Nearby Cosmology

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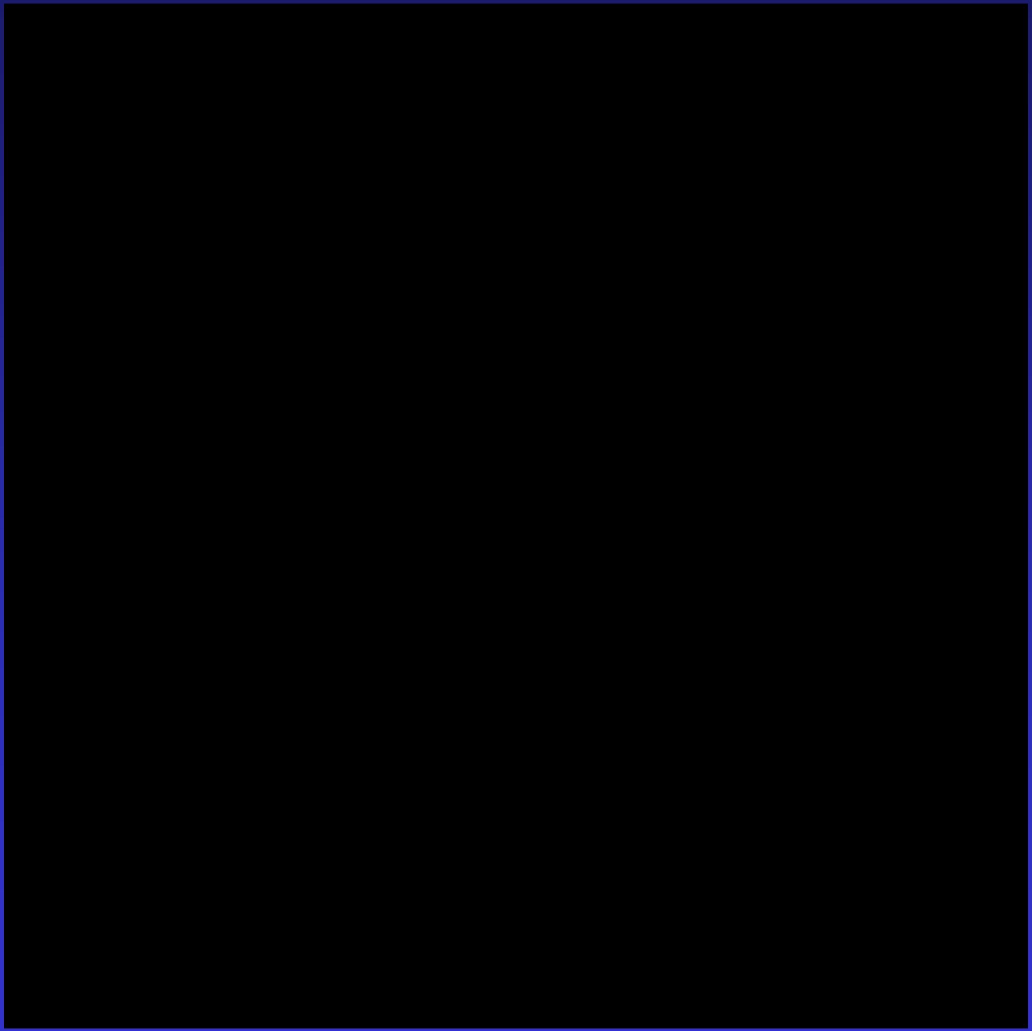
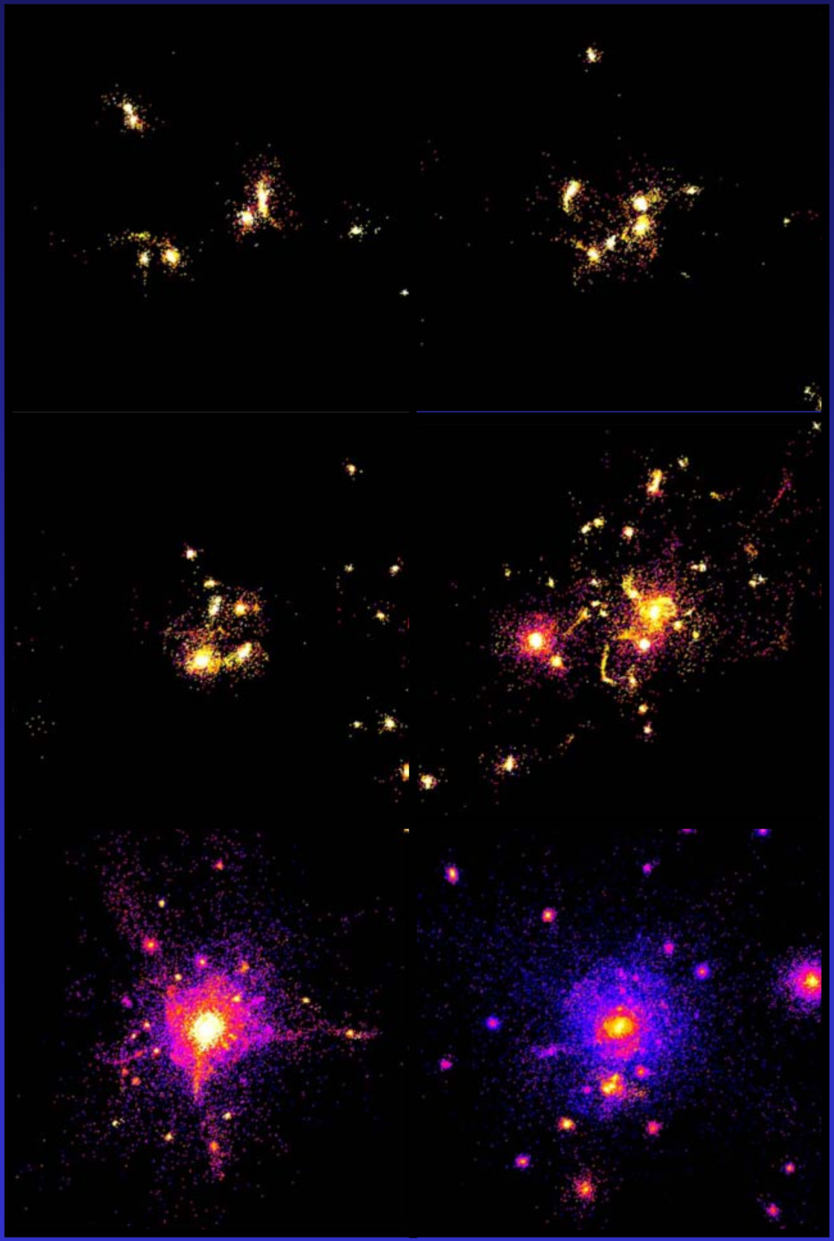
RuG

