Clues to galaxy formation from the Milky Way and Local Group

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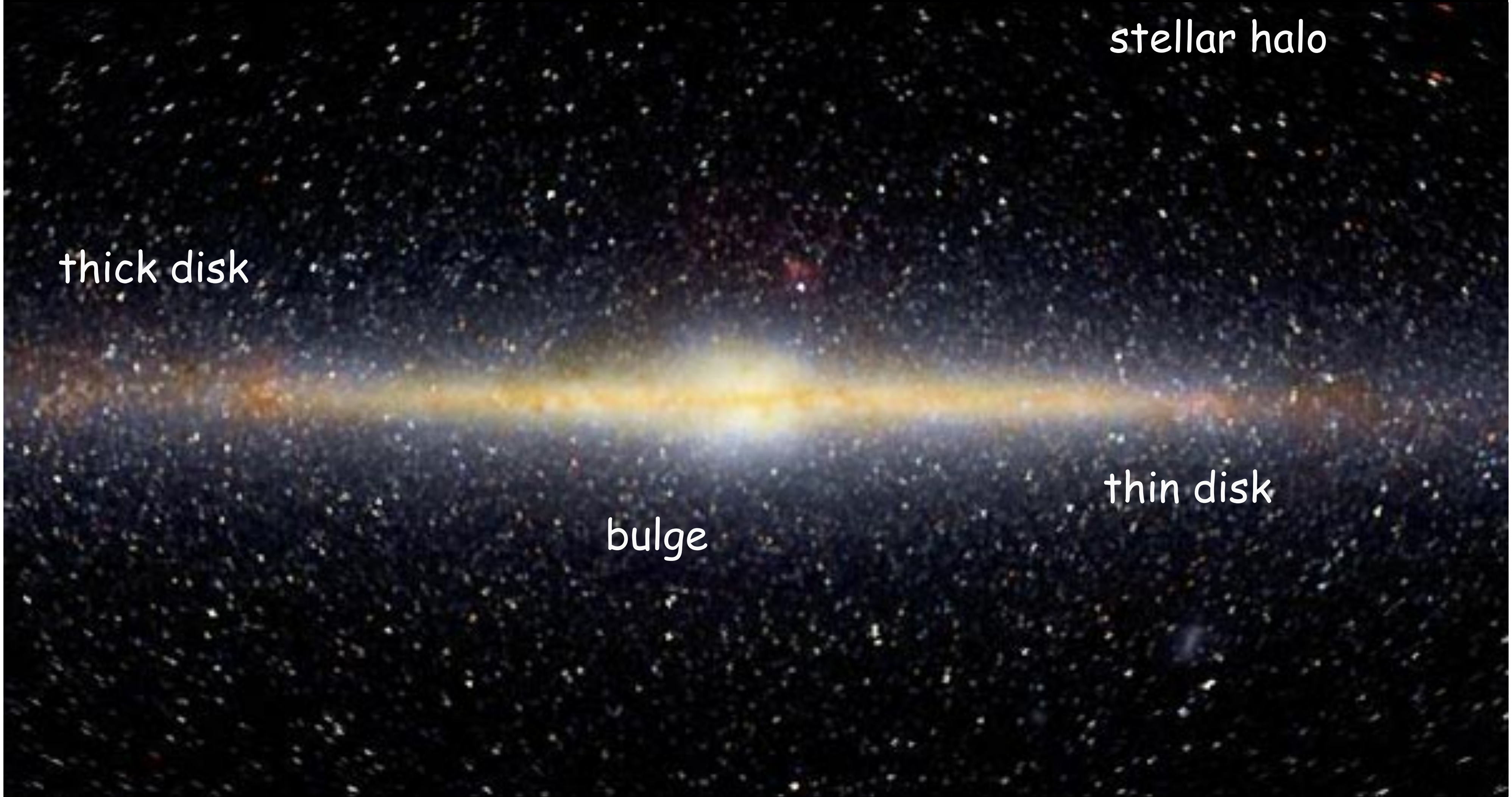
The Milky Way and satellites in context

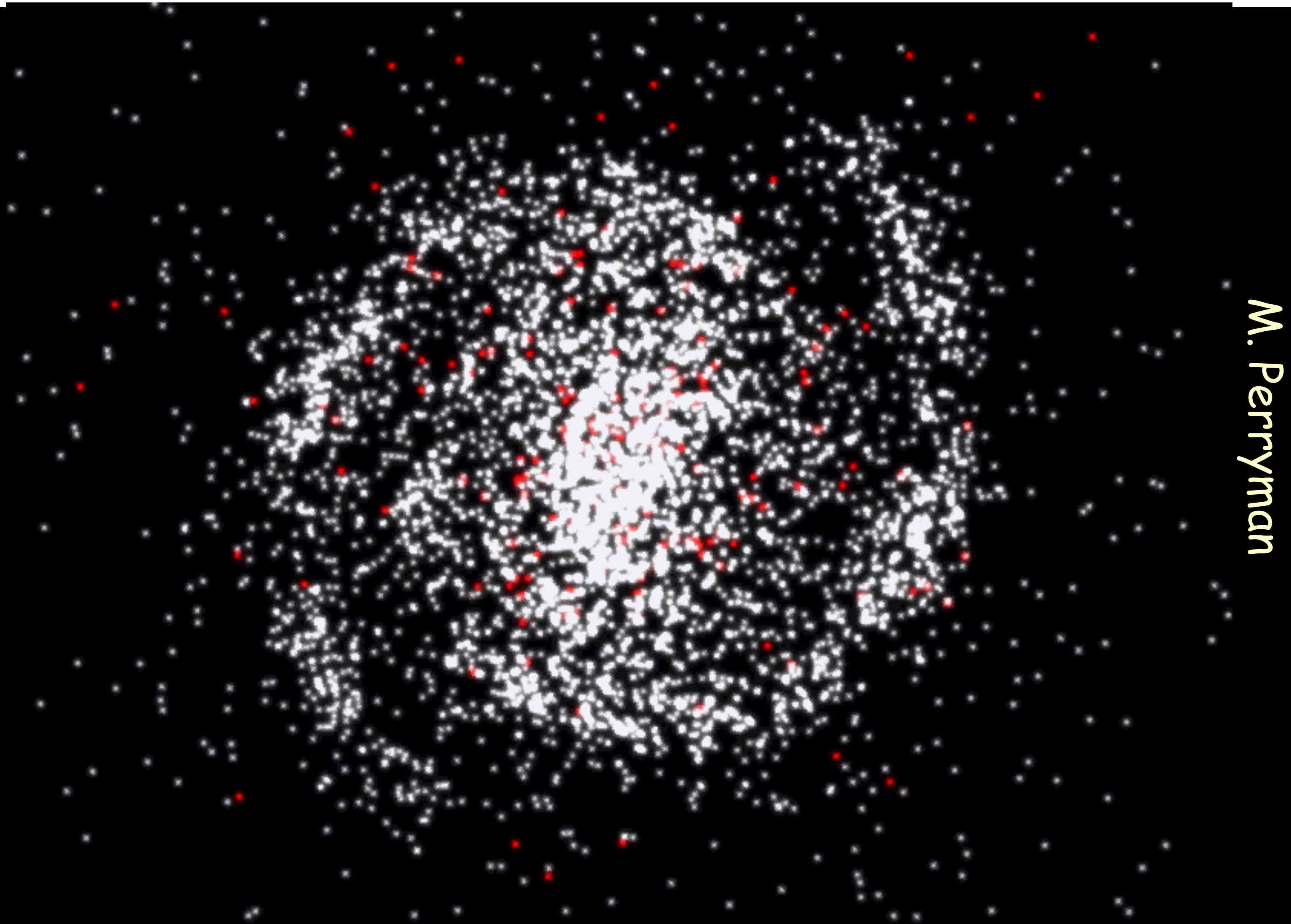
- Traditional approach to galaxy evolution
  – Distant Universe: observing galaxies as they form
  – Statistical (global) properties of galaxy population

- Detailed studies of Milky Way & near-field cosmology
  – Representative system
  – Old stars in main components: "fossils"

The Galaxy



How did the Galaxy come to be like this ?



- Stars retain memory of origin: Orbits; chemical abundances; age distrib

  -> trace internal evolution

  -> mergers leave imprints in remnant: phase-space substructure

Dynamics -> clues to history (and also about DM df)

Outline

- Milky Way and satellites
  - Relevance in a cosmological context
- Clues from the components of the Milky Way
  - Disk(s): thin and thick
  - Bulge/Bar
  - Stellar halo: history and realm of dark matter
- Satellites
  - Galaxy formation on the smallest scales
  - Dynamics and constraints on dark matter
- Summary

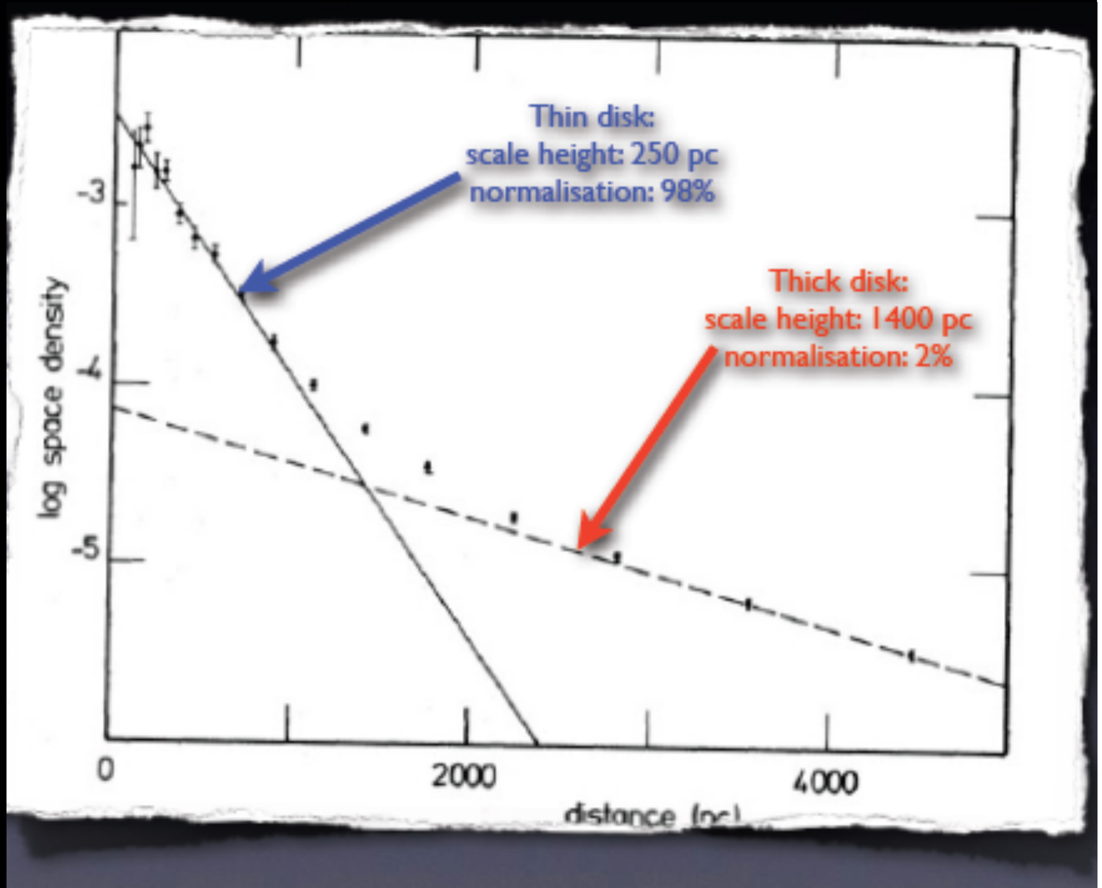
The (thin and thick) disk(s)

Rix's review talk

Steinmetz (this afternoon)

The disk(s)

- Two distinct disk populations in the solar neighbourhood
  - Discovered via star counts
  - Hz(thick)/Hz(thin) ~ 3
  - Normalization ~ 2 – 10%
  - (Robin et al. 2004, Juric et al. 2008)

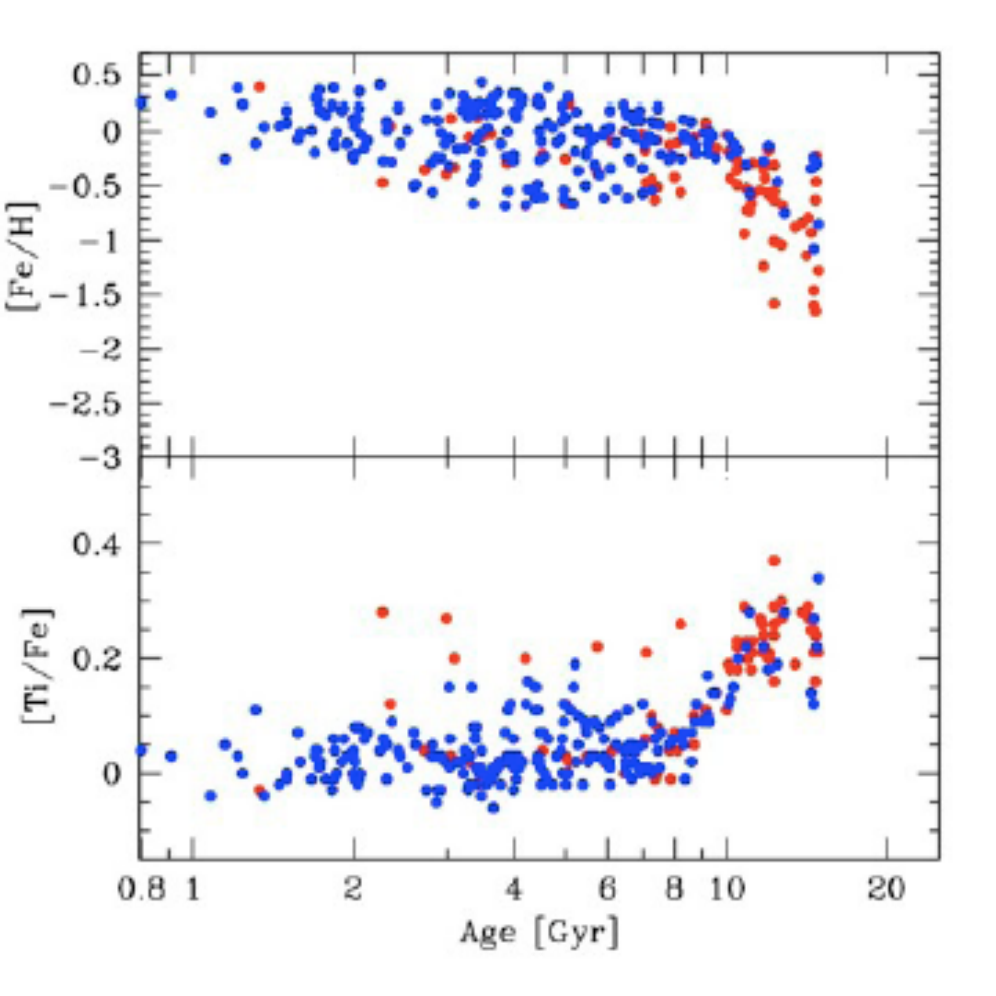


(Gilmore & Reid, 1983, MNRAS, 202, 102)

