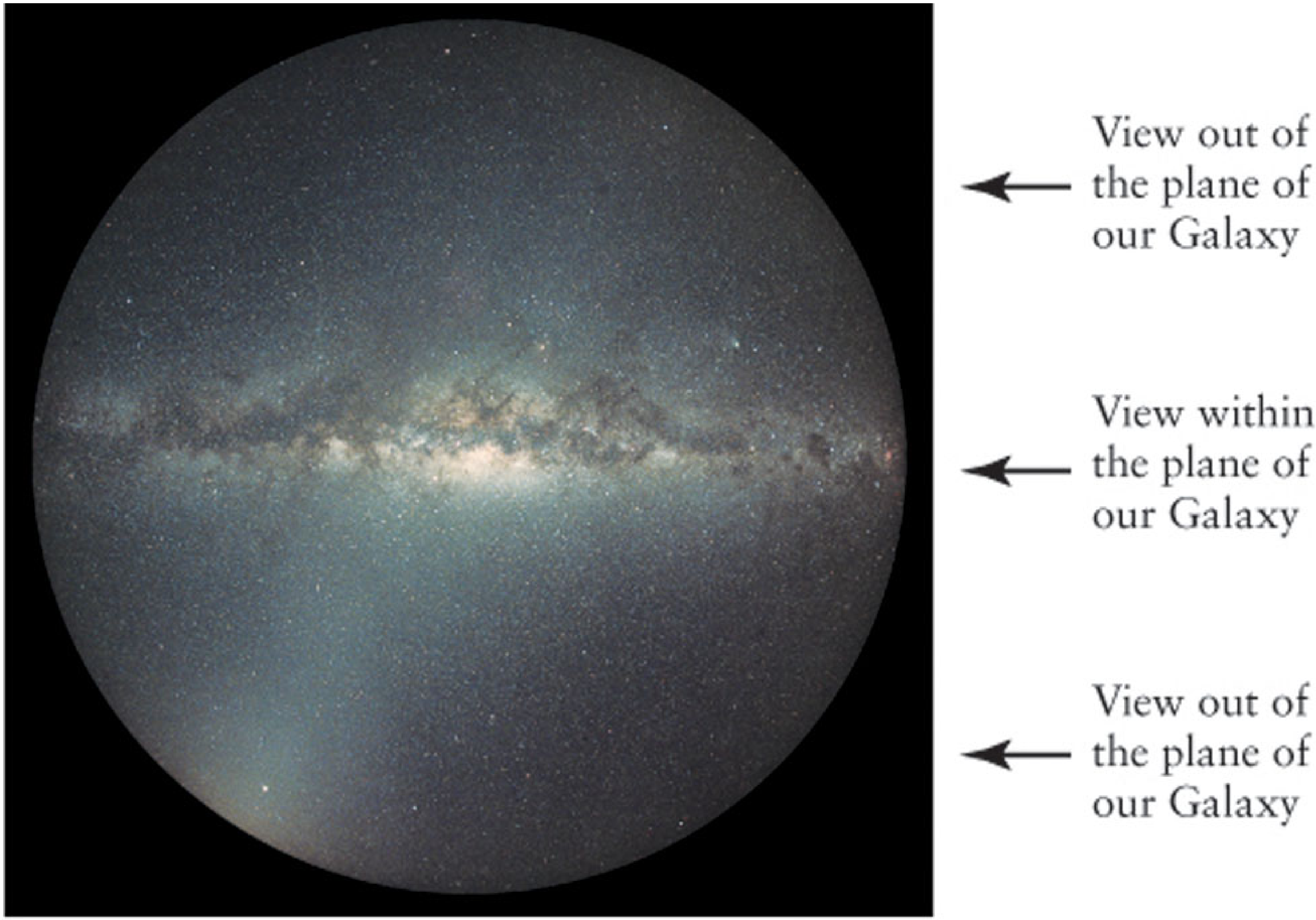
Our place in the Galaxy

- We live in a large disk galaxy of average mass
  - The sun is in the disk, towards the edge (8kp from center)
  - Projected onto the sky, this disk of stars looks like a band of light that rings the sky… the Milky Way
- This realization came somewhat slowly…
  - Disk-like nature of galaxy realized by Thomas Wright (1780); refined by Kant
  - First attempt to map out galaxy made by William Herschel (1785); refined by Kapteyn in 1920
  - Herschel came to the conclusion that we sit at the center of the Galactic disk. In fact, **he was wrong**… had not accounted absorption by dust! *(something that he did not know about)*

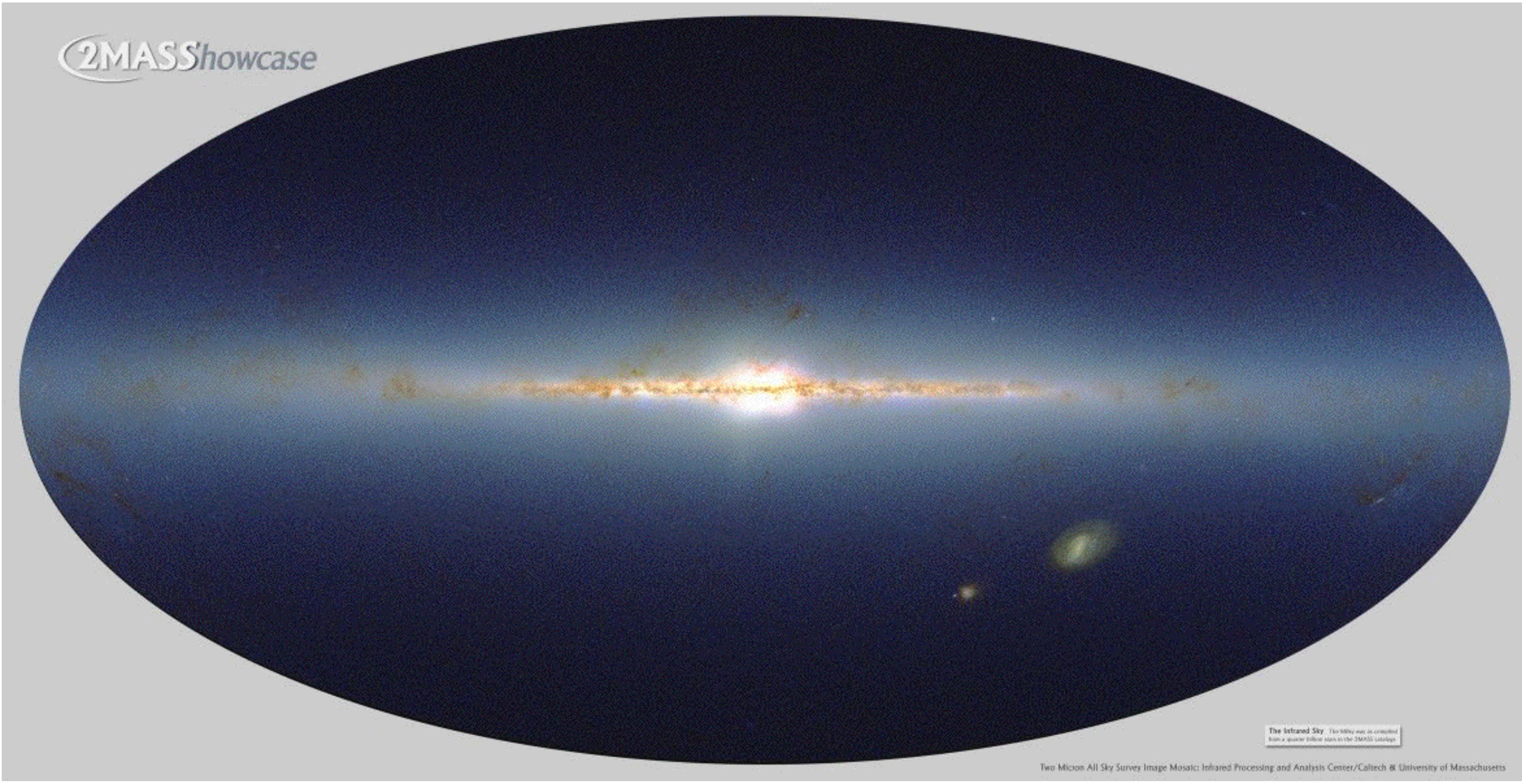


Herschel’s map of the Galaxy

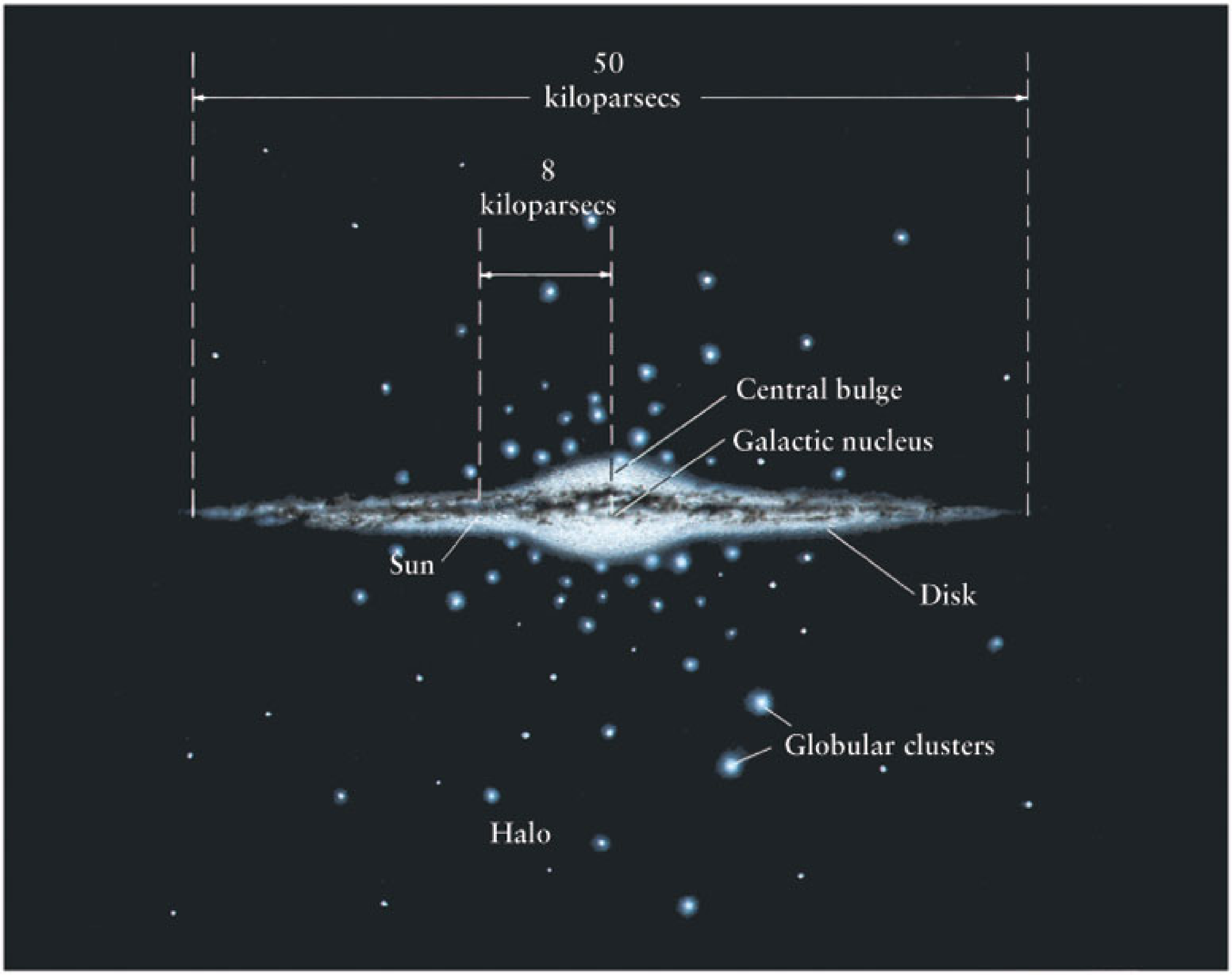



View out of the plane of our Galaxy
View within the plane of our Galaxy
View out of the plane of our Galaxy

(b)



The MW galaxy as seen by an infrared telescope- IR light is much less sensitive to 'extinction' by dust than optical light

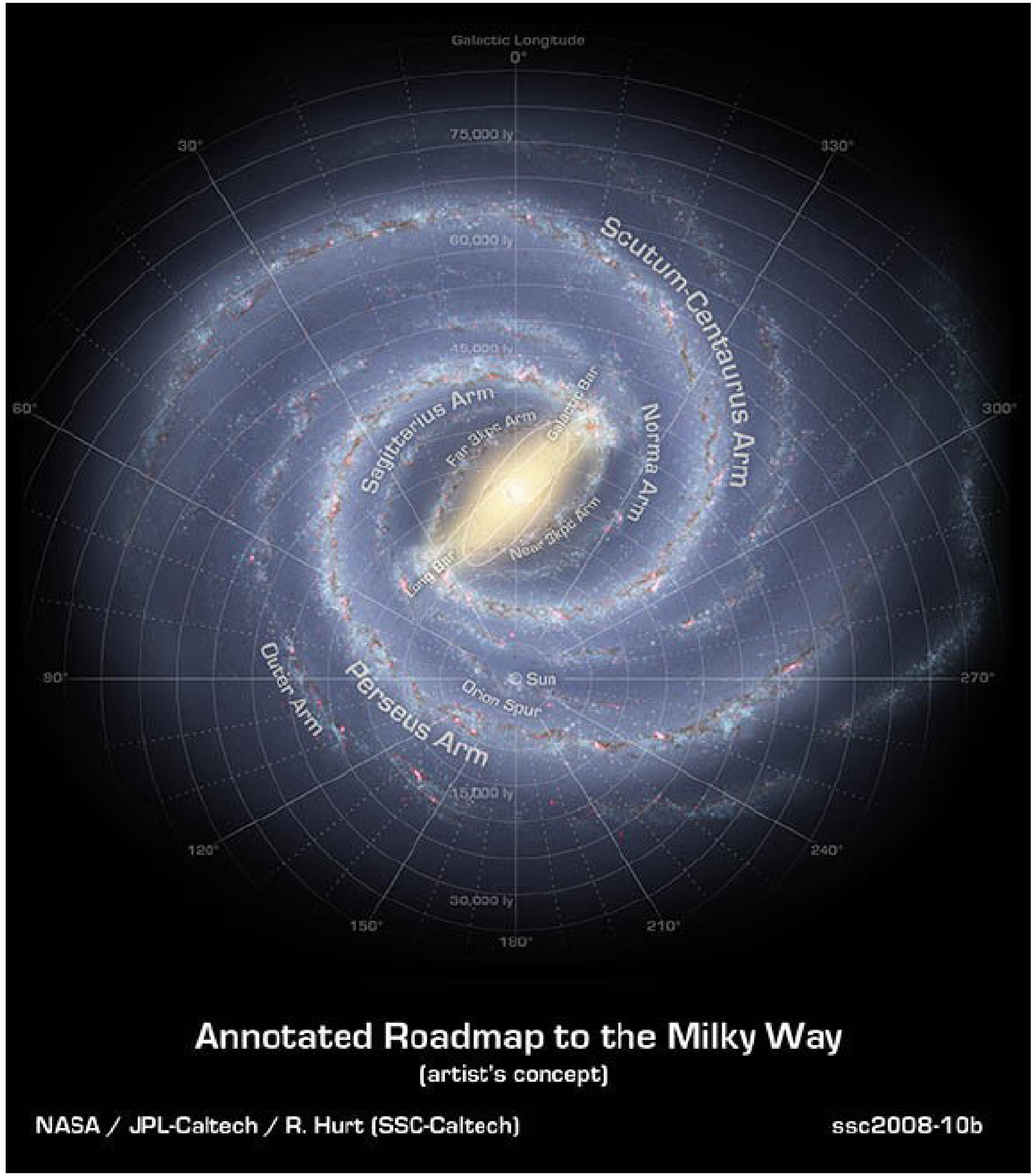


1 kiloparsec=3.26×10^{3} lightyears=3.08×10^{19}m

- Its only in the MW and a few other nearby galaxies that fossil signatures of galaxy formation

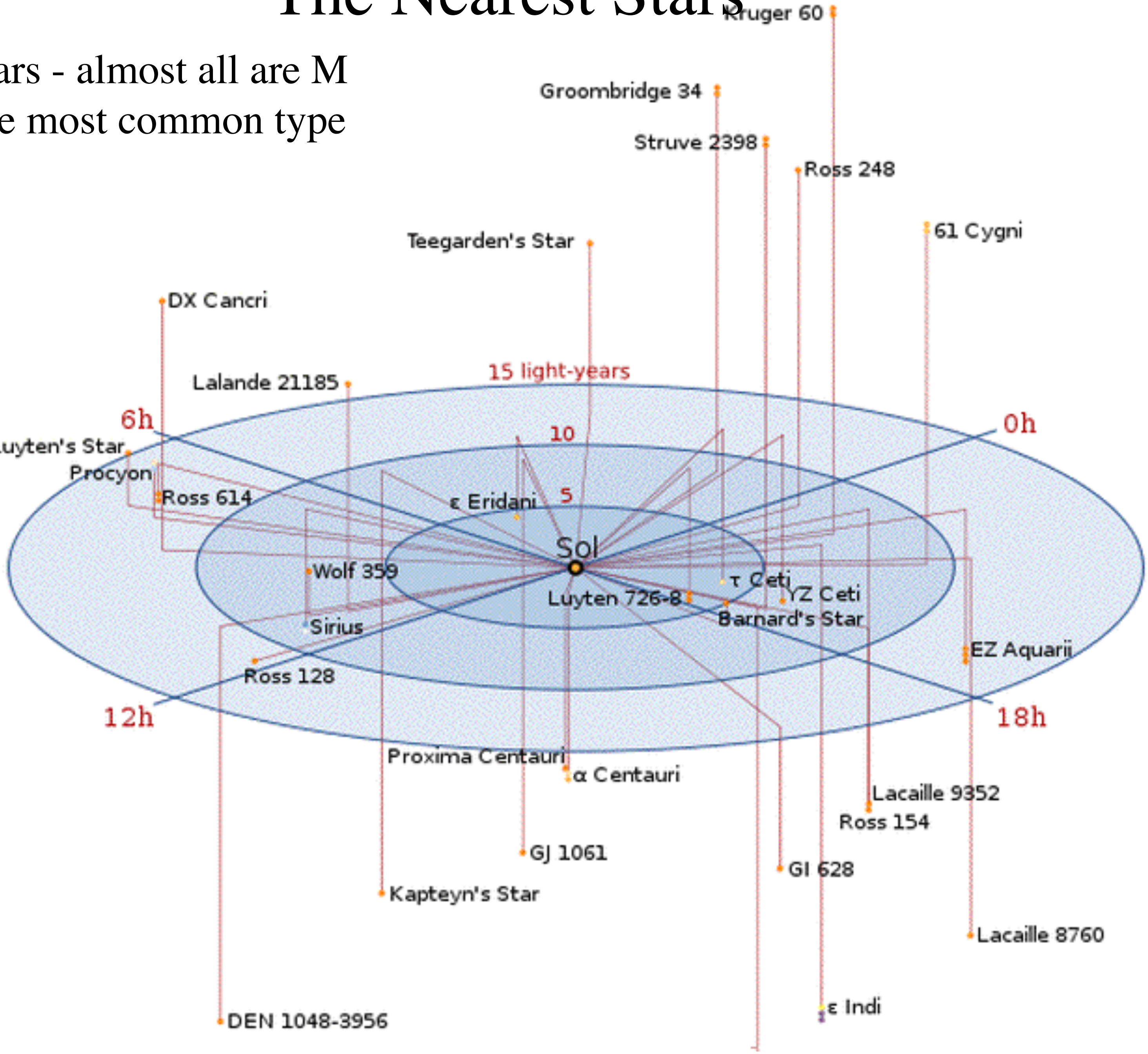
  + evolution (ages dynamics and abundances for individual stars) is possible.

These signatures allow a probe back to early epochs and constraints on theories of galaxy formation

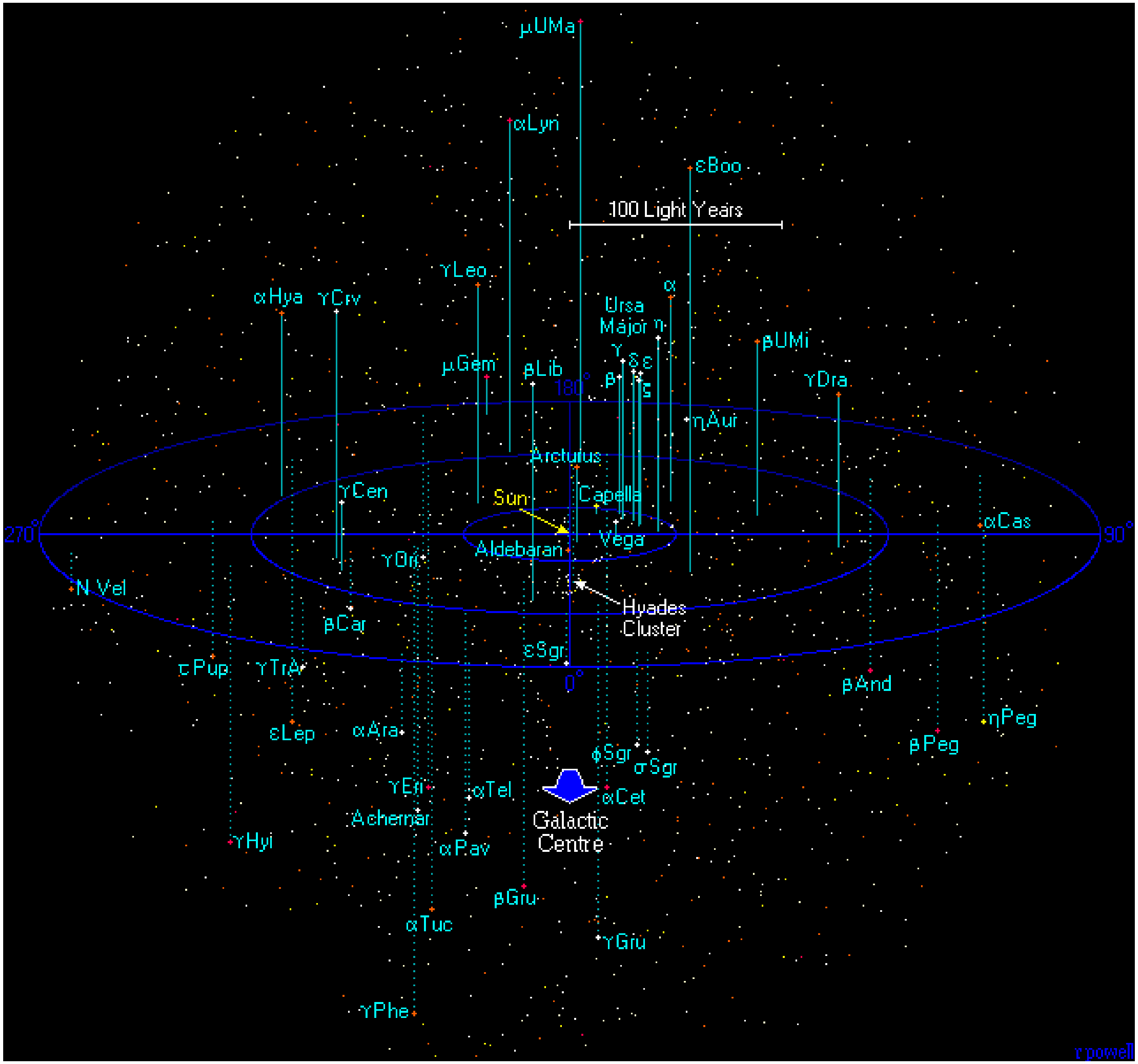


The Nearest Stars

- Nearest stars - almost all are M dwarfs- the most common type of star



Stars Within 250pc



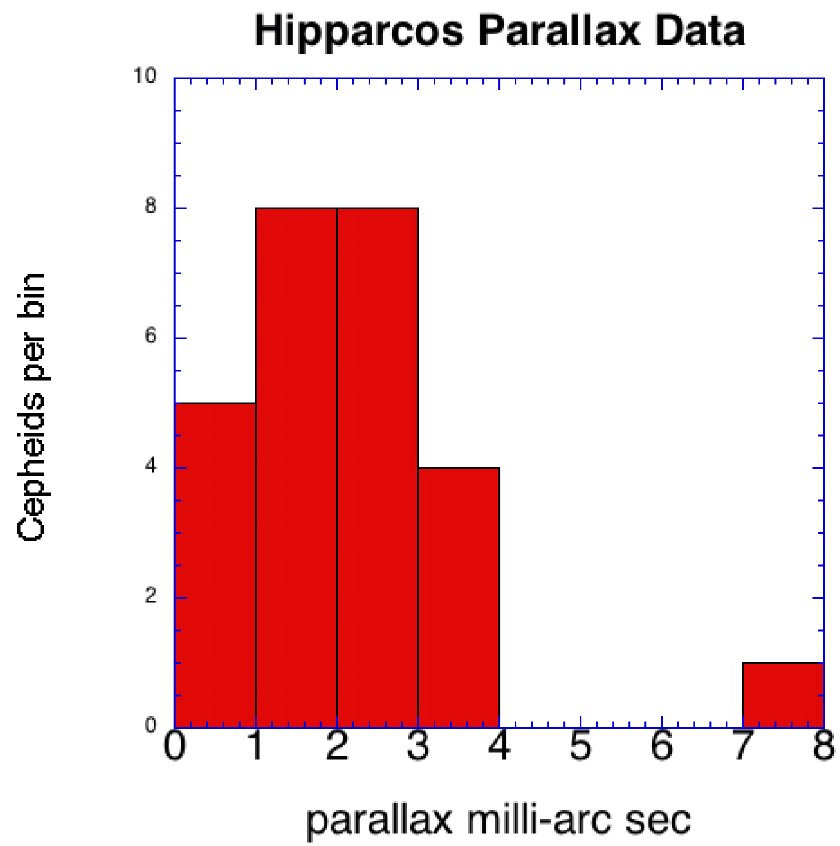
Nearby Stars

- Historically one dealt with flux (magnitude) limited samples of stars
- Gas is much more complex Thanks to the Hipparchos satellite which measured the absolute distances to many stars via parallax we now have a proper census of the very nearby (<100pc) region near by the sun (at this close distance effects of dust are small)

