The Milky Way

Soon we will have vast amounts of data
on the motions and chemical properties
of millions to billions of stars
in the Milky Way.

What can we learn in this new era
about
the formation and dynamics of our Galaxy

Lecturer: Amina Helmi; Kapteyn Instituut, Room 190; ahelmi@astro.rug.nl

Bibliography:

•Freeman & Bland-Hawthorn, ARA&A (2002)

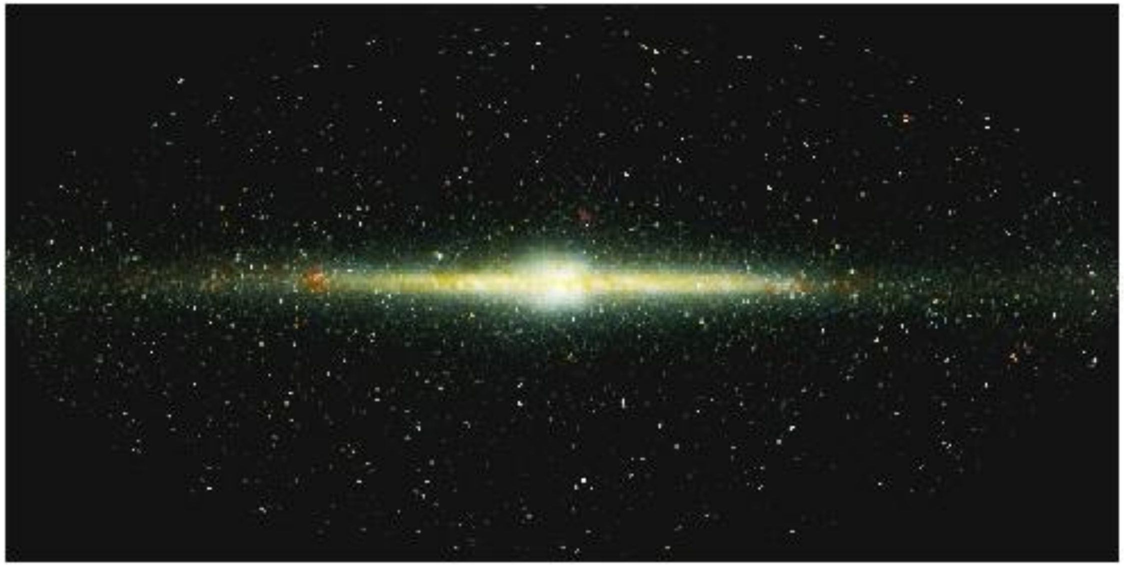
•Binney & Tremaine, Galactic dynamics

•Turon et al., "Galactic populations, Chemistry and dynamics", ESA-ESO Working Group, Report No. 4 (2008)

•Papers to be selected

What does our Galaxy look like ?

Near infrared image from COBE/DIRBE - dust is transparent in near-IR



NGC 891: our Galaxy probably looks much like this in visible light

The Milky Way is a disk galaxy with a small bulge

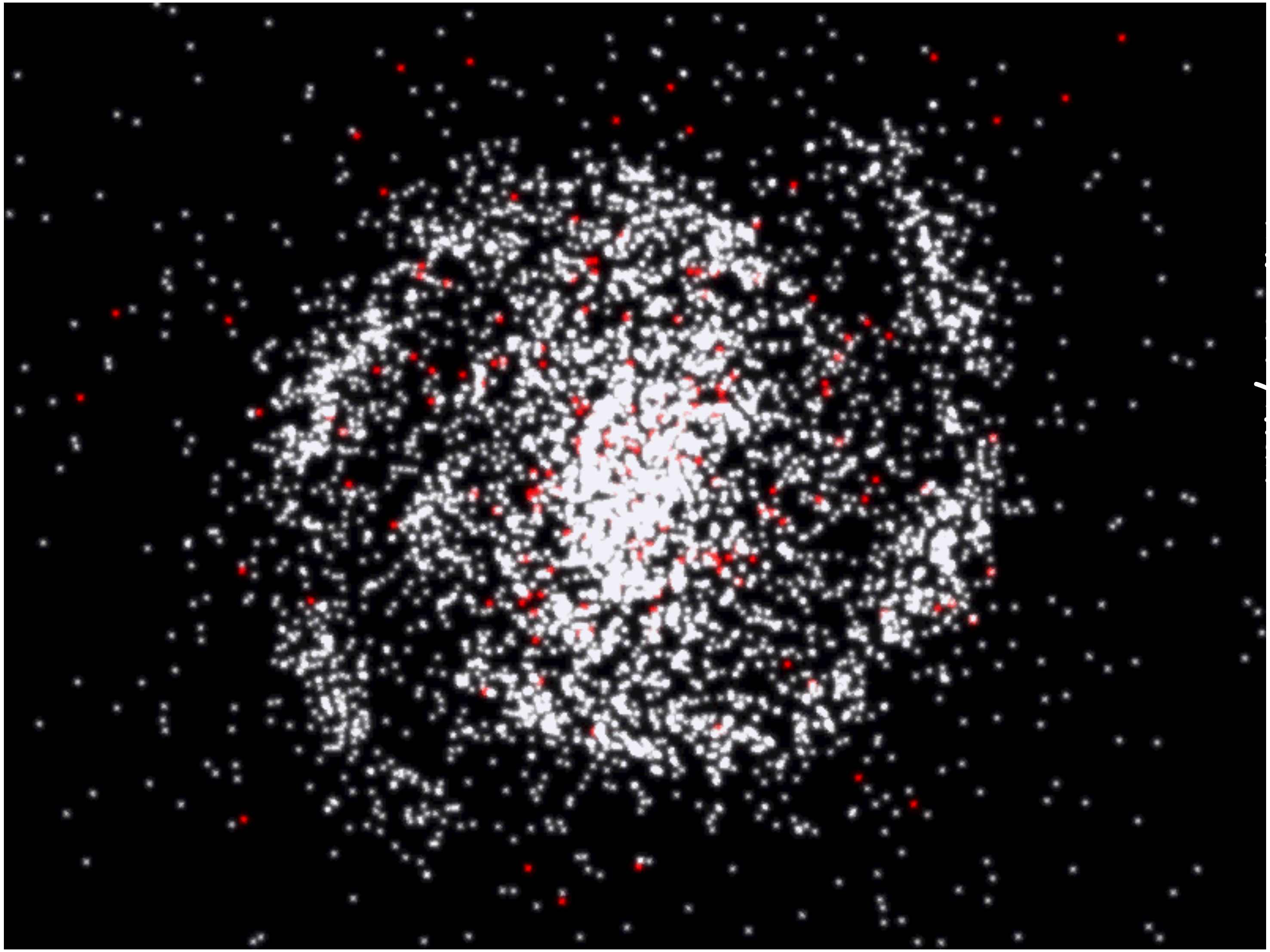
How did the Galaxy come to be like this ?

To study the formation of galaxies observationally,
we have a choice ...

we can observe distant galaxies at high redshift -
we see the galaxies directly as they were long ago,
at various stages of their formation and evolution

but not much detail can be measured about their
chemical properties and motions of their stars


Hubble Deep Field



Dynamical/Kinematical/Chemical/Ages information all available, and constrain assembly history

or we can recognise that
the main structures of the Galaxy formed long ago
at high redshift.

the halo formed at $z > 4$
the disk formed at $z \sim 2$

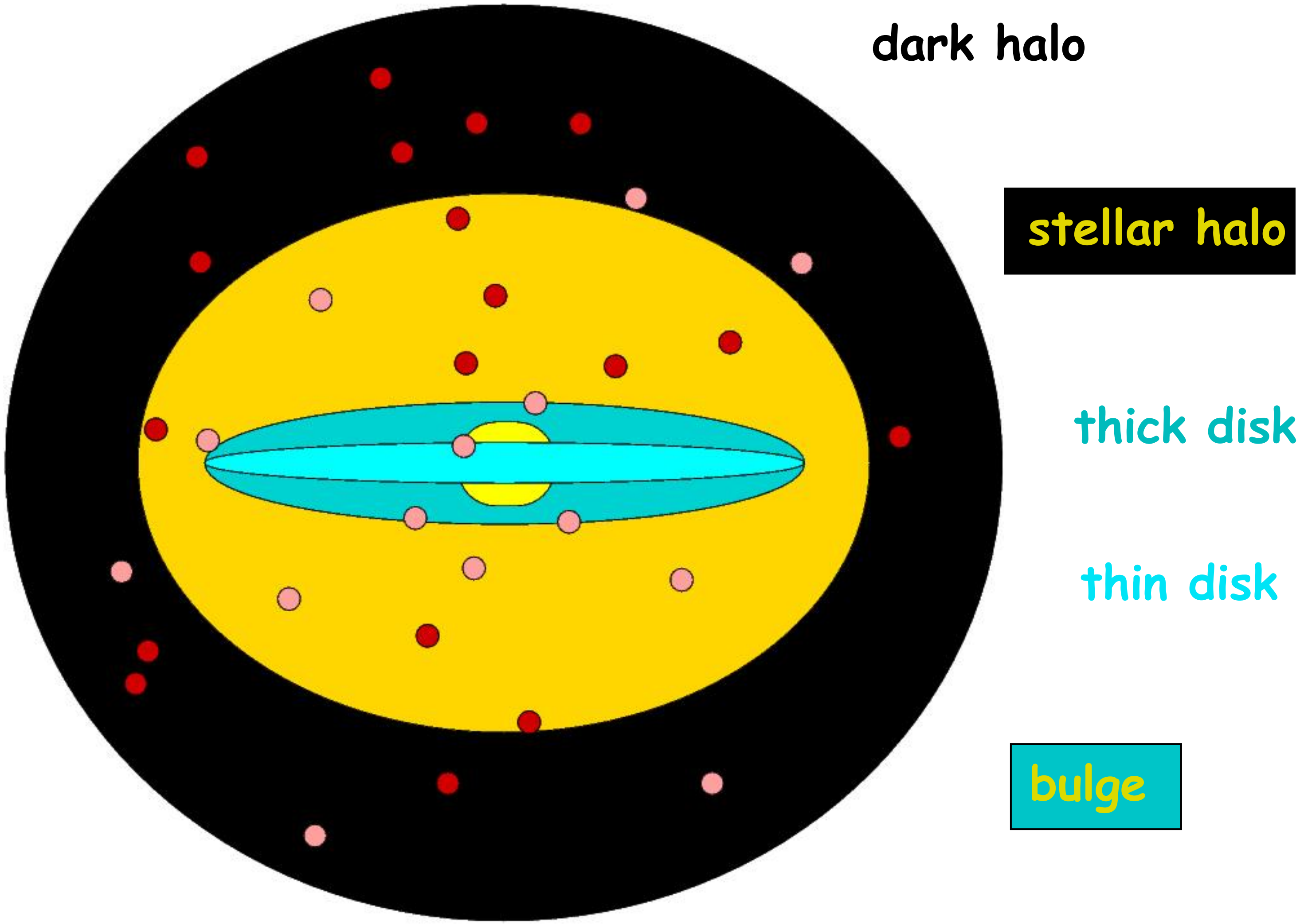
We can study the motions and chemical properties of
stars in our Galaxy
at a level of detail that is impossible for other galaxies,
and probe into the formation epoch of the Galaxy.

This is near-field cosmology.

The ages of the oldest stars in the Galaxy
are similar to the lookback time
for the most distant galaxies
observed in the HDF.

