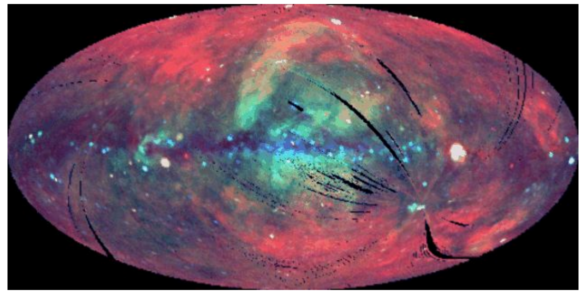
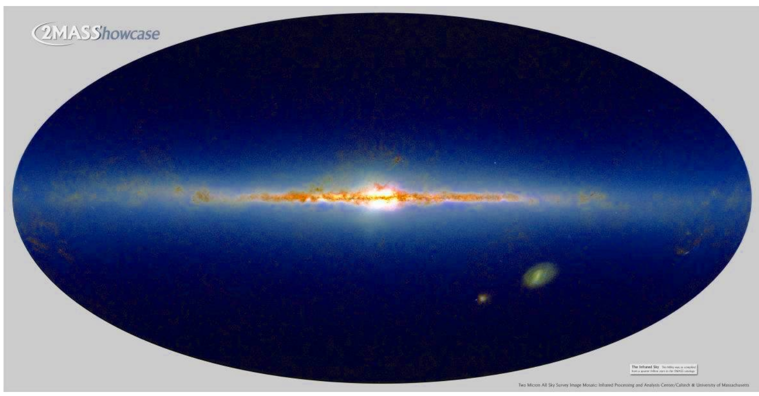
Milky Way S&G Ch 2

- **Why study the MW?**
  - its "easy" to study: 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

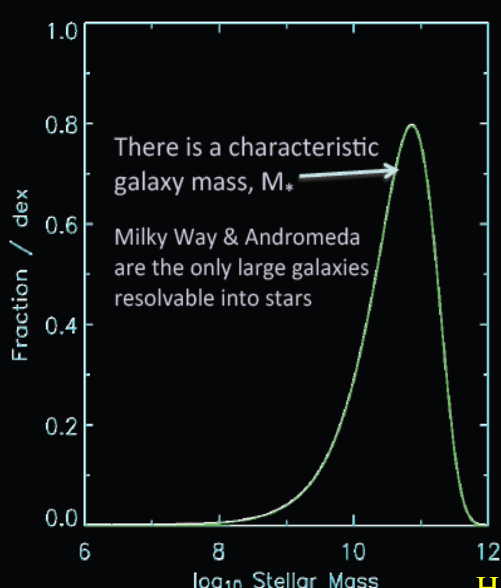


Milky Way in X-rays- Image of the Hot ISM



Milky Way in near IR
www.milkywaproject.org

Why might the Milky Way be a good test-bed for galaxy formation?



- The Milky Way is an unusually typical galaxy
  - $6x10^{10}M_{Sun}$ in stars, ¾ in a disk

[redacted]

- It's what we got (best)
  - star-by-star in 6+N dimensions

  $p(\boldsymbol{r},\boldsymbol{v}, M_*, L_*, \log g, T_{eff}, t_{age}, [X/H]...)$

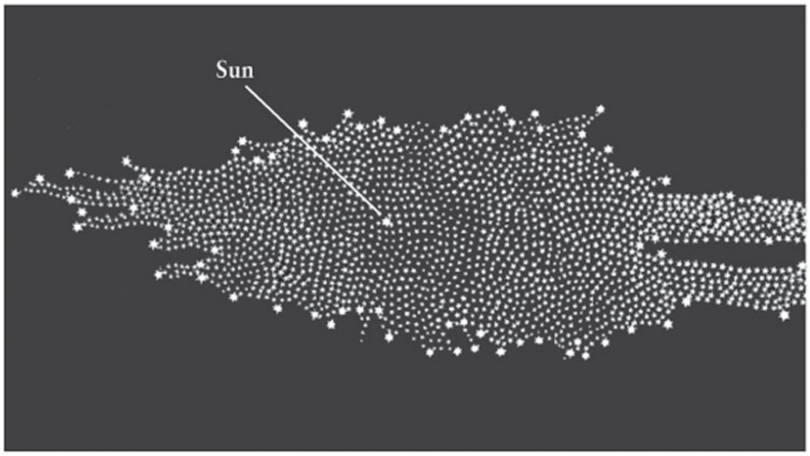
H-W Rix-
http://online.kitp.ucsb.edu/online/galarcheo-c15/rix/

What aspects of (disk) galaxy formation can be uniquely tested/inferred in the Milky Way?

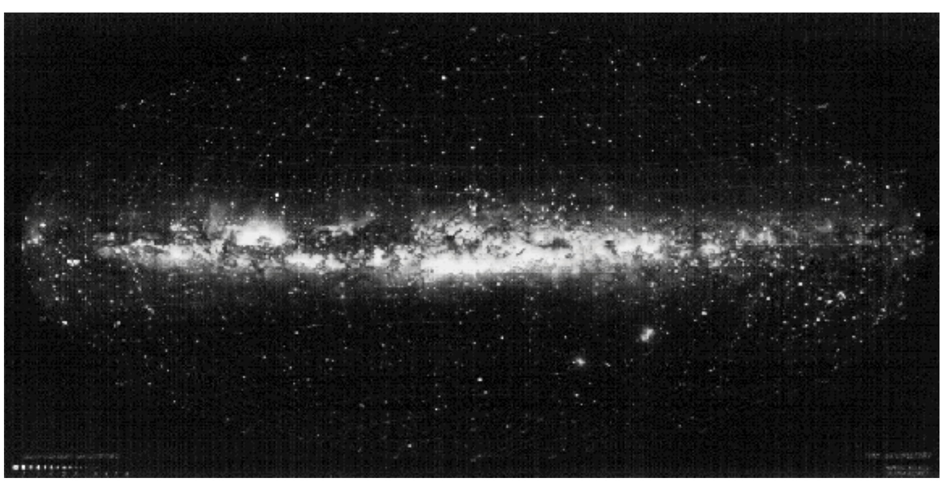
- 3D distribution of the (dark) matter
- What processes create a stellar halo?
  - What processes shape the population of satellite galaxies?
- What (init) conditions & processes set stellar disk structure?
- What processes shape the "innards" (bulge, bar, etc..)?
- How does chemical enrichment "work"?
  - How does gas inflow/accretion & feedback work?
  - Is primeval IMF dramatically different?

Our place in the Galaxy

- We live in a large disk galaxy of average mass
  - The sun is in the disk, towards the edge (~8kpc 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 for absorption by dust! *(something that he did not know about)*



Herschel's map of the Galaxy

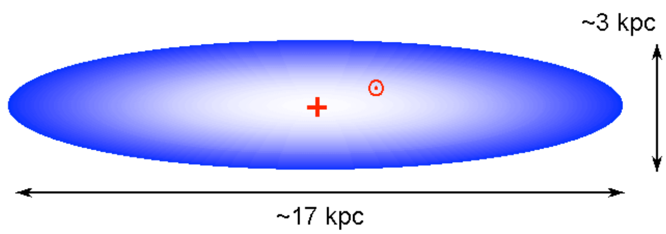


MilkyWay in optical light

Kapteyn (1920's)- photographic star counts and estimated distances using parallaxes and examining the proper motion of nearby stars. Found MW ~ 33,000 light years x 6,500 light years and that the Sun was around 2,000 light years from the center of the galaxy. (present values- 80,000 light years x 2,000 light years in size and that the Sun is 25,000 light years from the center of the galaxy)

Kapteyn deduced that we were very nearly at MW center

Kapteyn Model (1922)



kpc = kiloparsec = 1000 pc

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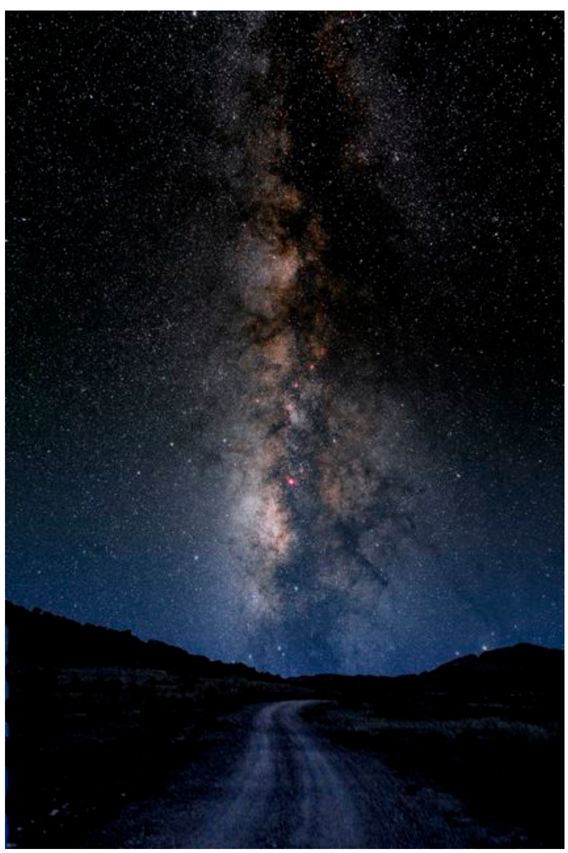

