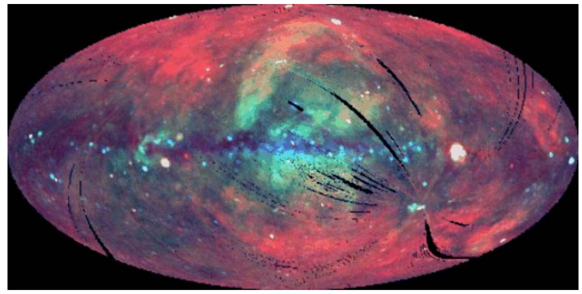
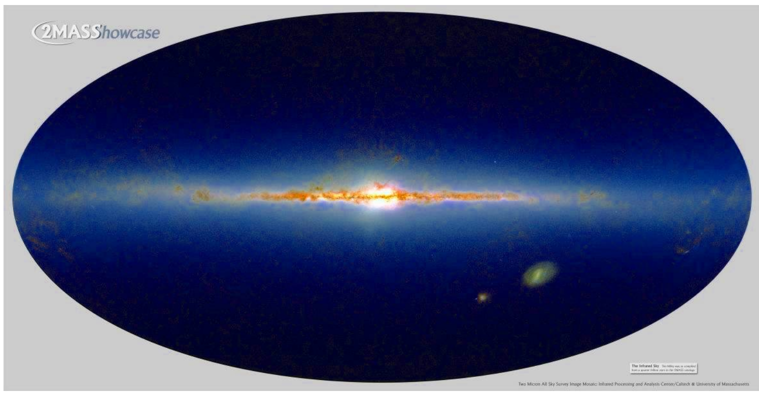
Milky Way S&G Ch 2,B&M Ch9-10

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

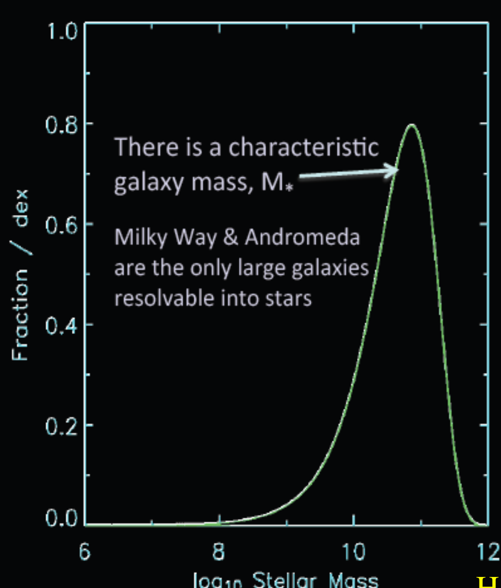


Milky Way in X-rays- Image of the Hot ISM



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
  - $6\times10^{10} M_{Sun}$ in stars, ¾ in a disk
  - Making 'realistic galaxy disks' in *ab initio* simulations remains difficul
- It's what we got (best)
  - star-by-star in 6+N dimensions

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

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

Is our galaxy normal?

The SAGA Survey is studying Milky Way siblings to find out.

By Alison Klesman | Published: Wednesday, September 20, 2017

The Andromeda Galaxy (shown here with some of its satellites), though larger and older, is sometimes considered a galaxy similar to our Milky Way. New survey results suggest that the Milky Way may not be as "normal" as we think.

Geha et al ApJ 847
These early results indicate that the
Milky Way has a different satellite
population than typical in our sample
, potentially changing the physical
l interpretation
of measurements based only on the
Milky Way's satellite galaxies.

The Galaxy in Context: Structural, Kinematic, and Integrated Properties

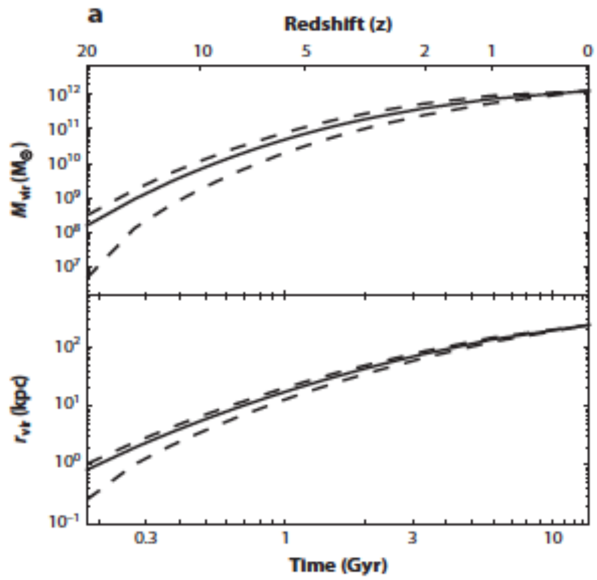
Joss Bland-Hawthorn and Ortwin Gerhard for an **extensive** detailed review AR&A 2016,54,529

Please 'scan' it- I will try to give enough material so it is accessible.

For Dynamics specialized for the MW see 2013A&ARv..21...61R
Rix, Hans-Walter; Bovy, Jo
The Milky Way's stellar disk. Mapping and modeling the Galactic disk
(see sec 2.2 for a nice description of attempts to model spirals)

How Did the MW Grow

- Theory indicates that the central regions form early on, and most of the *accreted* matter settles to the outer halo.
- How typical is the MW??
- the Milky Way is typical of large galaxies today in low-density environments (Kormendy et al. 2010) (e.g., current SFR, baryon fraction, kinematics) for its total stellar mass (cf. de Rossi et al. 2009
- But- its colors are unusal (half-way between blue and red sequence) and it has not had a major merger in 10^{10} yrs



Adapted from Correa et al. (2015)

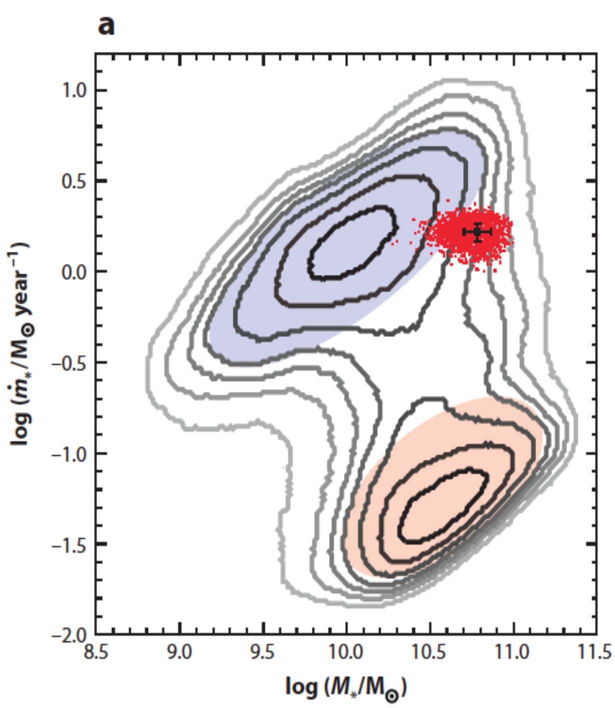
Milky Way Formation (Stars) SkyandTelescope

Published on Jun 16, 2016

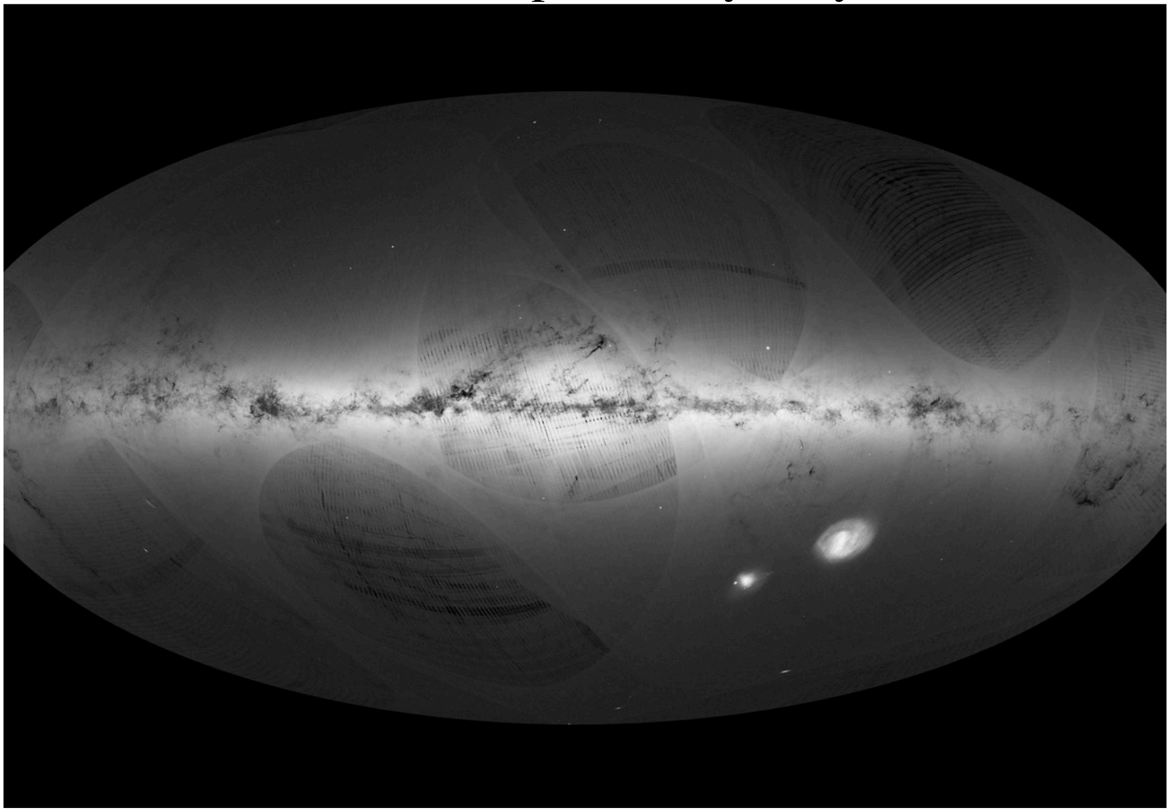
MW Formation Gas- FIRE (P. Hopkins) simulation Face on and Edge on view