Both give clues to the sequence of events
that led to the formation of galaxies
like the Milky Way

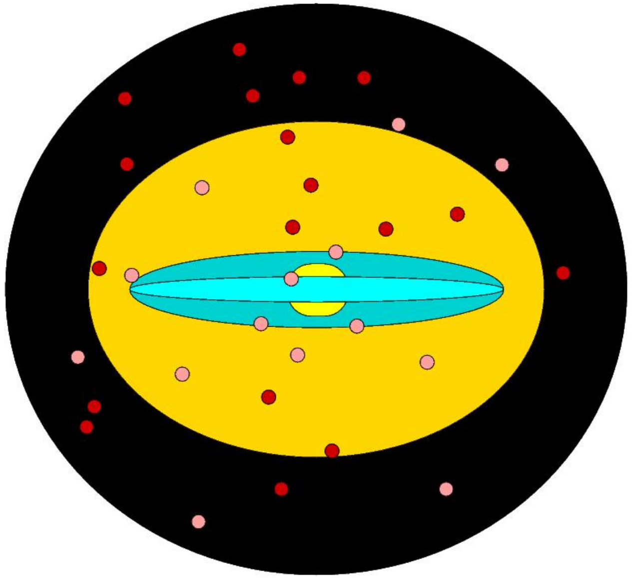
Overview of our Galaxy



Total mass ~ 10^{12} M_sun :

(5 x 10^{11} M_sun out to 50 kpc)

Wilkinson & Evans (1999), Battaglia et al (2005)



Stellar mass in bulge ~ 1 x 10^{10} M_sun

disk 6 x 10^{10} M_sun

halo 1 x 10^{9} M_sun

Ages of components:

globular clusters ~ 12 Gyr; some outer clusters 1-2 Gyr younger

thick disk : > 10 Gyr

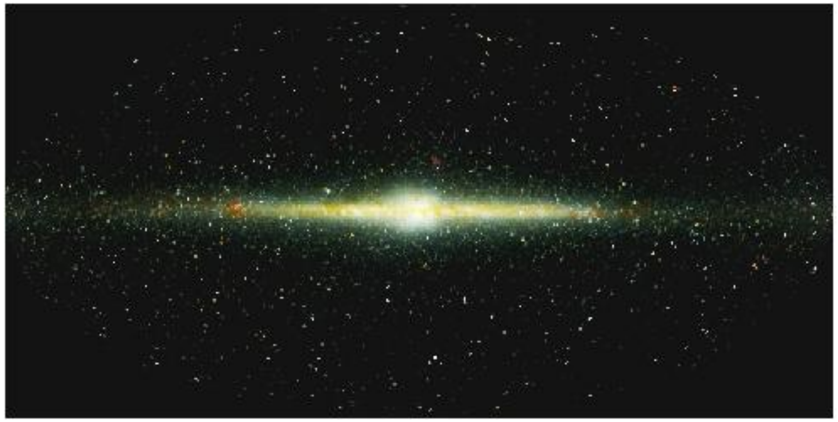
thin disk : star formation started about

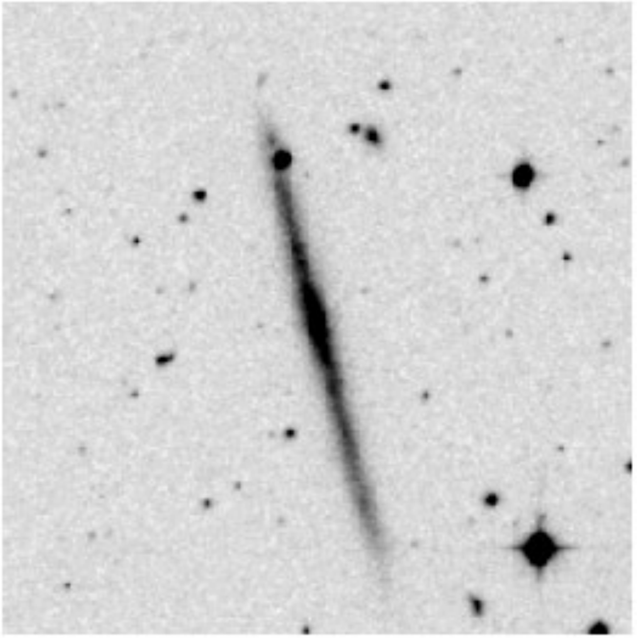
10 Gyr ago from white dwarfs (eg Legget et al 1998)

8 Gyr ago from old subgiants (Sandage et al 2003)

star formation in the disk has continued at a more or less constant rate to the present time

The thin disk





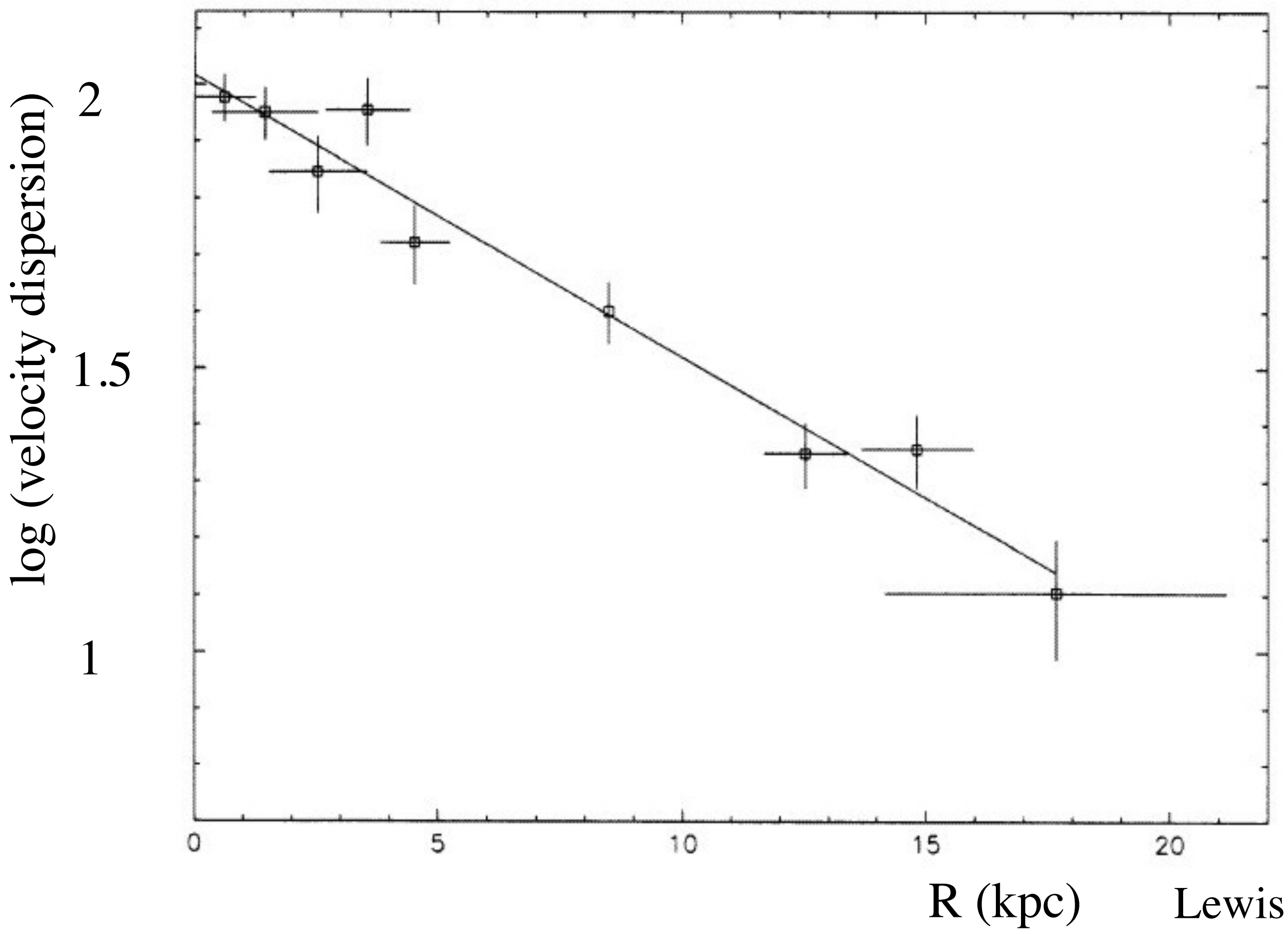
The thin disk is the most massive stellar component of the Milky Way

- Most of the gas is found here
- dust hides stellar light in optical wavelengths
- Sun is near the outer edge, at d ~ 7.6 +- 0.3 kpc

Structure of the thin disk

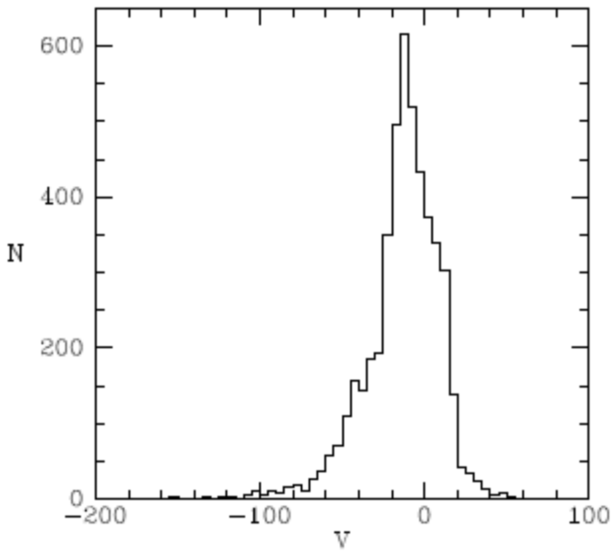
exponential in R and z : scaleheight ~ 300 pc, scalelength 2-4 kpc (!)

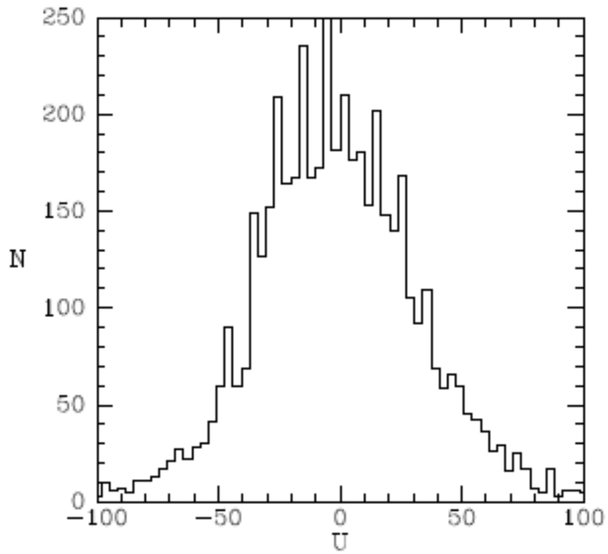
velocity dispersion decreases from ~ 100 km/s near the center (similar to bulge) to ~ 15 km/s at 18 kpc



Lewis & Freeman 1989

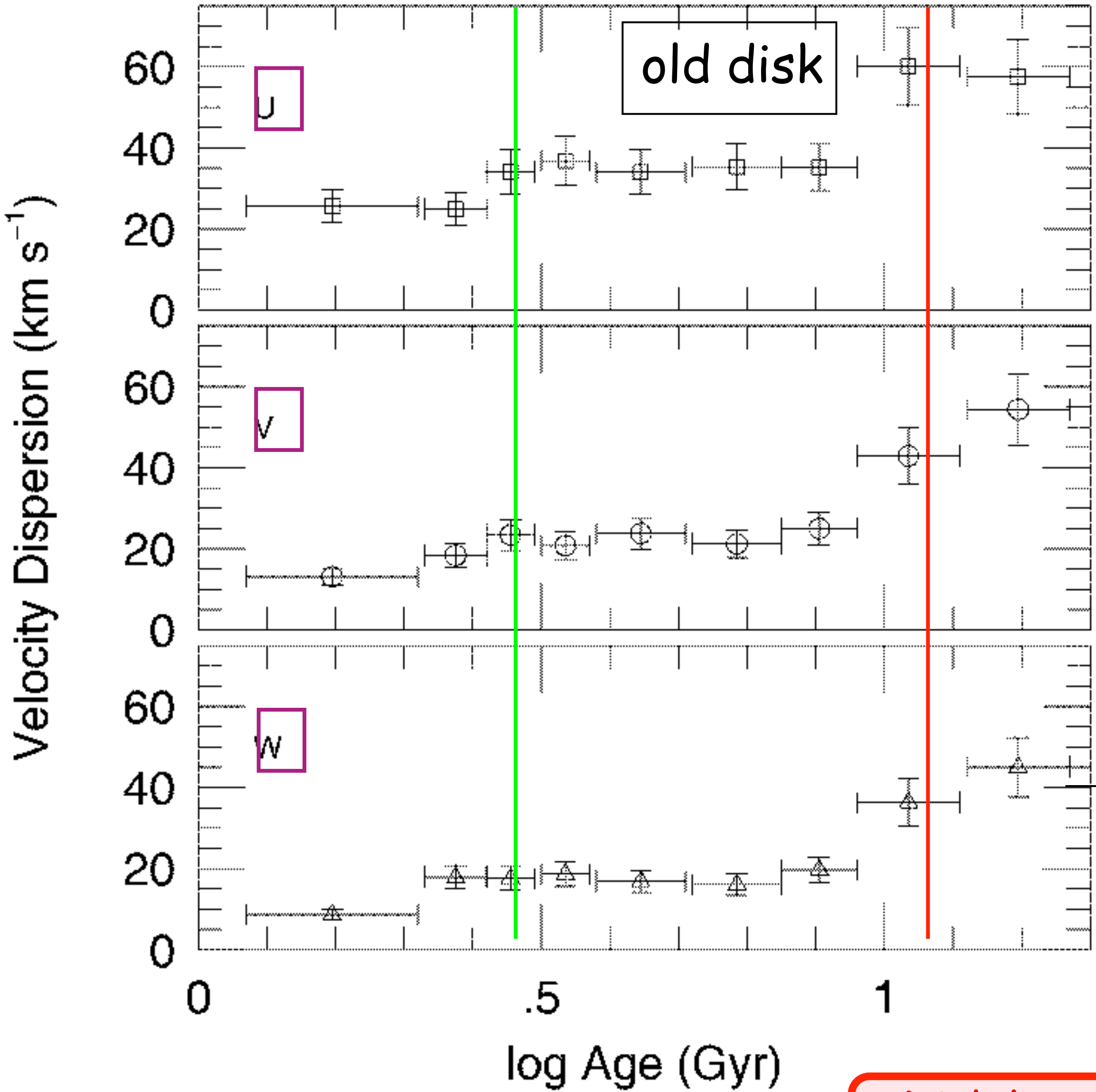
Solar neighborhood kinematics:





Nordstrom et al. 2005

- Stars move on nearly circular orbits
- Distributions are approximately Gaussian (in U and W)
- V-velocity is skew (more stars with $V < 0$; moving slower than the LSR)
- Velocity dispersion depends on colour (as a tracer of the age)



Velocity dispersions of nearby F stars

thick disk

appears at age ~ 10 Gyr

Disk heating appears to saturate at 2-3 Gyr; jump at 10 Gyr?

