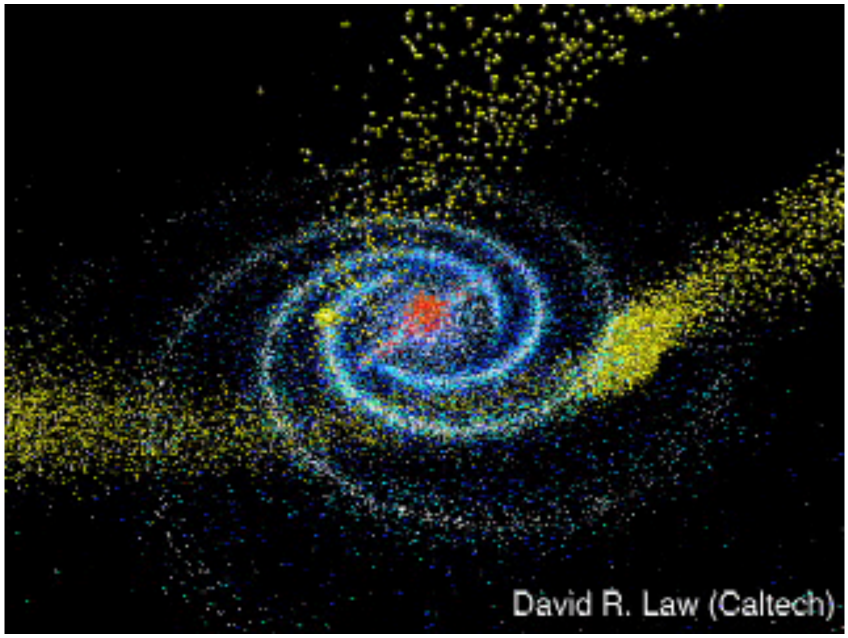
- Milky Way Galaxy (blue/ white points and orange bulge) with the Sun (yellow sphere), inner and outer Sgr stream models (yellow/red points respectively), Monoceros tidal stream model(violet points), and observed Triangulum-Andromeda structure (green points).

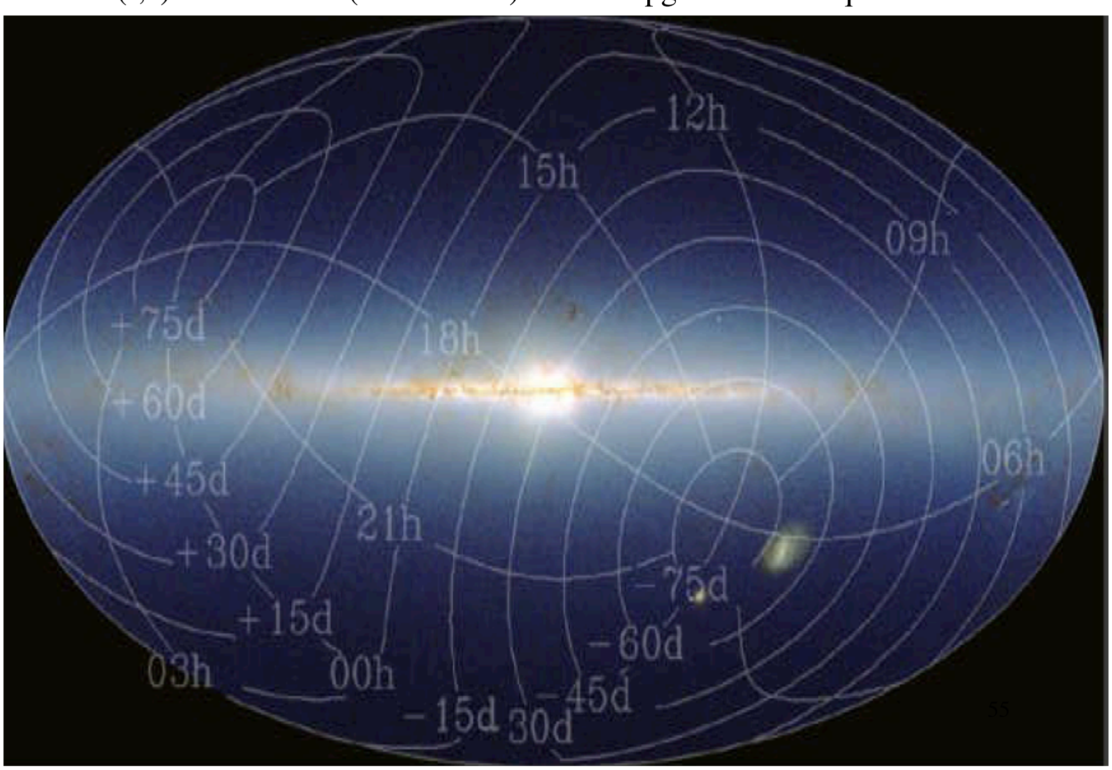


The geometry of the stream requires an oblate near-spherical halo

http://www.astro.caltech.edu/~drlaw/MWstreams.html

Coordinate Systems

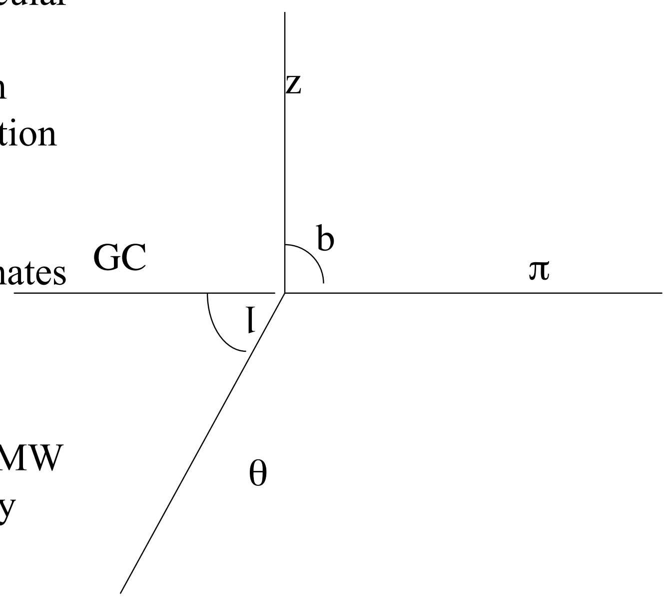
- Galactic (l,b) and celestial (Ra and Dec) see S+G pg 34-37 for a quick refresher



