The Formation of Stellar Halos

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January 12th, 2018

Outline

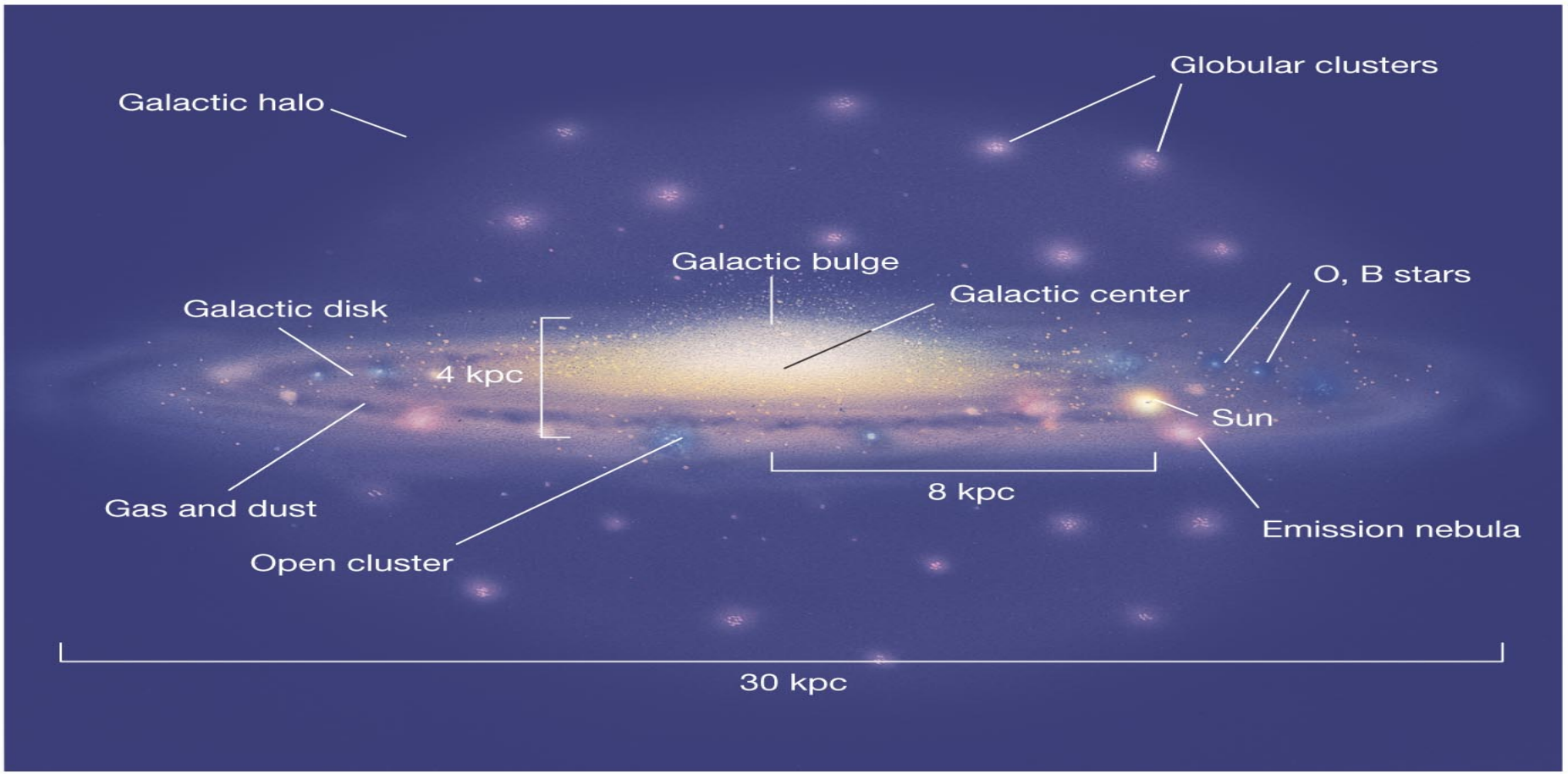
Source: Composite Image: European Southern Observatories, Subaru Telescope and Amateur Data. Image Processing and Assembly Robert Gendler, Roberto Colombari

Motivation

- Most metal-poor (and thus probably oldest) stars are found in the halo
- Picture of a galaxy in its early stages of evolution
- Understanding the halo's formation could lead to a better understanding of galaxy formation

Recap: Structure of the Milky Way

- $\sim 1\%$ of Milky Way's mass in stellar halo ($\sim 10^9 M_\odot$)



Source: http://pages.uoregon.edu

The Milky Way's Stellar Halo

- Very metal poor and old (>12Gyr) field stars (Population II)
- Low rotational velocity, high velocity dispersions
- $\sim$ 150 globular clusters
- Approximation for density profile: $\rho \propto r^{-3.5}$
- Effective radius within solar radius but some stars reaching out at least 100 kpc