Freeman 1991; Edvardsson et al 1993; Quillen & Garnett 2000

Solar neighborhood kinematics:

Several mechanisms for heating disk stars:

- stochastic in the disk:
  - transient spiral arms
  - Giant Molecular Clouds scattering (eg Fuchs et al 2001),

- stochastic because of external agents
  - accretion events

Internal heating mechanisms should saturate after a few Gyr:

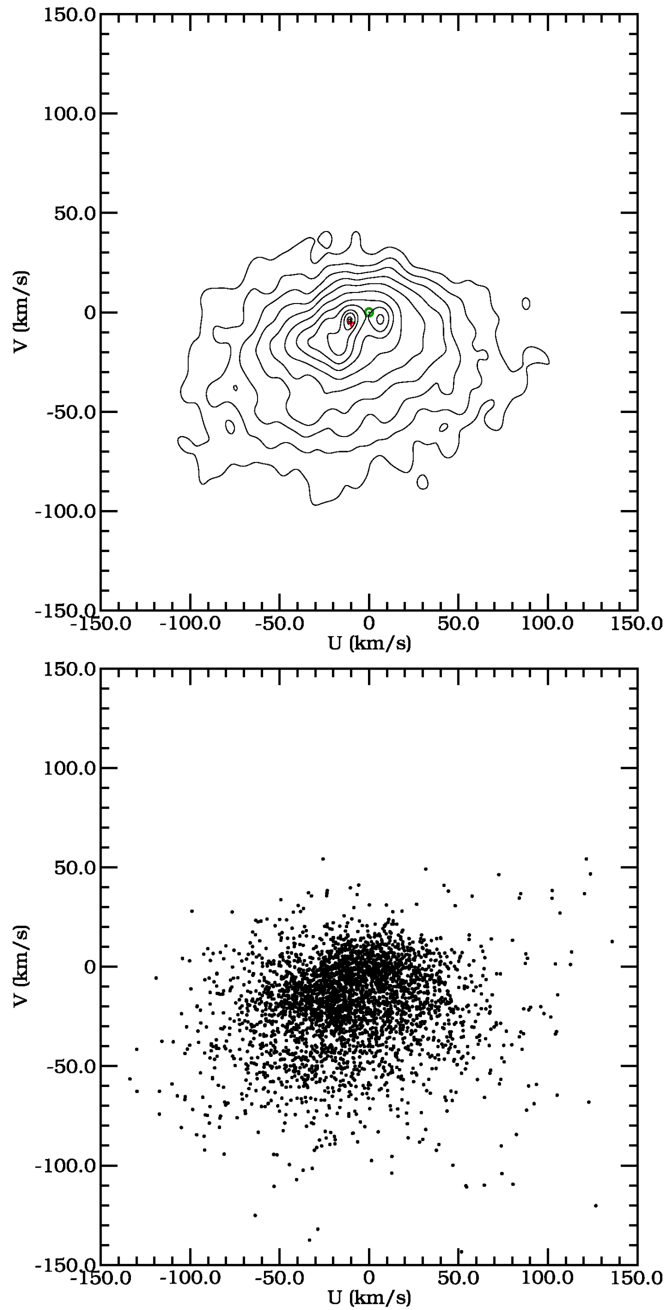
since the heated stars spend less time near galactic plane (and so are less subject to these mechanisms)

However, the bar may also lead to change in the orbits of stars, and act as a "scattering agent"… radial migration

Velocity distributions near the Sun

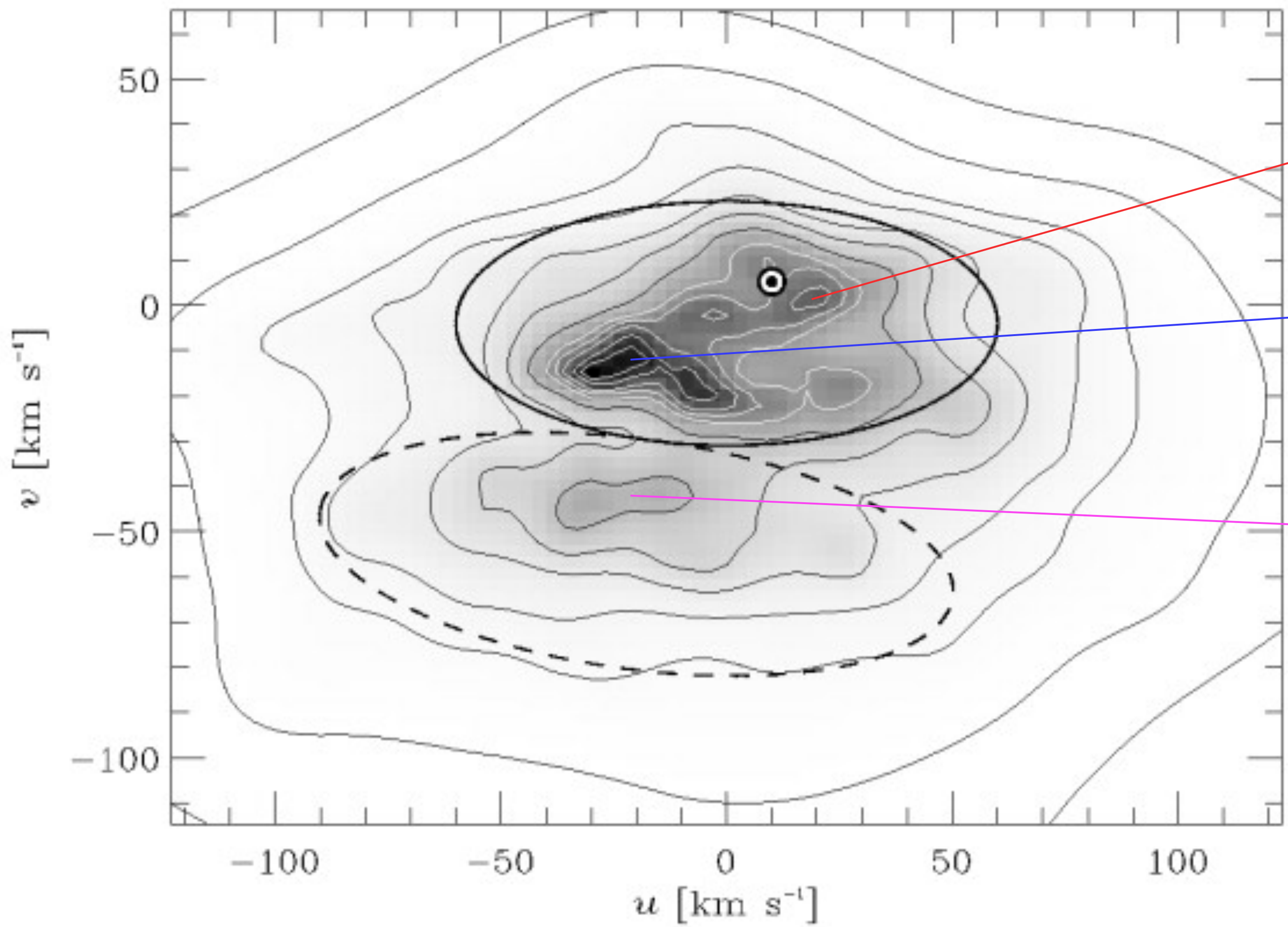
- Not completely smooth
- Substructures are evident

- "Moving groups"
  - Clusters, associations or dissolved clusters
  - Associated to dynamical perturbations
  - Accreted stars



Breddels et al. 2009

Some moving groups are probably associated with local resonant kinematic disturbances by the inner bar : OLR is near solar radius (Hipparcos data) : Dehnen (1999), Fux (2001), Feast (2002)

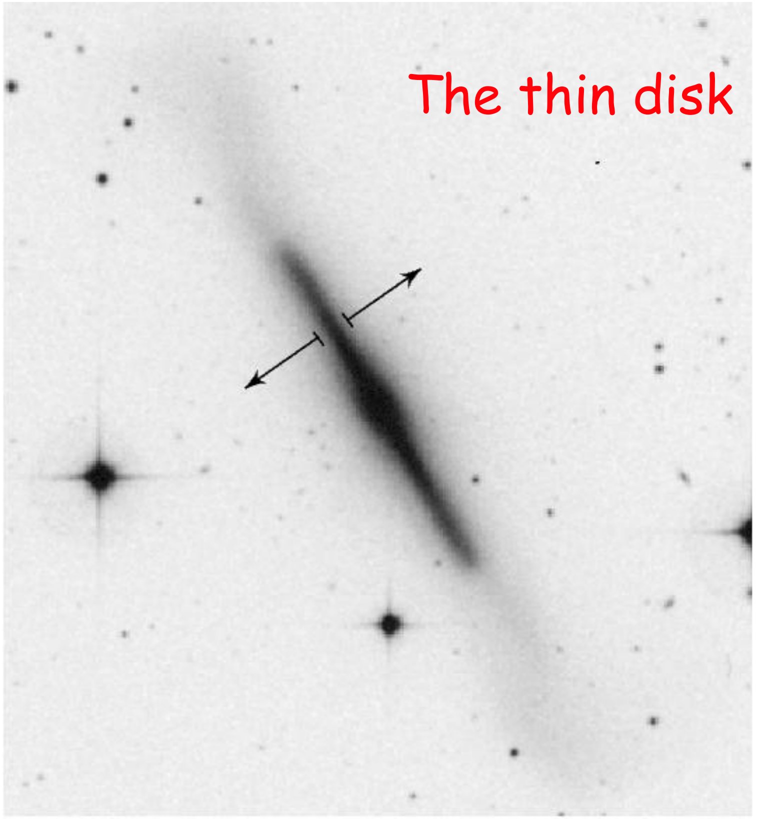


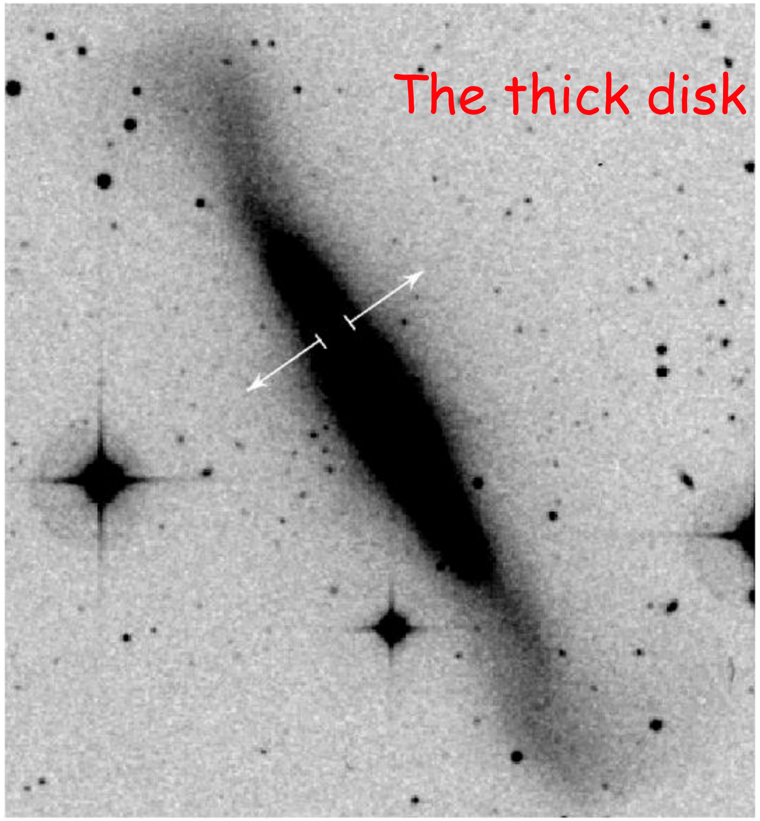
Sirius and Hyades streams - mainly earlier-type stars

Hercules disturbance from OLR -mainly later-type stars

Dehnen 1999

Most spirals (including our Galaxy) have a second thicker disk component . In some galaxies, it is easily seen