Coordinate Systems

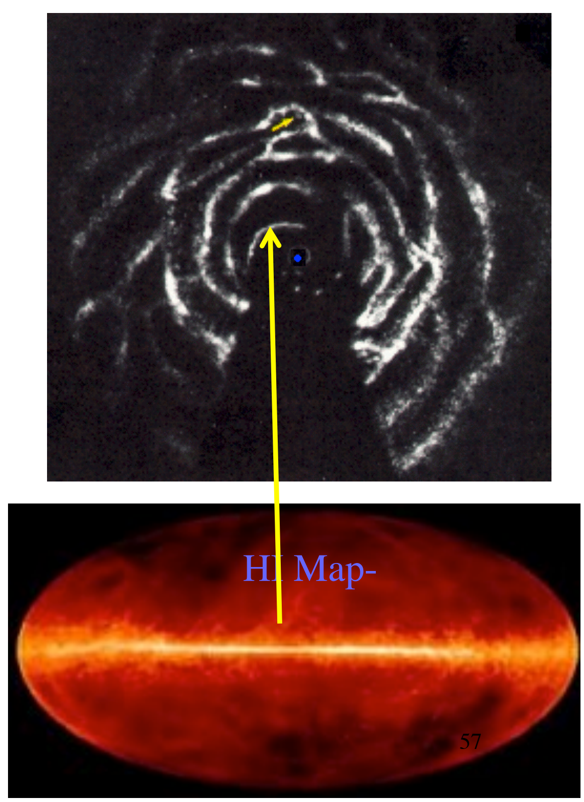
The stellar velocity vectors are
z:velocity component perpendicular to plane
θ: motion tangential to GC with positive velocity in the direction of rotation
π: radial velocity wrt to GC
With respect to galactic coordinates
+π= (l=180,b=0)
+θ= (l=30,b=0)
+z= (b=90)
Local standard of rest: assume MW is axisymmetric and in steady state
(π,θ,z)LSR$=(0,\theta_0,0)$;

GC=Galactic center



HI Maps- Major Way to Trace MW Velocity Field

- 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.
- see review article by Kalbela and Kerp on the web page
- Neutral atomic hydrogen (HI) traces the interstellar medium (ISM) over a broad range of physical conditions.
- 21-cm emission line is a key probe of the structure and dynamics of the Milky Way Galaxy.



Velocity of HI

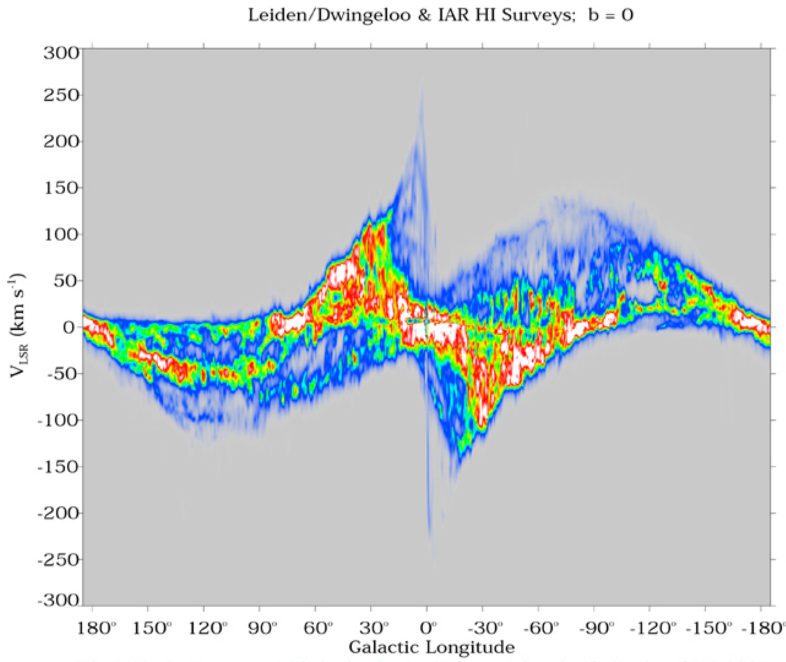


Fig 2.20 (D. Hartmann) 'Galaxies in the Universe' Sparke/Gallagher CUP 2007

- In the plane of the disk the velocity and intensity of HI gas (Sparke and Gallagher fig 2.20)
- The distribution of HI and CO emission in the longitude-velocity plane yield a characteristic maximum ("terminal") velocity for each line of sight (e.g. Binney & Merrifield 1998§9.1.1).

The terminal velocities are related to the circular speed $v_c(R)$ by $v_{term}(l) = (\sin l)\ v_c(R) - v_c(R_0))\sin l$

Galactic Rotation- S+G sec 2.3, B&T sec 3.2

- 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 for circular motion
- $V_{observered, radial}$=V(cos α)-V_0sin(l)
- $V_{observered ,tang}$=V(sin α)-V_0 cos(l)
- using the law of sines

sinl/R~ cosα/R_0

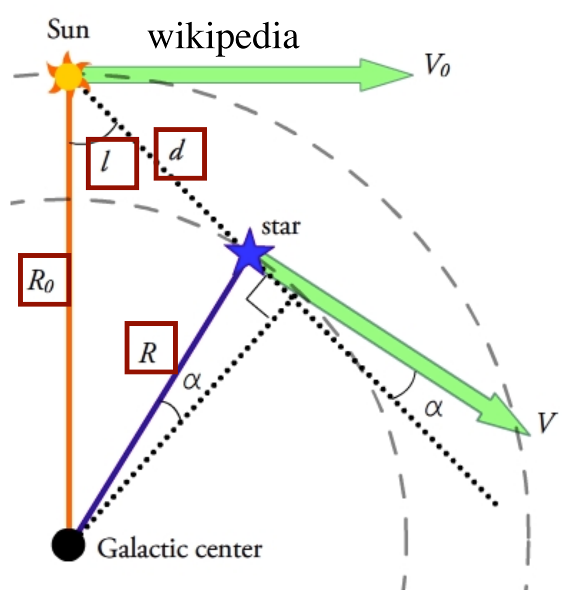
which gives

$V_{observered, radial}=R_0\sin(l)[(V/R)-(V_0/R_0)]$

S&G 2.11

Much more later

wikipedia



Since we have 'poor' idea of distance rely on tangent point

at 0<l<90 radial velocity is highest at the tangent point where los passes closest to galactic center

HI Observables- How to 'De-project'

