The Milky Way and its components: overview

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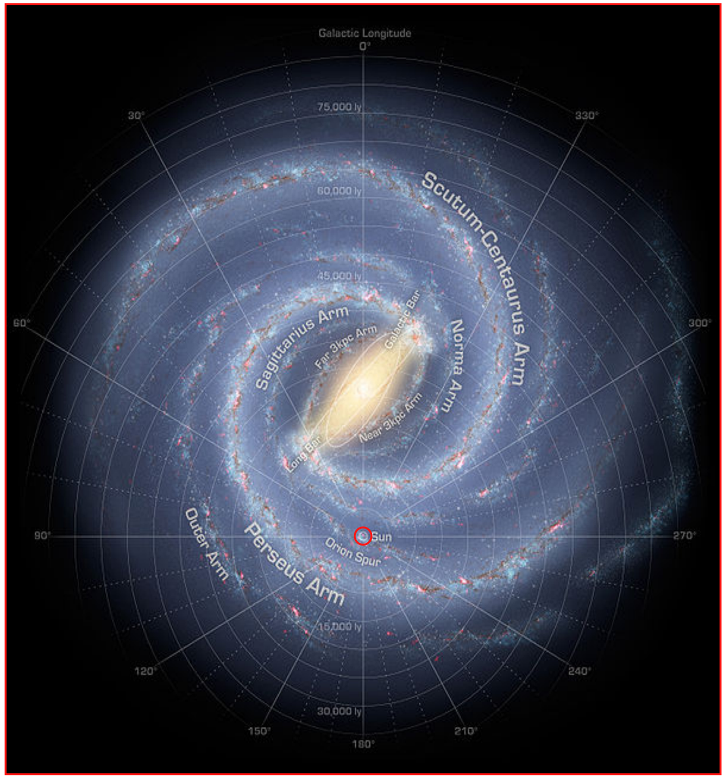
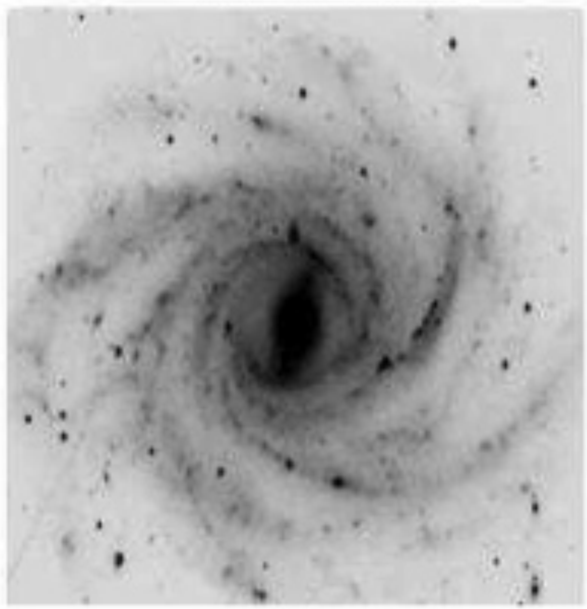
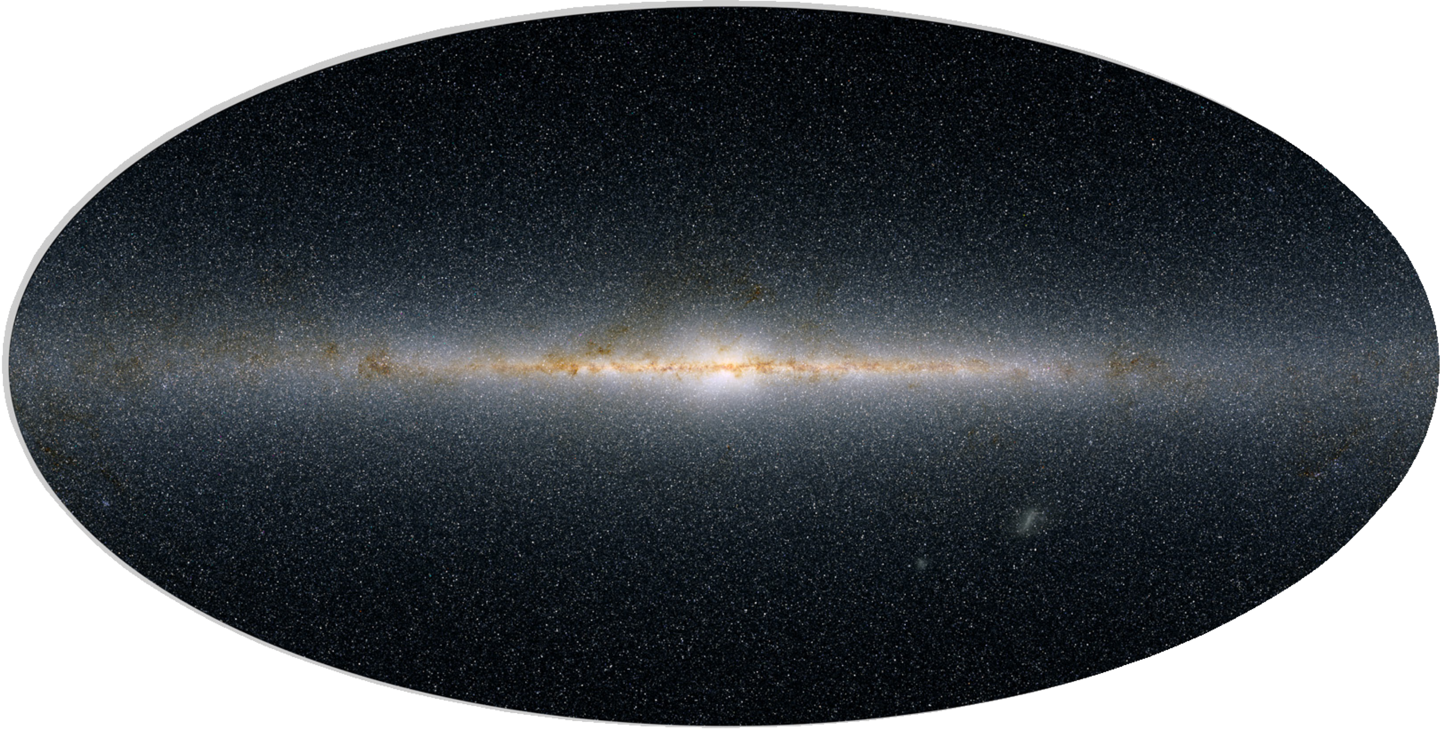




NGC 2336

(R. Hurt)

IAP September 2016: The Milky Way and its environment



(2MASS)

The Milky Way components:

- thin disk
- thick disk
- bulge
- halo - stellar, gaseous, dark

Talk about
- structure and content,
- formation concepts
- some of the important processes

Quick Overview of MW

M_B = -20.7, V_c = 238 km/s (similar to M31)

Masses of the components:

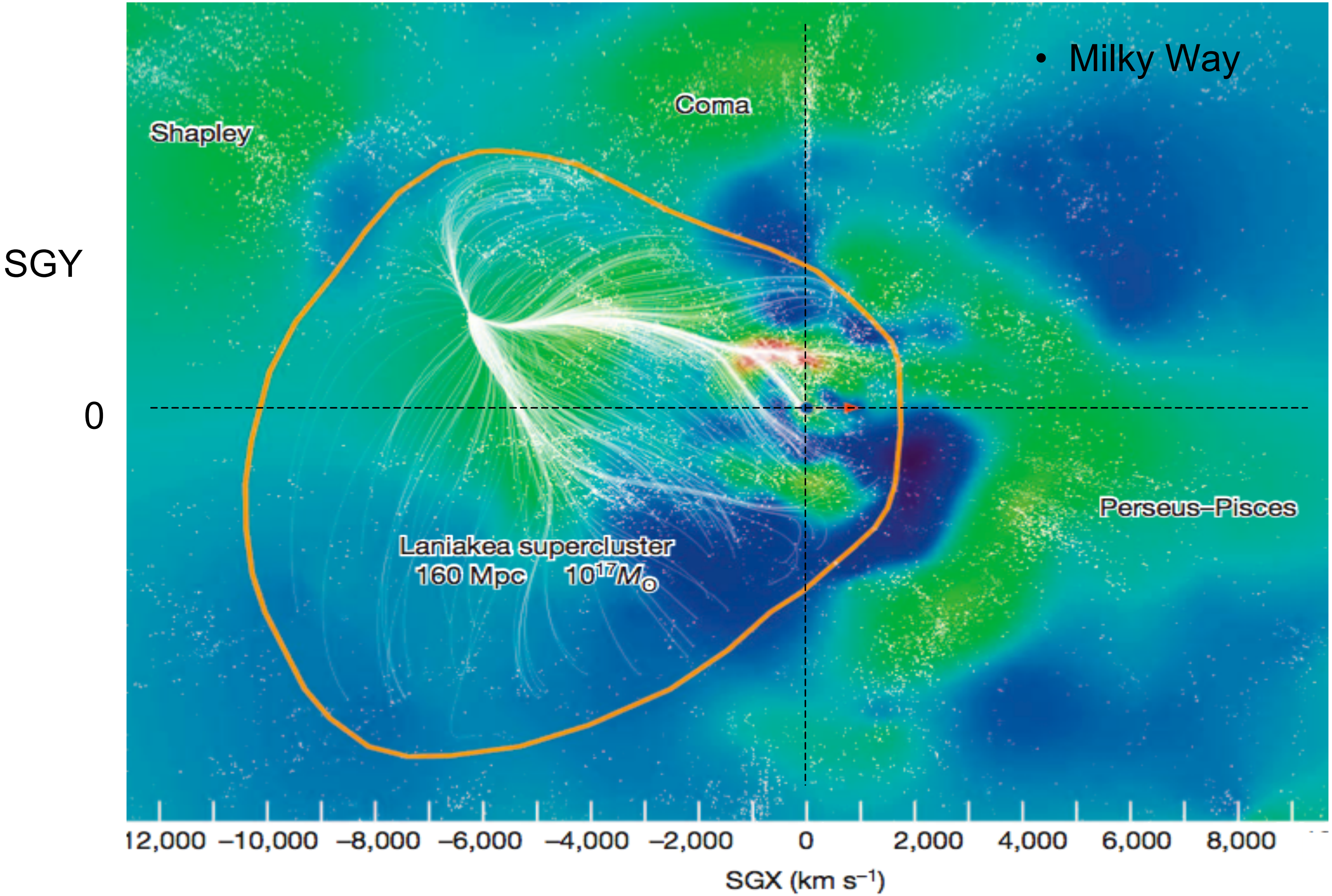
thin disk	4.10^{10} $M_\odot$
thick disk	5.10^{9} $M_\odot$
bulge	2.10^{10} $M_\odot$
halo	
• stellar	8.10^{8} $M_\odot$
• gas	2.10^{10} $M_\odot$
• dark	1.10^{12} $M_\odot$

See Bland-Hawthorn & Gerhard ARAA 2016 for recent compilation of MW parameters

What is goal of having a good detailed descriptive model of MW involving its components ? Helps us to visualise how the Galaxy was assembled. MW provides detailed knowledge of one large galaxy to which similar galaxies may tend in their evolution from high-z.