Hierarchical paradigm



Jeffrey Gardner

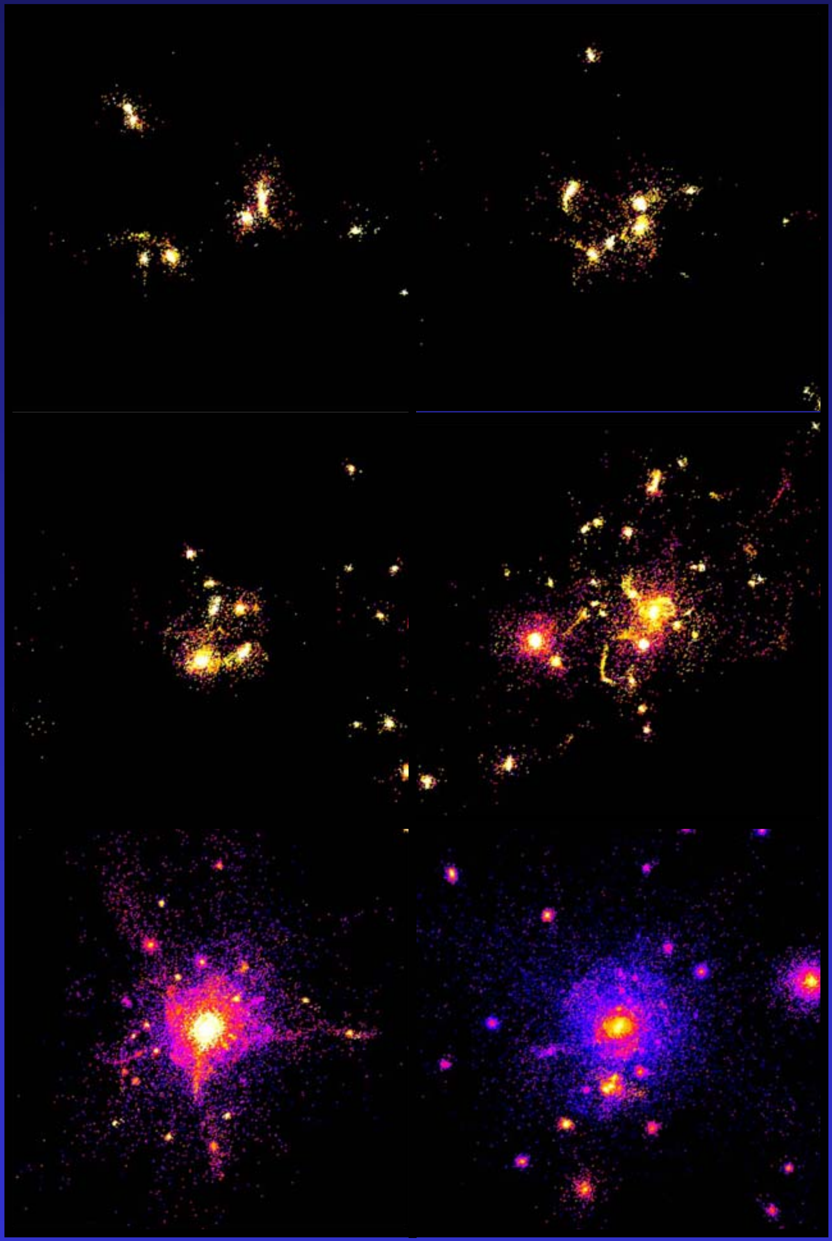
Testing the hierarchical paradigm. I



Main characteristic of model: mergers

- <u>Can we find the signatures?</u>
  - Substructure and the search for tidal streams
- <u>How did the building blocks look like?</u>
  - what is the link to today's nearby small galaxies (dSph)?

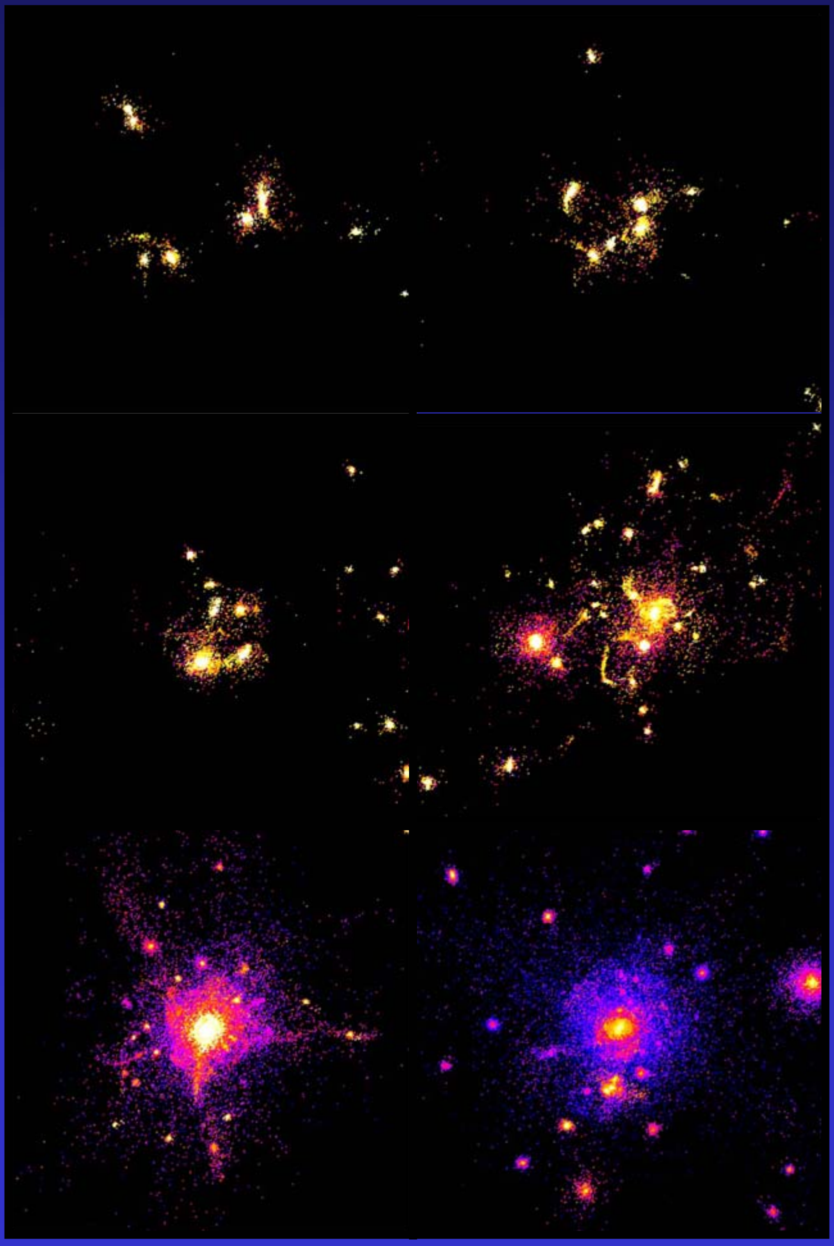
Testing the hierarchical paradigm.II



Fundamental ingredient of the model: dark-matter

- how is it distributed?
  - density profile
  - shape
- what are its properties?