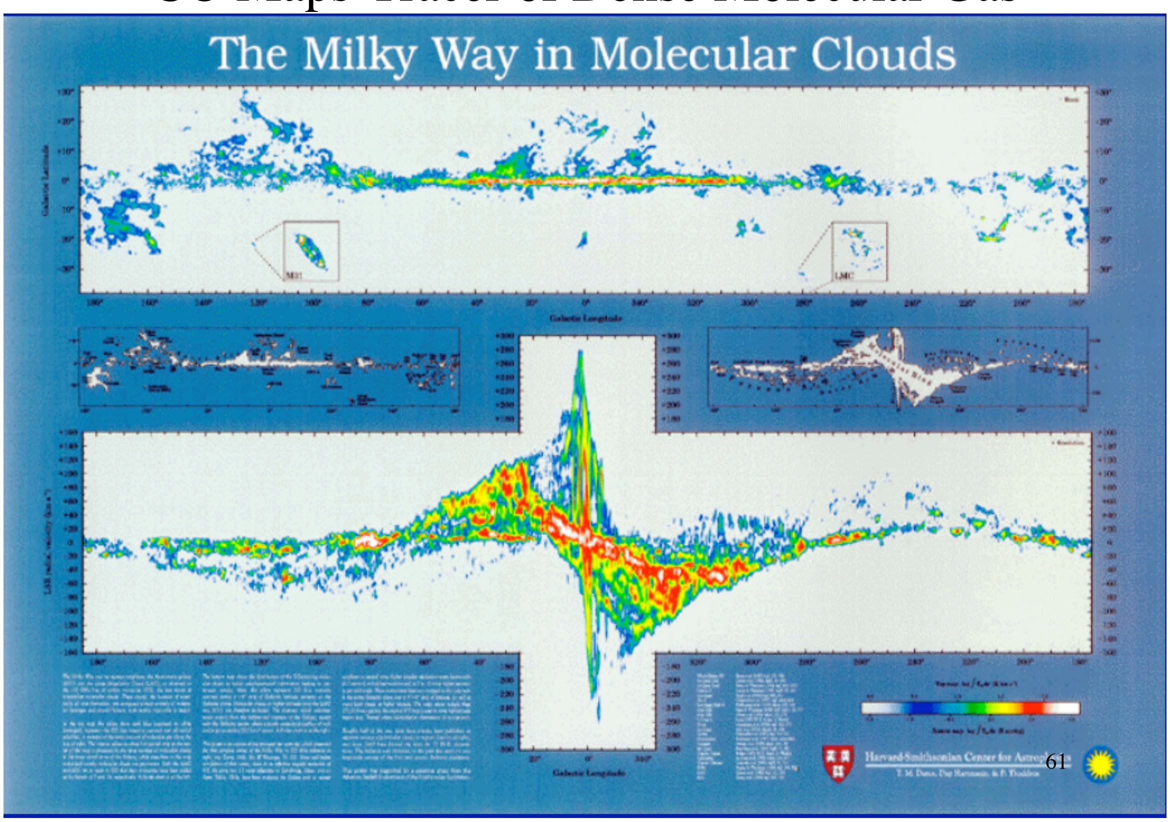
- Observed intensity $T_B(l, b, v)$ observed in Galactic coordinates longitude l and latitude b need to be converted into volume densities n(R, z) (Burton & te Lintel Hekkert 1986, Diplas & Savage 1991).
- Assuming that most of the gas follows an axisymmetric circular rotation yields a relation for the differential rotation velocity (e.g., Burton1988)

  $v(R, z)=[(R_\odot/R)\ \Theta(R, z)-\Theta_\odot]\sin l\ \text{-}\cos b$ where v is the radial velocity along a line of sight(directly measurable); and Θ is the **tangential velocity**

- for $R < R_\odot$, distances are ambiguous,
- for $R > R_\odot$, one needs to know the Galactic constants $R_\odot$ and $\Theta_\odot$ and the form of $\Theta(R, z)$ e.g. the rotation curve shape.
- See S&G pg 92-94.

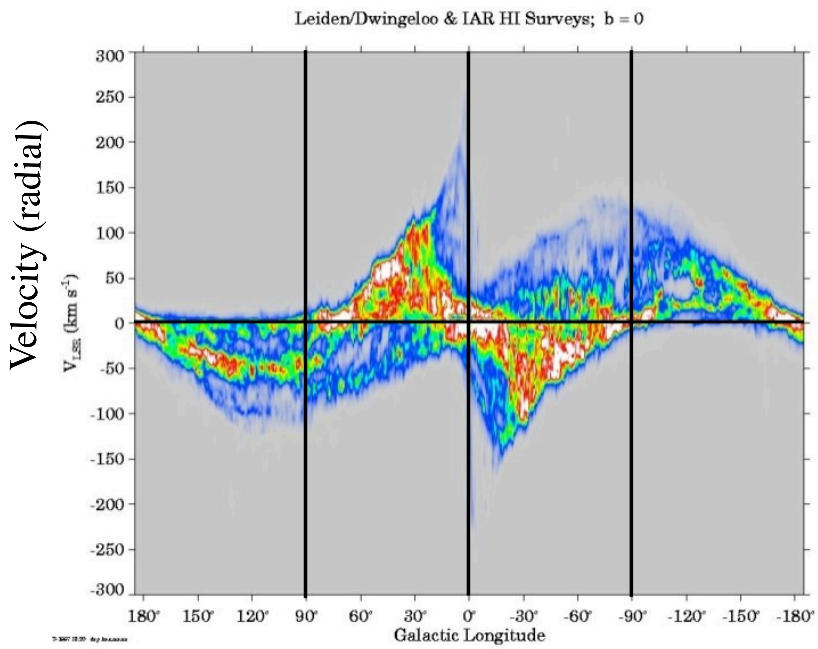
$R_\odot$ is the distance of the sun from the galactic center and $\Theta_\odot$ is the velocity of rotation at the sun (a lot more later)