- Kinematically cold/hot

- Different average metallicities (cf Bensby et al. 2011)

- Distinct abundance trends and age distribution



Bensby et al. 2011

Thin disc

$$\langle[\mathrm{Mg/H}]\rangle = -0.009 \pm 0.012\,\mathrm{dex},$$

$$\langle[\mathrm{Fe/H}]\rangle = -0.034 \pm 0.015\,\mathrm{dex},$$

Thick disc

$$\langle[\mathrm{Mg/H}]\rangle = -0.207 \pm 0.049\,\mathrm{dex},$$

$$\langle[\mathrm{Fe/H}]\rangle = -0.584 \pm 0.057\,\mathrm{dex},$$

Age errors < 3 Gyr

Thin disk younger than 7-8 Gyr

Thick disk older than 8-9 Gyr

Stars with thick disk kinematics follow age-metallicity relation

Stars with thin disk kinematics: No AMR

Chemical Abundance ratios for thin and thick disk

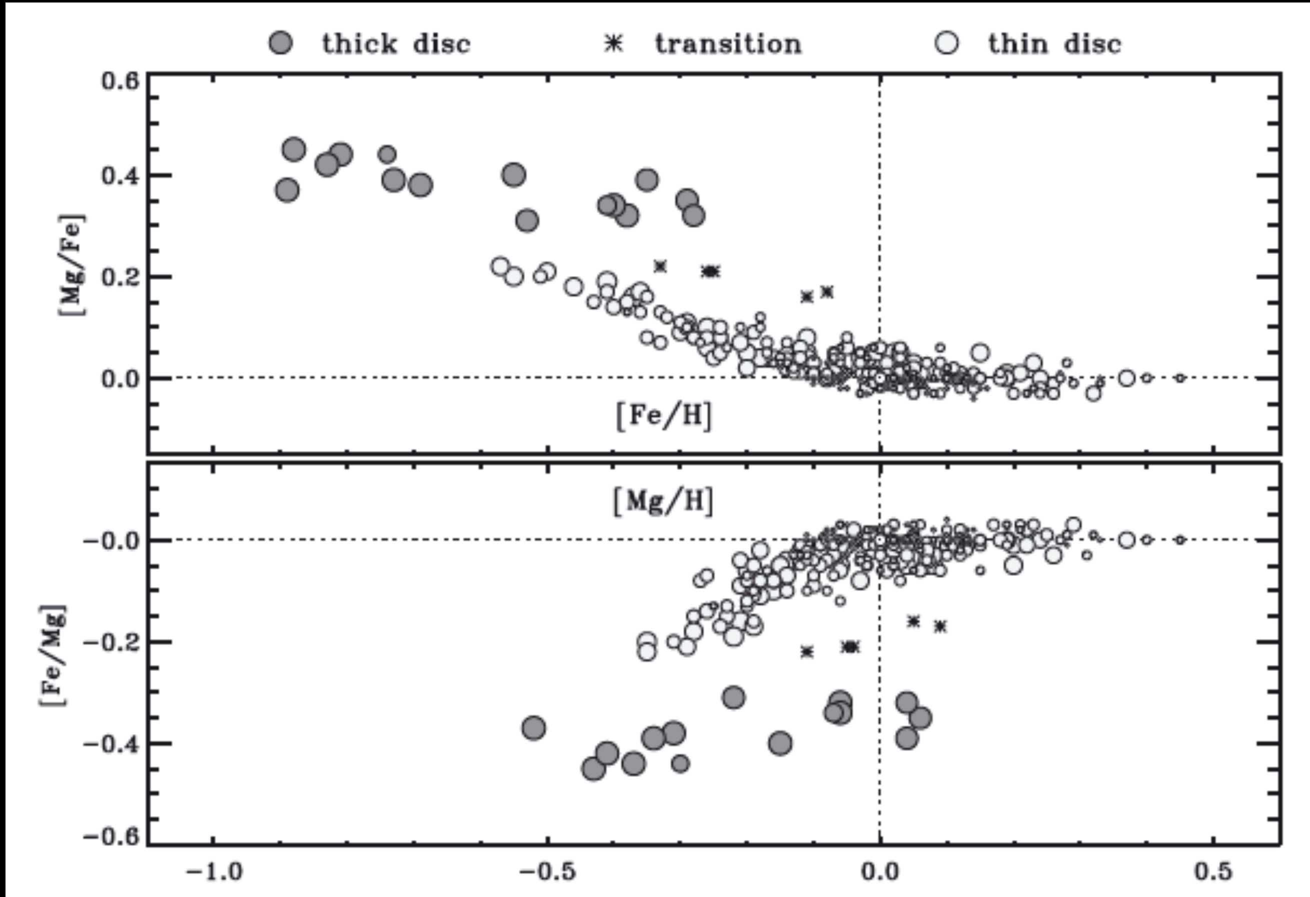
Sample is volume complete

(no kinematic biases)

Elemental abundance ratios clearly evidence two distinct populations

Thick disk: is enhanced in alpha-elements compared to thin disk

- Old ages >10 Gyr



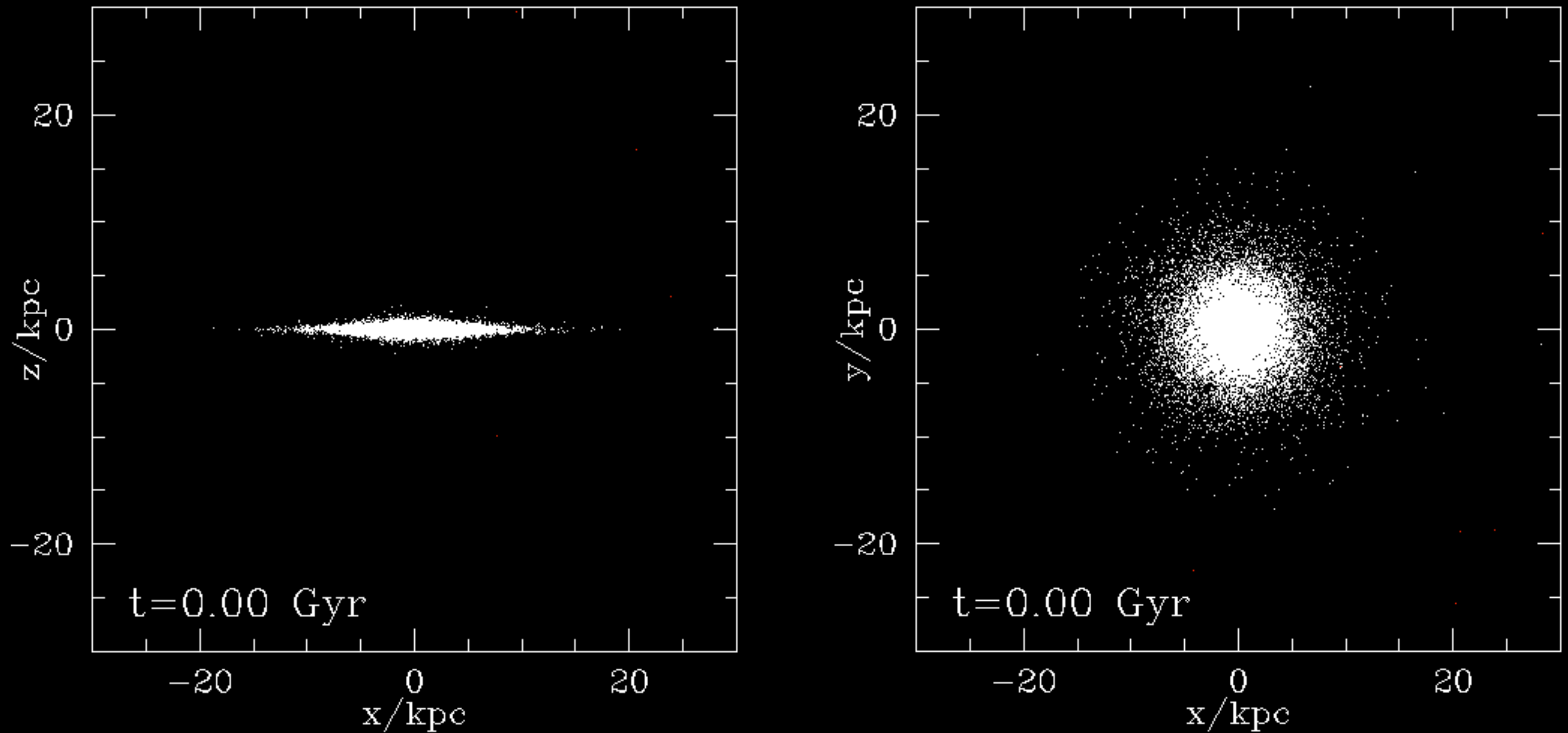
Fuhrmann et al. 2008, 2011

This suggests truly physically distinct components

Thick disk formation paths

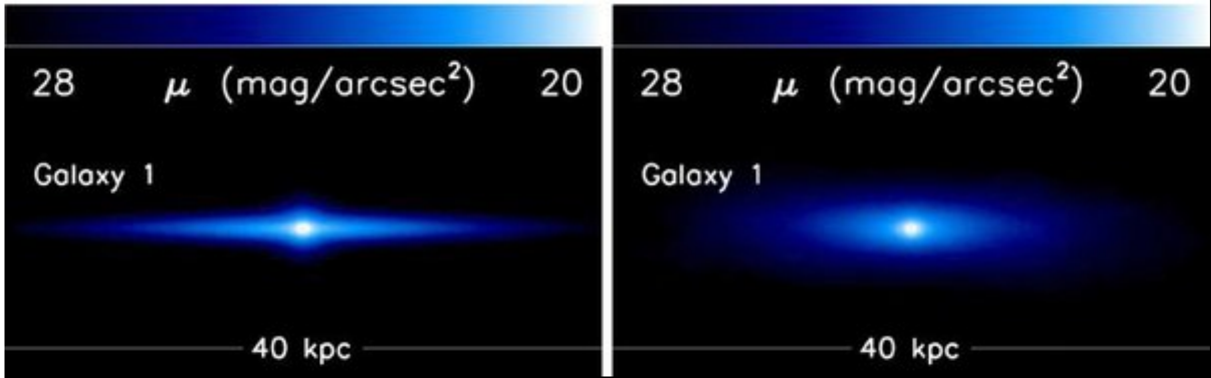
Thick disk formation simulations

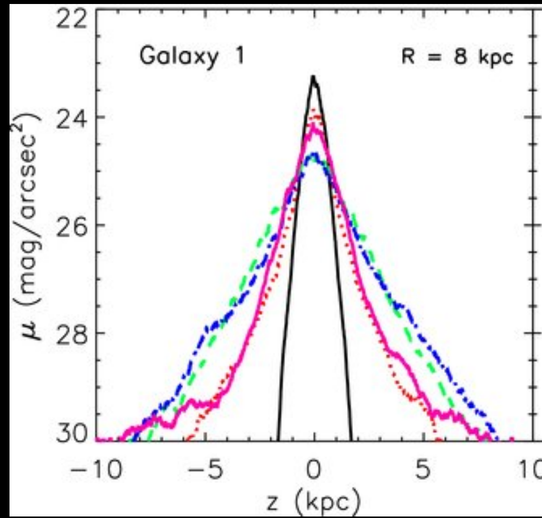
- Thick disk can result from heating by minor merger of pre-existent disk (Quinn et al 1986…)



Villalobos & Helmi 2008

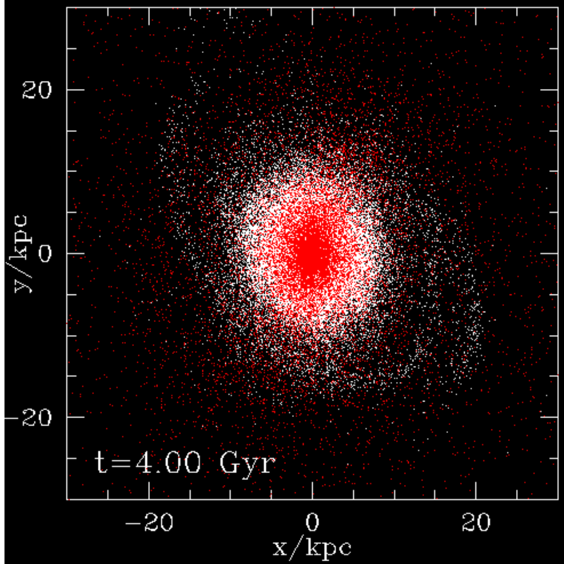
Mergers and the disk: thick disk?