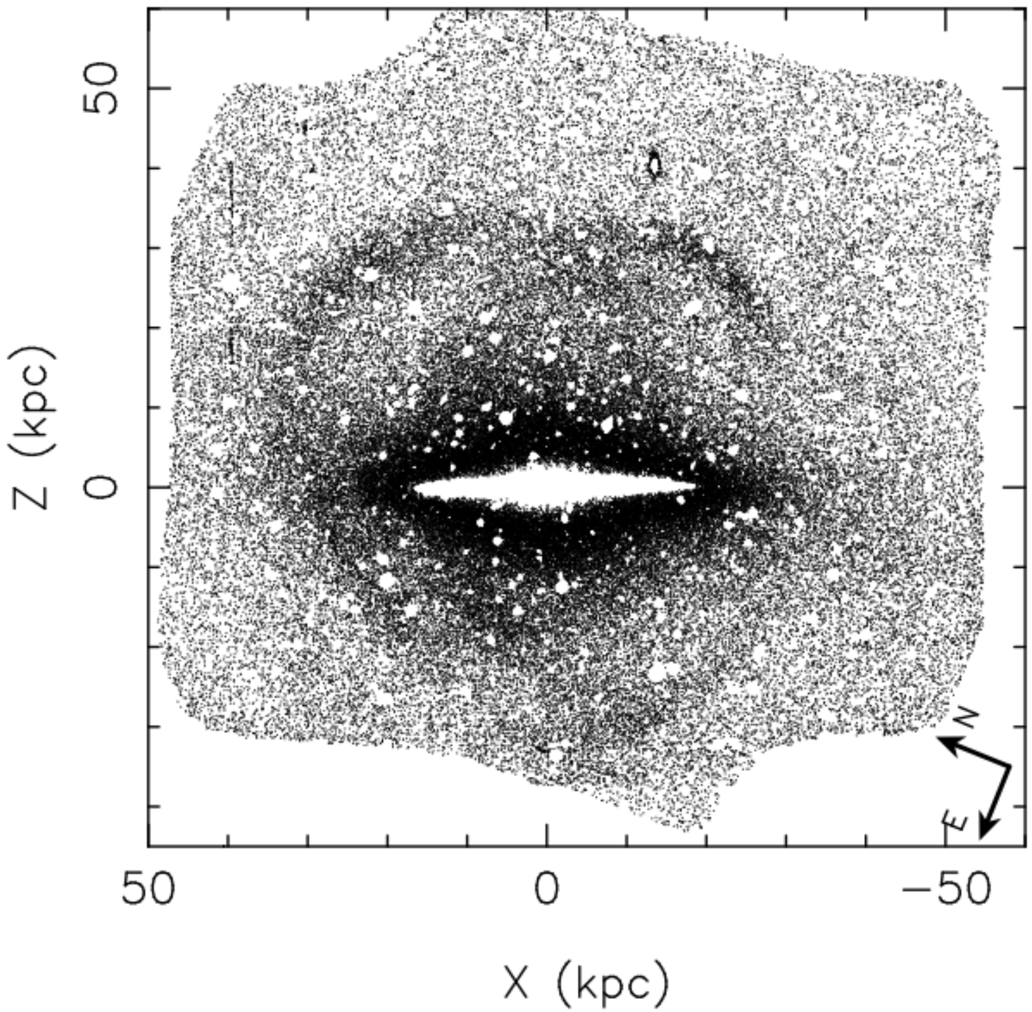
After Gaia and current spectroscopic surveys, we will know 6D positions and velocities, and element abundance data for vast number of stars. We will be able to construct a distribution function for the observable part of phase space and chemical space:

e.g. a DF with three dynamical variables (actions), 2 or 3 chemical cordinates ([Fe/H], [alpha/Fe], maybe [Ba/Fe] - suspect the rest of elements are not so basic), and age.

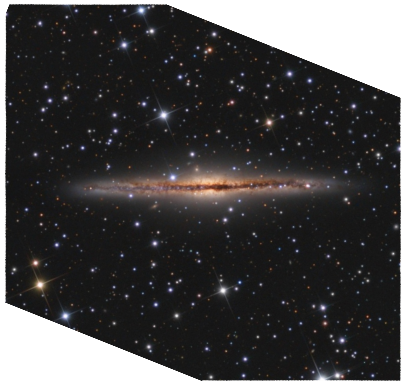


Environment: several authors have made the point that the MW has had a quiet history of interaction with other galaxies. (Not for much longer: M31 and MW will merger in a few Gyr.

Tully et al 2014



The thick disk of NGC 891



The diamond-shaped outer isophotes of the thick disk of the Milky Way analog NGC 891, from Subaru star counts: consistent with a simple structure e.g. $\rho_L \sim \exp(-R/h_R + z/h_z)$ $h_R/h_z \approx 2/1$

Also see halo substructure in NGC 891

Mouhine et al 2010

The Galactic thick disk: structure, kinematics, age ....

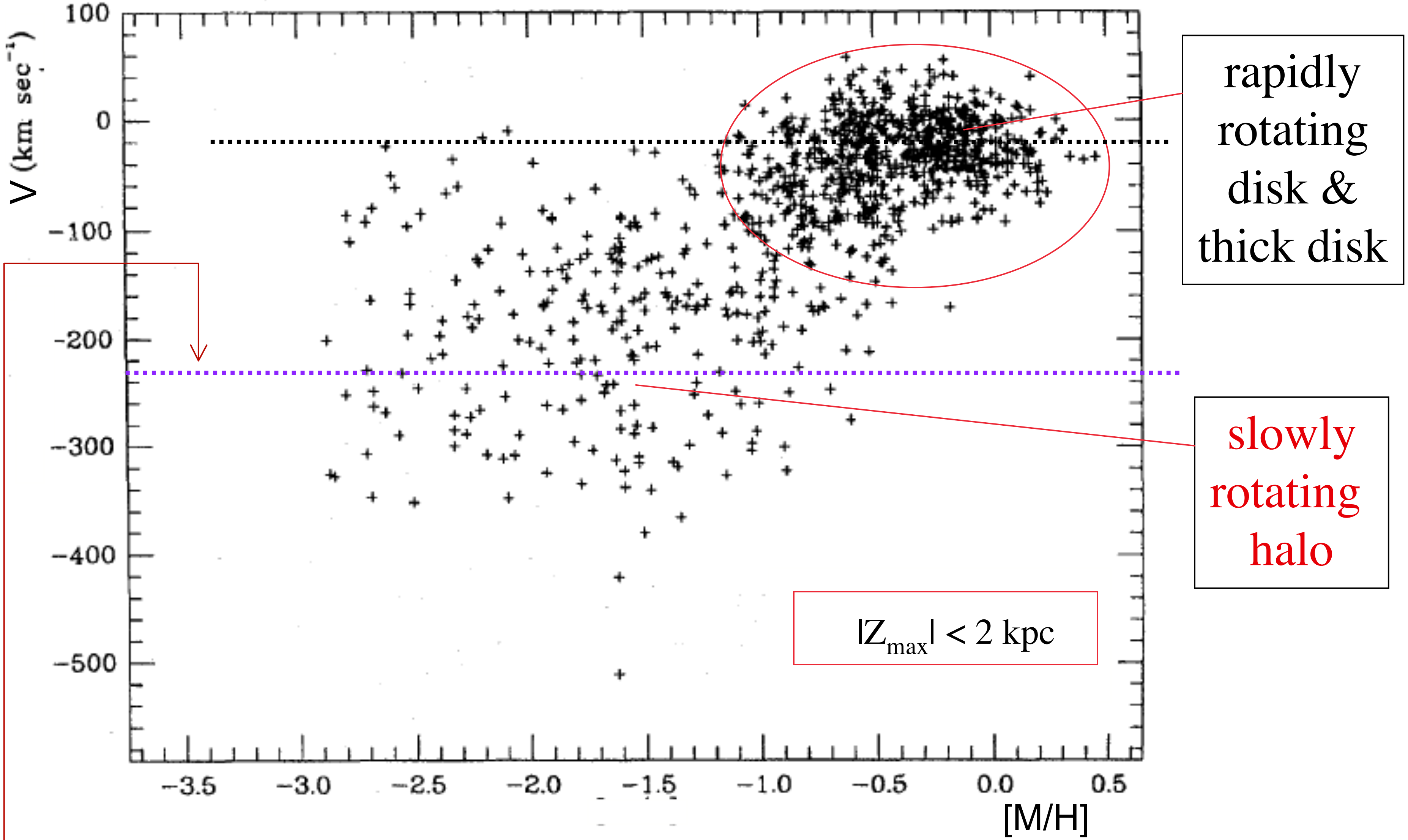
The thick disk presents a kinematically and chemically recognizable relic of the early Galactic disk going back to z ~ 2+

age believed to be older than 10 Gyr

scale height = 800 to 1200 pc (thin disk ~ 250 to 300 pc)
surface density = 5 to 20% of the local thin disk
(similar to thick disks of other large spirals)

velocity dispersion in (U,V,W) = (65, 55, 40) km/s, roughly double the dispersion of the thin disk

abundances [Fe/H] mostly between about -0.3 and -1, and alpha-enhanced relative to the thin disk (rapid chemical evolution)



Rotational velocity of nearby stars relative to the sun vs [M/H]
(V = -232 km/s is zero angular momentum)