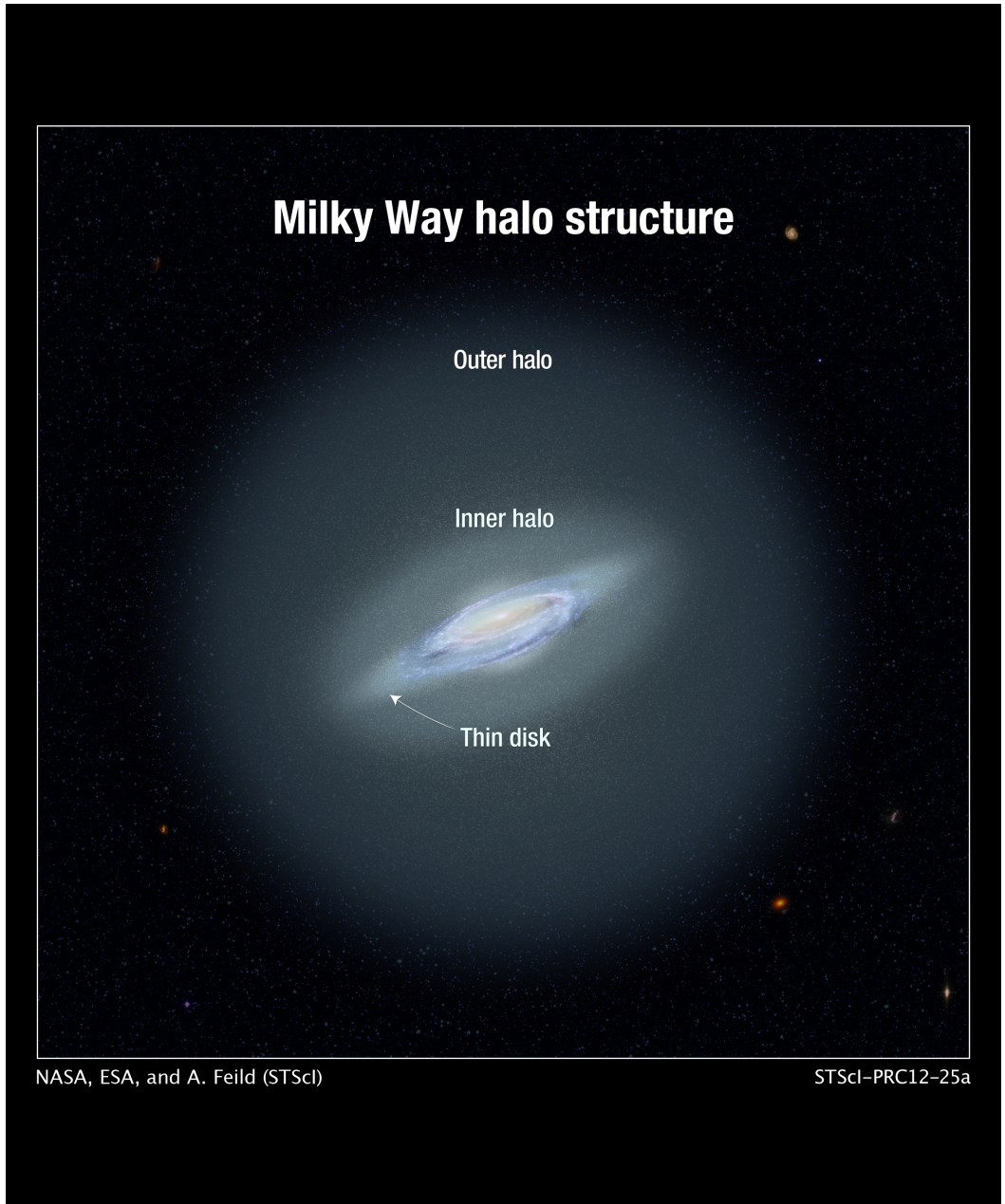
The Inner and Outer Stellar Halo

Inner Halo

- flattened (q $\sim$ 0.6)
- less metal-poor ([Fe/H]$\approx$-1.6)
- net prograde rotation

Outer Halo

- roughly spherical
- more metal-poor ([Fe/H]$\approx$-2.2)
- net retrograde rotation
- dominates at $r \gtrsim 20$ kpc

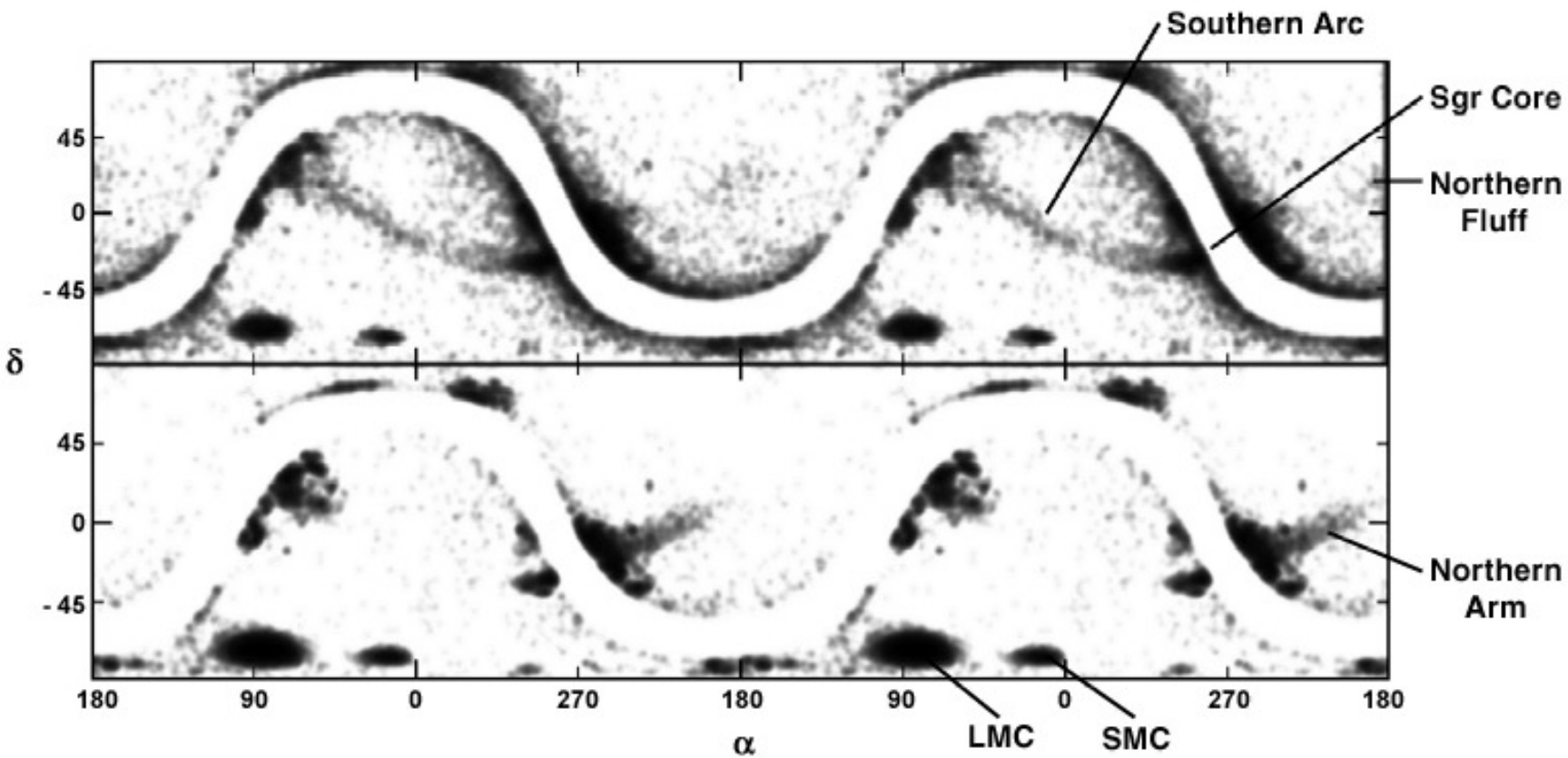


The Dark Halo

- Luminous matter is surrounded by a dark matter halo
- $\sim$ 90 - 95 % of the Milky Way's mass is contributed by the dark halo
- Probably spheroidal in shape