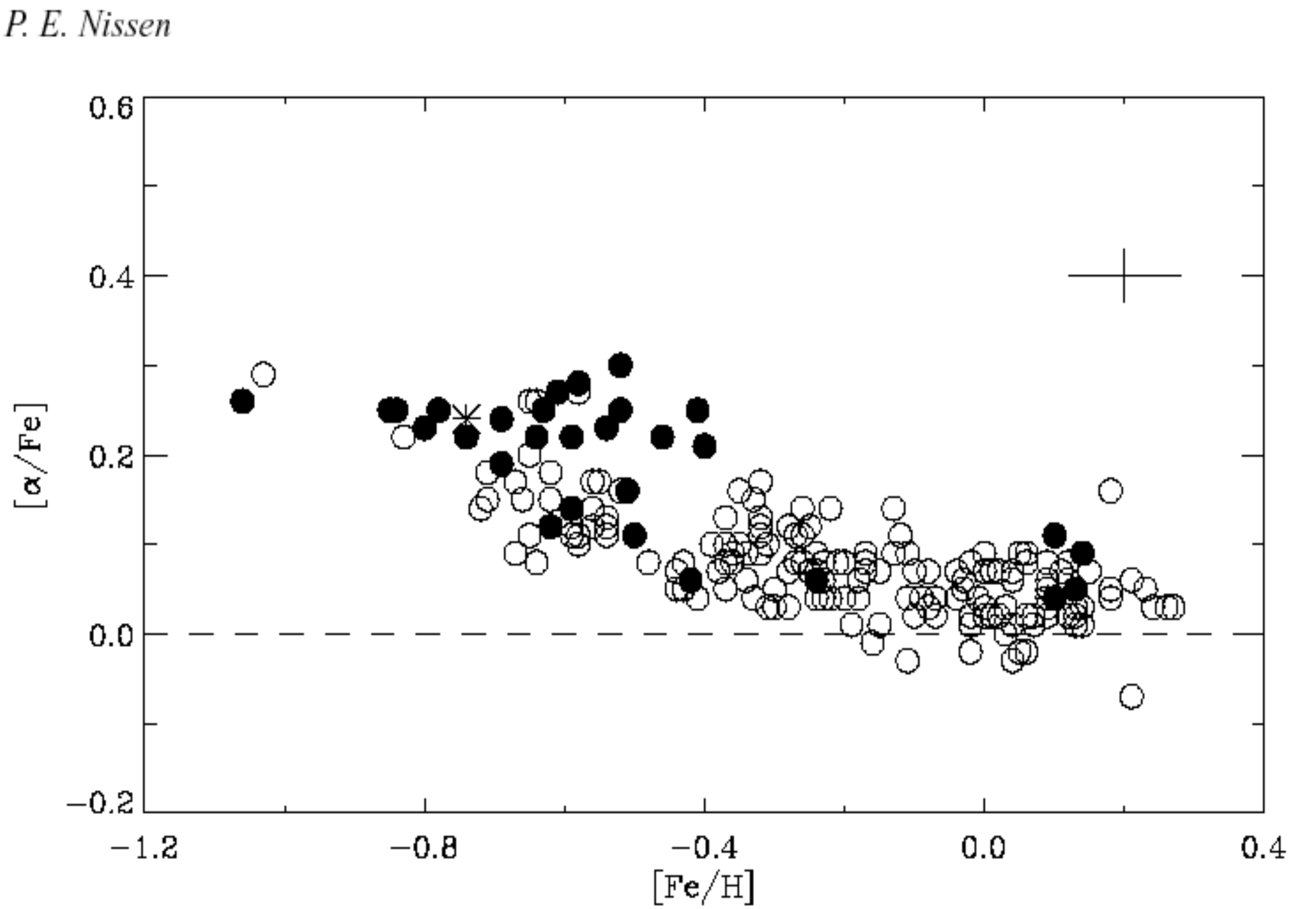


NGC 4762 - a disk galaxy with a bright thick disk (Tsikoudi 1980)

Our Galaxy has a significant thick disk

- its surface brightness is about 10% of the thin disk's.
- it rotates almost as rapidly as the thin disk
- its stars are older than 12 Gyr, and are
- significantly more metal poor than the thin disk (-0.5 > [Fe/H] > -2.2) and
- alpha-enriched

The galactic thick disk: α-enriched



kinematically selected

- ● thick disk
- ○ thin disk

α elements: produced by SNII (massive stars; short timescales)

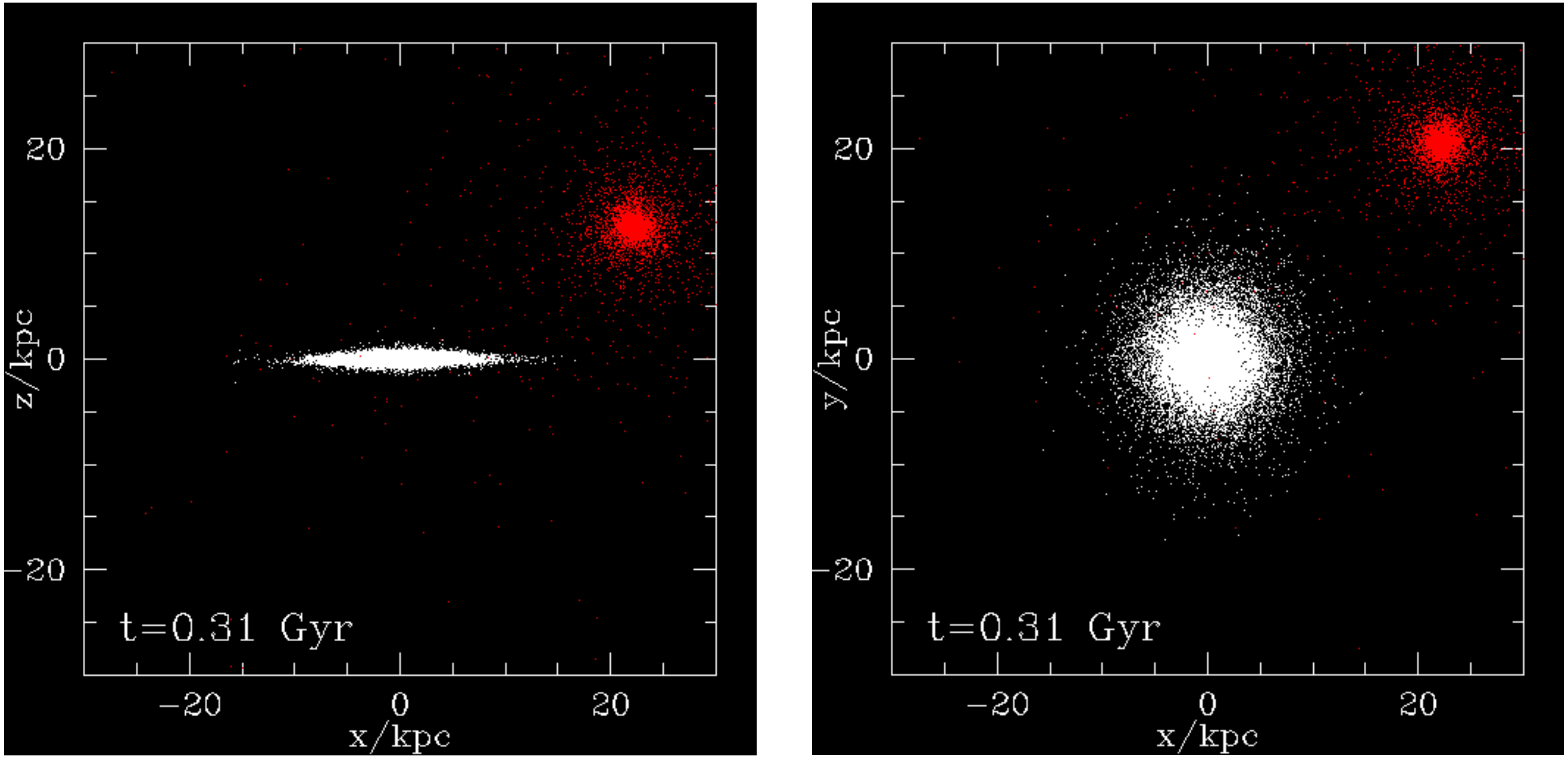
Fe produced by SNIa (binary stars with WD; longer timescales)

higher [α/Fe] ⇒ more rapid formation

Because of its rapid rotation, the Galactic thick disk may have formed from heating of the early stellar disk by accretion events or minor mergers

Thick disks

Possible formation scenario is heating by minor merger of pre-existent disk (e.g. Quinn et al 1986)



Villalobos & Helmi (2008)

How can we tell observationally the "red" and "white" stars from eachother?

Because of its rapid rotation, the Galactic thick disk may have formed from heating of the early stellar disk by accretion events or minor mergers

- In some models, the thick disk may have come from an early rapid phase of gas accretion or from merger debris
  (Abadi et al 2003; Brook et al 2004, Yoachim & Dalcanton 2004)

- No agreement yet on the origin of the Galactic thick disk

- Debate as to whether it is really independent of the thin disk, and about the importance of radial migration (Schoenrich & Binney 2008, 2009, Roskar et al. 2008).

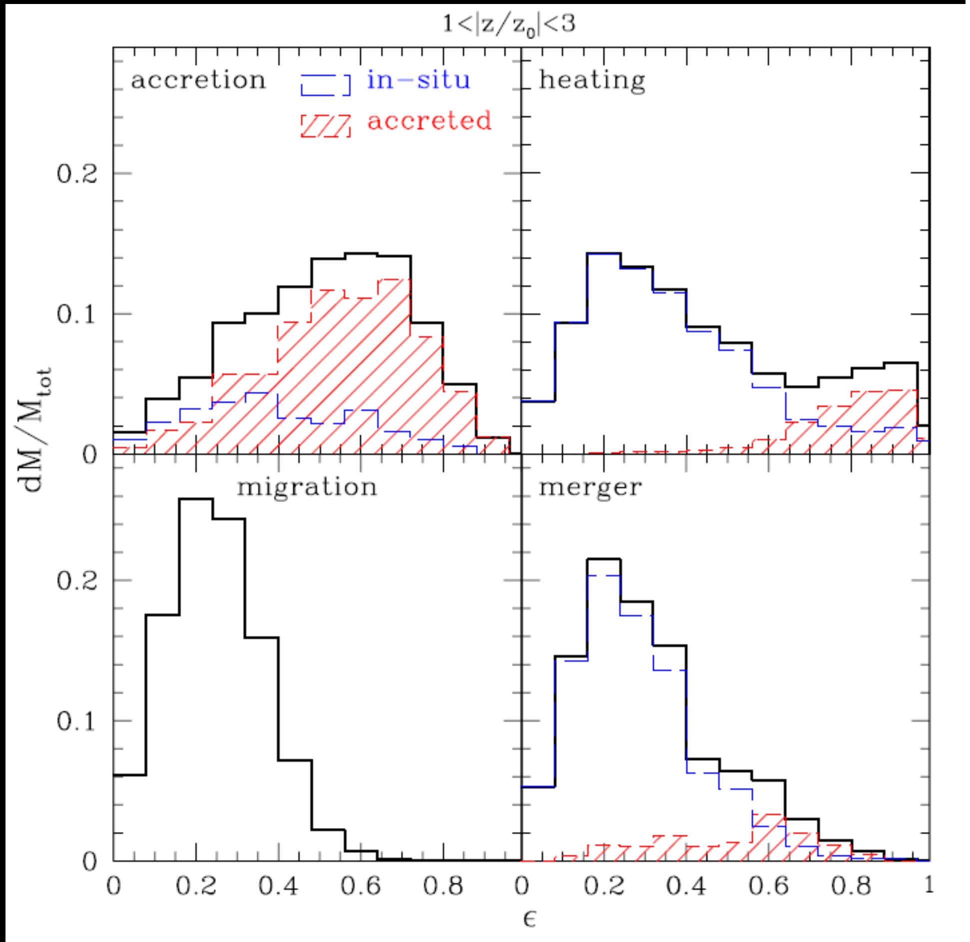
A powerful test of formation: orbital eccentricity

- Stars' orbits:
  - pre-existing disk: fairly circular
  - from satellite: eccentric