One Way in Which the MW is NOT Typical

- Remember the red and blue sequences and the green valley
- Red pts are MW 'analogues' MW is the cross.
- MW has colors and mass of analogues (by construction) but is not typical for its star formation rate



GAIA 'Map'of Milky Way



Glimpse Maps

- **GLIMPSE360: Spitzer's Infrared Milky Way-**
- Galactic Legacy Mid-Plane Survey Extraordinaire. It consists of more than 2 million snapshots taken in infrared light over ten years, beginning in 2003 when Spitzer launched.
- http://www.spitzer.caltech.edu/glimpse360

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?

H-W Rix

Extensive New Work

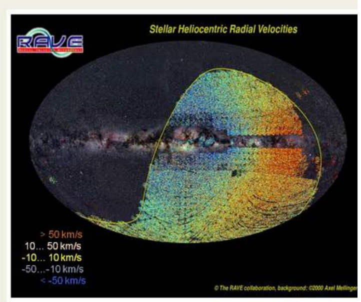
- See KITP Conference: The Milky Way and its Stars: Stellar Astrophysics, Galactic Archaeology, and Stellar Populations (http://online.kitp.ucsb.edu/online/galarcheo-c15/)
- Huge New data sets SEGUE, RAVE, APOGEE, PanSTARRS, Gaia-ESO, *LAMOST*, Galah, Gaia

Main Science Goals:
Galactic archaeology- history of star formation, chemical evolution, dynamical evolution and mergers

RAVE: 4th public data release

- Intermediate resolution (R~7500)
- 425 561 stars,
- 482 430 spectra *(DR3: 77 461 stars)*
- 9 < I < 12 mag

Database:
- ✓ **Radial velocities**
- ✓ **Spectral morphological flags**
- ✓ **T_{eff}, logg, [M/H]**
- ✓ ***Mg, Al, Si, Ti, Ni, Fe***
- ✓ **Line-of-sight Distances**
- ✓ **Photometry**: *DENIS, USNOB, 2MASS, APASS*
- ✓ **Proper motions:** *UCAC4, PPMX, PPMXL, Tycho-2, SPM4*



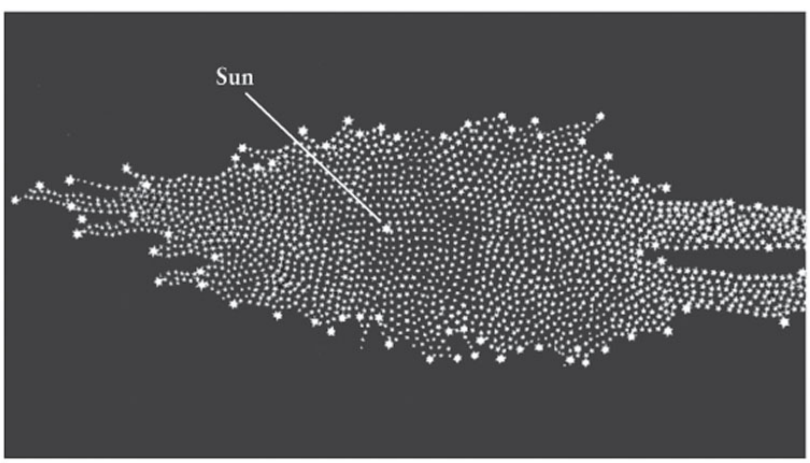
Kordopatis et al. 2014 - VizieR

Sharma talk

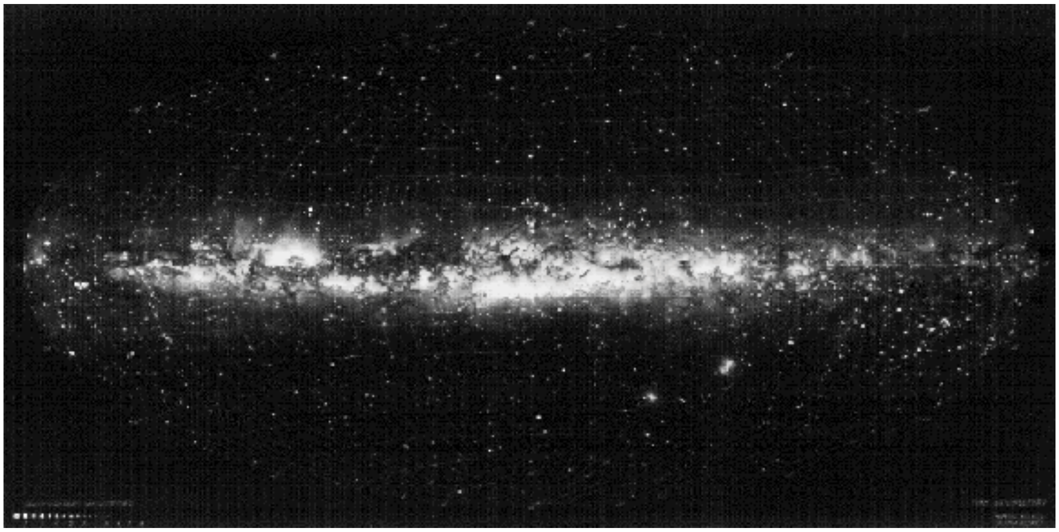
2

Our place in the Galaxy

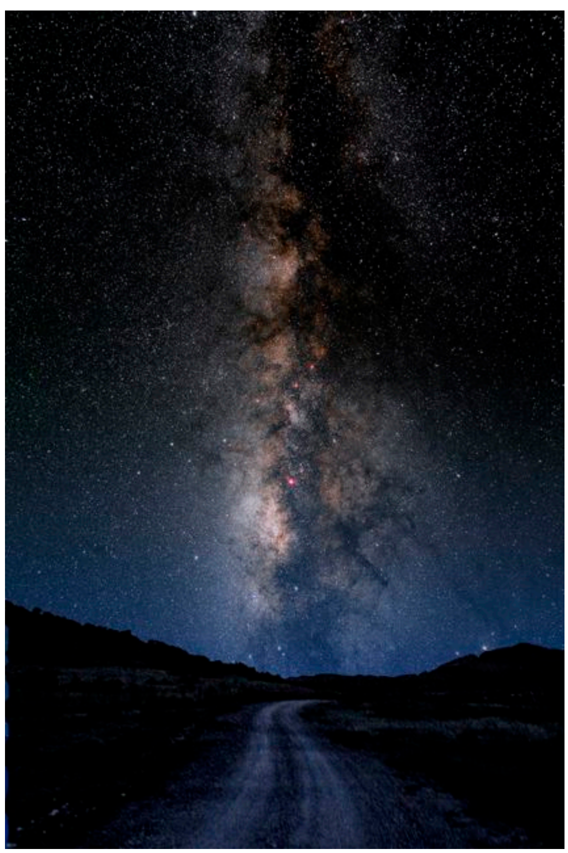
- We live in a large disk galaxy of average mass
  - The sun is in the disk, towards the edge (~8kpc from center)
  - Projected onto the sky, this disk of stars looks like a band of light that rings the sky… the Milky Way
- This realization came somewhat slowly…
  - Disk-like nature of galaxy realized 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