Relative vs Absolute Distances

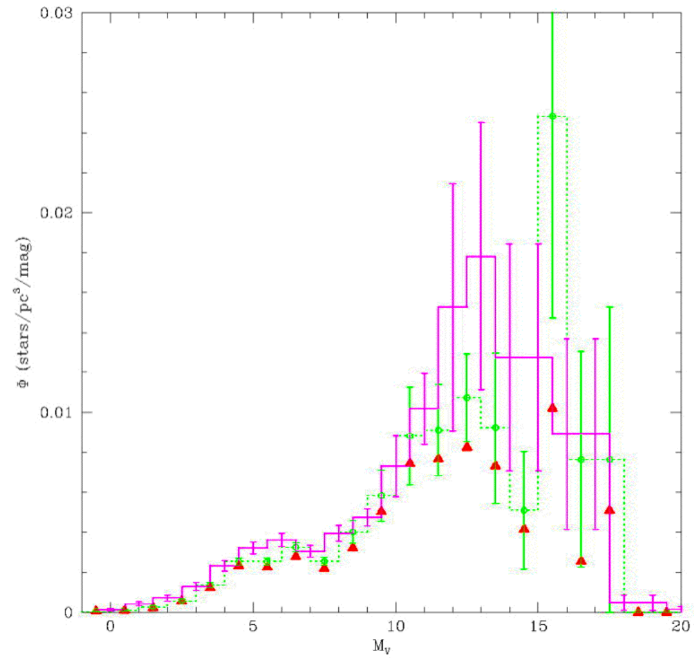
- H. Levitt determined that Cepheids were very good relative distance determiners- how to connect with stellar parallax absolute distance measurements??
- This was done in 1913 by Hertzsprung using statistical parallax-Traditional annual parallax techniques are not capable of determining distances to even the closest Cepheids because the 2AU base line is not long enough.

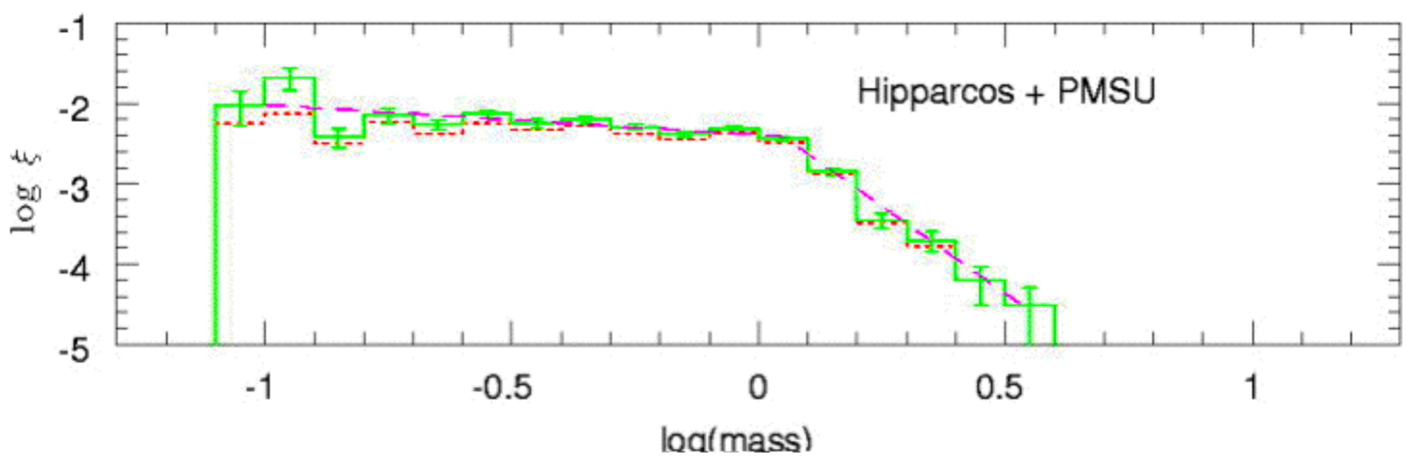
It wasn't until 1997 that the parallax was directly to the nearest Cepheids using the Hipparcos satellite- the reason is that the closest Cepheids have parallaxes of **milliarc** secs- now HST has 10



Luminosity and Mass Function

- A fundamental property of stars is how they are distributed in mass and luminosity- the mass and luminosity functions
- One has to transform the observables (flux, color etc) into physical units (luminosity in some band, temperature) using theoretical stellar models and distances determined via a variety of means
- The best set of distances are from parallax and the largest data set is for the solar neighborhood (R~25pc) from the Hipparchos satellite set by its ability to measure small parallaxes

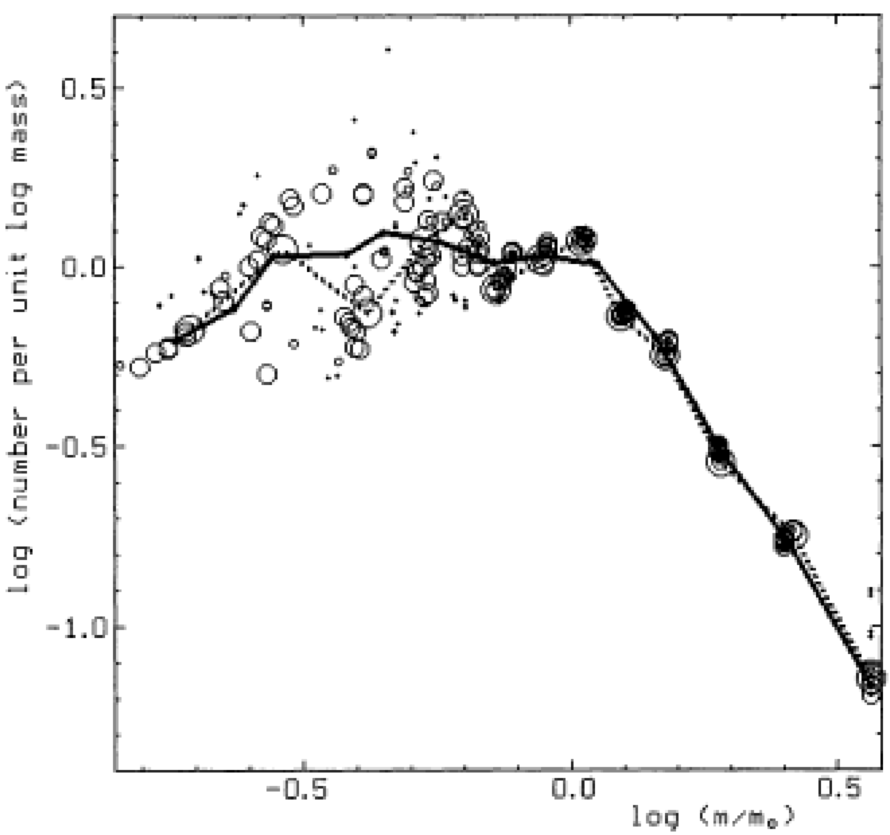




Luminosity and Mass Function

- There are several 'nasty' problems
  - since stars evolve the 'initial' mass function can only be observed in very young systems
  - none of these are close enough for parallax measurements

842 H. Meusinger et al.: The mass function of the Pleiades down to 0.3 $M_\odot$



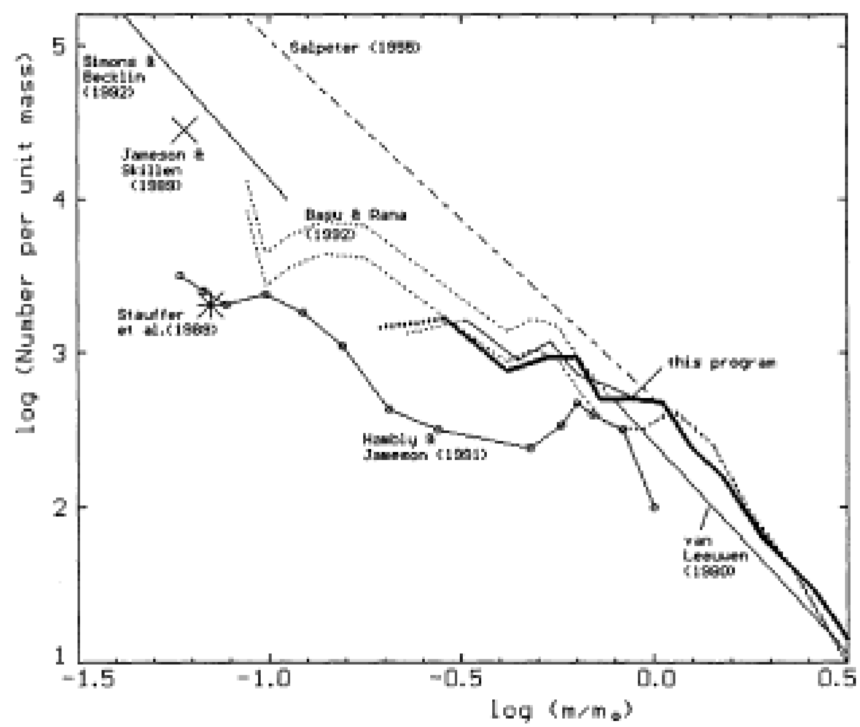
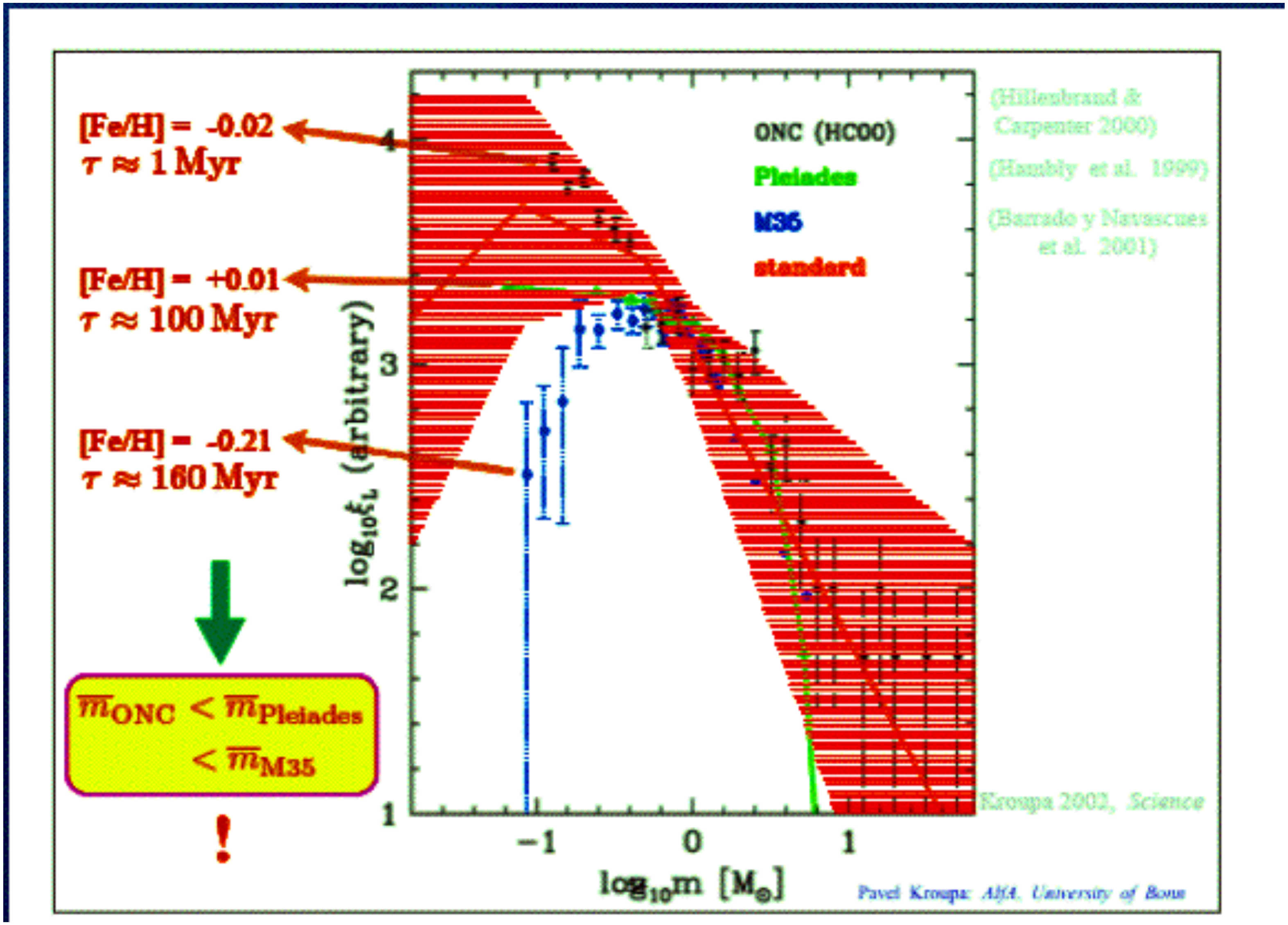


Fig. 11. A comparison of the Pleiades IMF from the present program (the weighted-averaged IMF from Fig. 10) with results from other stud-

IMF


[Fe/H] = -0.02
$\tau \approx 1$ Myr
[Fe/H] = +0.01
$\tau \approx 100$ Myr
[Fe/H] = -0.21
$\tau \approx 160$ Myr
$\overline{m}_{ONC} < \overline{m}_{Pleiades} < \overline{m}_{M35}$
!
ONC (HC00)
Pleiades
M35
standard
(Hillenbrand & Carpenter 2000)
(Hambly et al. 1999)
(Barrado y Navascues et al. 2001)
Kroupa 2002, Science
$\log_{10}\xi_L$ (arbitrary)
$\log_{10} m$ [$M_\odot$]
Pavel Kroupa: AIfA, University of Bonn

IMF of MW Stars

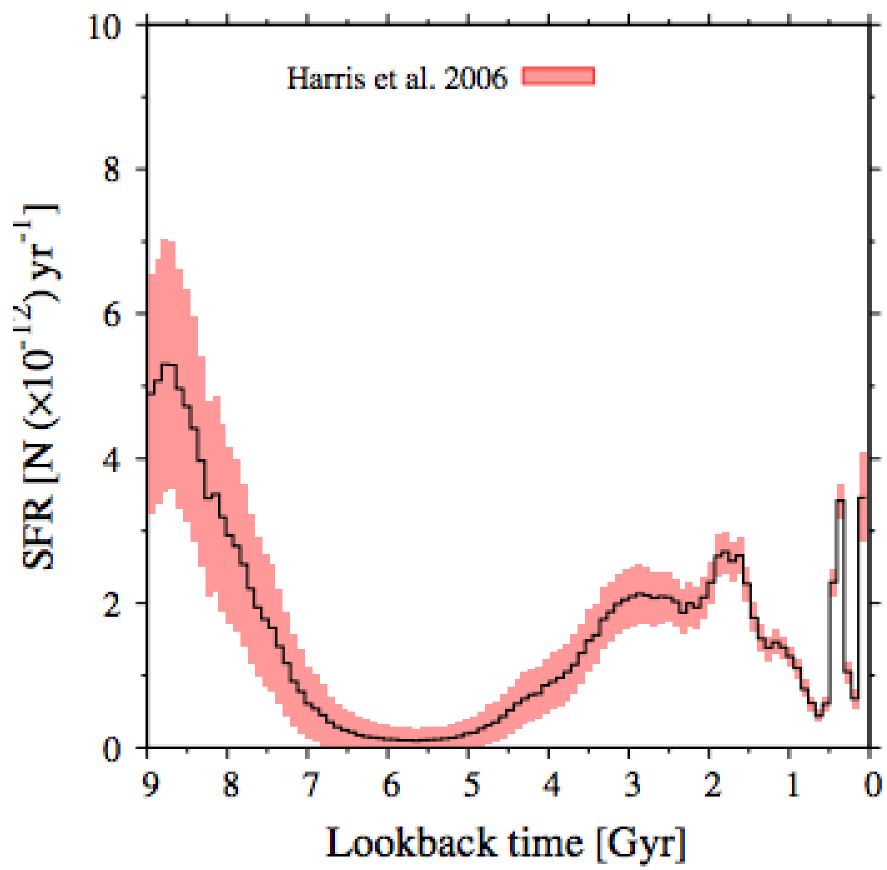
- Observing the IMF is tricky, 3 approaches
- Observe a young cluster and count the stars in it as a function of mass. (e.g. the Pleidaes) straightforward , but limited by the number of young clusters where we can directly measure individual stars down to low masses. get a clean measurement, but the statistics are poor.
- field stars in the solar neighborhood whose distances are known. statistics are much better, but only use this technique for low mass stars, few massive stars in local volume and numbers controlled by star formation hitory
- get limits on the IMF from the integrated light and colors of stellar populations
- despite these problems most results show that the IMF is very similar from place to place

Open Star Clusters

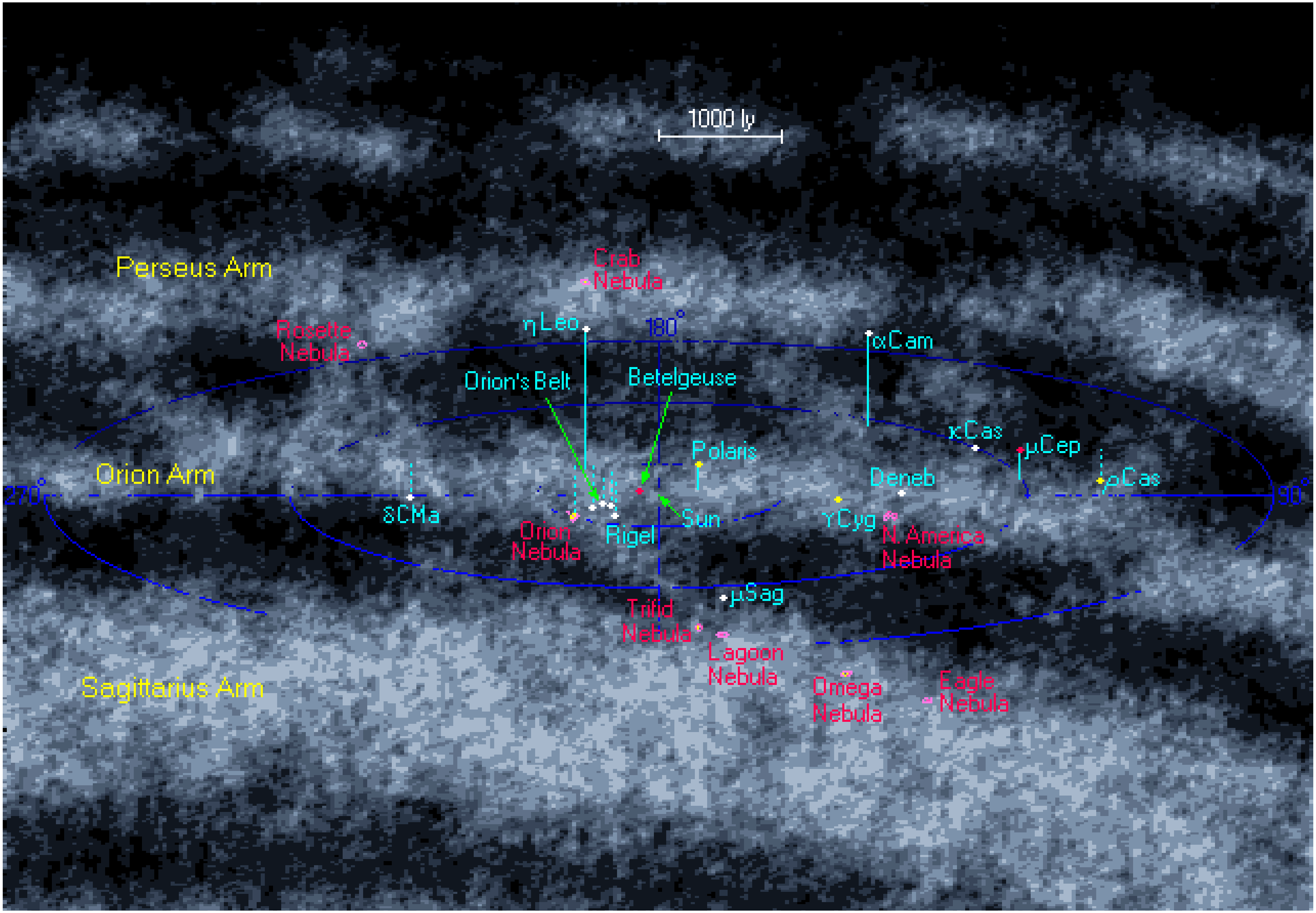
- the individual stars of the Galactic plane different not only in the masses and angular momenta, but also in their ages and in their chemical compositions at birth.
- This multiplicity of free-parameters complicates the study of stars. For instance, the initial mass, the initial chemical composition, and the age of a star determining the star's color and luminosity.
- Open star clusters are sets of stars that differ only in their masses at birth and in their angular momenta. They formed at the same time from the same molecular cloud with ~ the same chemical composition at birth and the same age.
- The stars of a single open cluster show how initial mass alone affects color and luminosity, and the comparison of stars from two different clusters shows how initial chemical composition affects color and luminosity and how stars evolve over time.
- The extent to which the massive stars deviate from the main sequence defines an age for the cluster. The Hyades cluster is estimated to be 625±50 million years old
- Over 1 billion years, encounters with molecular clouds cause an open cluster to totally dissipate.