- Generic test for any model of formation:
  e-distribution

1. Whole disk by accretion > Flat

2. Pre-existing disk >
   - Pronounced peak at low e
   - Secondary peak at high e
     (if by merger event)

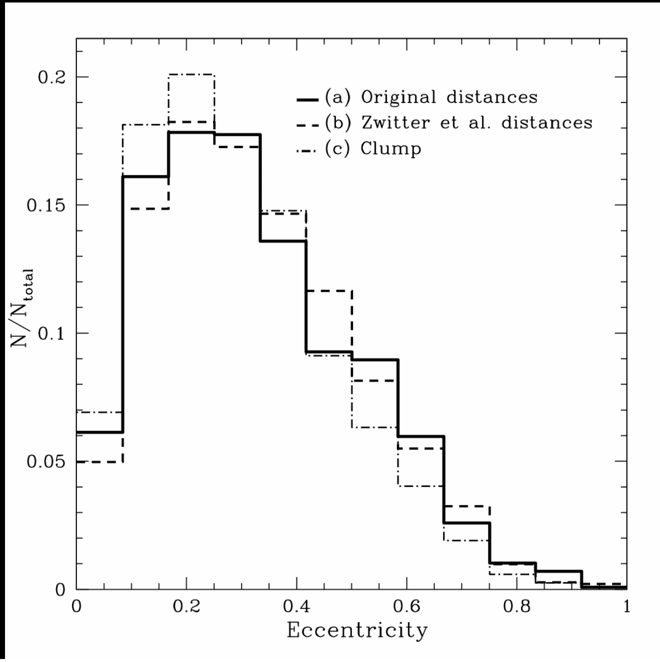


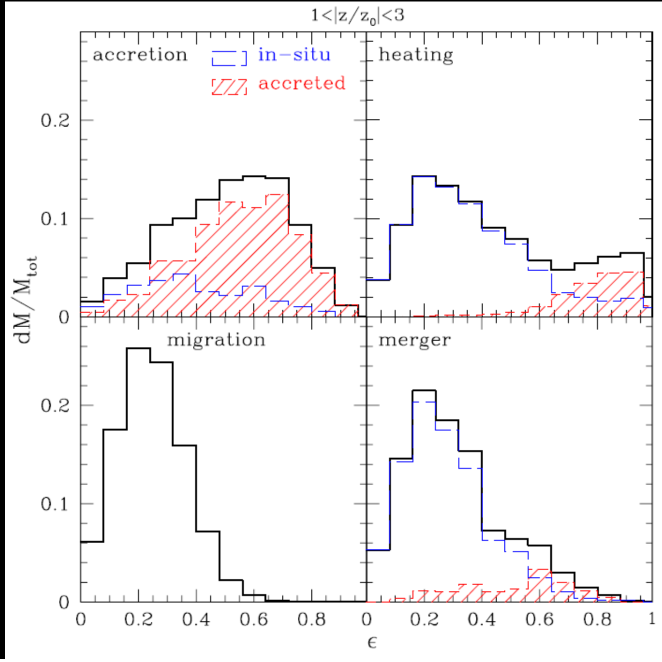
Sales et al. 2009

Eccentricity distribution and models

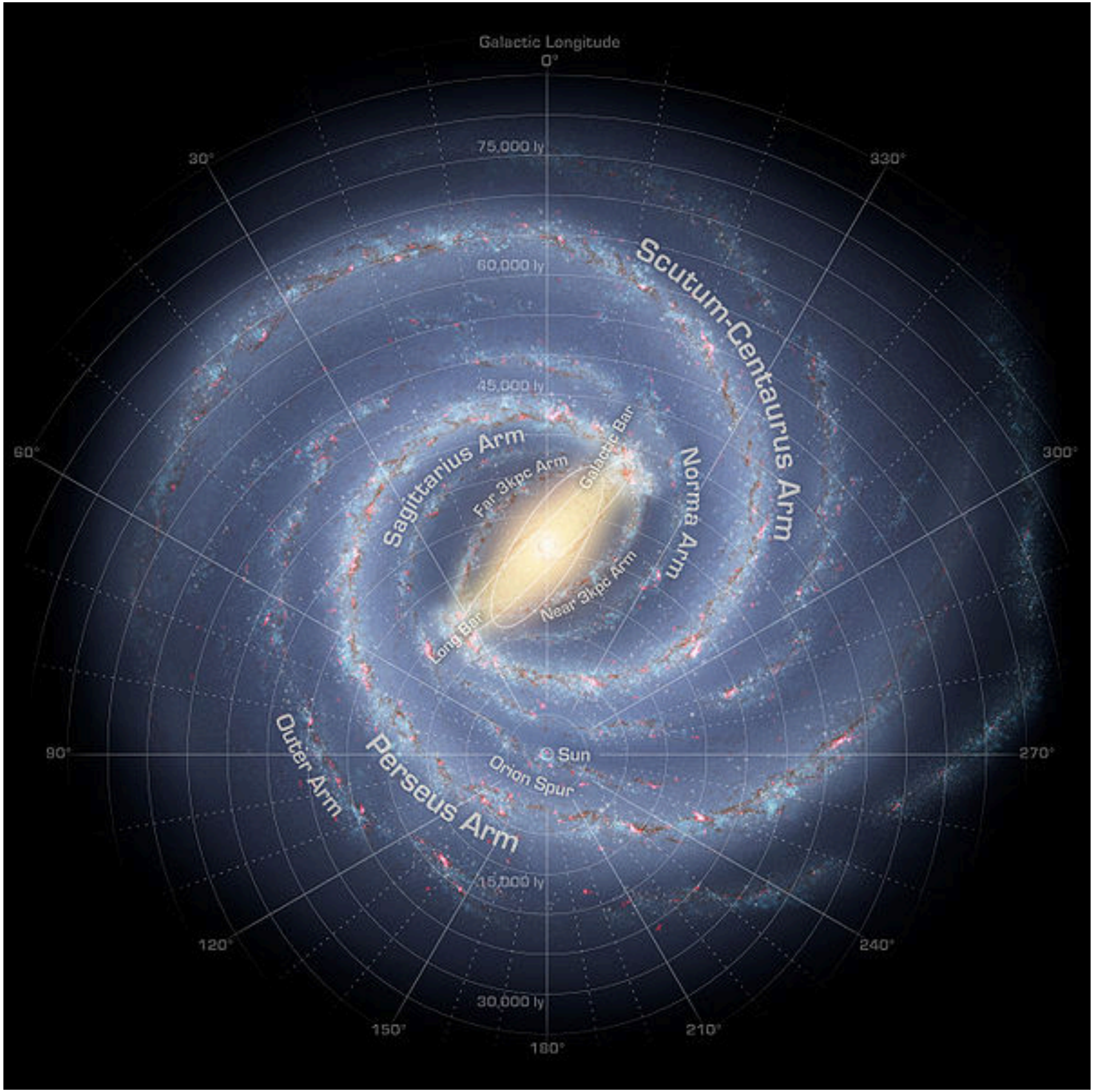
- Integrate orbit in Galactic potential to derive e-distr for RAVE sample of stars
- Prominent peak at low ecc rules out accretion model
  - Most thick disk stars formed in-situ
- Shape appears most consistent w/merger model
  - Heating model shows second peak (not present in data; see Di Matteo et al 2010)
  - Migration model more symmetric than apparent in data

Sales et al. 2009



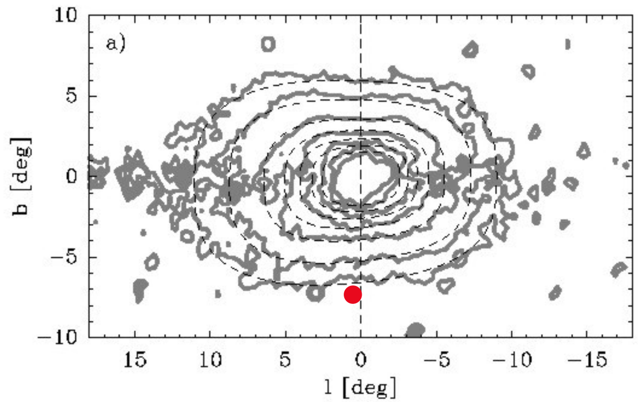


Wilson et al. (2011)
Dierickx et al.(2010)

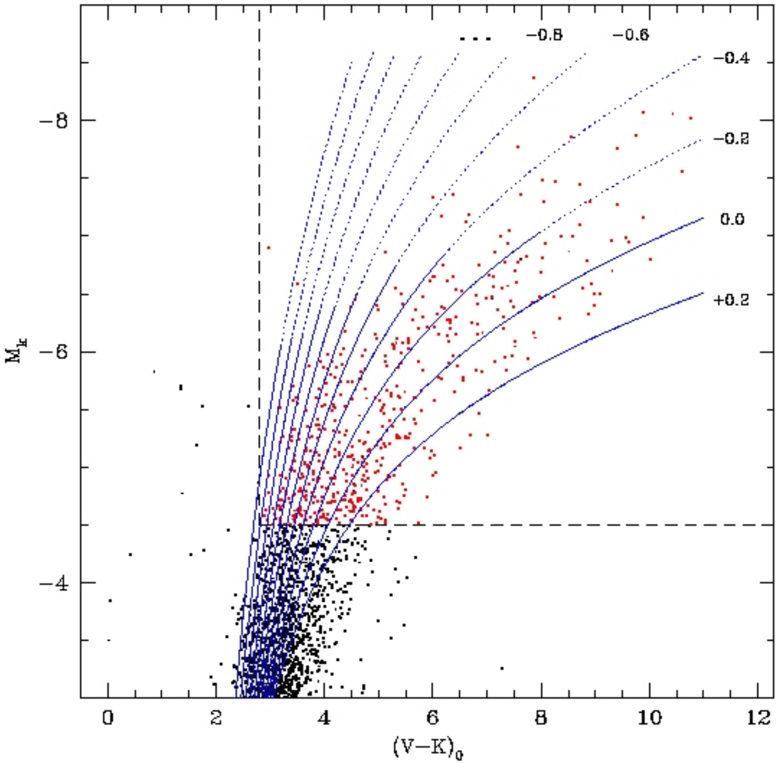


Galactic Longitude
0°
30°
330°
75,000 ly
60,000 ly
45,000 ly
Scutum-Centaurus Arm
60°
300°
Sagittarius Arm
Far 3kpc Arm
Galactic Bar
Norma Arm
Near 3kpc Arm
Long Bar
90°
270°
Outer Arm
Perseus Arm
Sun
Orion Spur
15,000 ly
120°
240°
30,000 ly
150°
210°
180°

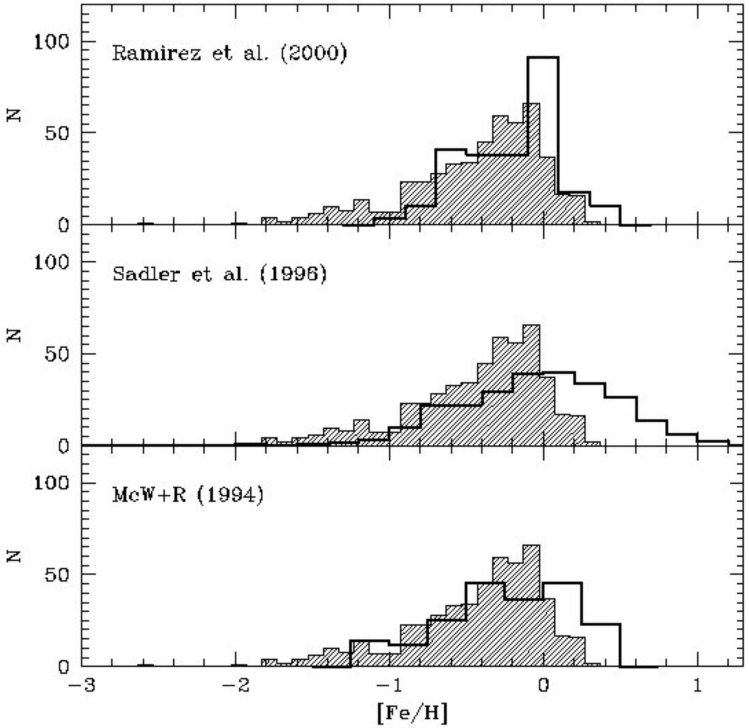
Age and metallicity of the bulge



Zoccali et al 2003 : stellar photometry at
(l, b) = (0°.3, -6°.2) : **old population > 10 Gyr**.
No trace of younger population.