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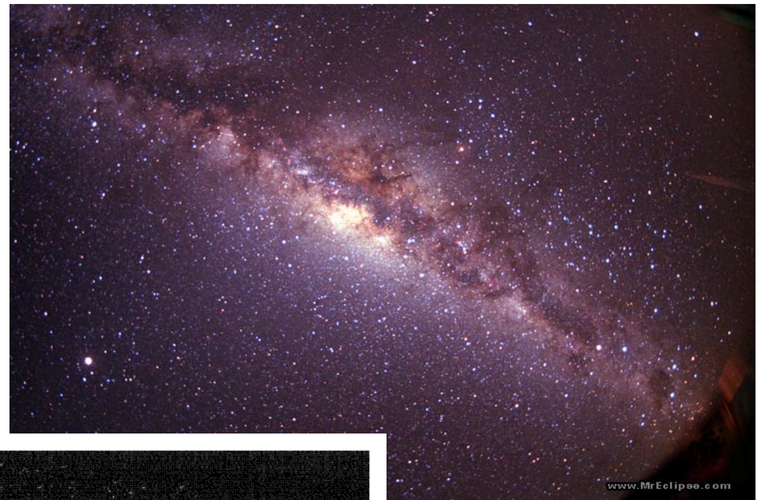
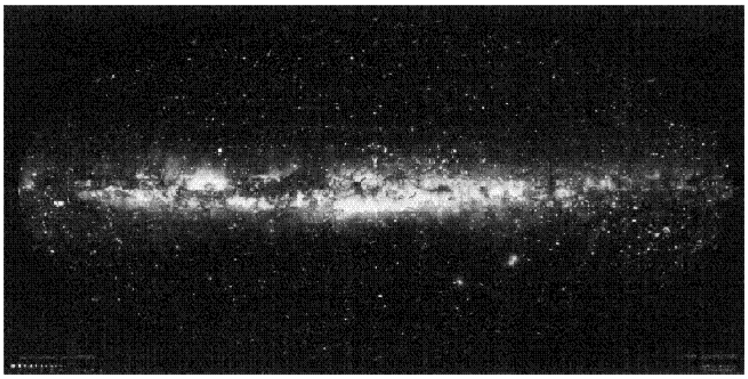
MW in Optical

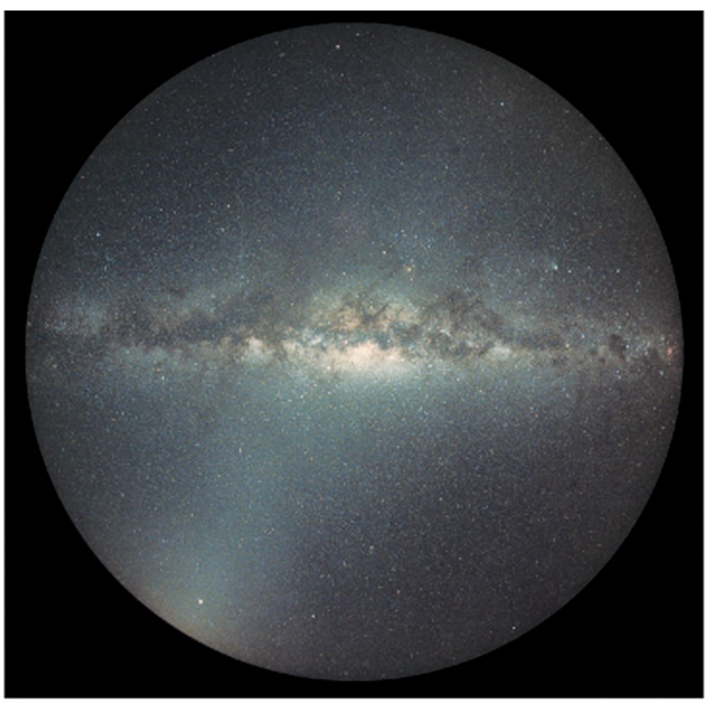
- Notice the strong effect of dust.





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

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



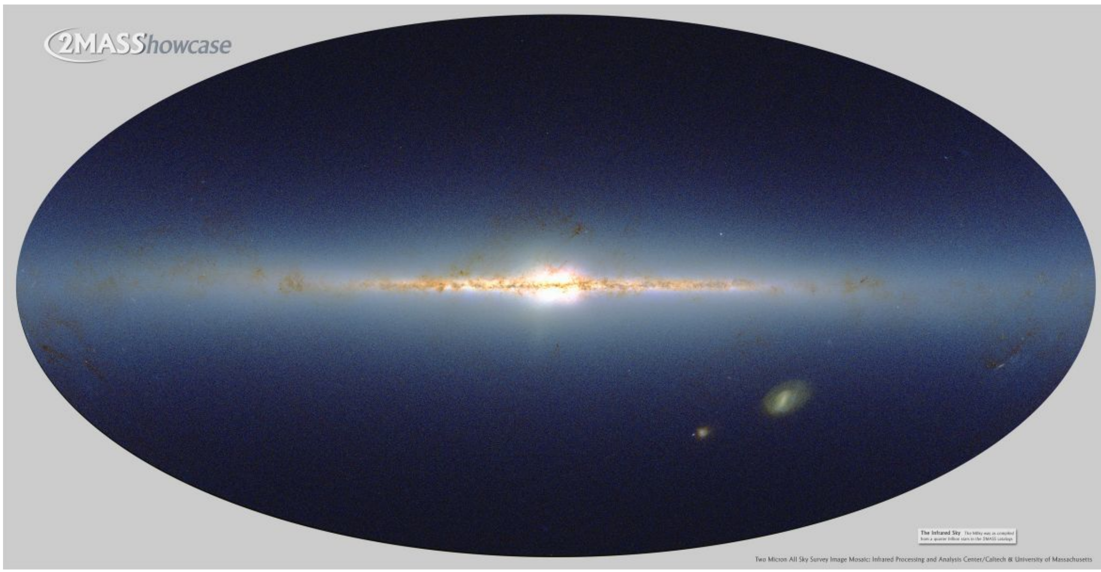
View out of the plane of our Galaxy

View within the plane of our Galaxy

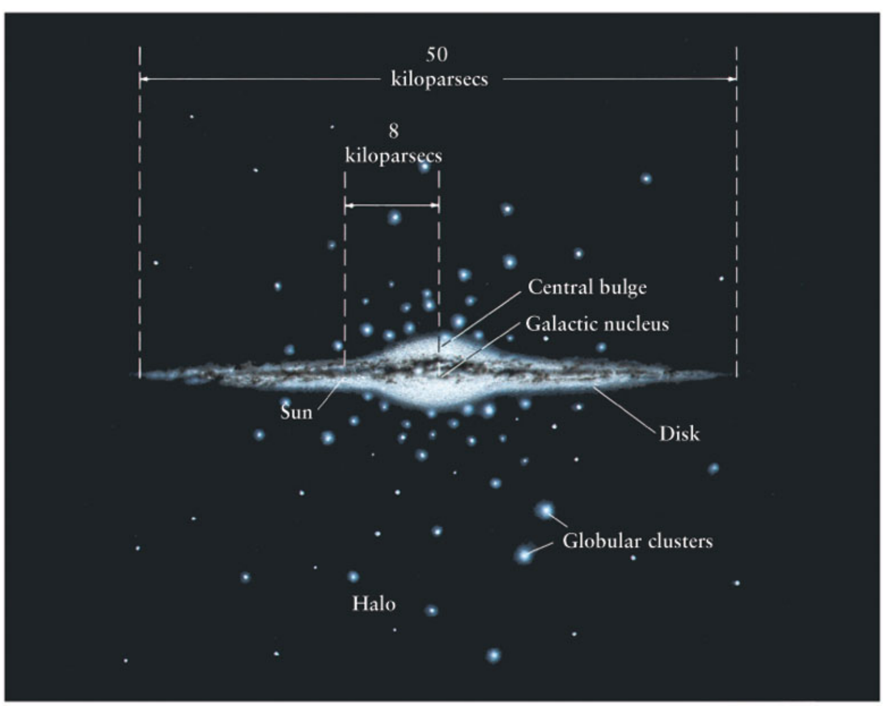
View out of the plane of our Galaxy

(b)

Galactic coordinates (l,b), Galactic center at (0,0) S&G 1.2.2

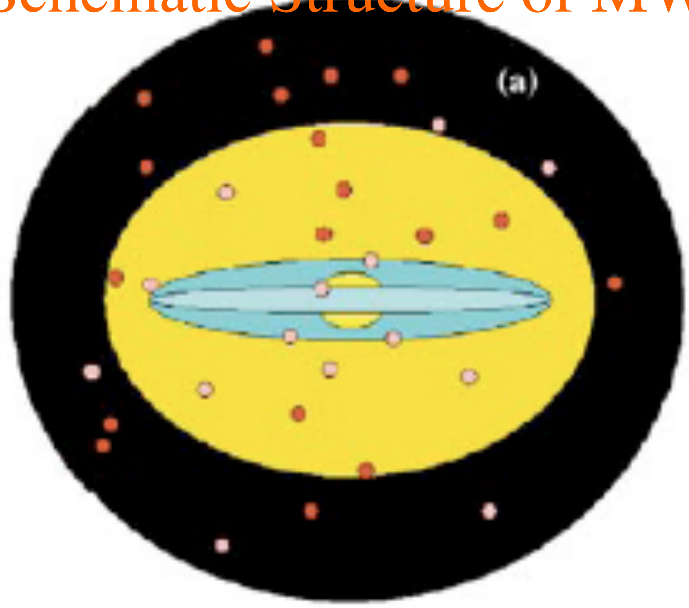


The MW galaxy as seen by an infrared telescope- IR light is much less sensitive to 'extinction' by dust than optical light



1 kiloparsec=3.26x10^3 lightyears=3.08x10^{19}m

Schematic Structure of MW

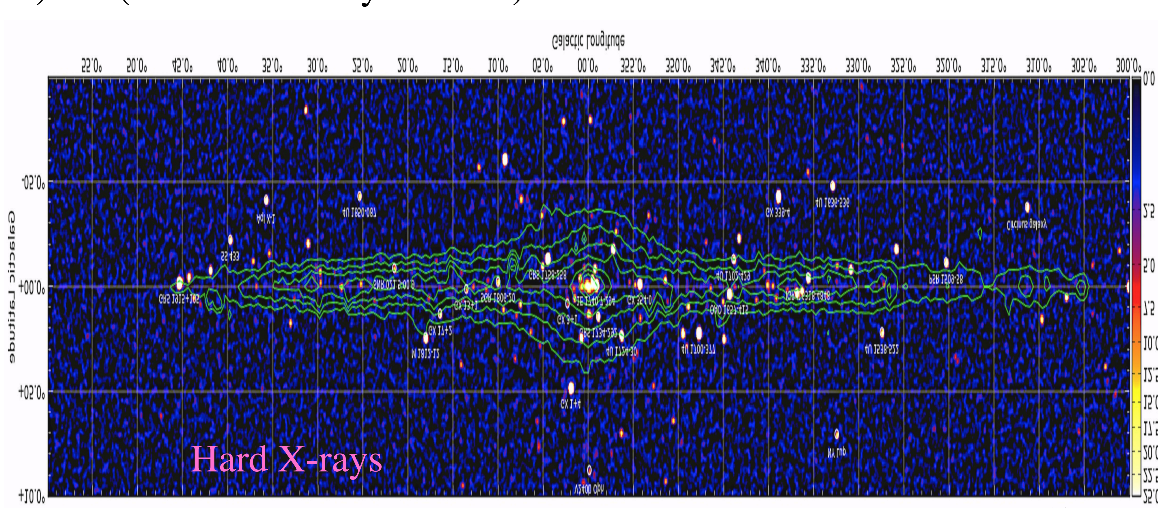


stellar disk (*light blue*), thick disk (*dark blue*), stellar bulge (*yellow*), stellar halo (*mustard yellow*), dark halo (*black*) and globular cluster system (*filled circles*). (Freeman and Bland-Hawthorn 2002)