SFR In Solar Neighborhood

- By modeling the white dwarf age/density distribution one can estimate the SFR rate 'nearby' (Rowell 2012)
- We will later compare this to the overall rate of SF of the universe and find significant differences
  - is it because the local neighborhood is not representative of the whole MW
  - or because the MW is not representative of the average of the universe??

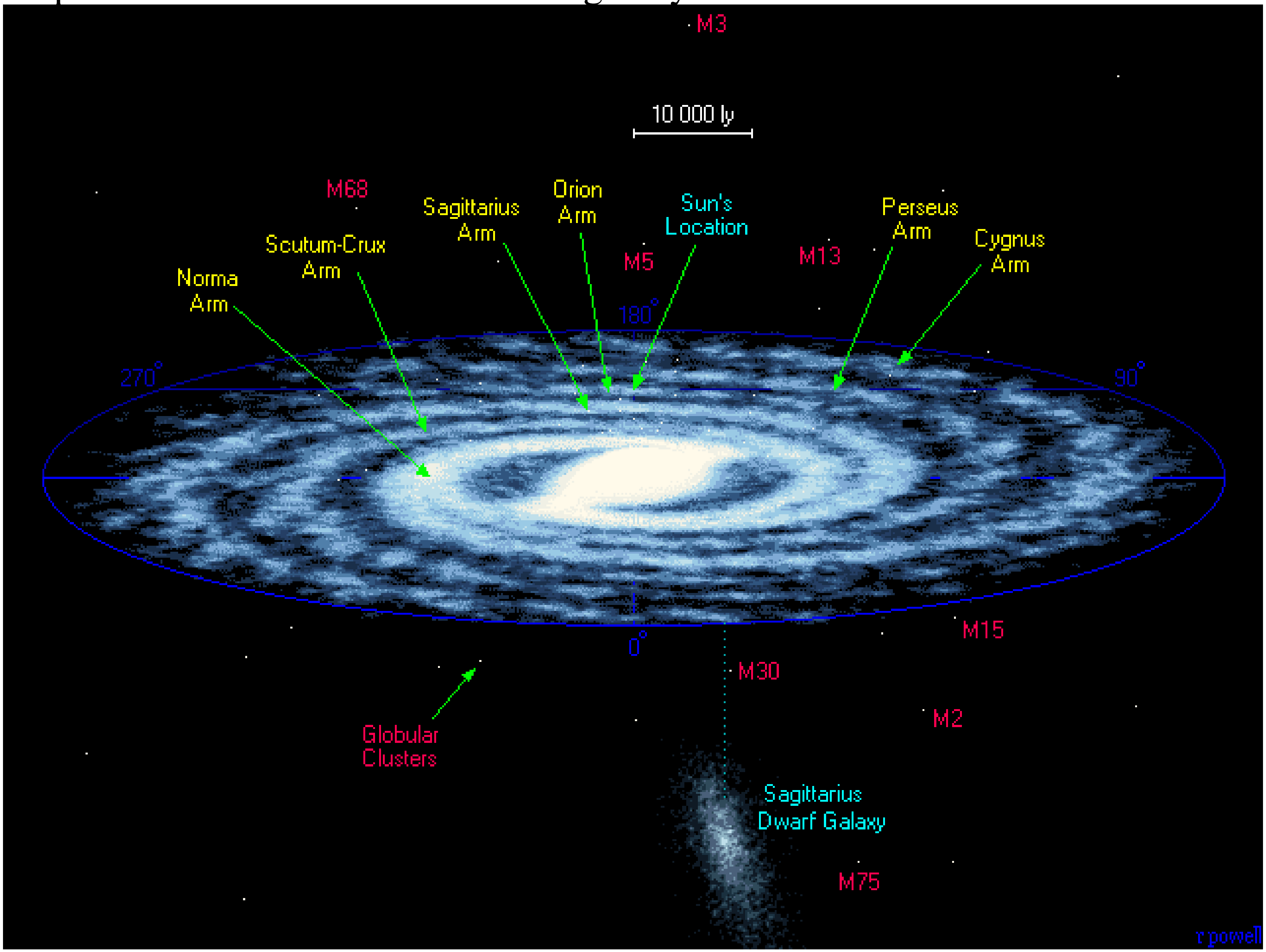


5kpc- Orion Arm

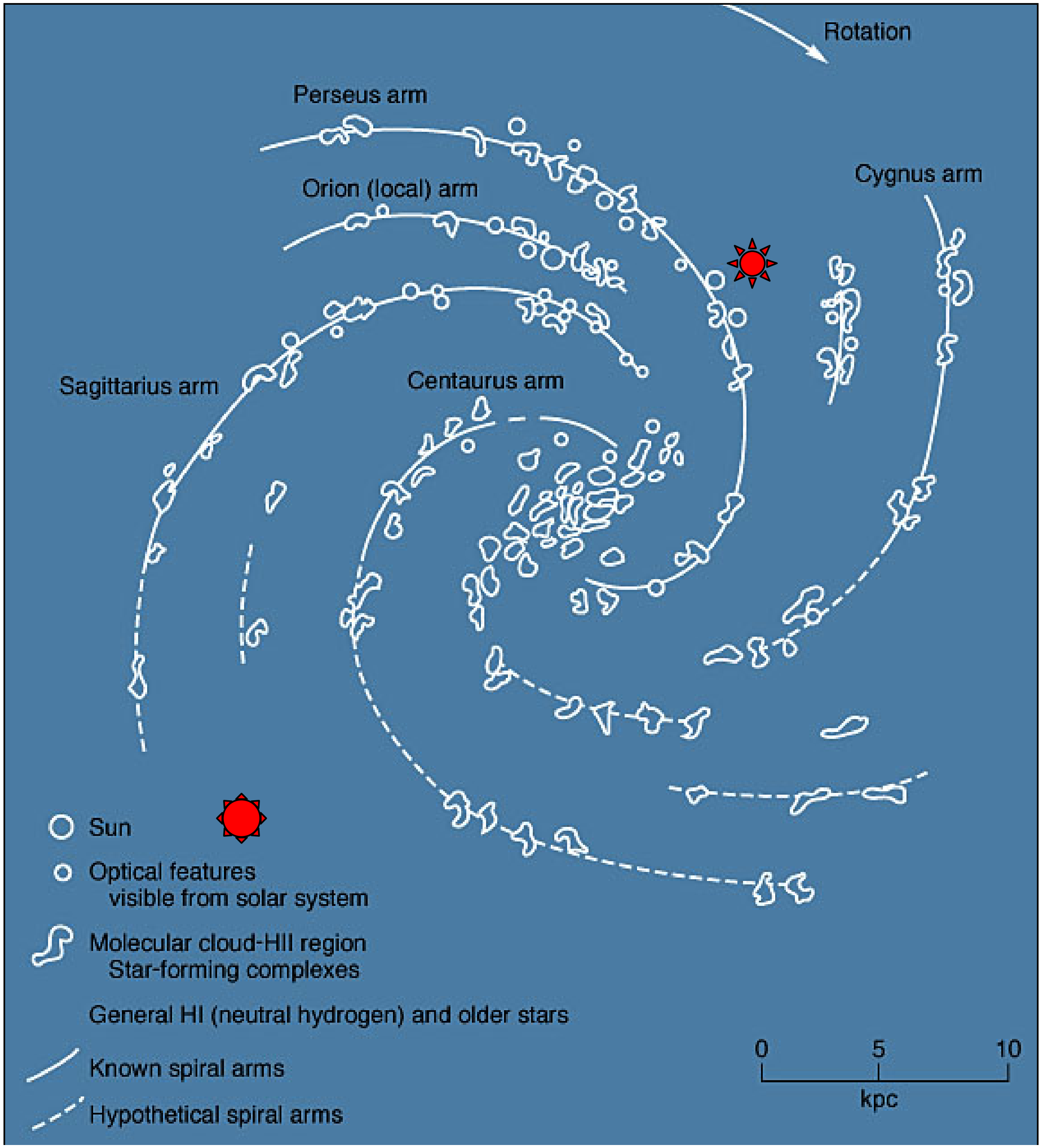


The MW

- http://www.atlasoftheuniverse.com/galaxy.html



Map of the Milky Way Galaxy

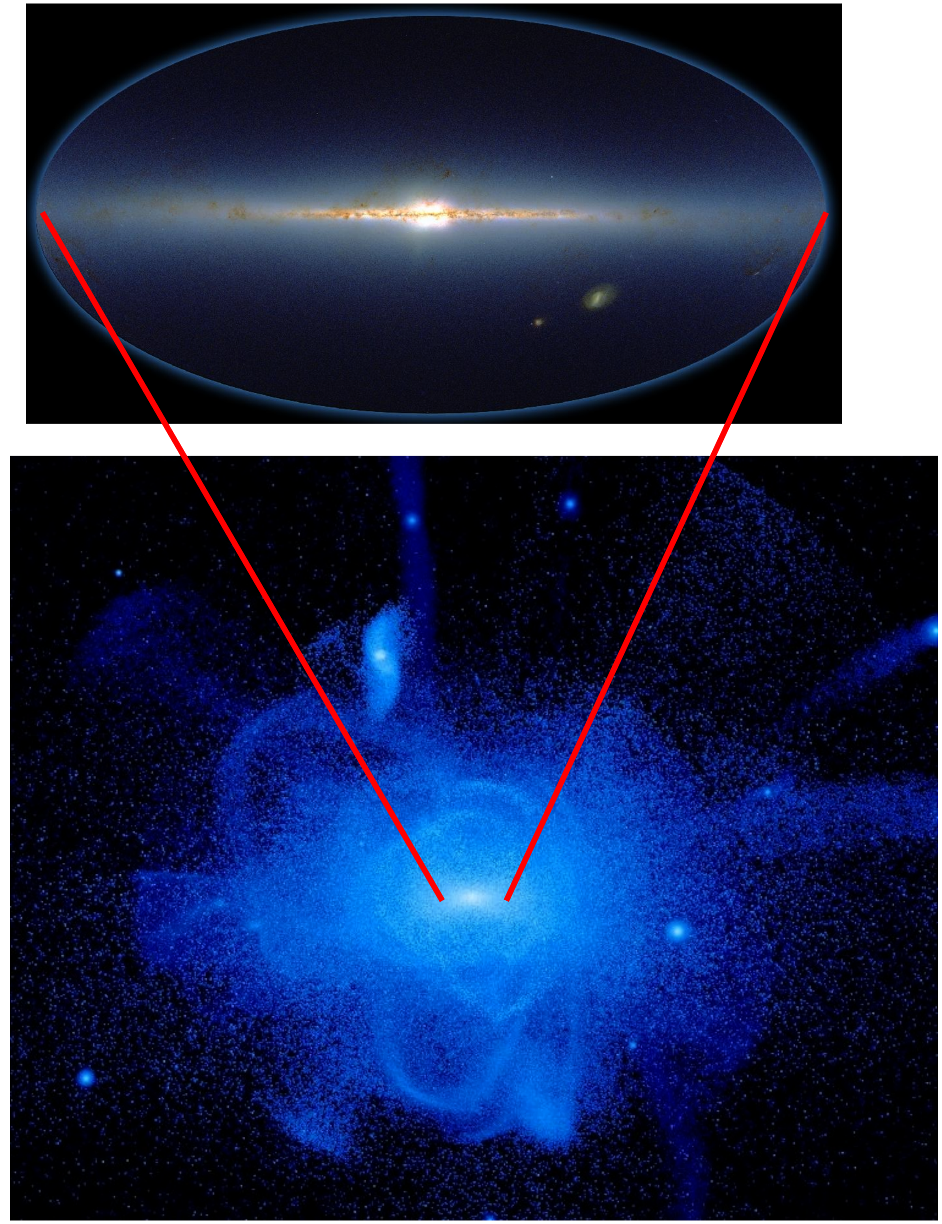


The map has been using HI velocity data sec 2.3.1 in S+G

Theorists View of Dynamics of Stars in MW

- In cold dark matter theories of structure formation many mergers have occurred - it takes a VERY long time for the orbits to 'relax' and thus there should be dynamical signatures of the mergers

- Only in MW and LMC/SMC is there any chance to determine the 3-D distribution of velocities and positions to constrain such models in DETAIL.
- Look for signs of assembly of MW galaxy in our stellar halo (and thin/thick disk)
  - Stellar halo is conceivably all accreted material
  - Stellar streams in the solar neighborhood



H. Rix

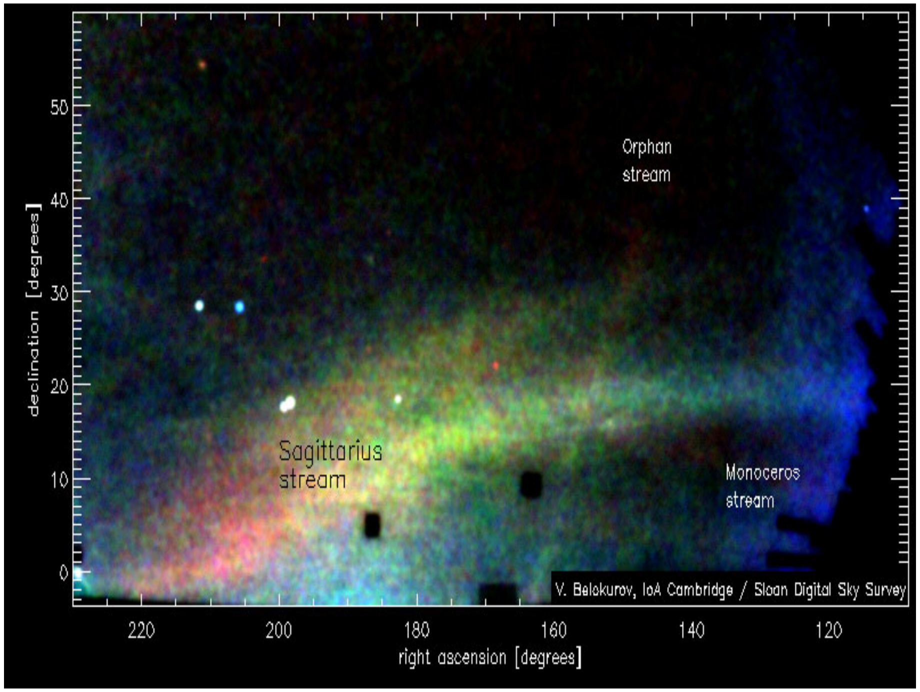
Future Problems for Analytic Methods for Detailed Mass Measurements

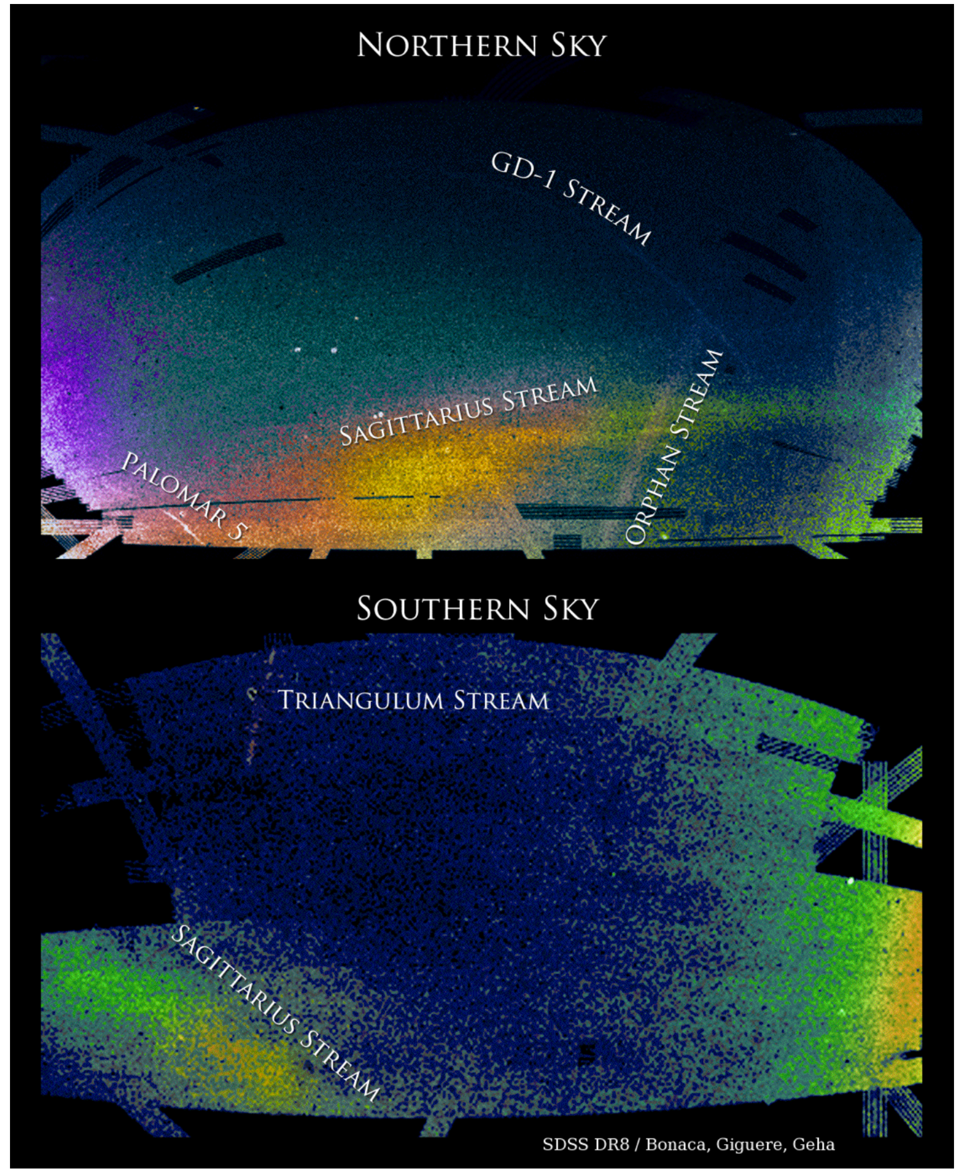
- Tidal stripping of dark matter from subhalos falling into the Milky Way produces narrow, "cold" tidal streams as well as more spatially extended “debris flows” in the form of shells, sheets, and plumes.

- The dark matter in the solar neighborhood is commonly assumed to be smoothly distributed in space and to have a Maxwellian velocity distribution
- High resolution numerical simulations of the hierarchical formation of Milky-Way-like dark matter halos, however, predict large phase-space substructure throughout the halo
- in agreement with collisionless dynamics and Liouville's theorem, which imply that the initial cold dark matter three-dimensional phase-space manifold evolves in a continuous manner by folding and stretching, but never tearing.
- Tidal effects tend to make the density distribution smooth, but these tidal disruption processes are sources of velocity substructure.
- the speed distributions measured in high resolution numerical simulations exhibit deviations from the standard Maxwellian assumption, especially at large speeds.

Kuhlen et al 2012

Streams in the MW





- map of stars in the outer regions of the Milky Way (1/4 of sky). The trails and streams that cross the image are stars torn from disrupted Milky Way satellites. The color corresponds to distance, with red being the most distant and **blue being the closest**. The large, forked feature is the Sagittarius stream, further away from us (lower left) and closer to us (middle right). Other features marked are the Monoceros ring

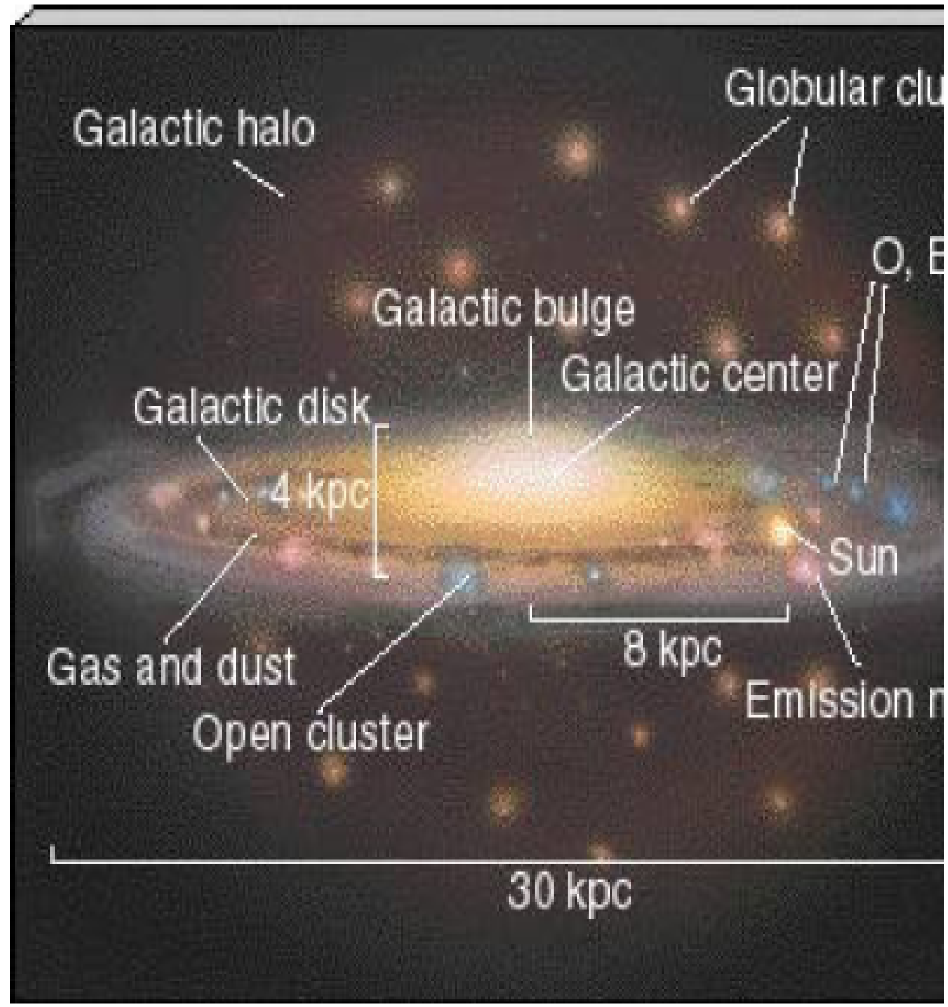
V Belokurov, SDSS-II Collaboration)

Basic Structure of Milky Way

Bulge is quite spherical and is dominated by old stars

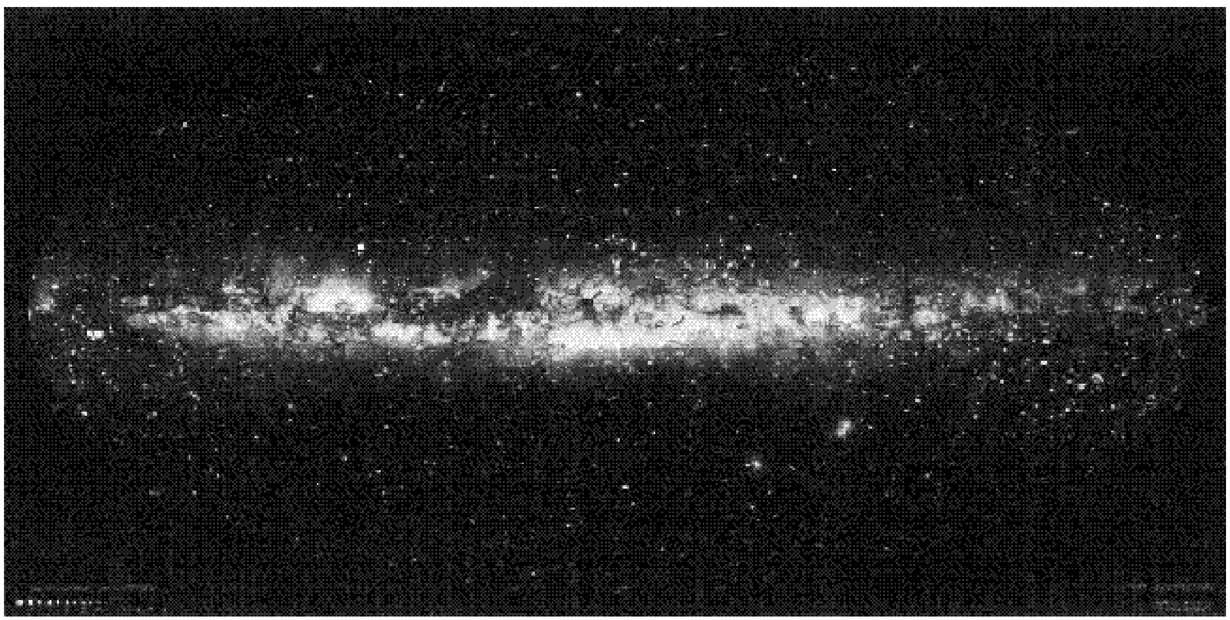
Disk- location of almost all the cold gas and most of the HI- site of star formation and thus young stars- wide range in metallicity

Halo- globular clusters, most of MW dark matter, only 1% of stars



MW in Optical

- Notice the strong effect of dust.