Stellar streams

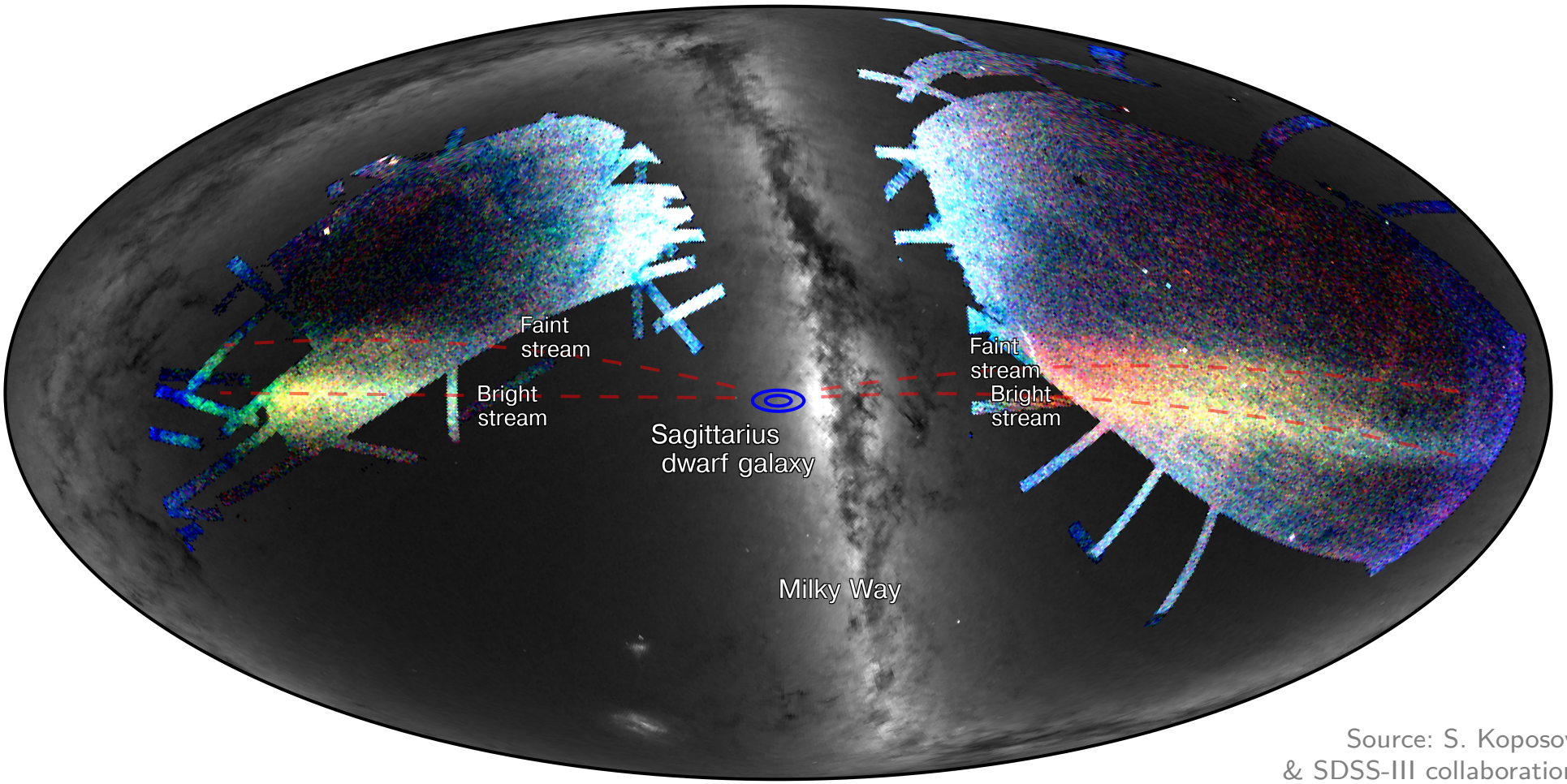
- Star distribution in the halo is not smooth but shows substructure (stellar streams)
- Streams can be linked to tidally stripped dwarf galaxies (e.g Sagittarius (Sgr) Dwarf Elliptical Galaxy)



Source: Majewski et al. (2003)

The Sagittarius Stream

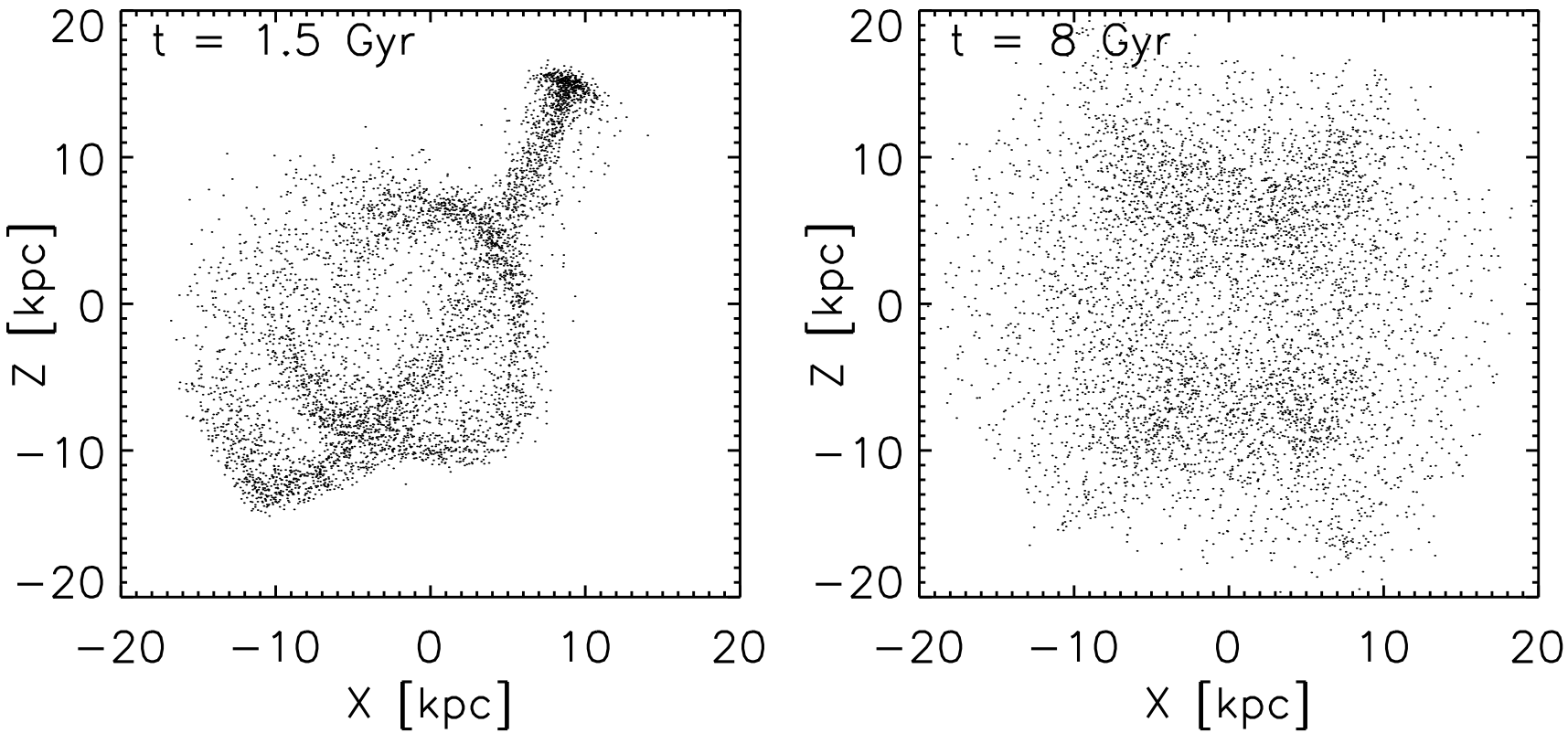
- Map of the Sky from SDSS showing stars counted in the Sgr stream
- Color indicates distance (red: further away, blue: closer)