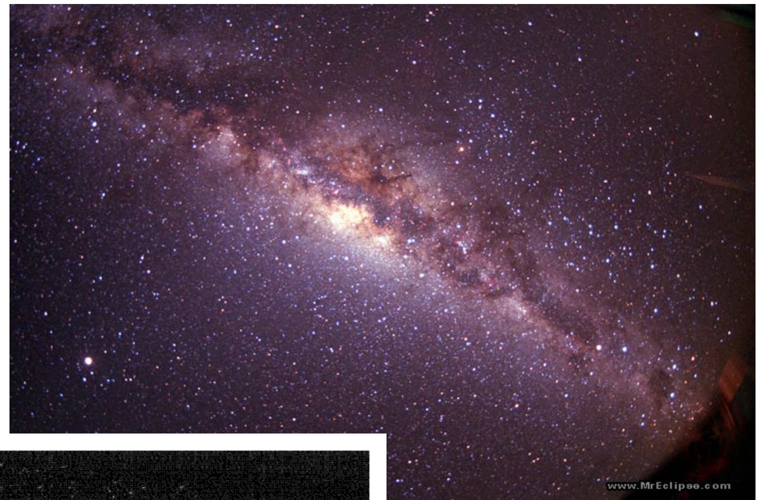


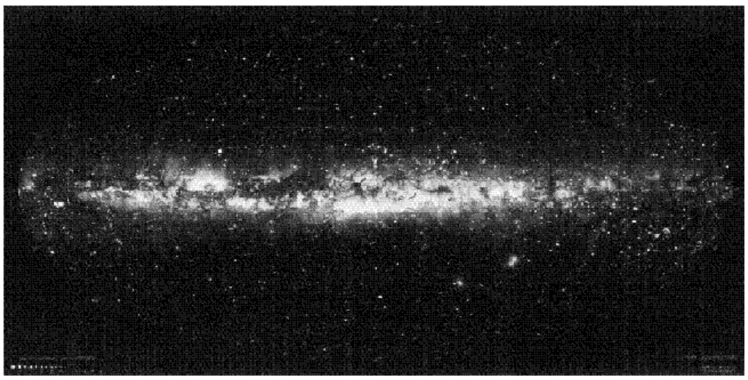
MilkyWay in optical light



MW in Optical

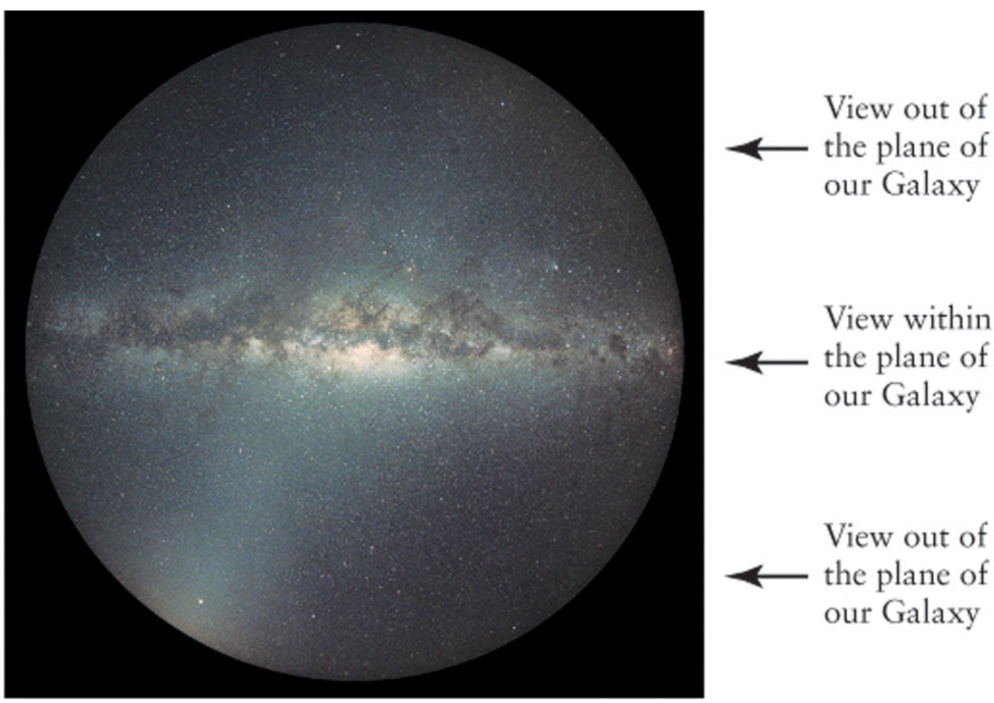
- Notice the strong effect of dust.



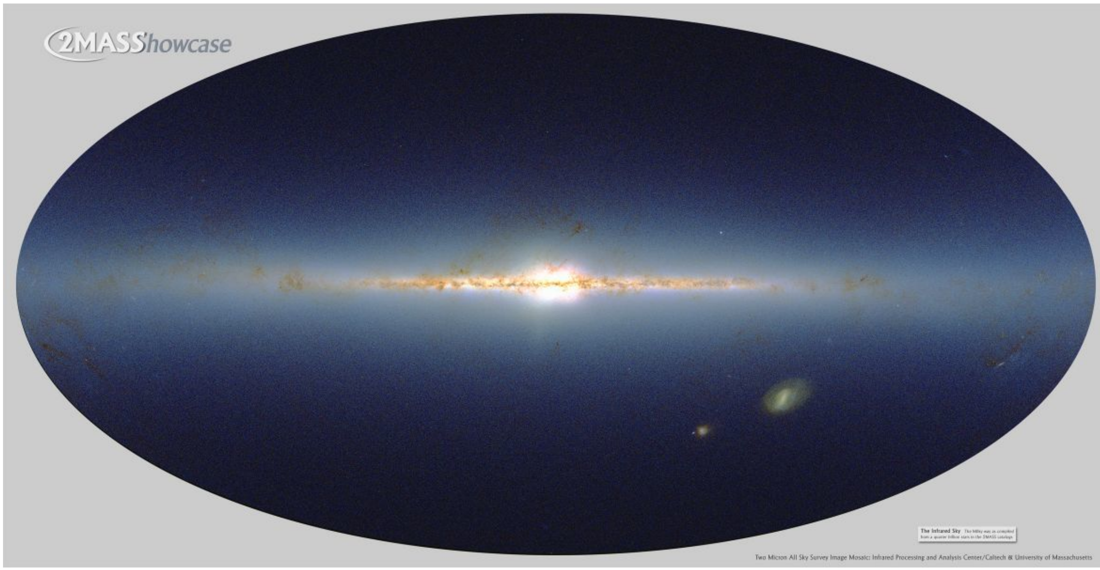


Milky Way, Sbc-galaxy (all-sky projection in optical)

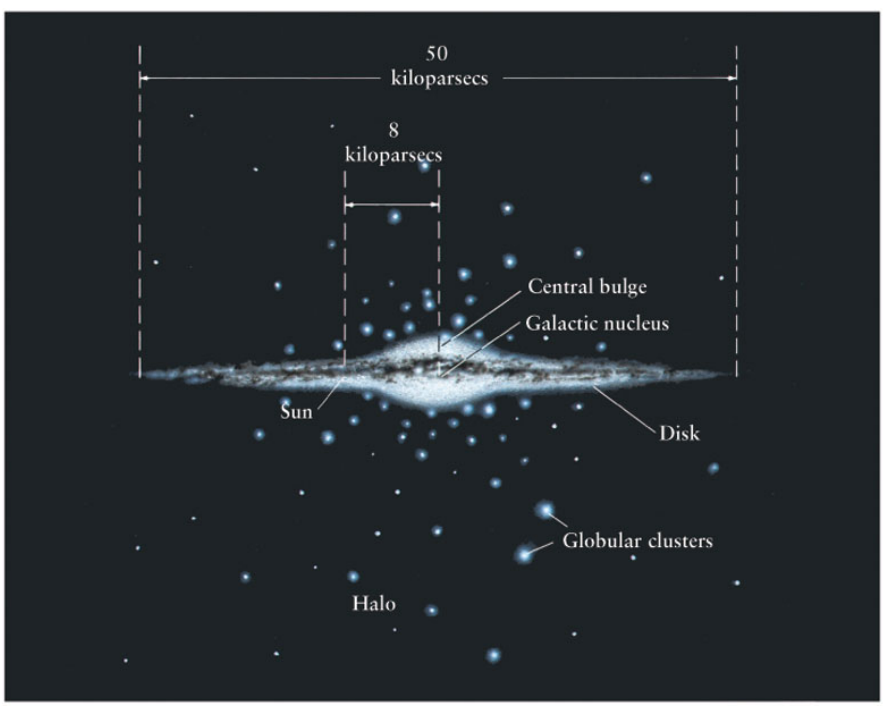
this is a drawing of the MW all sky- state of the art 1950's



(b)



