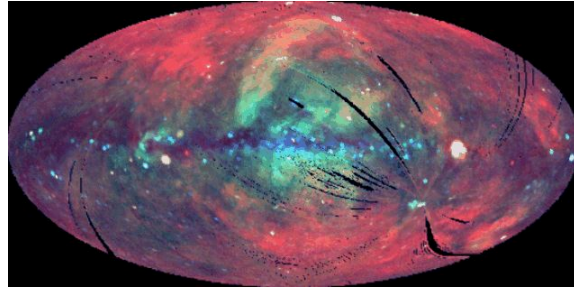
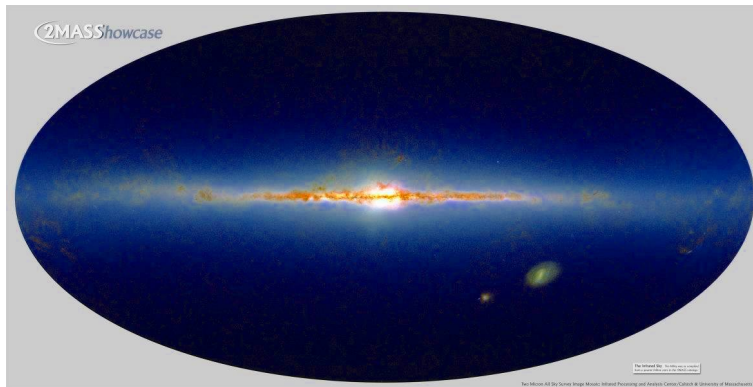


- Why study the MW?
  - its big, bright, close
  - Allows detailed studies of stellar kinematics, stellar evolution, star formation, direct detection of dark matter??
- Problems
  - We are in it
  - Distances are hard to determine
  - Dust is a serious issue

## Milkyway S&G Ch 2



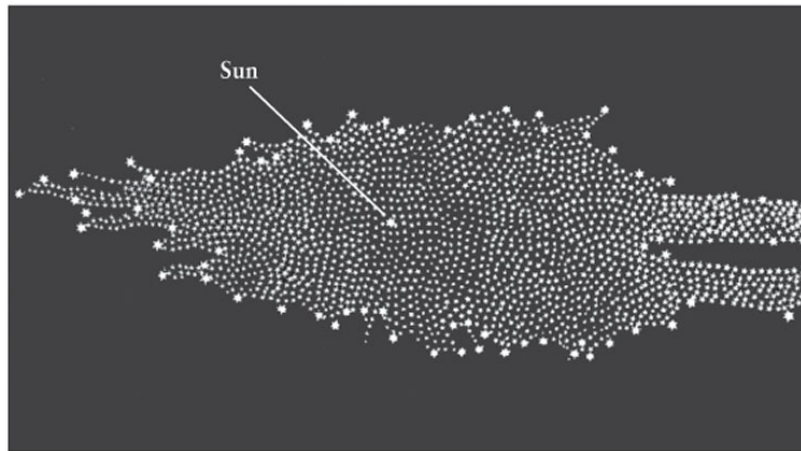
Milky Way in X-rays- Image of the Hot ISM



Milky Way in near IR  
[www.milkywayproject.org](http://www.milkywayproject.org)

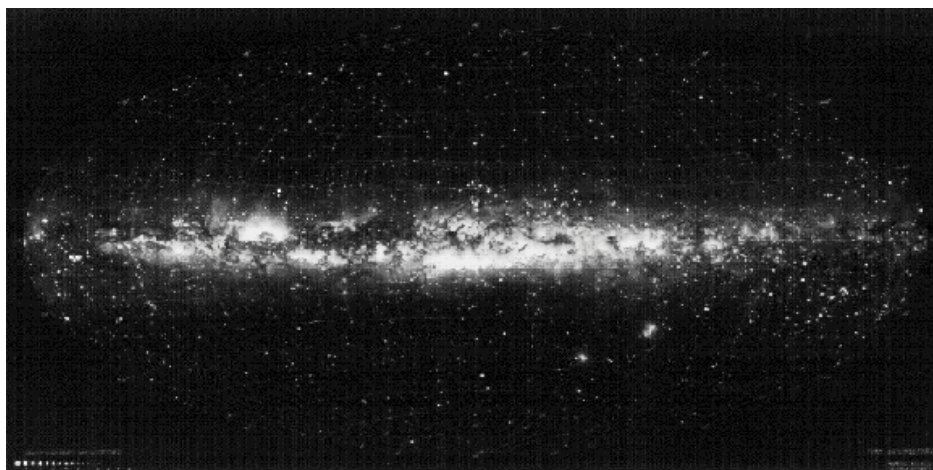
## Our place in the Galaxy

- We live in a large disk galaxy of average mass
  - The sun is in the disk, towards the edge ( $\sim 8$  kpc 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)*



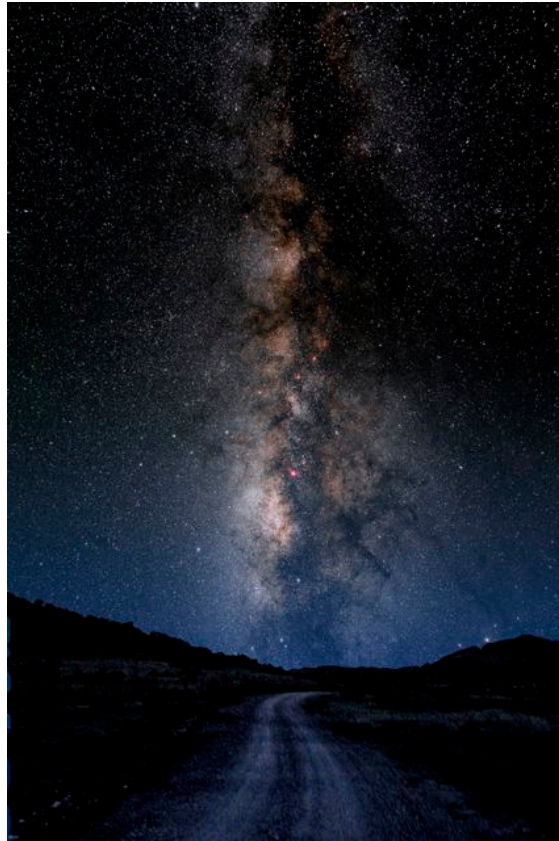
Herschel's map of the Galaxy

3



Milky Way in optical light

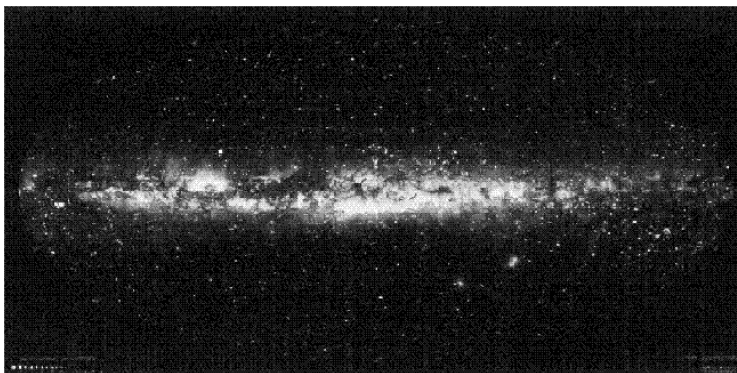
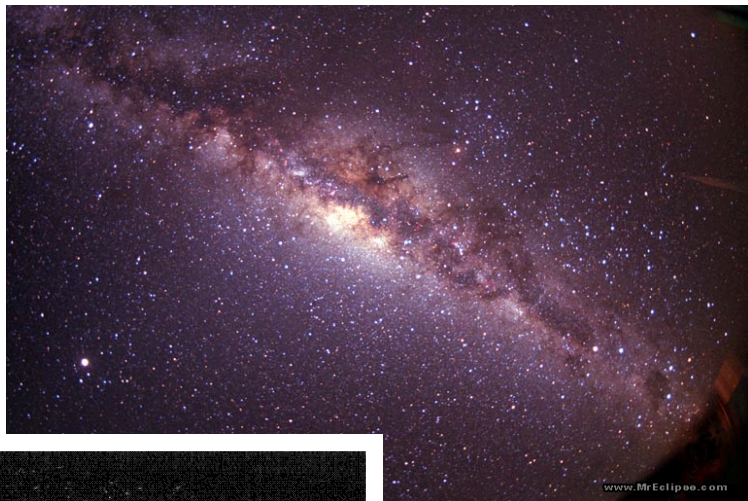
4



5

## MW in Optical

- Notice the strong effect of dust.