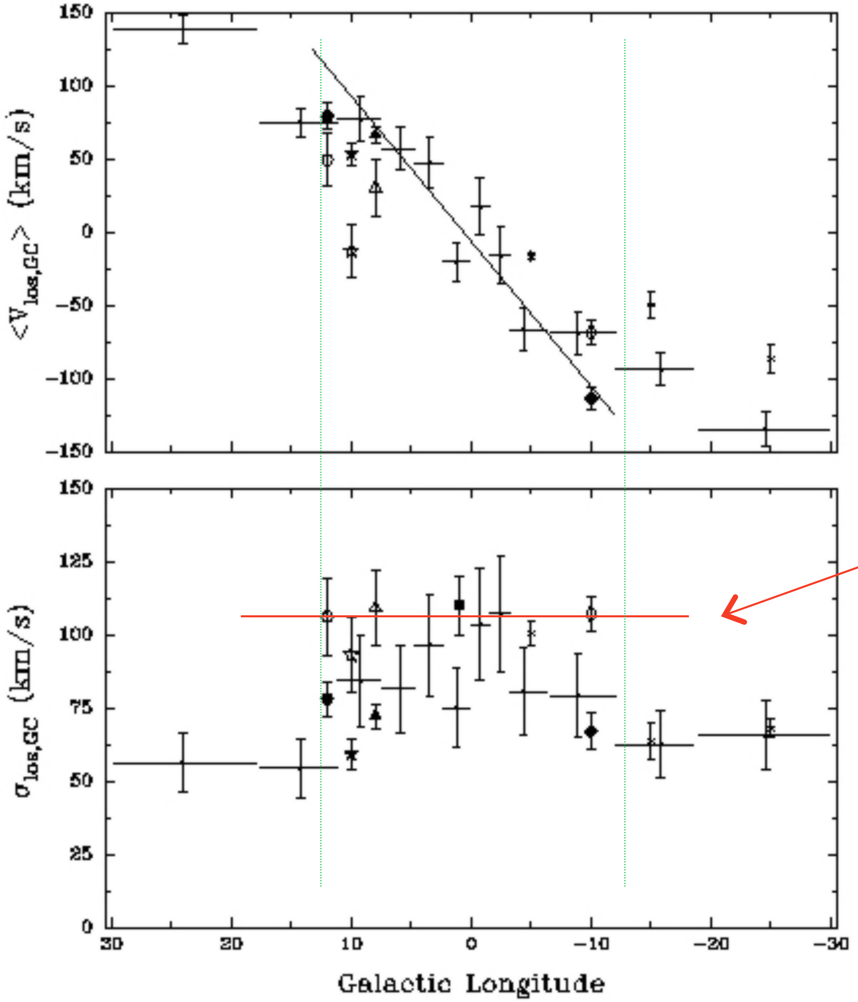


Extended metallicity distribution,
from [Fe/H] = -1.8 to +0.2



The galactic bulge is rotating, like most other bulges:

(Kuijken & Rich (2002) HST proper motions)



Rotation (Beaulieu et al 2000)
K giants from several sources and planetary nebulae (+)

Velocity dispersion of inner disk and bulge are fairly similar
- not easy to separate inner disk and bulge kinematically

Bulge ends at $|l| \sim 12^o$

How did the Galactic Bulge form ?

Later type galaxies like the Milky Way mostly have small near-exponential boxy bulges, rather than $r^{1/4}$ bulges.
(eg Courteau et al 1996)

These small bulges are probably not merger products: more likely generated by disk instability

Boxy bulges, as in our Galaxy, are associated with bars, believed to come from bar-buckling instability of disk.
theory: eg Combes & Sanders 1981 ...
observations: eg Bureau & Freeman 1999 ...

The Galactic Bulge - summary

The bulge is not a dominant feature of our Galaxy - only about 25% of the light.

The bulge is probably an evolutionary structure of the disk, rather than a feature of galaxy formation in the early universe. Structure and kinematics (so far) are well represented by product of disk instability.

The α-enhancement indicates that star formation in this inner disk/bulge region proceeded rapidly. The bulge structure may be younger than its stars.

The stellar halo

- Most metal-poor and ancient stars in the MW
  - window into the early Universe

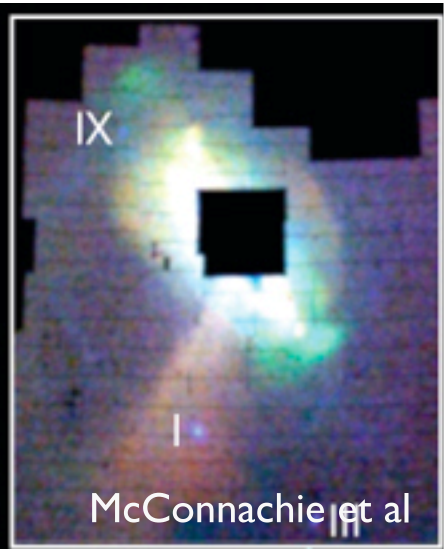
- Very steep and centrally concentrated density profile:
  - $\rho \sim \rho_0 (r_0/r)^n$, with n ~ 2.5, 3
  - half-light radius ~ 3.5 kpc (indicative of an early formation epoch)

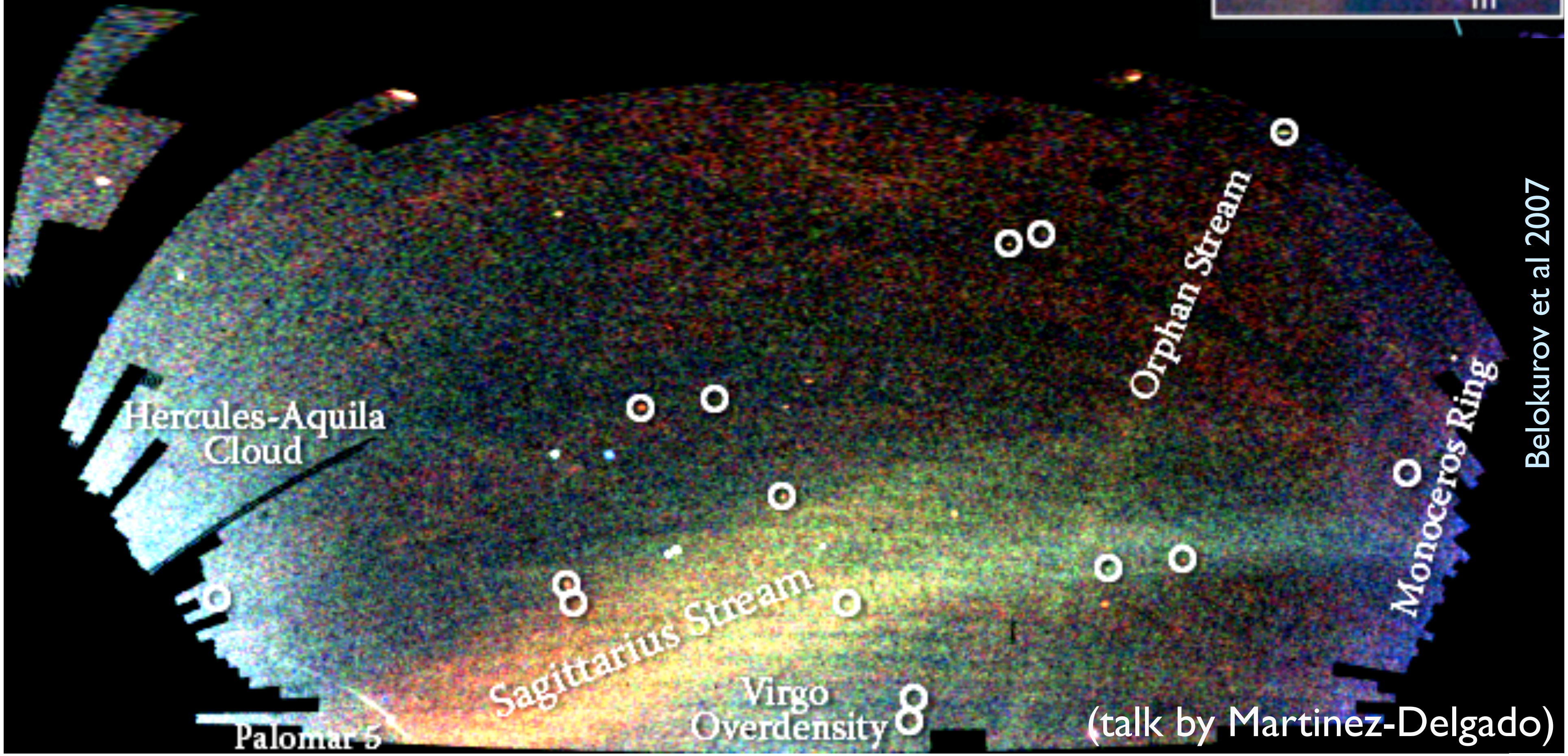
- Shape:
  - oblate, c/a ~ 0.6 - 0.7 near the Sun
  - rounder in the outskirts

- Kinematically hot (large velocity dispersions)
  - Some fraction of the stars orbit outskirts of the Galaxy: good mass probes

Outer Stellar halo

- Substructure common in the halo (SDSS, 2MASS…)
  - -> mergers
  - -> Broad, diffuse streams (large progenitors? …but beware of biases)
  - overdensities -> nature not always clear





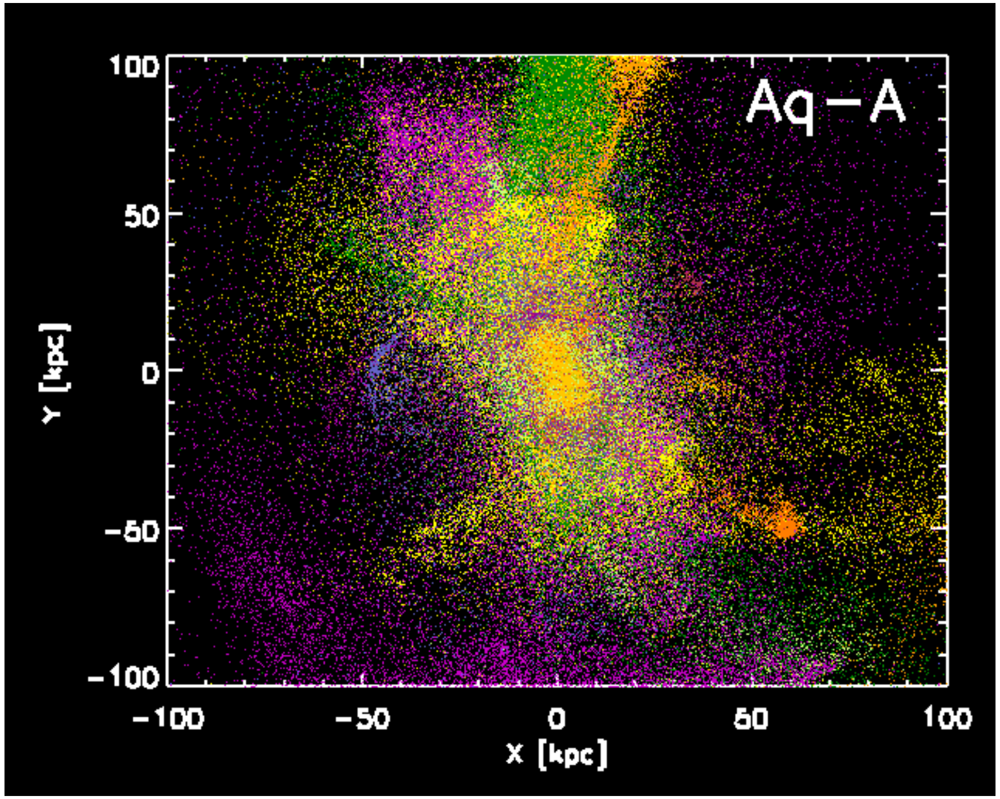
Substructures in the (outer) halo

Shortly after infall ($t/t_{dyn} \sim 1$)

Outer Galaxy always in this regime

Accreted stars are visible as tidal tails

Tidal tails can be easily found by mapping the positions of halo stars in the sky.



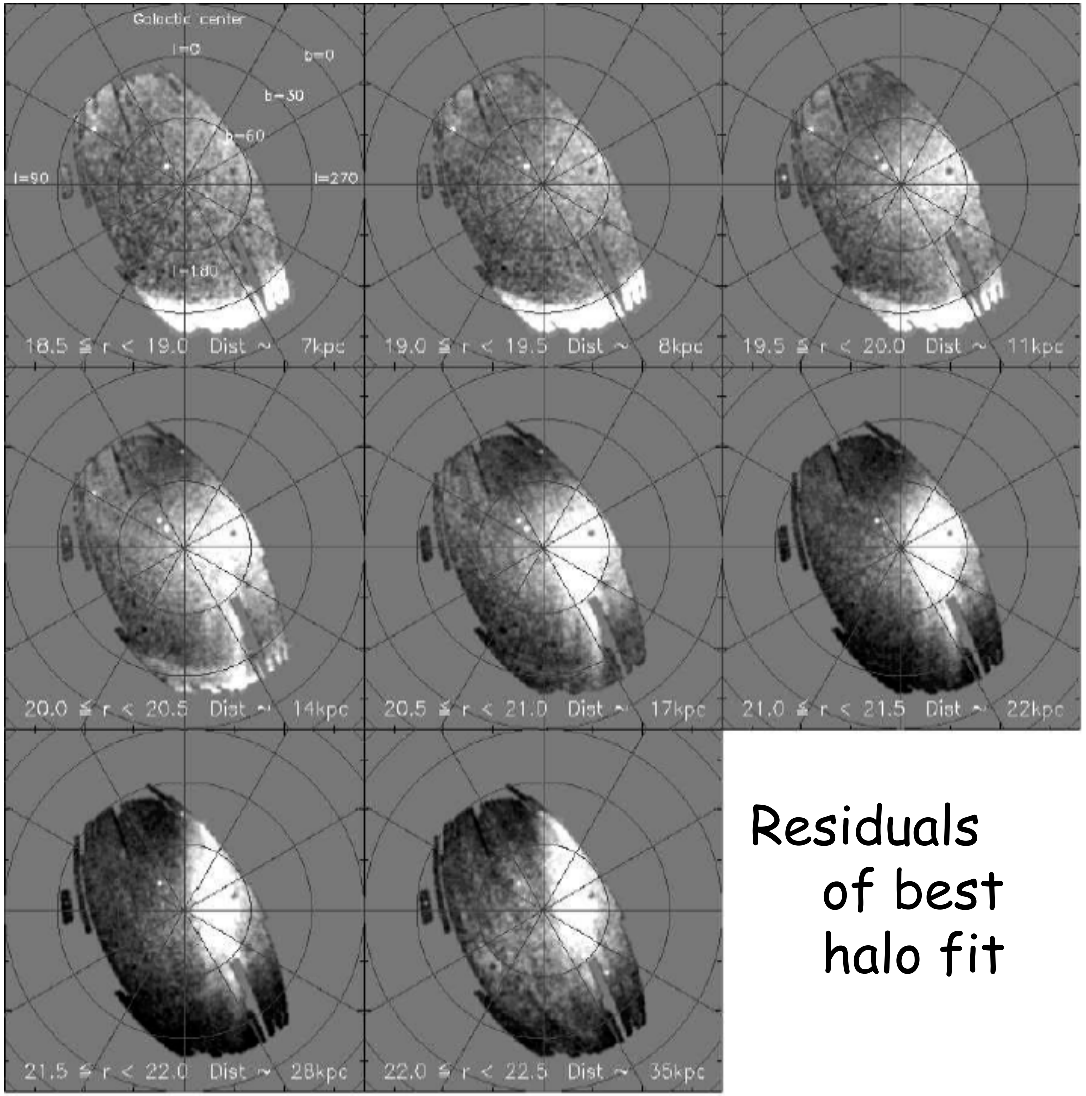
Substructure in the halo

Bell et al (2007) quantify the amount of substructure using RMS measure

$\sigma \sim (\text{Data - Smooth halo})^2$

Level of RMS ~ 30-40%

How does this compare to models MW stellar halo?