Mergers and substructure

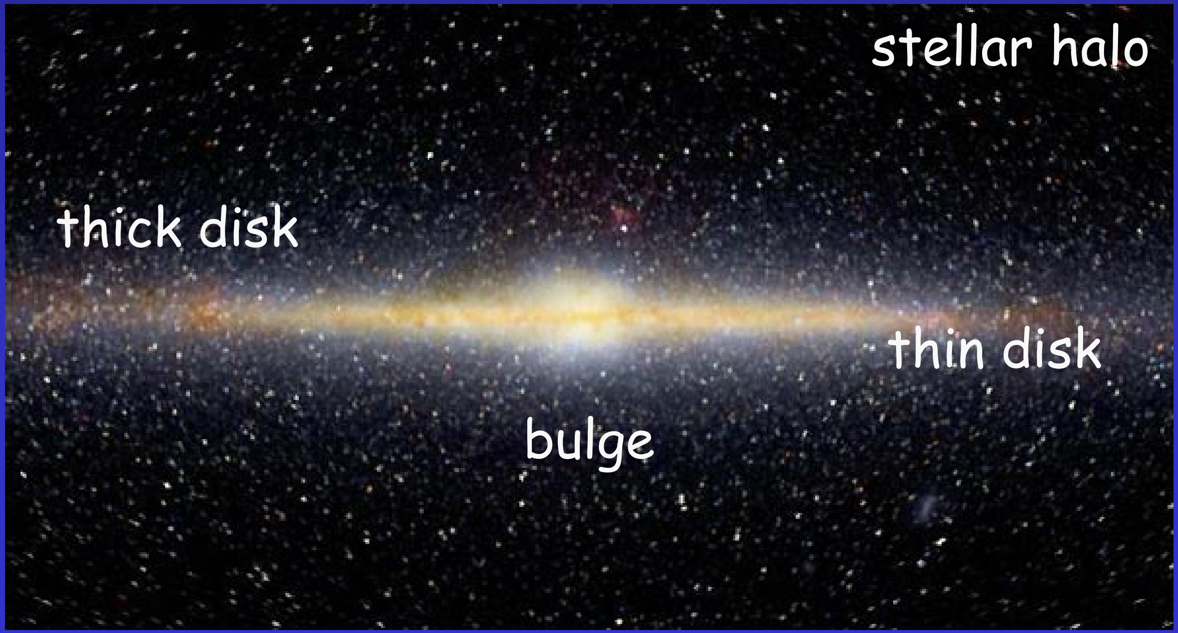


- Can we find the signatures?
  - Substructure and the search for tidal streams

- How did the building blocks look like?
  - what is the link to today's nearby small galaxies (dSph)?

Where to look for substructure?

- Stellar halo
  - Most metal-poor and ancient stars in the MW
  - It can form from the superposition of disrupted satellites
- Thick disk
  - Old and metal-weak stars
  - Disks are fragile: easily heated up by minor mergers



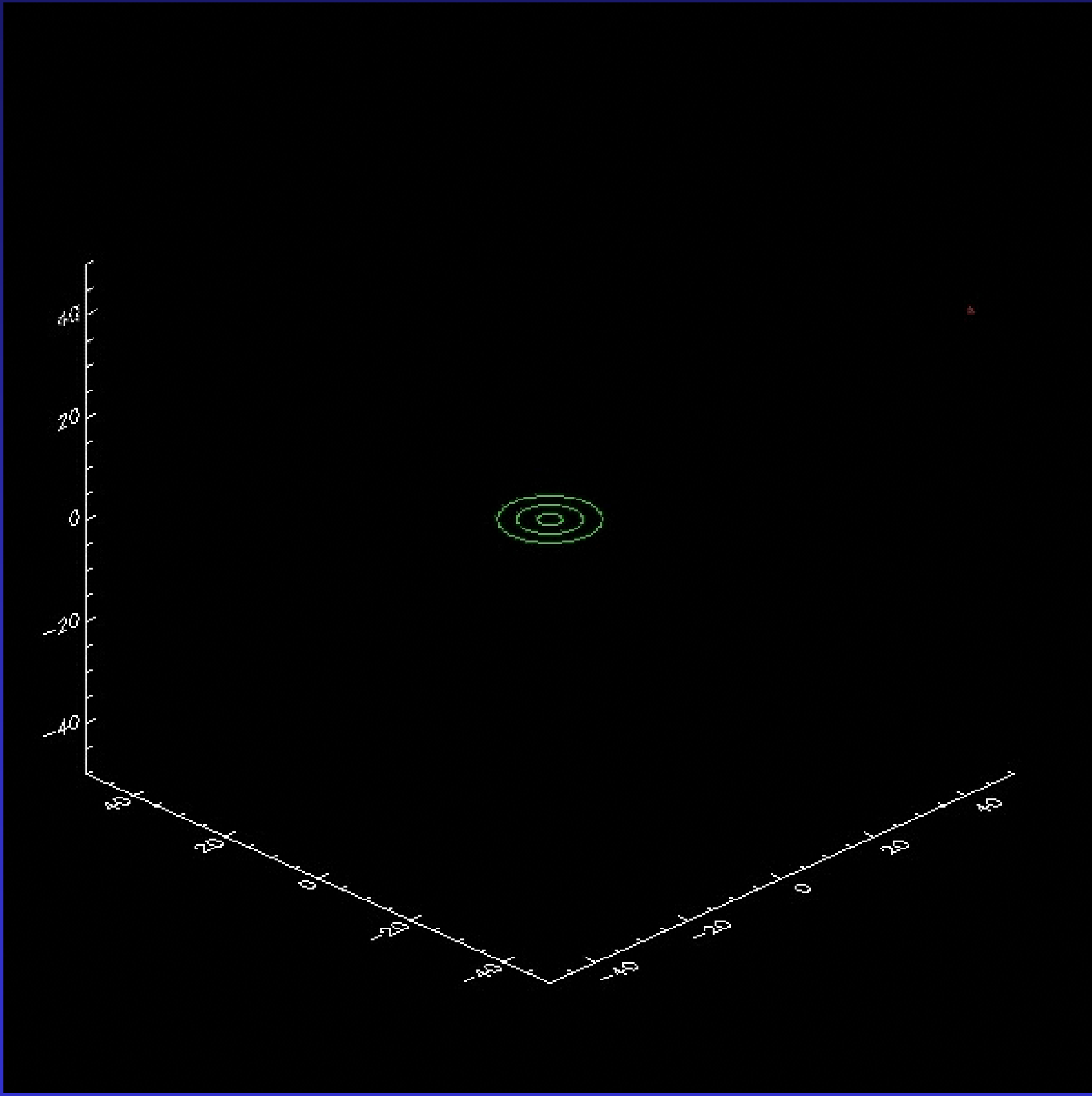
Substructures in the (outer) halo

Shortly after infall (t/t_{dyn} ~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.