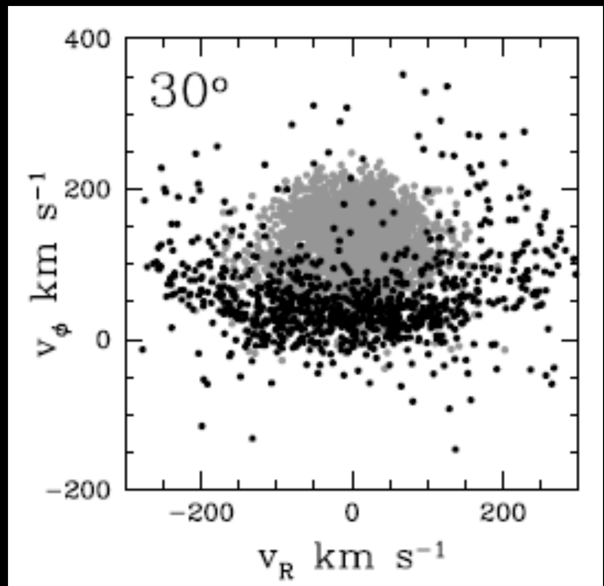




- No strong spatial features (after few Gyr)
- Most stars originate in disk

Purcell, Kazantzidis & Bullock 2009





Villalobos & Helmi 2009

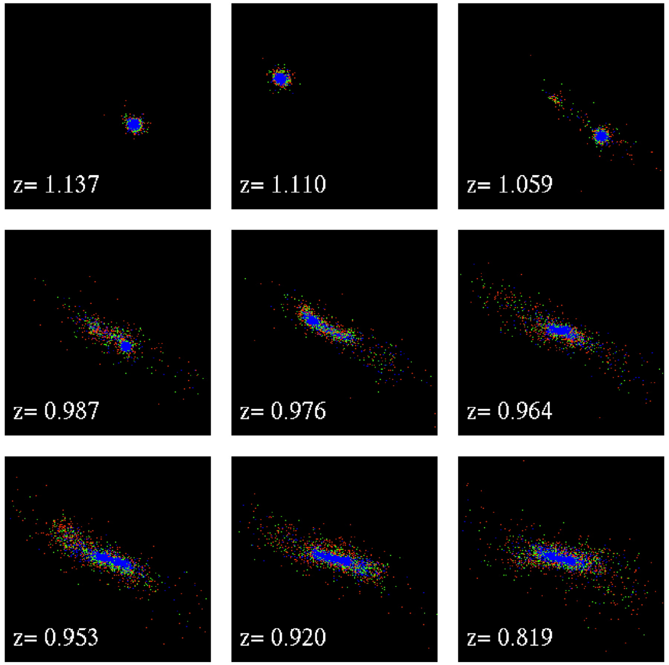
Volume around "Sun":

- Debris velocity distribution distinct from disk
- Characteristic "banana" shape

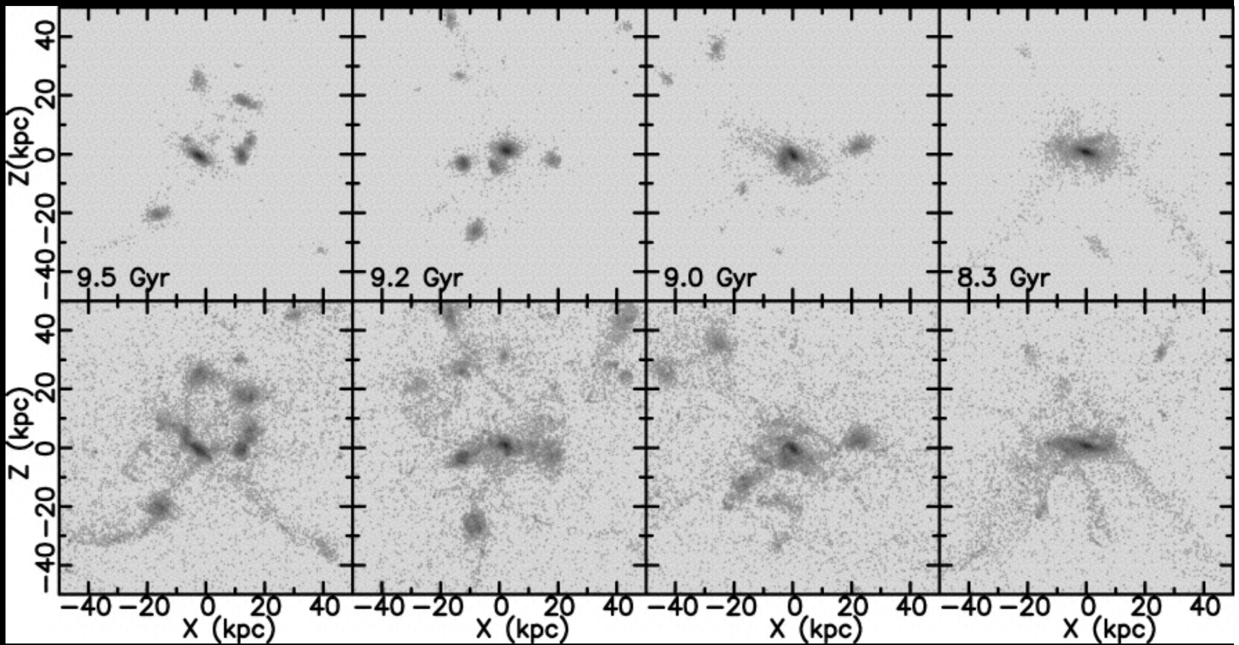
(e.g. Helmi et al. 2006)

Galactic thick disk: formation paths++

- Accretion: purely from disrupted satellites
  - Satellites accreted on preferential directions (Abadi et al. 2003)
- Gas-rich mergers/giant SF clumps
  - Intense star formation (gas unsettled; Brook et al 2004, Bournaud et al 2008)
- Radial migration
  - (Resonance) scattering by spiral arms drives stars from inner Galaxy to solar neighbourhood (Schoenrich & Binney 2009)



Abadi et al. 2004



Brook et al. 2004

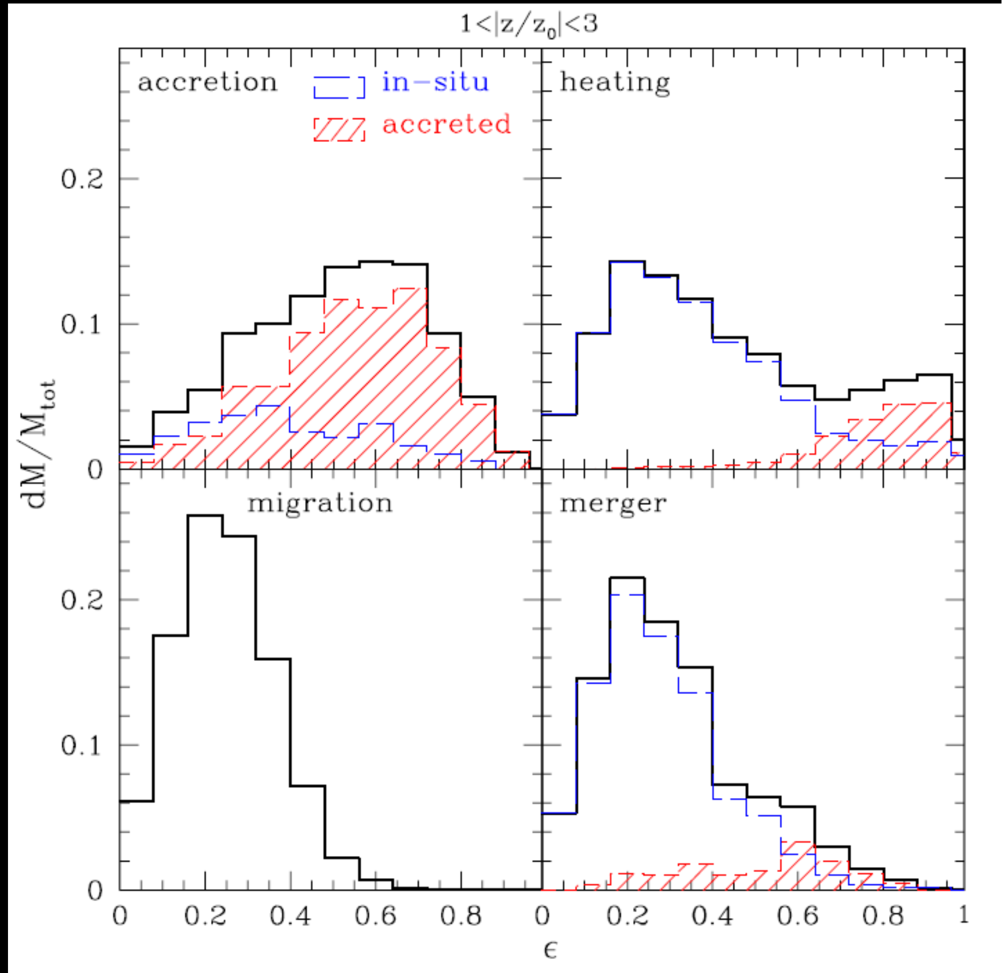
A powerful test of formation: orbital eccentricity

- 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)

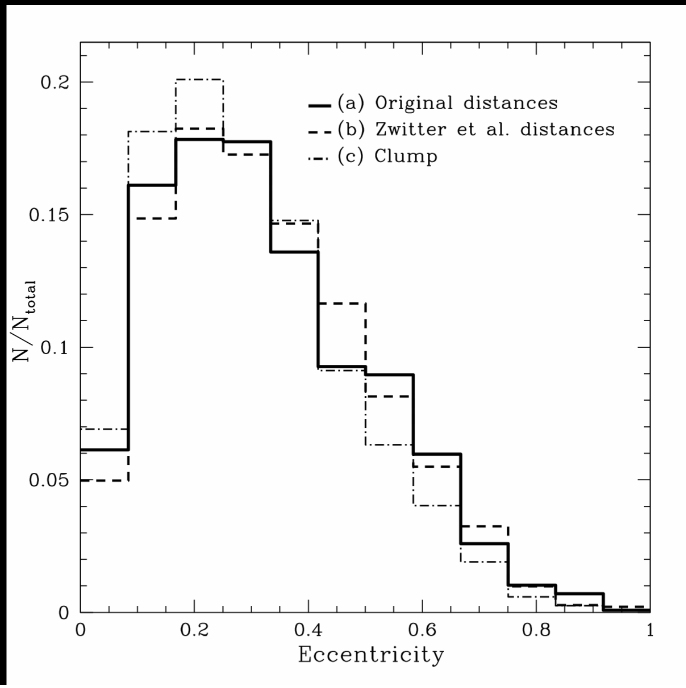


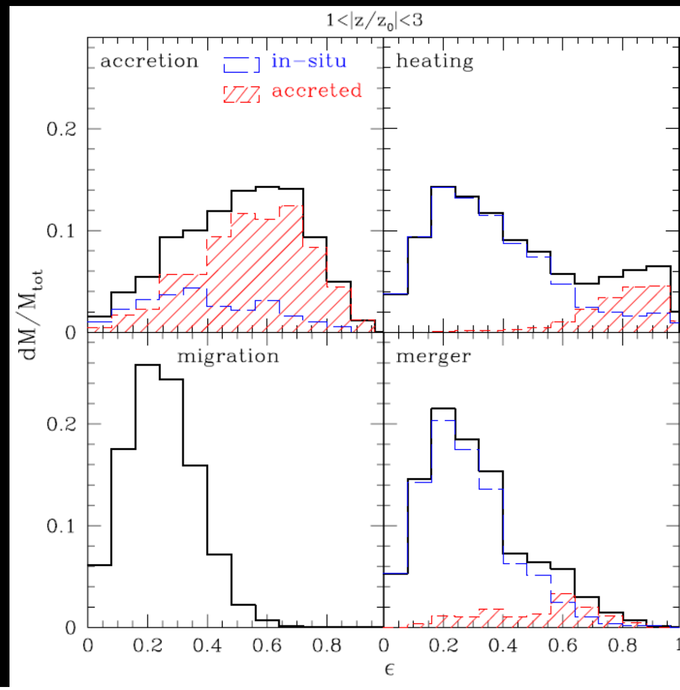
Sales et al. 2009

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)