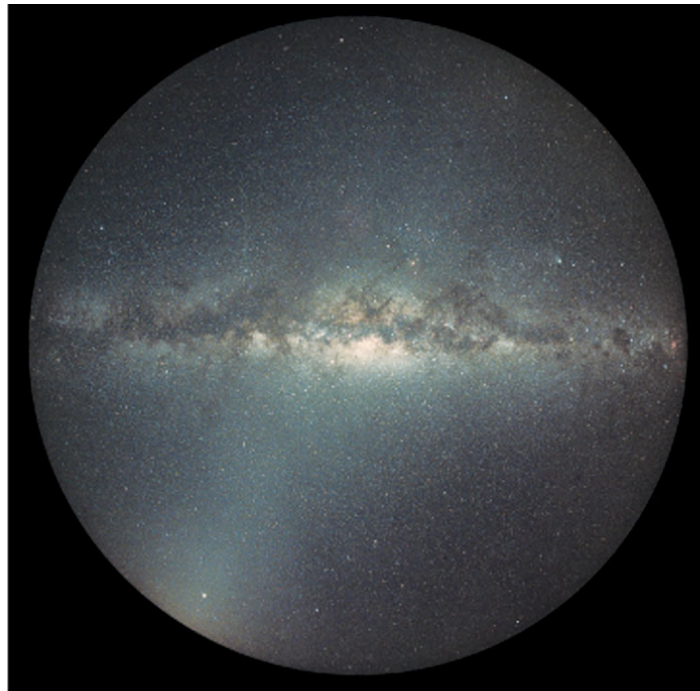


this is a drawing of  
the MW all sky- state  
of the art 1950's

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

6





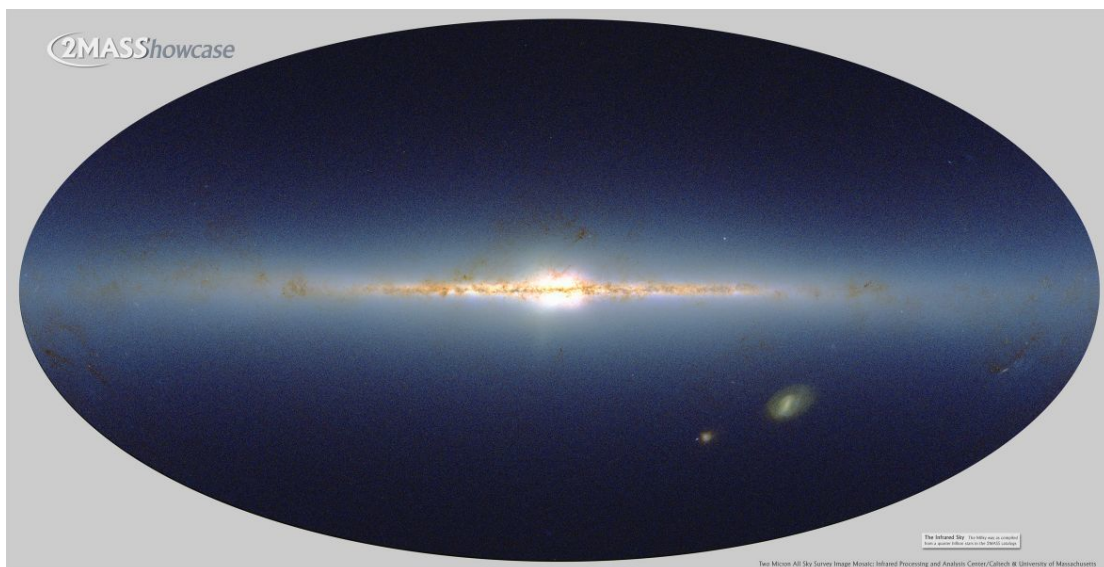
(b)

← View out of  
the plane of  
our Galaxy

← View within  
the plane of  
our Galaxy

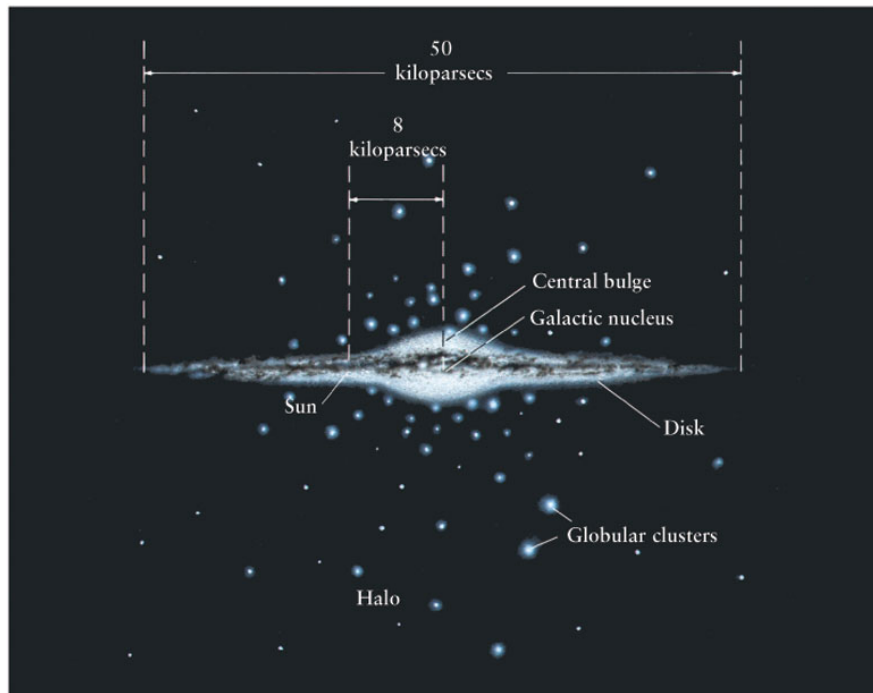
← View out of  
the plane of  
our Galaxy

7



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





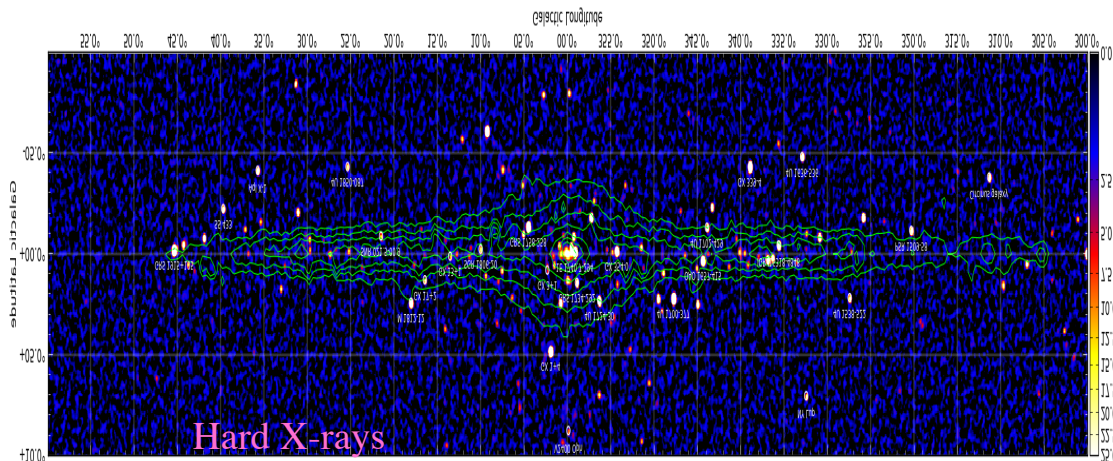
1 kiloparsec =  $3.26 \times 10^3$  lightyears =  $3.08 \times 10^{19}$  m

9

## Other Wavelengths

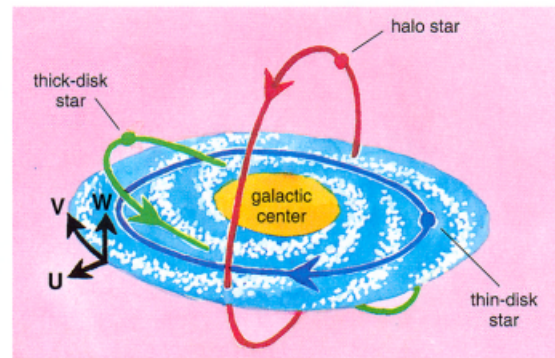
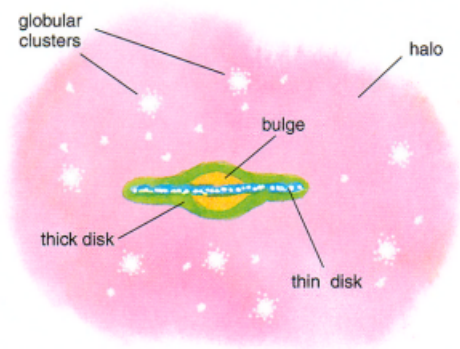
In 'hard' (2-10 keV) x-rays one sees  
 accreting x-ray binaries Neutron stars and black holes  
 - 2 Populations companions