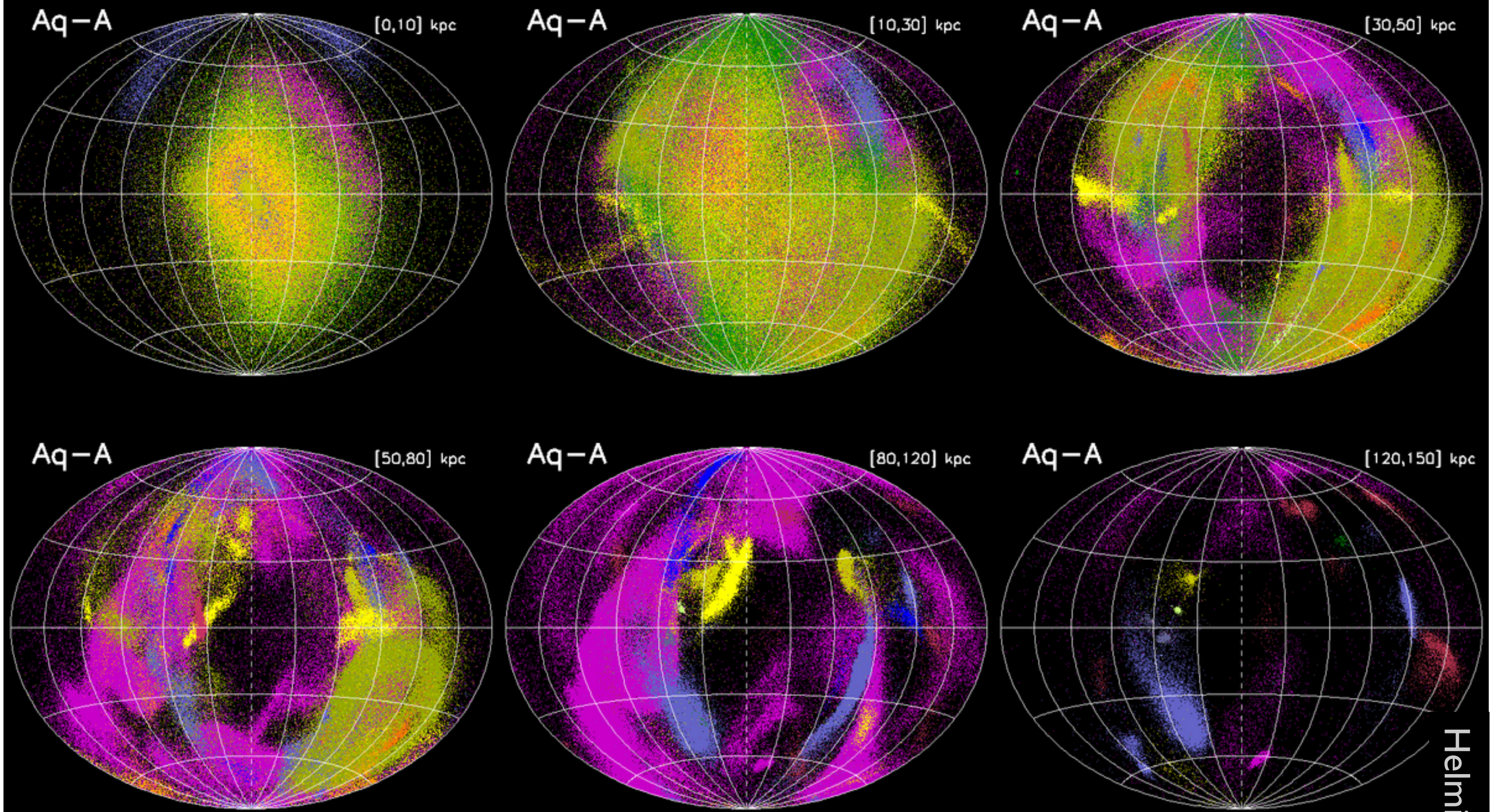
Residuals of best halo fit

Stellar halo formation in the Aquarius simulations

Cooper et al. 2010

Helmi et al. 2011

Aquarius on the sky



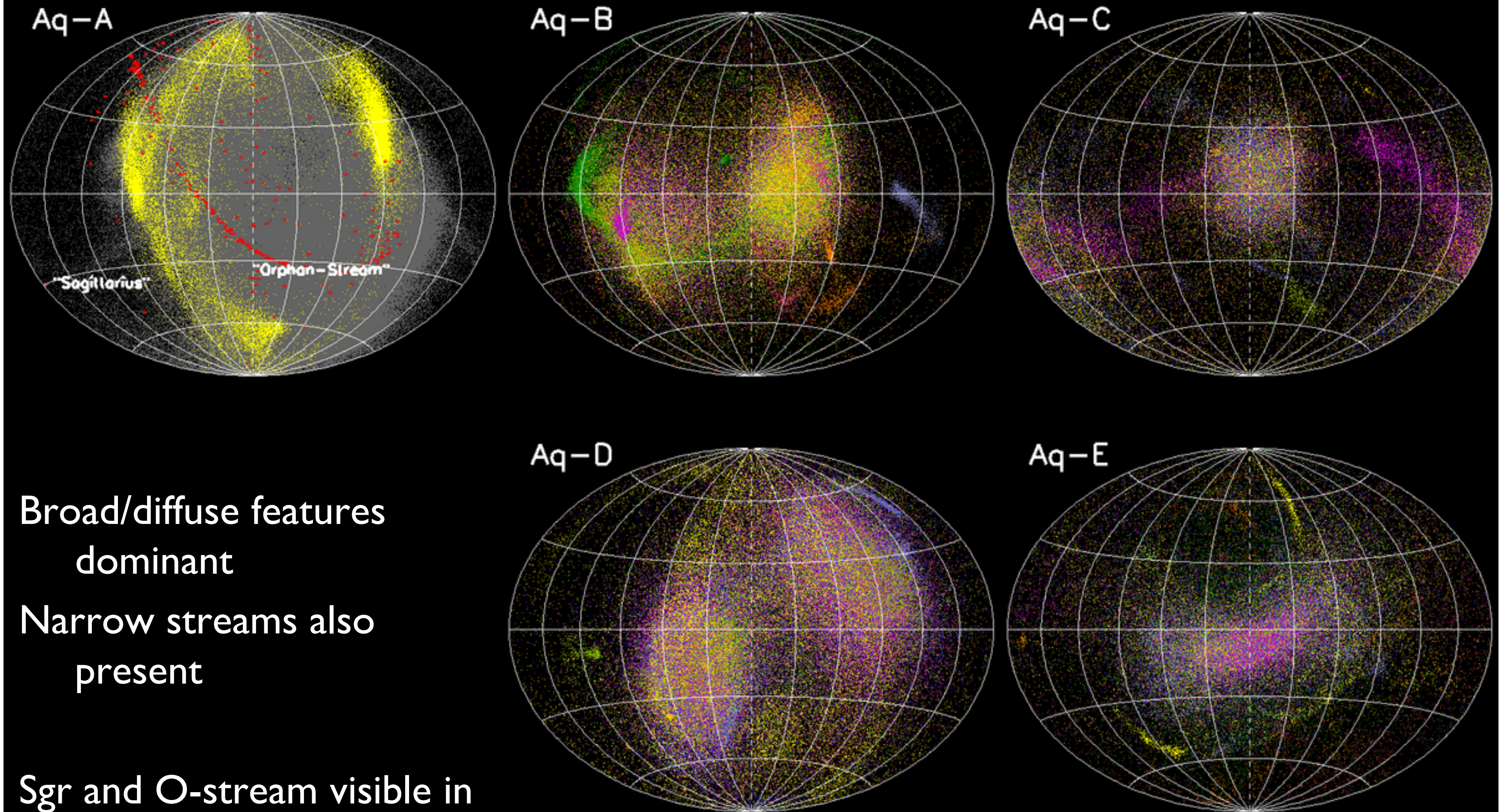
Inner halo (d < 10 kpc): very smooth (triaxial in shape)

Substructure apparent at d > 10 kpc and dominant at d > 30-50 kpc

Anisotropically distributed (coherent in dist): infall pattern!

Helmi et al. 2011

Stellar halos at d ~ 10-30 kpc



Broad/diffuse features dominant

Narrow streams also present

Sgr and O-stream visible in the Aq-A sky!

Helmi et al. 2011

Quantitative comparison

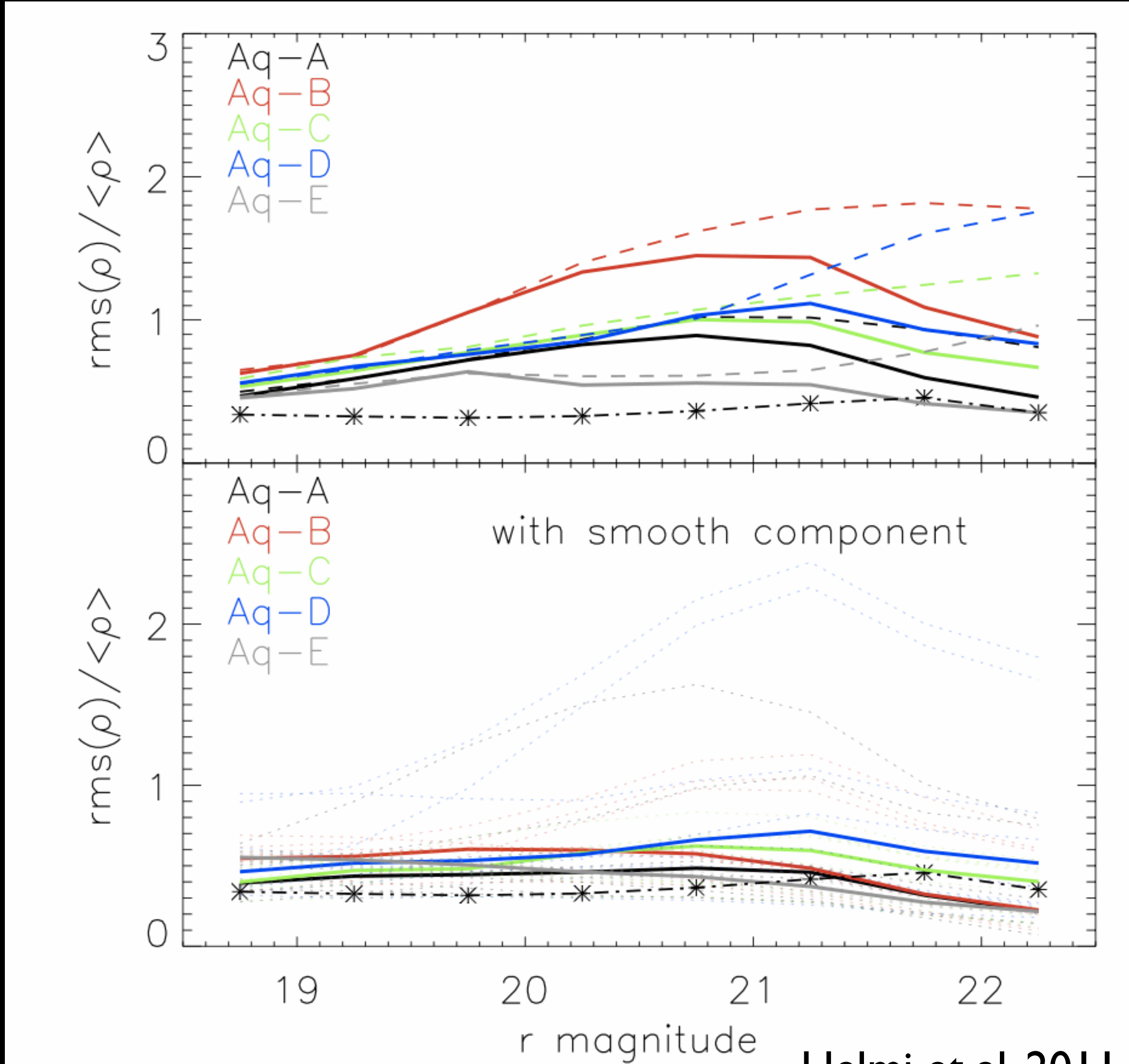
•RMS measure

stellar halos have too much substructure compared to Bell et al (2008)

•Contamination by QSOs and by non-MSTO stars leads to better agreement

•Need for 10% smooth or in-situ pop.