Milky Way, Sbc-galaxy (all-sky projection in optical)

this is a drawing of the MW all sky- state of the art 1950's

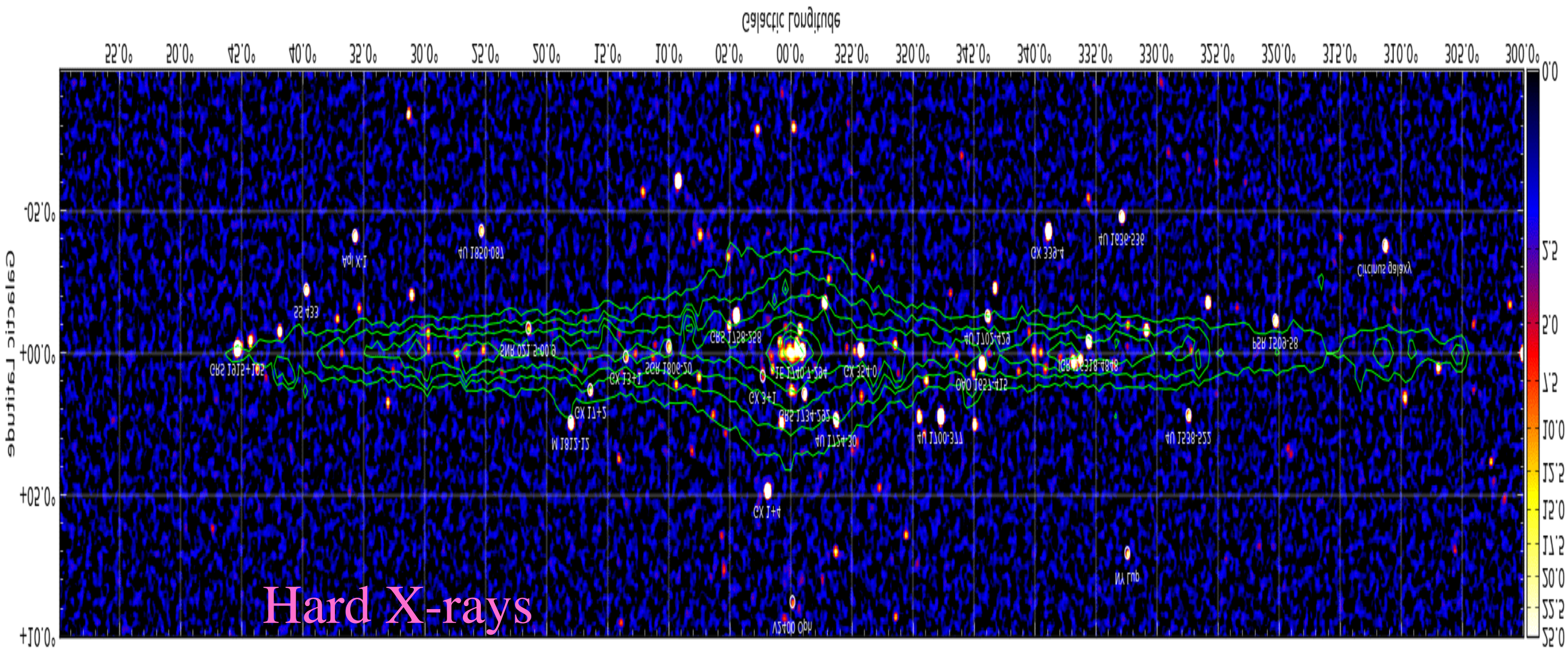
Other Wavelengths

In 'hard' (2-10 kev) x-rays one sees

accreting x-ray binaries Neutron stars and black holes

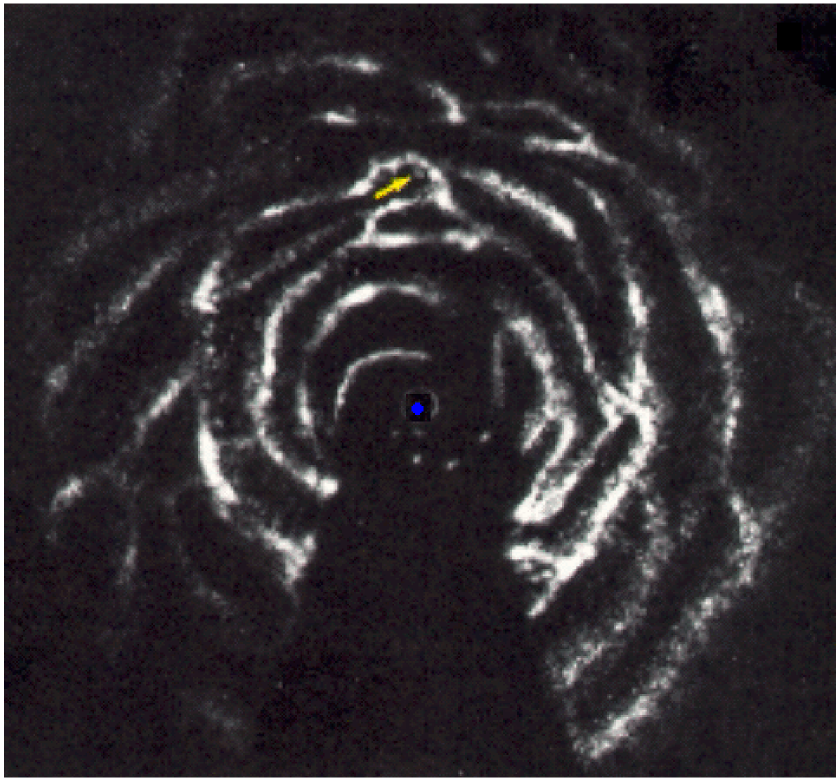
- 2 Populations companions

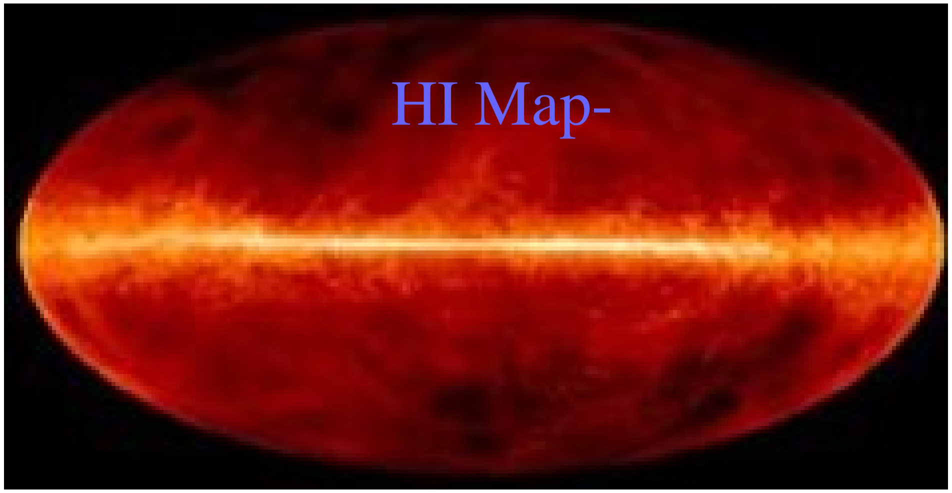
1) are massive and young (high mass x-ray binaries) POP I
2) old (Low mass x-ray binaries) POP II

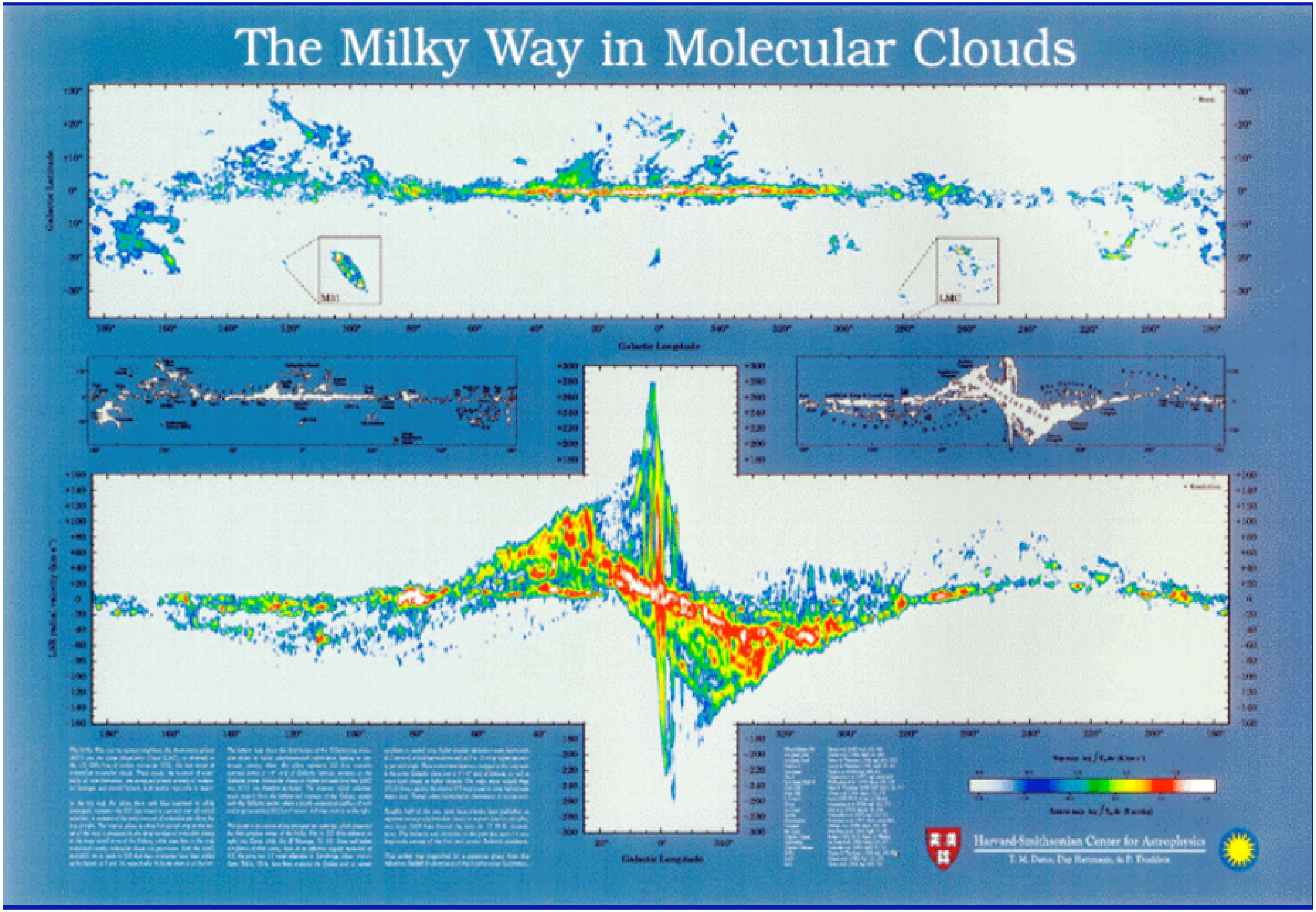


HI Maps

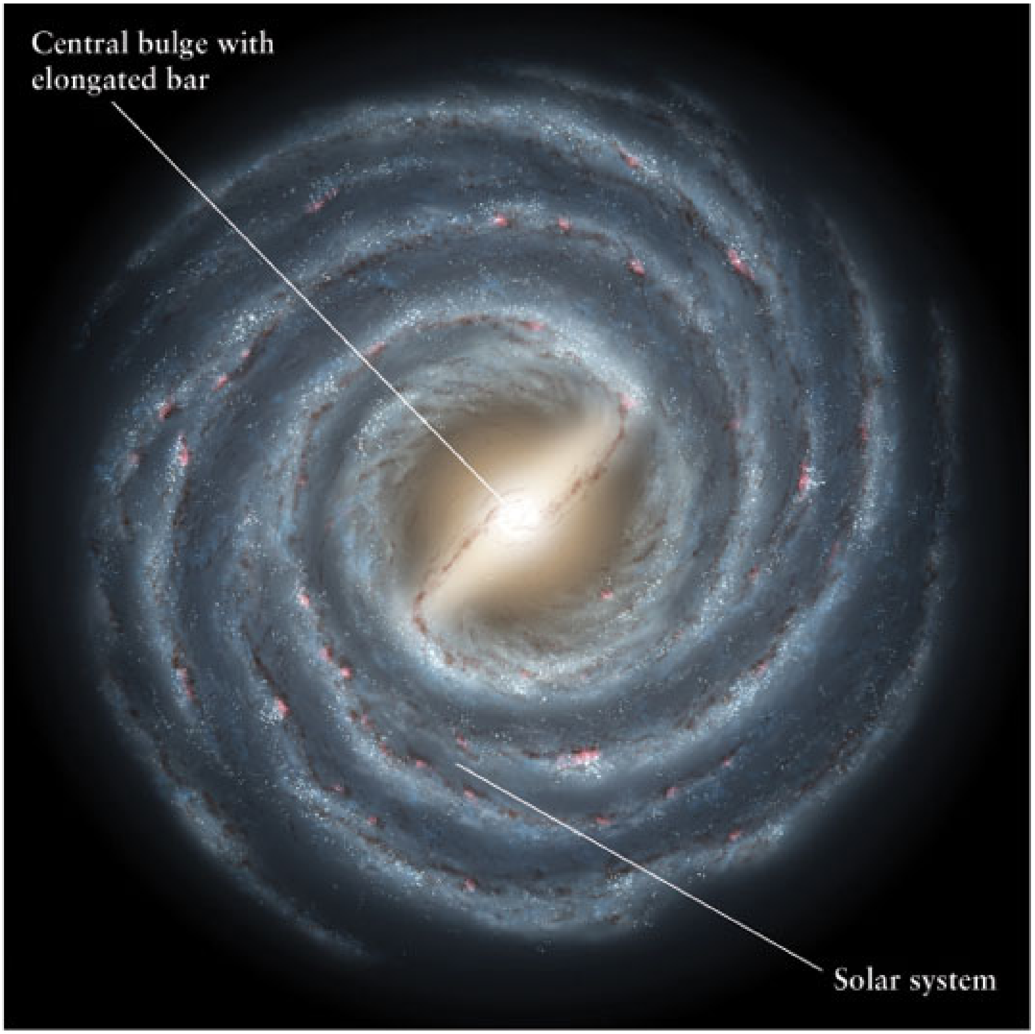
- HI lies primarily in the plane- maps have velocity data associated with them allows dynamics to be determined
  - deproject HI velocity and intensity map to show total structure of the galaxy
- Not affected by dust- shows detailed structures.



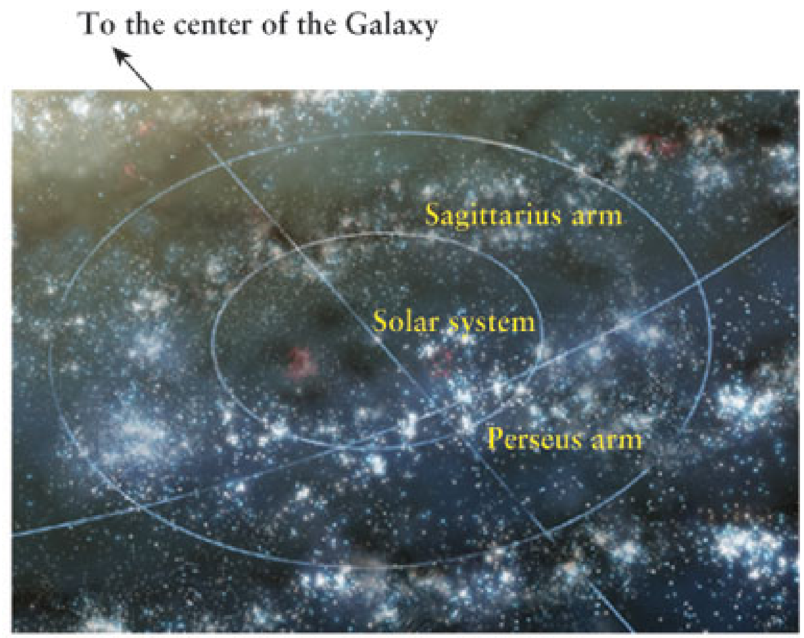



The Milky Way in Molecular Clouds
Galactic Longitude
M31
LMC
Harvard-Smithsonian Center for Astrophysics

MW is a Barred Galaxy



(a) The structure of the Milky Way's disk

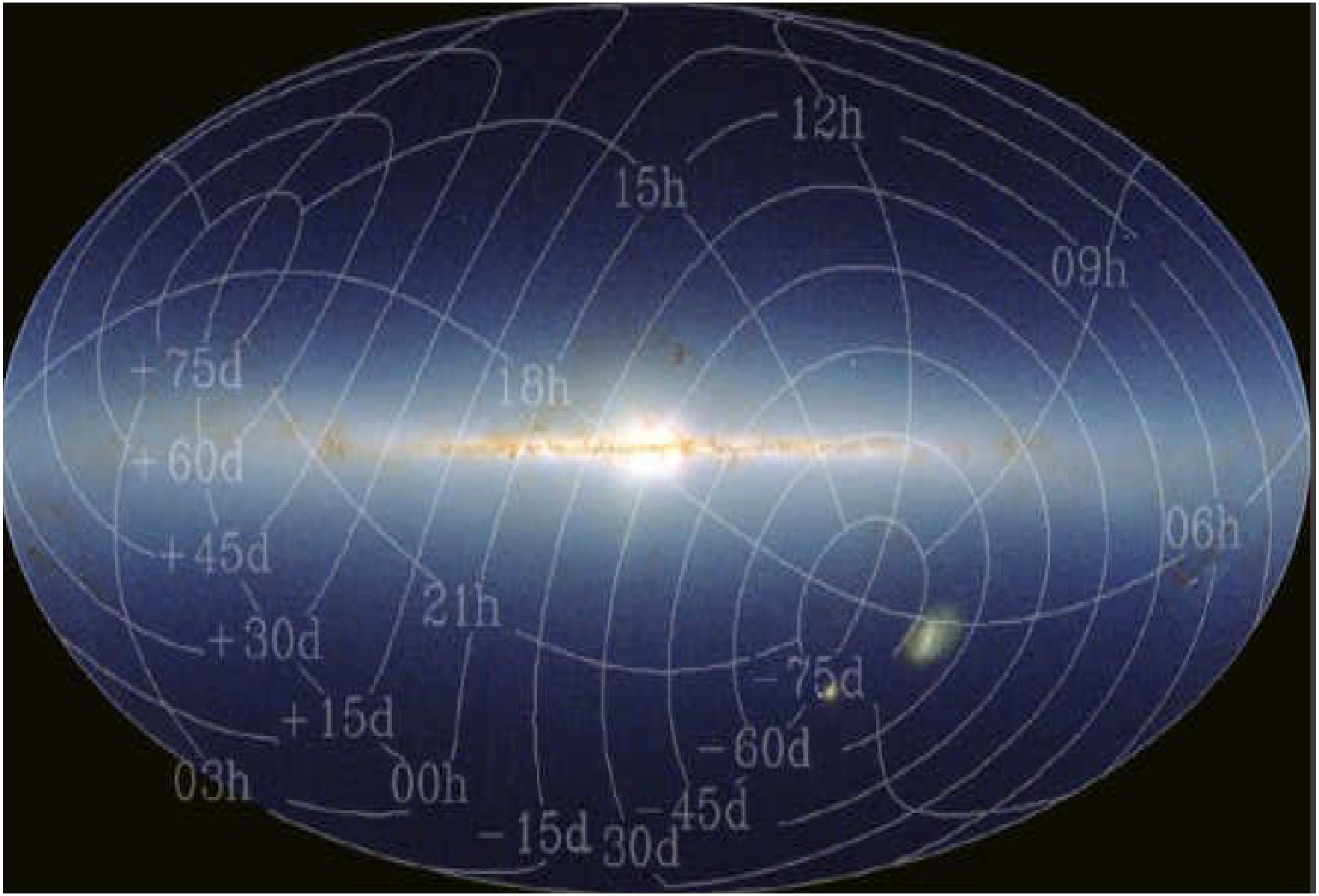


(b) Closeup of the Sun's galactic neighborhood

The MW bar, consists of relatively old red stars,
roughly 9 kpc in length
oriented at about a
45-degree angle relative to a line joining the sun
and the center of the galaxy.