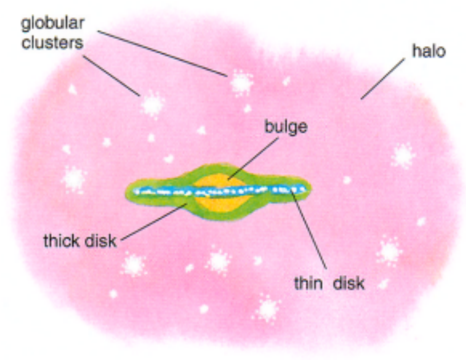
Other Wavelengths

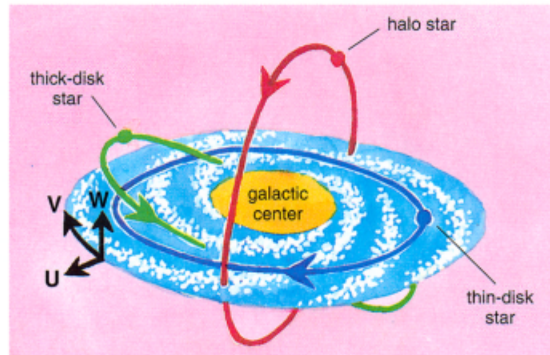
In 'hard' (2-10 kev) x-rays one sees
accreting x-ray binaries neutron stars and black holes
- 2 Populations, companions

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



Schematic Image and Dynamics of MW



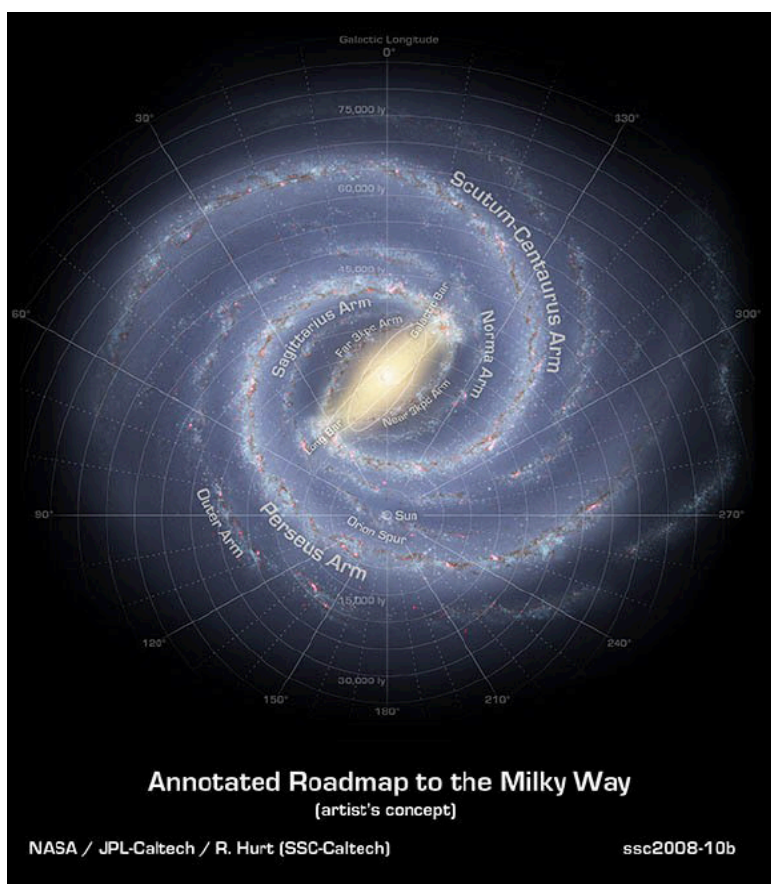


Cristina Chiappini

- 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



Components of MW Disk

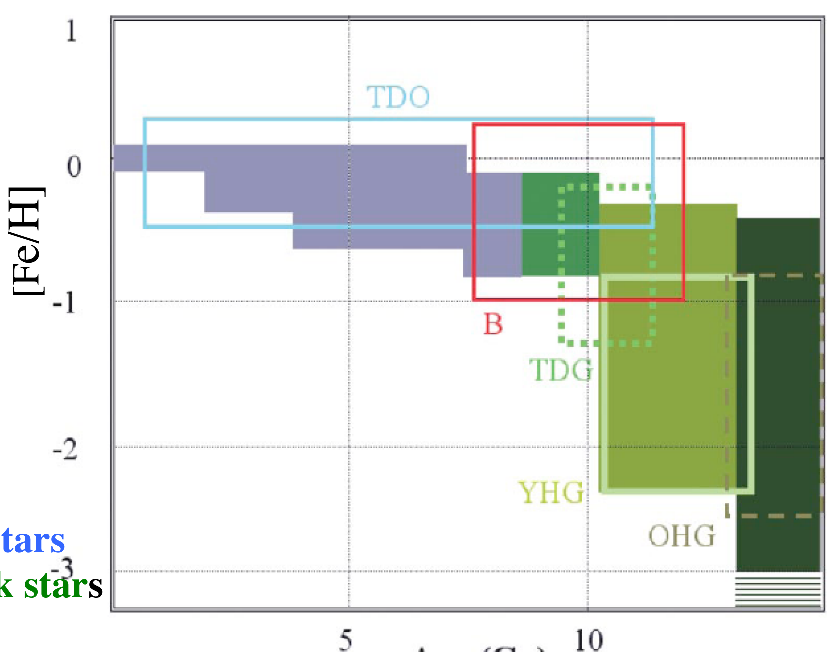
- The positions, velocities, chemical abundances, and ages of MW stars are very strongly and systematically correlated
  - For example in the disk:
    - younger and/or more metal-rich stars tend to be on more nearly circular orbits with lower velocity dispersions.
- Subcomponents of the Disk can be defined on the basis of the spatial distribution, kinematics, or chemical abundances.
- Disk components
  - dominant thin disk
  - a thick disk

can be defined spatially, kinematically, or chemically

Components of MW Disk

- The age-metallicity relation of the Galaxy for the different components

Freeman and Bland-Hawthorn

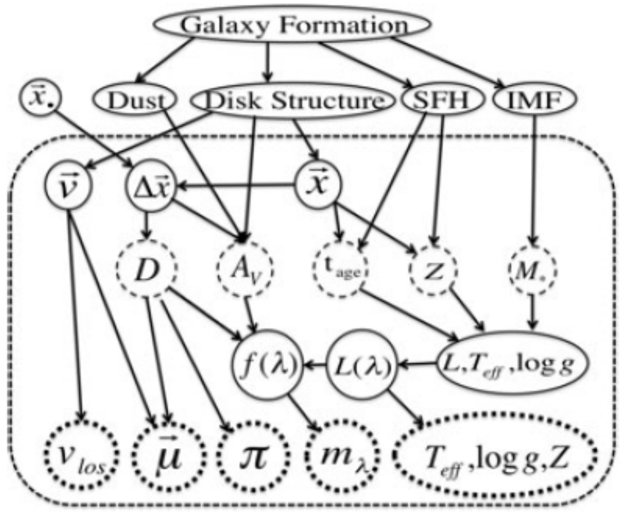


AGE (Gyrs)

blue= thin disk stars
green =thick disk stars
B= bulge stars
black= halo stars

Observables and What we Want to Learn

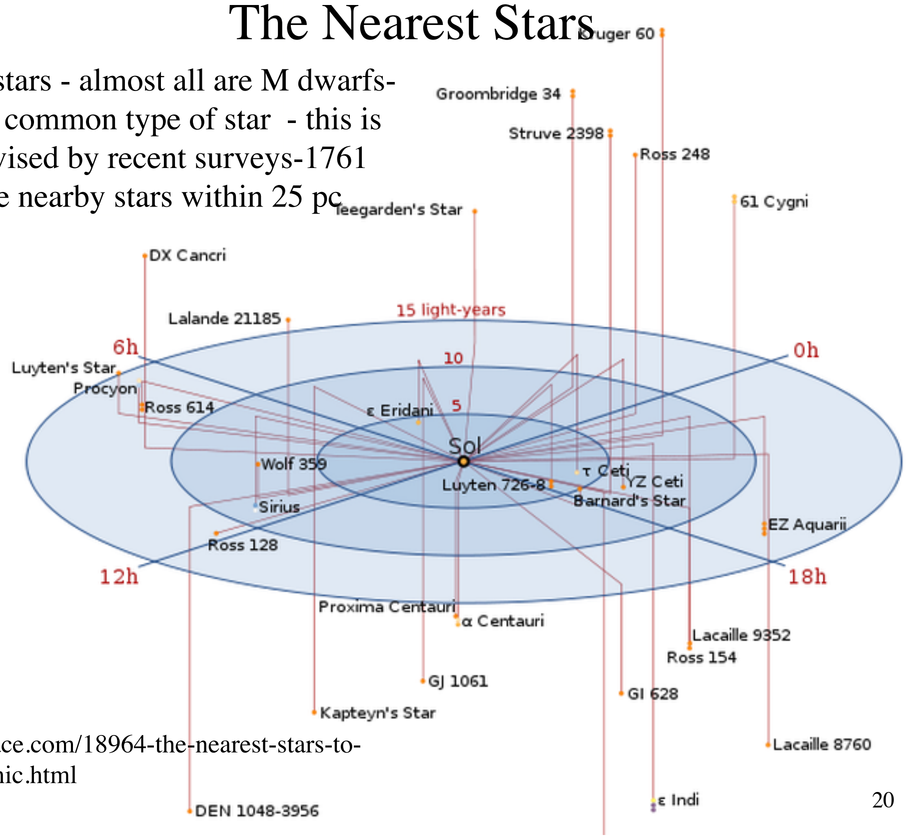
- Observables and desired information (solid ellipses)
- Observables:
  line-of-sight-velocity, v_{los}, proper motions, $\boldsymbol{\mu}$, parallax π, multi-band photometry m_λ, and stellar parameters derived from spectra (T_{eff}, log g, abundances, Z); most of them depend on the Sun's position x , $\Delta\boldsymbol{x}$.
- Desired information is
  stellar masses M, age t_{age} and abundances Z, distance D from the Sun and the (dust) extinction along the line of sight, A_V .