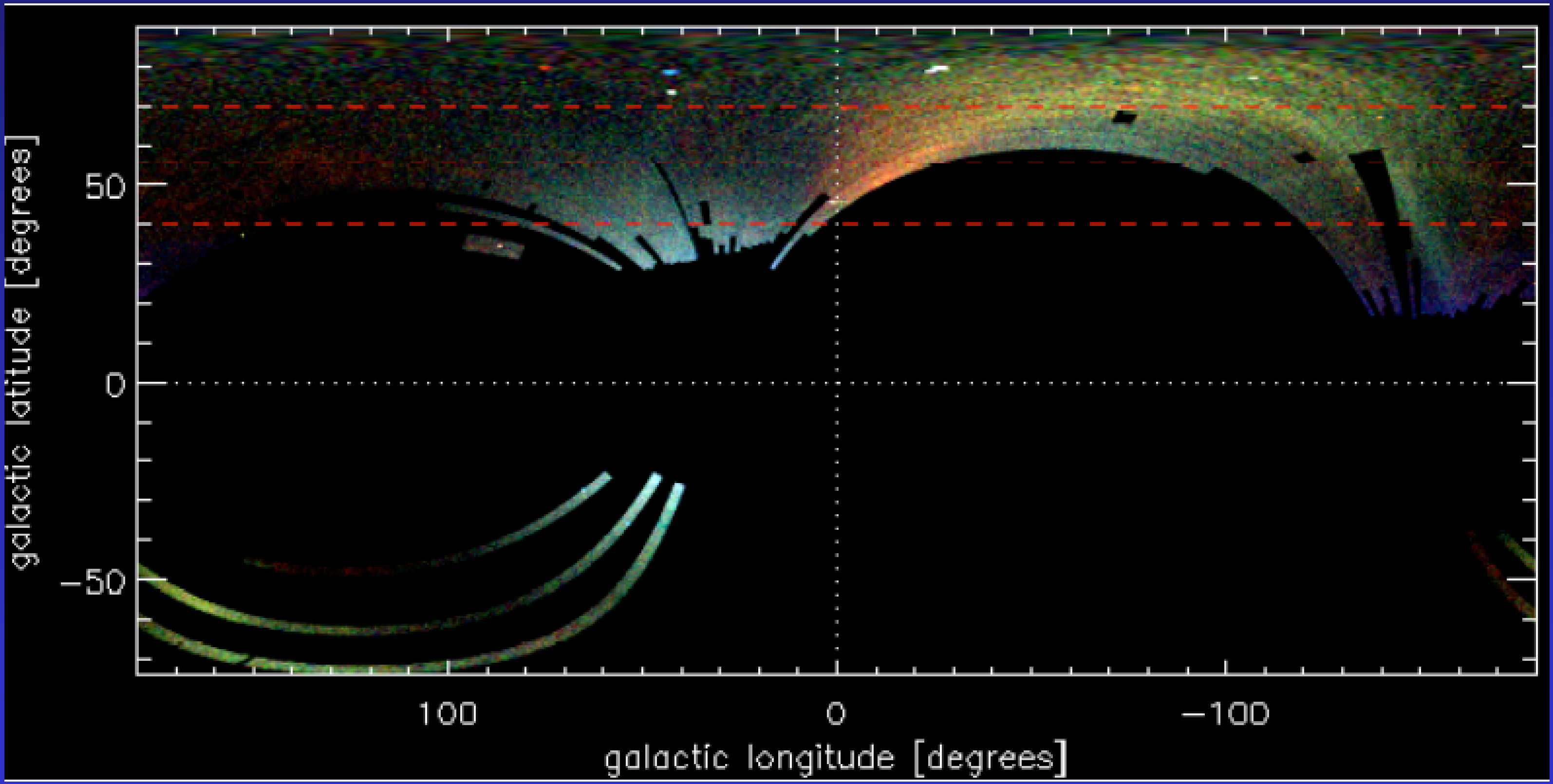


Bullock & Johnston

Wide-field surveys

SDSS, 2MASS, … yielding spectacular results:

- Substructure appears to be common

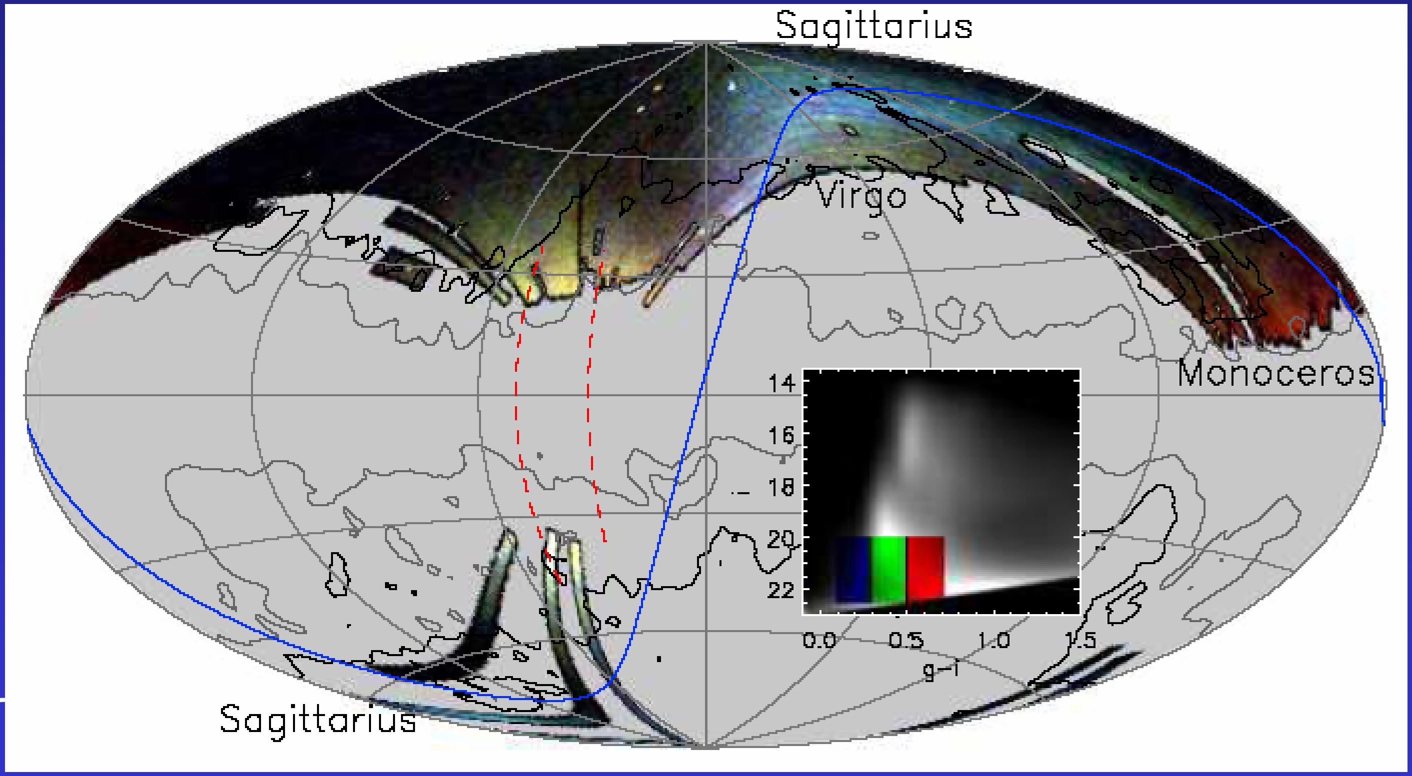


Belokurov et al 2006

Substructure in the halo

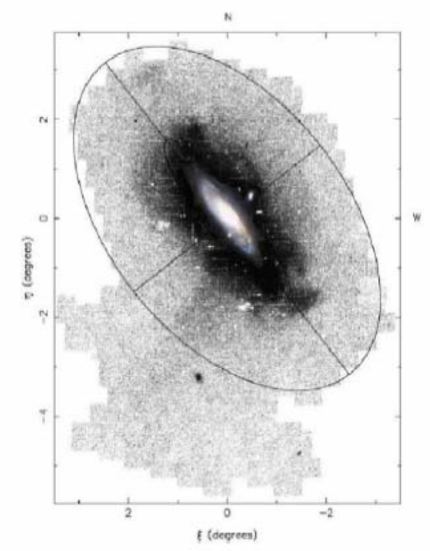
SDSS, 2MASS, … yielding spectacular results:

- Substructure appears to be common
- Kinematics needed to understand nature of the overdensities
- Properties seem to suggest large-ish progenitors



Belokurov et al. 2007

Ferguson et al



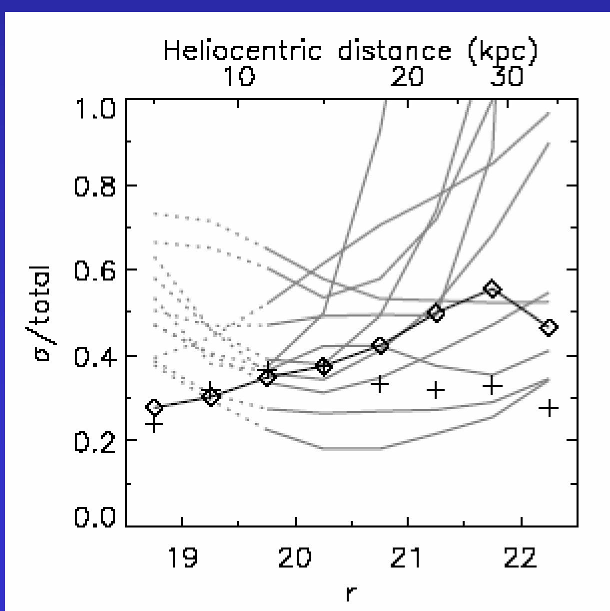
Substructure in the halo

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

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

Level of RMS ~ 30-40%

Compared to SA models MW stellar halo MW halo is typical



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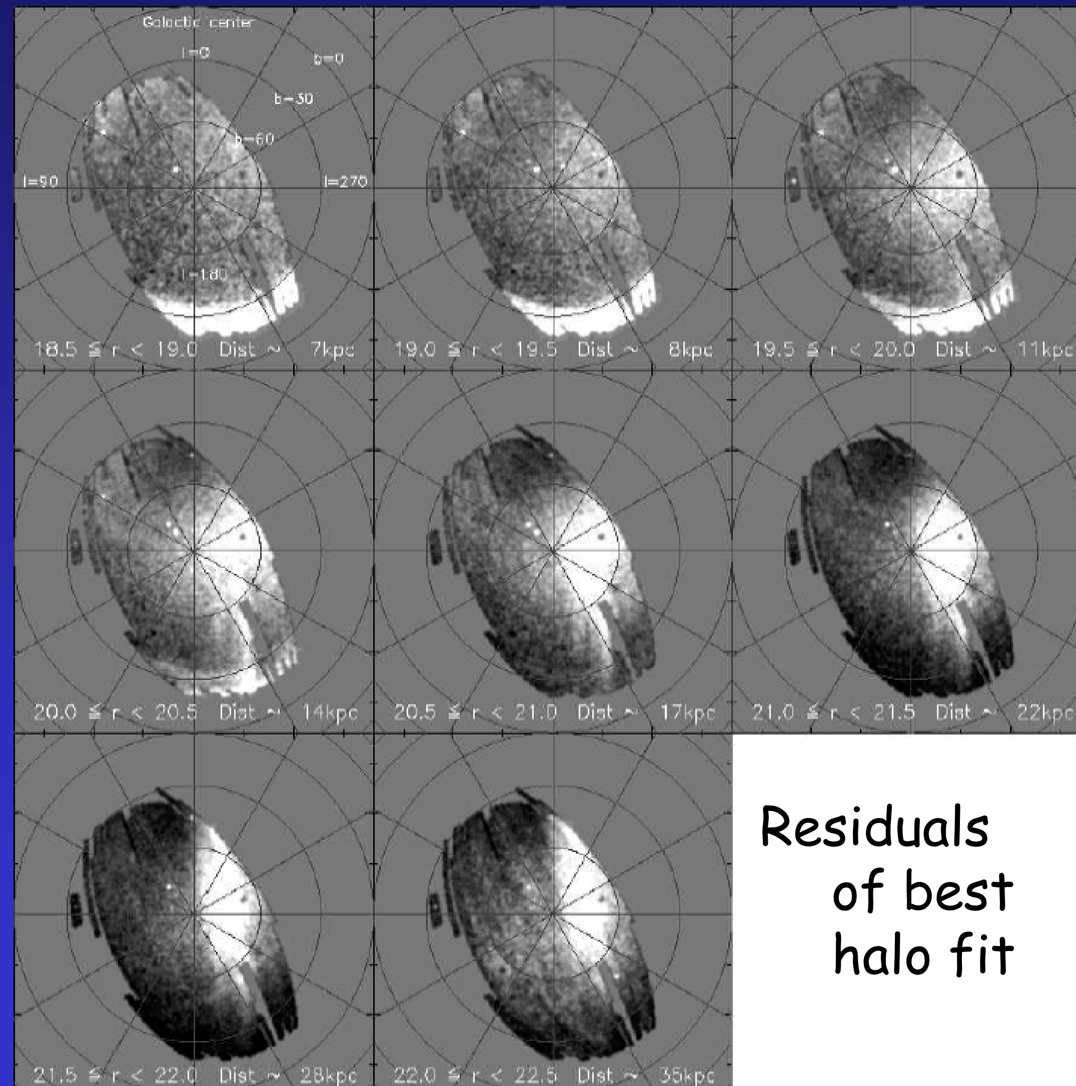
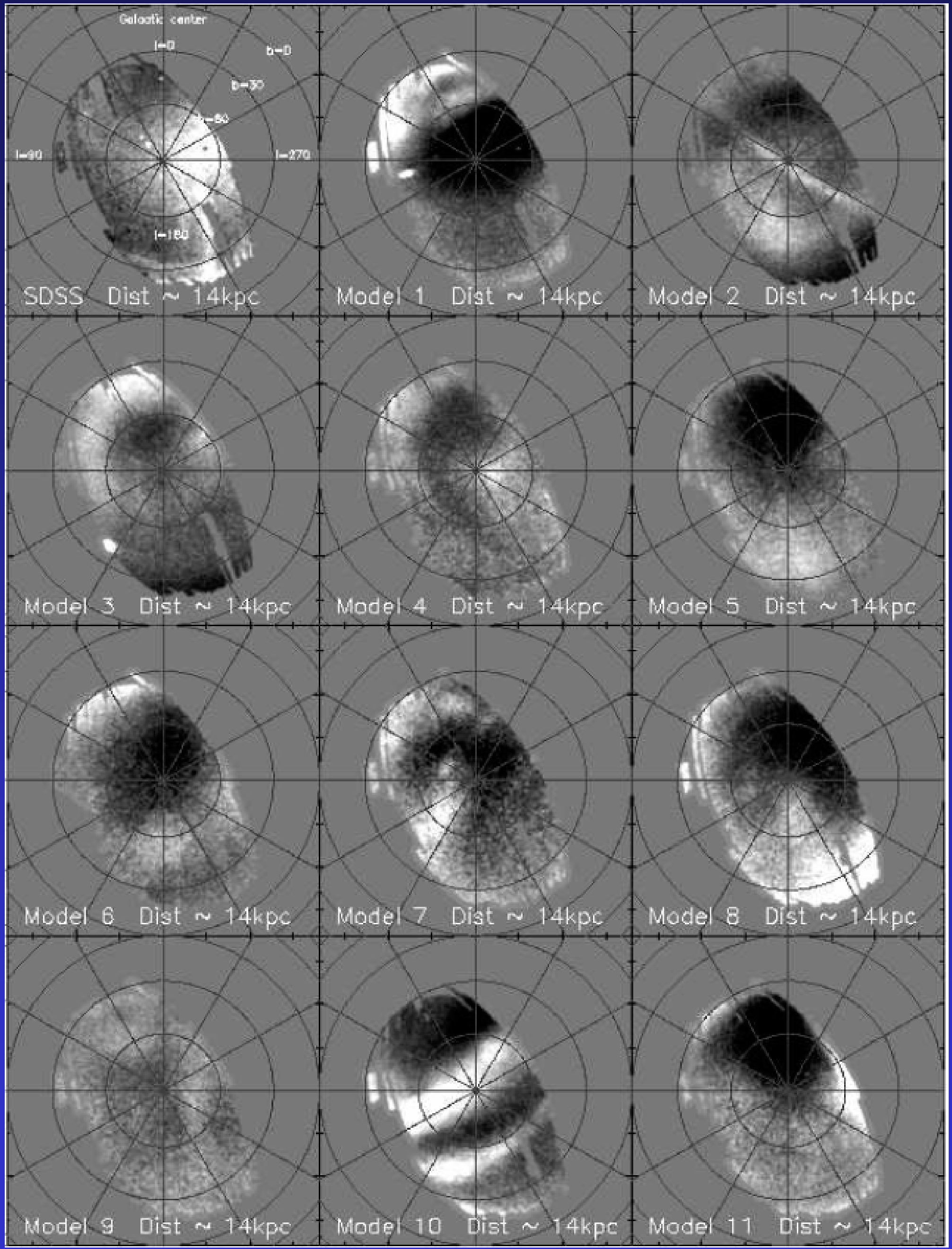