CO Maps-Tracer of Dense Molecular Gas



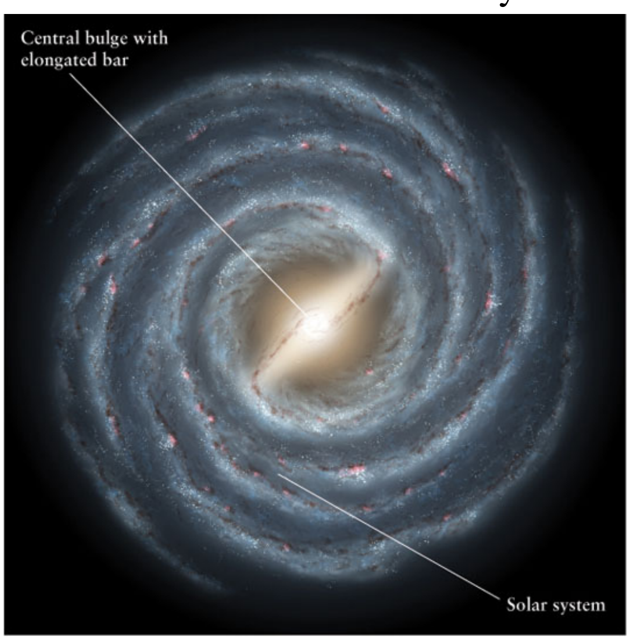
Galactic Rotation Curve HI data

- 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 (S+G pg 92-93) (see next lectures) are not correct and one must use the full up equations.**

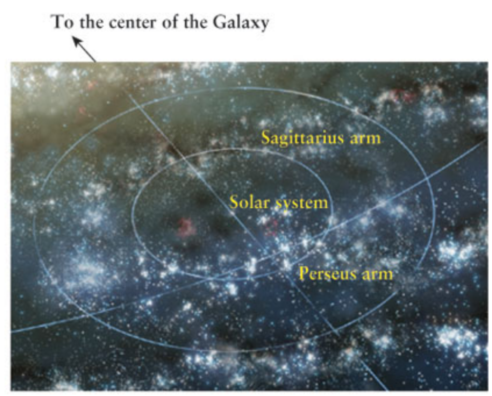


Galactic Longitude

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

Disk Big Picture Numbers MWB 2.3.4

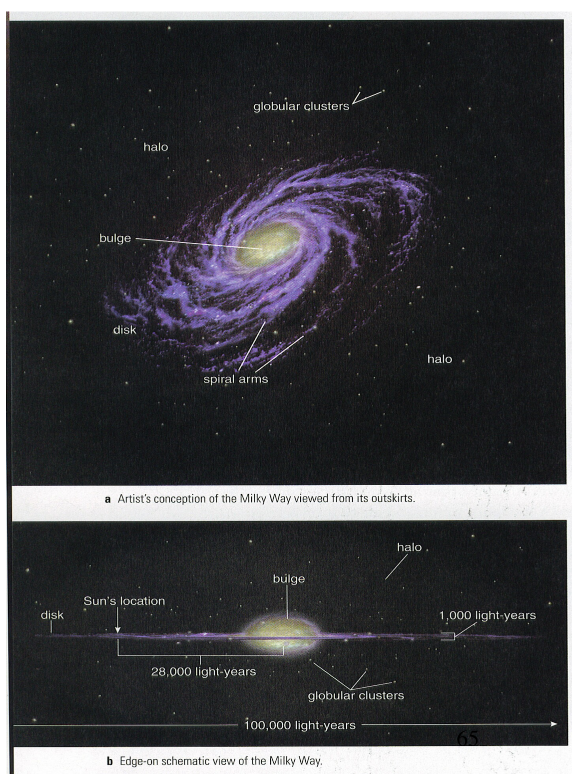
- MW disk is
- highly flattened structure with an (exponential) radial scale length of 2.5–3 kpc if model the disk as an infinitesimally thin, exponential disk, with surface density distribution $\Sigma(R) = \Sigma_0 \exp(-R/R_d)$, *whose mass is* $M_d = 2\pi\Sigma_0 R^2_d$
- scale **height** of 0.3 kpc which is kinematically cold in the sense that the characteristic stellar

velocity dispersions near the Sun of σ_z σ_ϕ σ_R ~25 kms^{-1}- far less than v_{circ} 220 kms^{-1}.

- A diameter of ~30 kpc (not the virial radius, but the radius out to which stars can be 'seen')

Basic Properties of MW

at sun orbital period ~$2.5\text{x}10^8$ yrs
Mass ~$2\text{x}10^{11}$ $M_\odot$ (details later)
M/L_V~10-15 (on average including DM)
Official distance of sun from GC is 8.5kpc, $v_{circular}$~220km/sec



a Artist's conception of the Milky Way viewed from its outskirts.
b Edge-on schematic view of the Milky Way.

Vertical Structure

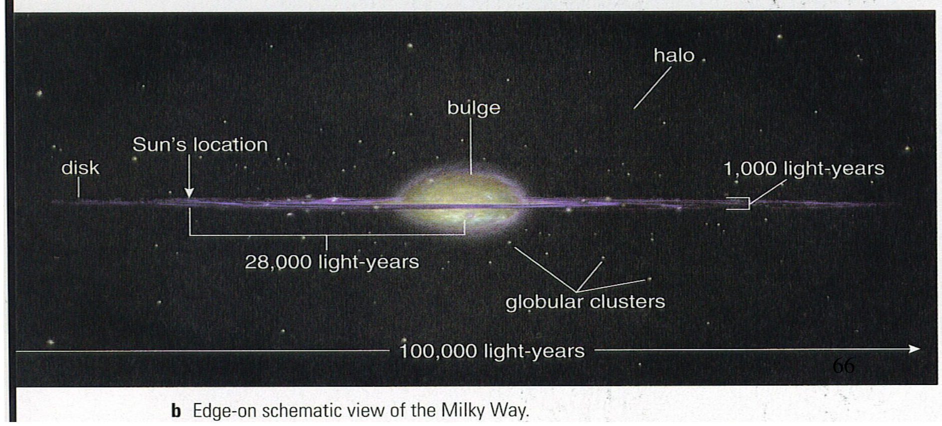
Perpendicular to the disk the stellar distribution(s) can each be 'well' described as

n(z)~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~1.0kpc older, lower metallcity population, less gas- only makes up 2% of mass density **at z~0**.