Source: S. Koposov
& SDSS-III collaboration

Identification of stellar streams - Spatial domain

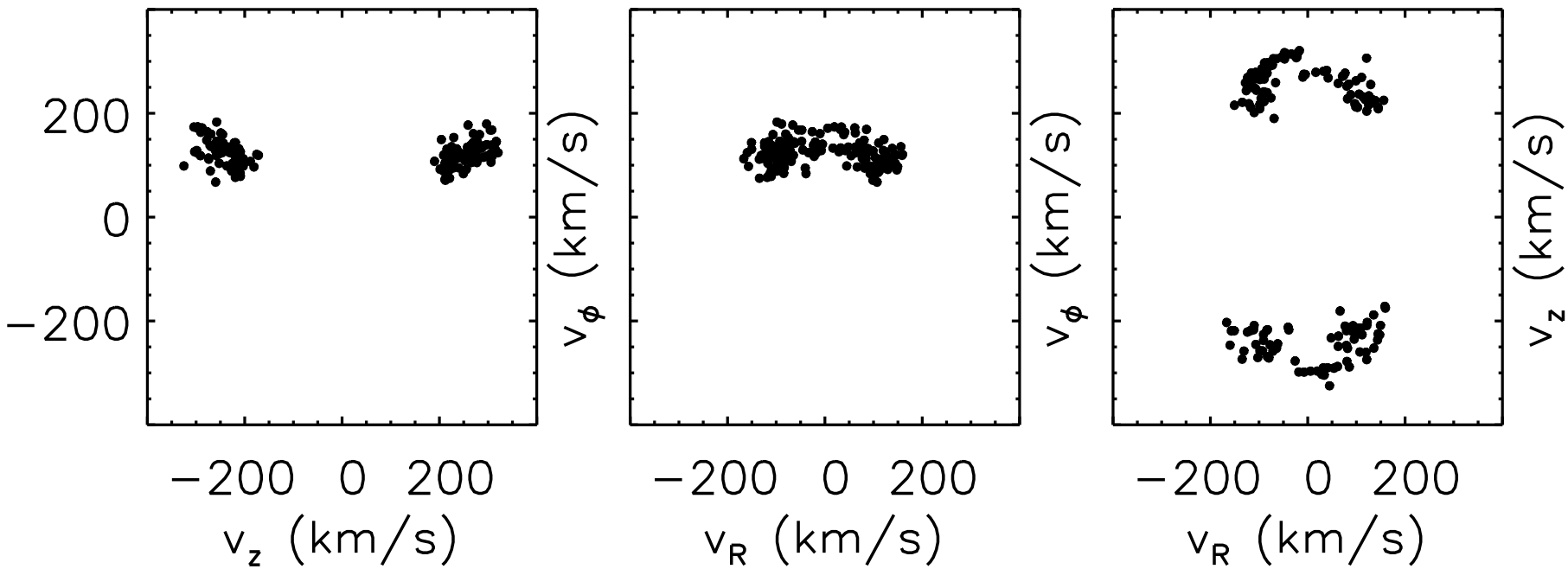
- Simulation of a satellite galaxy's disruption in the inner halo
- t $\sim t_{orb}$ (short after infall or in outer halo): Streams are coherent in space
- Streams can be identified via mapping of the sky



Source: Helmi et al. (1999)

Identification of stellar streams - Velocity domain

- Velocities of simulated stars in a spherical volume of ~ 2 kpc around the sun at t ~ 8 Gyr are strongly clustered
- Observationally more demanding



Source: Helmi et al. (1999)

Two Theories of Galaxy Formation

Monolithic collapse

Galaxies form and evolve isolated through collapse of large gas clouds (Eggen, Lynden-Bell & Sandage (1962))