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

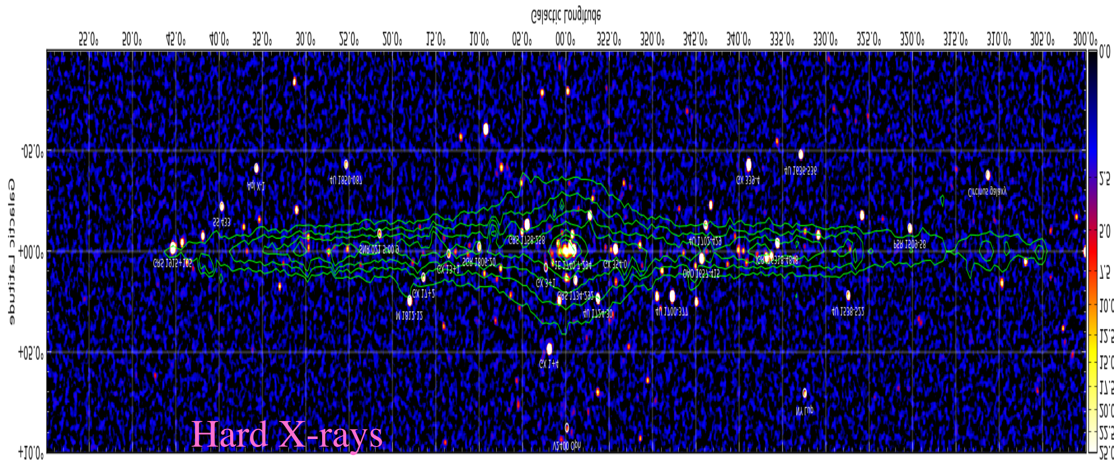


1 kiloparsec=3.26×10^3 lightyears=3.08×10^{19}m

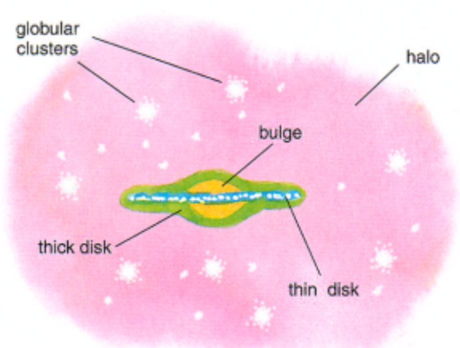
Other Wavelengths

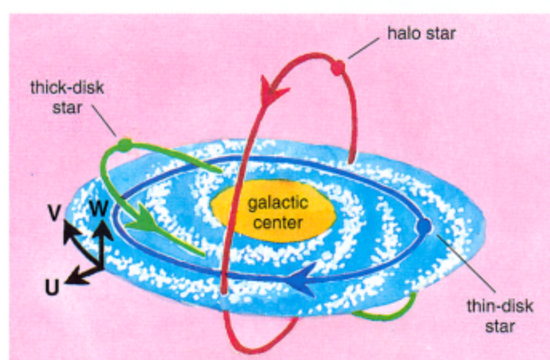
In 'hard' (2-10 kev) x-rays one sees
accreting x-ray binaries Neutron stars and black holes
- Companions consist of 2 Populations

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





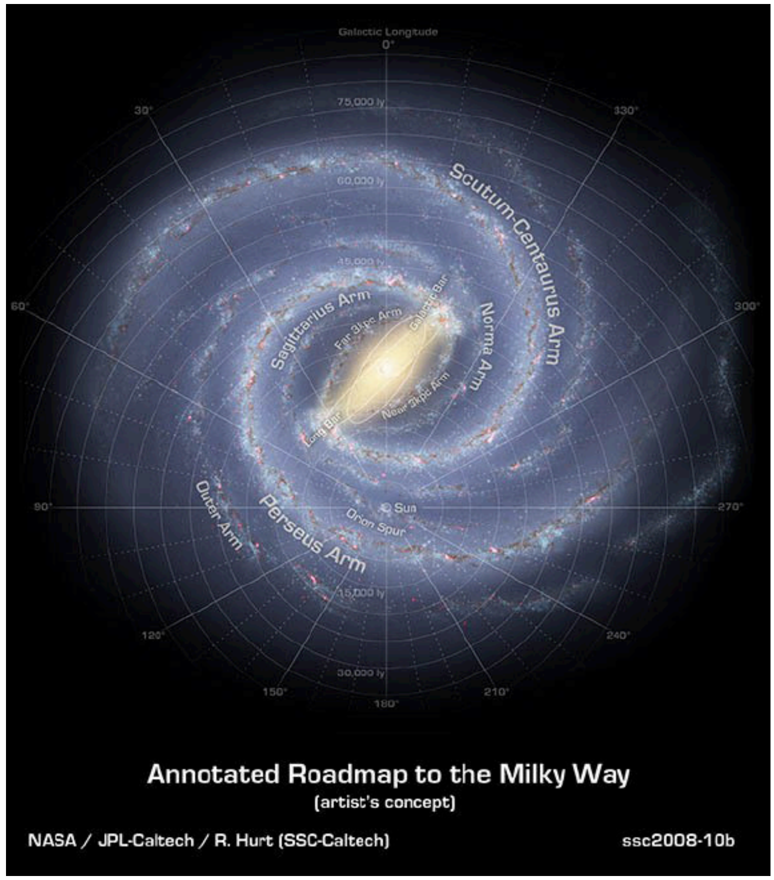
Cristina Chiappini

Unfortunately we will not discuss globular clusters

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

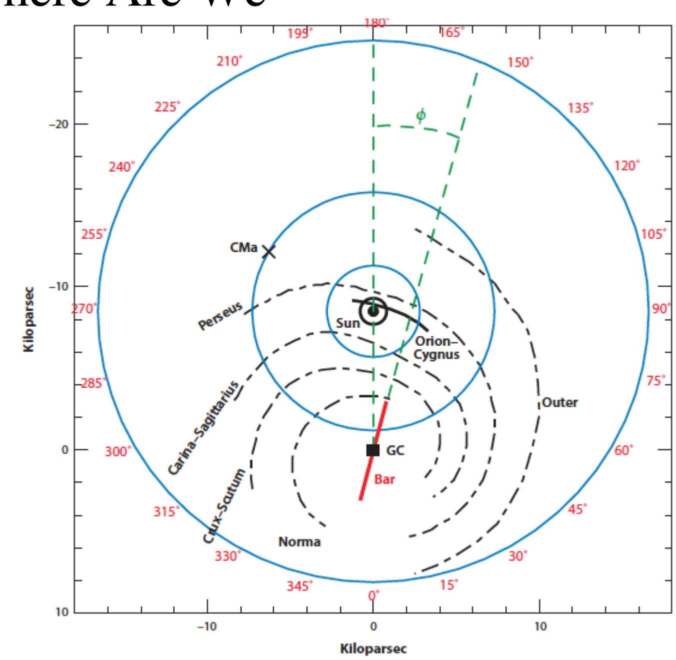
  + evolution (ages dynamics and abundances for individual stars) is possible.

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



Where Are We

- Our position in MW allows
  - a good view of the stellar halo and the outer bulge
  - off-center position at the Solar Radius is a distinct advantage it complicates any attempt to learn about large-scale nonaxisymmetries
- BUT lots of source confusion and interstellar extinction



Adapted from Momany et al. (2006)

Why the MW

- Our Galaxy is a unique laboratory for the detailed exploration of the physical processes determining galaxy evolution.
- It is the only place where we can engage in "Galactic archaeology" and use the stars as fossil indicators of chemical evolution and the cosmic matter cycle.
- New data allow tests of the predictions of cosmological models on galaxy formation,
  - model the assembly history of our Milky Way,
  - constrain the role of accretion,
  - to investigate the small-scale distribution of dark matter,
  - to study modes of star formation in different Galactic components from molecular clouds to star clusters and field stars,
  - trace our Galaxy's star formation history, chemical evolution, and dynamical history across cosmic time.

adapted from http://sfb881.zah.uni-heidelberg.de/index.html

Result of Numerical Model for MW Formation

- Bulge forms first, then thick disk, then thin disk
- BUT at all time there are stars forming everywhere!

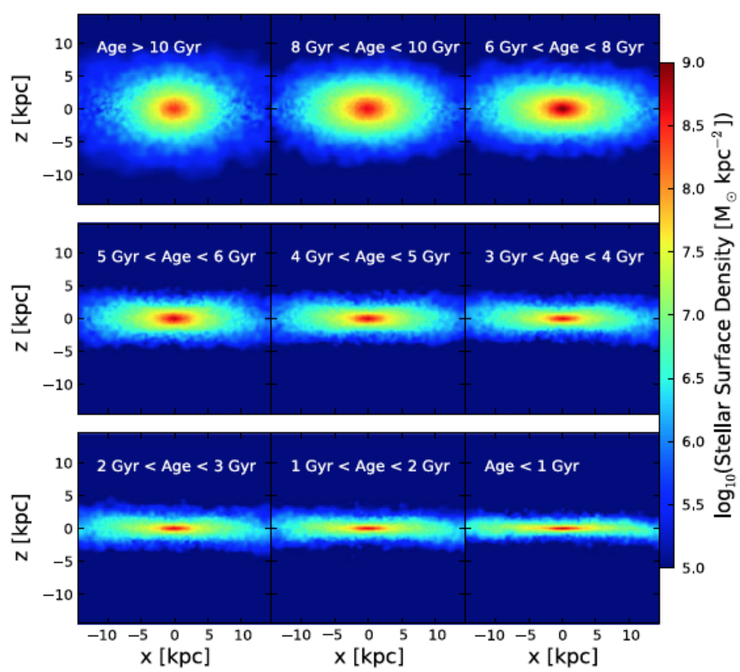


Fig. 17 Present-day structure of 'mono-age populations' in a cosmological formation simulation that led

Stinson et al 2013

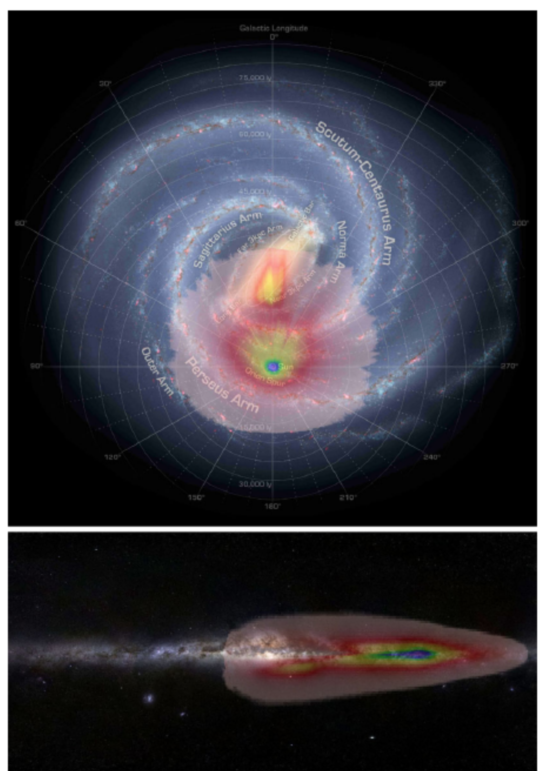
Why a Detailed analysis of the MilkyWay

- What processes might determine galaxy disk structure?

  what sets the exponential radial and vertical profiles of stars
- Were all or most stars born from a well-settled gas disk near the disk plane Or was some fraction of disk stars formed from very turbulent gas early on
- Are there discernible signatures of the stellar energy feedback to the interstellar medium a crucial 'ingredient' of (disk) galaxy formation models
- What was the role of mergers –an integral part of ΛCDM cosmogony?
  - How much stellar debris did they deposit ?
- All of these questions are not only relevant for the Milky Way in particular, but to spirals as a whole. (Adapted from Rix and Bovy 2013) and for formation models-the question of how to test for the importance of galaxy formation *ingredients* through comparison with observational data is actively under way.