Rix and Bovy 2013

The Nearest Stars

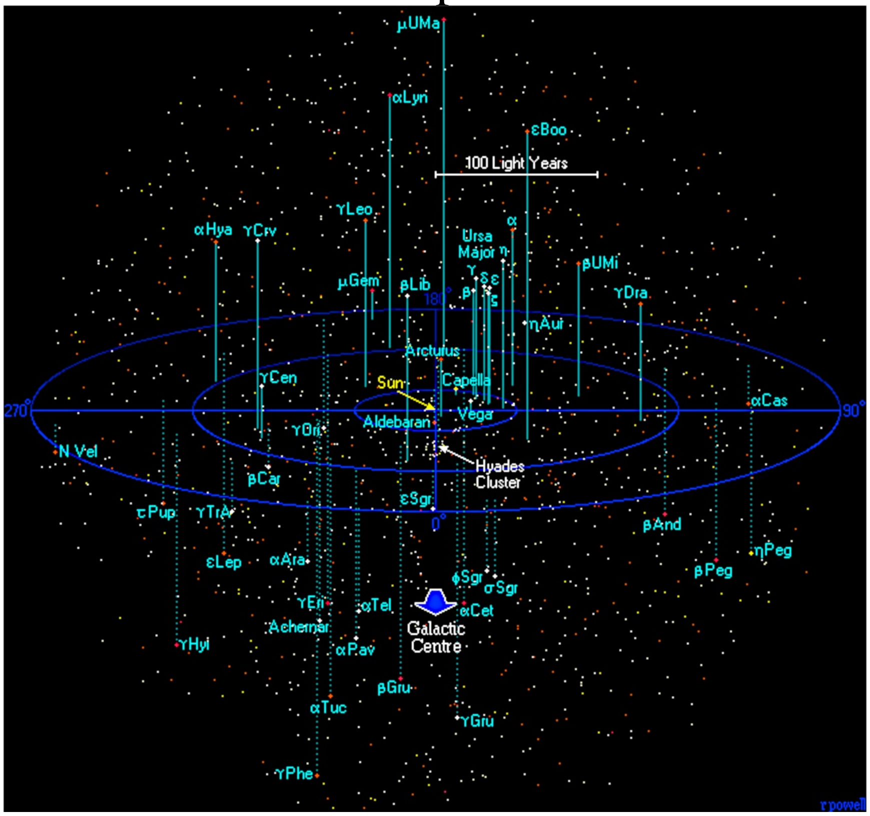
- Nearest stars - almost all are M dwarfs- the most common type of star - this is being revised by recent surveys-1761 candidate nearby stars within 25 pc



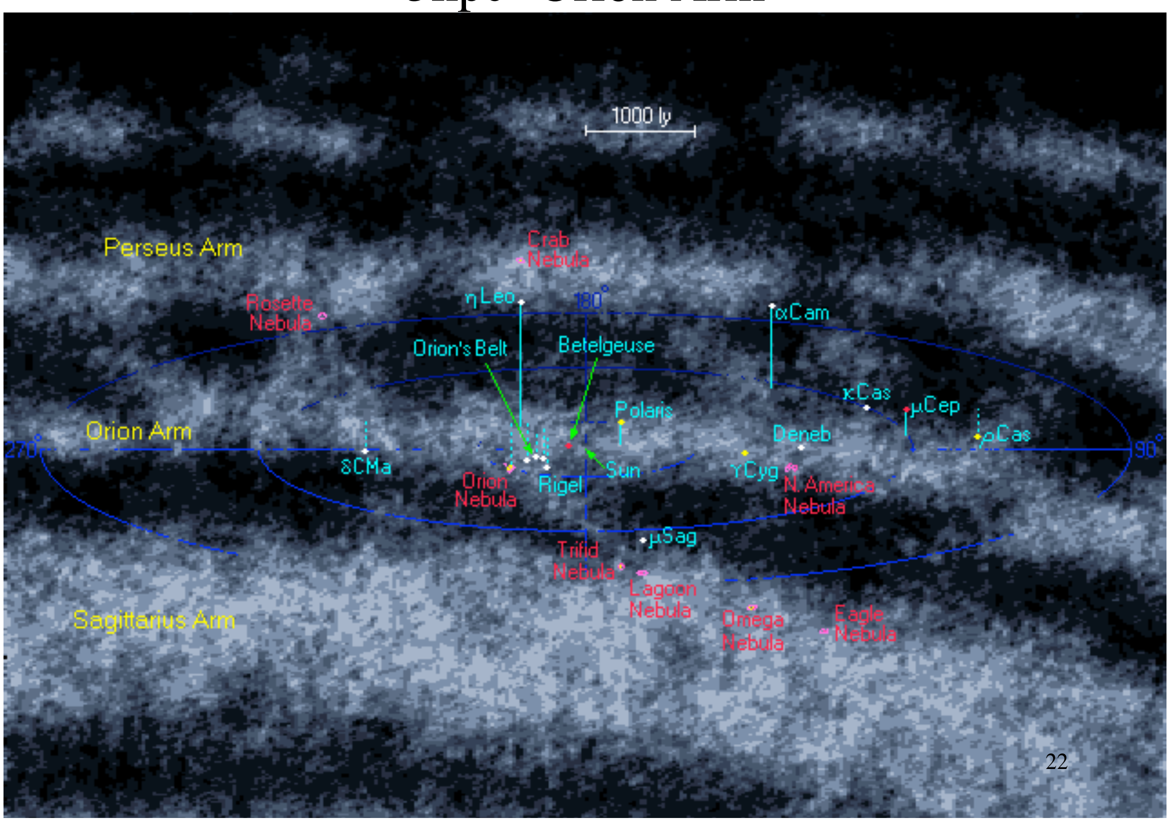
http://www.space.com/18964-the-nearest-stars-to-earth-infographic.html

Stars Within 250pc

- This is a small subset of the stars
- Volume limited sample dominated by low mass red dwarfs