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



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# Schematic Image and Dynamics of MW

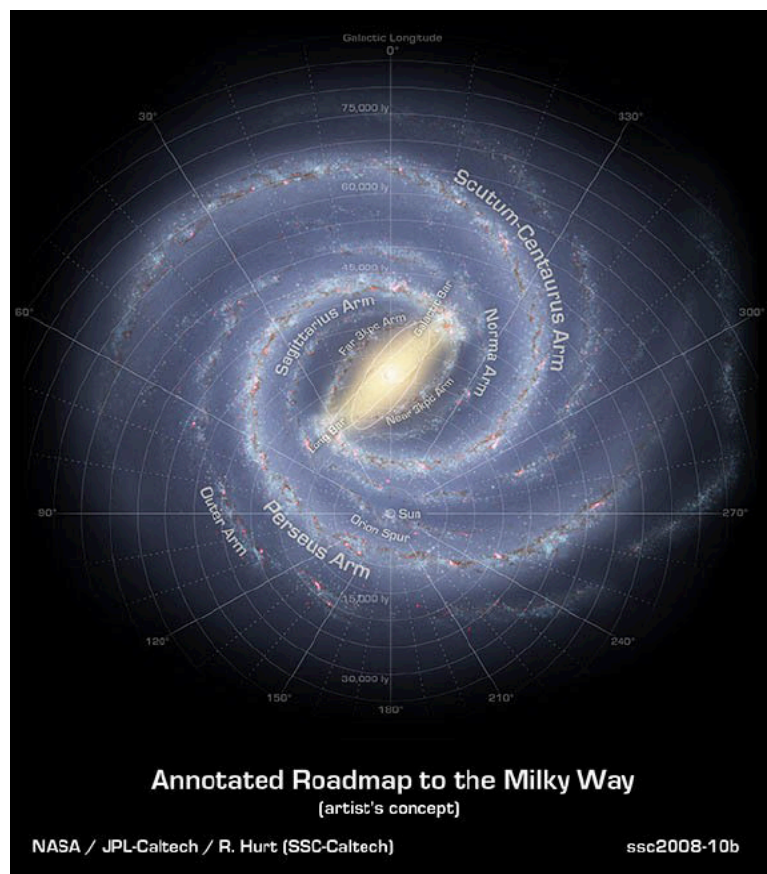


Cristina Chiappini

11

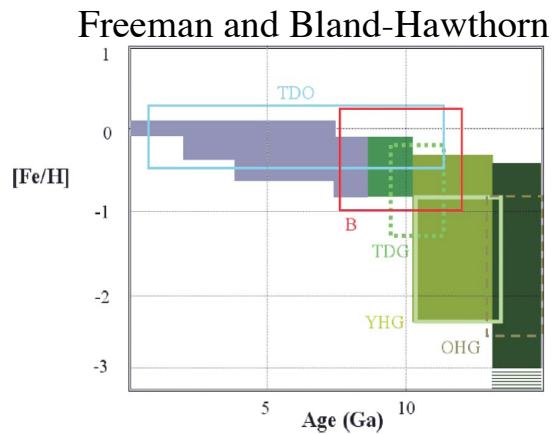
- Its only in the MW and a few other nearby galaxies that fossil signatures of galaxy formation + evolution (ages dynamics and abundances for individual stars) is possible.

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
- 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.
- Most common has been to describe the Disk in terms of a dominant thin disk and a thick disk, with thin–thick disk samples of stars defined spatially, kinematically, or chemically



blue= thin disk stars

green =thick disk stars

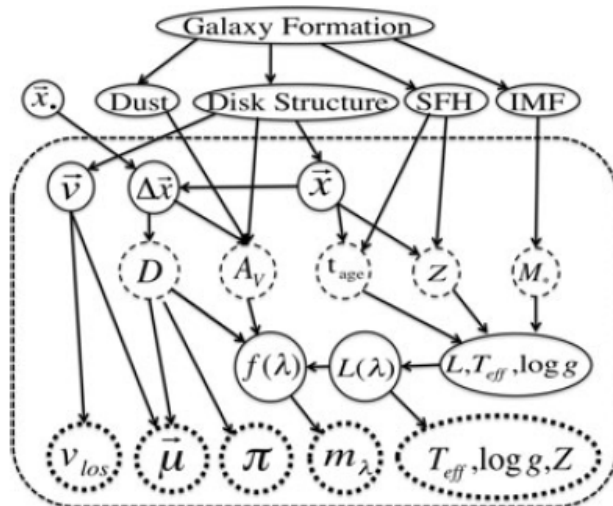
B= bulge stars

black= halo stars

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## Observables and What we Want to Learn