- •30% at r ~ 19
- •See sims. Zolotov et al. 2009, Purcell et al. 2010, Font et al. 2011
- •Foregrounds (thick disk?)



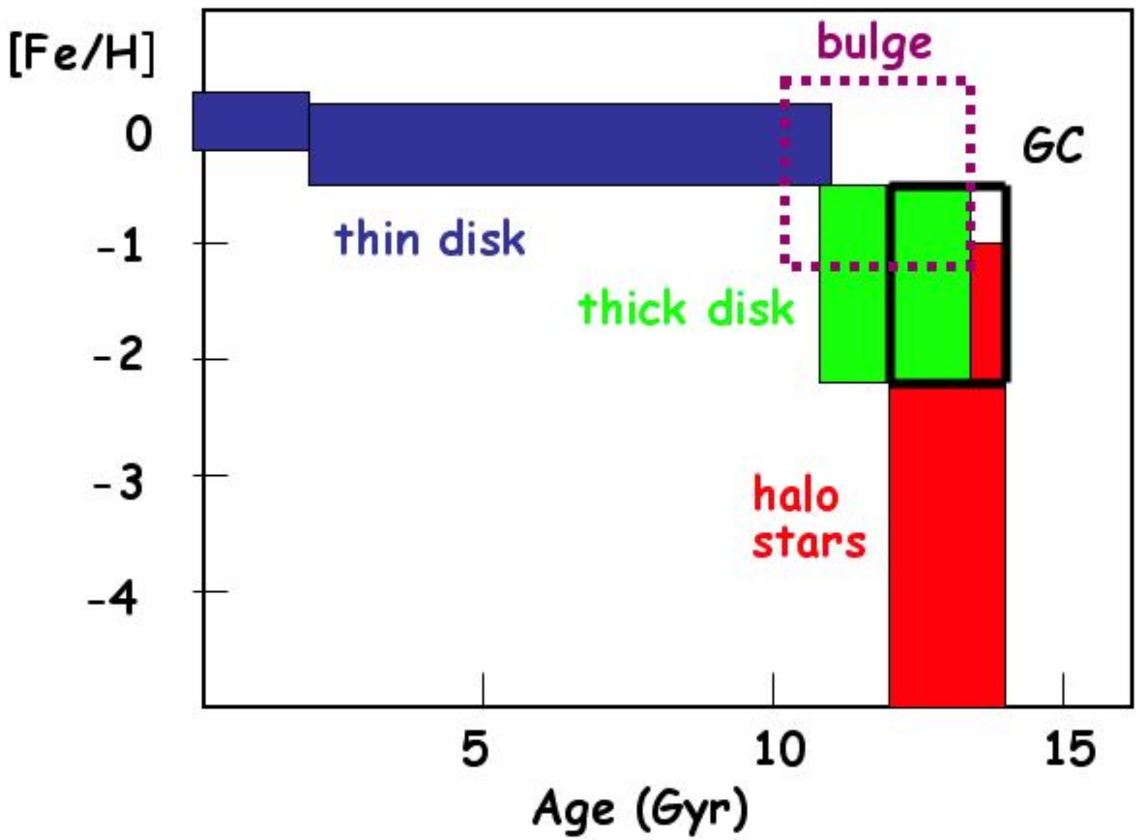
Helmi et al. 2011

The thin disk is metal-rich and covers a wide age range

The other stellar components are all relatively old

(note similarity of [Fe/H] range for thick disk and globular clusters)

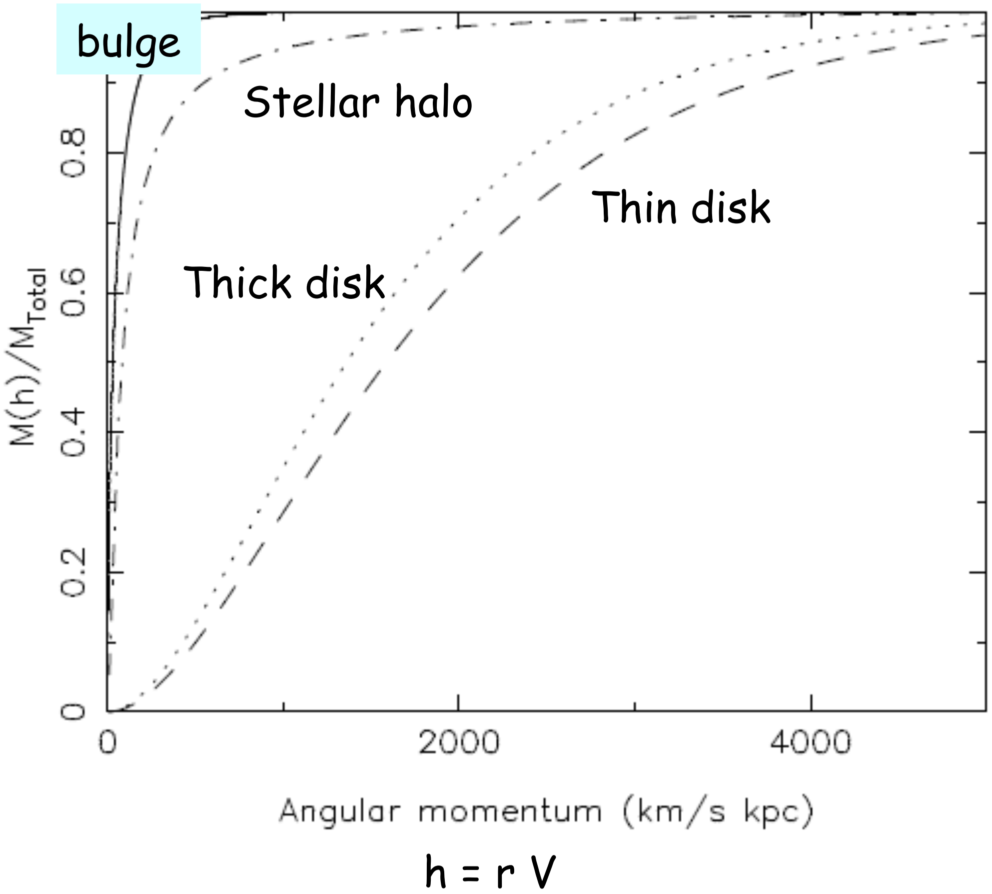
[Fe/H] - age relation for components of the Galaxy



- The thin and thick disks have similar angular momentum distributions

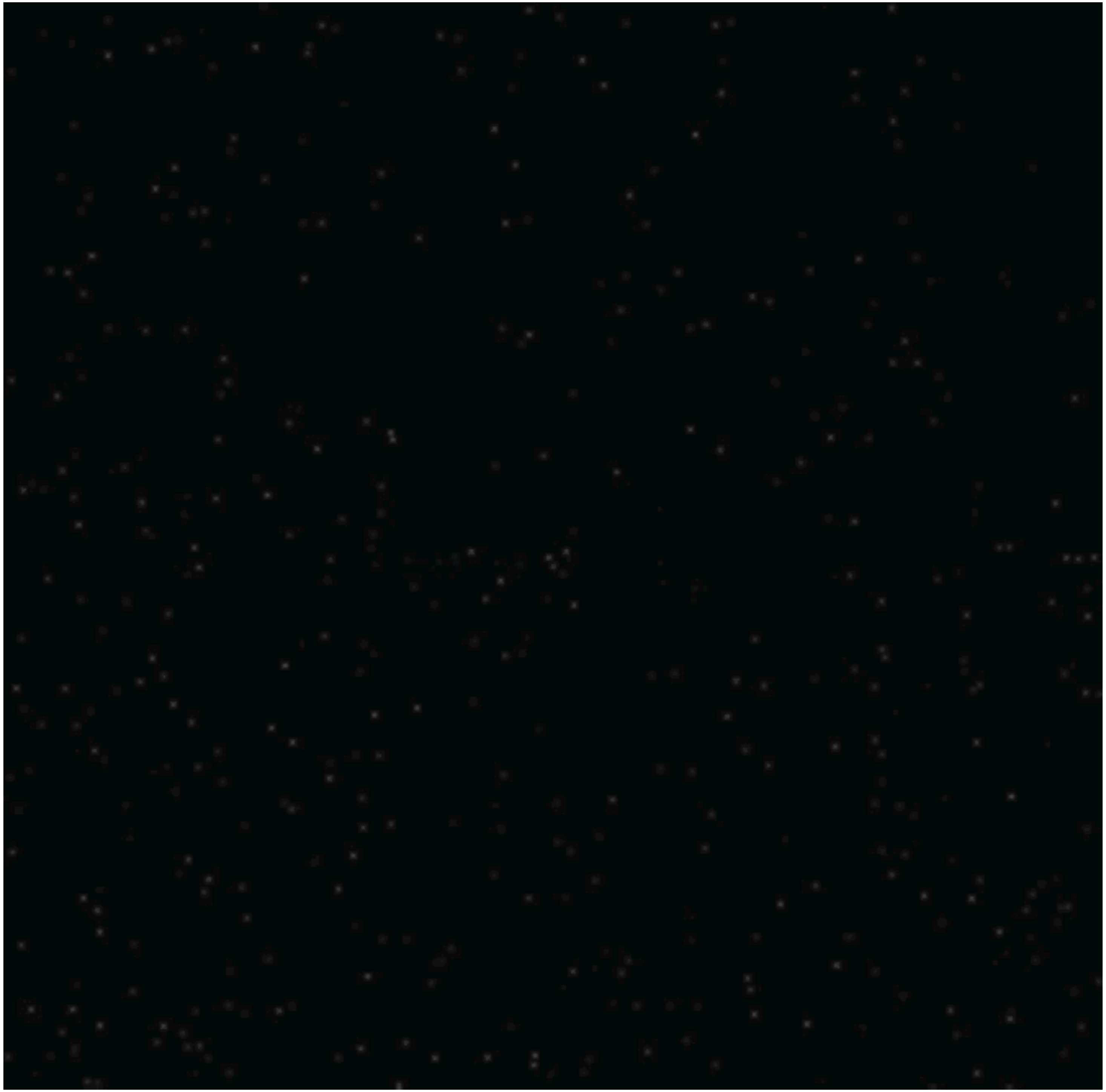
- The stellar halo and the bulge as well

- Spheroidal components are quite distinct from disky components in their angular momentum content



Wyse, Gilmore & Franx 1997

Simulations of the formation of a disk galaxy



Jesper Sommer-Larsen

The formation of a disk galaxy

- Gas cools in halos / filamentary structure is visible also in gas
- At high-z: strong starbursts drive gas out of proto-galactic mini-haloes.
- z ~ 3: Initial disk starts to form, mainly grows by cool-out of hot halo gas
- The disk is harassed by discrete accretion events,
    - cold gas from accreted systems is mixed into disk gas
    - accreted stars generally end up in the halo.
- Two fairly large sub-systems are responsible for the formation of the thick disk at z ~ 1
    - puffing up the already present thin disk.
- At z ~ 0.1 the spinning disk is at the center of a slowly rotating cooling flow, feeding the disk with mass and angular momentum.

The formation of a disk galaxy

Distribution of metals:

- At the center of the galaxy $\langle[O/Fe]\rangle \sim 0$,
  - most of the star-formation has taken place already, so that there has been time for the SNIa's to recycle the Iron.

- In the outer disk $\langle[O/Fe]\rangle$ is larger than zero.
  - the star-formation history is much more flat: star-formation is on-going and not all the Iron from to come SNIa's has been recycled

The formation of a disk galaxy

Formation epoch of the various galactic components

- Halo stars are either very old (first generations) or typically originate from tidally stripped/disrupted satellites.

- Bulge stars have z_{form} ~ 2-3

- Disk stars have z_{form} <~ 2-3, the disk forming inside-out in this case.

Is this model consistent with the properties of the Galaxy?