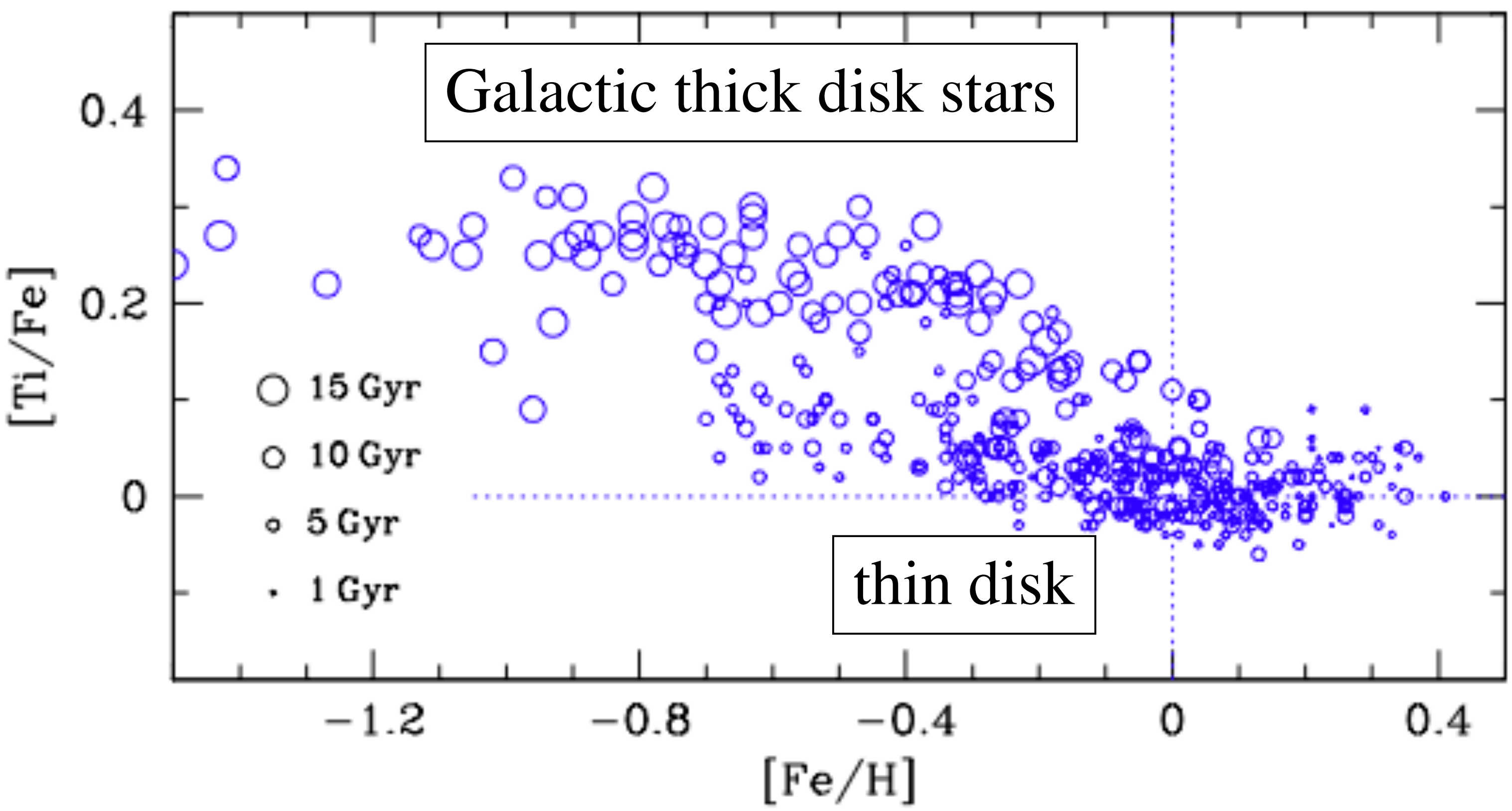
(Carney et al 1990)

The Thin Disk

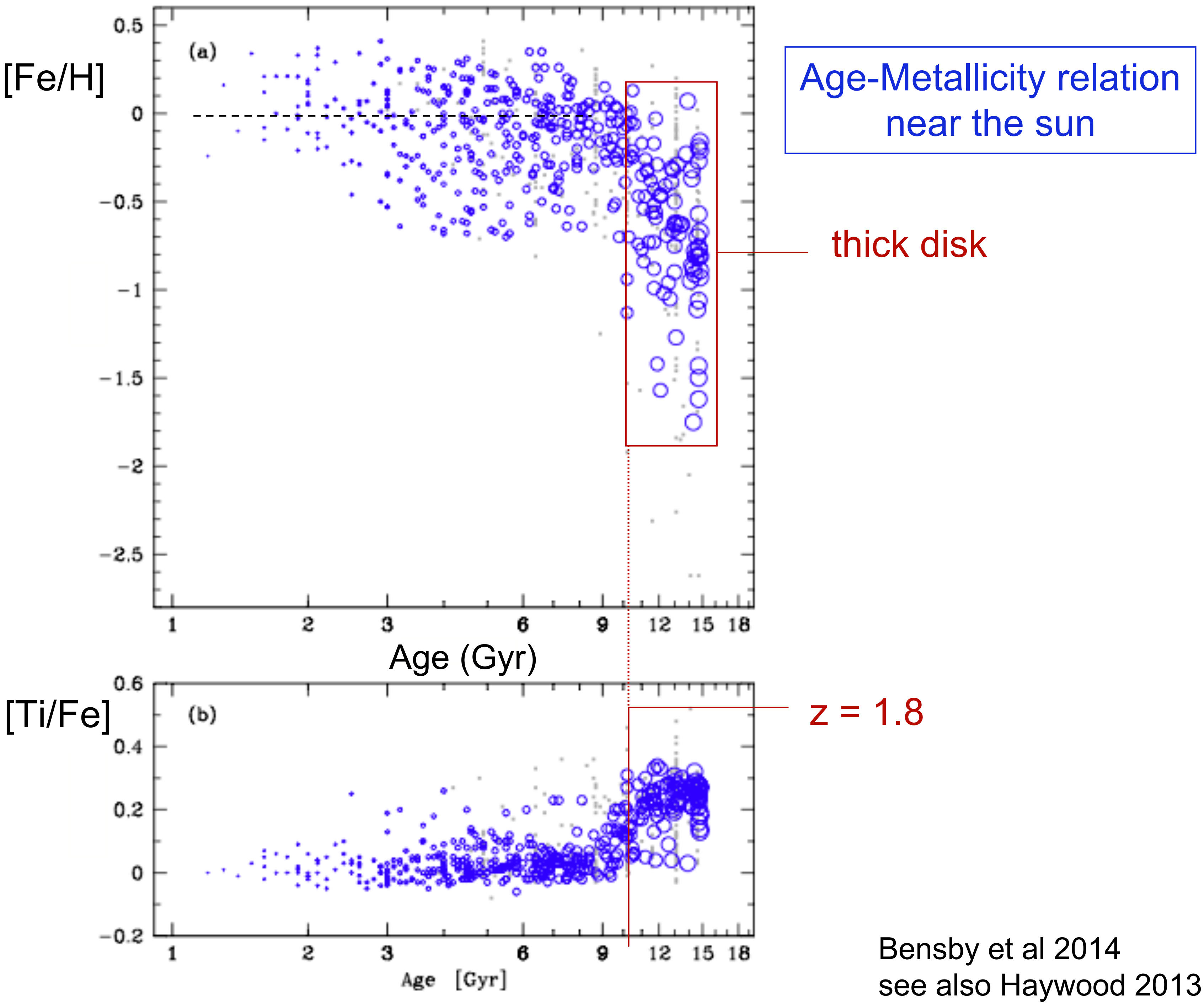
- abundance gradient
- the $[\alpha/Fe]$ - $[Fe/H]$ relation for thin and thick disks
- the metallicity distribution function
- radial migration
- disk heating/cooling

Thin and thick disk stars near the sun have different [α/Fe] - [Fe/H] distributions
(α = Mg, Si, Ca, Ti)

α-rich means that enrichment was quick, by massive star SNII
Fe-rich means that enrichment was gradual, by white dwarf SNIa