Bulge/Bar

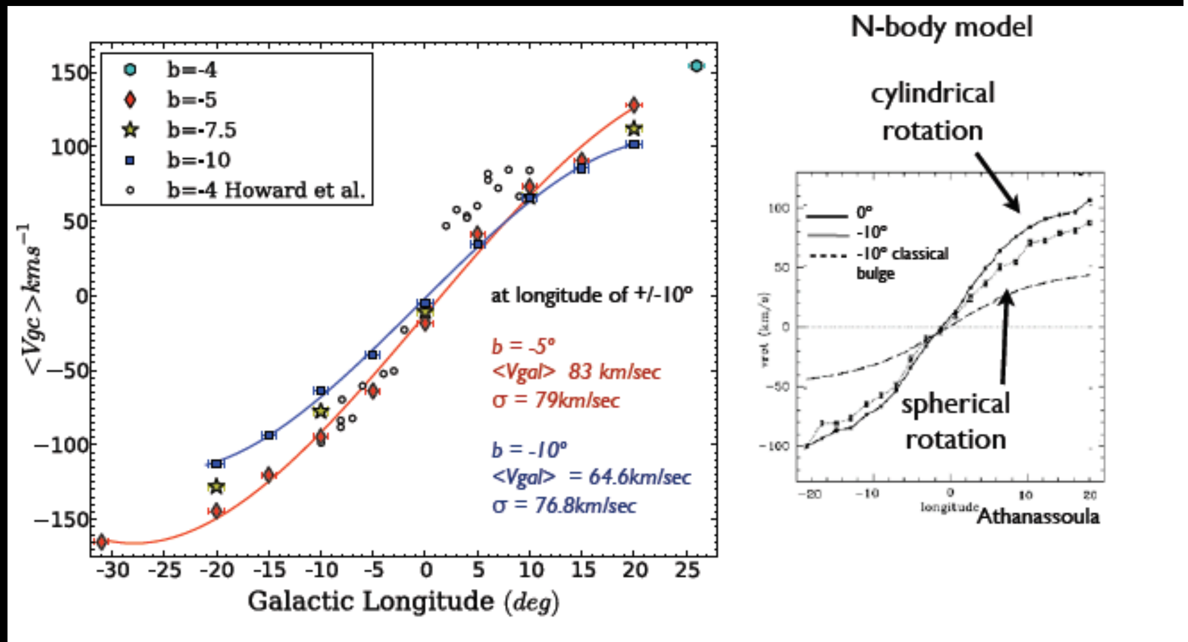
Structure and kinematics of the bulge

Bar / bulge is ~ 3.5 kpc long, axial ratio ~ 1: 0.35: 0.25

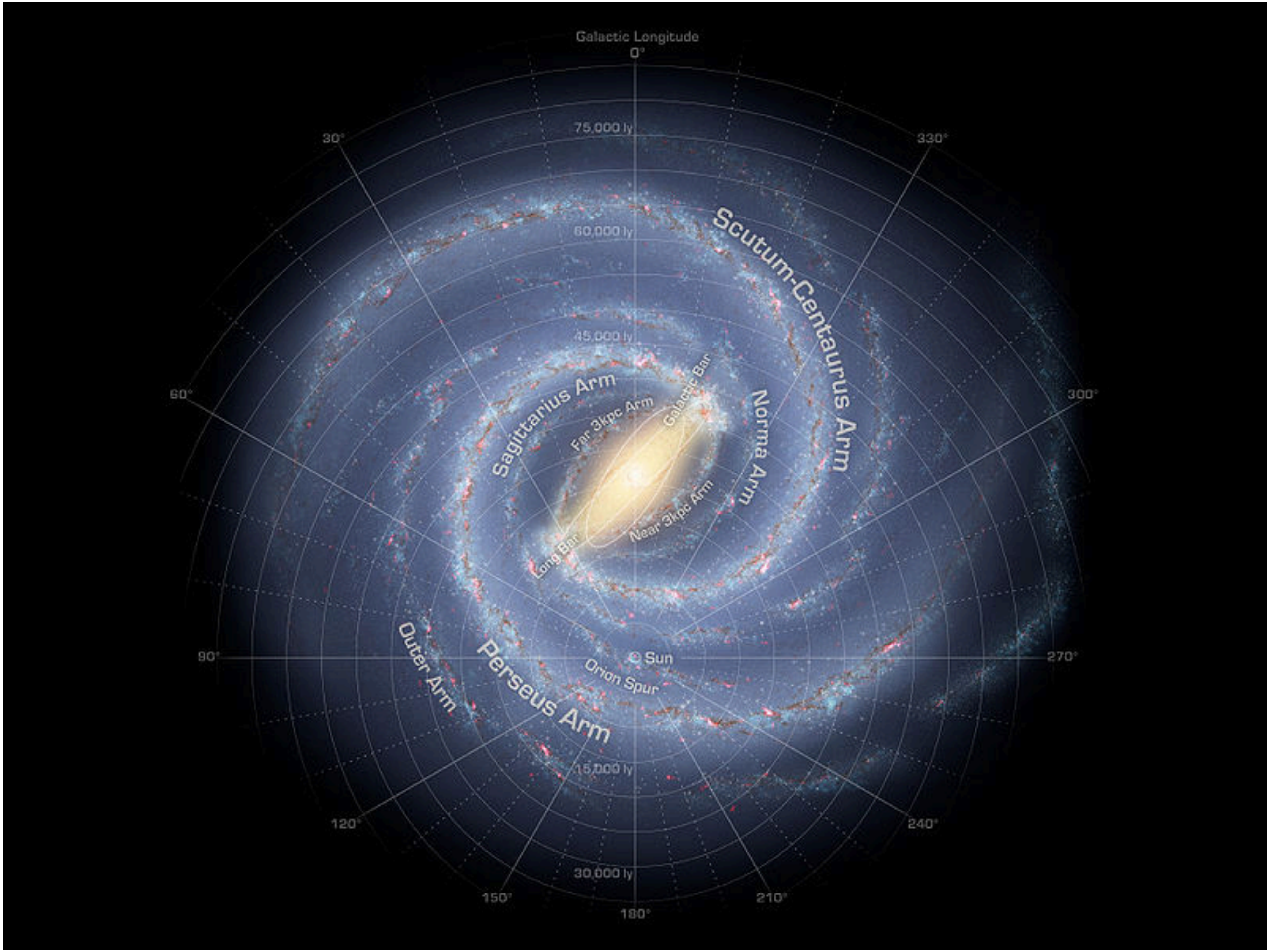
Position angle ~ 25deg from sun-center

Consistent with formation via a bar instability (Combes' review)

Best constraints on presence of classical bulge (via mergers) by Shen et al. (2010) from modeling of BRAVA data (Howard et al. 2008, 2009)



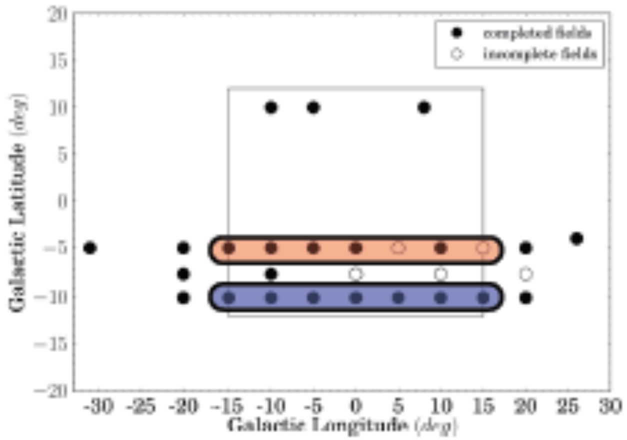
Ness et al (2011); Babusieux et al. 2010

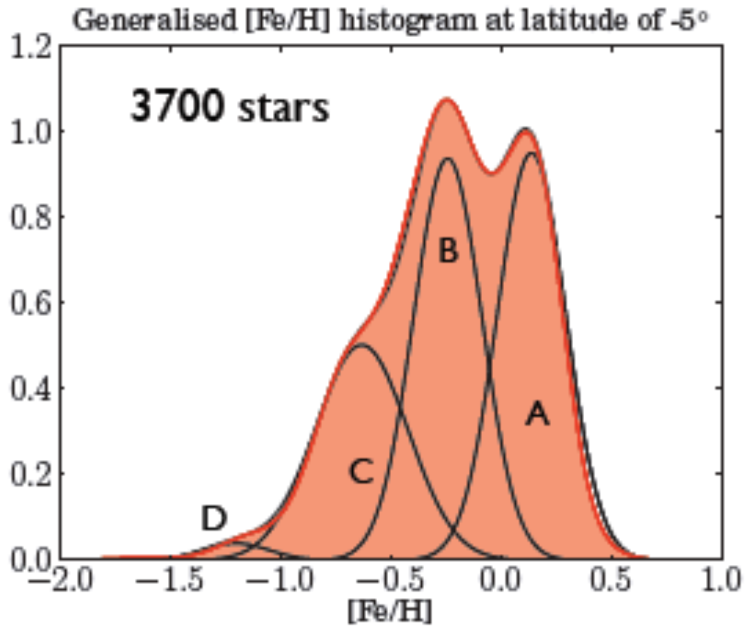

Galactic Longitude
0°
30°
330°
75,000 ly
60,000 ly
45,000 ly
Scutum-Centaurus Arm
Sagittarius Arm
Far 3kpc Arm
Galactic Bar
Norma Arm
Near 3kpc Arm
Long Bar
60°
300°
90°
270°
Outer Arm
Perseus Arm
Sun
Orion Spur
15,000 ly
30,000 ly
120°
240°
150°
210°
180°

MDFs across latitudes -5 degrees, -10 degrees

See 4 components

cut in radius < 3.5kpc

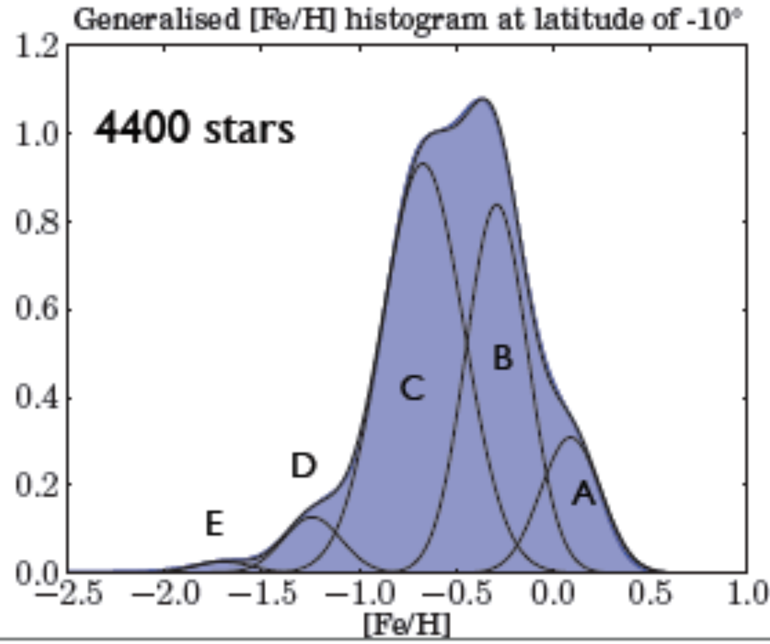




Same 4 components

At -0.05 lower mean in [Fe/H] for -10° latitude field

A <Fe/H> = 0.14/0.09, σ = 0.155
B <Fe/H> = -0.24/-0.29, σ = 0.155
C <Fe/H> = -0.64 /-0.69, σ = 0.21
D <Fe/H> =-1.2 /-1.25 σ = 0.15
E: <Fe/H> =-1.7 , σ = 0.15

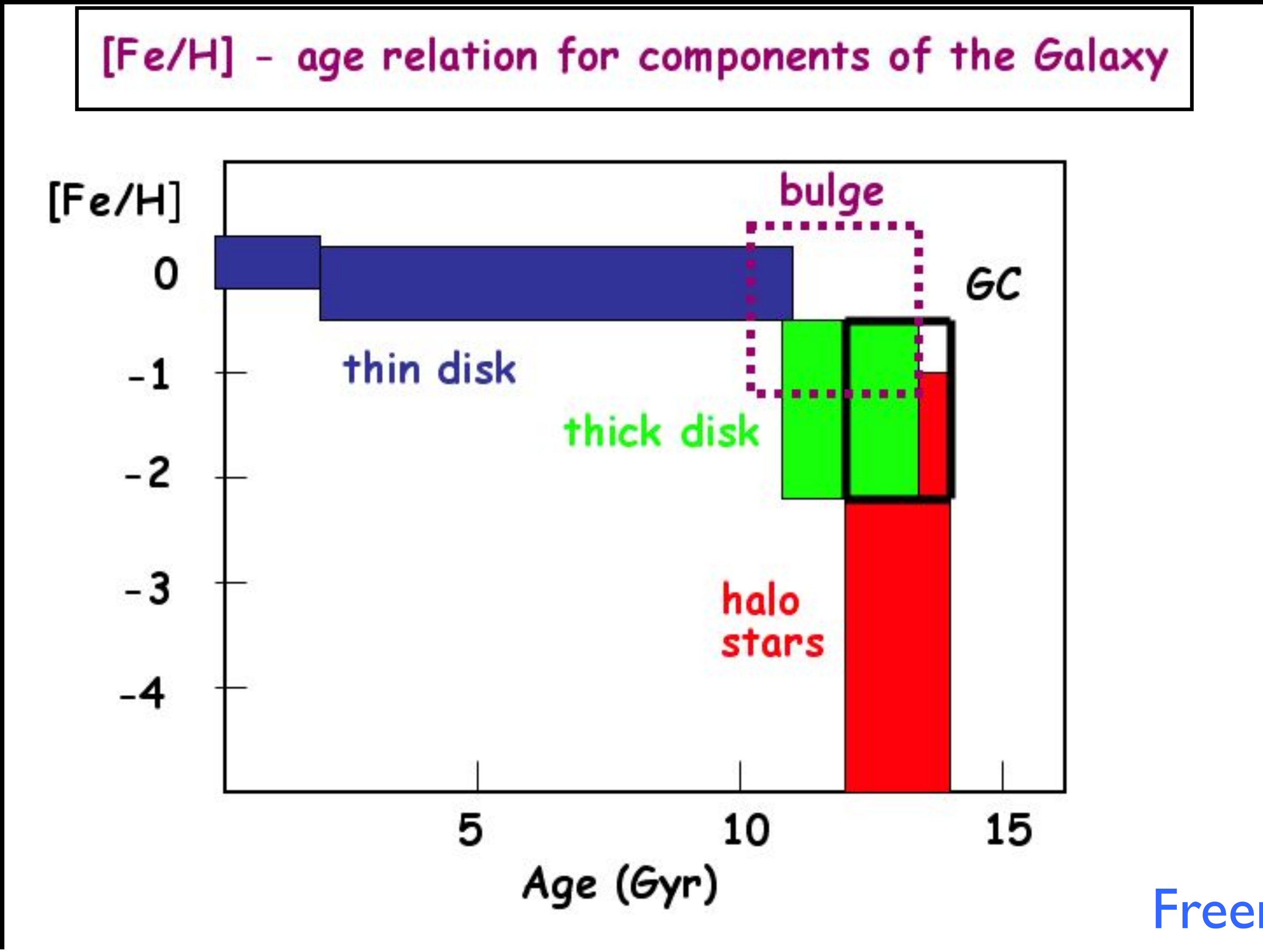


Ness et al. 2011; ARGOS

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, globular clusters and metal-poor bulge)



Freeman 2007

Stellar halo

Why care about stellar halos?