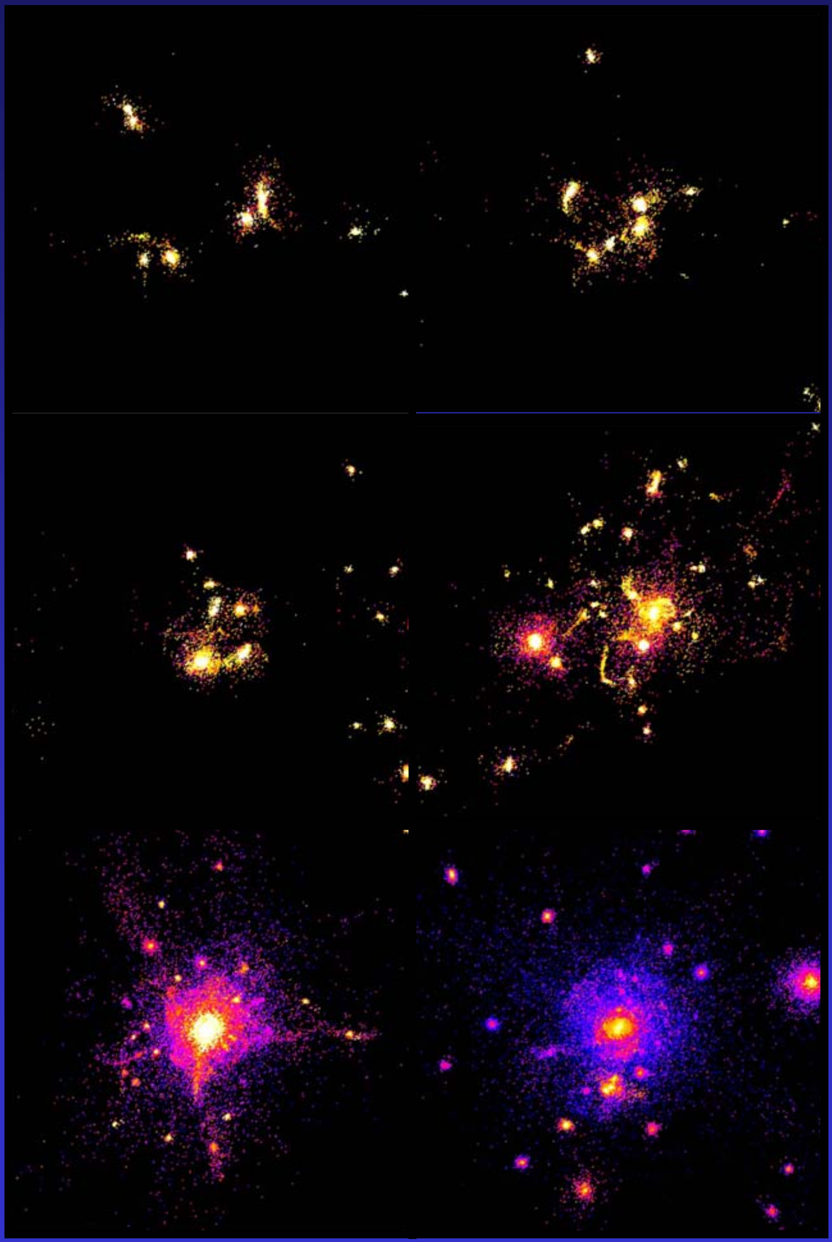
Residuals of best halo fit

Stellar halos from SA models by Bullock & Johnston (2005)

Overall good agreement



Mergers and substructure

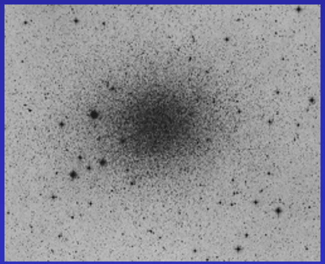


- Can we find the signatures? YES!
  - Substructure is ubiquitous in halo
- Still need to quantify/understand
  - What fraction is built by mergers?
  - Properties suggest large-ish progenitors (selection bias?)
- How did the building blocks look like?
  - what is the link to today's nearby small galaxies (dSph)?