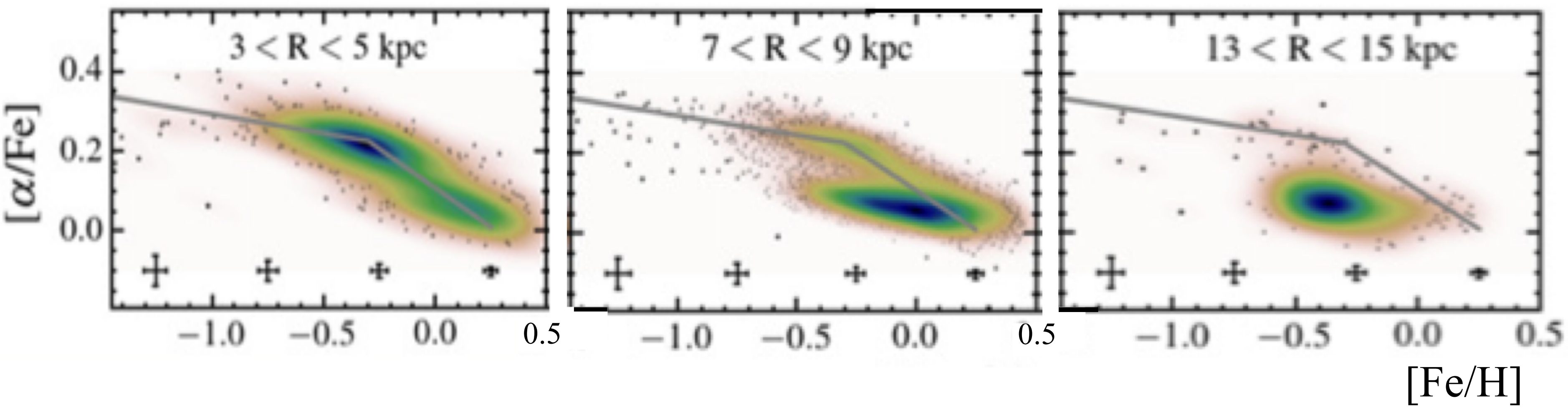


Fuhrmann 2008, Bensby et al 2014



Bensby et al 2014
see also Haywood 2013

0.5 < |z| < 1.0 kpc

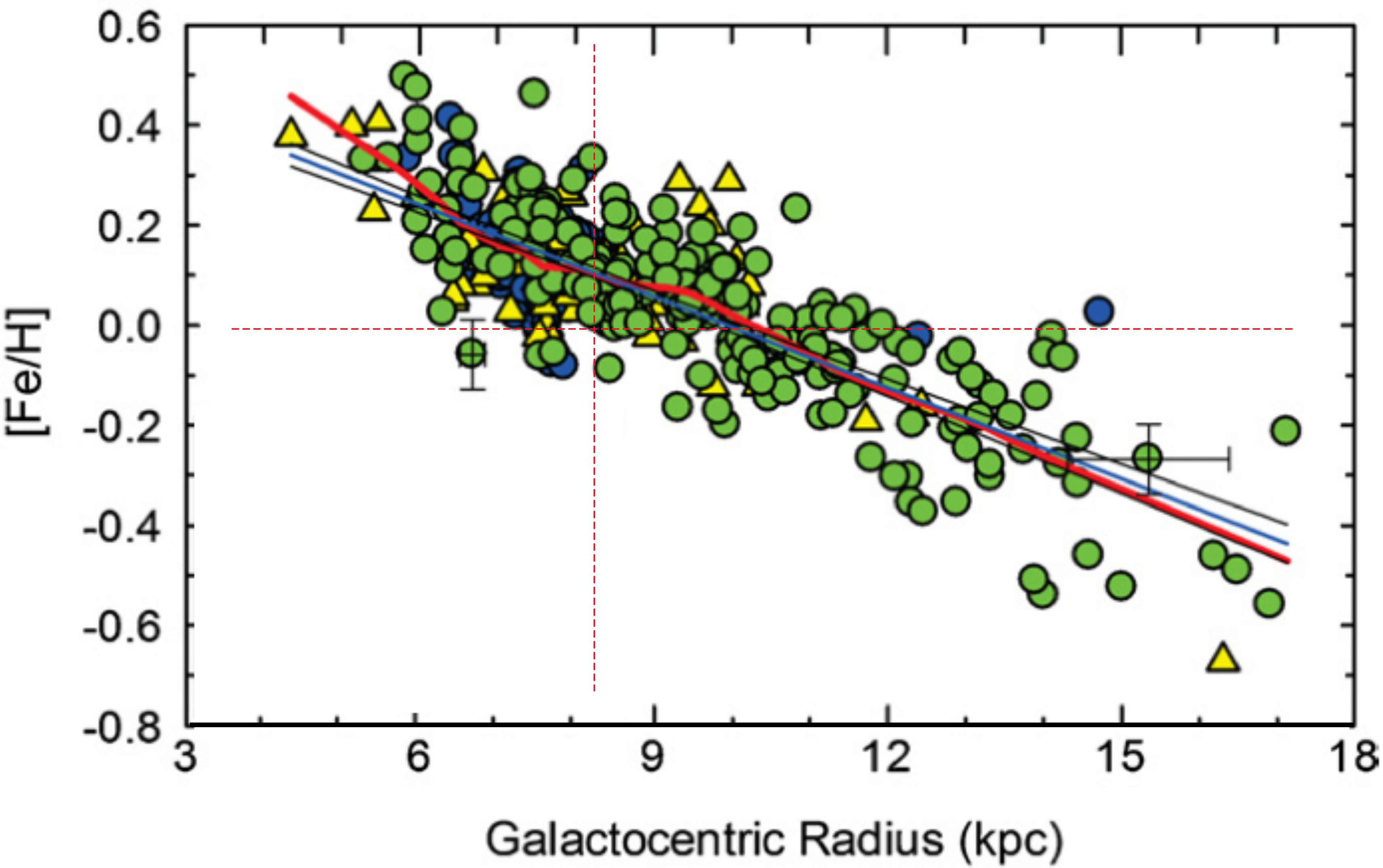


The [α/Fe] - [Fe/H] relation changes with R and z

The inner disk: more high-α
The outer disk: almost all low α
High-α contribution is larger at higher z-heights - thick disk

(See also Bovy et al 2016)

APOGEE: Hayden et al 2015



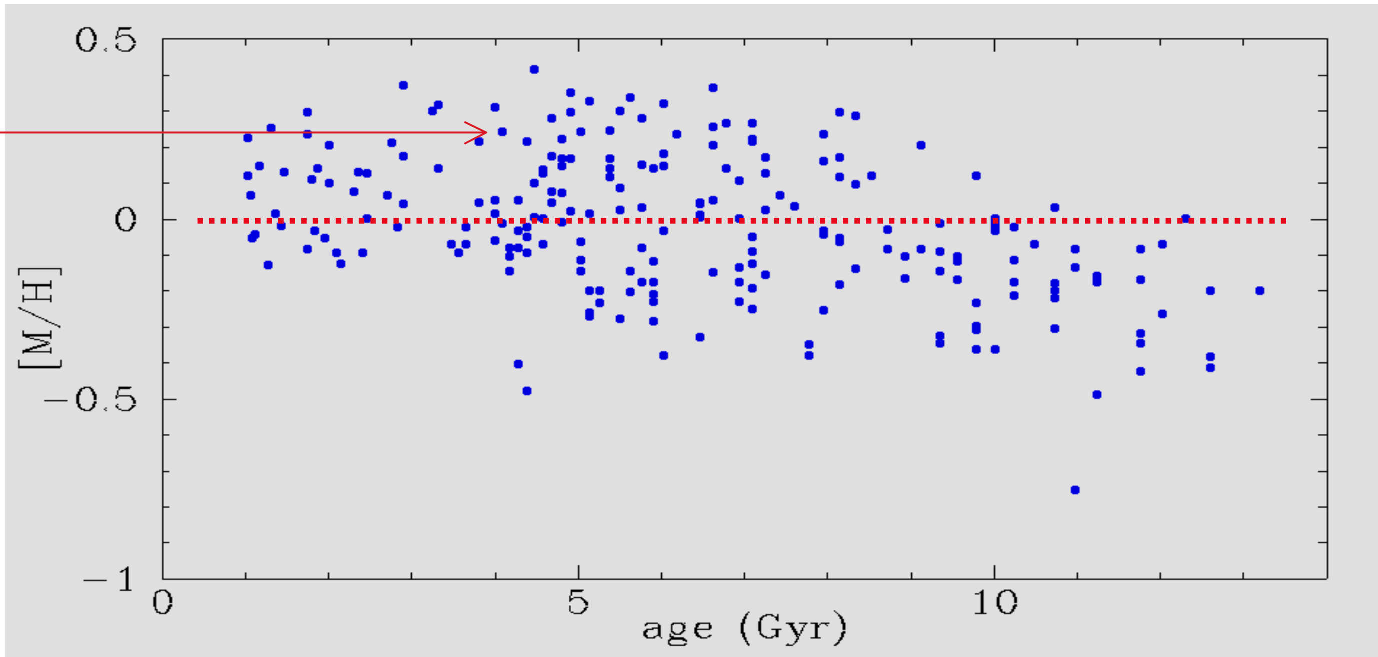
The Galactic Abundance Gradient: cepheids in the disk

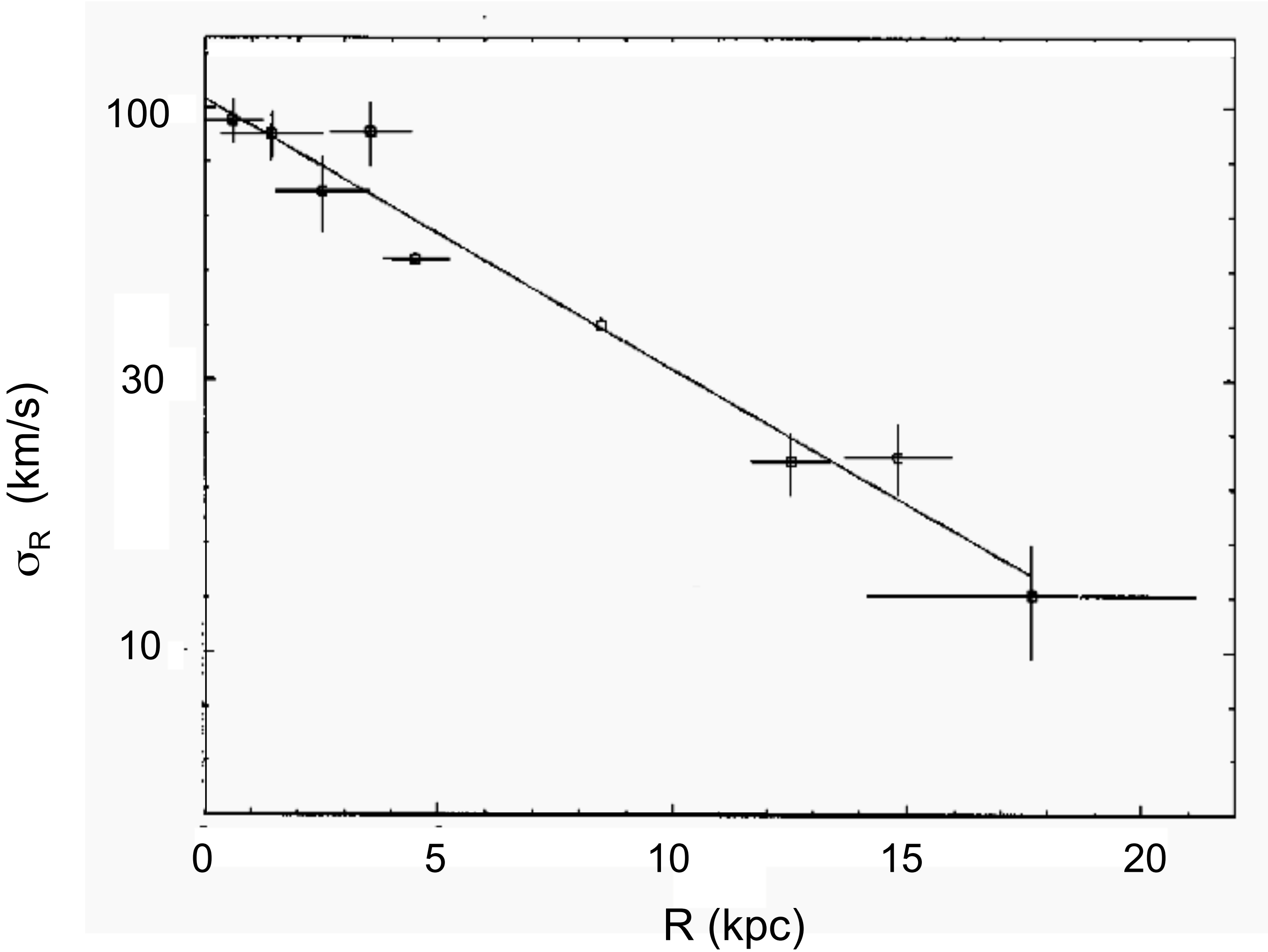
Luck & Lambert 2011

What is the origin of the metal-rich stars ([Fe/H] > 0) near the sun ? They are more metal rich than the nearby gas and young stars. Believed to have migrated out from the metal-rich inner Galaxy (Grenon 1990 ...)

Radial migration of stars (in and out) can occur via transient spiral and bar disturbances (Sellwood & Binney 2002; Minchev et al 2011; Di Matteo et al 2014 ....). Moves stars from one near-circular orbit to another.