- Halo stars form 'in situ' through the dissipative collapse of a gaseous cloud

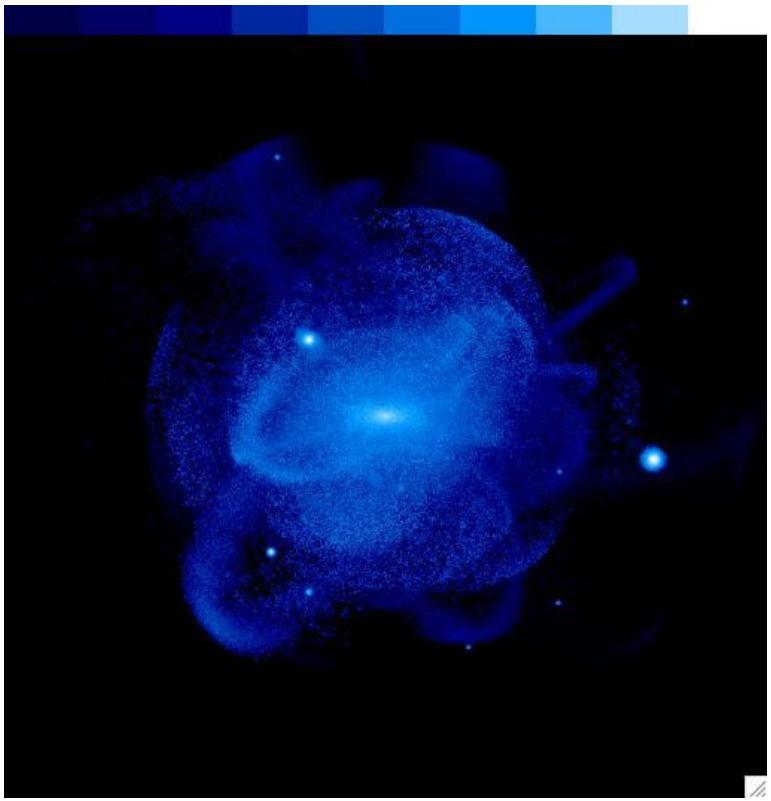
Hierarchical Formation

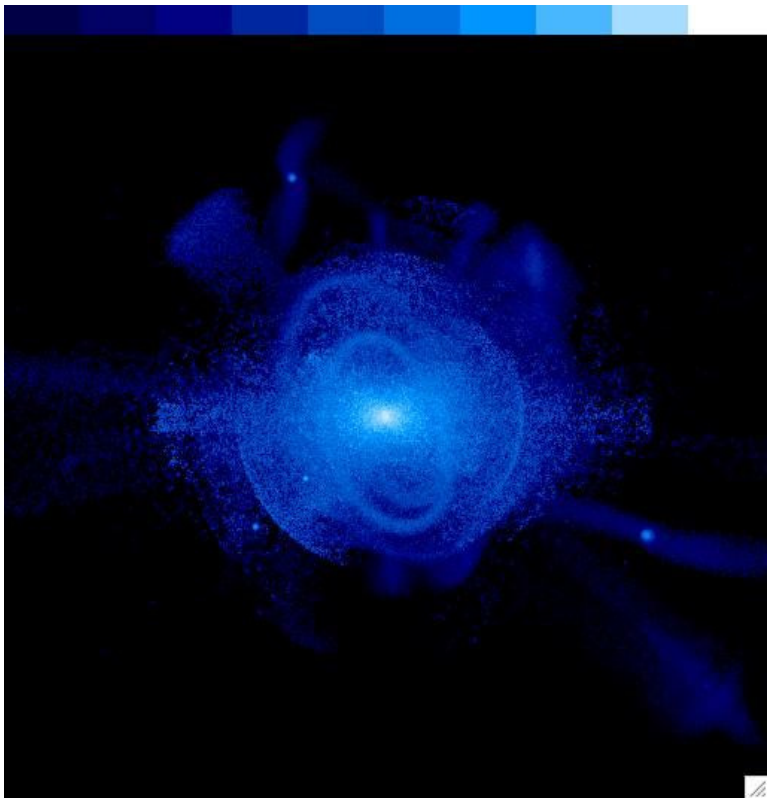
Galaxies form and evolve through successive mergers of smaller bodies (Searle & Zinn (1978))

- Halo stars form in small protogalaxies that subsequently merge without dissipation

The Formation of the Outer Halo

- Observations: Outer halo is very lumpy
  $\Longrightarrow$ Can better be explained by accretion of dwarf galaxies
- Simulations by Bullock & Johnston (2005) (only accretion) describe the outer halo well



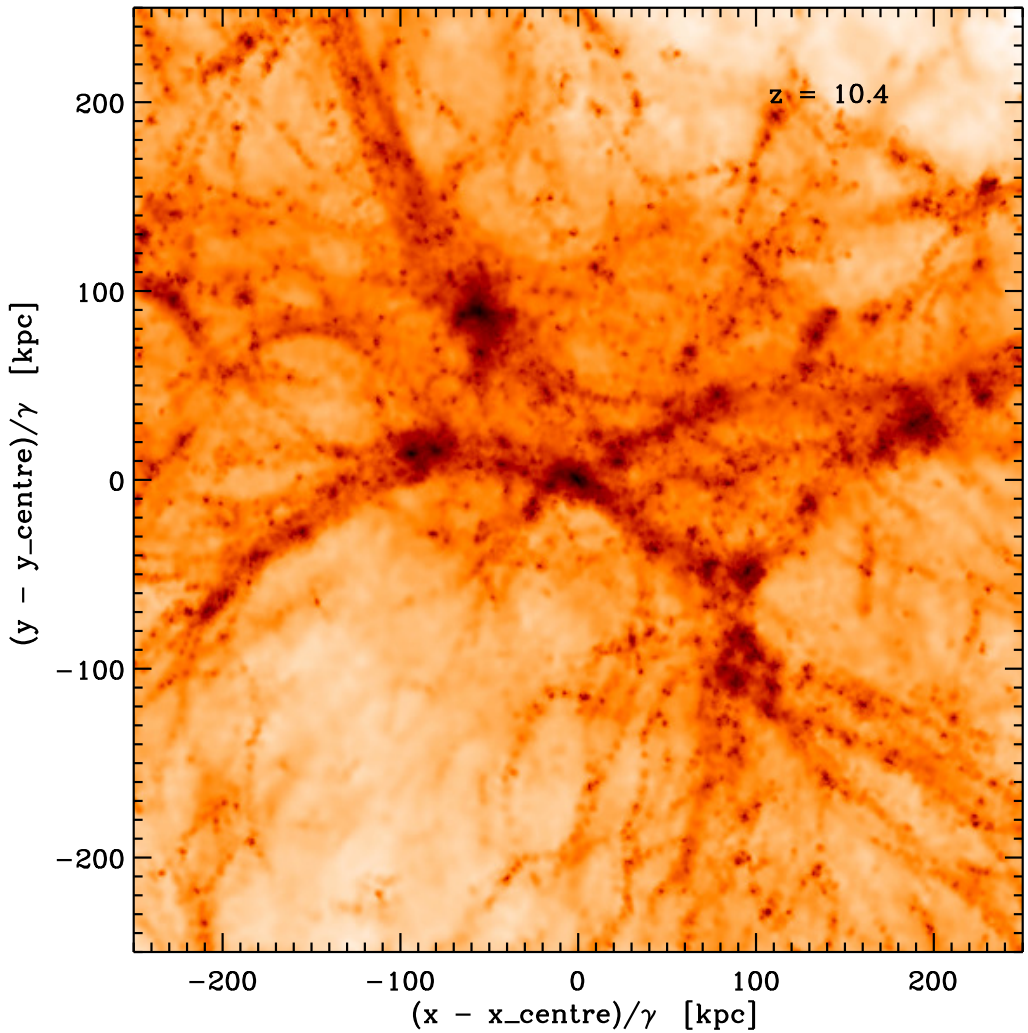


Source: Bullock & Johnston (2005)