Milky way Coverage of GAIA

- X. Luri and A. Robin



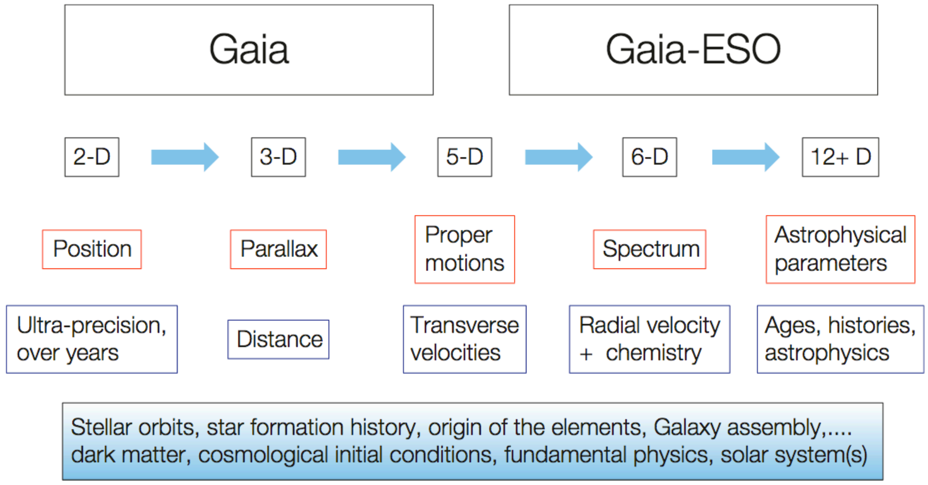
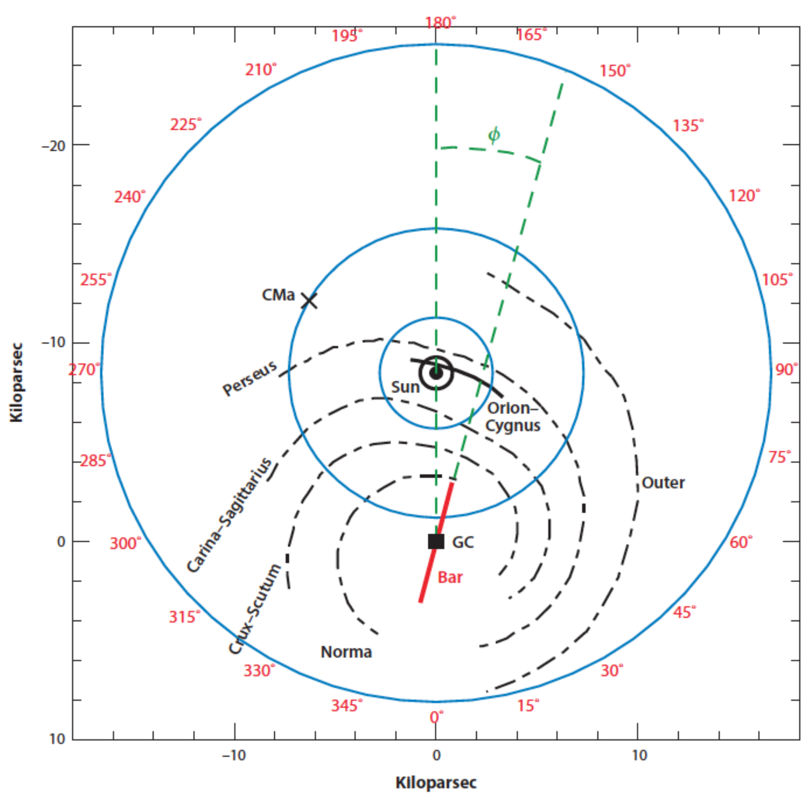


Figure 4. Illustration of the gain in physical probes with the combination of astrometry from the Gaia satellite and wide-area spectroscopic surveys, in this case the Gaia-ESO survey (Gilmore et al. 2012).

- https://arxiv.org/pdf/1604.04745.pdf R. Wyse

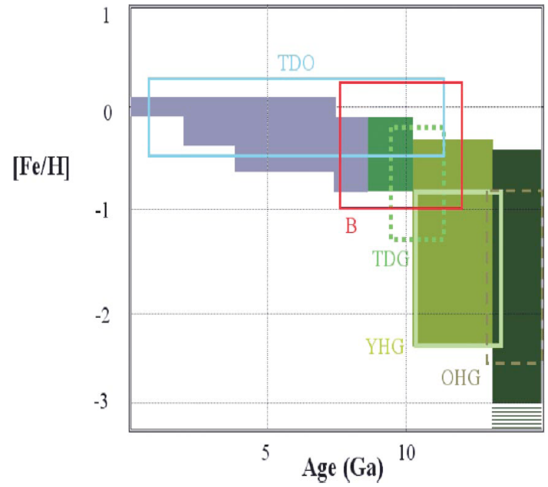
Where are We?



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 are "statistically" older.
- 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

Freeman and Bland-Hawthorn



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

- APOGEE/Segue data now allow a 3 D map of abundance variations.
- Gaia will provide distances
- RAVE (velocity information)
- DECcam- The DECam plane survey: optical photometry of two billion objects in the Southern galactic plane

arxiv 1710.01309.pdf

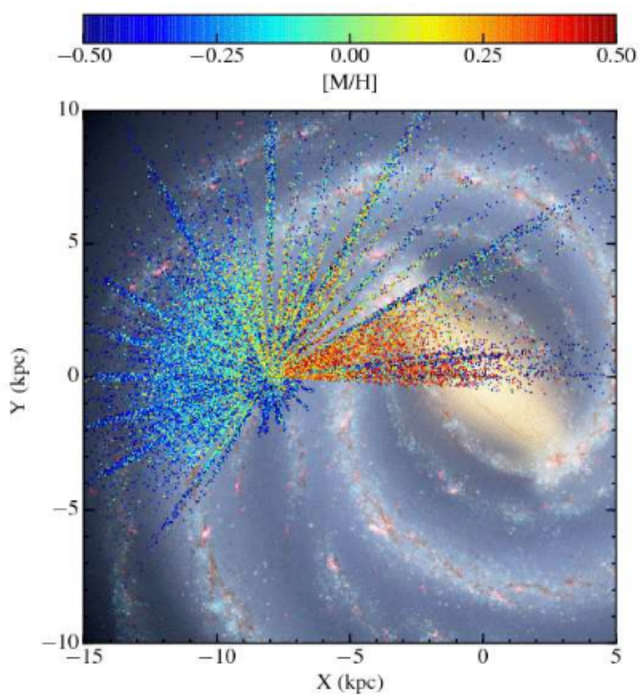


FIG. 25.— Same as Fig. 24, but with points color-coded by metallicities [M/H] and using stars with projected $|Z_{GC}| < 2$ kpc.