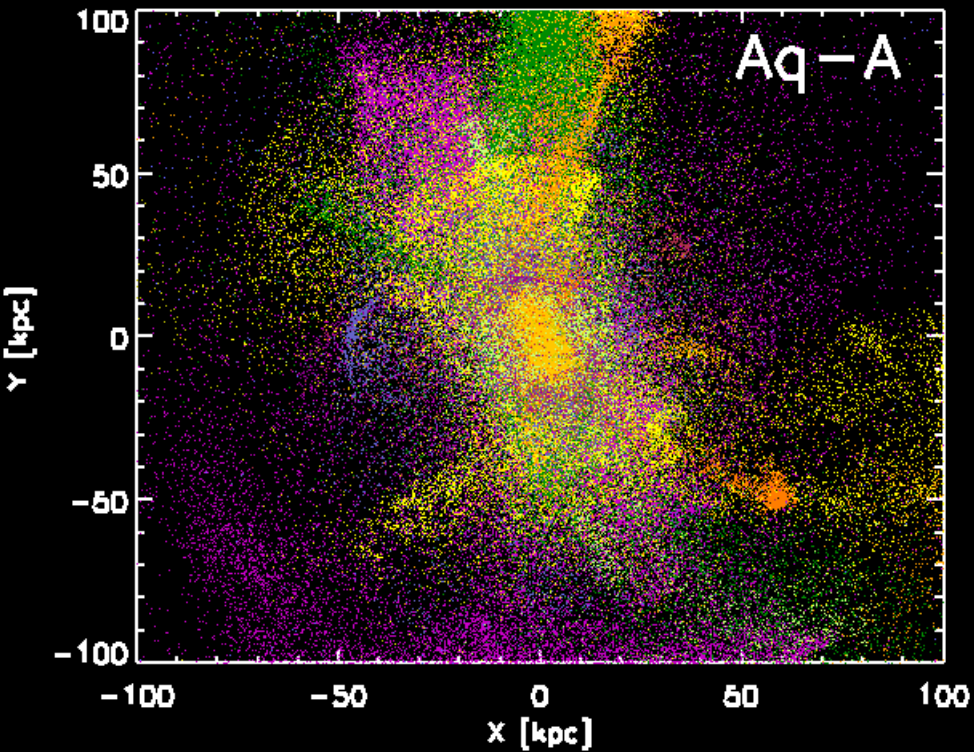
- Most metal-poor and ancient stars
  - window into the early Universe

- Orbiting outskirts of galaxies: good mass probes

- Can form from the superposition of disrupted satellites

  •stars retain memory of their origin
  -> merger history

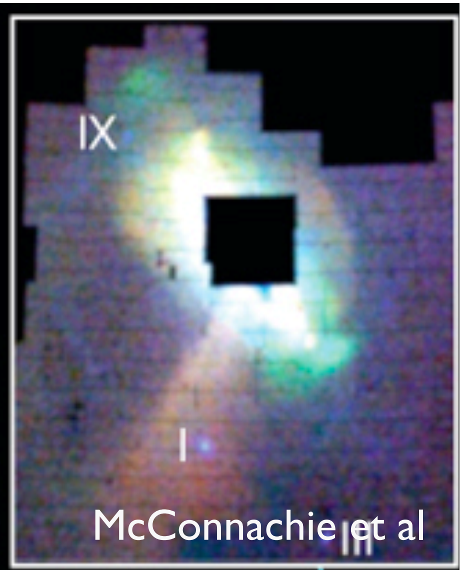
- Some fraction likely formed in-situ
  •In gas rich mergers (Zolotov, Font, Tissera)
  •Scattered off from disks during mergers (Purcell, Zolotov)

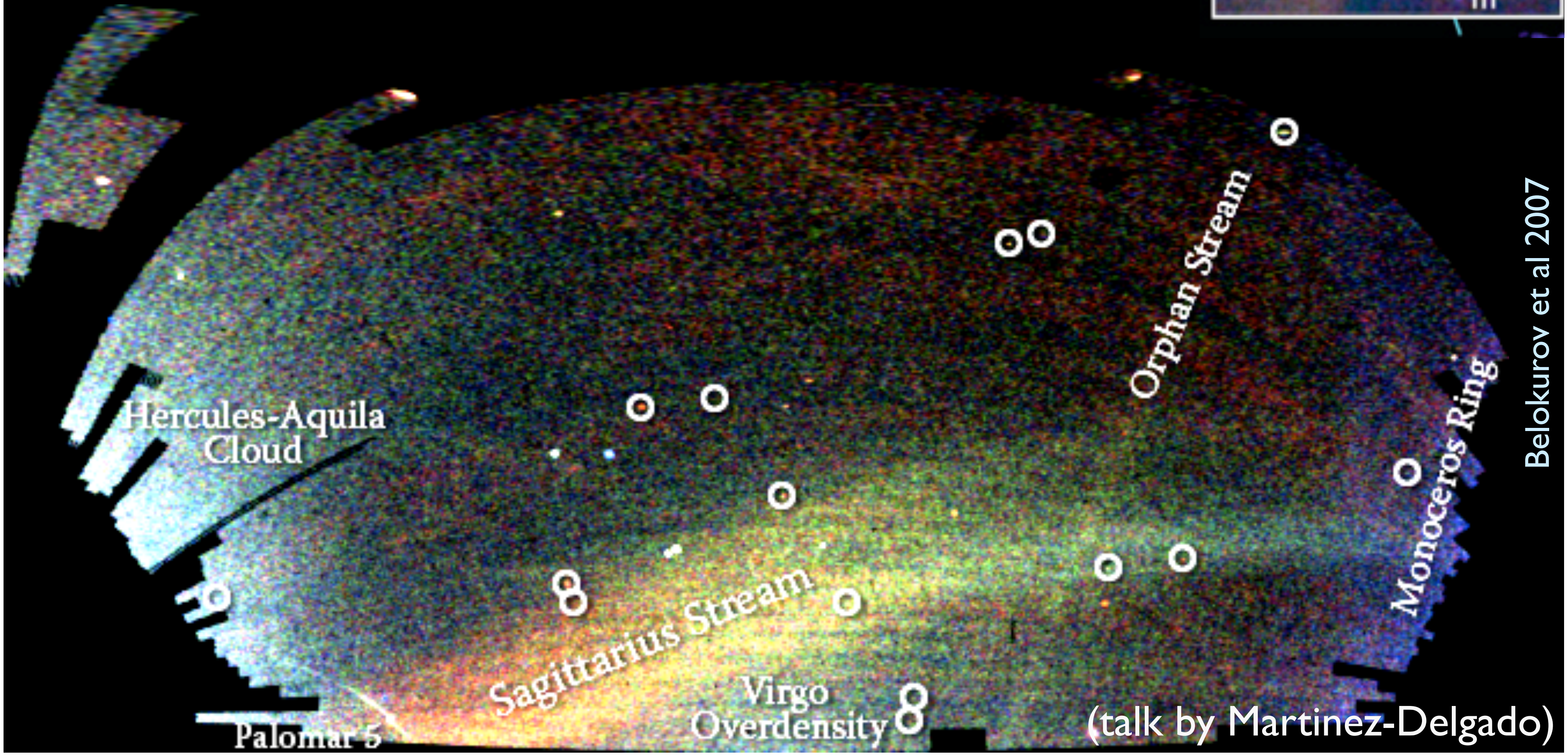


Helmi et al. (2011)

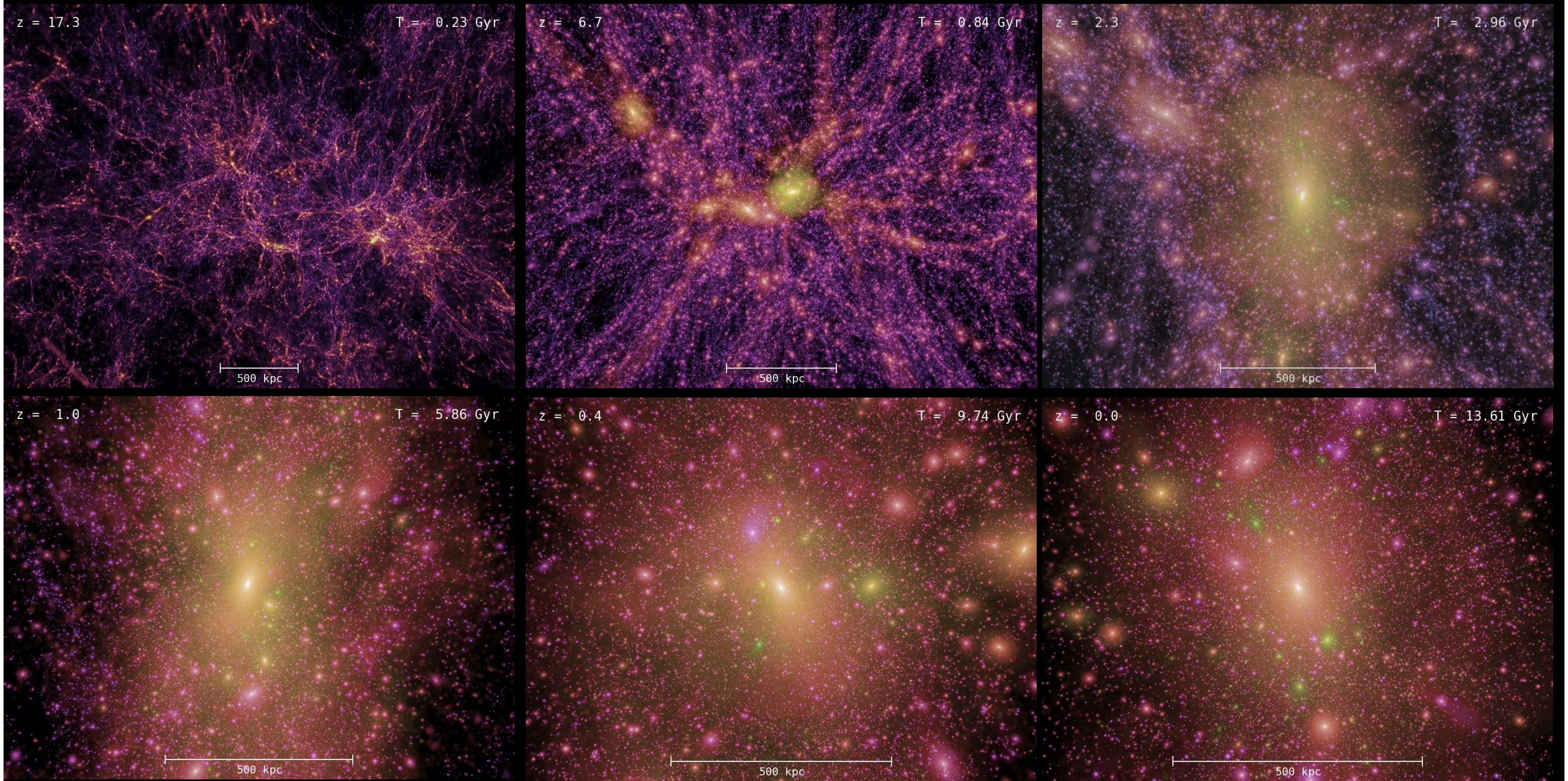
Outer Stellar halo

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





Aquarius halos coupled to SA models



Springel et al. 2008

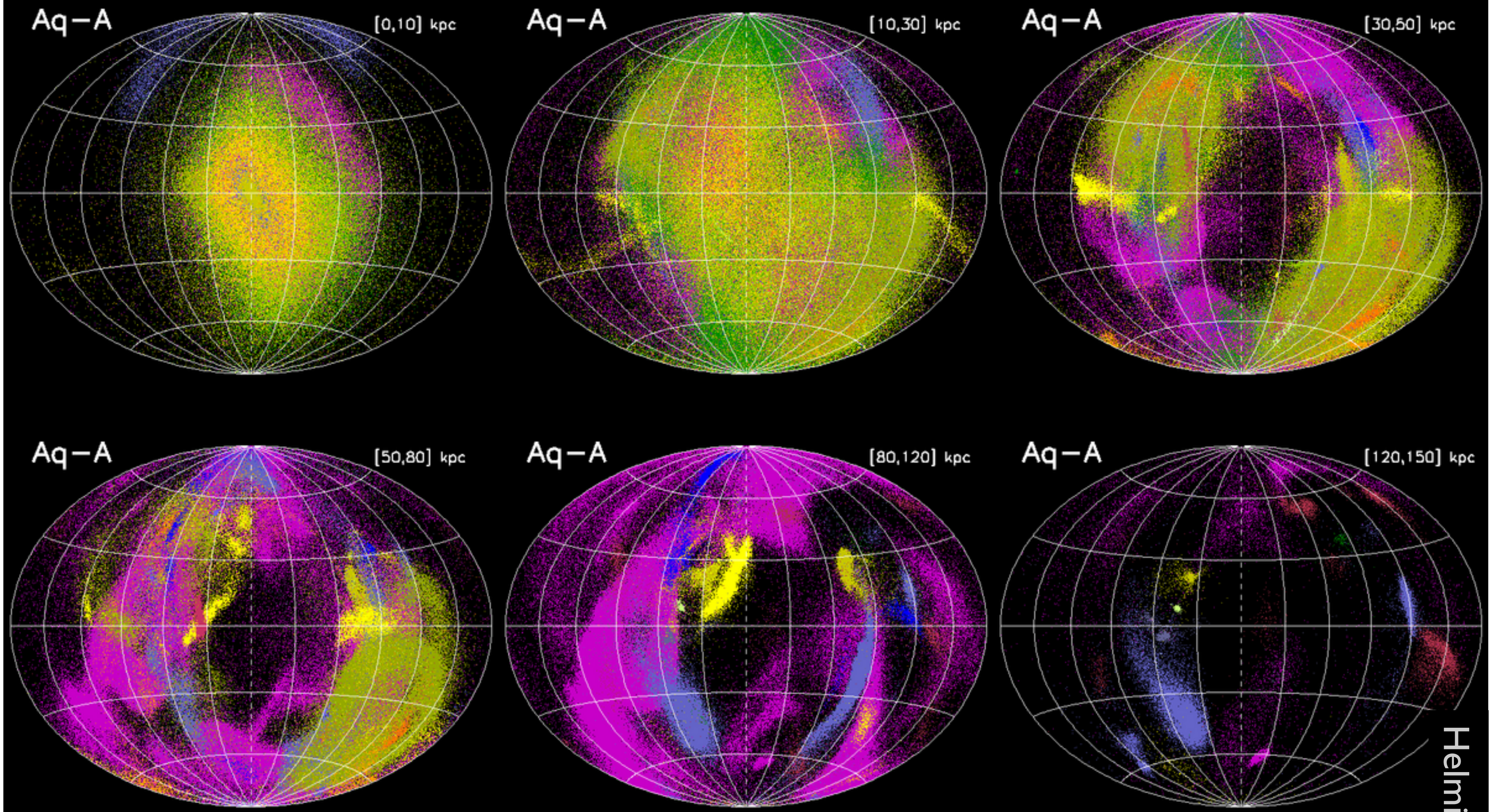
- 1% most bound particles represent stars/stellar pops in these objects
- Follow the history, their present-day location and dynamics (talk by Cooper)