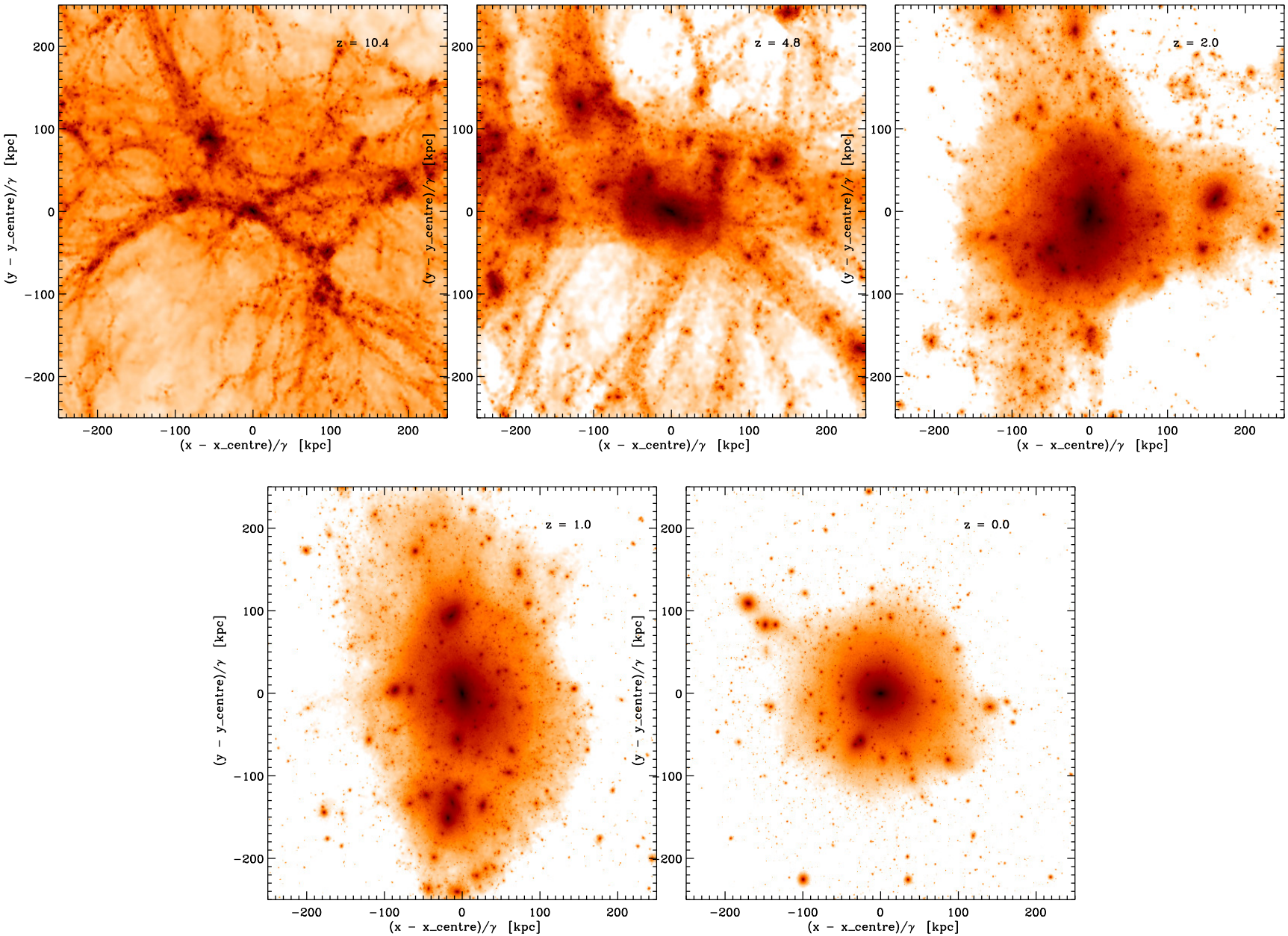
The Formation of the Outer Halo

- Simulations by De Lucia & Helmi (2008) (accretion only) also describe the outer halo well
- High resolution cosmological simulation

- Initial condition:



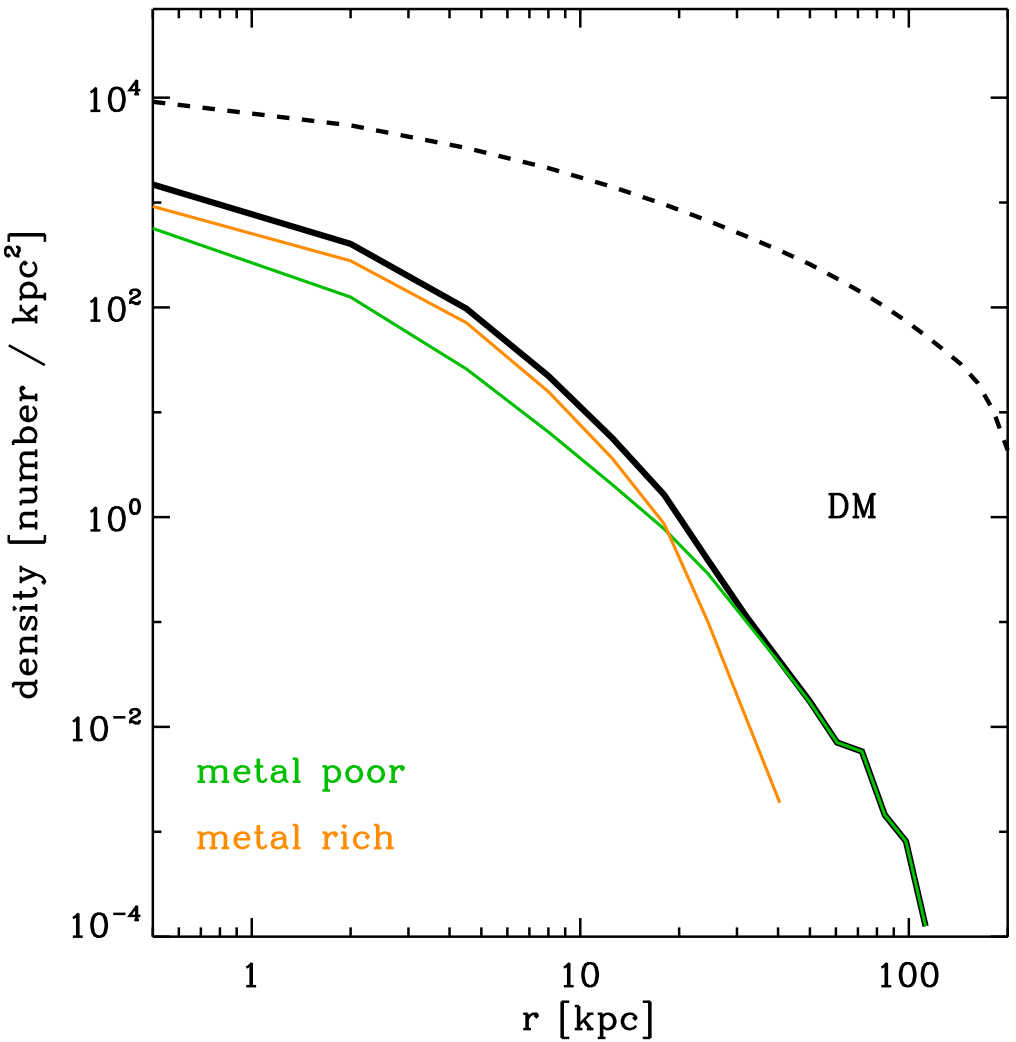
Source: De Lucia & Helmi (2008)