Coordinate Systems

- Galactic (l,b) and celestial (Ra and Dec) see S+G pg 34-37 for a quick refresher



Basic Properties of MW

Diameter ~23Kpc- at sun orbital period ~2.5×10^8 yrs

Mass ~$2\times10^{11}\ M_\odot$ (details later)

M/L~10 (on average)

<u>Official distance</u> of sun from GC is 8.5kpc,$v_{circular}$~220km/sec

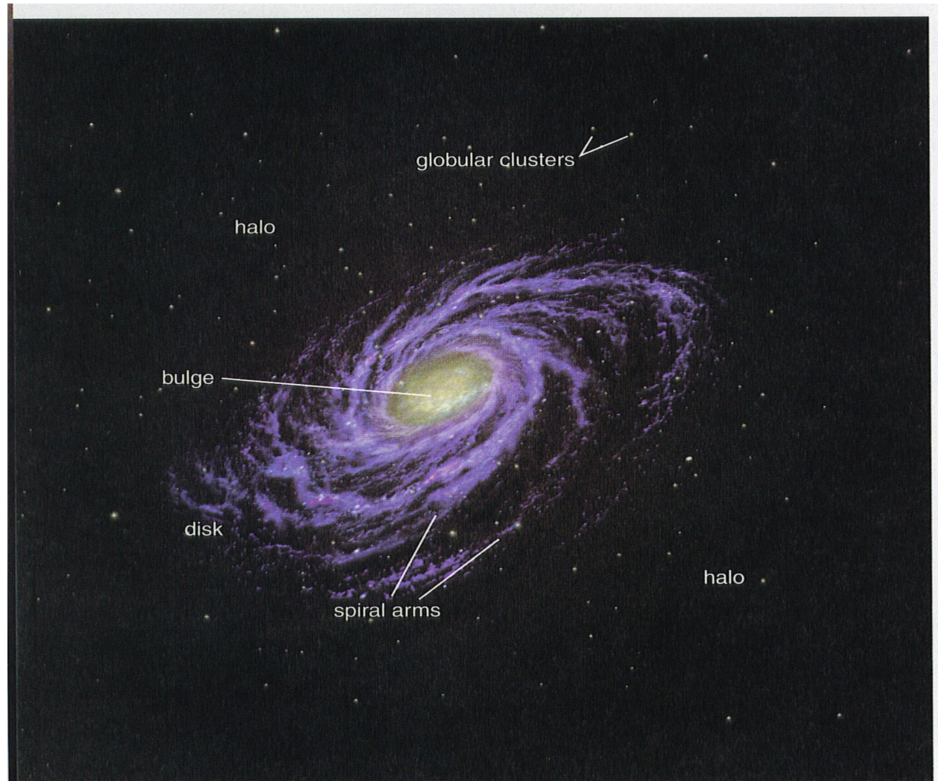
the Milky Way is a barred galaxy

Perpendicular to the disk the stellar distribution(s) can each be well described as

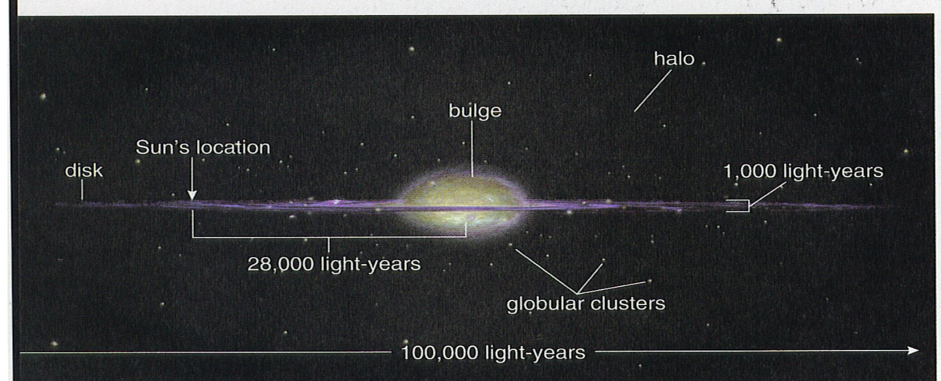
n(x)~exp(-z/h); h=scale height

The disk is NOT simple and has at least 2 components

1) thin disk has the largest fraction of gas and dust in the Galaxy, and star formation is taking place ; h~100pc,σ_z~20km/sec
2) thick disk h~1.5kpc older, lower metallcity population, less gas- only makes up 2% of mass density **at z~0**.



a Artist's conception of the Milky Way viewed from its outskirts.

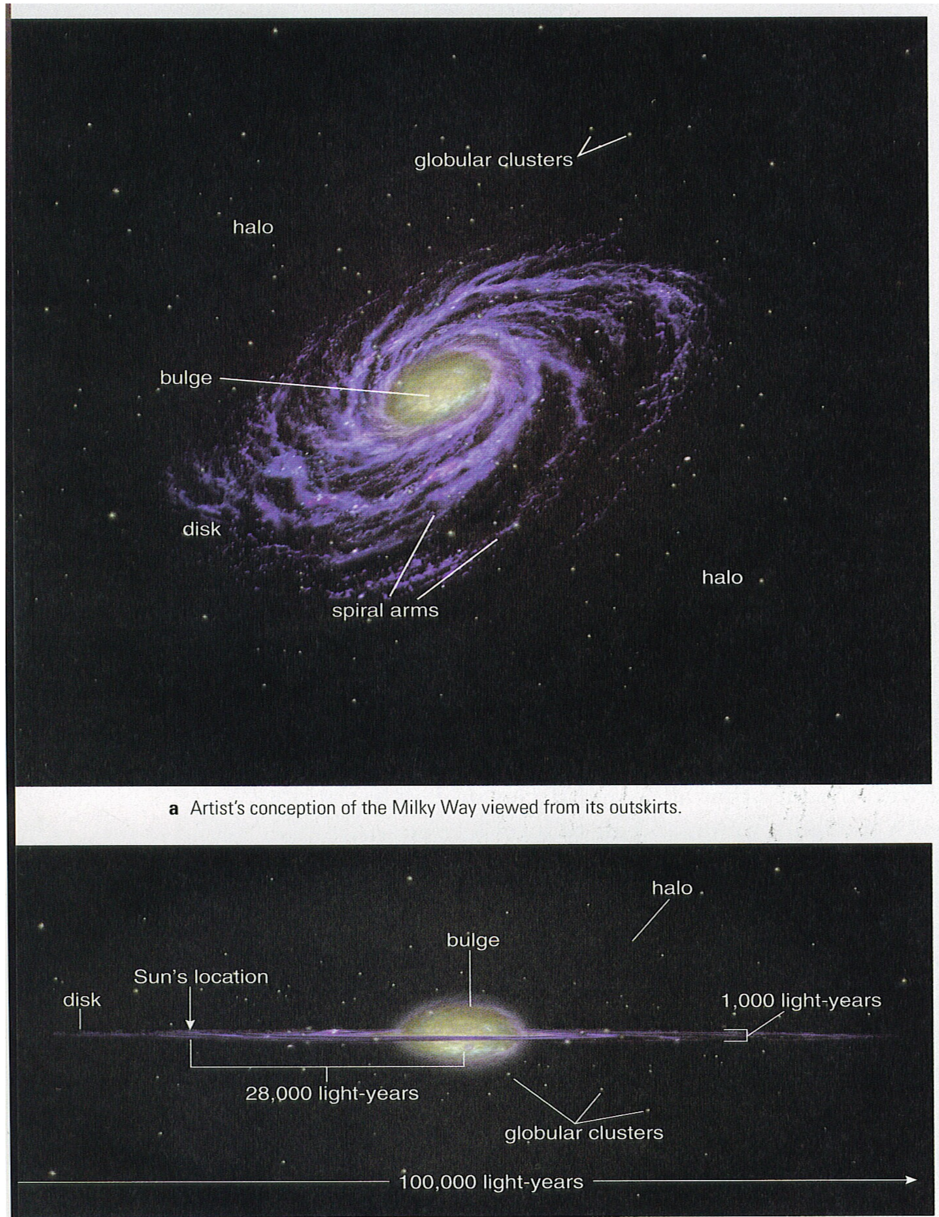


b Edge-on schematic view of the Milky Way.

Components of MW

HII scale height: 1 kpc
CO scale height: 50-75 pc
HI scale height: 130-400 pc
Stellar scale height: 100 pc in spiral arm, 500 pc in disk
Stellar mass: ~$5 \times 10^{10}\ M_\odot$
HI mass: ~$3 \times 10^{9} M_\odot$

H_2mass (inferred from CO mass):~$0.8 \times 10^{9} M_\odot$
Total MW mass within viral radius
Milky Way's dark-halo mass within the virial radius is ~$8 \times 10^{11} M_\odot$: About 50% dark matter
The mass values depend on the radius within which they are estimated



a Artist's conception of the Milky Way viewed from its outskirts.

b Edge-on schematic view of the Milky Way.

Mass Distribution near Sun

- The (surface) density distributions can be derived from dynamical studies
- The total surface mass density of all gravitating matter within 1.1 kpc of the centerline of the disk at the position of the sun is 67 +/-6 $M_{\odot}pc^{-2}$ and that of all identified matter (stars and gas) is 42+/-5 $M_{\odot}pc^{-2}$
- The local density of **dark matter** is 0.0075+/-0.0023 $M_{\odot}pc^{-3}$ (Zhang et al 2012) (see next lecture for how this is done)
- This dark matter density is consistent with fits to the MW halo models
- However this is very technically challenging and the amount of dark matter is rather uncertain.
- This analysis is done using the vertical distribution of stars and their velocities (more later)

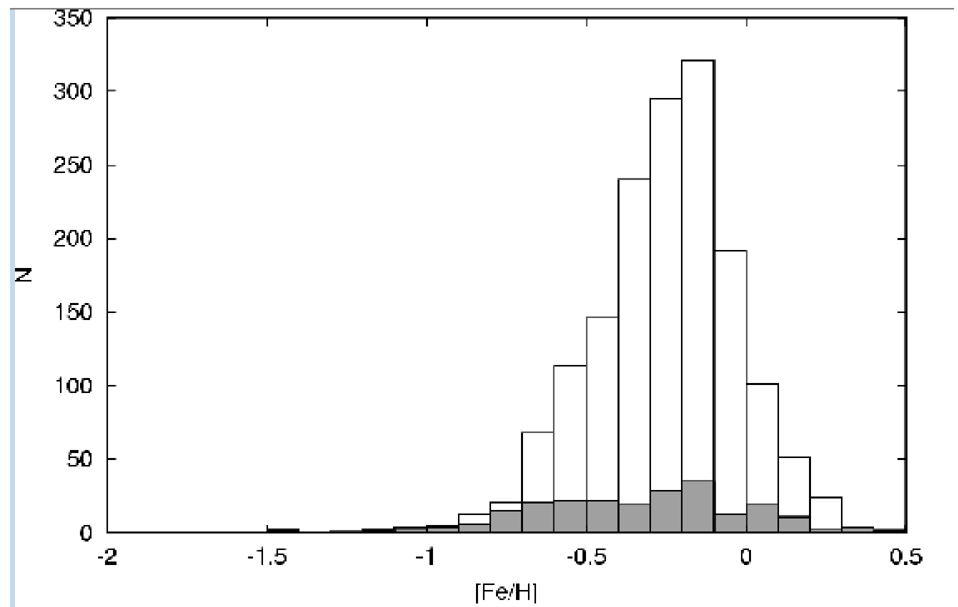
RESULTS FOR GALACTIC PARAMETERS A

Parameter	Flat rotation curve
$V_c(R_0)$ [km s^{-1}]	218±6
A [km s^{-1} kpc^{-1}]	$13.5^{+0.2}_{-1.7}$
B [km s^{-1} kpc^{-1}]	$-13.5^{+1.7}_{-0.2}$
$(B^2 - A^2)/(2\pi G)$ [M$_\odot$ pc^{-3}]	...
Ω_0 [km s^{-1} kpc^{-1}]	$27.0^{+0.3}_{-3.5}$
R_0 [kpc]	$8.1^{+1.2}_{-0.1}$
$V_{R,\odot}$ [km s^{-1}]	$-10.5^{+0.5}_{-0.8}$
$V_{\phi,\odot}$ [km s^{-1}]	242^{+10}_{-3}
$V_{\phi,\odot} - V_c$ [km s^{-1}]	$23.9^{+5.1}_{-0.5}$
$\mu_{\mathrm{Sgr\ A^*}}$ [mas yr^{-1}]	$6.32^{+0.07}_{-0.70}$
$\sigma_R(R_0)$ [km s^{-1}]	$31.4^{+0.1}_{-3.2}$
R_0/h_σ	$0.03^{+0.01}_{-0.27}$
$X^2 \equiv \sigma_\phi^2/\sigma_R^2$	$0.70^{+0.30}_{-0.01}$

Thin and Thick Details Composition

- Each of the 'components' of the MW has a 'different' (but overlapping) chemical composition (Metallicity)
- stars in the thin disk have a higher metallicity and M/L (~3). than those in the thick disk, high M/L~15 (age and metallicity effect)
- Thin disk $M_{stars} \sim 6x10^{10}\ M_{\odot}$; $M_{gas} \sim 0.5x10^{10} M_{\odot}$. Stellar luminosity $L_B \approx 1.8x10^{10} L_{\odot}$
- Thick disk has low mass and luminosity $M \sim 3x10^{9}\ M_{\odot}$ and $L_B \approx 2x10^{8} L_{\odot}$
- the metallicity of stars in the Galactic halo and in the bulge is even lower. - in the older literature one has 'PopI' and 'Pop II'

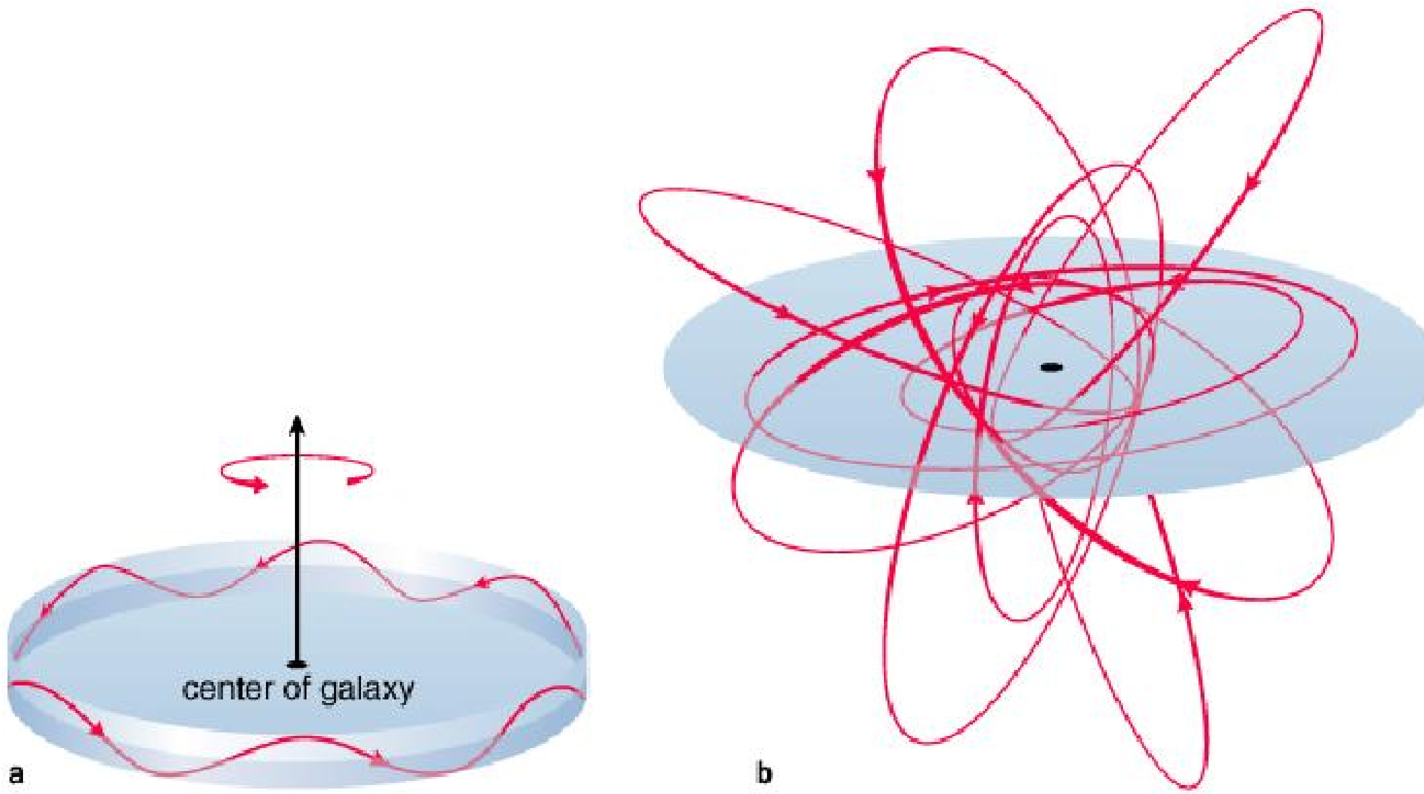
thin disk-open
thick disk shaded



[Fe/H]

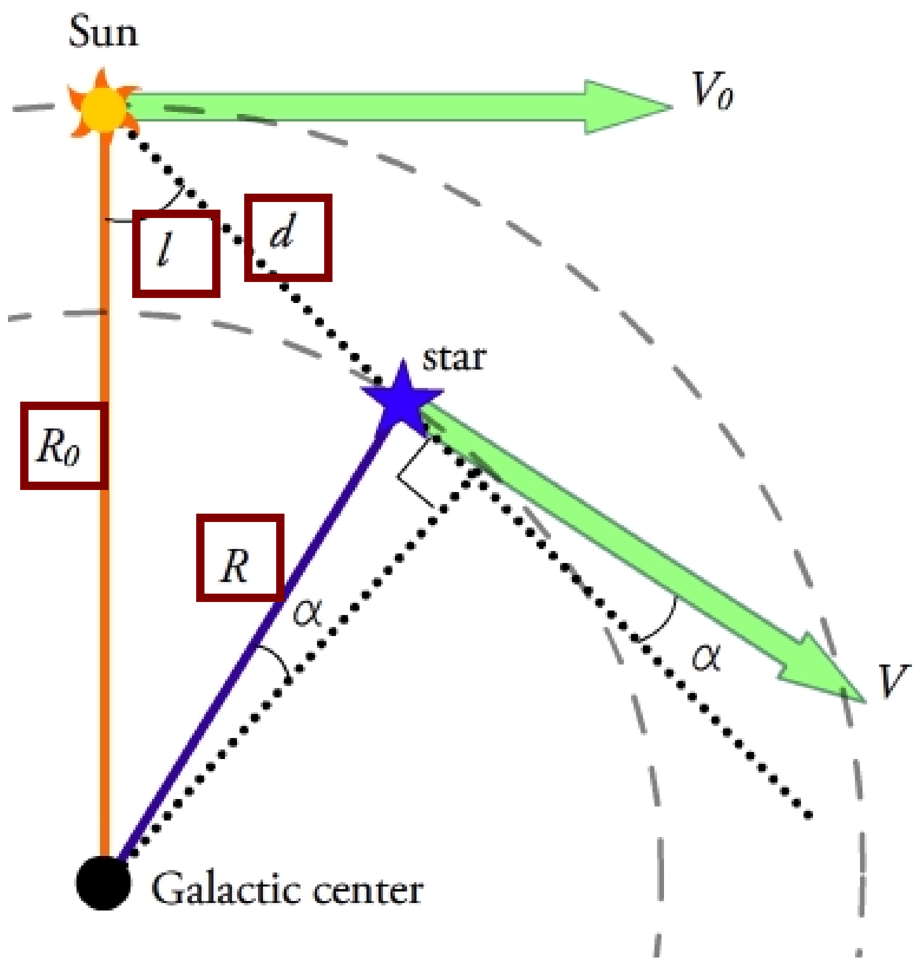
Zeroth Order Dynamics

- Stars in disk have mostly rotational velocity- very little random or r or z components
- Stars in bulge and halo mostly random orbits, but some rotation.
- Need to use different techniques to estimate the mass of these '2' components



Galactic Rotation- S+G sec 2.3

- Consider a star in the midplane of the Galactic disk with Galactic longitude, l, at a distance d, from the Sun. Assume circular orbits radii of R and R_0 from the galactic center and rotational velocities of V and , V_0
- The 2 components of velocity- radial and transverse are then
-
- The 2 components of velocity- radial and transverse are then
- $V_{\text{observered, radial}} = V(\cos\alpha) - V_0 \sin(l)$
- $V_{\text{observered ,tang}} = V(\sin\alpha) - V_0 \cos(l)$
- Convert to angular velocity ω
- $V_{\text{observered,radial}} = \omega R(\cos\alpha) - \omega_0 R_0 \sin(l)$
- $V_{\text{observered,tang}} = \omega R(\sin\alpha) - \omega_0 R_0 \cos(l)$



wikipedia

Galactic Rotation

- Then using a bit of trig

$R(\cos\alpha) = R_0 \sin(l)$

$R(\sin\alpha) = R_0 \cos(l) - d$

so

$V_{\text{observered,radial}} = (\omega - \omega_0)\, R_0 \sin(l)$

$V_{\text{observered,tang}} = (\omega - \omega_0)\, R_0 \cos(l) - \omega d$

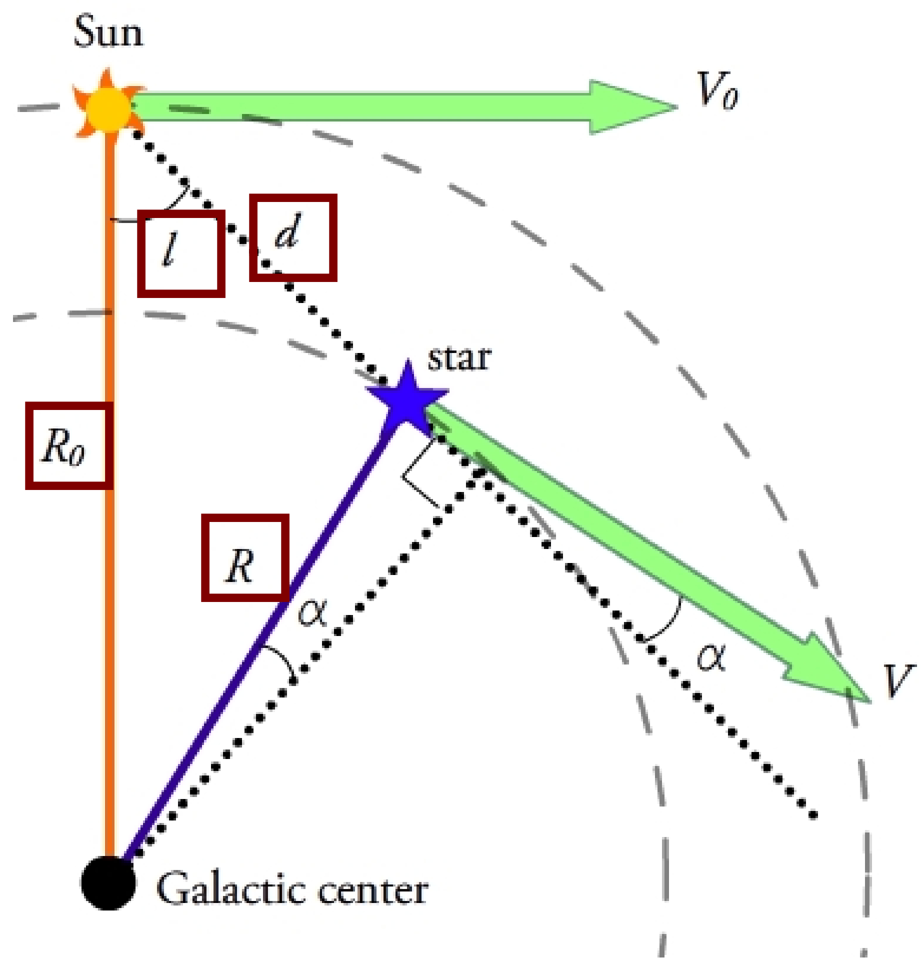
then following the text expand $(\omega - \omega_0)$ around R_0 and using the fact that most of the velocities are local e.g. $R-R_0$ is small and d is smaller than R or R_0 (not TRUE for HI) and some more trig

get

$$V_{\text{obs, r}} = A d \sin(2l)$$
$$V_{\text{obs, t}} = A d \cos(2l) + B d$$

where

$$A = -\frac{1}{2} R_0 \frac{d\omega}{dr}\Big|_{R_0}$$
$$B = -\frac{1}{2} R_0 \frac{d\omega}{dr}\Big|_{R_0} - \omega$$



wikipedia

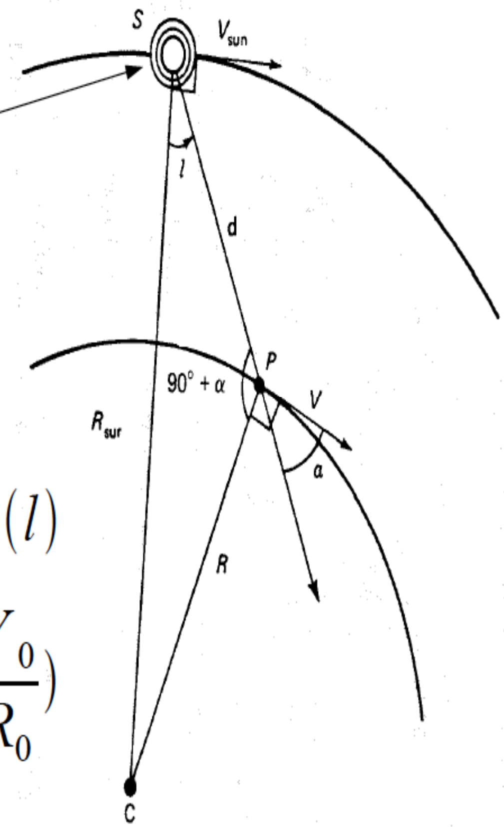
Galactic Rotation Curve- sec 2.3.1 S+G

1)
Assume gas/star has
a perfectly circular orbit

At a radius R_0 orbit with velocity V_0; another star/parcel of gas at radius R has a orbital speed V(R)

since the angular speed V/R drops with radius V(R) is positive for nearby objects with galactic longitude 1<l<90 etc etc (pg 91 bottom)