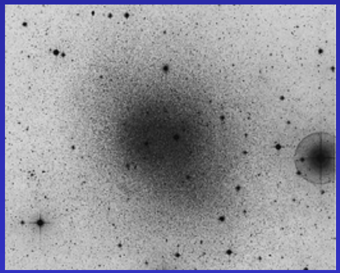
The dwarf spheroidals

- Dwarf spheroidals are the smallest nearby galaxies

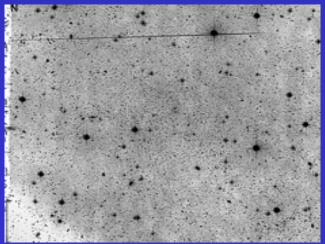
- All contain ancient (> 10 Gyr) and metal-poor stars (< -1.6 dex)
  - fossil record of the conditions of the very early Universe … constrain IMF at high-z, could be linked to reionization



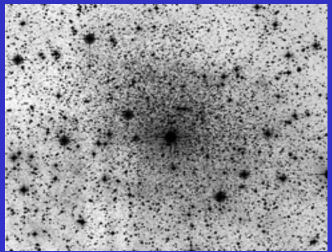
Sculptor



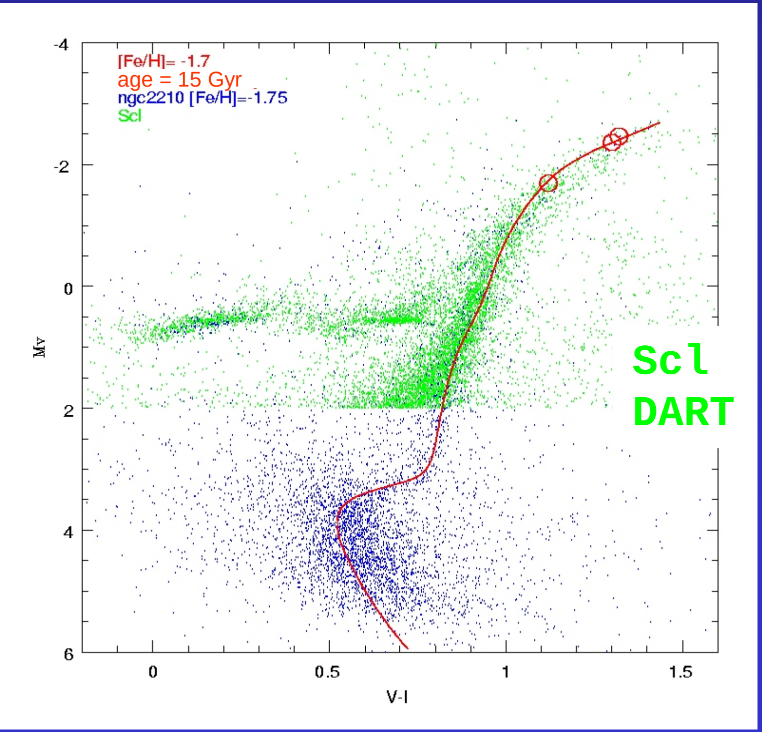
Fornax



Sextans



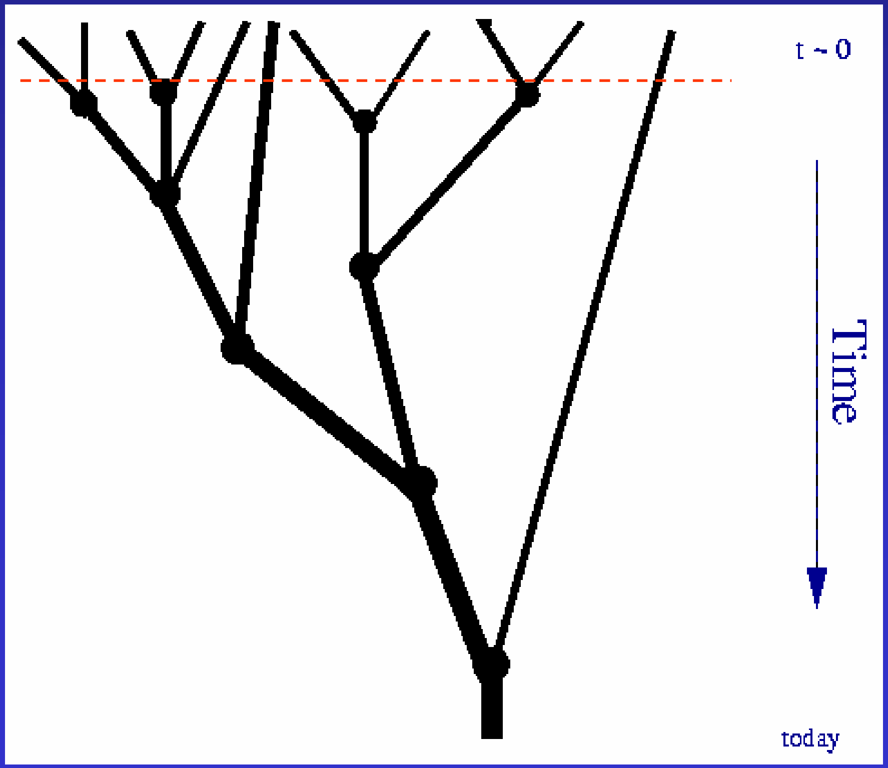
Carina



The dSph and the Galactic building blocks

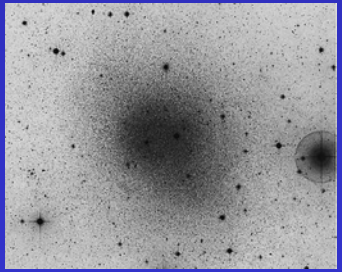
- The oldest stars in the dSph (hence the most metal-poor) presumably formed about the same time as the first stars in the building blocks

- Therefore, one may compare the metallicity distribution of the stars at the metal-poor end both in the dSph and in the Galactic halo

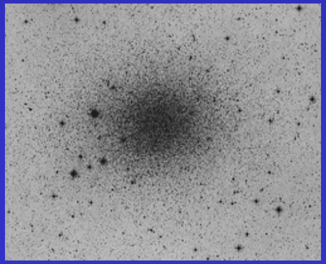


DART and the dwarf spheroidals

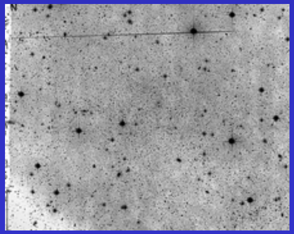
- Dwarf Abundances and Radial velocities Team, PI: E. Tolstoy
- ESO Large Program on the VLT/FLAMES
- Spectra for several 100s of stars in 4 dwarf spheroidals
  - HR detailed chemical abundance studies in the centre
  - LR metallicity and radial velocity from CaT across the system