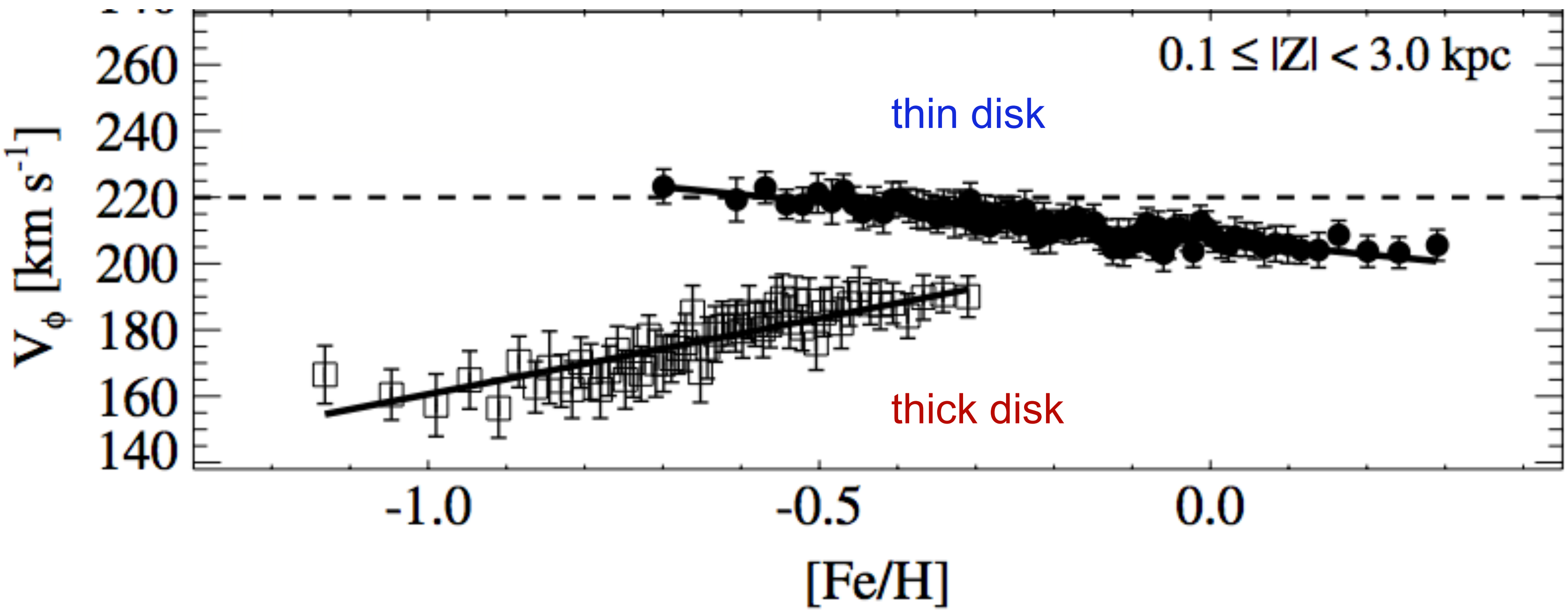
Believed to be an important process in the evolution of the thin disk.





The velocity dispersion of the Galactic thin disk

Lewis & Freeman 1989



Interpretation: thick disk velocity dispersion and asymmetric drift are larger for more metal-poor stars - age effect ?

thin disk asymmetric drift is smaller for the more metal-poor stars: why ? These have more angular momentum because they come from the metal-poor outer disk and their angular momentum transfer is incomplete (Schönrich). And their velocity dispersion is smaller - so smaller asymmetric drift

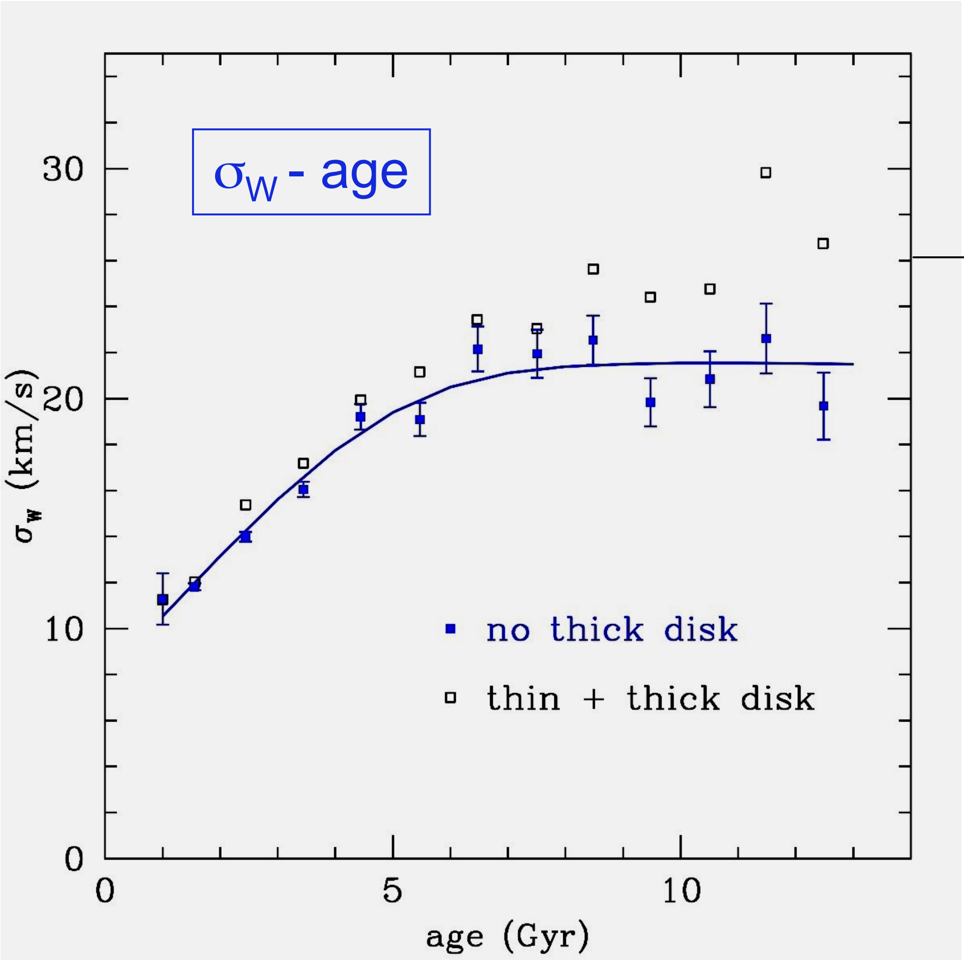
Lee et al 2011

Thin Disk Heating

The dispersion is small for young stars and increases with age, for a few Gyr, due to heating processes which are not well understood.

ISM dispersion ≈ 8 km/s

Then thin disk heating for the past ~ 5 Gyr, up to $\sigma_W \approx 22$ km/s



W-dispersion vs age for GCS stars with [Fe/H] > -0.3 (*excludes most thick disk stars*).

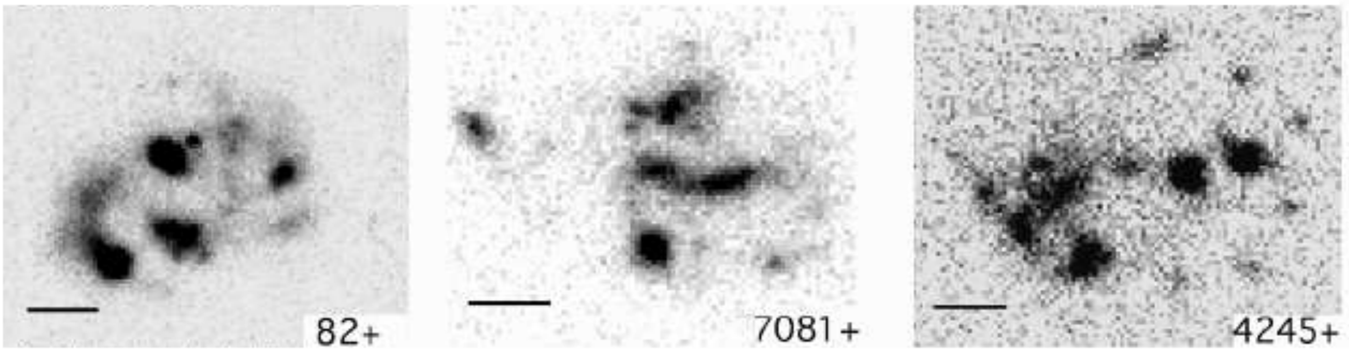
Thick disk dispersion σ_W is about 40 km/s near sun: where does that come from ?

Casagrande et al 2011

This narrative about disk heating may be at least partly wrong.

Clues comes from ideas about thick disk formation, and observations of disk galaxies at $z = 1$-3.