- Galactic Rotation Curve
  - At R_{sun} the lsr has a velocity of V_0
  - A star at P has an apparent velocity of



1) $$V_r = V\cos(\alpha) - V_0\sin(l)$$

2) $$V_r = R_0\sin(l)\left(\frac{V}{R} - \frac{V_0}{R_0}\right)$$

In terms of Angular Velocity

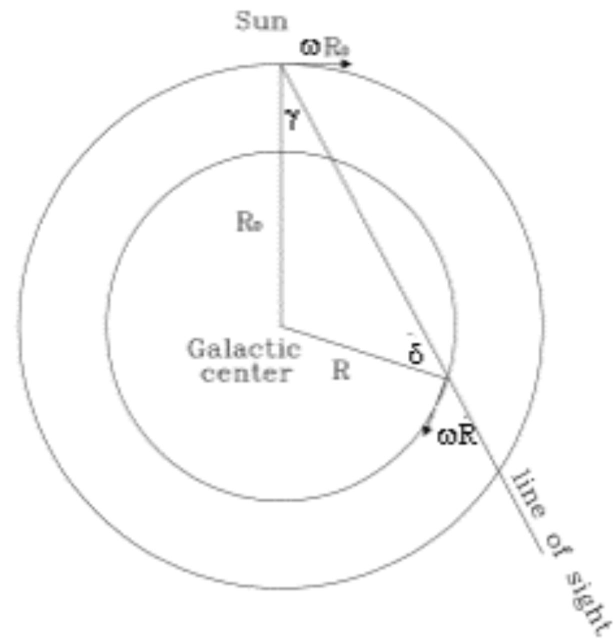
- model Galactic motion as circular motion with monotonically decreasing angular rate with distance from center.
- Simplest physics:if the mass of the Galaxy is all at center angular velocity ω at R is $\omega = M^{1/2} G^{1/2} R^{-3/2}$
- If looking through the Galaxy at an angle l from the center, velocity at radius R projected along the line of site minus the velocity of the sun projected on the same line is
- $V = \omega R \sin d - \omega_o R_o \sin l$
- ω = angular velocity at distance R

  ω_o = angular velocity at a distance R_o

  R_o = distance to the Galactic center

  l = Galactic longitude
- Using trigonometric identity $\sin d = R_o \sin l / R$

  and substituting into equation (1)
- $V = (\omega - w\, \omega_o) R_o \sin l$



http://www.haystack.mit.edu/edu/undergrad/srt/SRT Projects/rotation.html

Oort Constants

- If the distance to the object is such that d<<R than then (l is the galactic longitude)
- $V(R) \sim R_0 \sin l \, (d(V/R)/dr)(R-R_0)$ $\sim d\sin(2l)[-R/2(d(V/R)/dr) \sim d\mathbf{A}\sin(2l)$
- A is one of 'Oorts constants'
- The other (pg 93 S+G) is related to the tangential velocity of a object near the sun $V_t = d[A\cos(2l)+B]$
- So, stars at the same distance r will show a systematic pattern in the magnitude of their radial velocities across the sky with Galactic longitude.
- A is the Oort constant describing the shearing motion and B describes the rotation of the Galaxy

$$A = \frac{1}{2}\left[\frac{V_\circ}{R_\circ} - \left(\frac{dV}{dR}\right)_{R_\circ}\right]$$

$$B = -\frac{1}{2}\left[\frac{V_\circ}{R_\circ} + \left(\frac{dV}{dR}\right)_{R_\circ}\right]$$

$$A + B = -\left(\frac{dV}{dR}\right)_{R_\circ} \quad ; \quad A - B = \frac{V_\circ}{R_\circ}$$

$A=-1/2[R d\omega/dr]$

Useful since if know A get kinematic estimate of d

Radial velocity $v_r \sim 2AR_0(1-\sin l)$ only valid near $l \sim 90$ measure $AR_0 \sim 115 \text{km}/_s$

Oort 'B'

- B measures 'vorticity' $B=-(\omega+=-1/2[Rd\omega/dr])=-1/2(V/R+dV/dR)$

  $\omega=A-B=V/R$; angular speed of Local standard of rest (sun's motion)

  I will not cover epicycles: stars not on perfect circular orbits:

  important point $\sigma^2_y/\sigma^2_x= -B/A-B$

Timescales

- crossing time t_c=2R/σ
- dynamical time t_d=sqrt(3π/16Gρ)- related to the orbital time; assumption homogenous sphere of density ρ
- relaxation time- the time for a system to 'forget' its initial conditions

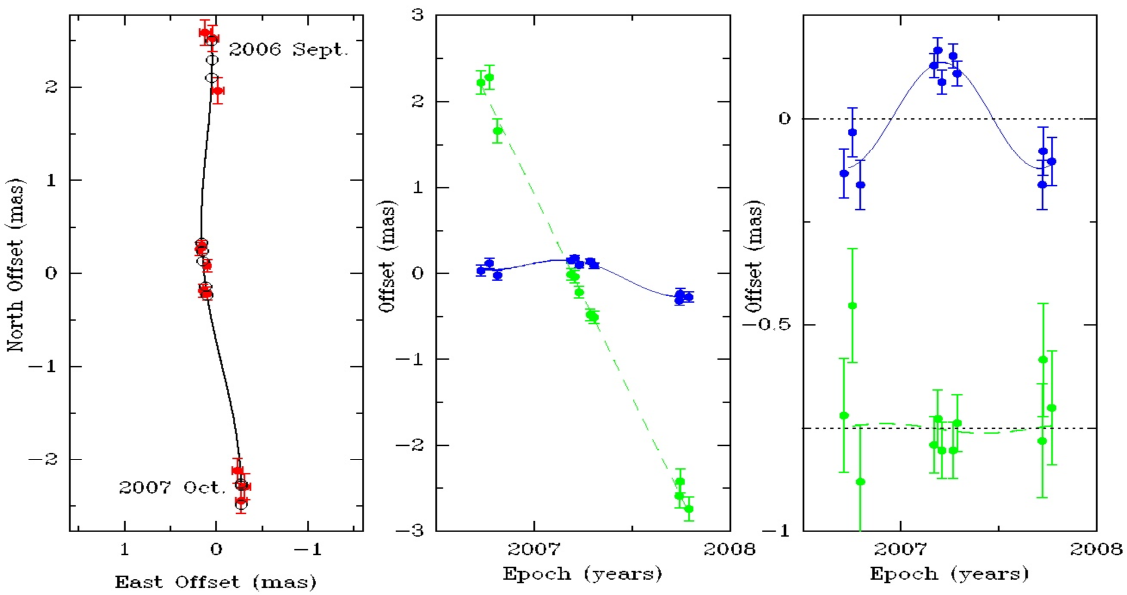
t_r~Nt_c/48f^2 : N objects carryng f of total mass :

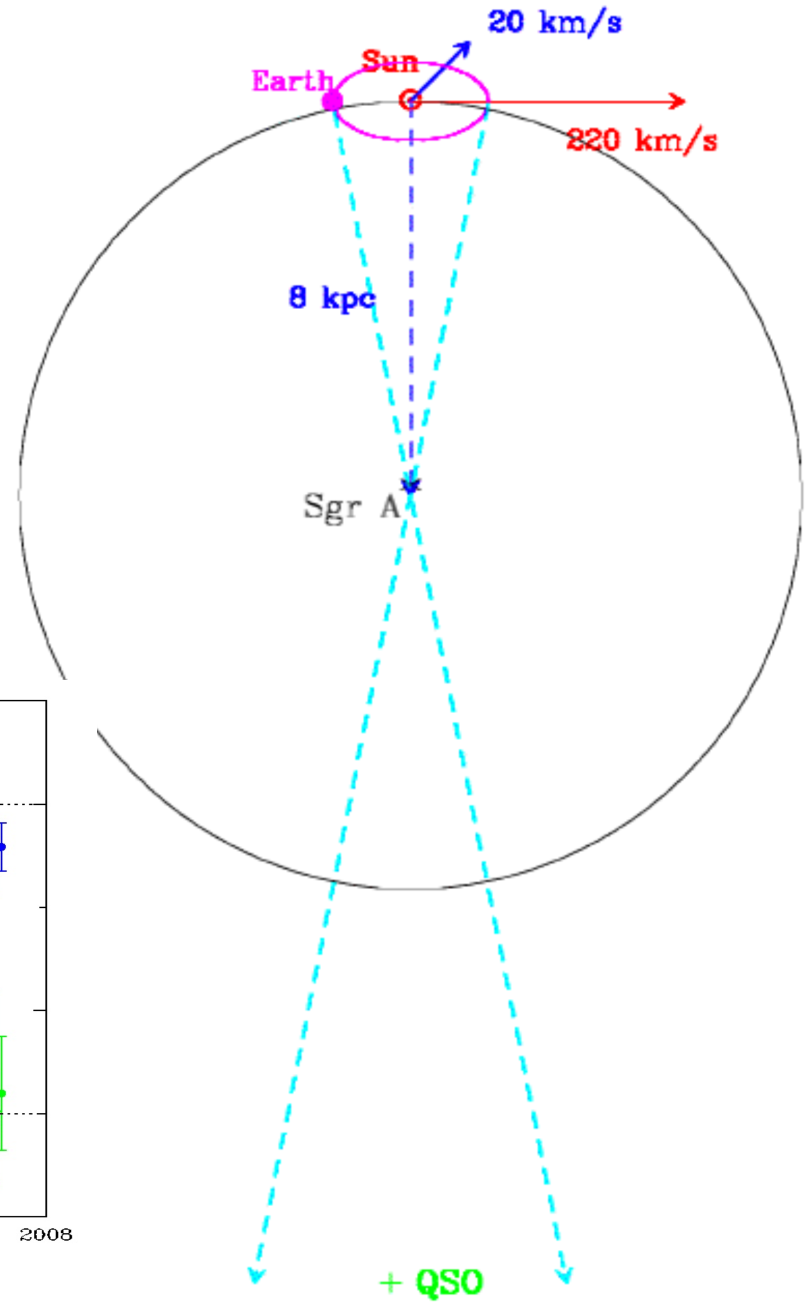
S+G gives $t_r = V^3/8\pi G^2 m^2 n \ln\Lambda \sim 2\times10^9 \mathrm{yrs}/[(V/10)^3 (m_\odot)^{-2} (n/10^3 \mathrm{pc}^{-3})^{-1}$

major uncertain is in lnΛ– numerical simulations

Distances From Motions

- Distance to the galactic center (R0) is rather important; in problem 2.6 the text discusses one way to use the observed positions and velocites of stars in orbit around the galactic center to get the distance
- Another way of doing this: measure the proper motion+parallax of SgrA* caused by the velocity of the sun
- East in blue, north in green -right panel has proper motion removed. left panel motion on sky

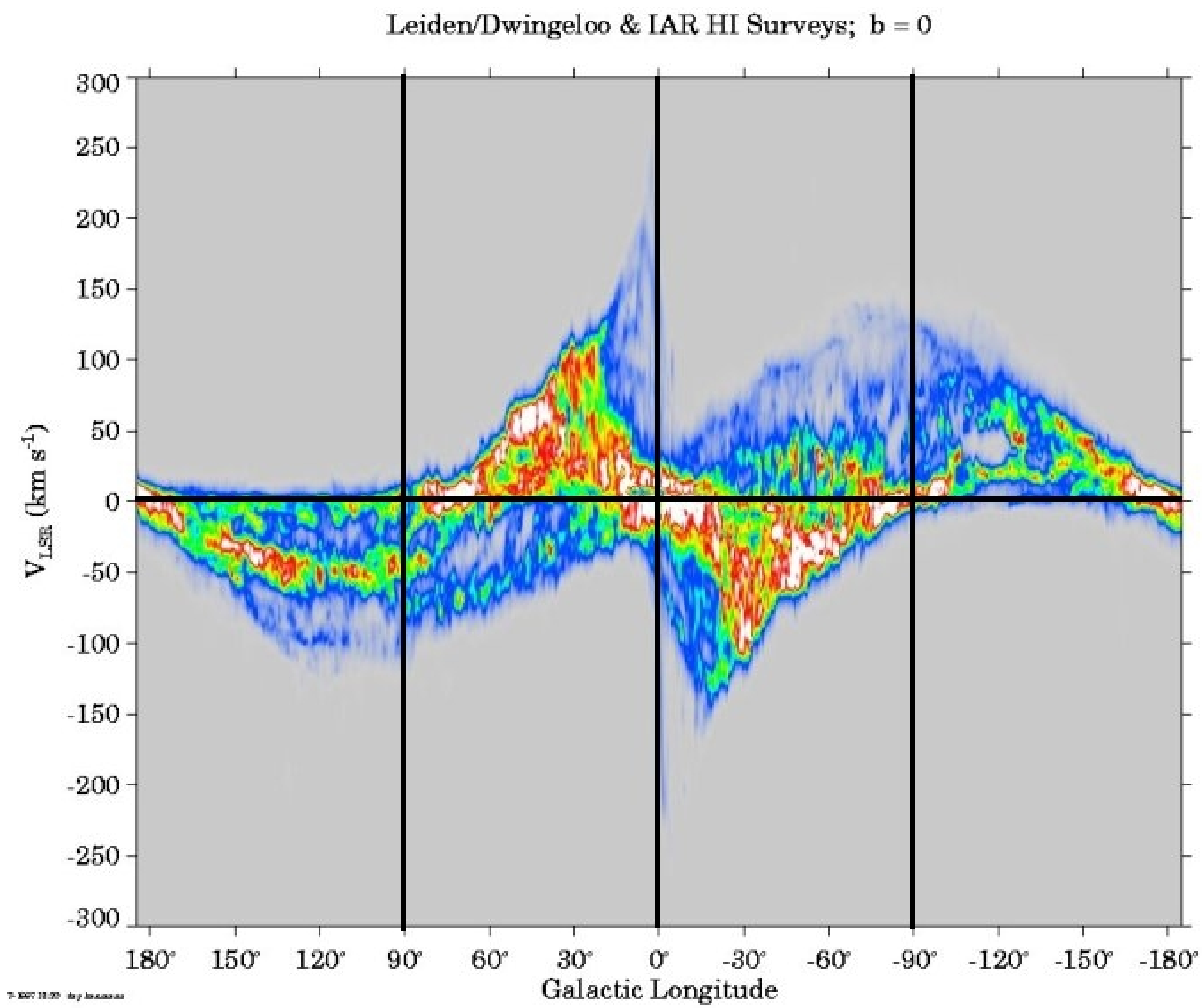




Galactic Rotation Curve HI data

- Velocity, longitude, intensity graph of HI in the MW fig 2.20 in S+G
- The HI probes very large scales and **so many of the approximations in the derivation of the Oort constants are not correct and one must use the full up equations.**

Velocity (radial)



Galactic Longitude

Distribution of Light in Disk (S+G eq 2.8

- t

the thin disk and the thick disk has a similar form but different scale height and density of stars

Radial scale length of a spiral disk

$\Sigma(r)=\Sigma_0 \exp(-R/R_d)$**;** integrate over r to get total mass $M_d=2\pi\Sigma_0 R^2{}_d$

Vertical density distribution is also an exponential $\exp(-z/z_0)$ so total distribution is product of the two

$\rho(R,z)=\rho_0 \exp(-R/R_d)\exp(-z/z_0)$

while we may know the scale length of the stars, that of the dark matter is not known.

Also the nature of the dark matter halo is not known:- disk/halo degeneracy

Somewhat more precisely the luminosity distribution is $L(R,z)=L_0\exp(-R/h)/\cosh2(z/z_0)$ with $=0.05L_\odot/pc^3$

Even more detail

Each spectral type can be characterized by a scale height, a posssible indicator of age. The older the star, the more dynamical interactions it has had (Spitzer and Schwarzschild 1951).
The result is an increase in the spatial velocity of older stars (particularly along the vertical axis of the disk).

M dwarfs have relatively large scale heights, ~ 300 pc, in contrast to the younger A-type stars with ~ 100 pc (see table 2.1 in S+G)

Cosmic Rays-100th Anniversary of their Discovery

http://www.aps.org/publications/apsnews/201004/physicshistory.cfm

- These are very hard to study in other galaxies
  - they are visible by the synchrotron emission emitted by electrons spiraling in the magnetic field
  - γ-rays emitted by relativistic particles hitting gas
- MW

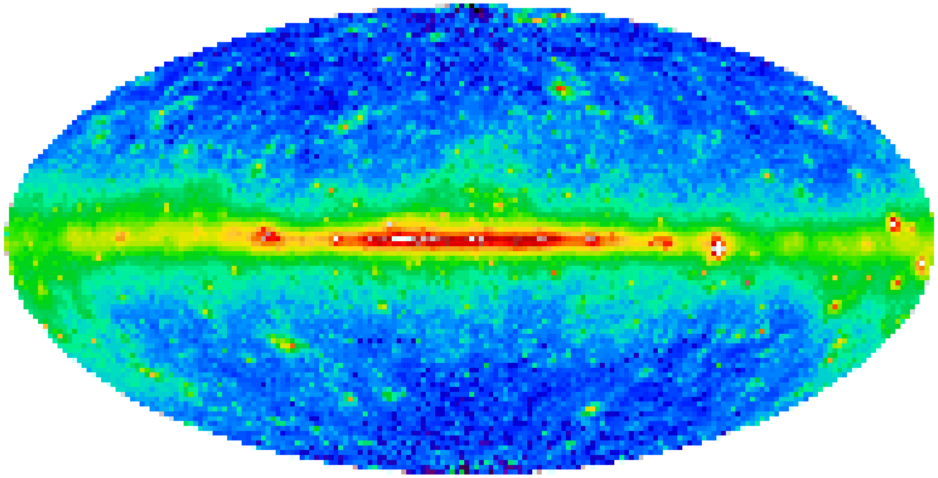
  direct measures of CRs e.g. in situ

  detailed γ-ray maps of MW

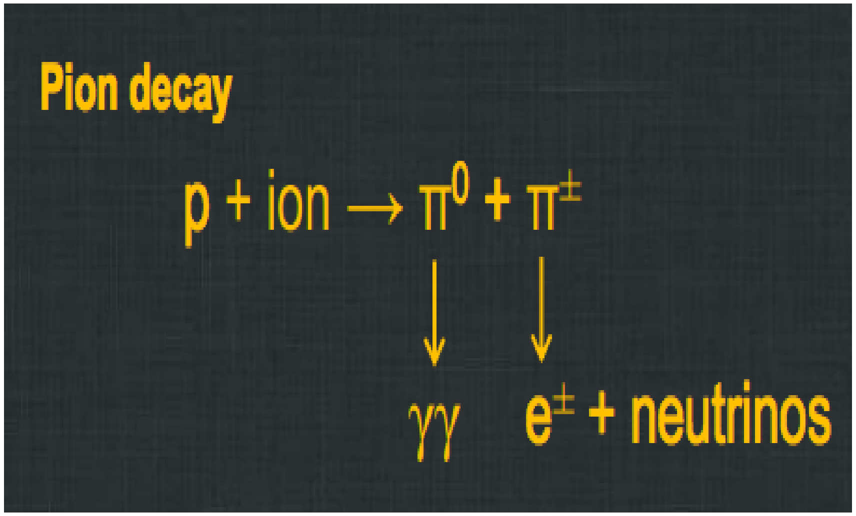
  convolution of cosmic ray energy spectrum and intensity with target (gas) density

  Very detailed radio maps

Origin: acceleration of particles in supernova shocks via first order Fermi process - total power ~10^{41} ergs/sec~10% of SN shock energy



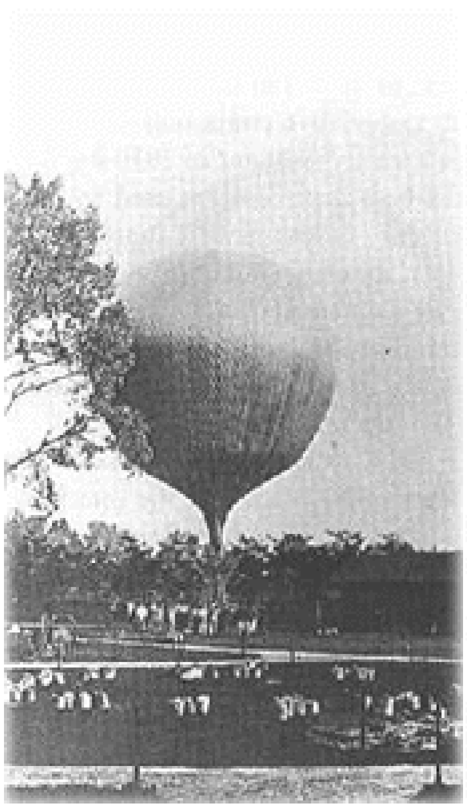
Fermi map of MW



Cosmic Rays-100th Anniversary of their Discovery
Why Did He do This

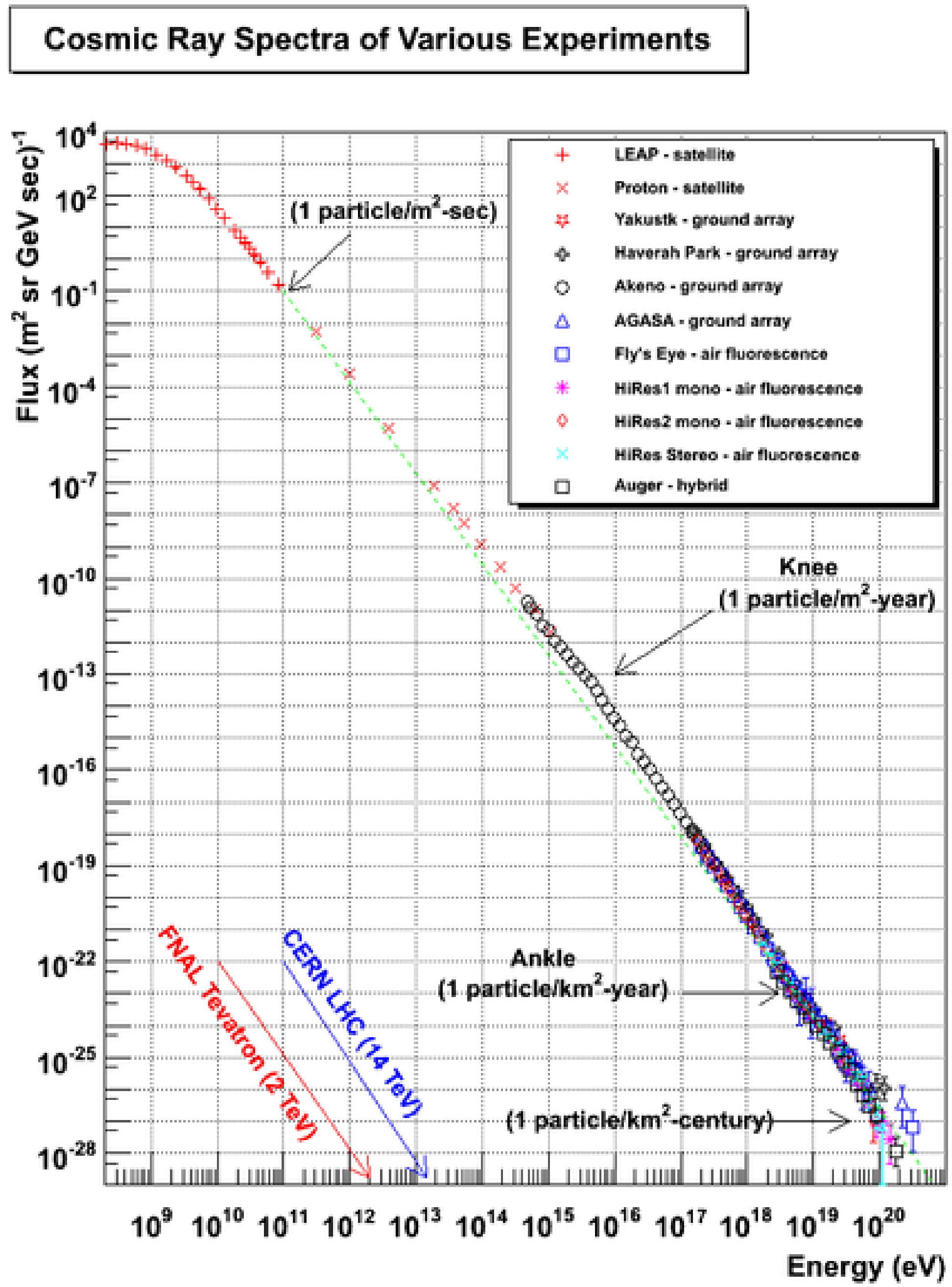
- scientists had been puzzled by the levels of ionizing radiation measured on the earth and in the atmosphere.
- The assumption was that the radiation from the earth and would decrease as one went away from the surface.
- Hess greatly increasing the precision of the electroscopes*and then by personally taking the equipment aloft in a balloon. He measured the radiation at altitudes up to 5.3 km during 1911-12 without oxygen. The daring flights were made both at day and during the night, at significant risk to himself and showed that the level of radiation increased as one went higher- observed durir
- *He concluded* *prize 1936)*