Stellar halo formation in the Aquarius simulations

Cooper et al. 2010

Helmi et al. 2011

Aquarius on the sky



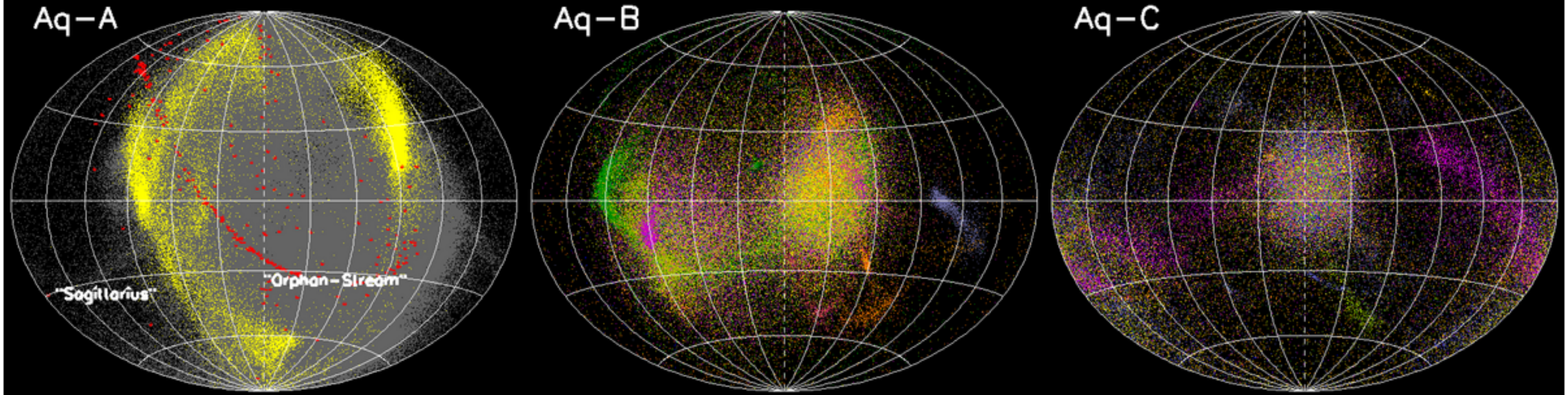
Inner halo (d < 10 kpc): very smooth (triaxial in shape)

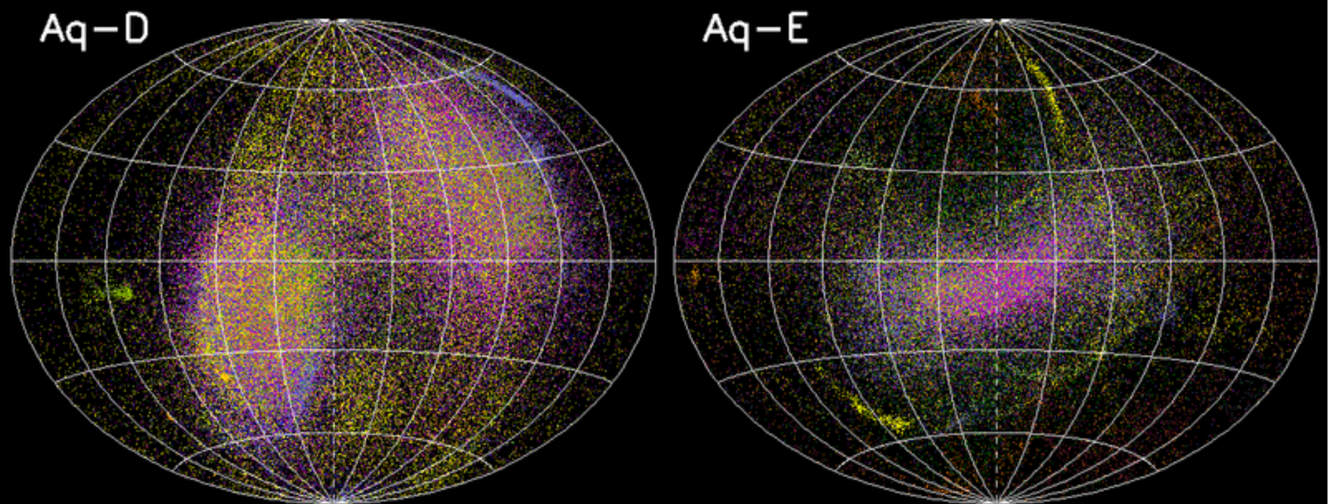
Substructure apparent at d > 10 kpc and dominant at d > 30-50 kpc

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

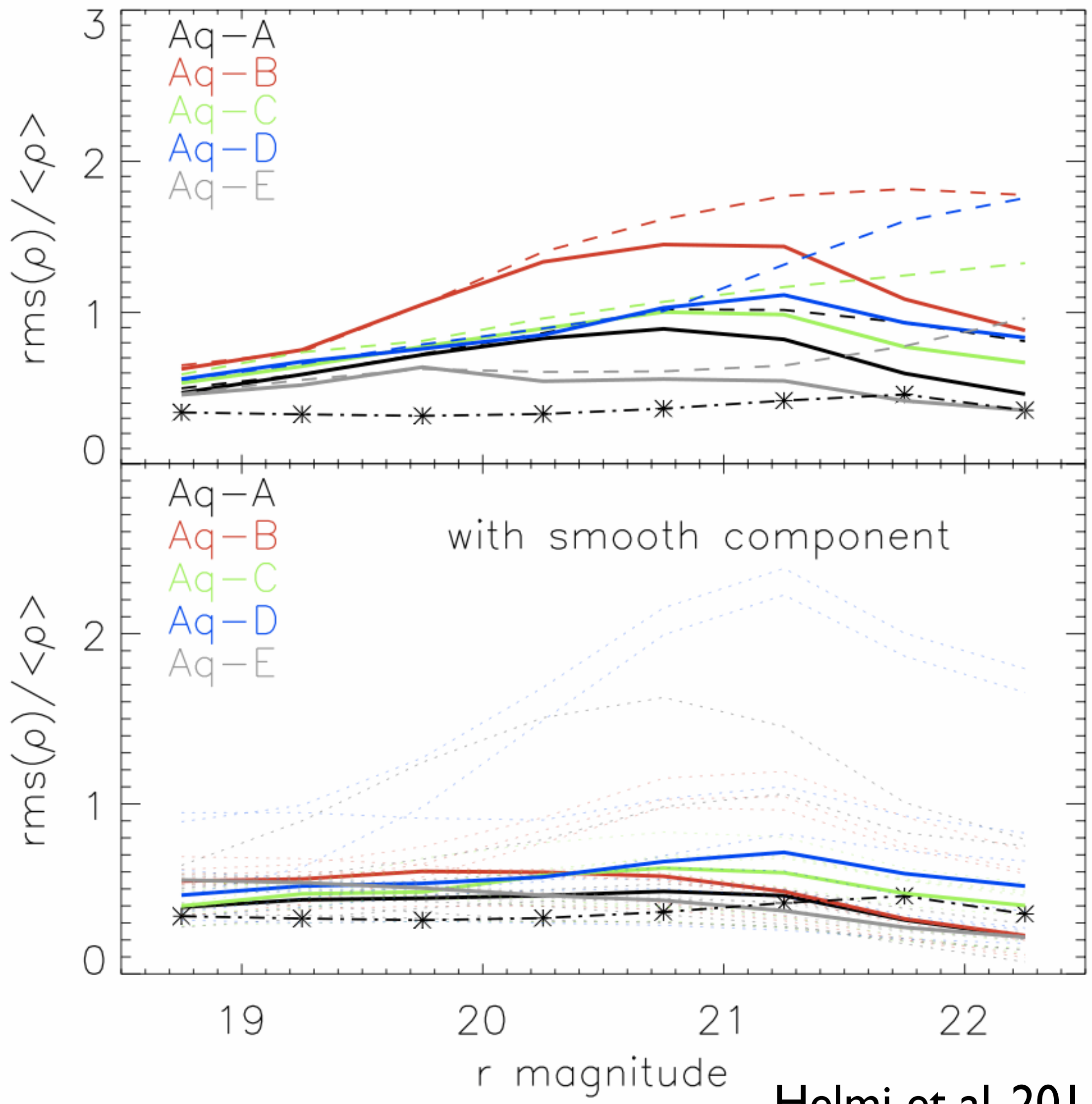
Quantitative comparison

- 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

Satellites

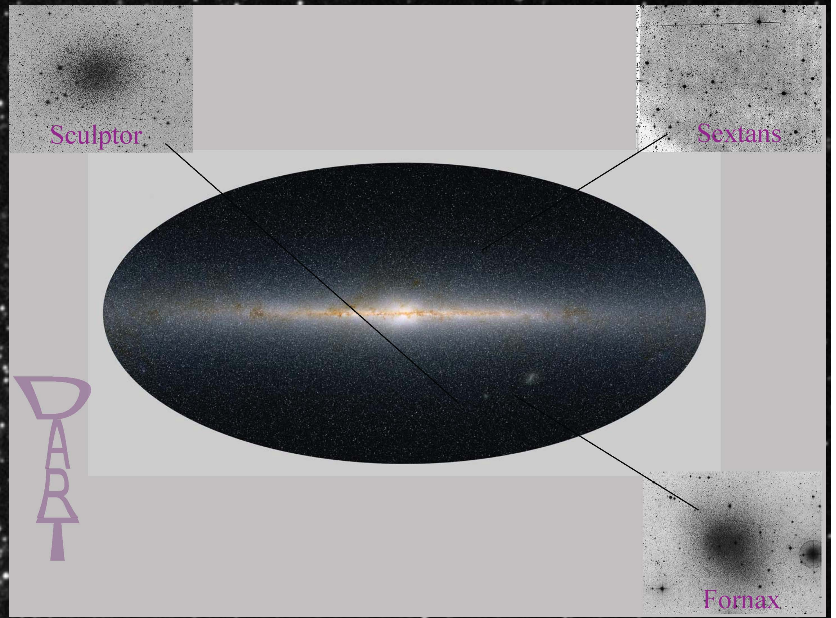
Frenk's review

The satellites of the Milky Way: dwarf spheroidal galaxies

Very faint systems: 100 – 10^7 Lsun

Dynamical mass estimates: 10^7 – 10^9 Msun

- Most DM dominated systems known
  - Dynamical modeling can neglect the effect of baryons
  - Probe the innermost regions (constraints on cusps vs cores)



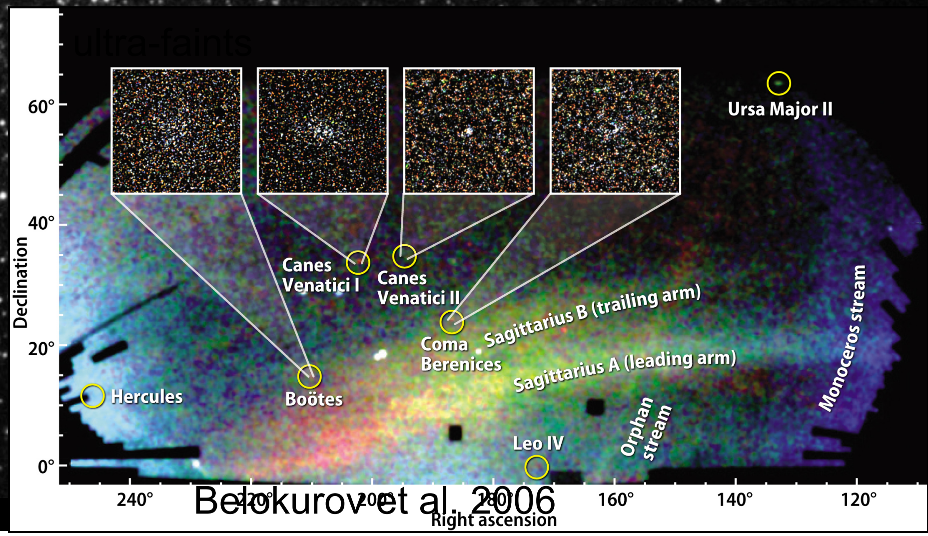
Contain very old populations

windows into the early universe

Reionization

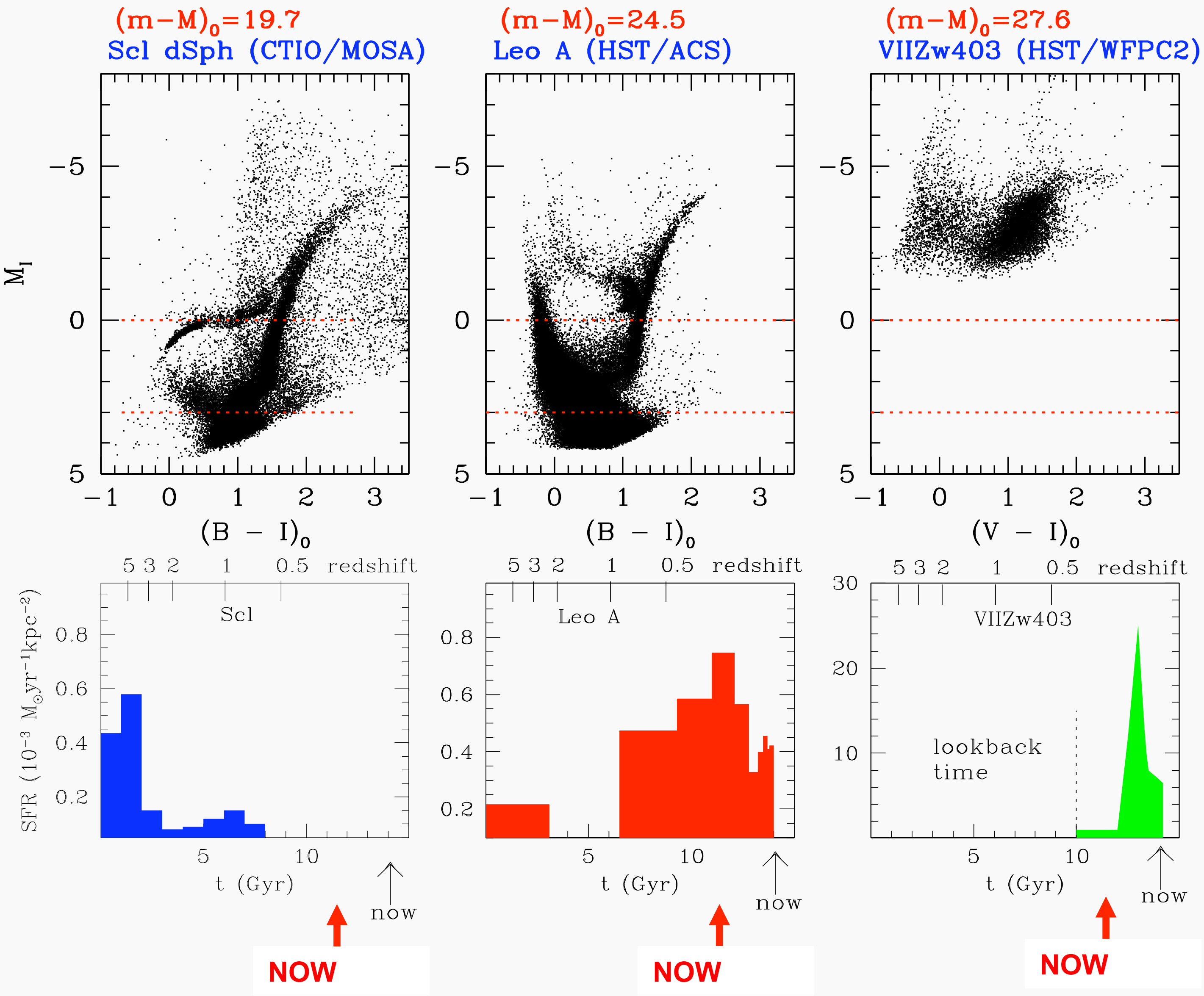
Relation to galactic building blocks?