Formation of thick disks



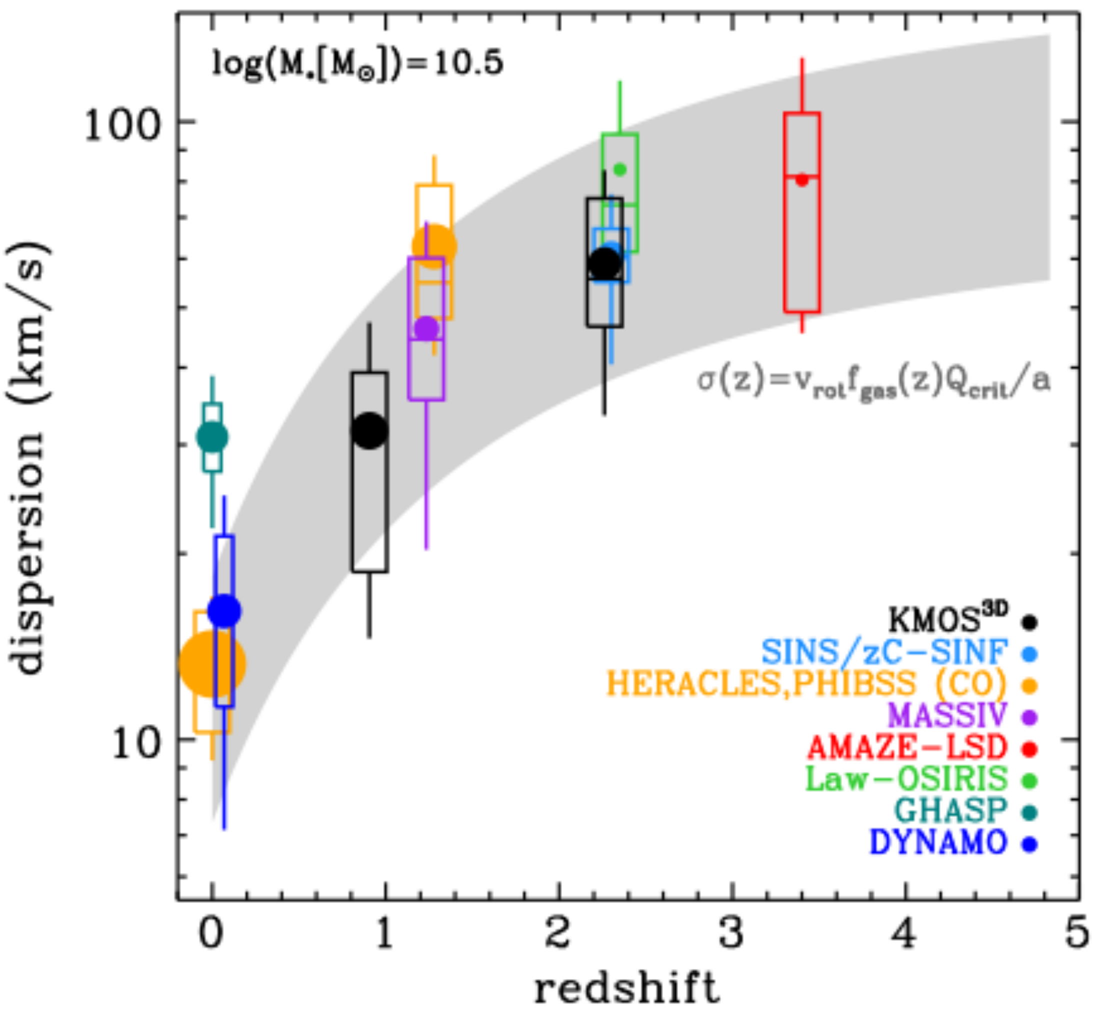
Elmegreen[2] 2005

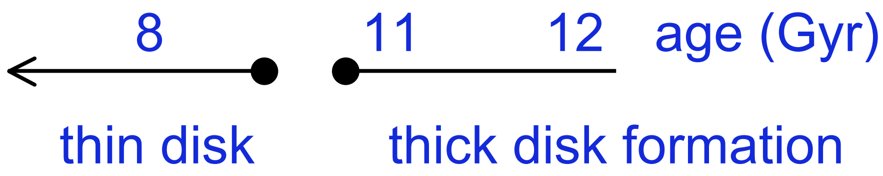
Thick disks may form by dissolution of giant clumps observed in high-z disk galaxies (Elmegreen[2] 2006, Bournaud et al 2008).

These short-lived star-bursting clumps have masses up to about 10^9 $M_\odot$ (Förster-Schreiber et al 2011) and star formation rates ~ 20 $M_\odot$ yr^{-1}.

Clumps generated by gravitational instability of a turbulent disk (Elmegreen talk). Velocity dispersion of thick disk then associated with disk turbulence at high z, rather than heating.

High disk turbulence dropping towards low z





- high-z disks are turbulent: their turbulent velocity dispersion decays from about 100 km/s at z > 3 to 30 km/s at z = 1.

- The observed decay of turbulent velocities from z ~ 3 extends into the epoch of thin disk formation 8-10 Gyr ago

- The (velocity dispersion) - age relation for the thick disk and the older thin disk stars may reflect the decaying turbulence at high-z rather than disk heating.

Wisnioski et al 2015

Upside-down disk formation (Bird et al 2013)

Idea of upside-down disk formation is not new: see Elmegreen^2 2006, Bird, Brook, Bournaud, Bershady. Haywood et al 2013 note the likely evolutionary link between the thick disk and the older thin disk.

The younger thin disk stars (ages < few Gyr) are likely to have formed from gas whose turbulence had decayed to the present value of around 8 km/s. Their velocity dispersions are likely to reflect disk heating.

Bershady: how do we observationally disentangle the contributions from a cooling gas disk and from later heating of a very thin stellar disk ?

Thanks to N. Förster-Schreiber, R. Genzel, O. Gerhard, L. Tacconi, H. Übler, and others at MPE for discussions, and to M. Berschady and B. Elmegreen for emails about upside-down star formation.

The Bulge

Bulges are not an essential part of disk galaxy formation

Some galaxies have no bulges NGC 5907 (Not rare: Kormendy et al 2010)

Some have boxy bulges like the MW NGC 5746

Some have large classical bulges NGC 4594

Spectra of boxy bulge galaxies show complex gas flows associated with the bar-like potential of the boxy bulge (Bureau & KF 1999)

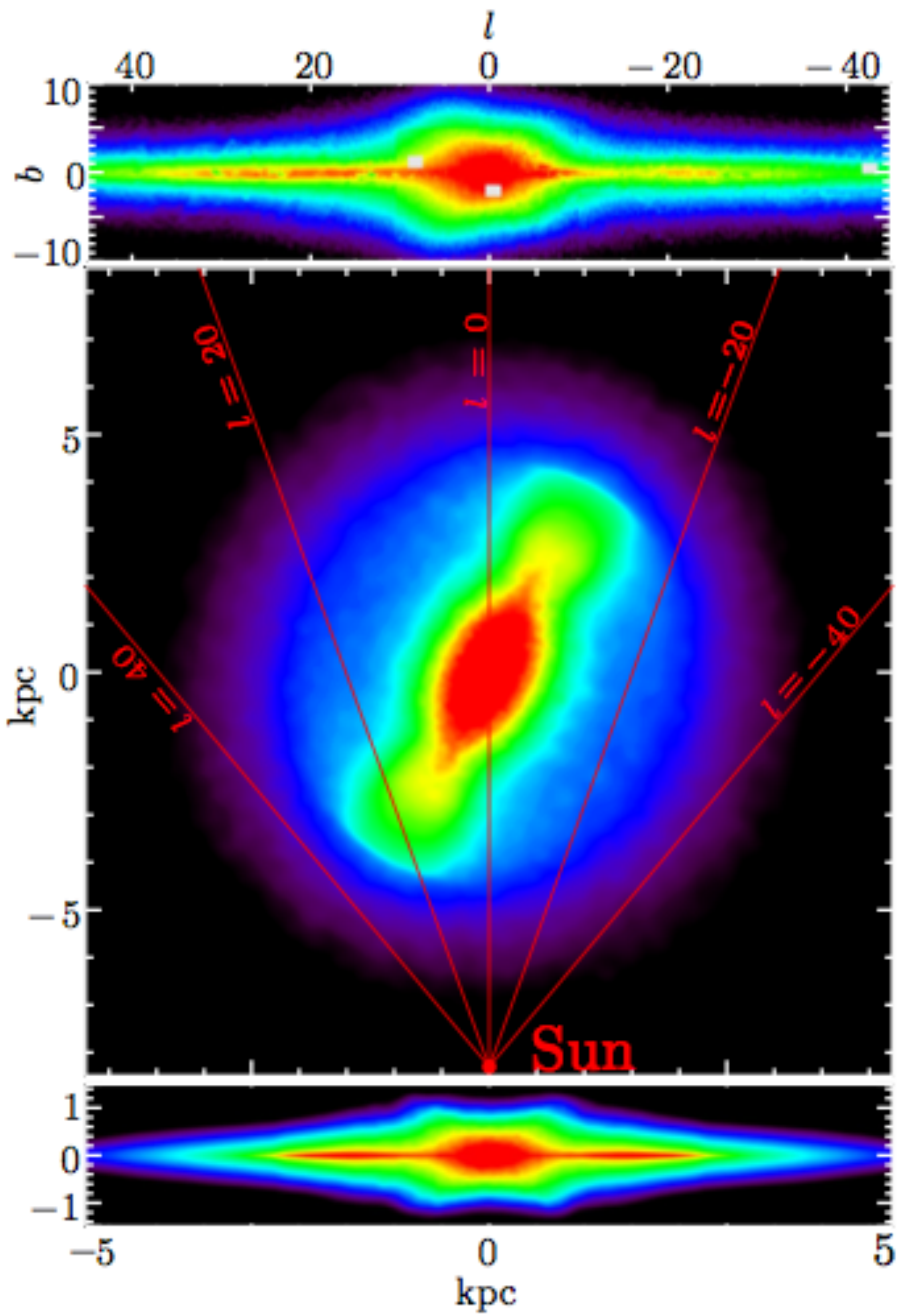
The boxy appearance of the Galactic bulge is typical of galactic bars seen edge-on.

Where do these boxy bar/bulges come from ? They are common in later-type disk galaxies.

Simulations show that they come from bar-forming and bar-buckling instabilities of the disk that occurred many Gyr ago. (Combes & Sanders 1981 ......)

Stars of the early thin and thick disk are trapped in the bulge, as fossils of the disk at the time of the instability.

The stars of the bulge are probably older than the bulge structure



For the Milky Way

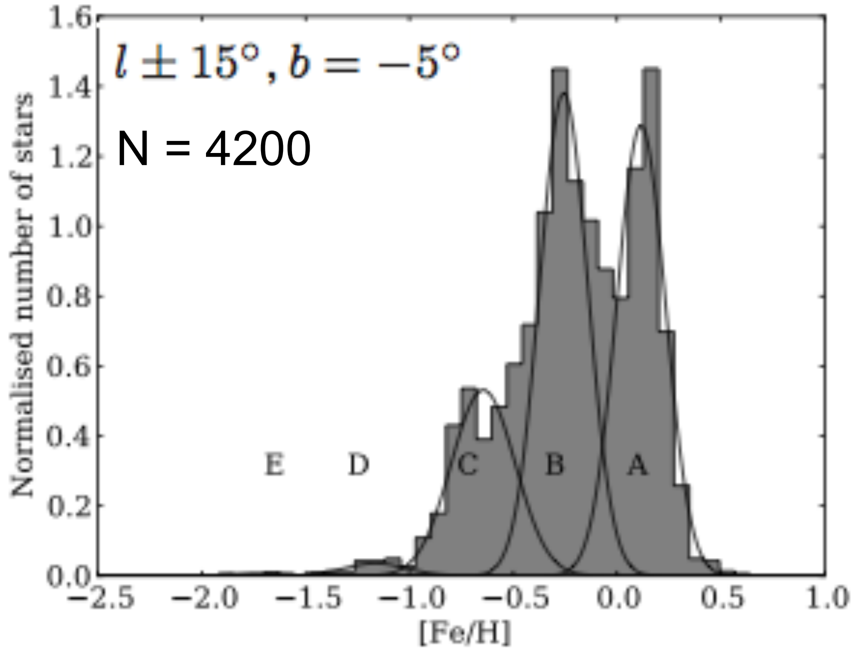
$M = 1.8.\ 10^{10}\ M_{\odot}$
for the boxy bulge
(Portail et al 2015).