Next presentation

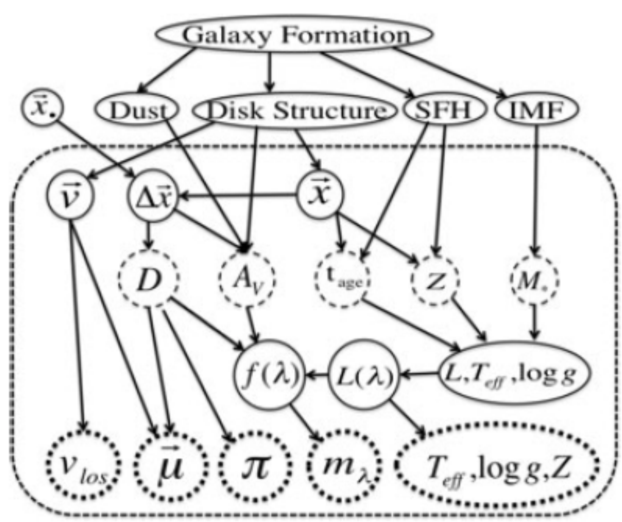
- GALAH- MNRAS Volume 449, pg21 chemical abundance of 10^6 stars

next paper to read (sections 1,2,3,6.4,6.5)

- Will be on Monday Oct 23 and is from Milena ?
- First presentation of round 2

Observables and What we Want to Learn

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



Rix and Bovy 2013

New surveys provide such information for large part of the MW

Gaia Capability

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

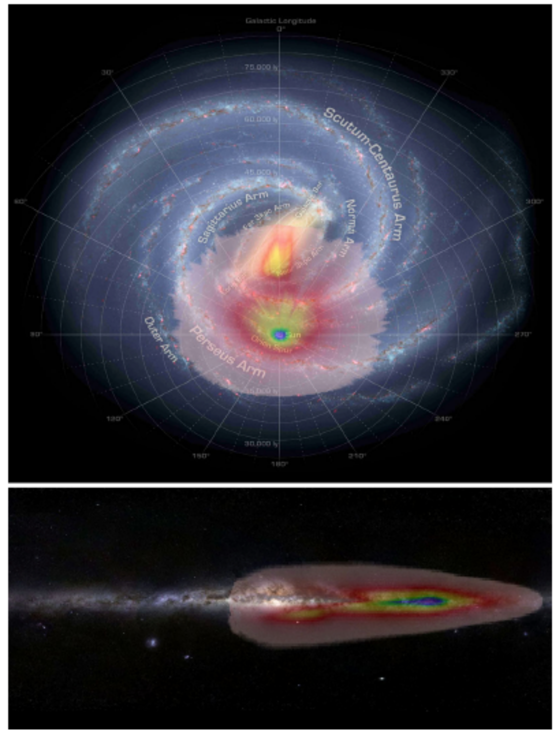
 Astron Astrophys Rev (2013) 21:61

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

SEGUE

- Designed to explore the Milky Way structure; formation history; kinematics; dynamical evolution; chemical evolution; and dark matter distribution.
- The images and spectra obtained by SEGUE-1 mapped the positions and velocities of hundreds of thousands of stars, over a wide range of luminosities and distances.
- Encoded within the spectral data are the composition and temperature of these stars, vital clues for determining the age and origin of different populations of stars within the Galaxy

- Observational data of stellar populations
- 1) Star counts (luminosity functions, colour-magnitude diagrams, metallicity distribution,velocity distribution functions) provide quantitative information about the stellar populations.

But require complete datasets or a detailed understanding of incompleteness.

2) Correlations (e.g metallicity vs scale height, age velocity distribution etc) provide information on the dominating physical processes of the the MW evolution. They require an unbiased selection of stars (or a grasp of the biases).

- These types of data will allow construction of full models of the formation of the disk and bulge. Constraining possible scenarios of growth of the disc in time and space.

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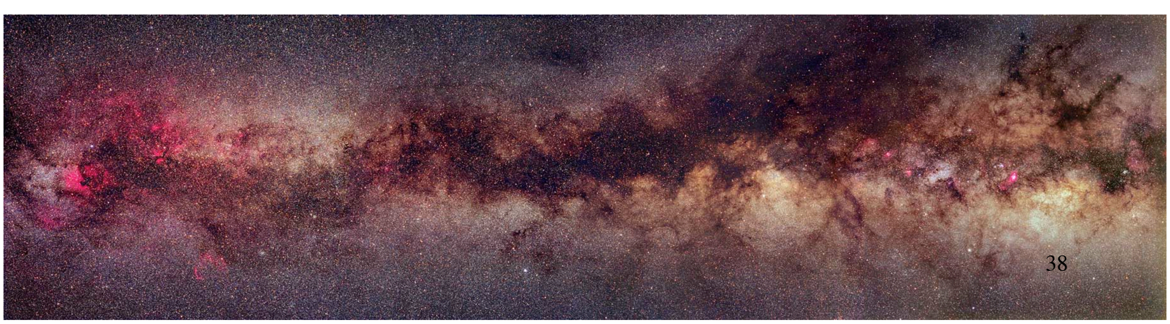
Nearby Stars

- 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 <100pc) (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 DPM≈ 50mas/yr ,corresponds to a velocity accuracy $\delta v \approx (D/4)$ km/s at distance D kpc.
  - 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 $9 < I < 12$. The average velocity errors that these surveys can achieve are of the order of 10 and 1 km/s, respectively.



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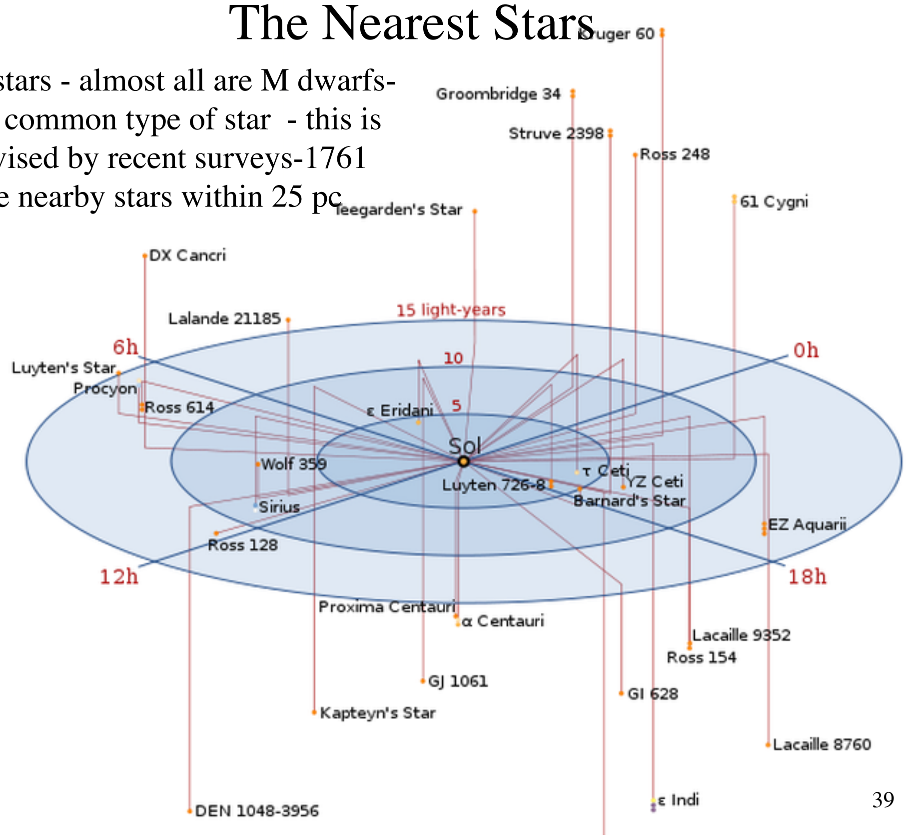
The Nearest Stars