*they spontaneous of discharge of an electroscope is



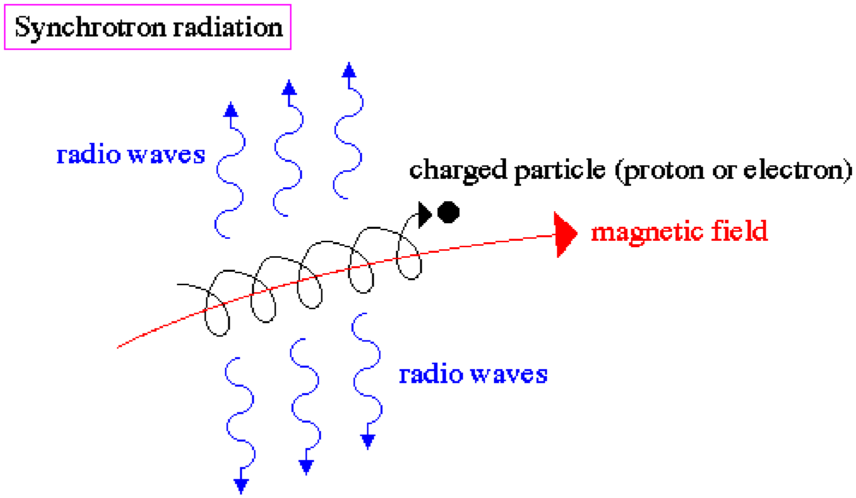

100 Years of Cosmic Rays

- In August 1912, the Austrian physicist Victor Hess flew in a balloon to altitudes of 5.3 km, measuring the flux of particles in the sky. The expectation was that the flux would decrease with altitude, precisely the opposite of what Hess found. The shocking conclusion was that particles were raining down on Earth from space.
- http://www.npr.org/blogs/13.7/2012/07/25/157286520/cosmic-rays-100-years-of-mystery



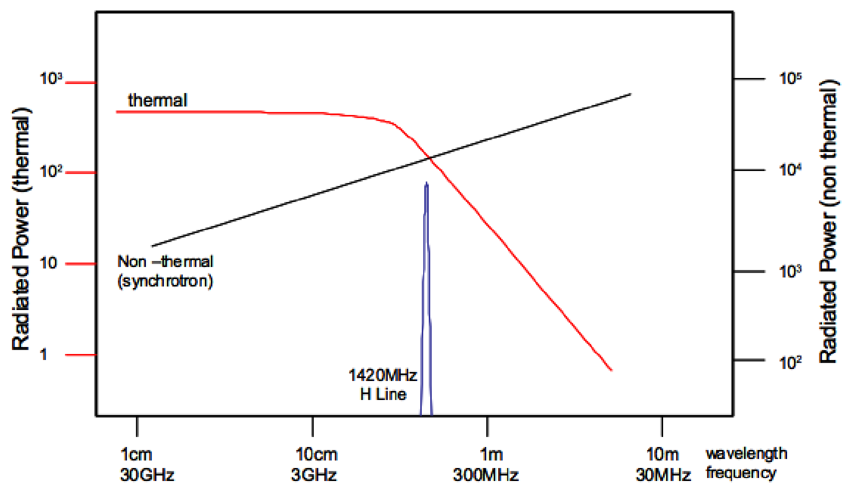
Cosmic Rays

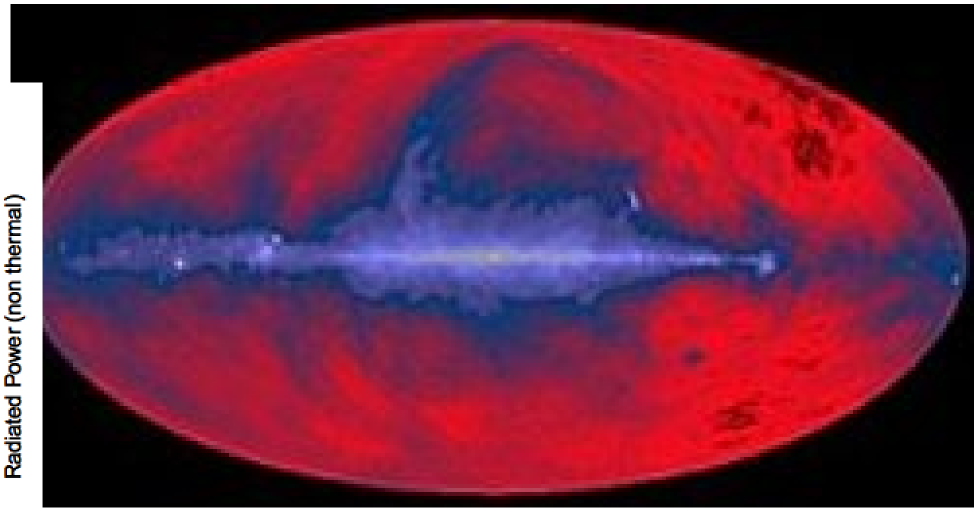
- Have appreciable energy density ~1 eV/cm^3
- Synchrotron emission is convolution of particle spectrum and magnetic field- also emission from 'non-thermal' bremmstrahlung
- Can ionize deeply into molecular clouds



http://abyss.uoregon.edu/~js/glossary/synchrotron_radiation.html

radio emission from galaxy





Cosmic Rays

- Accelerated particles propagate through the Galaxy where, due to the magnetic field, they move along complicated helical tracks.
- Therefore, the direction from which a particle arrives at Earth cannot be identified with the direction to its source of origin (Larmor radius, $m_e c(\mathrm{sqrt}(\gamma^2\text{-}1)/eB$; 3.3×10^6km for 1μG, 100Mev))
- The magnetic field is also the reason why particles do not leave the Milky Way along a straight path, but instead are stored for a long time ($\sim 10^7$ yr) before they eventually diffuse out, an effect also called confinement

γ-ray Imaging of Star Forming Regions

- Fermi has imaged the γ-rays coming from star forming regions and γ-ray spectra show that this is due to cosmic rays interacting with dense gas (Lingenfelter 2012) in superbubbles (places of high massive star formation rate and thus high S/N rate).

γ-rays come from the interaction of CRs and dense gas- Fermi has imaged sites of CR creation !

Fig. 1 Typical ~1pc Star Forming Region Shown by Bright O & B Stars

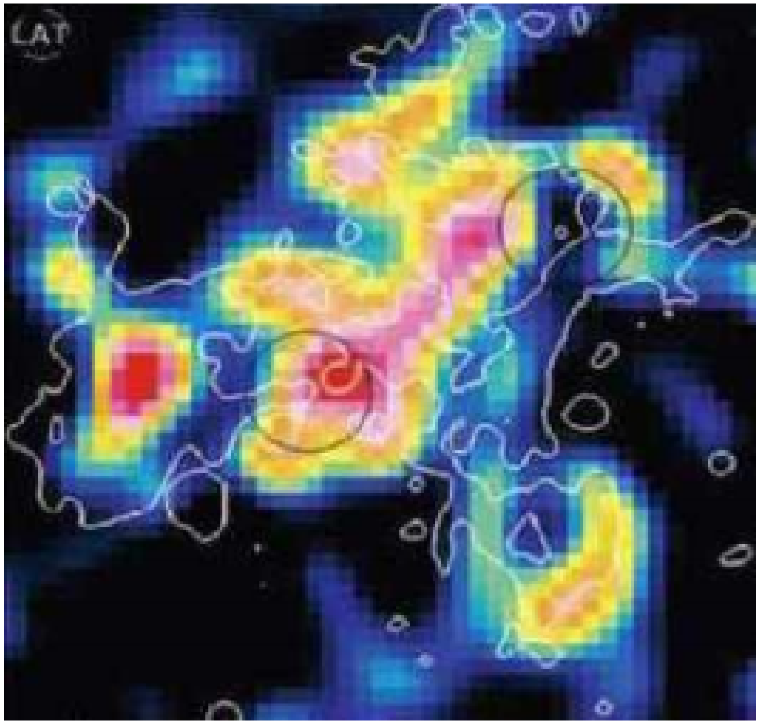


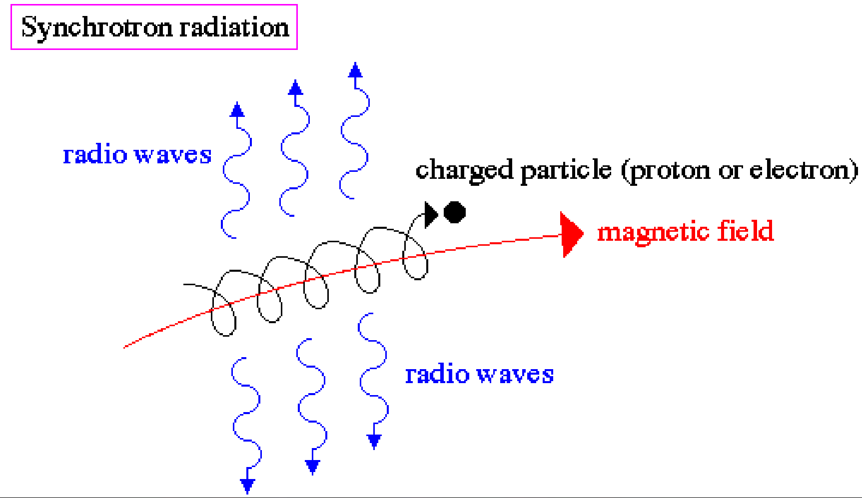
Fig. 2 ~100 pc Cygnus Superbubble in 10-100 Gev γ-Rays from Fermi [11]

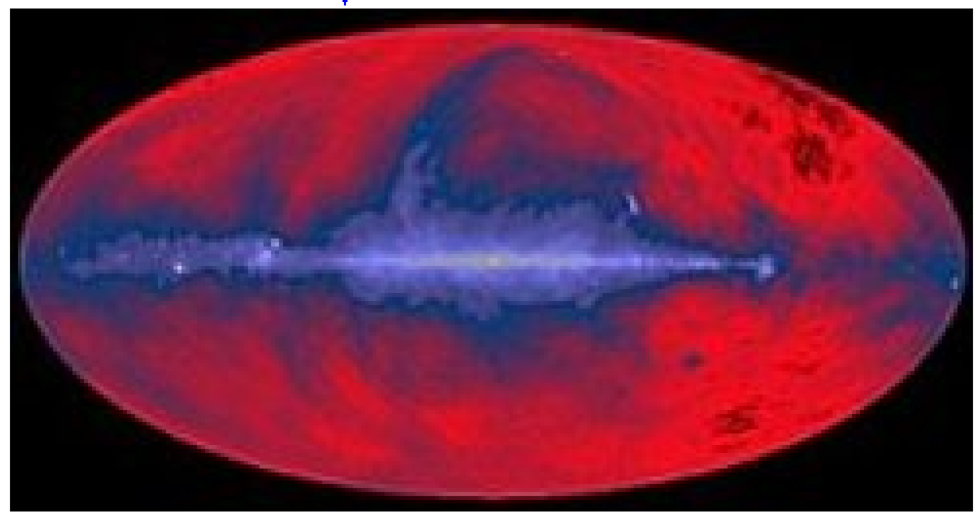
Radio Continuum Emission

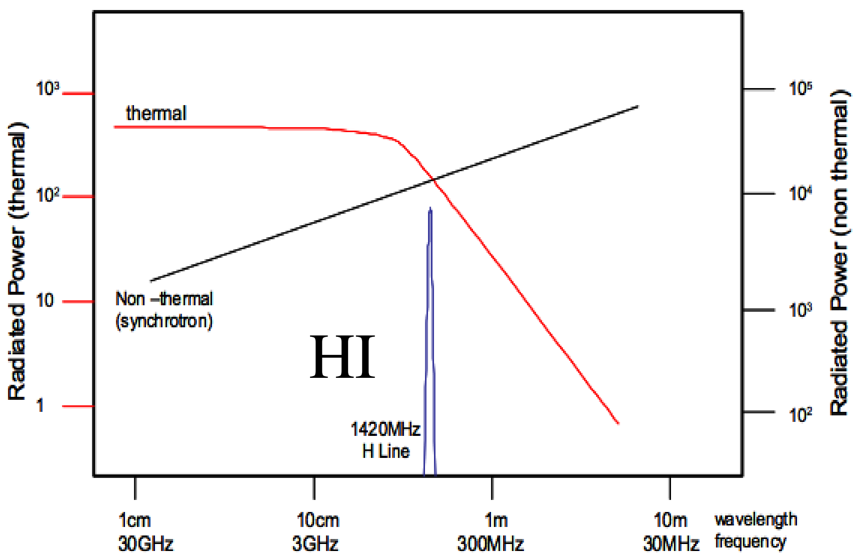
- Synchrotron emission: convolution of particle spectrum and magnetic field- power law spectrum- power law spectrum $F_\nu \sim A\nu^{-\alpha}$

slope,α depends on spectrum of CRs and intensity on magnetic field

- Thermal bremmstrahlung: fast, non-relativistic particles running by gas (breaking radiation)-exponential spectrum
- Relative intensity of the two components changes greatly with position.







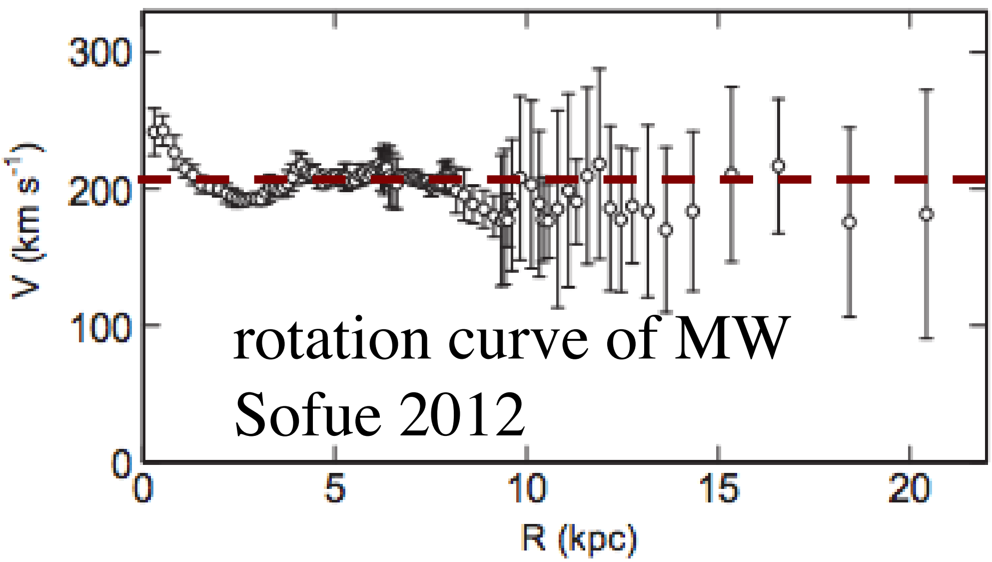
Simple Estimate of Mass of Milky Way

- If we follow problem 2.18 and use $M \sim RV^2/G$- of course this is for a sphere ... ignore the details (discuss later what is correct for a disk+sphere)

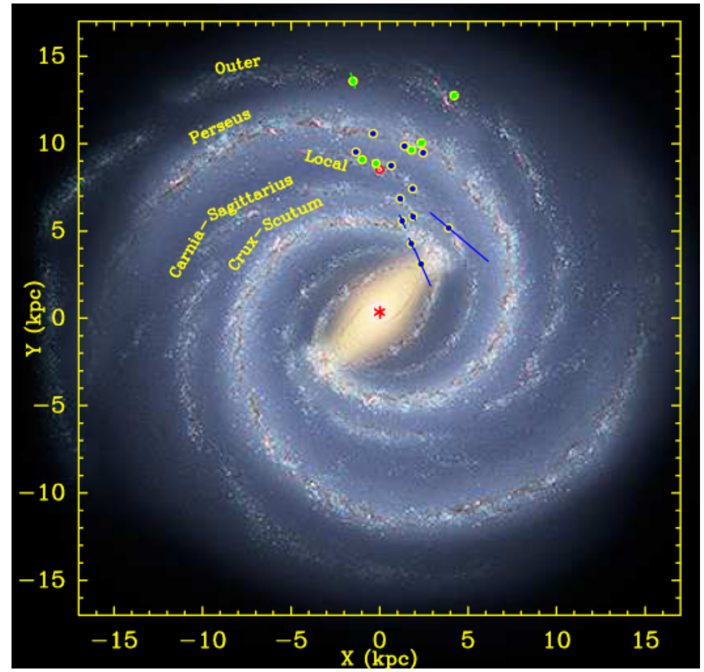
- suns distance from enter $R_0 \sim 8$kpc and rotational velocity ~220km/sec
  $M = 9\times10^{10}\,M_\odot$ - corresponds to a density of ~$4\times10^{-3} M_\odot/pc^3$ (uniform sphere) - mass within 8kpc; if extend to 350kpc (virial radius) get $4\times10^{12}\,M_\odot$; factor of 2-4 too high but right 'order'
- critical density of universe today $\rho_{crit} = 3H_0^2/8\pi G \sim 1.45\times10^{-7}\,M_\odot/pc^3$
- So the MW is 'overdense' by ~2.7×10^5 at solar circle and 600 at viral radius (using above simple formula) and 150 using correct mass.
- In CDM theories the size of a virialized system is when the overdensity is >200

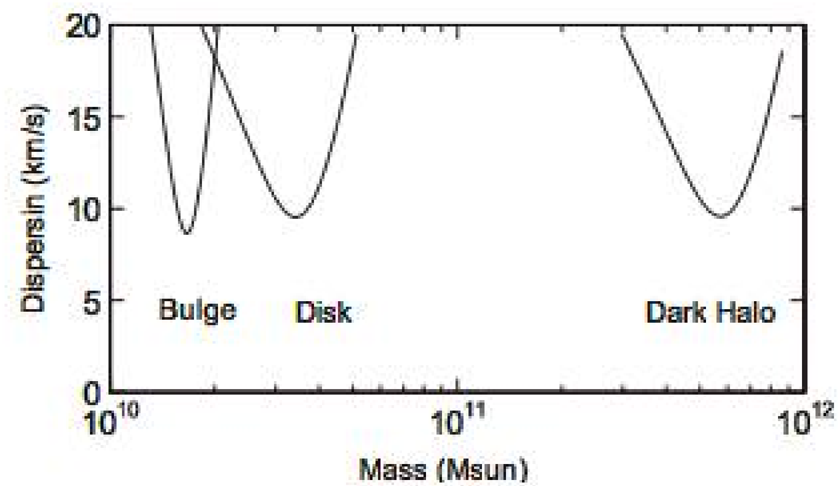
Mass of Milky Way

- This turns out to be rather hard to determine- there is a degeneracy between velocity and distance- use rotation curve fitting and 'proper' potentials
- New data allows absolute distance to be determined for several star forming regions (Reid et al 2009)
- Stellar mass of MW is ~$6\times10^{10} M_\odot$
- DM mass is 1-$2\times10^{12} M_\odot$; M/L~30
- DM inside overdensity of 200 1-$2\times10^{12} M_\odot$



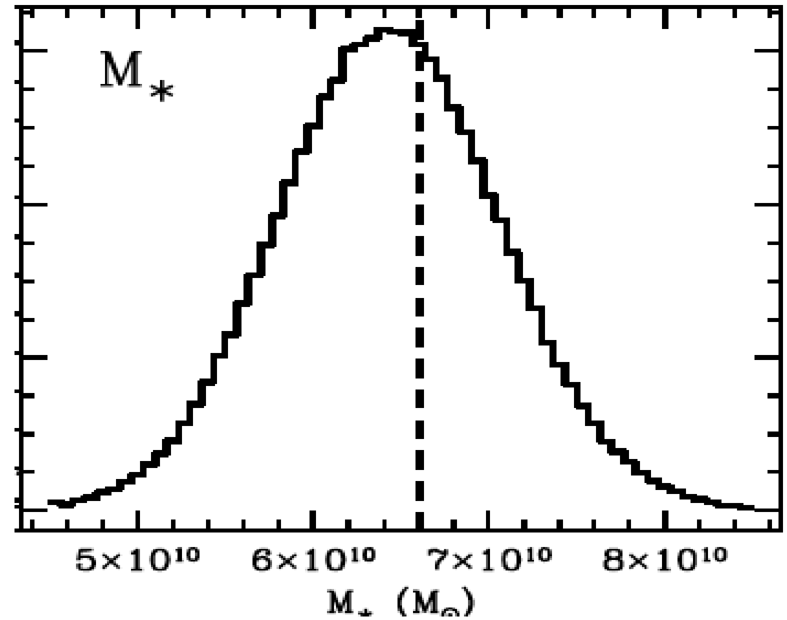
Locations of star-forming regions (dots) artist's Milky Way.