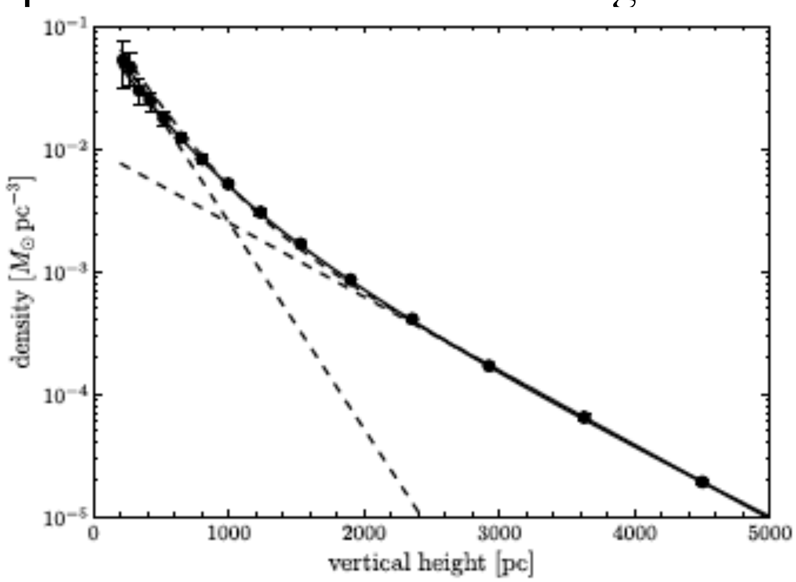
a Artist's conception of the Milky Way viewed from its outskirts.



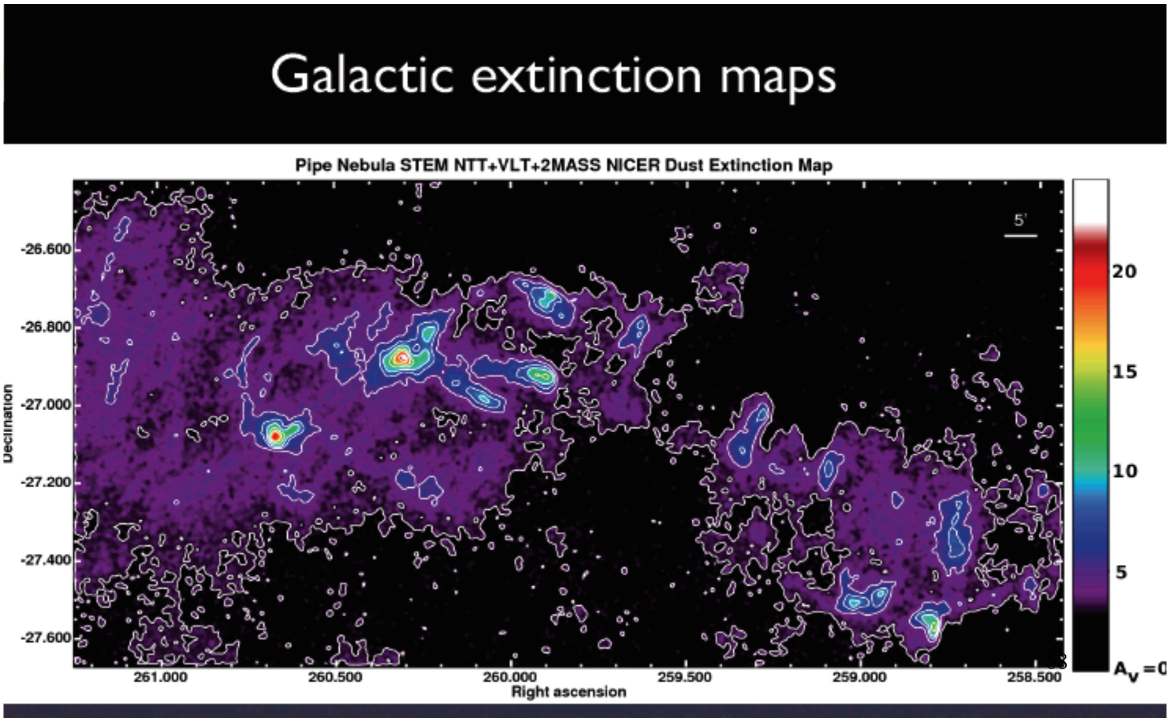
b Edge-on schematic view of the Milky Way.

Graphic Depiction of Vertical Scale Height

- decomposition of scale height of MW stars into 2 exponentials (mass weighted) (Rix and Bovy 2013)-
- Can only do this in edge on spirals (dust is a big problem)



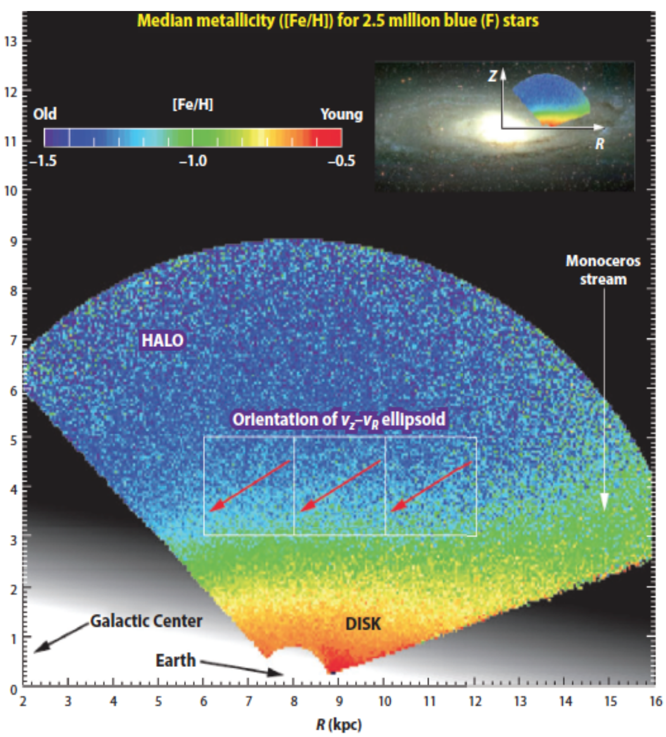
Need to Measure Extinction Accurately to Convert star Counts/Luminosity to Masses



Chemical Composition of Local Volume of MW

- Thin disk –red
- Thick disk yellow-green
- Bulge – blue
- Numbers are **abundance wrt sun**
- The stellar density is shown in half tone (Juri´c et al. 2008).