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

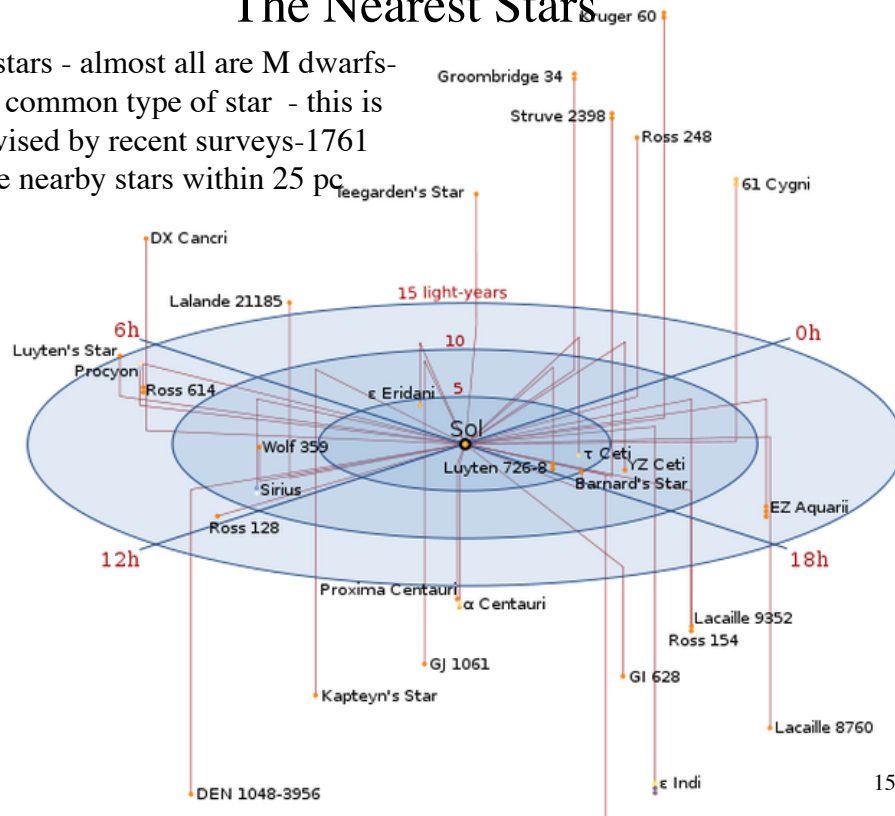


Rix and Bovy 2013



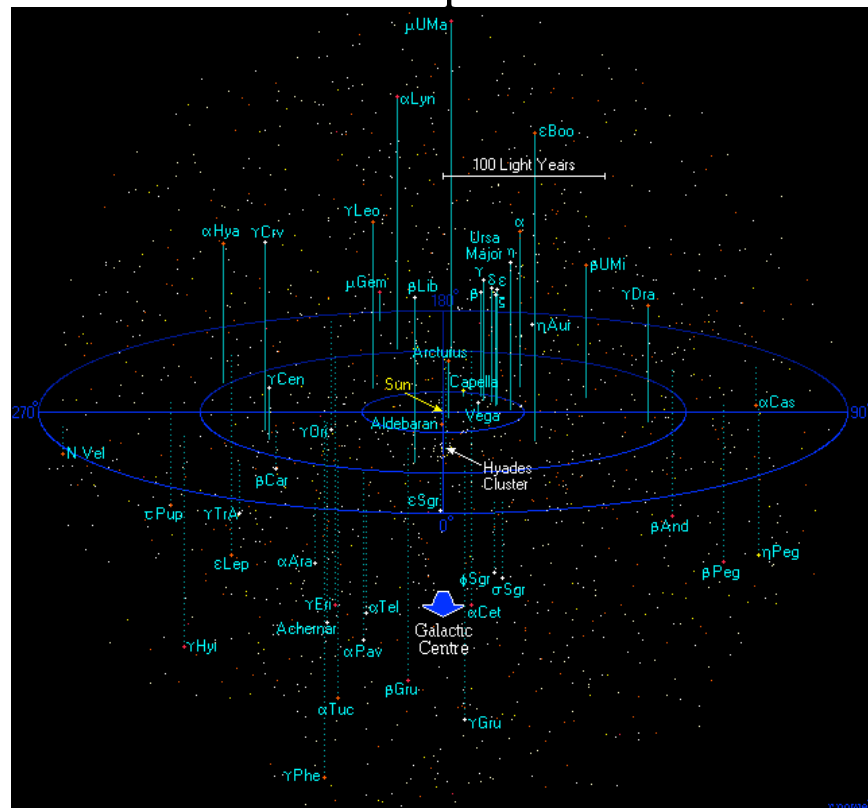
# The Nearest Stars

- 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

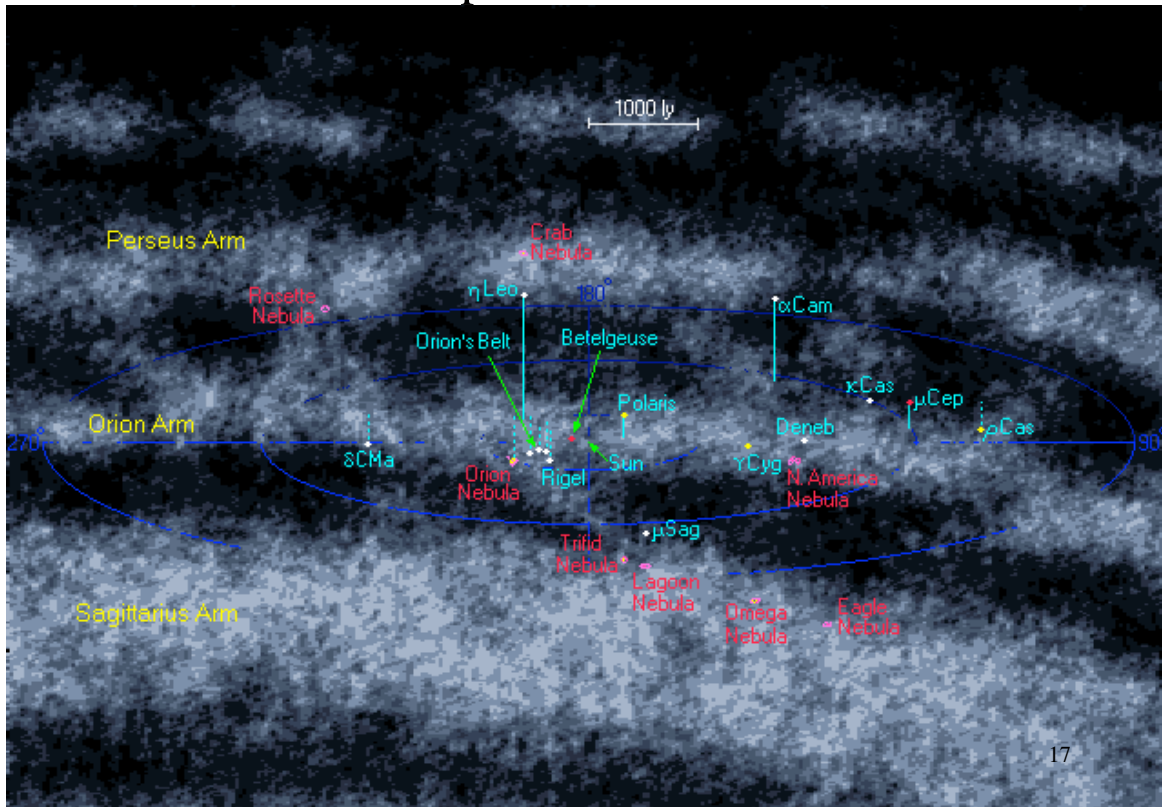


## Stars Within 250pc

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

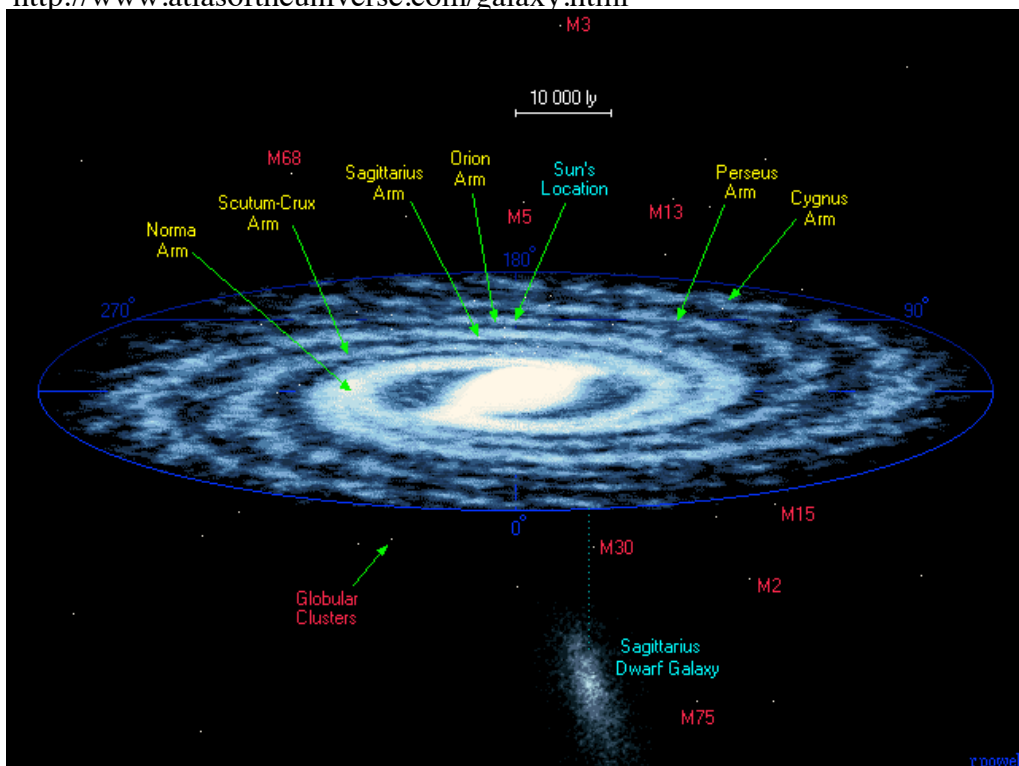


## 5kpc- Orion Arm



## The MW

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

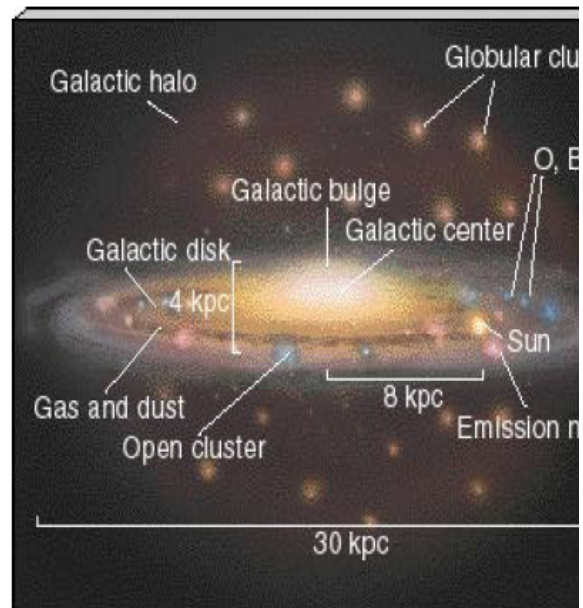


# Basic Structure of Milky Way

Bulge is quite spherical and is dominated by old stars

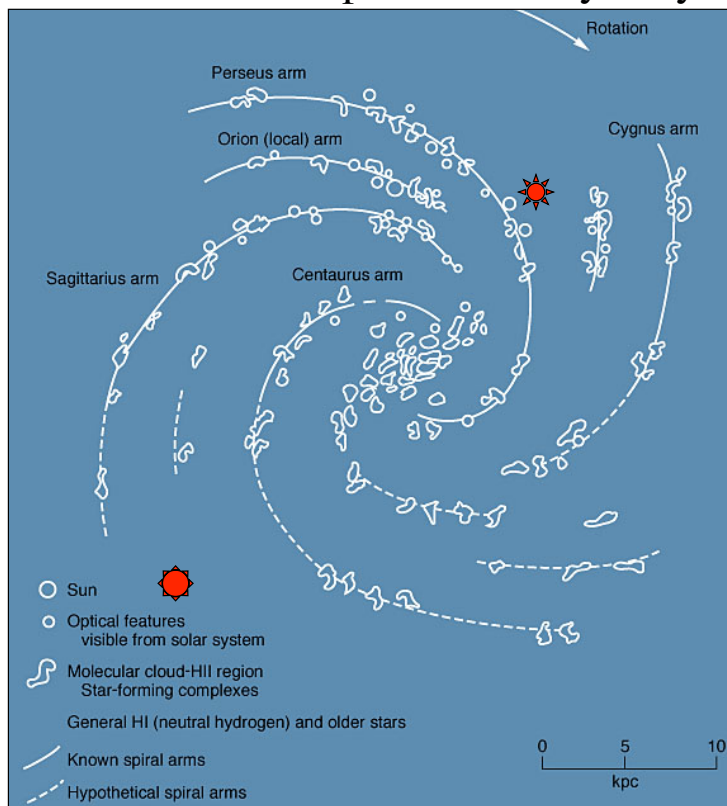
Disk- location of almost all the cold gas and most of the HI- site of star formation and thus young stars- wide range in metallicity

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



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## Map of the Milky Way Galaxy



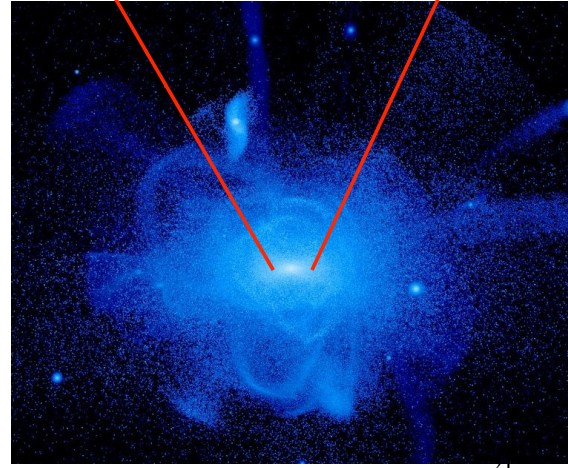
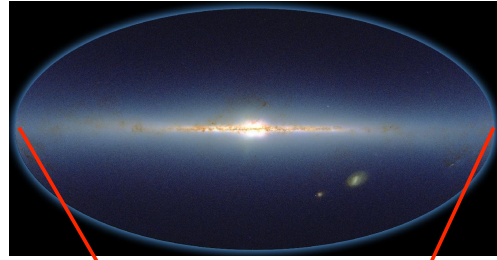
The map has been using HI velocity data sec 2.3.1 in S+G

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# Theorists View of Dynamics of Stars in MW

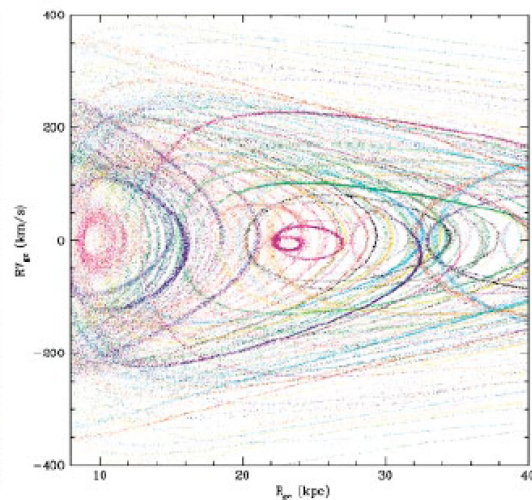