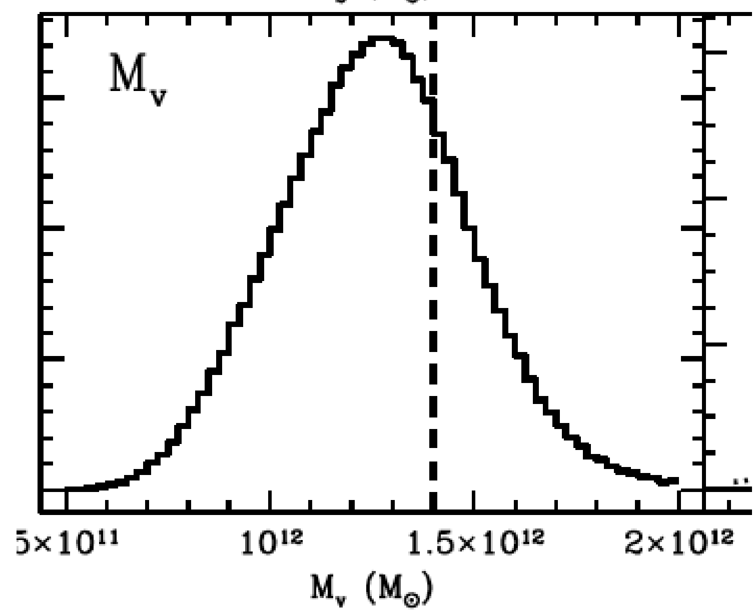




Mass of Milky Way

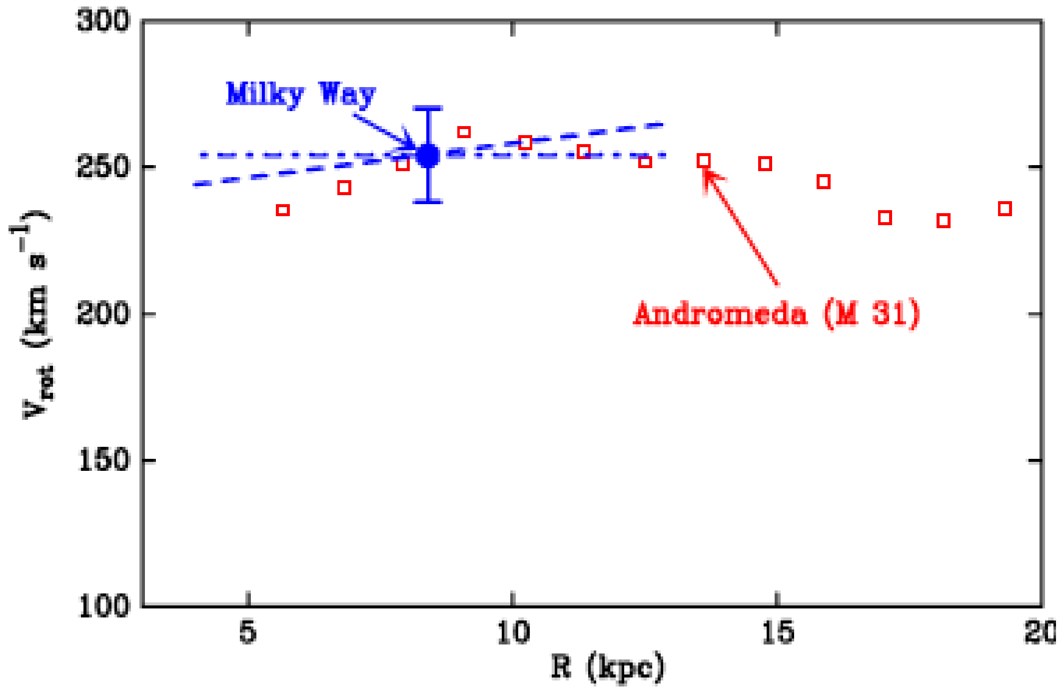
- The majority of the mass of the Galaxy is expected to lie in the CDM halo, which is only observable through its gravitational effect on luminous components of the Galaxy
- Most recent estimates (McMillian 2012, van den Maerl 2012) differ
- disc scale lengths of 3.00 ± 0.22 kpc and 3.29 ± 0.56 kpc for the thin and thick discs respectively;
- at sun thin disk has 89% of the mass and thick disk 12%
- R_0 Solar radius of 8.29 ± 0.16 kpc
- a circular speed at the Sun of 239 ± 5 km/s
- total stellar mass of $6.43 \pm 0.63 \times 10^{10} M_{\odot}$
- bulge mass $M_b = 8.9\ 10^9\ M_{\odot}$
- virial mass of $1.26 \pm 0.24 \times 10^{12} M_{\odot}$
- **a local** dark matter density of $0.40 \pm 0.04 \mathrm{GeVcm}^{-3}$ (or in more normal units $0.01\ M_{\odot}/\mathrm{pc}^3$)





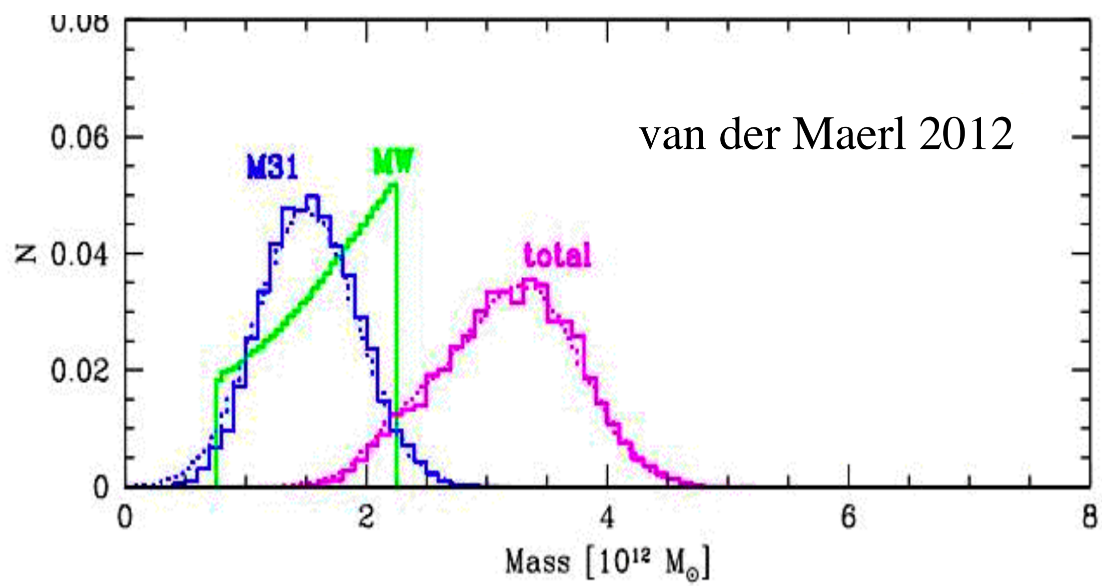
distribution functions of parameters McMillian 2012

Comparison with M31

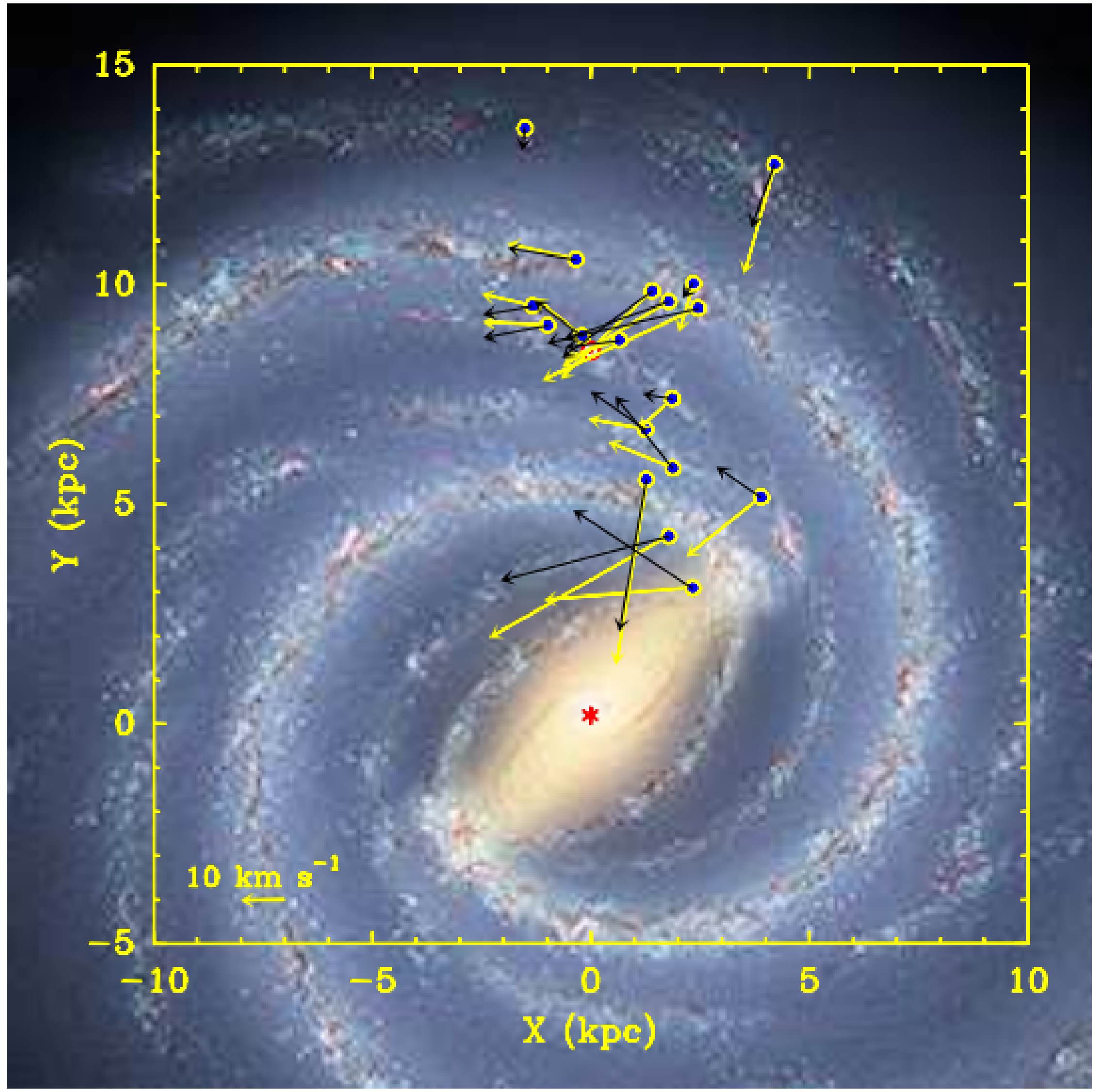


Blue line is from Reid 2009
notice it disagrees with
previous figure-
this is due to difficulties in
assigning accurate distances
to different tracers
and correcting for non-circular
motions

the Milky Way has a significantly higher rotational speed (or, equivalently, lower baryonic mass) than the Tully-Fisher relation predicts- more later



- The light (yellow) arrows are for IAU standard values of R_0 = 8.5 kpc and V_r = 220 km /s and a flat rotation curve, black arrows for V_r= 254 km/s
- high mass star forming regions orbit the Galaxy slower than the Galaxy rotates!

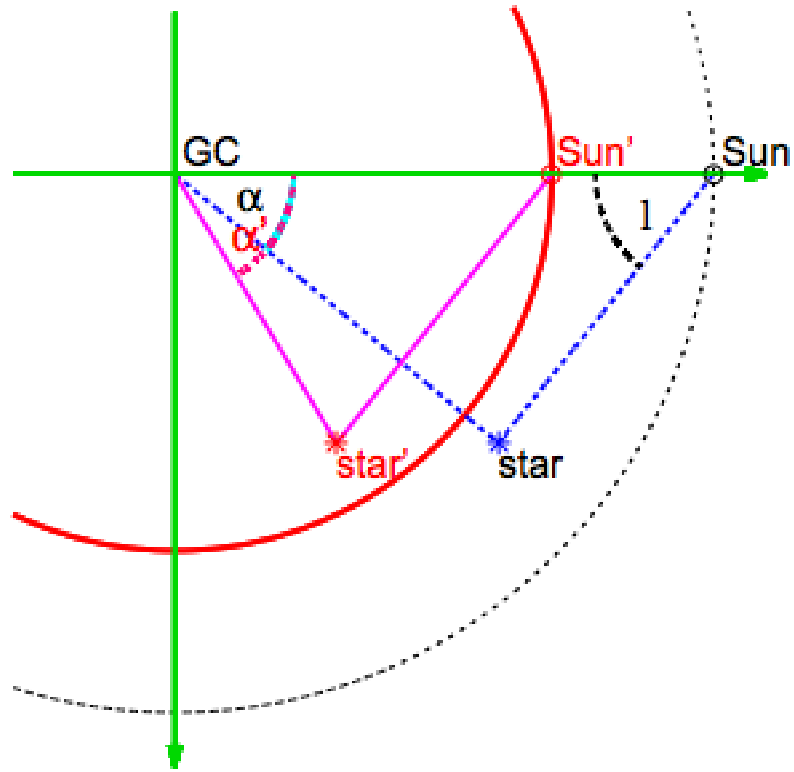


'ig. 3.— Peculiar motion vectors of high mass star forming regions (superposed on an artist onception) projected on the Galactic plane after transforming to a reference frame rotating with he Galaxy. A 10 km s^{-1} motion scale is in the lower left. The Galaxy is viewed from the north

Why Different Rotation Curves for MW

- Changing R0's effect on determination of the rotation curve
- Since the galactic longitude of the data source (star,gas) does not change the angle, a, must grow as R0 lessens
- This reduces the rotation speed estimated from the sources radial velocity

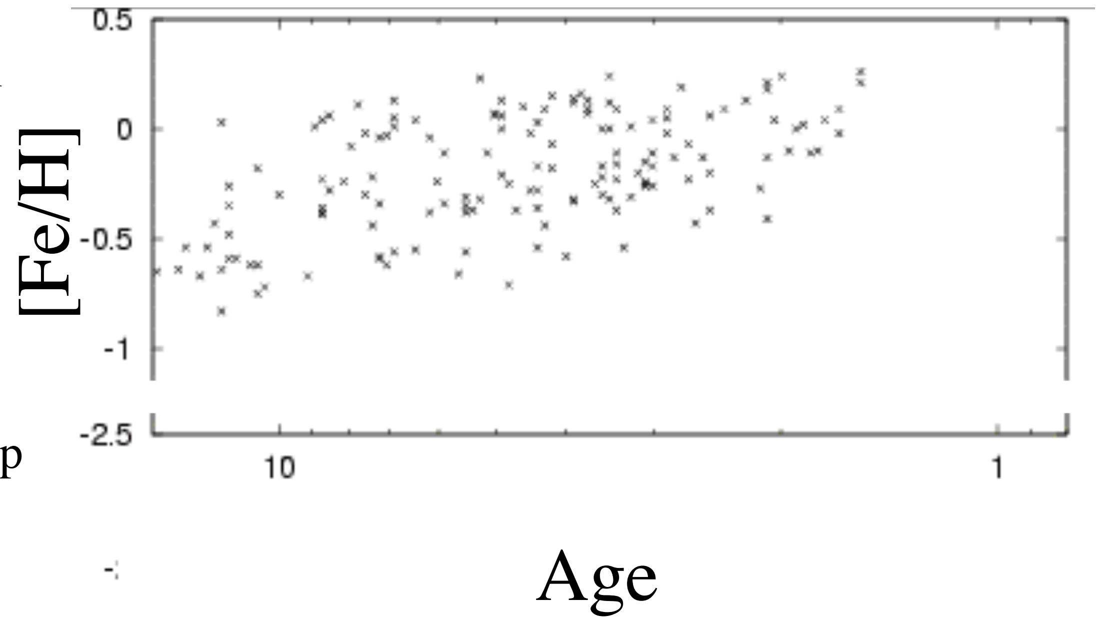
R. Schonrich



Age Metallicity

- Older stars **<u>tend</u>** to be metal poor: only in the MW can this be studied with great detail (SG 4.3.2)
- However the metallicity history of the MW is very hard to unfold
- Older stars (in the MW) tend to be metal poor
  - logic is that metals are created in SN over cosmic time, next generation of stars if formed from this enriched gas, so more metal rich
- Actually much more complex;
  - galaxy is not a closed box, gas flows in and out

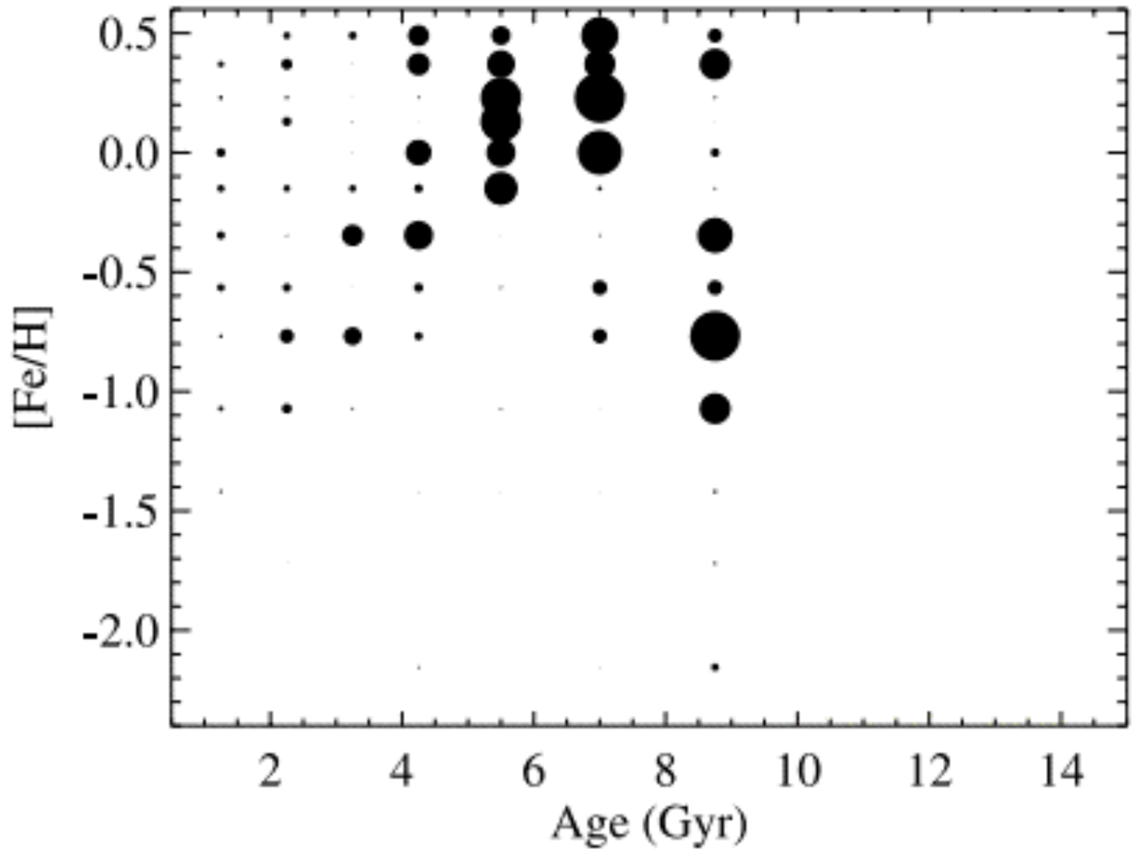
    galaxy mergers can mix things up
  - Two types of SN (type I produces mostly Fe, type II mostly O)
  - stars can move a long way from their regions of birth



Age Metallicity

- Now can do this in M31 with HST data (!)
- Pattern seems to be more variance at younger ages rather than a trend.
- In M31 spheroid things are very different than in MW; 40% of the stars are metal-rich and younger than 10 Gyr ! (M31 has undegone a major merger MW has not)

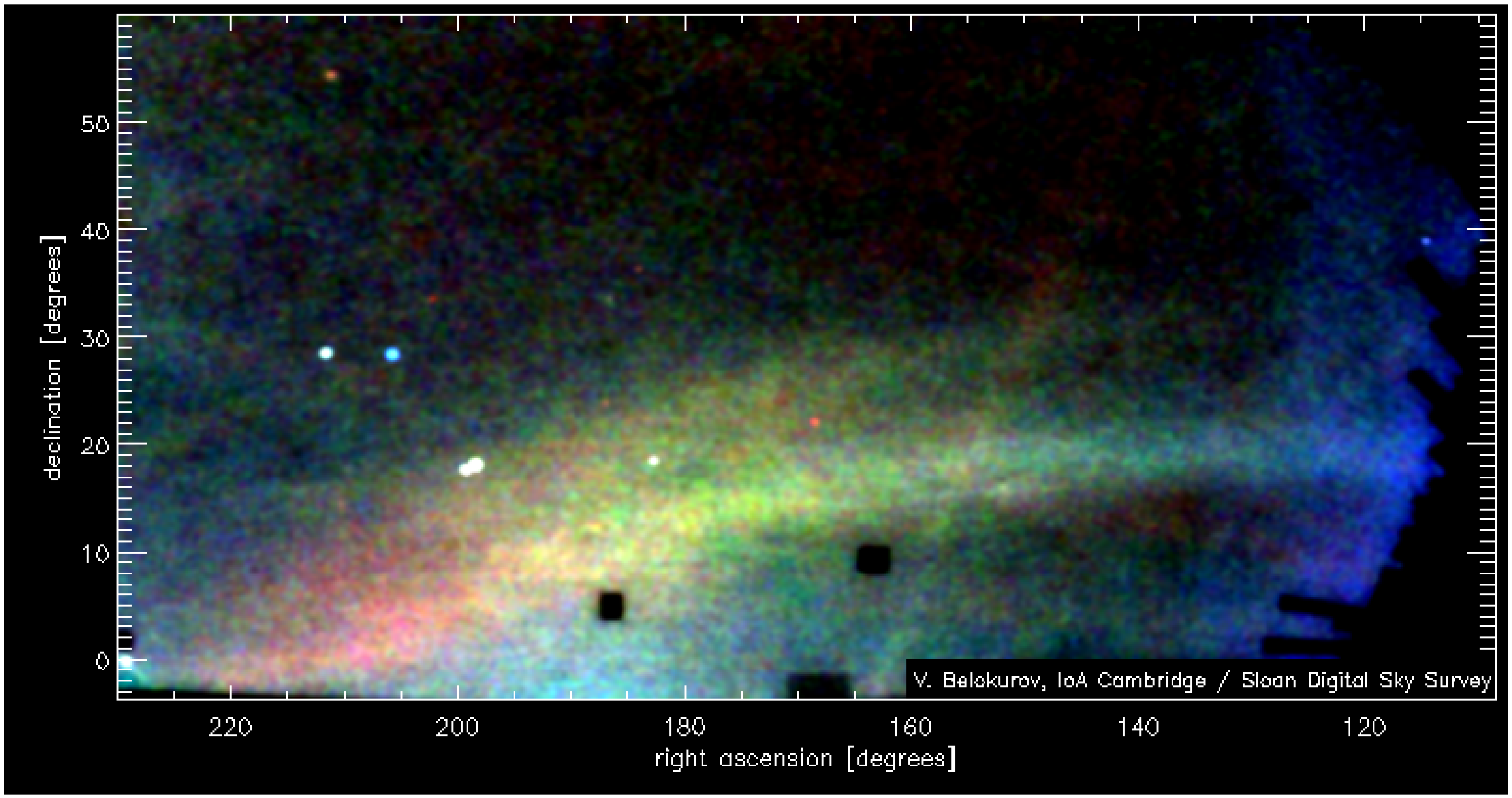
- Lesson: MW may not be representative of spirals



Size of symbol is ~ # of stars in box; Brown et al 2006

Stellar halo : fossil record of assembly?

- Dwarf galaxies are disrupting and contributing to the stellar halo
  - 1% of stellar mass of our galaxy
  - takes ~5Gyr for MW to 'digest' a merging dwarf
  - See such effects in nearby galaxies (see later lecture on mergers)



MW as Model for Other Galaxies

- the Milky Way experienced very few minor mergers and no major merger during the last ~10Gyrs- unexpected in a cosmological scenario
- The old stellar content of the thick disk indicates a possible a merger origin at that early epoch.
- The Milky Way is presently absorbing the Sagittarius dwarf though this is a very tiny event (<1% of the Milky Way mass)
- Stars do not 'stay put' ; they can migrate long distances from their origin.
- Detailed analysis of stellar distributions in 7-D time, position and velocity) allow measure of mass and dynamical history-see next lecture

How Typical is the MW??

- the Milky Way is systematically offset by ~1σ showing a significant deficiency in stellar mass, angular momentum, disk radius, and [Fe/H] at a given V^{rot}
- The Milky Way had an exceptionally quiet formation history having escaped any major merger during the last 10 Gyr;
- Milky Way like galaxies correspond to only 7% of local spirals, - so onto the rest of the universe!