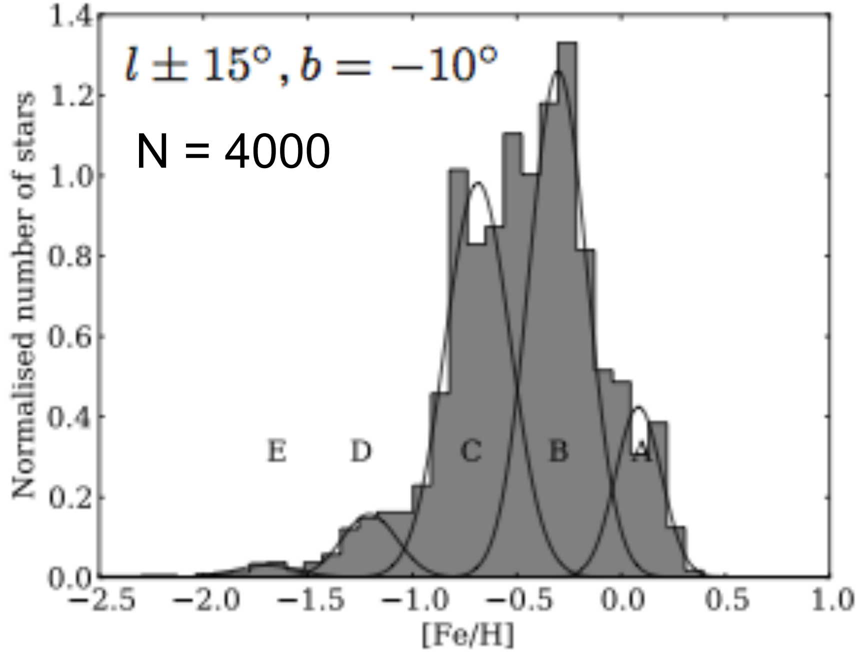
Star counts also show an underlying flatter bar extending out to ~ 5 kpc

Flat bar and boxy bulge likely to be part of a common structure that buckled to form the bulge (Portail talk)

Wegg et al 2015

The ARGOS bulge MDF shows 5 components for $R_G < 3.5$ kpc



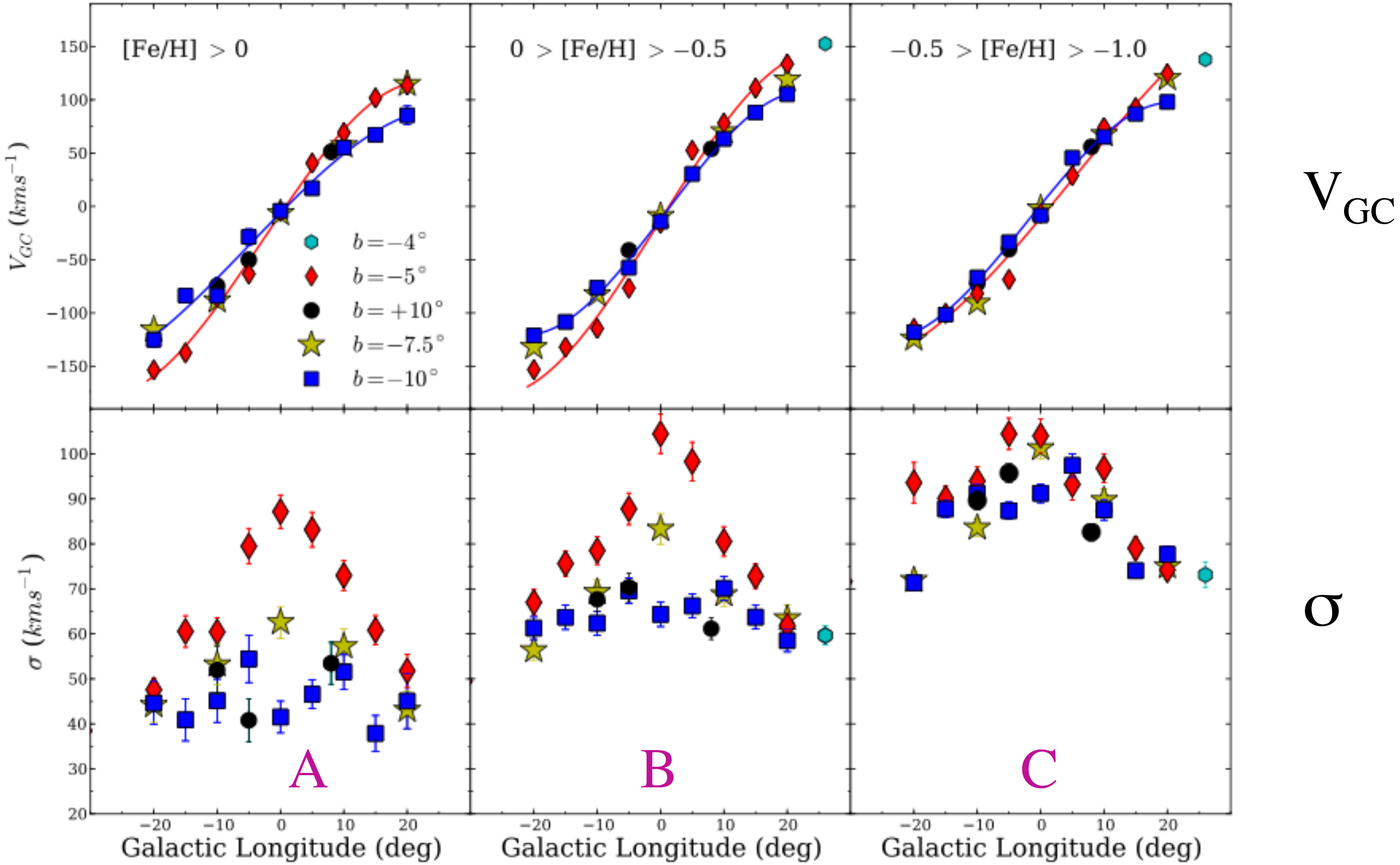


	[Fe/H]	origin
A	0.12 ± 0.02	young thin disk
B	-0.27 ± 0.02	old thin disk
C	-0.70 ± 0.01	thick disk
D	-1.18 ± 0.01	MP thick disk
E	-1.68 ± 0.05	halo

See change of relative weights with latitude. A is strong, C is weak at *b* = -5. A is weak, C is strong at *b* = -10

These same components are seen all over the bulge and surrounding inner disk

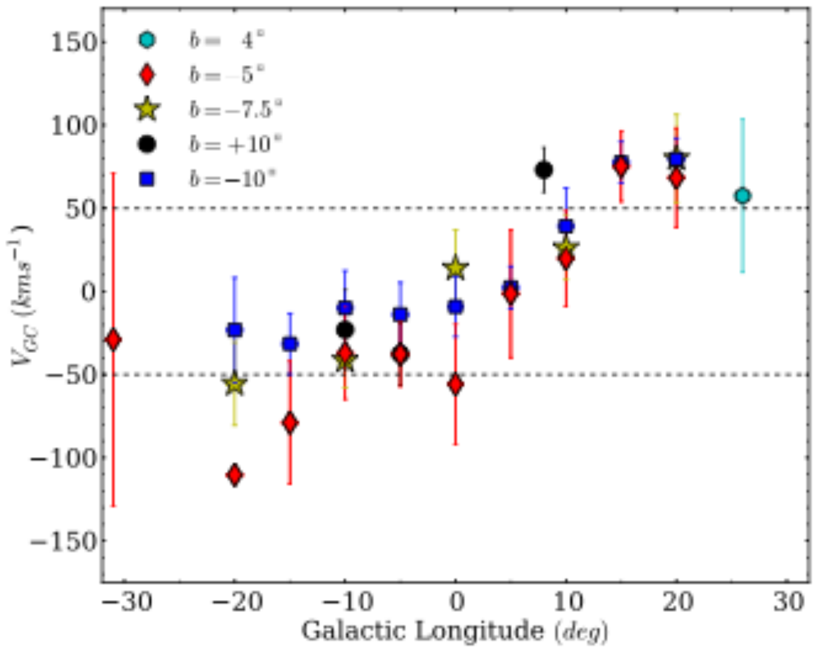
Ness et al 2013



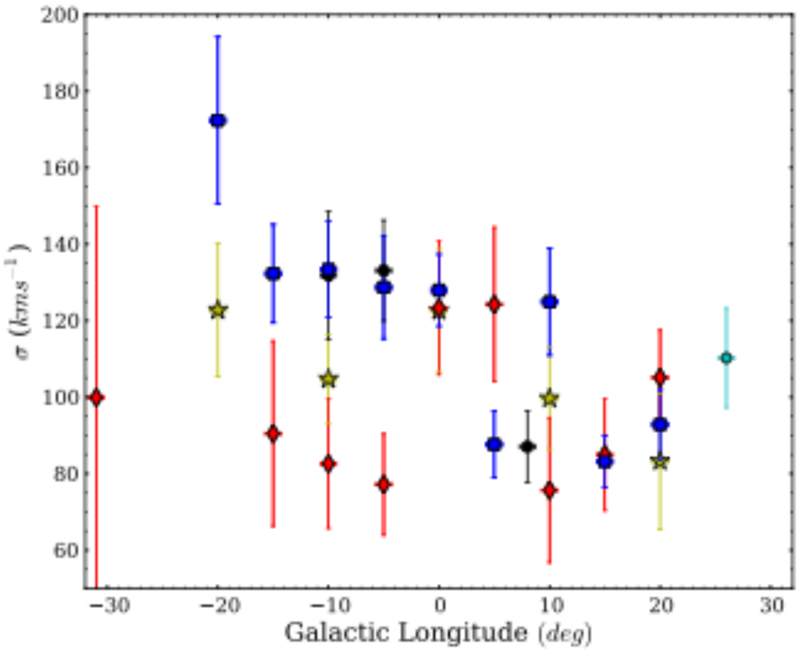
Kinematics of components A-C ([Fe/H] > -1)

All components are rotating rapidly and cylindrically: typical of boxy bulges

Ness et al 2013



V_{GC}



σ

Kinematics of metal-poor components D and E ([Fe/H] < -1)

Rotation of the metal poor stars is much slower and the dispersion is higher :
Dynamical different populations from components A-C

The metal-poor stars in inner Galaxy may include the first stars (Tumlinson et al 2010 ...) which formed in the early (z < 10-15) density peaks that lay near the highest density peak of the final system. How can we tell if these stars are the first stars, or just part of the inner stellar halo (Perez-Villegas poster) ?

Ness et al 2013

The Halo

Three components, all on 100+ kpc scales - but maybe only weakly related cosmogonically ?

The stellar halo: mainly debris from accretion.

Gaseous corona: reservoir of baryons. Not yet well understood.

The dark halo: > 95% of the Galactic mass.