- In cold dark matter theories of structure formation many mergers have occurred - it takes a VERY long time for the orbits to 'relax' and thus there should be dynamical signatures of the mergers
- Only in MW and LMC/SMC is there any chance to determine the 3-D distribution of velocities and positions 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

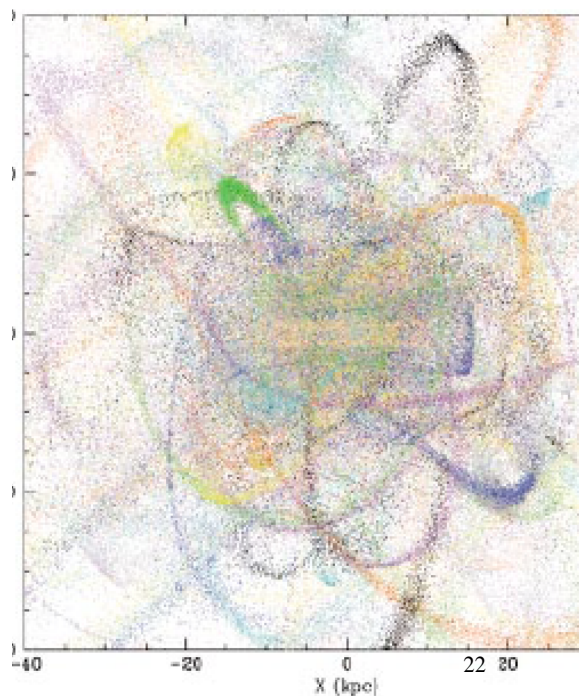
## Theorists View- Continued

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



radial velocity vs orbital radius

position of stars in x,z plane



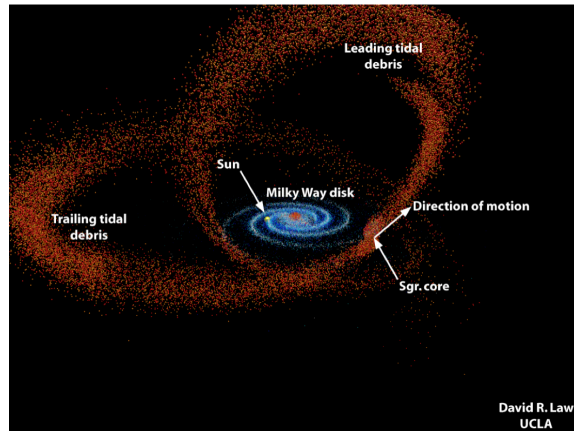
## Simplified View of Streams

- galactic haloes are threaded with the phase-mixed remains of dwarf satellites and globular clusters that have been destroyed by the tides of their host's gravitational potential (Law and Majewski 2009)

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

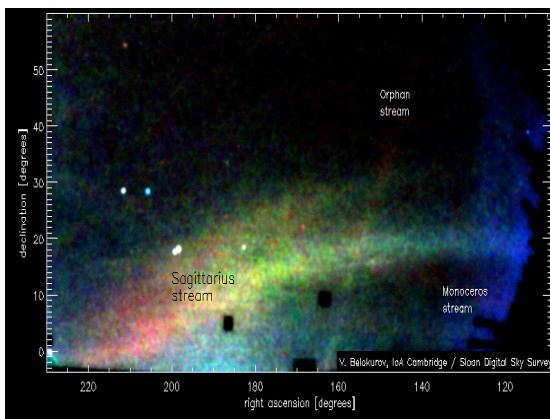
- these dynamical tracers can provide constraints on the mass distribution of the baryonic and dark matter components of the Milky Way
- Tidal disruption radius

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



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

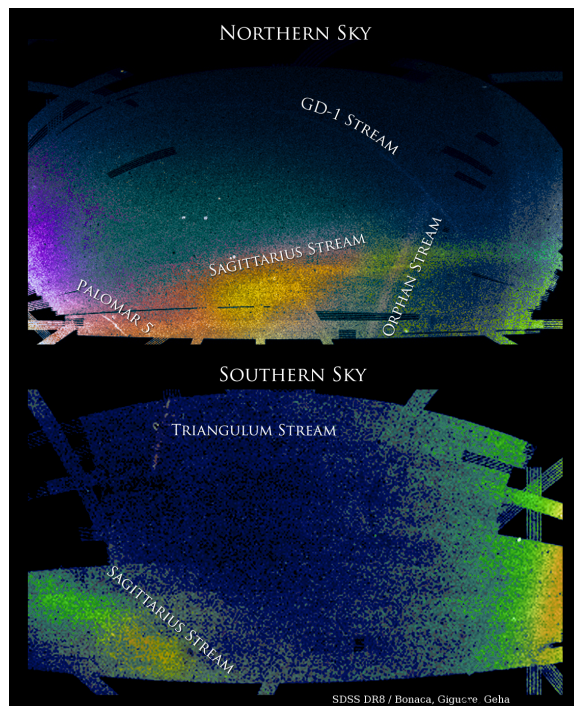
2 are equal when  $r \sim R(m/kM)^{1/3}$   
 **$k$  depends on structure of object**  
 See B&T sec 8.3 or Roche limit<sup>23</sup>