- 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

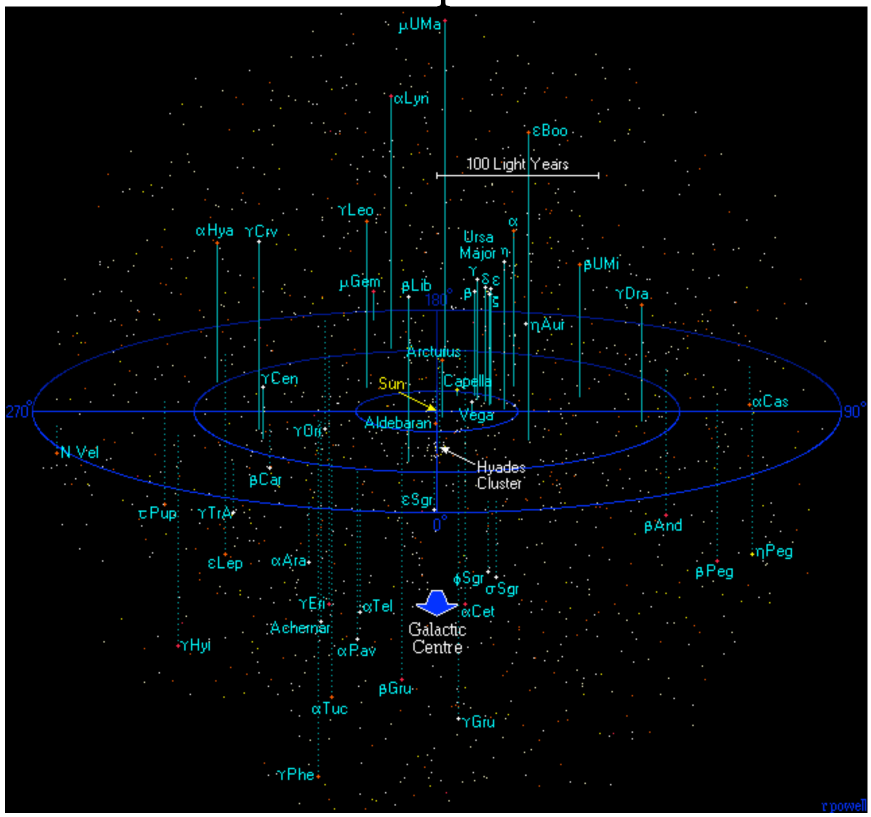


OnLine Tools

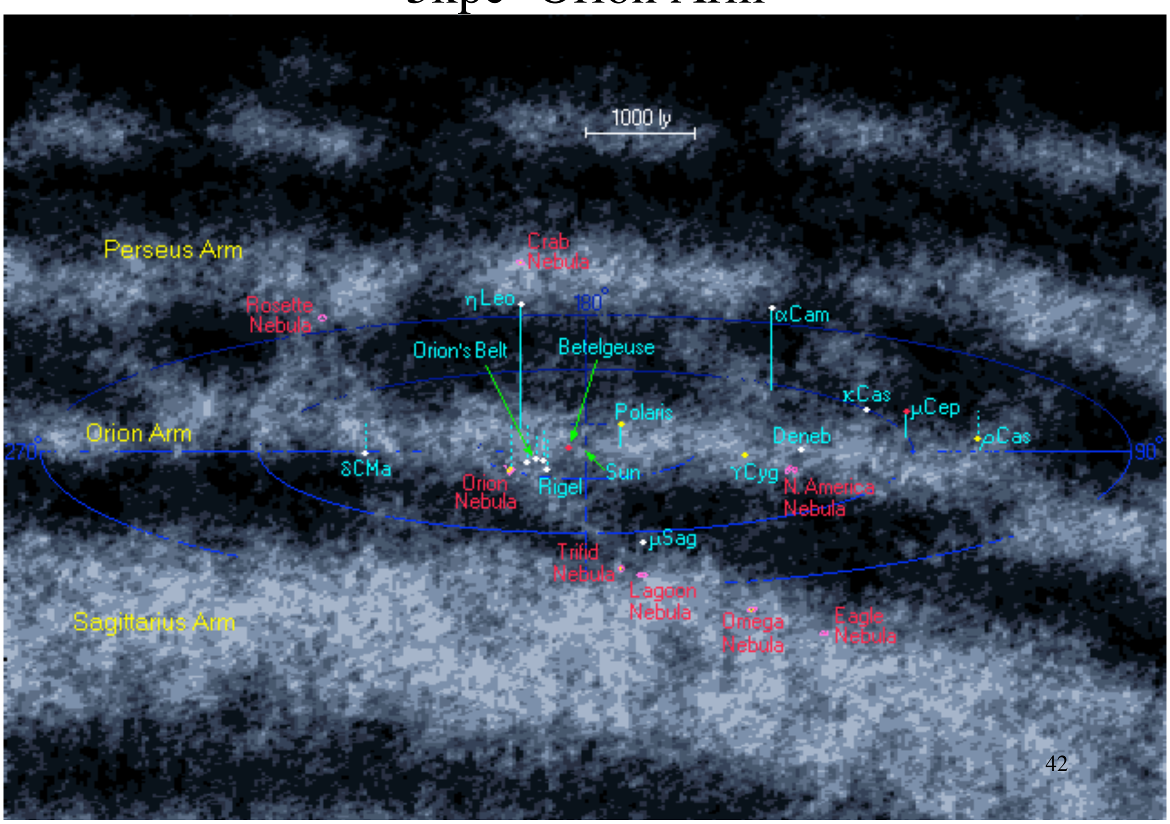
- Take a look at these to get a sense of the local stellar distribution(s)
- http://galaxymap.org/drupal/node/127
- stars.chromeexperiments.com/
- https://in-the-sky.org/ngc3d.php
  - Clicking on each marker brings up a information window containing links for further information. It may take a minute for the markers to display, so please be patien

Stars Within 250pc

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

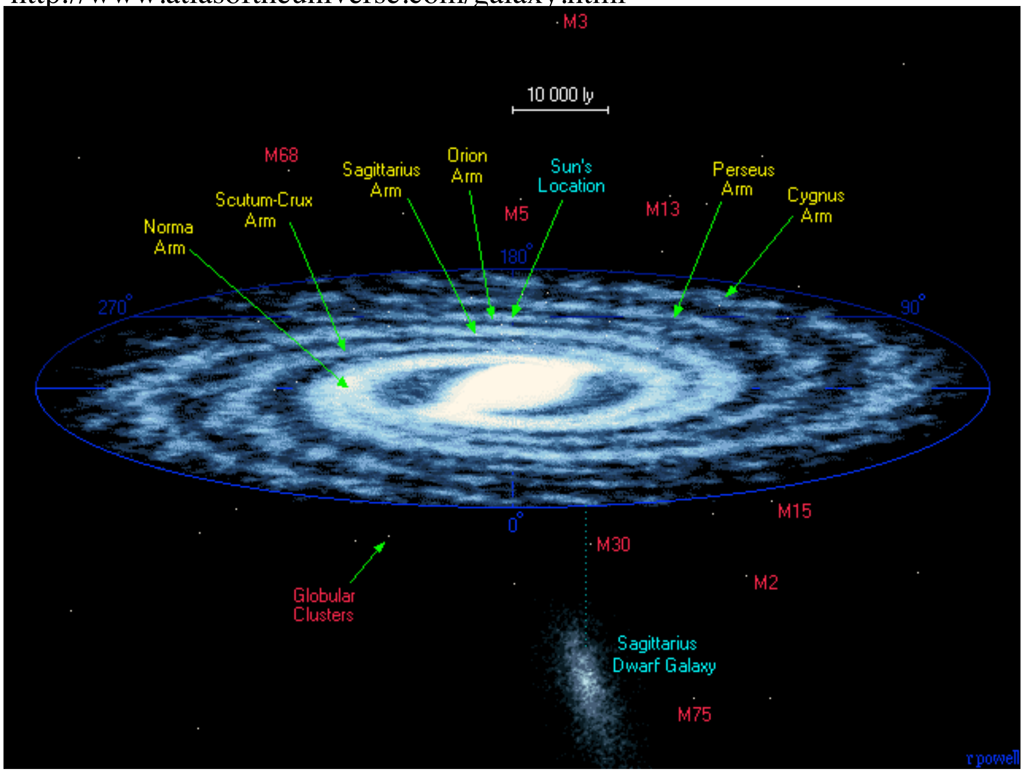


5kpc- Orion Arm

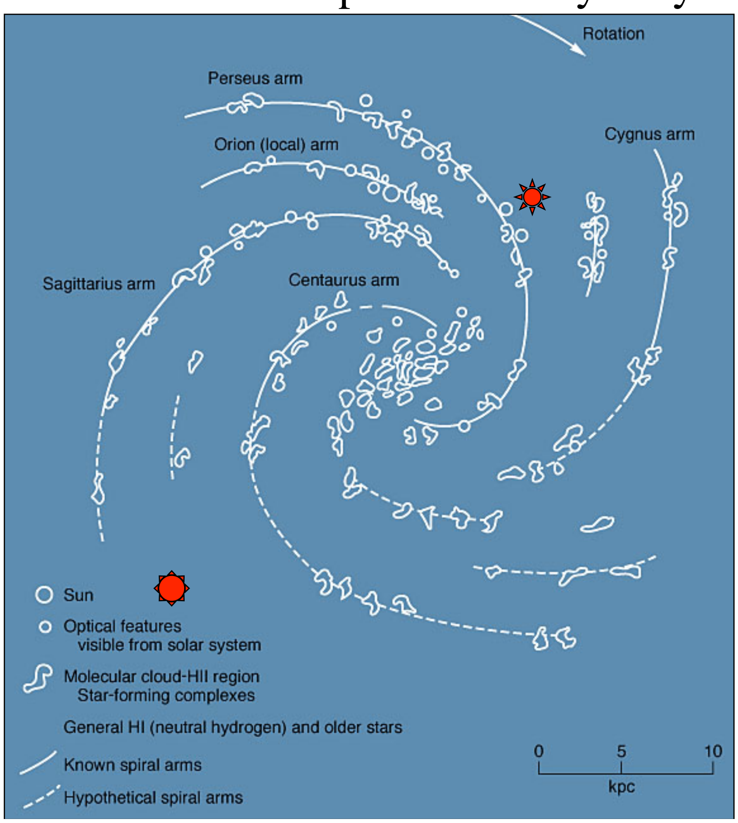


The MW

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



Map of the Milky Way Galaxy



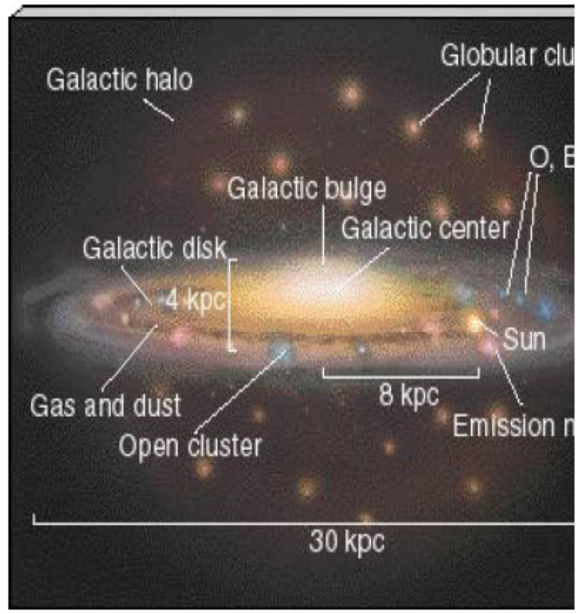
The map has been using HI velocity data sec 2.3.1 in S+G