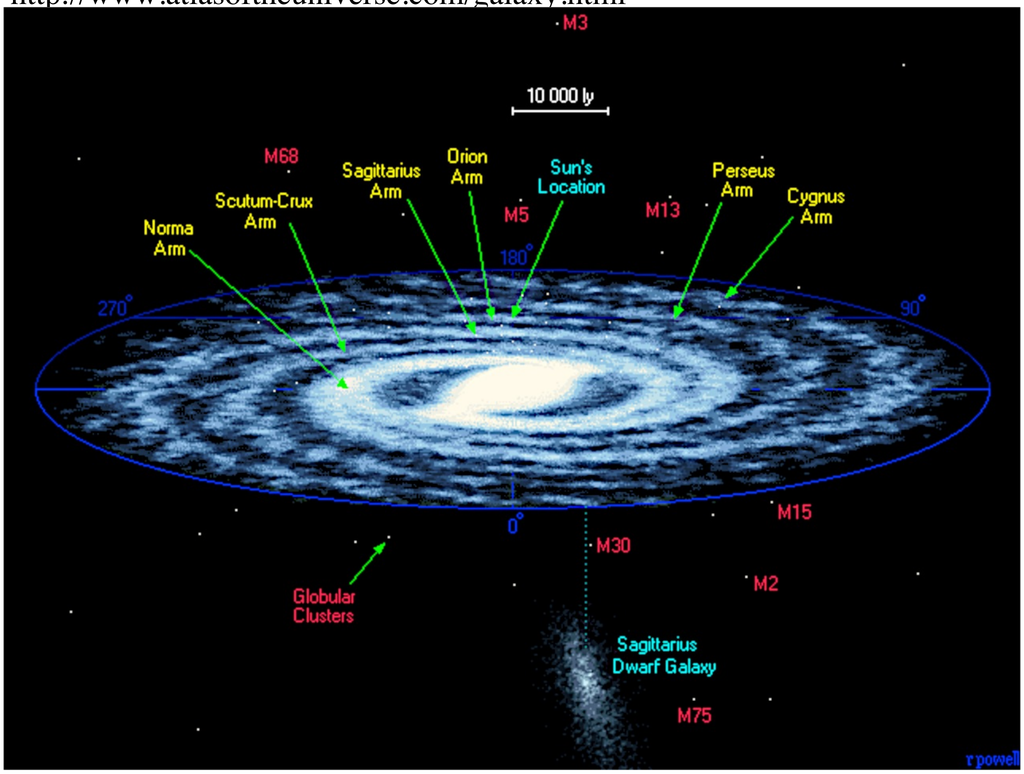


5kpc- Orion Arm



The MW

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

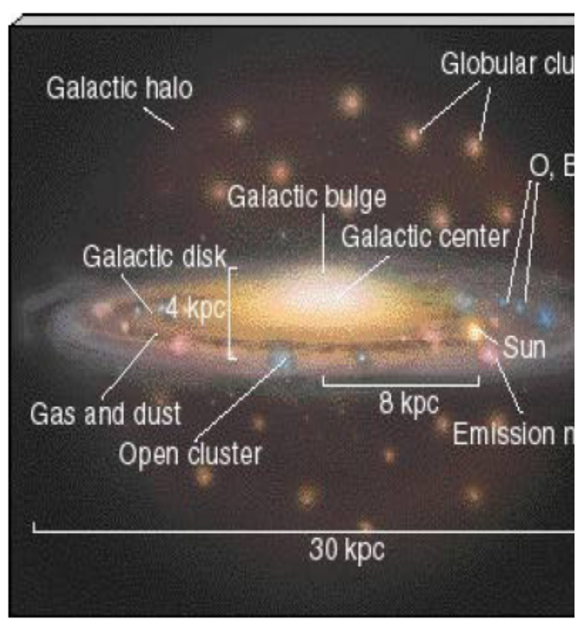


Basic Structure of Milky Way

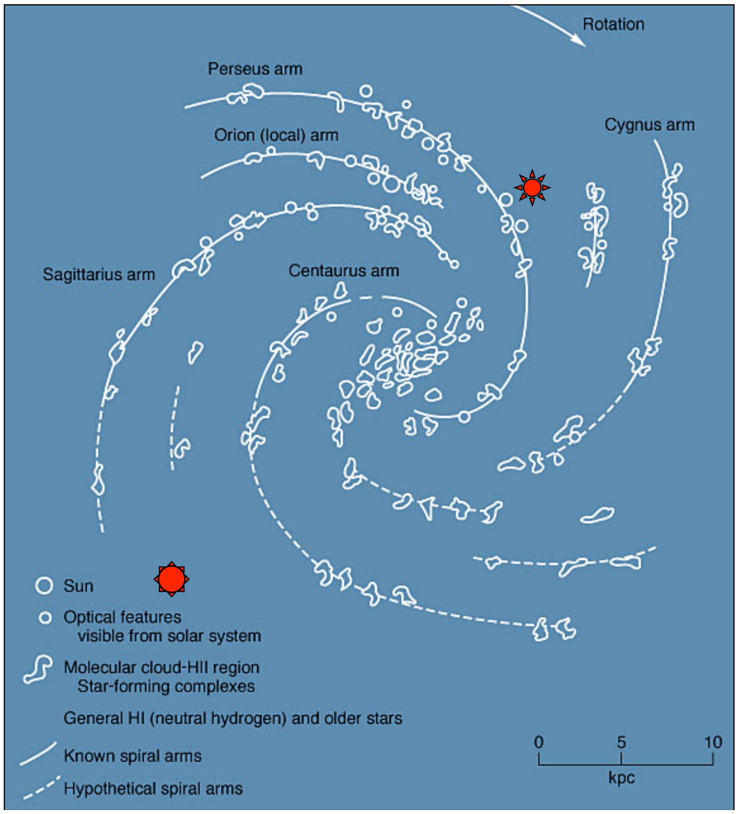
Bulge is quite spherical and is dominated by old stars

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



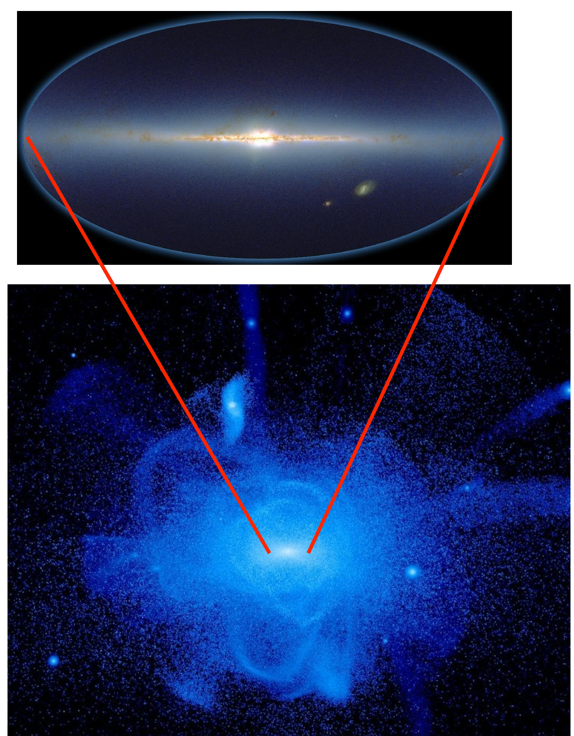
Map of the Milky Way Galaxy



map made from 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 can we determine the 3-D distribution of velocities and positions to constrain such models in DETAIL (galactic archeology)-http://science.sciencemag.org/content/338/6105/333.full
- 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

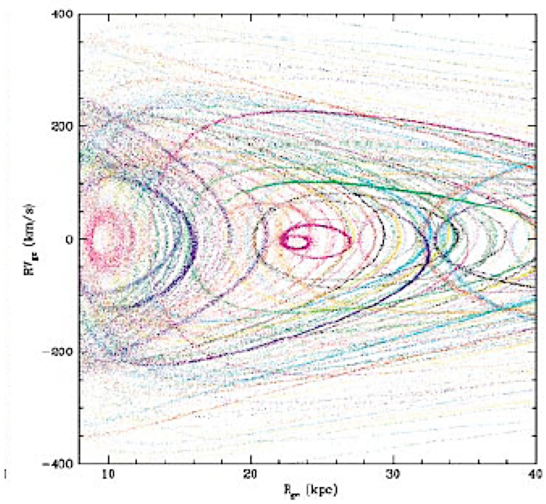


H. Rix

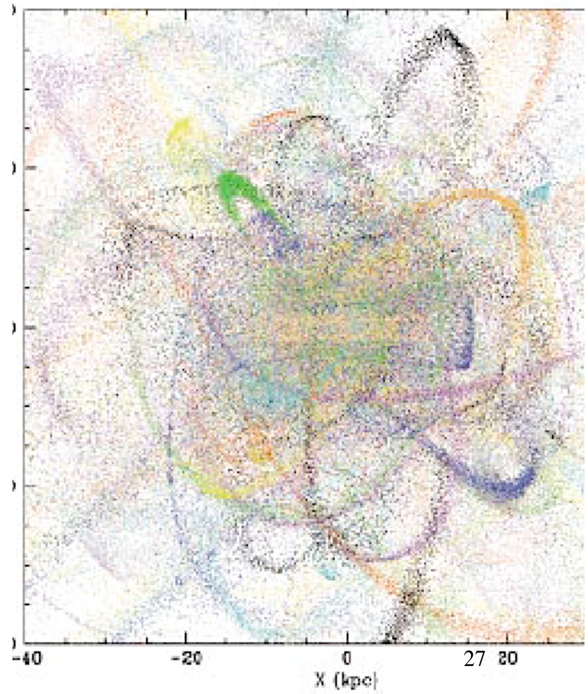
Theorists View- Continued

- Each merged galaxy is a separate color (Freeman and Bland-Hawthorn)

position of stars in x,z plane



radial velocity vs orbital radius



Simplified View of Streams

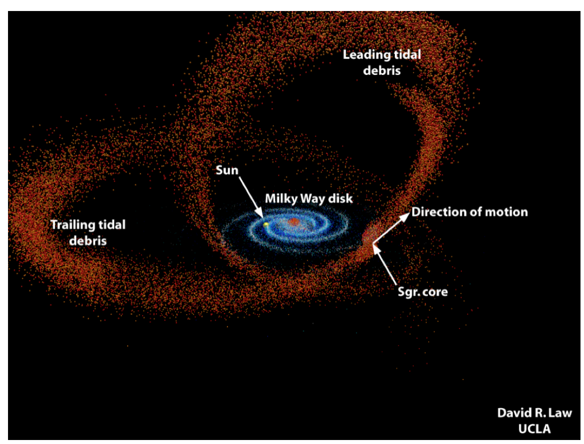
- galactic haloes are threaded with the remains of dwarf satellites and globular clusters that have been destroyed by the tides of their host's gravitational potential.

These tidally disrupted stars may make a significant fraction of the halo

- these dynamical tracers can provide constraints on the mass distribution of the baryonic and dark matter components of the Milky Way

- Tidal disruption radius (S&G 4.1.4)

dwarf has mass m and radius r, MW mass M and separation between the 2 is R - consider the dwarfs gravitational binding force Gm^2/r^2

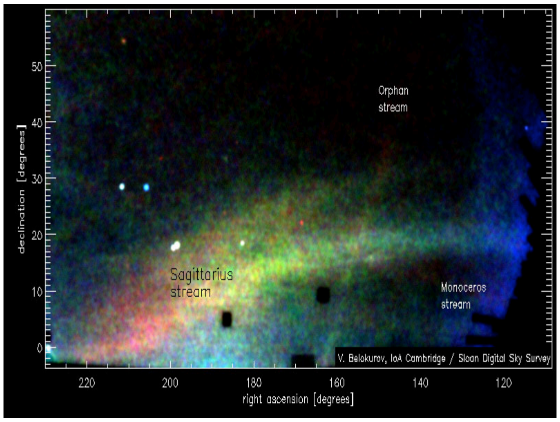


Disrupting force due to MW is $(GMm/2)[(1/(R-r)^2 - 1/(R+r)^2)]$; when $r<<R$ this is $\sim GMmR/r^3$

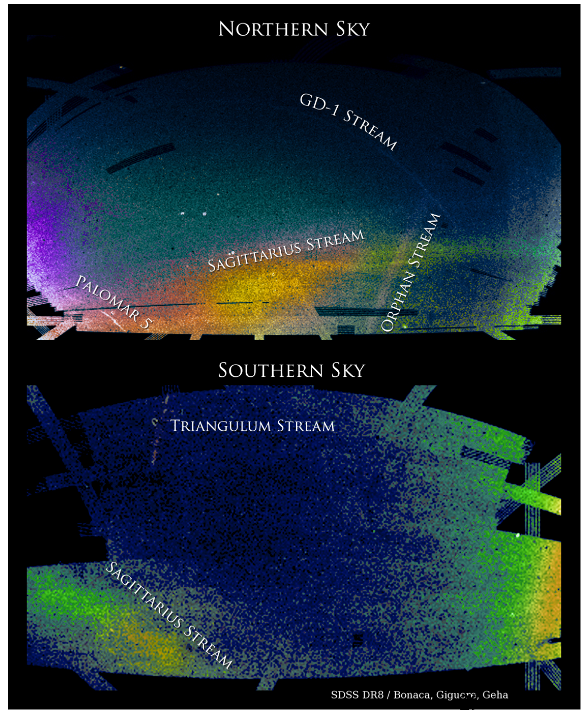
2 are equal when $\mathbf{r \sim R(m/kM)^{1/3}}$