height above plane

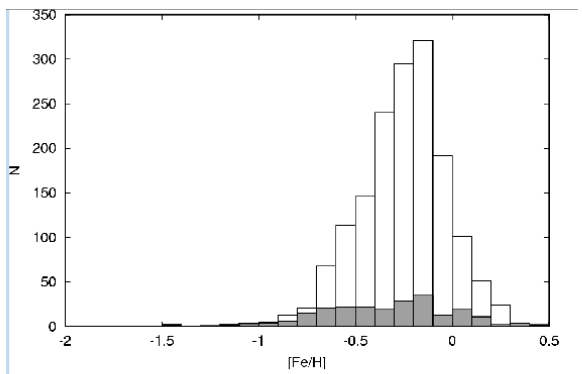


Distance from GC

Thin and Thick Disk -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 $M_{stars} \sim 6\text{x}10^{10}\ M_\odot$; $M_{gas} \sim 0.5\text{x}10^{10} M_\odot$. Stellar luminosity $L_B \approx 1.8\text{x}10^{10} L_\odot$
- Thick disk has low mass and luminosity $M \sim 3\text{x}10^9\ M_\odot$ and $L_B \approx 2\text{x}10^8 L_\odot$
- 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'
- PopI is the component which dominates the disk O,B stars, open clusters, dust HII regions
- Pop II - bulge; old relatively metal poor

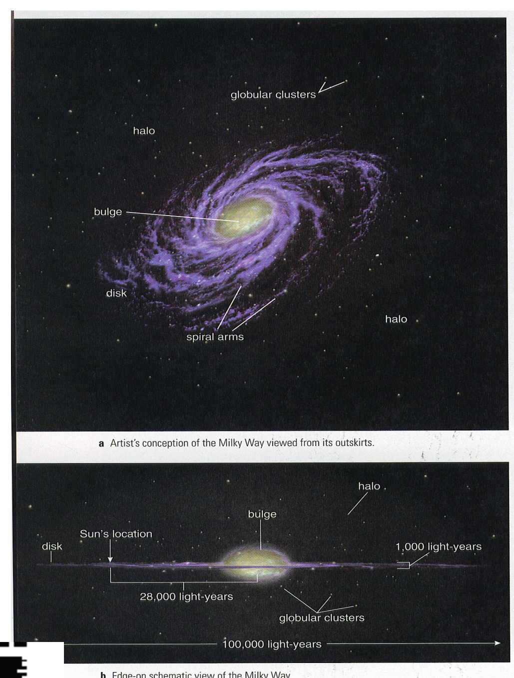
thin disk-open
thick disk shaded



[Fe/H]

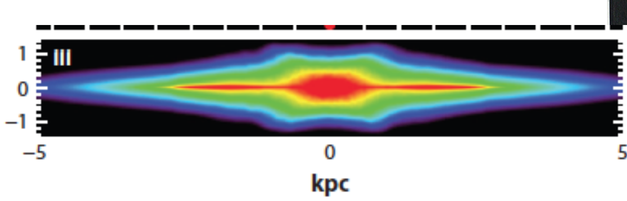
Components of MW

HII scale height: 1 kpc
CO scale height: 50-75 pc
HI scale height: 130-400 pc
Stellar mass: $\sim 5\text{-}7\text{x}10^{10}\ M_\odot$
HI mass: $\sim 3\text{x}10^9 M_\odot$
H_2 mass (inferred from CO mass): $\sim 0.8\text{x}10^9 M_\odot$
Total gas mass $\sim 0.7 \text{ x } 10^{10}\ M_\odot$
Total MW mass within viral radius is $\sim 8\text{-}12\text{x}10^{11} M_\odot$: Mostly DM
The mass values depend on the radius within which they are estimated

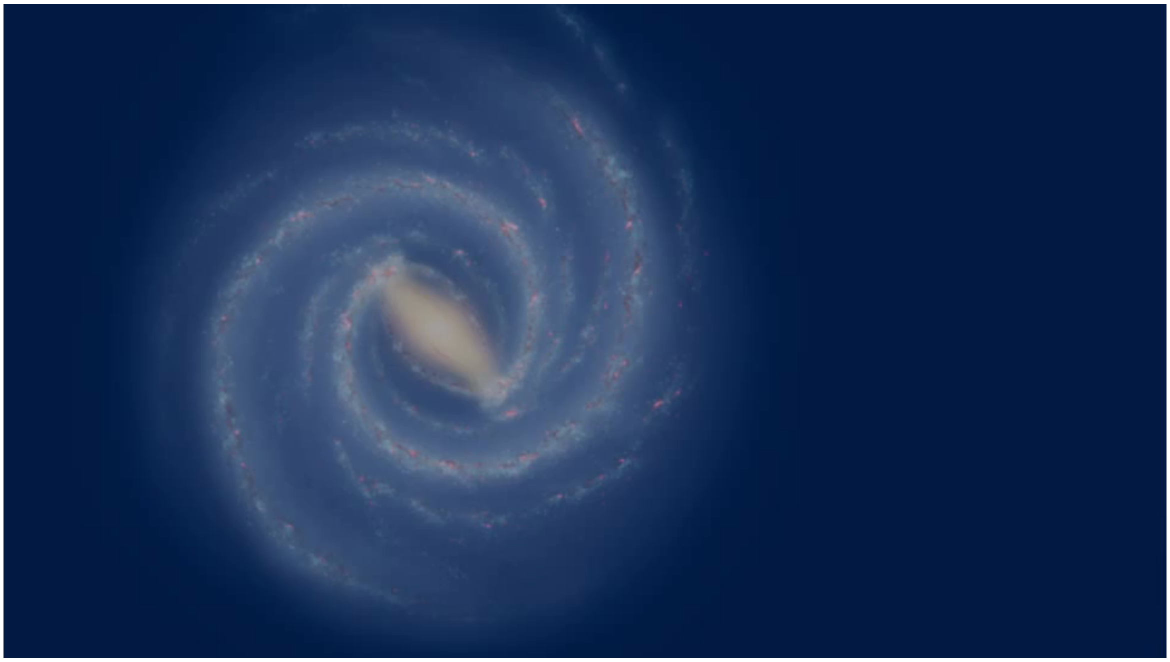


a Artist's conception of the Milky Way viewed from its outskirts.

b Edge-on schematic view of the Milky Way.