Source: De Lucia & Helmi (2008)

The Formation of the Inner Halo

- Can also model inner halo to some degree
- Inner halo is less metal poor (as observed)
- Stellar halo more centrally concentrated than dark matter halo
- Transition at $r \approx 20$ kpc



Source: De Lucia & Helmi (2008)

The Formation of the Inner Halo

Some observations cannot be explained by accretion:

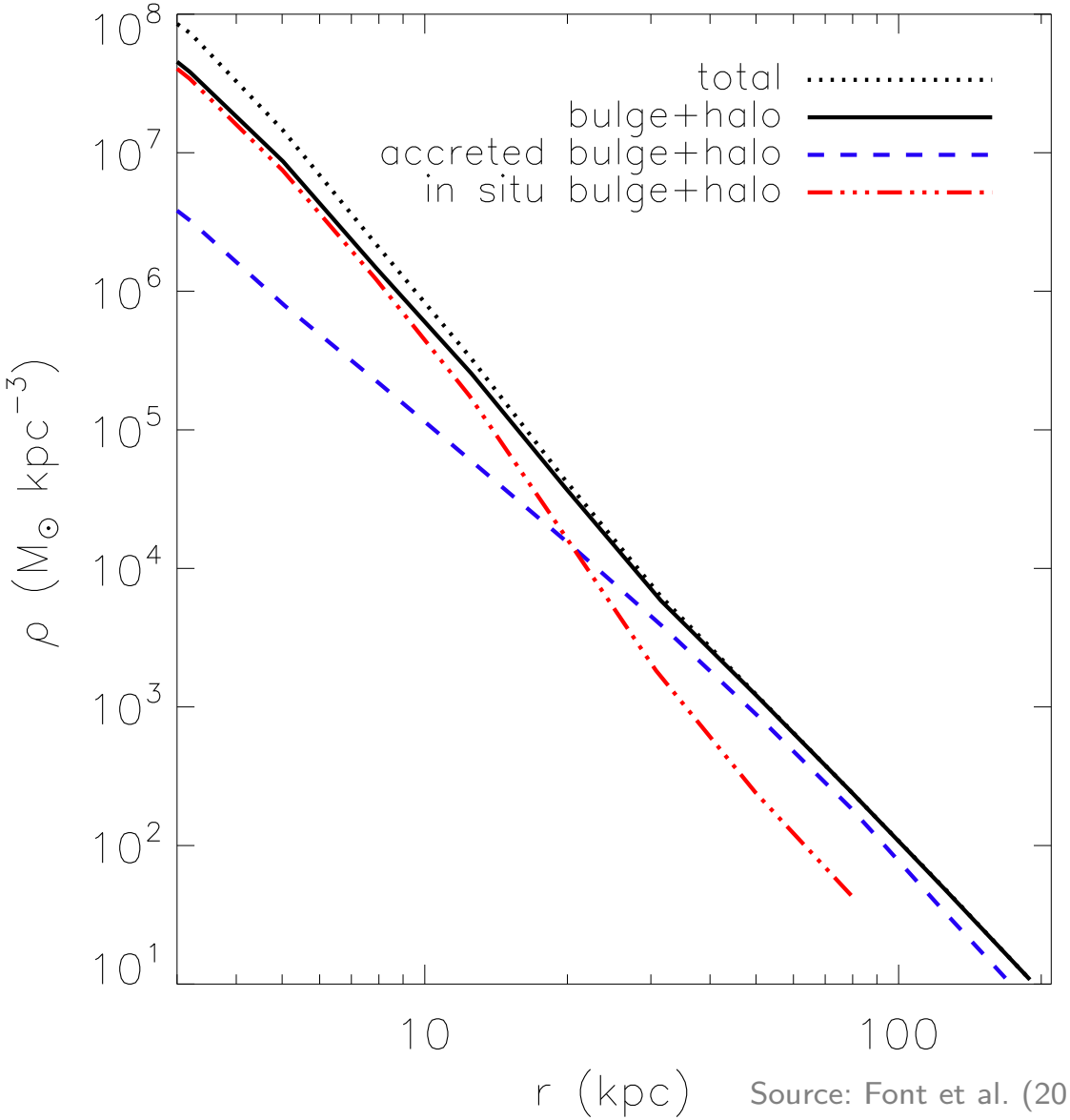
- Metallicity gradients
- High [Fe/H] halo population in solar neighborhood

Font et al. (2011) present cosmological hydrodynamical simulations including:

- Star Formation
- Metal dependent radiative cooling
- Supernova Feedback

The Formation of the Inner Halo

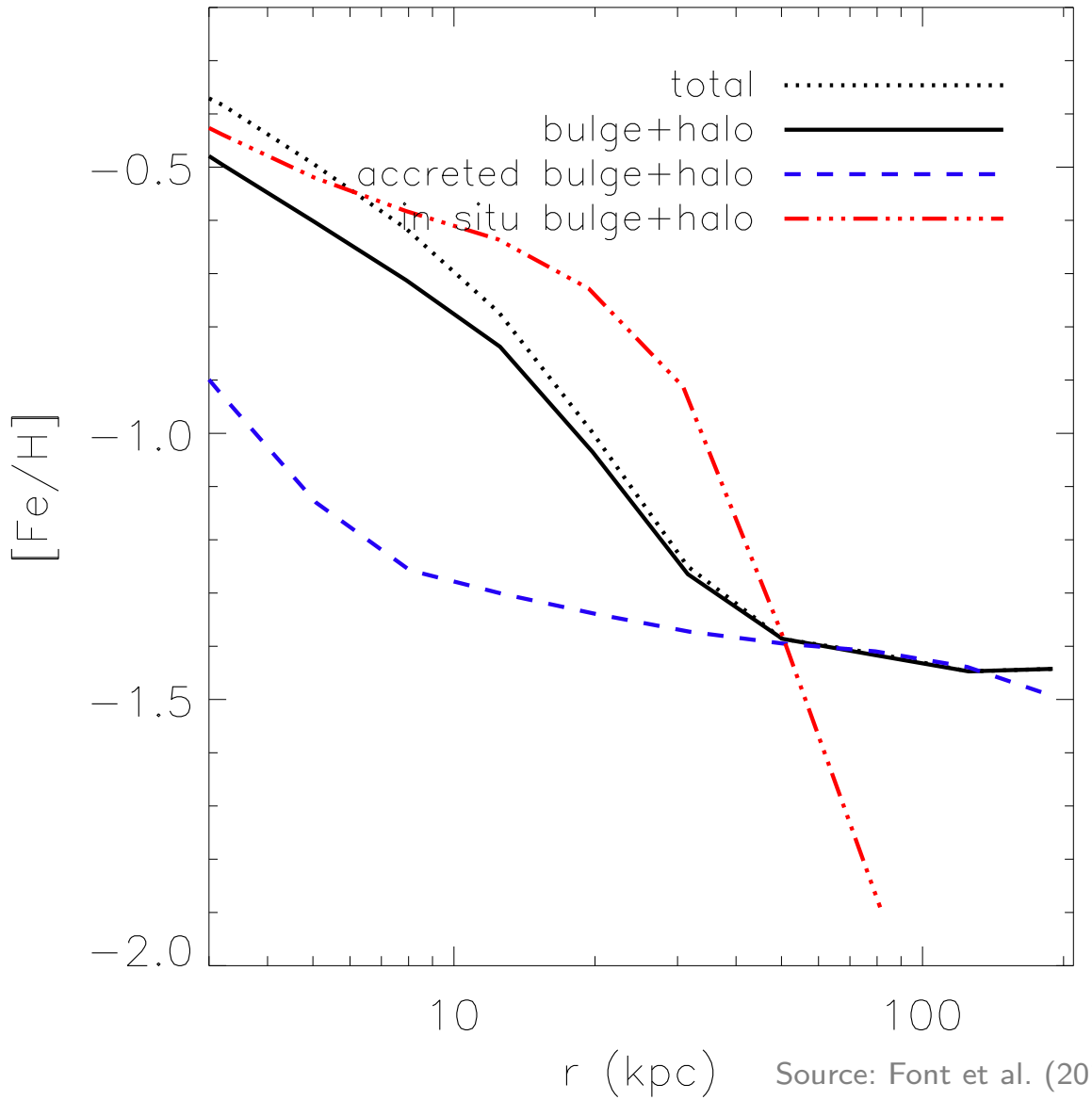
- 'In situ' dominates up to r $\sim$ 20-30 kpc, accretion beyond
- 'In situ' contributes 68% of current halo+bulge mass
- For outer halo ($r > 20$ kpc): 'in situ': 20 %, accretion: 80 %
- Both scenarios are important