Basic Structure of Milky Way

Bulge is quite spherical and is dominated by old stars

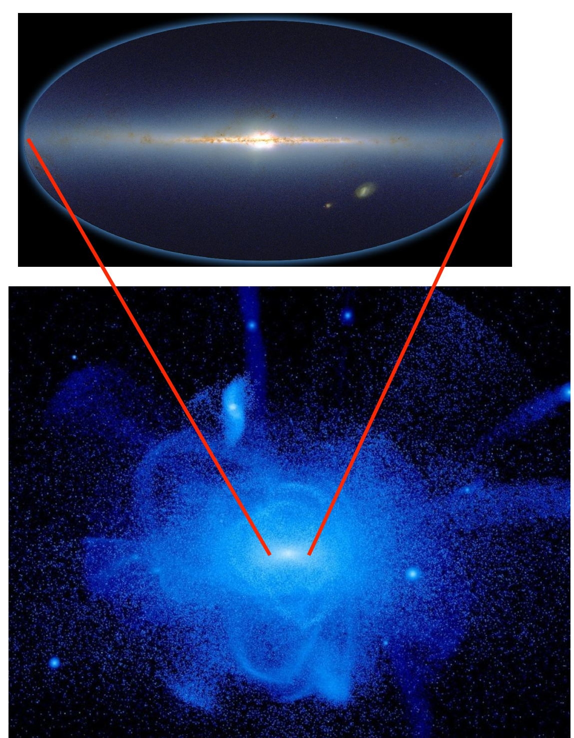
Disk- location of almost all the cold gas and most of the HI- site of star formation and thus young stars- wide range in metallicity

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



Theorists View of Dynamics of Stars in MW

- In cold dark matter theories of structure formation <u>many</u> mergers have occurred - it takes a VERY long time for the orbits to 'relax' and thus there should be dynamical signatures of the mergers
- Because of the long dynamical timescales in the halo, tidal tails, shells, and other overdensities arising from accreted dwarf galaxies remain observable over gigayears, constituting a fossil record of the Milky Way's accretion history
- Only in MW, M31 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

Tidal Streams-

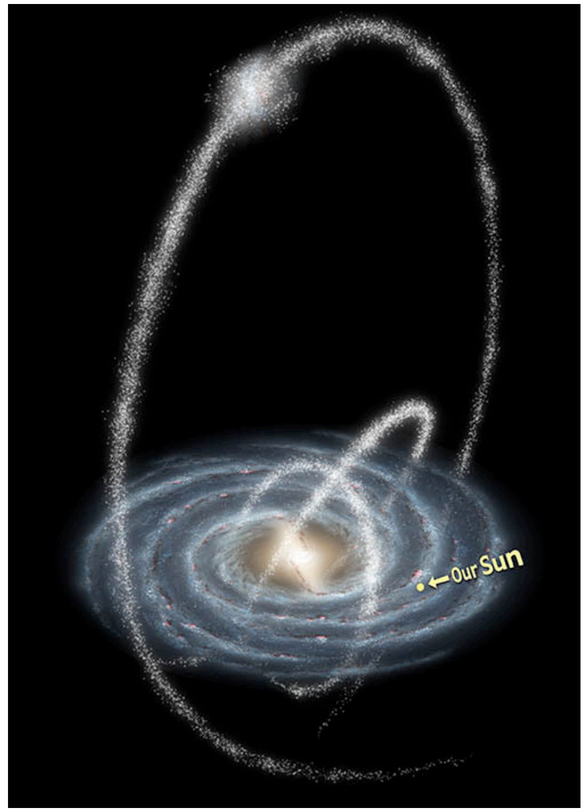
Test of standard formation paradigm

Within the context of the cold dark matter paradigm, structure formation proceeds hierarchically and galaxies are predicted to arise from the merger and accretion of many smaller sub-systems as well as from the smooth accretion of intergalactic gas

https://en.wikipedia.org/wiki/List_of_stellar_streams

Also in other galaxies-see

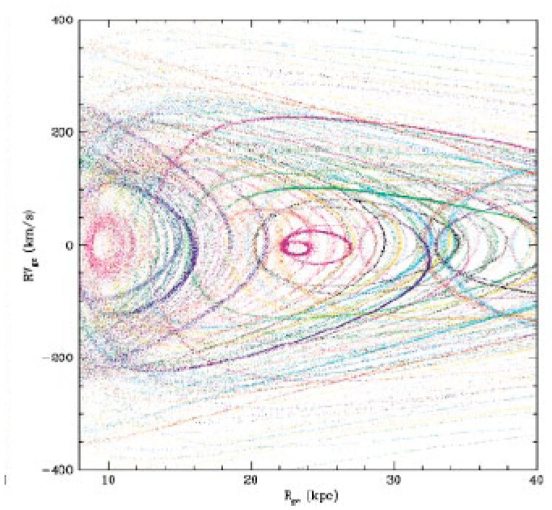
Substructure and Tidal Streams in the Andromeda Galaxy and its Satellites **arXiv:1603.01993**



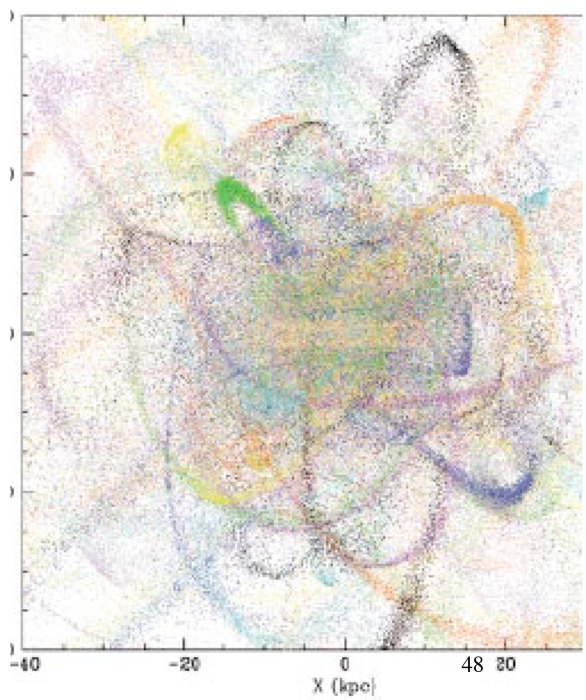
Theorists View- Continued

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

position of stars in x,z plane



radial velocity vs orbital radius

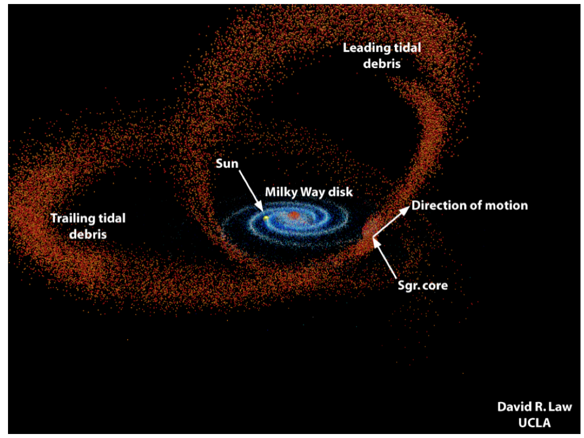


Simplified View of Streams MWB 12.2.2

- 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)- *cold streams*

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 streams are powerful diagnostics.

can be used to constrain the gravitational potential of their host system in a spherical potential, orbits (and thus also tidal streams) are confined to a plane. thus, the stream stars will be located on a great circle on the sky

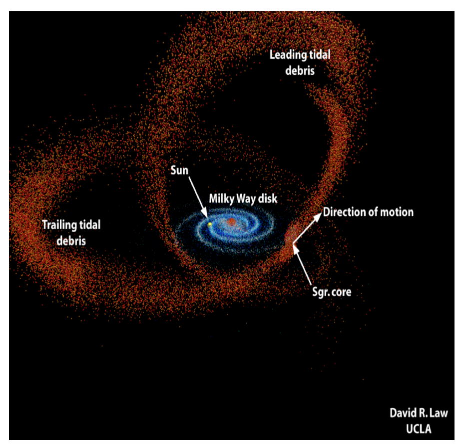
Simplified View of Streams

Tidal disruption radius MWB 12.2

dwarf has mass **m** and radius r_{dwarf}, 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

$(GMm/2)[(1/(R-r_{dwarf})^2 - 1/(R+r_{dwarf})^2)]$ $\sim GMmR/r^3$ when r<<R

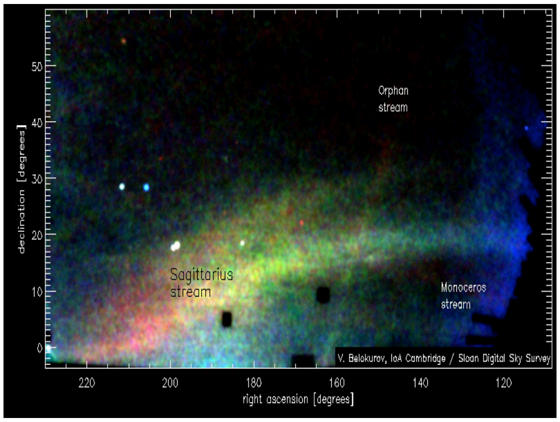


- 2 are equal when $\mathbf{r_{dwarf} \sim R(m/\mathit{k}M)^{1/3}}$
- ***k* depends on structure of object**
- See B&T sec 8.3 or Roche limit

$r_{tidal} = R[(m/M)/(3+m/M)]^{1/3}$

more precise derivation

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)