k depends on structure of object

See B&T sec 8.3 or Roche limit

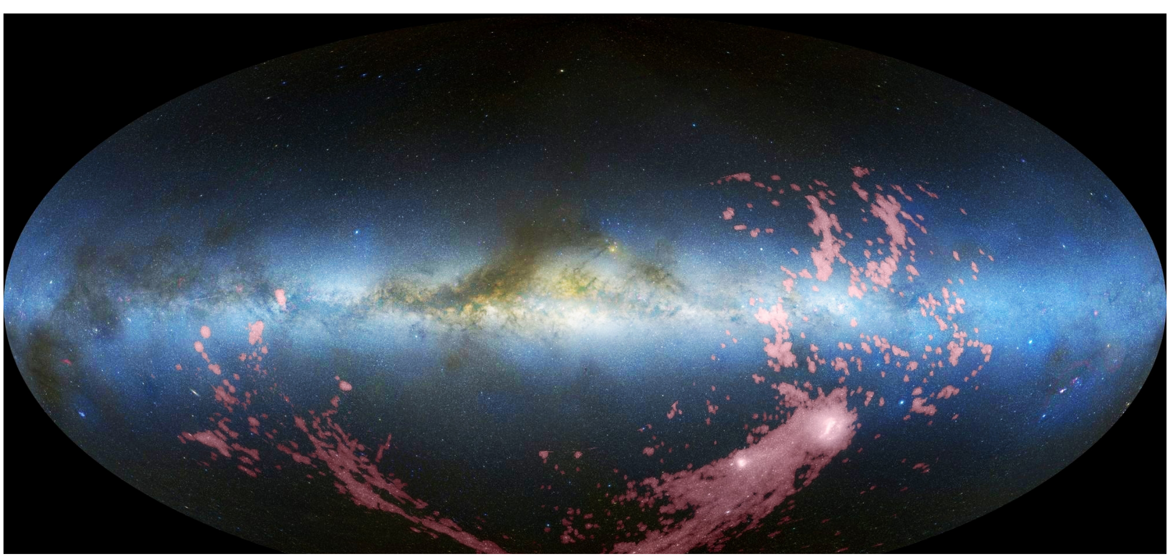


Streams in the MW



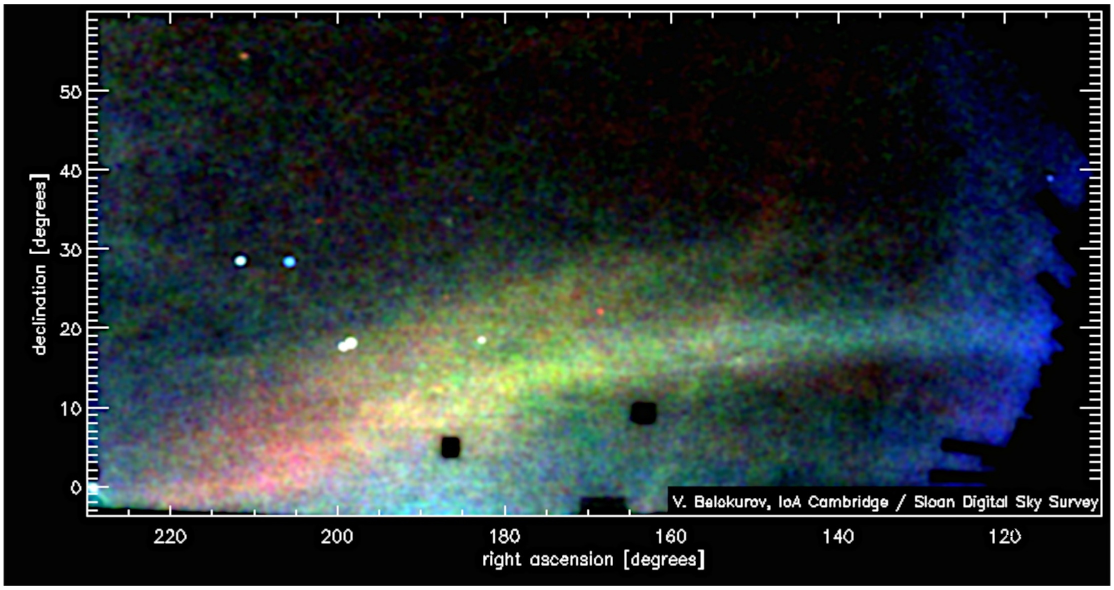
- map of stars in the outer regions of the Milky Way (1/4 of sky). The trails and streams that cross the image are stars torn from disrupted Milky Way satellites. The color corresponds to distance, with red being the most distant and **blue being the closest**. The large, forked feature is the Sagittarius 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)

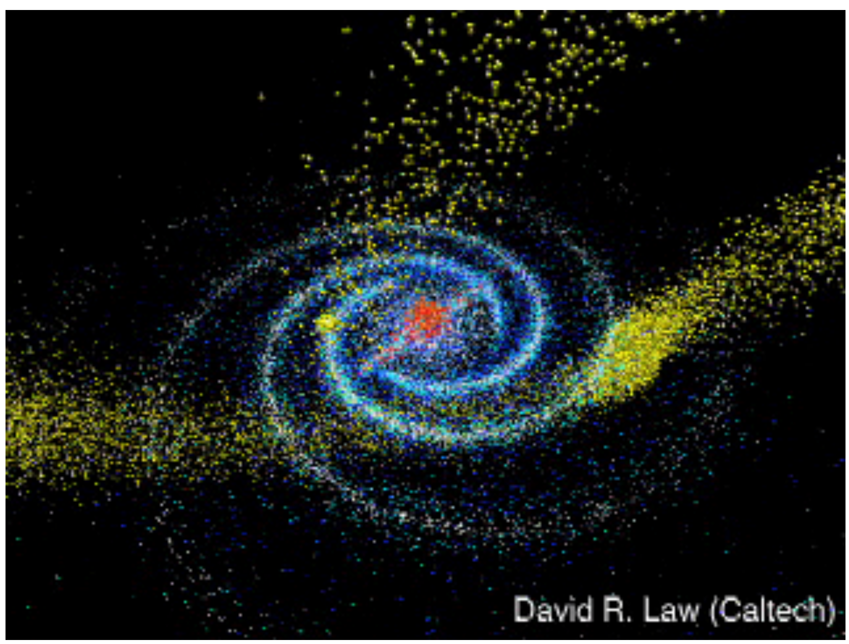


Stellar halo : fossil record of assembly?

- 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)



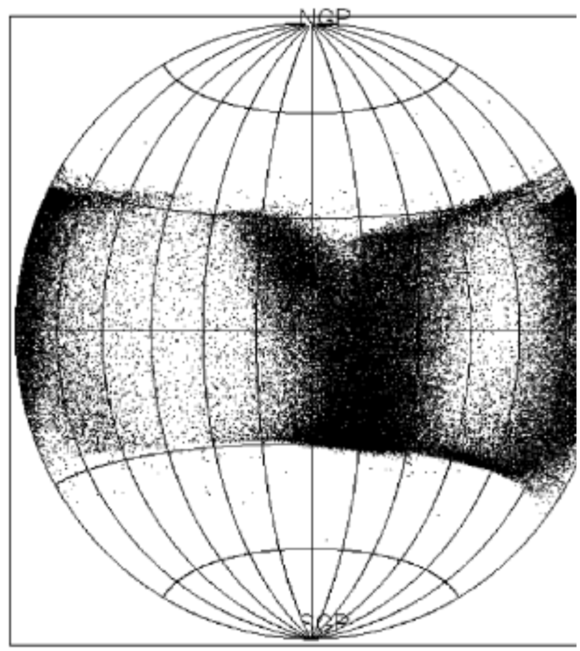
- Milky Way Galaxy (blue/white points and orange bulge) with the Sun (yellow sphere), inner and outer Sgr stream models (yellow/red points respectively), Monoceros tidal stream model(violet points), and observed Triangulum-Andromeda structure (green points).



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

What Happens to Disrupted Satellite

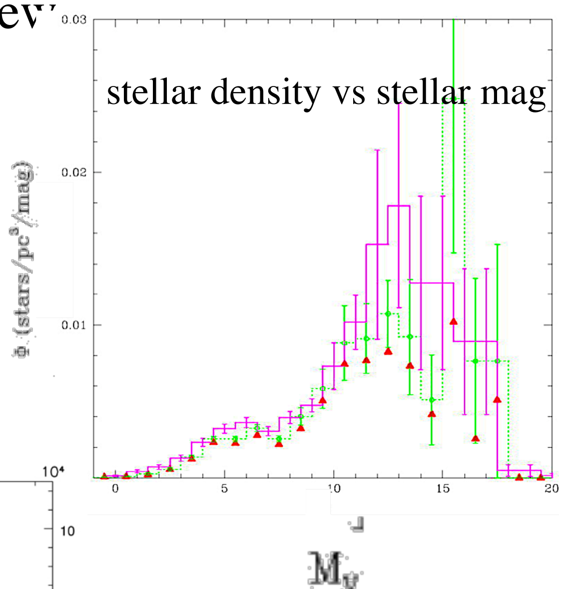
- One realization of how the stars from a disrupted satellite would appear 8Gyrs after the merger.



9 A satellite in orbit about the Milky Way as it would appear
stars from the disrupted satellite appear to be dispersed over a very
, it will be possible to deduce the parameters of the original event us
ques (see text). (We acknowledge A. Helmi and S. White for this im

Luminosity and Mass Function (S&G 2.1.2)- Review

- 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
- $\phi(x)$ = number of stars with $[M_V - 1/2 < x < M_V + ½]$/volume $V_{max}(MV)$ over which these could be seen (e.q. 2.3)
- .