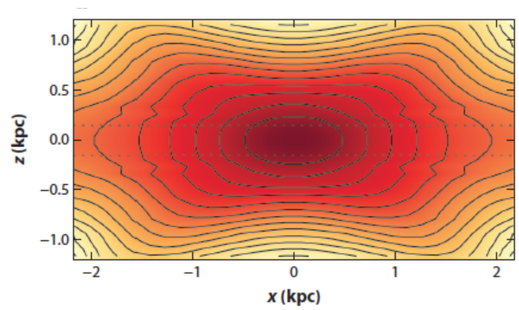


movie shows stars from **RAVE DR5**. Colors encode the heliocentric radial velocity of each star, from red for > 50 km/s over orange, yellow and cyan to blue for < -50 km/s



The Bulge

- The Galactic bulge *was* considered to be a structure built through mergers early in the formation of the Galaxy, -a classical bulge.
- Driven by the old ages of bulge stars inferred from color-magnitude diagrams
- Velocity field is complex as is the morphology (peanut shaped Wegg & Gerhard (2013))
- the density distributions inside~1 kpc are nearly exponential,
- Small but significant rotation



- Stellar mass ~1.3×10^{10} $M_\odot$
- $M*_{bulge}/M*_{MW} = 0.3 \pm 0.06$.
- IMF consistent with Kroupa

Distribution of Light in Disk (S+G eq 2.8)

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 $M_d=2\pi\Sigma_0 R^2_d$

$\Sigma(r)$ is surface density

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 3-D luminosity distribution is $L(R,z)=L_0 exp(-R/h)/sech^2(z/2z_0)$ with luminosity density $L_0=0.05L_\odot/pc^3$

Even more detail

Each spectral type can be characterized by a scale height, a possible 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)

Where is the Dark Matter?

- Can measure 3D structure from star counts
- Can measure dynamics from individual stars
- Can only do in the MW/local group: (a lot more later)
- **Need to find a good tracer of potential**

that probes the disk (z<~1kpc)

  - **numerous sufficiently old, well-mixed well-calibrated distances good radial velocity measurements**
  - **Lower main sequence stars (G - K dwarfs)**
- Parameterize possible potentials
- Known star populations + gas + dark disk + halo
- Bottom line No convincing evidence for 'cold' DM component in the disk .

Mass Distribution near Sun

- The (surface) density distributions can be derived from dynamical studies (much more later in class)
- 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 total 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 Disk- Thick Disk

- There are a variety of stellar populations in the disk.
- There is a strong tendency for age, metallicity, velocity dispersion and scale height to be correlated.
  - velocity dispersion of a disk stellar population $\sigma(R, \phi, z)$ increases with age
- It used to be that this was parameterized as a 'thin' and 'thick' disk.
- Of course things are more complex (Bovy et al 2013) and there seems to be a more continuous distribution.

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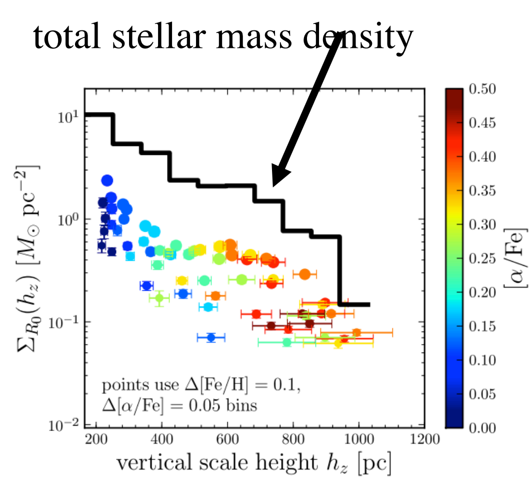


FIG. 2.— Distribution of stellar surface-mass density at the Solar radius $\Sigma_{R_0}(h_z)$ as a function of vertical scale height h_z. The thick black histogram shows the total stellar surface-mass density in bins in h_z, calculated by summing the total stellar masses of sub-populations in bins in [α/Fe] and [Fe/H]. The stellar surface-mass densities of the individual elemental-abundance bins in [Fe/H] and [α/Fe] are shown as dots, with values for Σ_{R_0}([Fe/H], [α/Fe]) on the y-axis. The points are color-coded by the value of [α/Fe] in each bin and the size of the points is proportional to the square root of the number of data points that the density fits are based on. Some of the errorbars are smaller than the points. Elemental abundance bins have a width of 0.1 in [Fe/H] and 0.05 in [α/Fe].

"The Formation and Evolution of the Milky Way," by Cristina Chiappini;2001

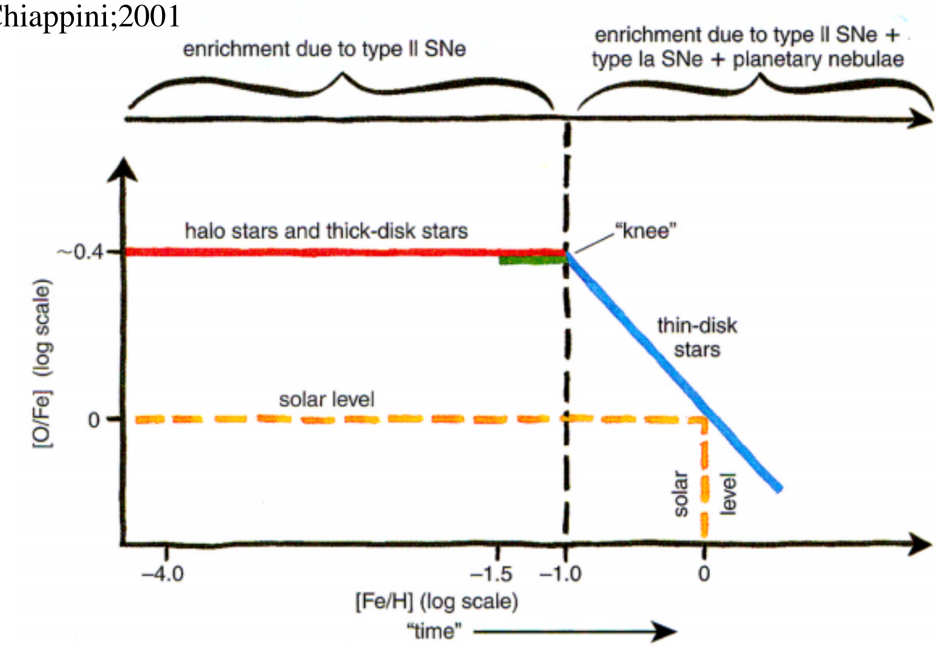
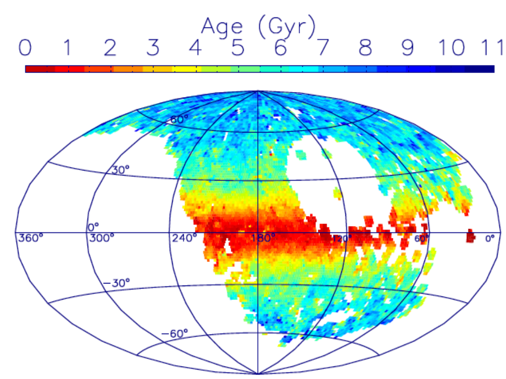