Talks by Okamoto, Martin and Peñarrubia

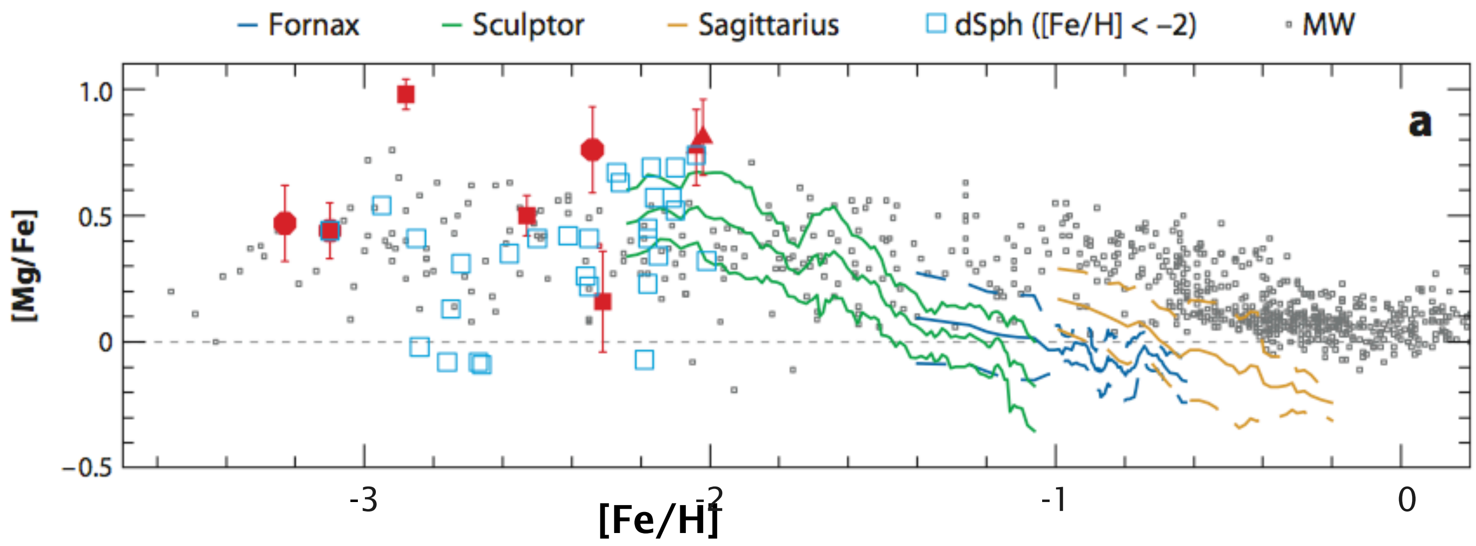


Belokurov et al. 2006

Comparing the different types



de Boer et al. 2010 | Cole et al. 2007 | Lynds et al. 1998



[Fe/H]

Frebel et al. 2010;
Koch et al. 2008;
Shetrone et al. 2003

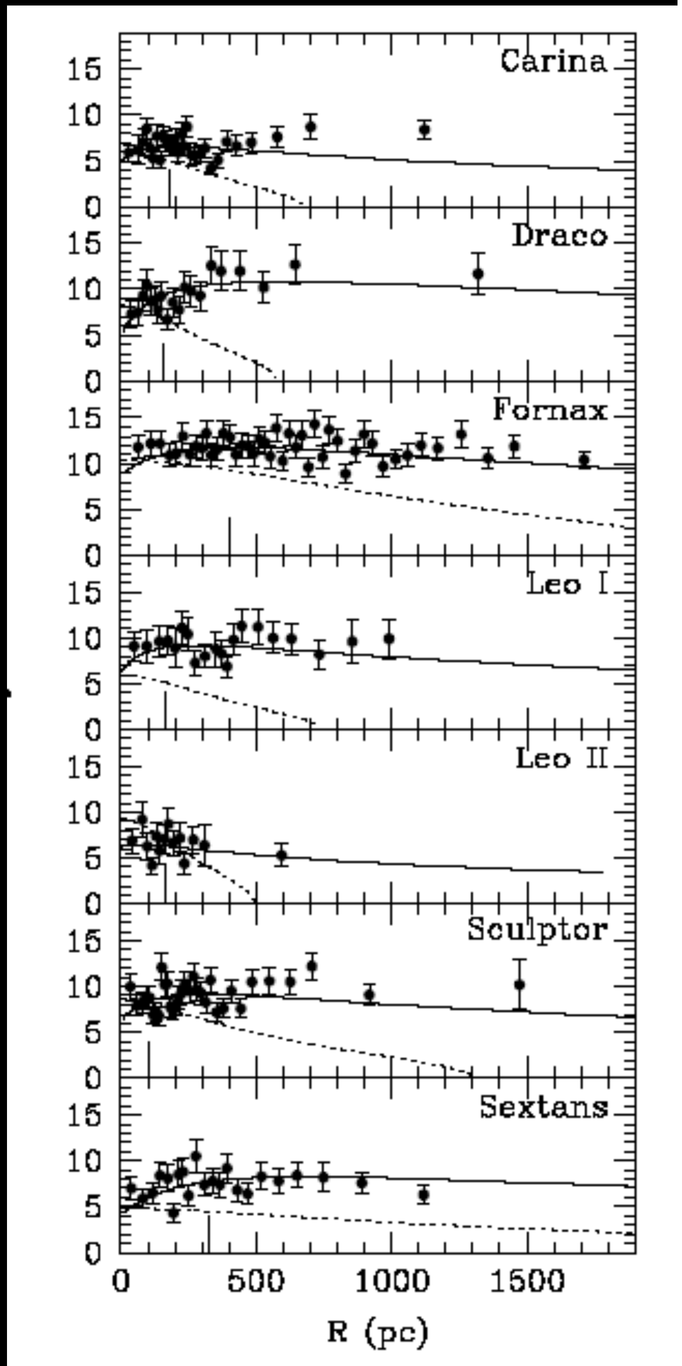
Tolstoy, Hill & Tosi 2009

MW satellites

- Recent years huge data growth: MOS on 4m & 8m-class telescopes

  WHT: Kleyna et al (Draco, Umi); VLT: Battaglia et al (Scl, Fnx, Sex) - Koch et al. (Leo I, Leo II); Magellan & MMT: Walker et al (7 dSph); Munoz et al (Carina)

- Latest results:
  - Fairly flat velocity dispersion profiles



Walker et al (2007)

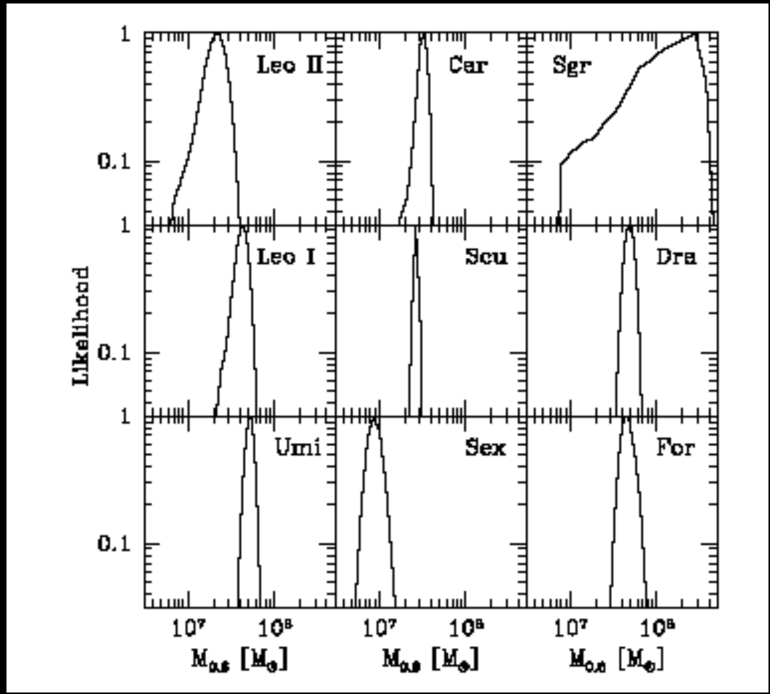
MW satellites

Latest results:

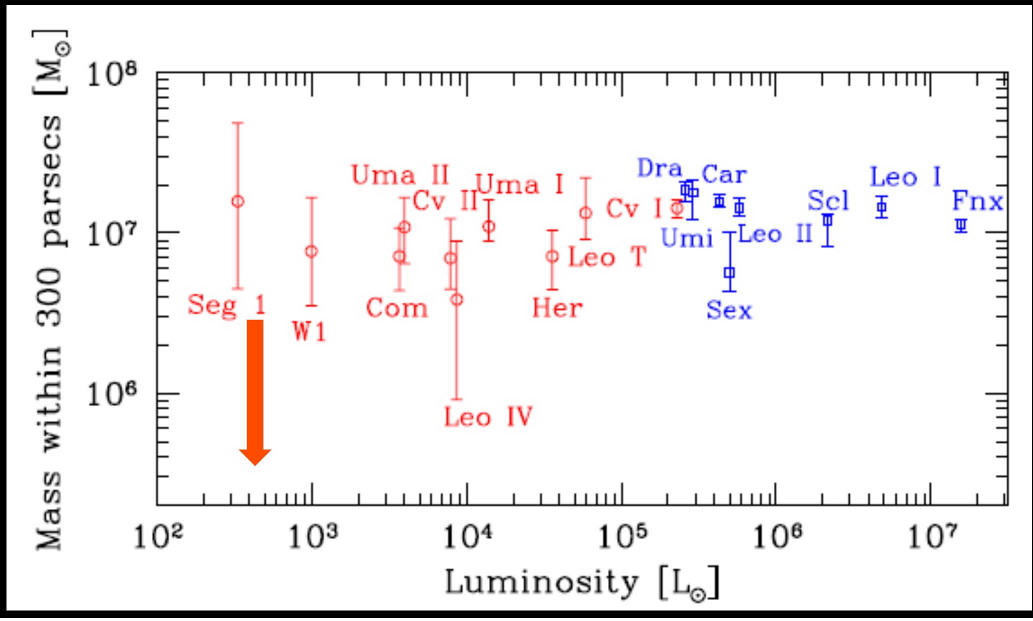
- mass scale within 0.3 kpc similar (also inside $r_{1/2}$; Wolf et al 2010)

- Indicative of a common (minimum or fundamental) mass scale?

- Expected in LCDM?



Strigari et al (2007)



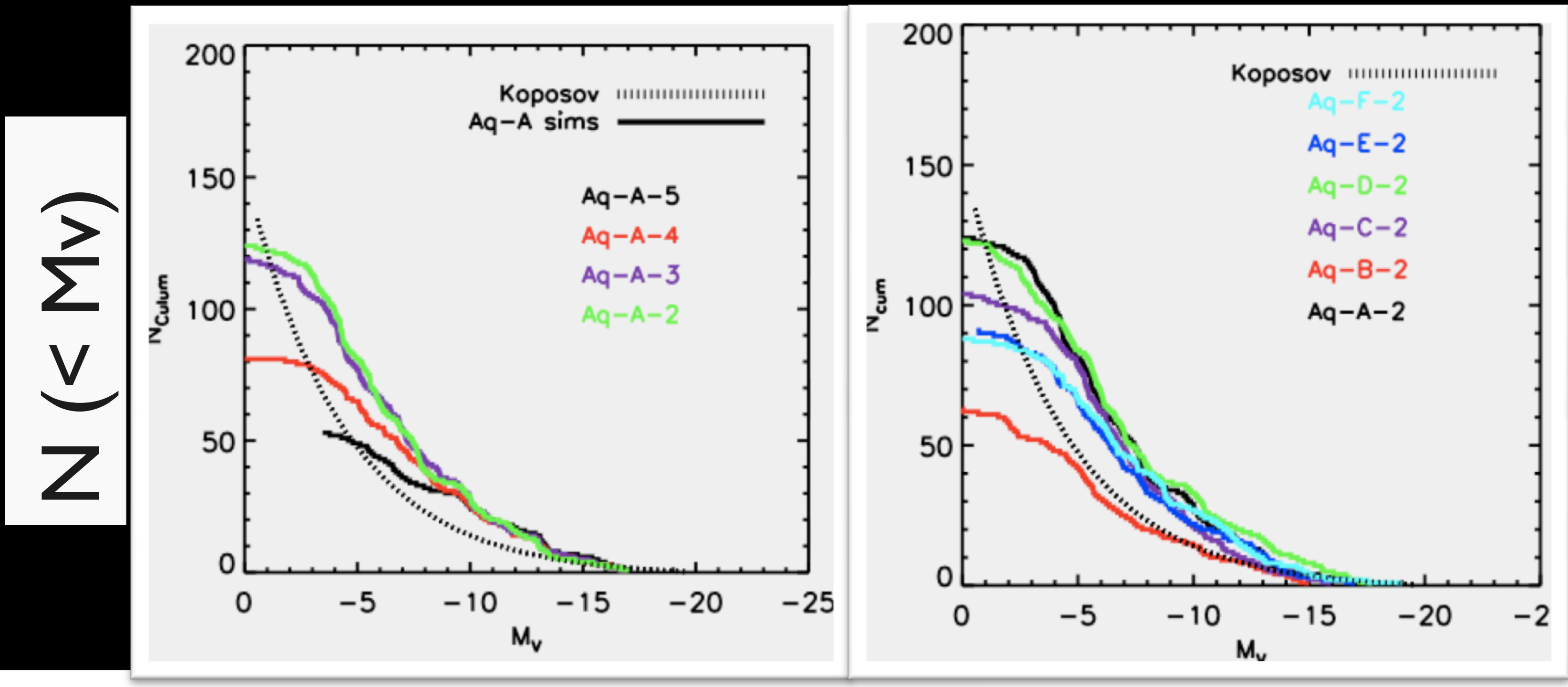
Strigari et al (2008)