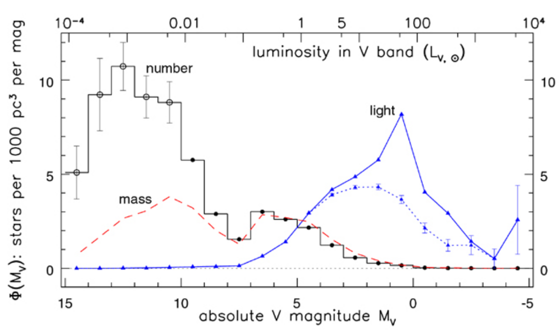
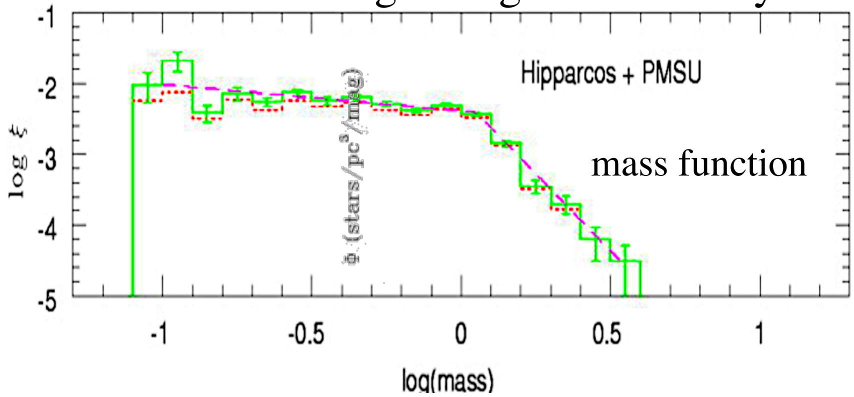


Fig 2.3 'Galaxies in the Universe' Sparke/Gallagher CUP 2007

Luminosity and Mass Function

Gaia launched 12/2013 will change things dramatically



for all objects brighter than 15mag Gaia will measure their positions to an accuracy of 24 μ arc sec as well as their brightness
the nearest stars will have their distances determined to 0.001%.
stars near the Galactic center will have their distances measured to within an accuracy of 20%.

Star Counts

- We wish to determine the structure of the MW
- Define 2 functions
  - A(m,l,b): # of stars at an **apparent mag m**, at galactic coordinates l,b per sq degree per unit mag.
  - N(m,l,b): cumulative # of stars with mag **< m**, at galactic coordinates l,b per sq degree per unit mag.
- Then clearly dN(m,l,b)/dm=A(m,l,b)
  - or N(m,l,b)=∫A(m',l,b) dm

Star Counts

- Simplest galaxy model : uniform and infinite

if ρ_*= density of stars and Ω= solid angle of the field, the volume of a shell at distance r is $\Omega r^2 dr$ and the number of stars is

$N(r)=\int_0^R \Omega r^2 \rho_* dr= 1/3\Omega R^3 \rho_*$

- Now if all the stars have the same luminosity (e.g. absolute magnitude) M and utilize (from the definition of absolute mag

  $m-M=5\log r-5$

- (e.g. $r=10^{(0.2(m-M)+1)}$ pc) then $dr=(0.2)(\ln 10)10^{(0.2(m-M)+1}dm$
- and thus $N(m)=\int_{-\infty}^m \Omega\rho_*=(0.2)(\ln 10)(10^{(0.2(m-M)+1})^3dm$

  oh the pain of magnitudes

Star Counts

- $N(m)= \int_{-\infty}^m \Omega\rho_*=(0.2x10^3)(\ln 10)\int_{-\infty}^m (10^{(0.6(m-M))})dm'$

  or (finally)

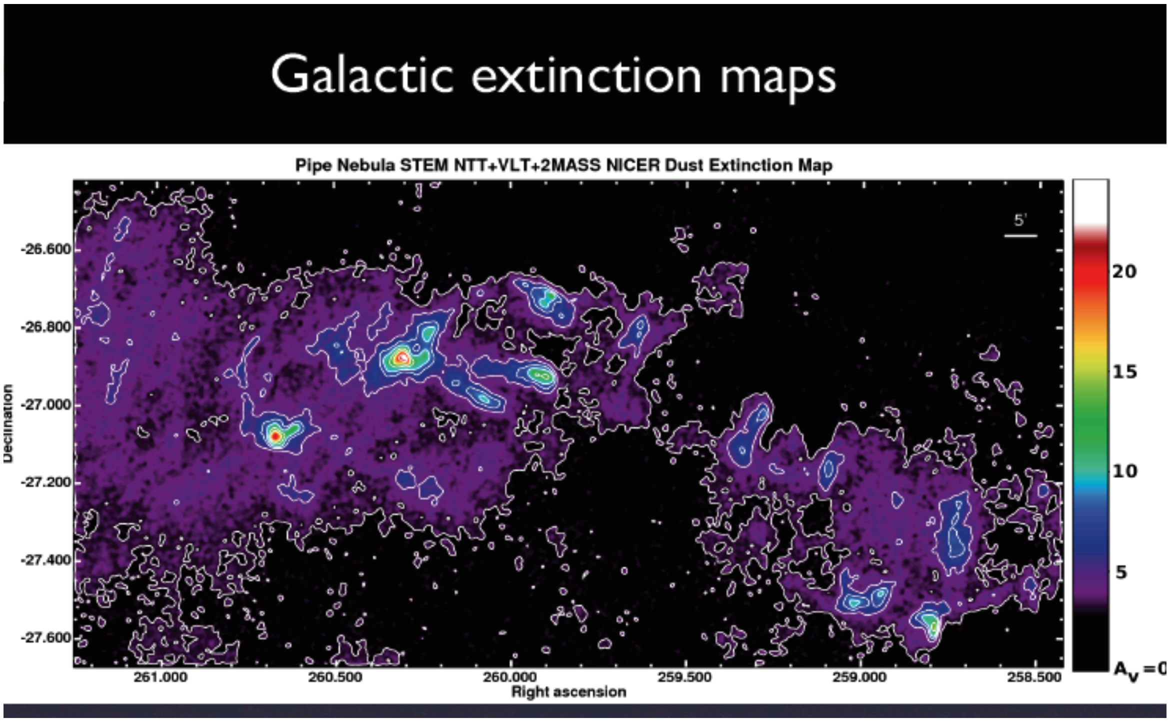
- $N(m)= 333\Omega\rho_*\ 10^{(0.6(m-M))}$

- ***This is not what is observed***
  - finite size of disk (not sphere)
  - effects of dust

- Olbers paradox: if galaxy (universe) was infinite the total light would diverge

- Goal is to find the true space density of stars as a function of distance, galactic coordinates, luminosity, spectral time, age, metallicity etc
- Luminosity function of stars f(m,etc)

Need to Measure Extinction Accurately



Luminosity Function S&G 2.1.2

- Simplest form f(m)=# of stars per unit volume with luminosity (absolute mag) between M and M+dm
- Observationally it is a time dependent quantity (since stars evolve and are born and die and since stellar ages are function of mass)
  - thus the luminosity function, while an observable, has to be carefully defined.
- Observational issues
  - incompleteness due to flux limited samples in a given bandpass,
  - uncertainty in distances (need to transform from observed flux to true luminosity)
  - effects of dust
  - need a large volume (high luminosity stars are very rare)
- Many of these problems were overcome by Hipparchos (large number of parallax distances) and near IR surveys (relatively free from effects of dust);
  - major advance expected with launch of GAIA in Dec 2013

IMF of MW Stars (S&G 2.1.2)

Determining the IMF is tricky, 4 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. A clean measurement, but the statistics are poor.
- Use field stars in the solar neighborhood whose distances are known. statistics are much better, but can only use this technique for low mass stars, few massive stars in local volume and numbers controlled by star formation history
- get limits on the IMF from the integrated light and colors of stellar populations
- Build yourself an experiment (APOGEE) or a satellite (GAIA) that can measure the distances to lots of stars and obtain their spectra

Despite these problems most results show that the IMF is very similar from place to place

The Form of the IMF Ξ(m) - Kroupa 2002

Thus $\Xi(m) = -\Psi(M_P)(dm/dM_P)^{-1}$

$\Psi(M_P)$ is the stellar luminosity function (LF).

to determine the IMF need to consider stars that have evolved off the main sequence.

Defining t= 0 to be the time when the system that now has an age $t=\tau_G$ formed, the number of stars per pc^3 in the mass interval m, m+dm that form in the time interval t, t+dt is

$$(1/\tau_G)\int_0^{\tau_G} b(t)\,dt = 1.$$

$dN=\xi(m, t)dm\times b(t)dt$

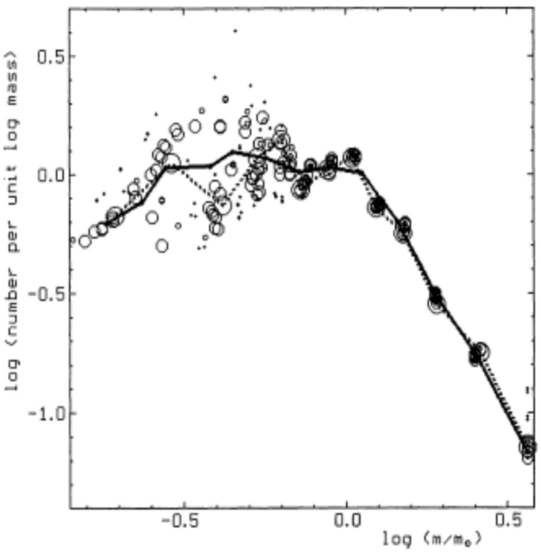
b(t) is the time-modulation of the IMF- e.g. due to star formation

$$\Xi(m) = \xi(m)\frac{1}{\tau_G}\begin{cases}\int_{\tau_G-\tau(m)}^{\tau_G} b(t)dt & , \quad \tau(m) < \tau_G, \\ \int_0^{\tau_G} b(t)\,dt & , \quad \tau(m) \geq \tau_G,\end{cases}$$