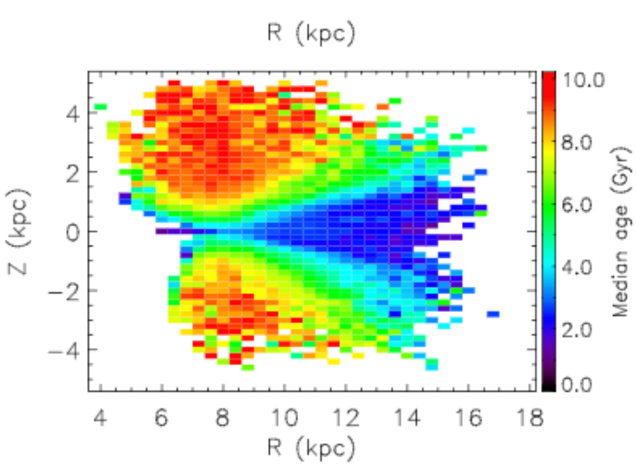
Figure 5. The general metallicity of the Galaxy—as measured by the abundance of iron (Fe), compared with hydrogen (H)—increases with time *(abscissa)* and so serves as a basis for comparing the relative abundances of two elements (such as oxygen (O) and iron; *ordinate*) that are created on different timescales. A plot of these quantities reveals a "plateau" of metal-poor stars (metallicity less than -1) that drops at a "knee" as the relative proportion of iron in the Galaxy increases. Since type Ia supernovae (SNe) are the primary source of iron, astronomers believe that the "knee" occurred about one billion years after the Galaxy began to form *(see Figure 4)*. The halo stars *(red line)* and some of the thick-disk stars *(green line)* tend to occupy the "plateau," whereas thin-disk stars *(blue line)* occupy the descending slope. These observations suggest that the halo, and part of the thick disk were formed in the first billion years of the Galaxy's evolution, and the think disk formed later.

Median Ages of Stars vs Location in MW

- LAMOST Data- detailed parameterization of median ages vs galactic coordinates and locaiton in galaxy Xiang et al 2017



7. Distribution of median stellar ages in Galactic co
m (l, b). The data are divided into patches of 1.5° ×
ie map.



Wide spread in median ages, disk young bulge old

What Do We Learn About the History of the MW??

LAMOST data confirm that

- The median stellar age increases with Z and decreases with R,
  - stellar age, [Fe/H] ([α/H]) and [α/Fe] are correlated- clues to the chemical formation history .
- metal-poor, α-enhanced stars are generally older than metal-rich, α-poor stars (stars whose chemical abundance is dominated by products of type IIs)- but big scatter
- thin disk developed ~ 8–10Gyr ago, while the thick disk has different chemical composition, formed earlier and stopped forming stars (quenched) 8Gyr ago.
- Stellar ages exhibit positive vertical and negative radial gradients across the disk,

Age Metallicity

- Older stars **tend** to be metal poor: only in the MW and local group 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;

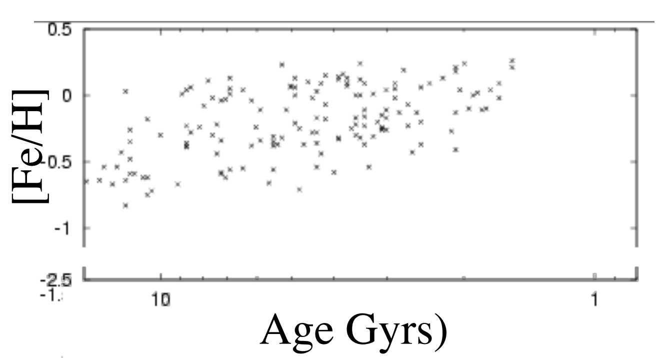
–galaxy is not a closed box, gas flows in and out

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

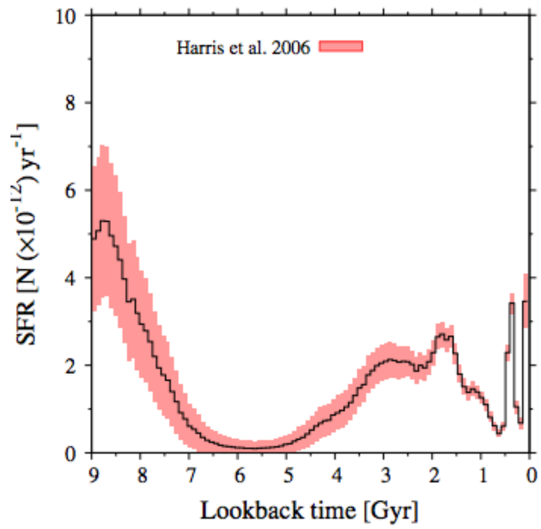
–star formation rate is not constant



Huge scatter- see http://arxiv.org/pdf/1308.5744.pdf
8.2Gyr old sun like star with Fe/H= -0.013 ± 0.004 and a solar abundance pattern

SFR In Solar Neighborhood

- By modeling the white dwarf age/ density distribution one can estimate the SFR rate 'nearby' (Rowell 2012)
- Notice that it is non-monotonic
- We will later compare this to the overall rate of SF of the universe and find significant differences



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 undergone a major merger MW has not)

- *Lesson: MW may not be representative of spirals*

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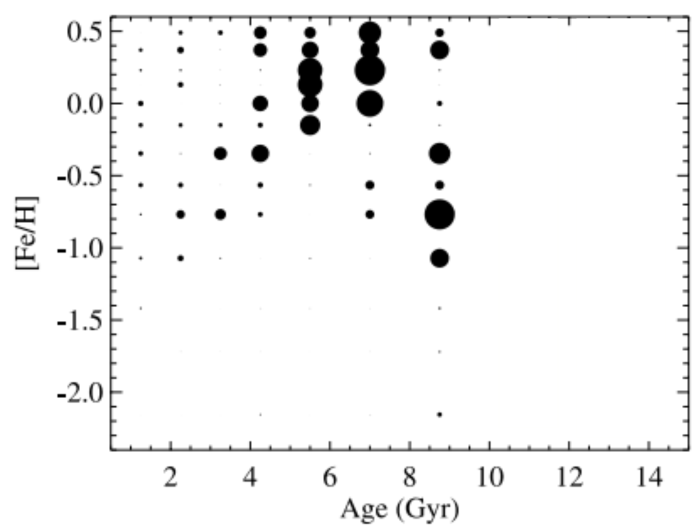

Size of symbol is ~ # of stars in box; Brown et al 2006