- 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)

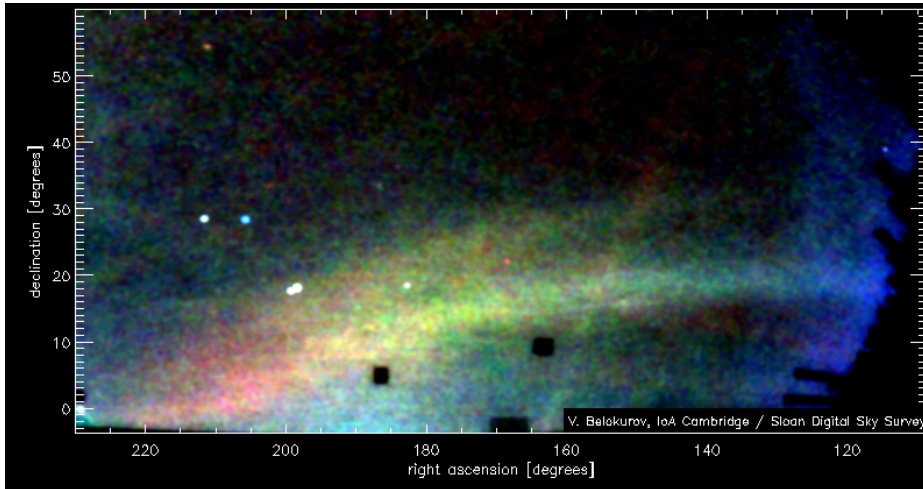
## Streams in the MW





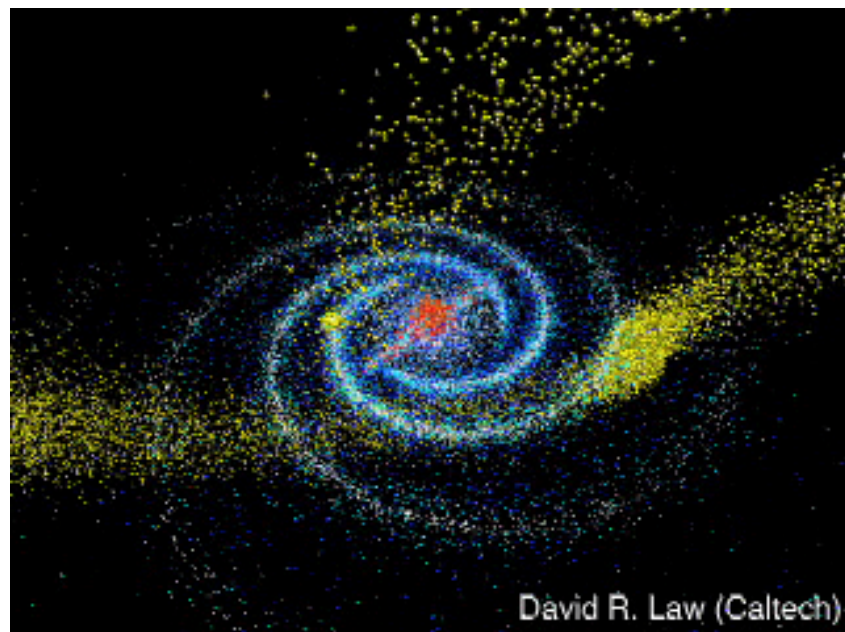
## Stellar halo : fossil record of assembly?

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



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- 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><sup>26</sup>



# Streams Originating from Globular Clusters

- Our colloquium this week by N. Kallivayalil is on 'streams'
- Useful in reconstructing the accretion history of the Galaxy,
- and as sensitive probes of the Galactic potential
- The streams tend to be 'cold' since they originate from infalling structures that are much less massive than the MW
- A large sample of such streams will ultimately allow a map of the distribution of Galactic dark matter with higher spatial resolution than presently possible and allow a search for dark matter 'sub-halos' ( see Kupper, A, Lane, R., & Heggie, D. C. 2012, MNRAS, 420, 2700)

**stream associated with  
Pal 5  
Grillmar et al 2012**

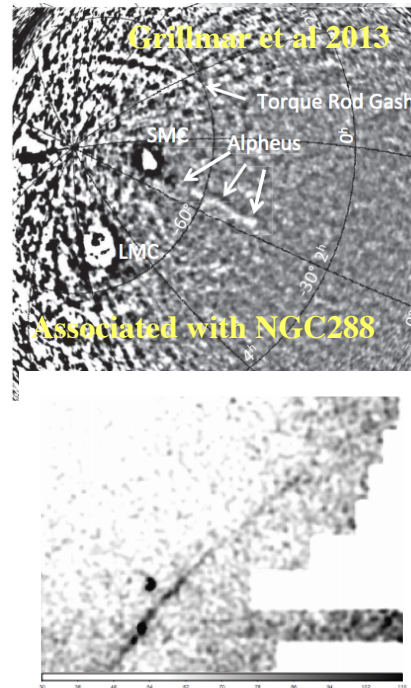


FIG. 1.— The match filtered star densities in the region of the Pal 5 stream in the SDSS  $\lambda$  and  $\eta$  co-ordinate system. The raw image has been smoothed with a 3 pixel Gaussian. The object above the stream is the foreground cluster M5.

## 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 matter in the solar neighborhood is commonly assumed to be smoothly distributed in space and to have a Maxwellian velocity distribution- but....
- 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

- 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

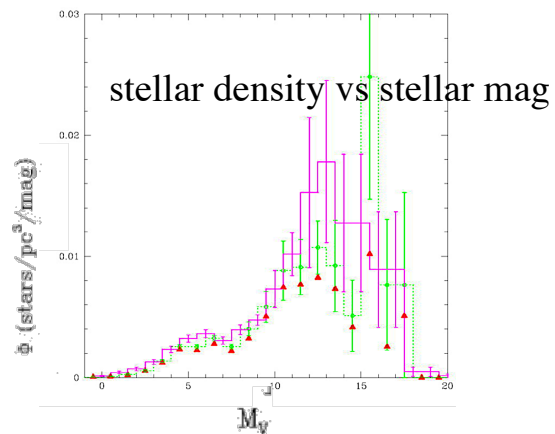
that probes the disk ( $z \sim 1 \text{ kpc}$ )

- 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 .

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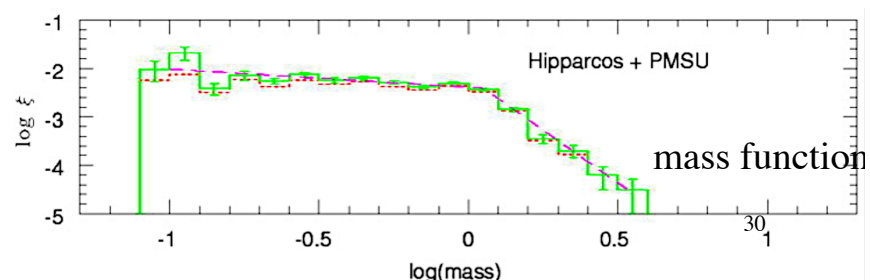
## Luminosity and Mass Function

- 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 ( $R \sim 25 \text{ pc}$ ) from the Hipparchos satellite set by its ability to measure small parallaxes\*



Gaia launched 12/2013 will change things dramatically

for all objects brighter than 15mag Gaia will measure their positions to an accuracy of 24  $\mu$  arc sec 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  $N(m,l,b) = \int A(m',l,b) dm'$
  - Simplest galaxy model : uniform and infinite
- if  $\rho_*$  = density of stars and  $\Omega$  = 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  $N(m)=\int_{-\infty}^m \Omega \rho_* = (0.2)(\ln 10)(10^{(0.2(m-M)+1)})^3 dm$ ; oh the pain of magnitudes