Luminosity and Mass Function

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

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



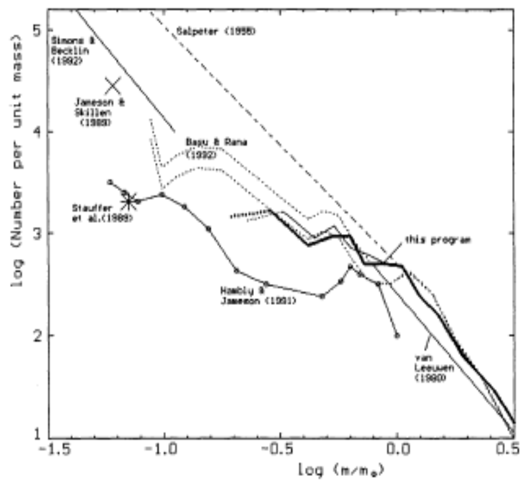
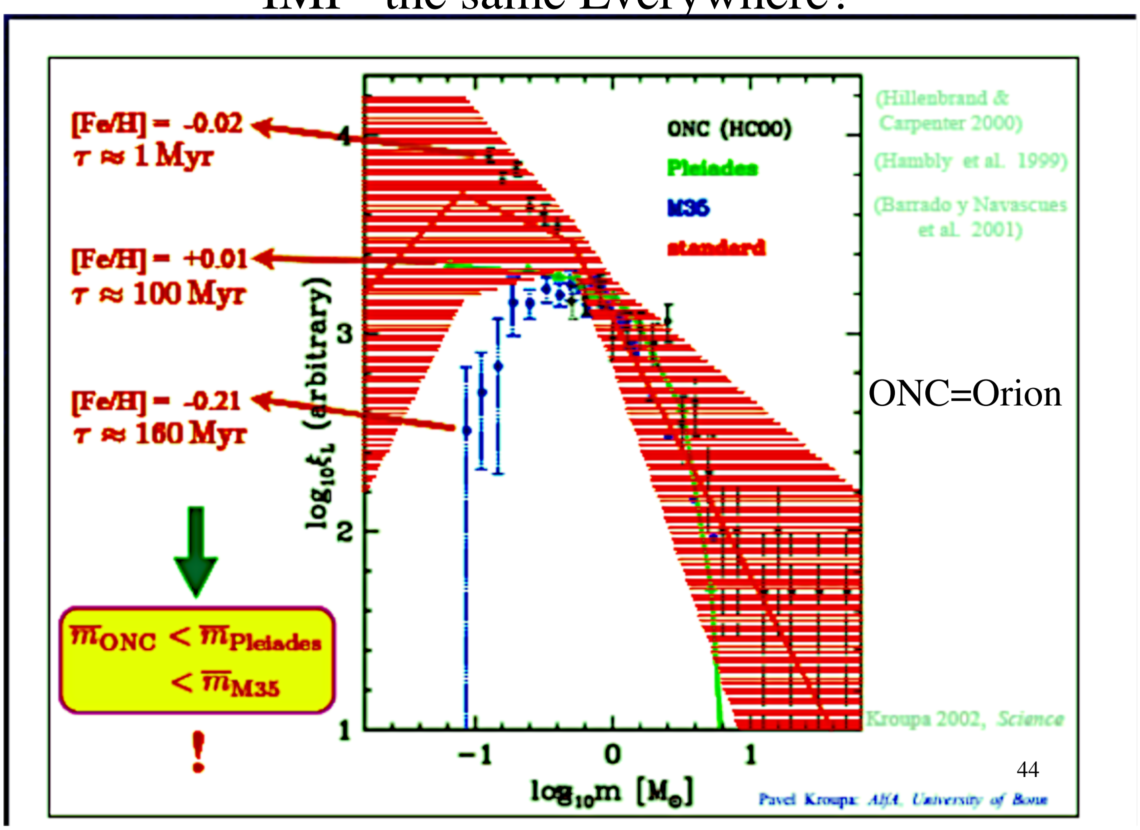


Fig. 11. A comparison of the Pleiades IMF from the present program (the weighted-averaged IMF from Fig. 10) with results from other stud-

43

IMF- the same Everywhere?



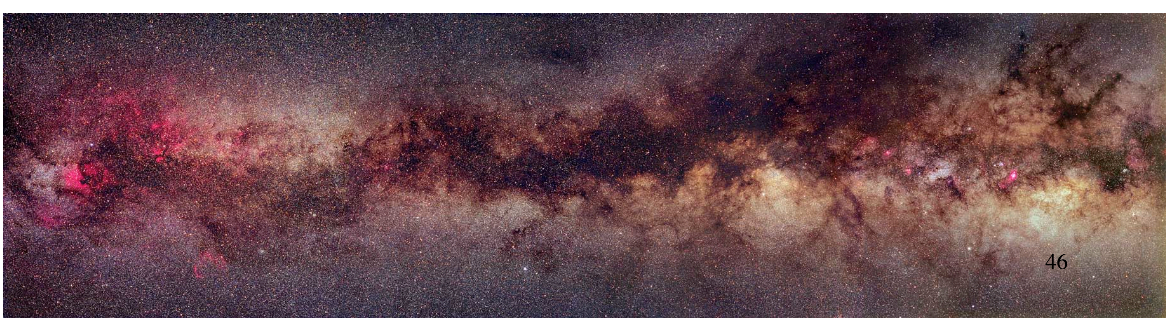
44

Open Star Clusters- A SSP

- the individual stars of the Galactic plane differ 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: e.g determining the initial mass, the initial chemical composition, and the age of a star
- 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.

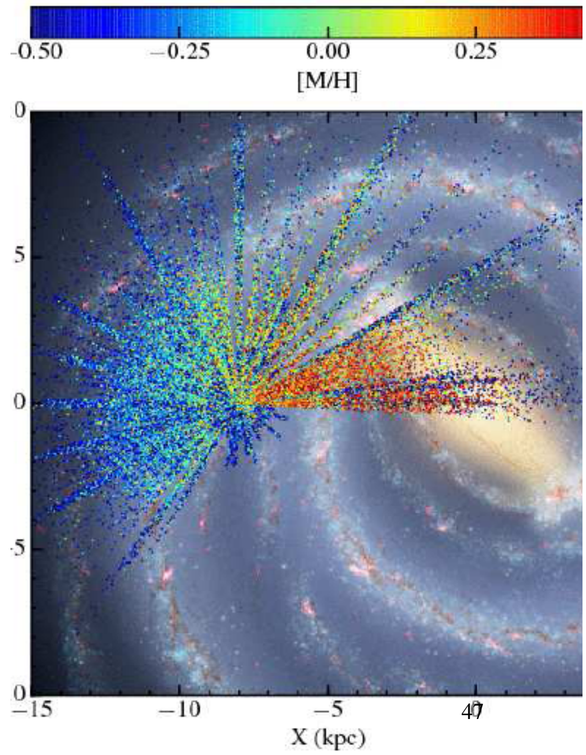
Nearby Stars

- Historically one dealt with flux (magnitude) limited samples of stars
- the Hipparchos satellite measured the absolute distances to many stars via parallax - now have a proper census of the stars at <100pc) (at this close distance effects of dust are small)- Major change coming up with release of GAIA data (being released NOW)- in the mean time
  - RAVE and SEGUE velocity surveys: SEGUE will observe ~ 240, 000 stars in the range $15 < V < 21$, while RAVE aims at 10^6 stars with $9 < I < 12$.
  - -APOGEE systematic, homogeneous spectroscopic survey 500,000 stars



APOGEE Results

- Metallicity across the Milky Way



Gaia Capability

- Gaia will survey ~1/4 of the MW (Luri and Robin)
-

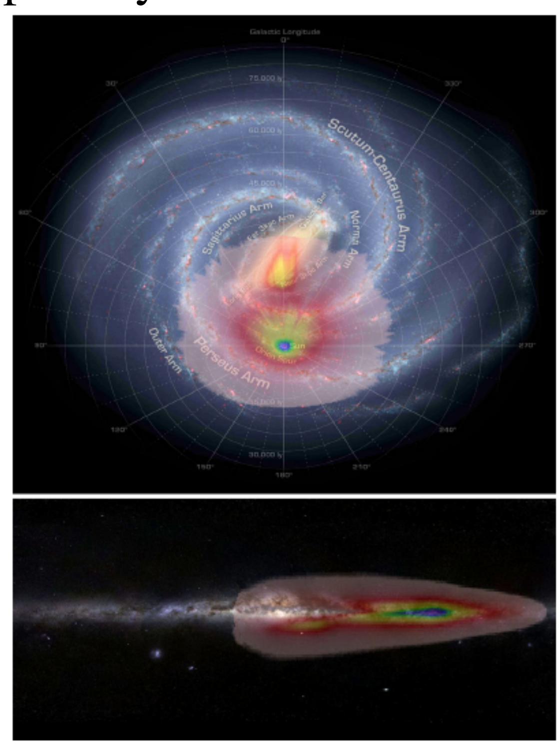
Astron Astrophys Rev (2013) 21:61

Table 1 Stellar photometric surveys of the Milky Way

Survey	Period	Sky Area	# of Filters	mag lim.	δ[Fe/H]
2MASS	1998–2002	all sky	5	$H = 15$	N/A
(Skrutskie et al. 2006)		40,000 deg^2	1.2μ–2.2μ		
SDSS I-III	2002–2012	North, $l > 20°$	5	$g = 22$	0.2
(Eisenstein et al. 2011)		15,000 deg^2	0.4μ–0.9μ		
PanSTARRS1	2011–2013	$\delta > -20$	5	$g = 22$	0.4
(Kaiser et al. 2002)		30,000 deg^2	0.5μ–1.0μ		
VHS	2010–2015	South	5	$J = 20$	N/A
(McMahon et al., 2012, in prep.)		20,000 deg^2	1.2μ–2.2μ		
SkyMapper	2012–2014	South	5	$g = 21$	0.1
(Keller et al. 2007)		15,000 deg^2			

Table 2 Stellar spectroscopy surveys of the Milky Way

Survey	Period	Sky Area	# of Spectra	app. mags	δv [km/s]	δ[Fe/H]	char. distance
GCS	1981–2000	South	16,000	$V \simeq 10?$	0.5	indiv	0.003 kpc
SEGUE I + II	2004–2009	North, $l > 20°$	360,000	$g = 15$–20	8	0.2	2 kpc
RAVE	2003–2012	South	370,000+	$i = 9$–12	3	0.2	0.5 kpc
APOGEE	2011–2014	North, $l < 20°$	100,000	$H < 13.8$	0.5	indiv.	10 kpc
Gaia-ESO	2012–2015	South	150,000	$V < 18$	0.5	indiv.	4 kpc
LAMOST	2012–2018	North	3,000,000	$V < 18$	10	0.2	4 kpc
Gaia	2013–2018	all sky	50,000,000	$V < 16$	10	0.25	4 kpc



l A view of our Galaxy and the effective volume that Gaia will survey (courtesy X. Luri a
bin), based on current simulations of Gaia mock catalogs. Even in the age of Gaia, dust extincti
nage crowding will limit the exploration of the Disk to only a quadrant with optical surveys

Another Approach to SFR In Solar Neighborhood

- By modeling the white dwarf age/ density distribution one can estimate the SFR rate as a function of lookback time 'nearby' (Rowell 2012)
- We will later compare this to the overall rate of SF of the universe and find significant differences