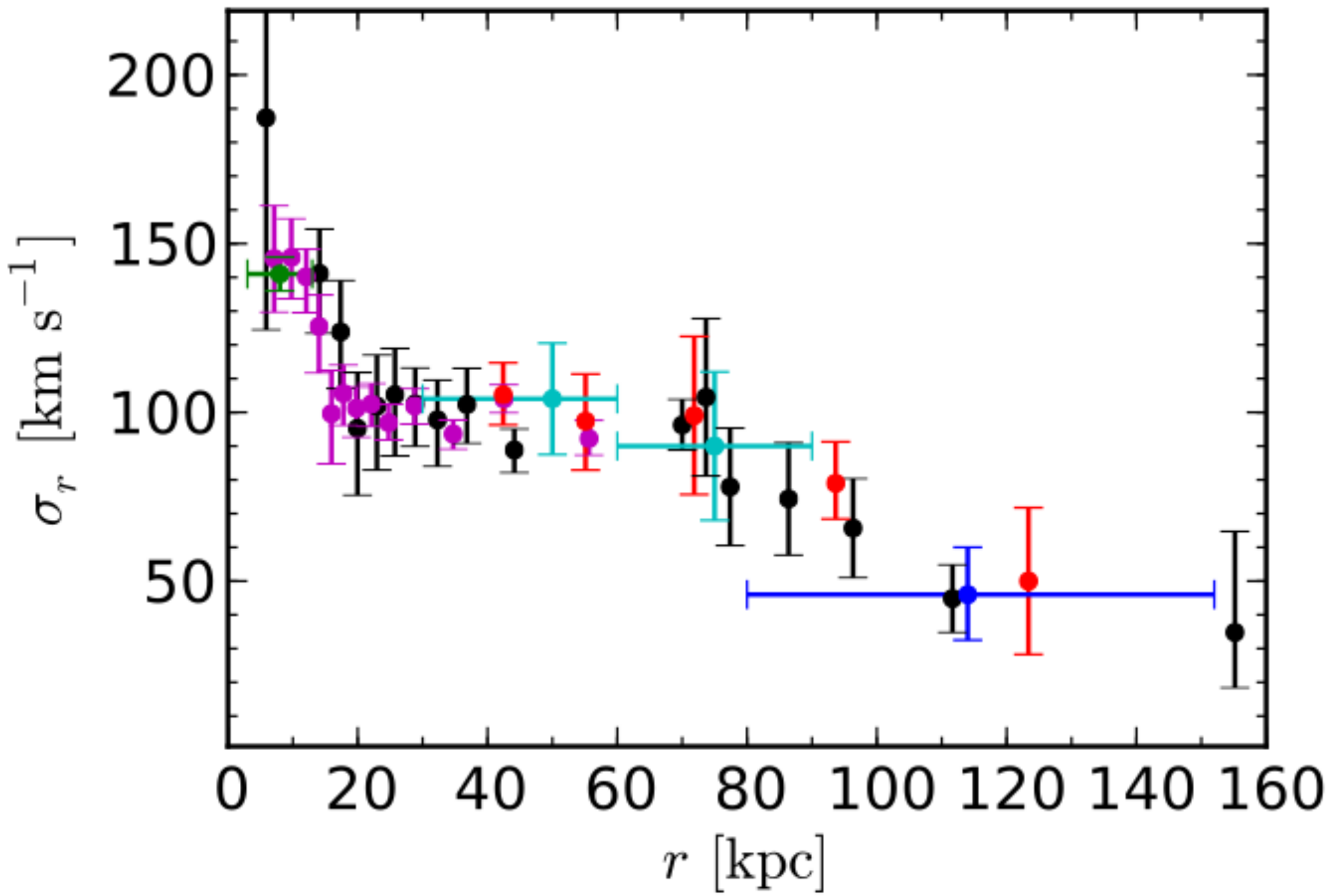
Stellar halo:

- Stars are metal-poor, with [Fe/H] from < -5 to -0.5. Only 1% of stellar mass of the MW.

- probably built up mainly from accreted small galaxies. Long dynamical time: see unmixed substructure on many scales : substructure makes up about half of the stellar halo mass.
- the stellar halo may tell us more about the chemical evolution of dwarf galaxies than it tells us about the evolution of the MW.

- Some evidence for a dual halo: the inner halo is flattened and slowly rotating; the outer halo is near-spherical and retrograde rotation.
- Power law density distribution, with inner slope -2.5, break at 25 kpc, outer slope -4.
- Traced out beyond 100 kpc by metal-poor stars (BHB, RRL, giants).

The metal-poor globular clusters are part of the stellar halo, but the link is uncertain. At least some GC may have been satellite nuclei.



Velocity dispersion of MW stellar halo: metal-poor stars, GCs, satellites

- halo is supported mainly by its velocity dispersion : σ_R = 140 km/s near sun, dropping to < 50 km/s at R ~ 150 kpc. σ(R) and kinematics of halo streams are useful tracers of the total potential of the Galaxy

Bland-Hawthorn & Gerhard 2016

Gaseous halo:

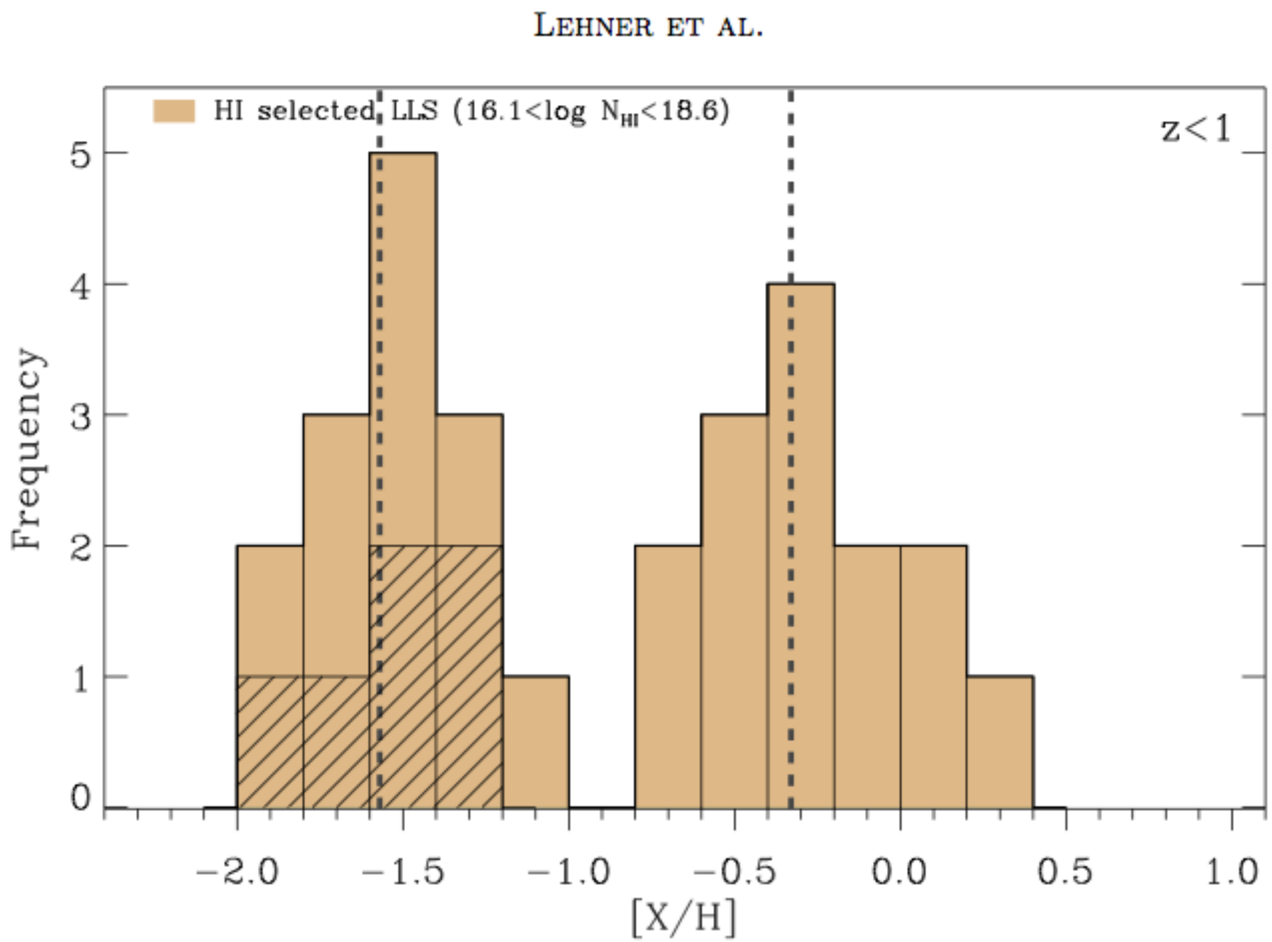
Seen in absorption against QSOs, soft X-ray background, pulsar dispersion measure, and ram pressure stripping of dwarf galaxies within about 250 kpc.
T ~10^4 to ~ 2.10^6 K. Mass ~ 2.10^{10} $M_\odot$ (uncertain) (see Richter talk) .

Gaseous halo probably contains a fair fraction of the galactic baryons.
stars and cold gas ~ 6.10^{10} $M_\odot$, + hot gas ~ 8.10^{10} $M_\odot$.
Then the MW baryon mass fraction ~ 6% (<< cosmic 16%)

Gaseous halo comes probably partly from gas accretion via filaments and partly from gas ejected into hot halo by evolving stars, winds... Bimodal metallicity distribution in cooler (10^4 K) CGM of other galaxies (Lehner et al 2013)

* Recall how little chemical evolution is seen in MW thin disk age-metallicity relation: the chemically enriched gas produced over the past several Gyr may be ejected into the hot halo rather than enriching the disk stars (Martig)

The gaseous halo is a potential source of baryons for continuing star formation (Fraternali talk).



Bimodal metallicity distributions CGM of Lyman limit systems
(X is C, O, Mg, Si)

Metal-poor mode may be gas accreted from filaments
Metal-rich mode may be recycled gas: winds, outflows ...

Lehner et al 2013

Dark halo:

(parameters not very secure)

Mass estimates from kinematics of stellar halo objects, escape velocity near the sun, M31 timing arguments:
$M_{200} \sim 1\text{-}2.10^{12}\, M_\odot$ $R_{200} \sim 200$ kpc.

By far the dominant component of the Galactic mass, though baryons dominate the gravitation field in the inner Galaxy (Wegg poster)

Shape uncertain: modelling halo streams indicates roughly spherical dark halo.

SImulations predict dark halo has a hierarchy of subhalos, many more the observed MW satellites of corresponding V_c (Frenk talk).

Nature of DM remains unknown.