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## Star Counts

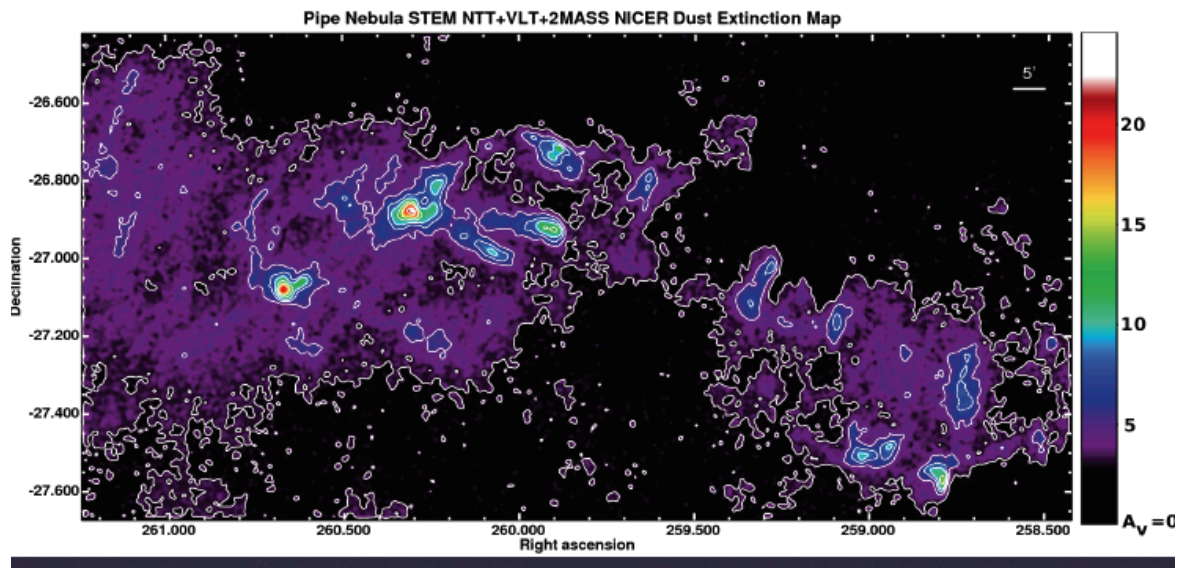
- $N(m) = \int_{-\infty}^m \Omega \rho_* = (0.2 \times 10^3)(\ln 10) \int_{-\infty}^m (10^{(0.6(m-M))}) dm'$
- or (finally)
- $N(m) = 333 \Omega \rho_* 10^{(0.6(m-M))}$
- *This is not what is observed*
  - finite size of **disk** (not sphere)
  - effects of dust
- Olbers paradox: if galaxy (universe) 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 type, age, metallicity etc
- Luminosity function of stars  $f(m, \text{etc})$

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# Need to Measure Extinction Accurately

## Galactic extinction maps



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## 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

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# 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 Pleiades) 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 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

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

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## The Form of the IMF

- Kroupa 2002

- Assuming all binary and higher-order stellar systems can be resolved into individual stars in some population and that only main-sequence stars are used,

then the number of stars per pc<sup>3</sup> in the mass interval  $m$  to  $m+dm$

is  $dN = \Xi(m)dm$  where  $\Xi(m)$  is the observed present-day mass function (PDMF).

The number of stars per pc<sup>3</sup> in the absolute magnitude interval  $M_p$  to  $M_p+dM_p$  is

- $dN = -\Psi(M_p)dM_p$
- where  $\Psi(M_p)$  is the stellar luminosity function (LF).
- It is constructed by counting the number of stars in the survey volume per magnitude interval,
- $P$  signifies an observational photometric band
- Binarity of massive stars a serious problem

Thus  $\Xi(m) = -\Psi(M_p)(dm/dM_p)^{-1}$  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<sup>3</sup> in the mass interval  $m$ ,  $m+dm$  that form in the time interval  $t$ ,  $t+dt$  is

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

$b(t)$  is the time-modulation of the IMF and  $\xi(m, t)$  is the IMF.

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

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

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# 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

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

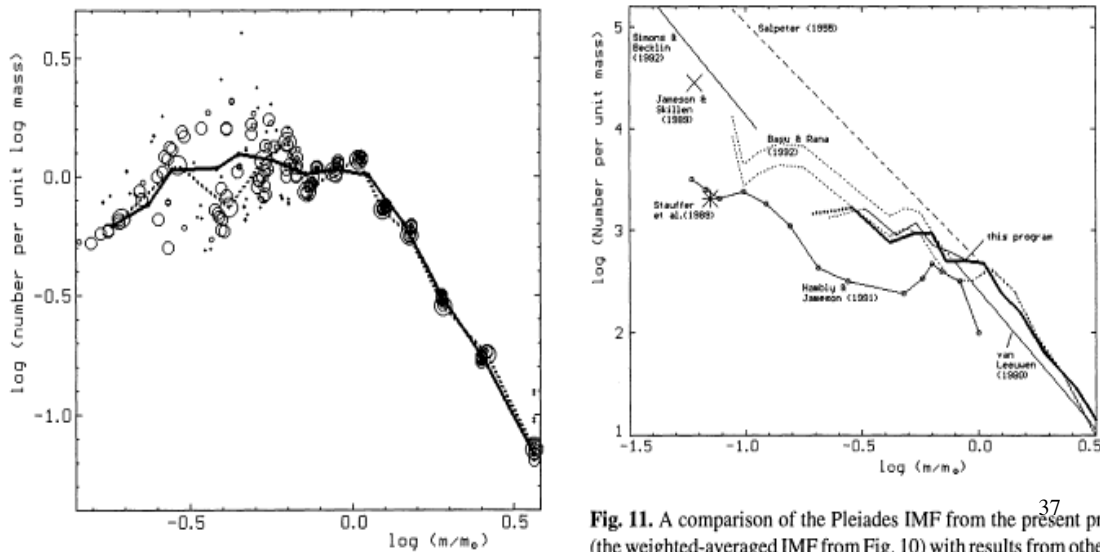
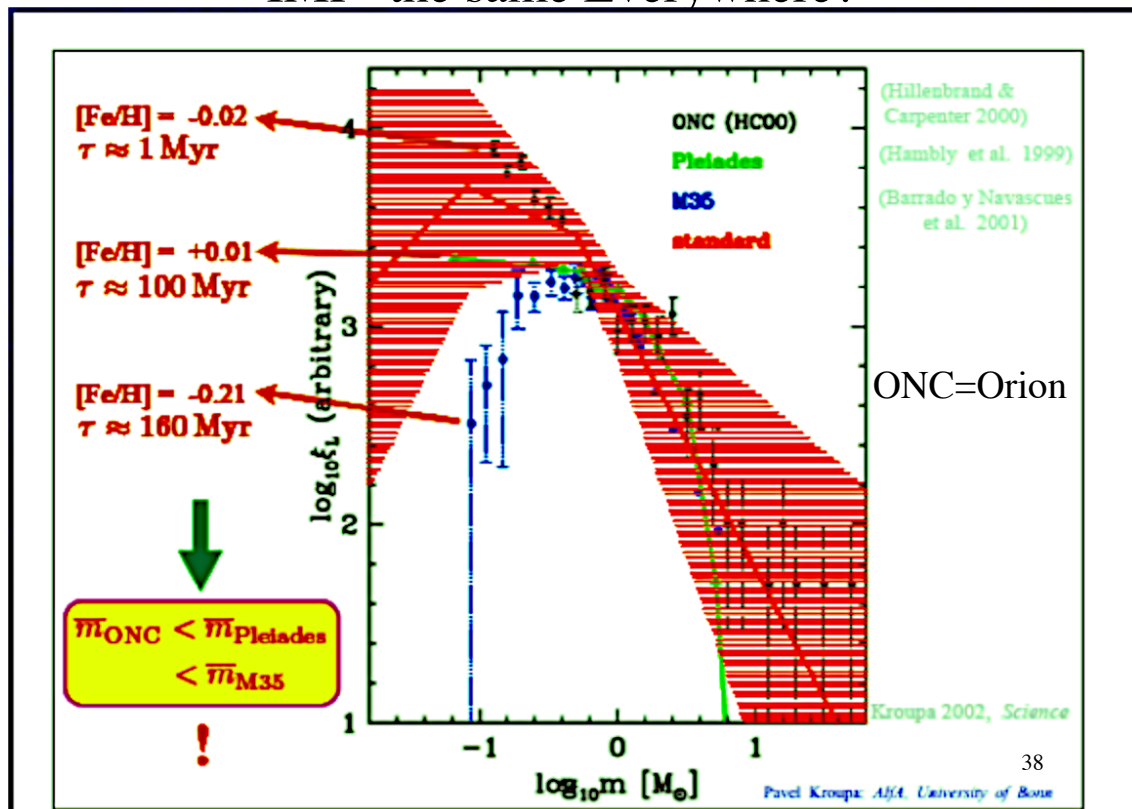


Fig. 11. A comparison of the Pleiades IMF from the present program (the weighted-averaged IMF from Fig. 10) with results from other stud-

## IMF- the same Everywhere?



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Pavel Kroupa, AFA, University of Bonn