Source: Font et al. (2011)

The Formation of the Inner Halo

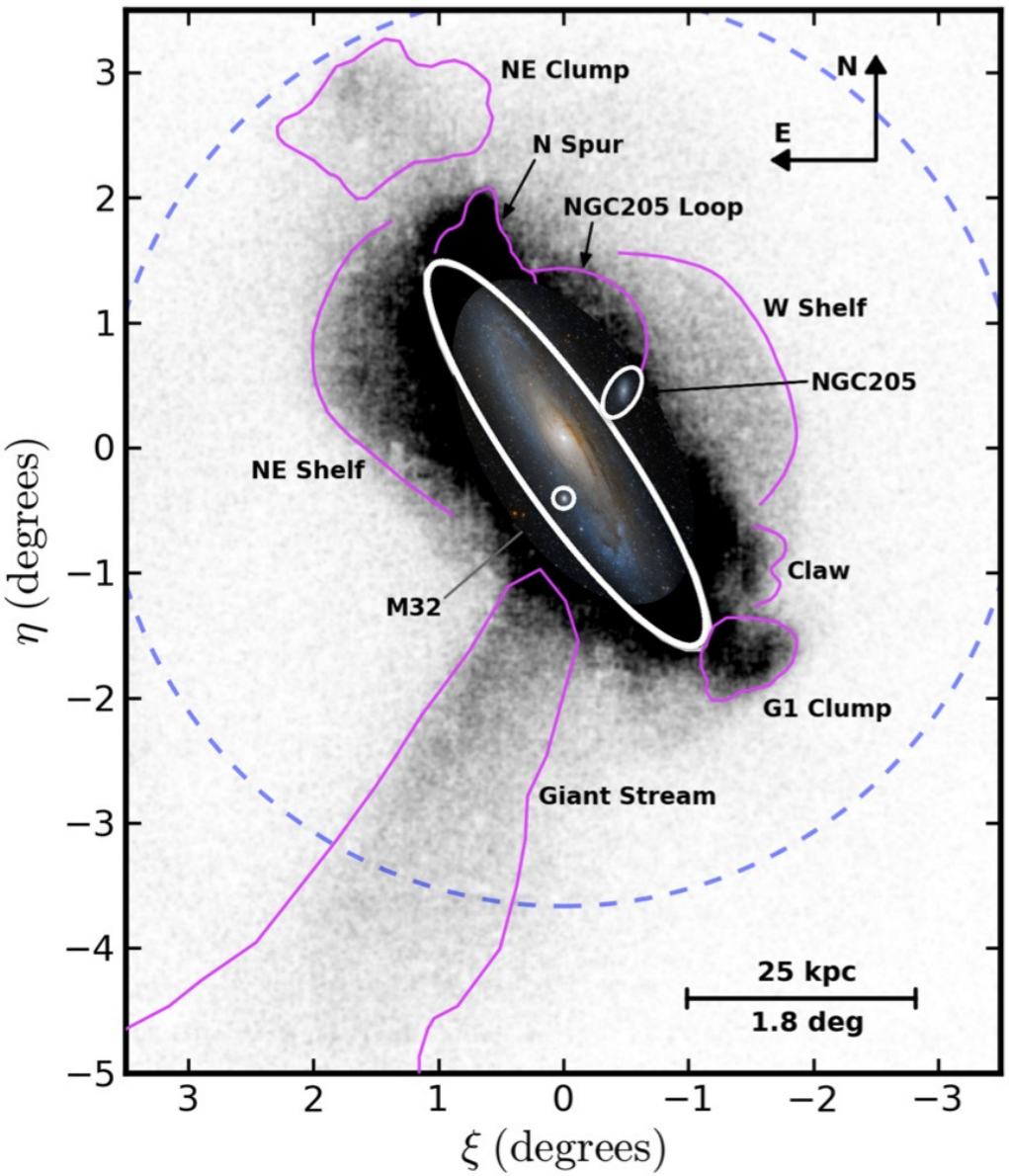
- Simulations predict observed metallicity behaviour
- 'In situ' star formation can explain the observed high metallicities
- Metallicity gradients can be explained by the transition from 'in situ' to accretion scenarios



Source: Font et al. (2011)

The Halo of M31 (Andromeda)

- PAndAS map of stars with $i_0 \leq 23,5$ and $-1 \leq$[Fe/H]≤ 0
- Blue circle: r=50 kpc
- Substructure is labeled and can be explained by tidal streams



Source: Ferguson & Mackey (2016)

Summary

3 key points to remember

- The Stellar Halo has substructure (stellar streams) originating from the accretion of dwarf galaxies
- The Outer Halo formed primarily via accretion of dwarf galaxies
- The Inner Halo was mainly built up by 'in situ' star formation

Thank you for your attention!