Modeling the satellites in ΛCDM

- Relevant physical processes on these scales
    - re-ionization: z_i = 15 to z_f = 11.5 (Gnedin 2000)
    - small halos ($T < 10^4$ K) cannot cool (inefficient coolants)
    - Feedback models need to account for shallow potential-wells

  (Bullock et al. 2000, Benson et al. 2003…Maccio et al. 2010, Font et al. 2011)

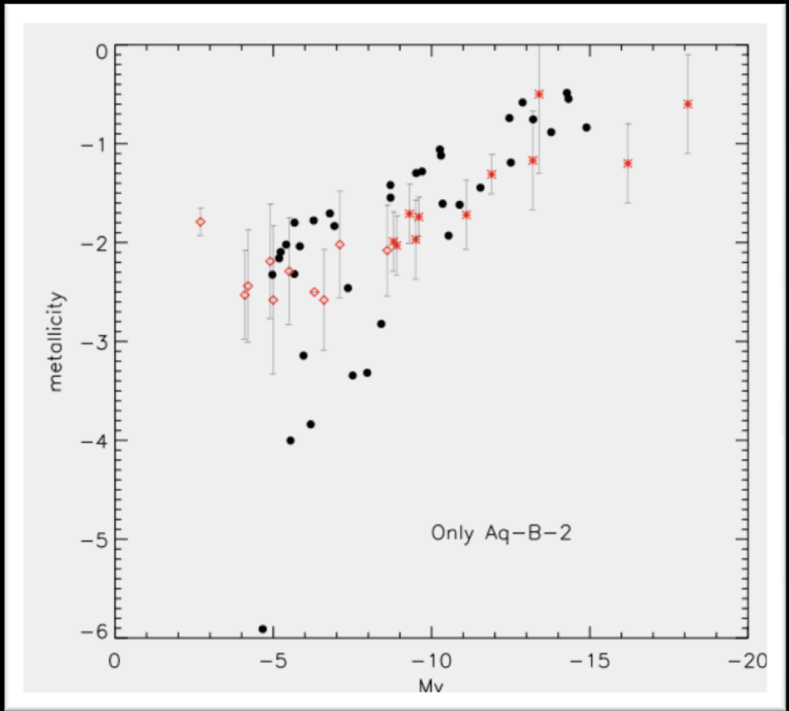
- Convergence in LF; variety in abundance of satellites (driven by halo mass).

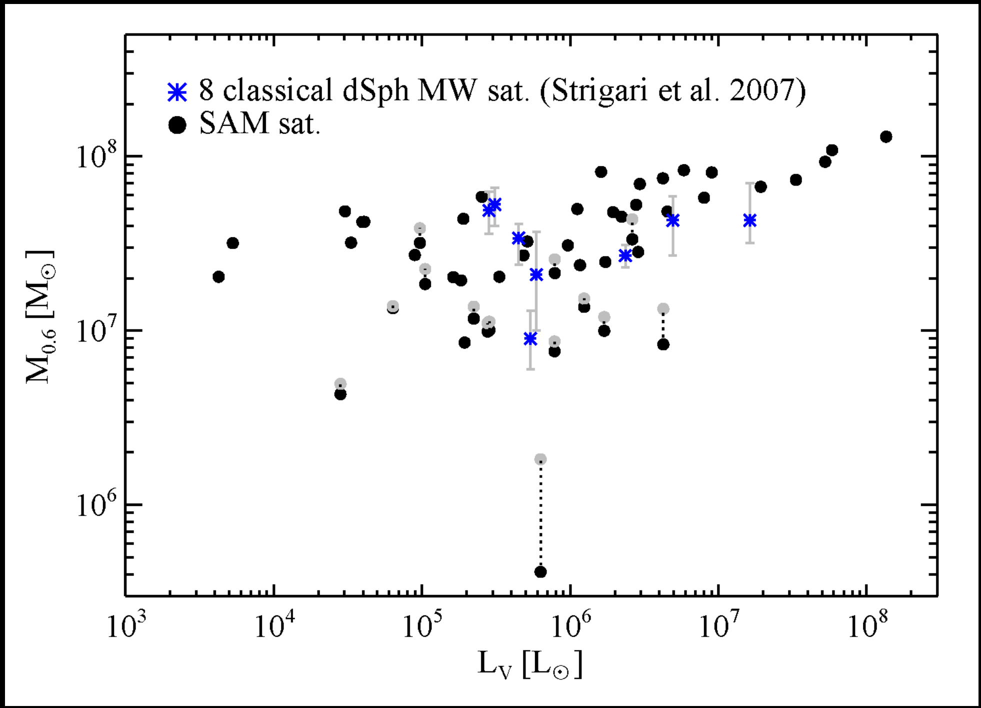


Starkenburg et al in prep

Internal properties

- Luminosity-metallicity relation
  - (also luminosity-size)
- Common mass-scale:
  - Factor 10 spread in innermost mass, a factor 10^5 in luminosity!
  - Most of the satellites have M(r < 600 pc) in the range observed





Li, Helmi et al. 2009

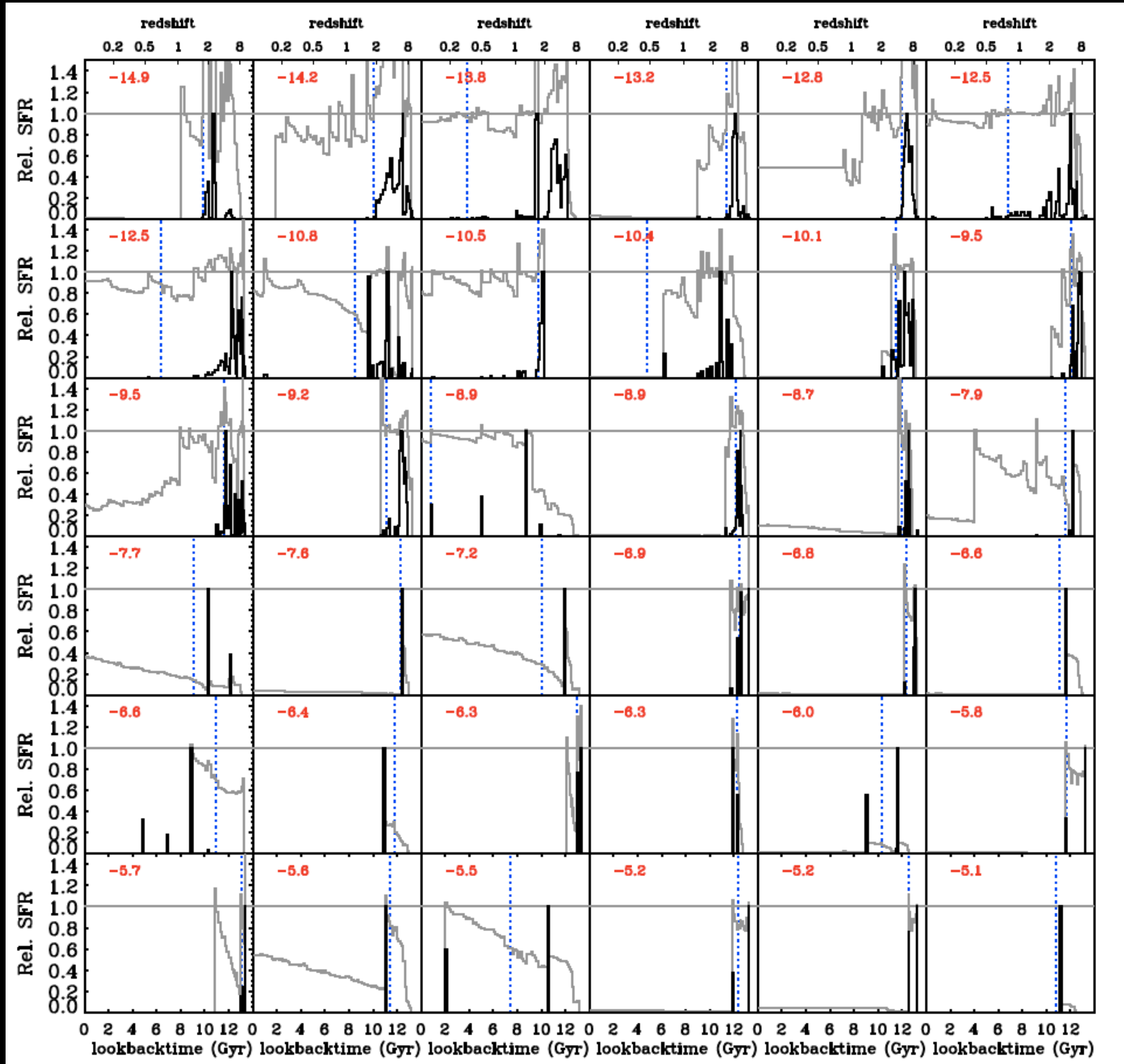
Star formation histories

Large variety in SFH histories

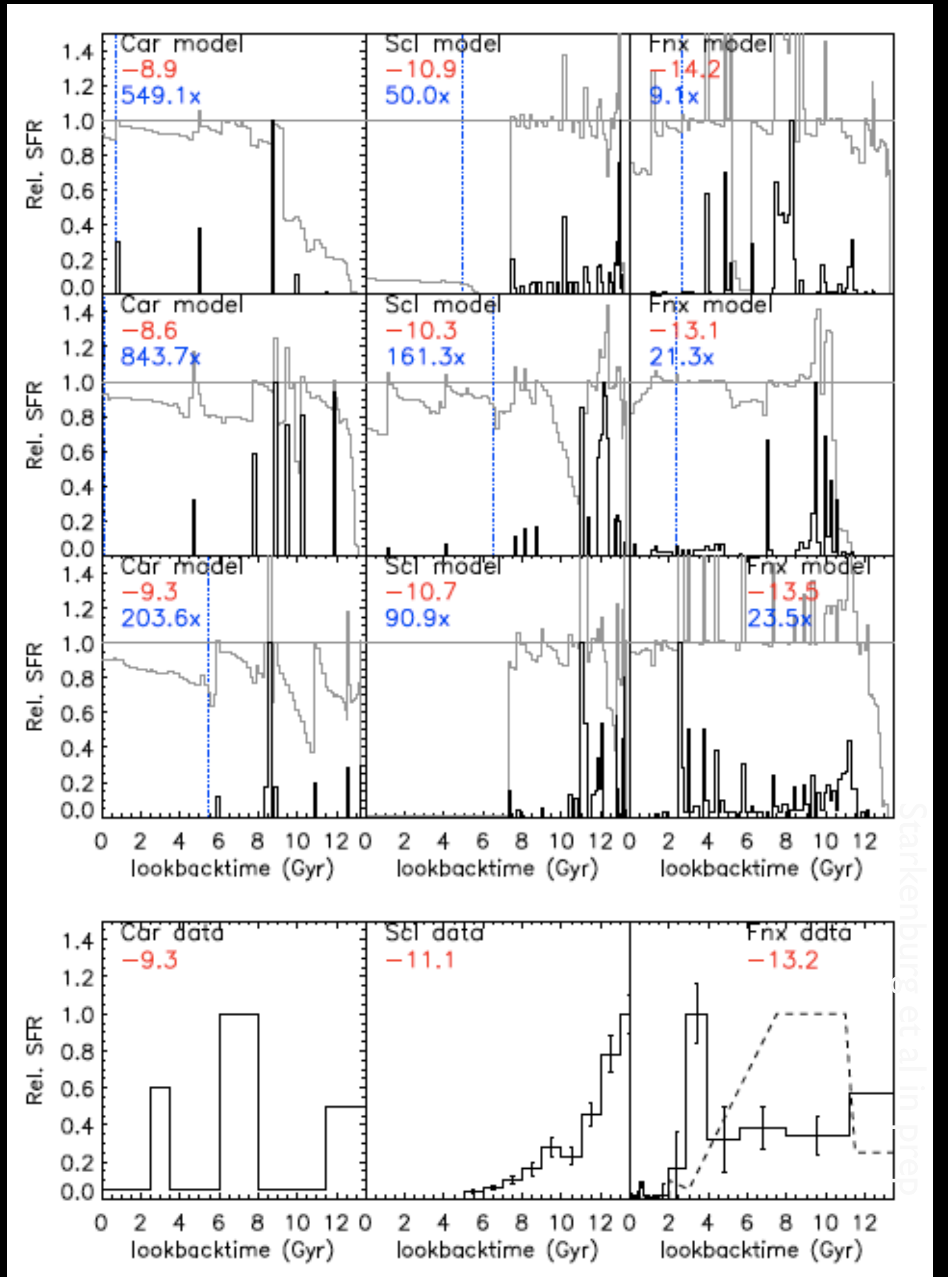
Driven by mass and by time of infall

Star formation rates very low for low mass objects

Fainter satellites have higher fraction of stars formed prior/around reionization



Our model produces galaxies similar to Fnx, Car, Scl



Starkenburg et al in prep

Summary

- Milky Way and satellites: unique testbeds of cosmology and galaxy evolution

- Different components contain different clues to assembly history
  - Thin and Thick Disk(s): distinct in all properties; unclear whether linked assembly
  - Bulge/Bar: (dynamical) properties consistent with disk instability
  - Stellar halo: repository of merger debris; evidence mostly in the outskirts
  - Satellites: old, ancient stars, survivors of a population (building blocks), interesting dynamically for DM

- Many photometric and spectroscopic surveys
  - Important to move away from solar neighbourhood
  - Chemistry and kinematics will lead new insights (e.g. First stars, DM lumps)

  - Culmination with Gaia mission: launch end 2012/spring 2013
  - 1 billion stars out to 100 kpc with (complete) phase-space information


Thank you for your attention