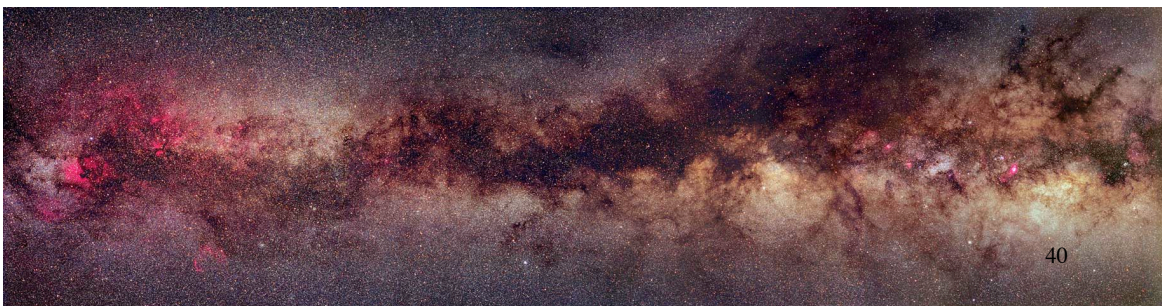
## Open Star Clusters- A SSP

- 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  $\sim$  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  $625 \pm 50$  million years old
- Over 1 billion years, encounters with molecular clouds cause an open cluster to totally dissipate.

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## 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  $< 100 \text{ pc}$  (at this close distance effects of dust are small)- Major change coming up with the launch of GAIA- in the mean time
  - Local Group and Star Cluster Dynamics from HSTPROMO (The Hubble Space Telescope Proper Motion Collaboration) R. P. van der Marel arxiv 1309.2014
    - Goal to determine fully three-dimensional velocities, need to determine Proper Motions. If get to  $\text{DPM} \approx 50 \text{ mas/yr}$ , corresponds to a velocity accuracy  $\delta v \approx (D/4) \text{ km/s}$  at distance  $D \text{ kpc}$ .
  - RAVE and SEGUE velocity surveys: SEGUE will observe  $\sim 240,000$  stars in the range  $15 < V < 21$ , while RAVE aims at  $10^6$  stars with  $9 < I < 12$ . The average velocity errors that these surveys can achieve are of the order of 10 and 1 km/s, respectively.



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# Gaia Capability

- Gaia will survey  $\sim 1/4$  of the MW (Luri and Robin)

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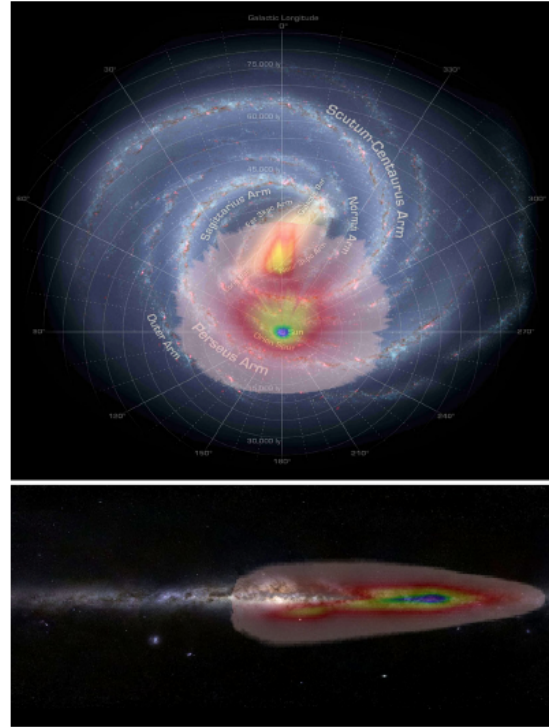
Astron Astrophys Rev (2013) 21:61

**Table 1** Stellar photometric surveys of the Milky Way

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

**Table 2** Stellar spectroscopy surveys of the Milky Way

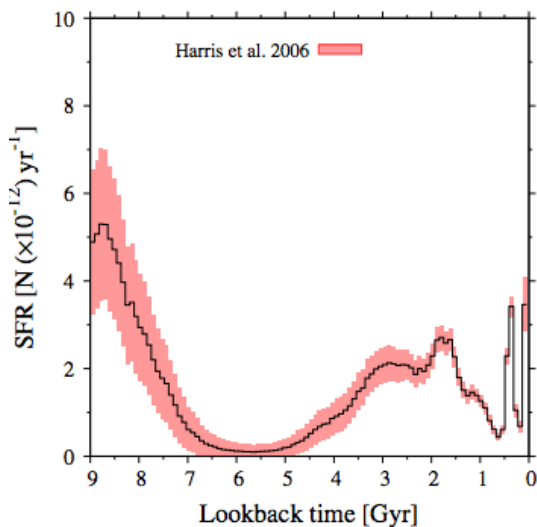
Survey	Period	Sky Area	# of Spectra	app. mags	$\delta v$ [km/s]	$\delta[\text{Fe}/\text{H}]$	char. distance
GCS	1981–2000	South	16,000	$V \approx 10?$	0.5	indiv	0.003 kpc
SEGUE I+II	2004–2009	North, $l > 20^\circ$	360,000	$g = 15$ –20	8	0.2	2 kpc
RAVE	2003–2012	South	370,000+	$i = 9$ –12	3	0.2	0.5 kpc
APOGEE	2011–2014	North, $l < 20^\circ$	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



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

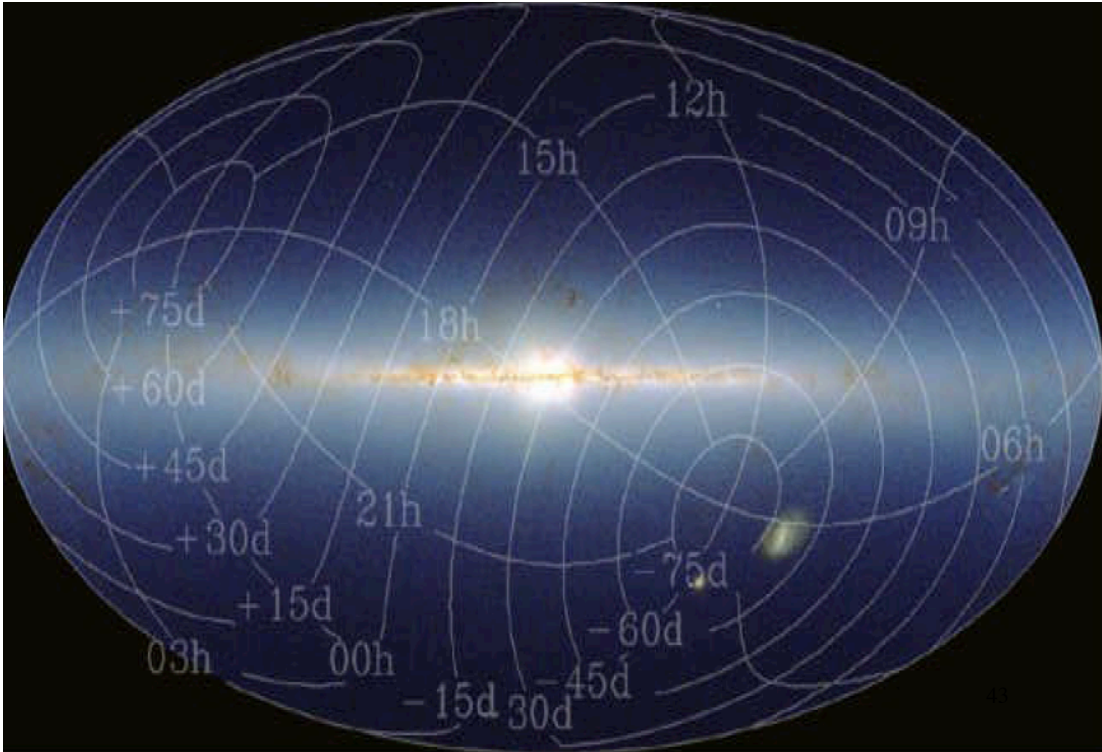
## Another Approach to SFR In Solar Neighborhood

- By modeling the white dwarf age/density distribution one can estimate the SFR rate '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??



# 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

$\theta$ : motion tangential to GC with positive velocity in the direction of rotation

$\pi$ : radial velocity wrt to GC

With respect to galactic coordinates GC

$+\pi = (l=180, b=0)$

$+\theta = (l=30, b=0)$

$+z = (b=90)$

Local standard of rest: assume MW is axisymmetric and in steady state

$(\pi, \theta, z)_{\text{LSR}} = (0, \theta_0, 0)$