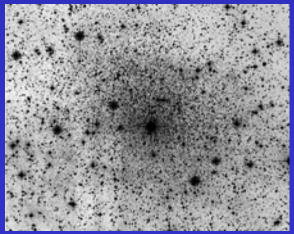
Fornax



Sculptor

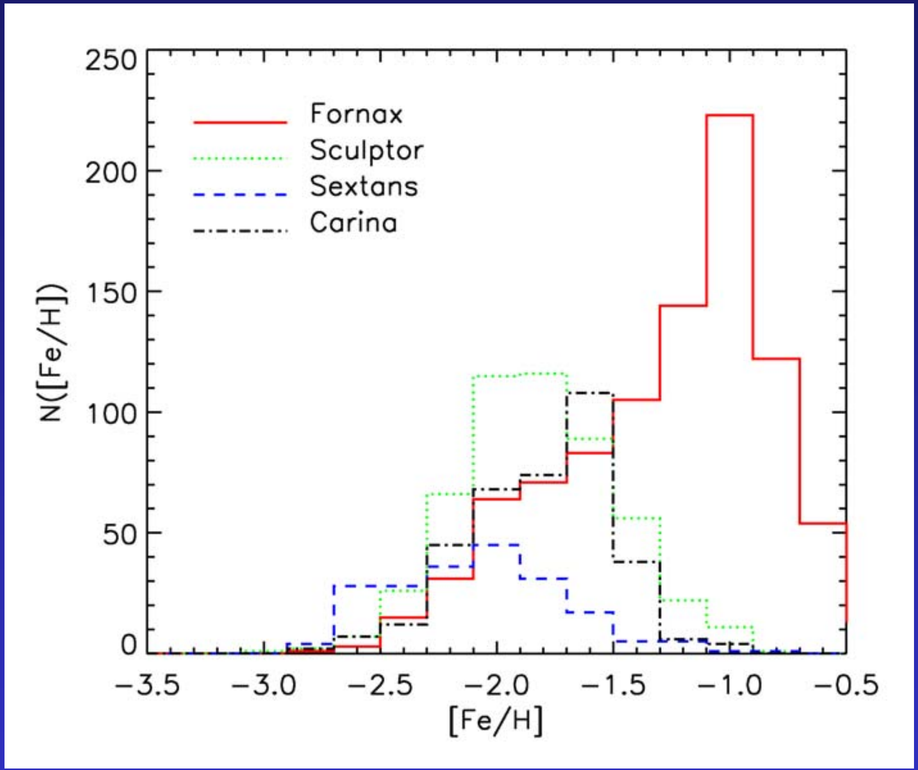


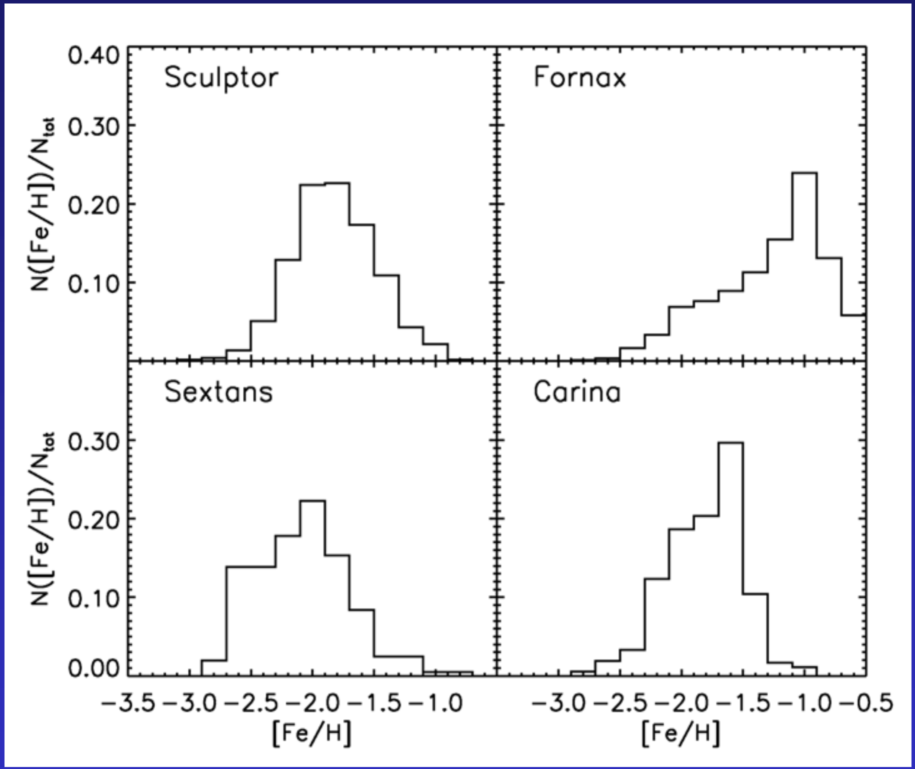
Sextans



Carina

Metallicity distribution





- Large variety in metallicity distribution (reflects widely varying star formation and chemical enrichment)
- Common denominator: no stars with [Fe/H] < -3 dex !

Metal-poor end of the metallicity df

- Simple model of chemical evolution

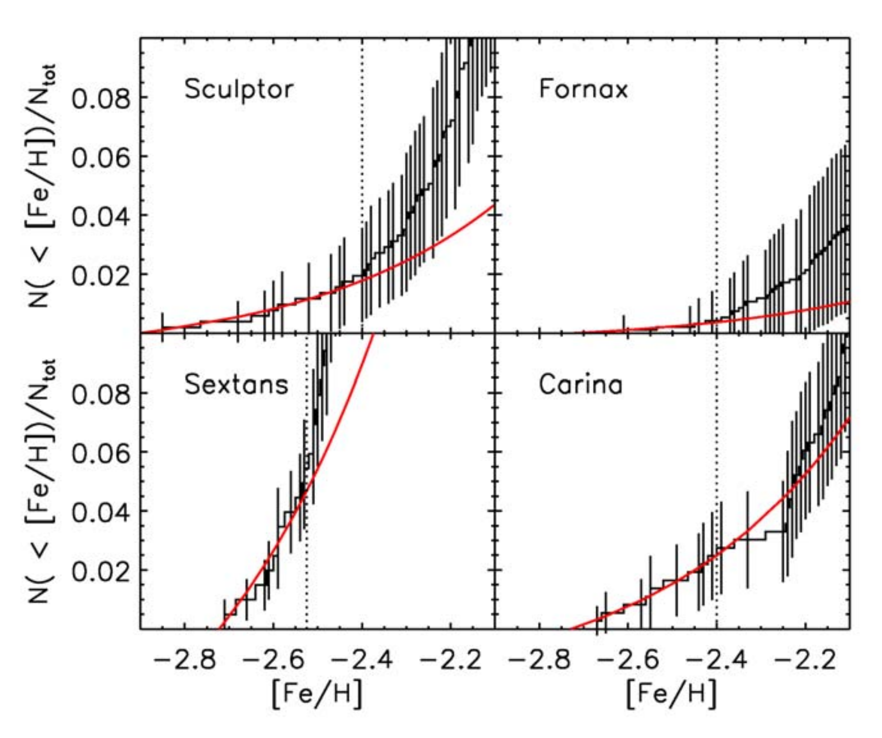
  $N(<Z) = A(1 - \exp\{-(Z-Z_0)/p\})$

  - A depends on initial gas available
  - Z_0 initial abundance, p=yield

- For small Z, and since $Z = Z_\odot\, 10^{[Fe/H]}$

  $N(<[Fe/H]) \sim a\, 10^{[Fe/H]} + b$

  where $a = A\, Z_\odot/p$, $b = -a\, 10^{[Fe/H]_0}$



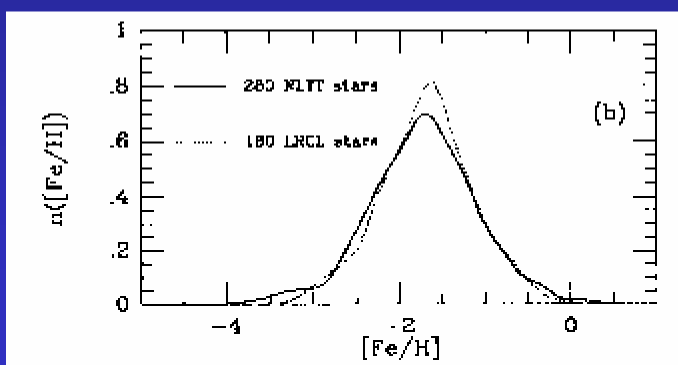
- Exponential decline at low [Fe/H] understood

- The initial metallicity of the gas $[Fe/H]_0$ is very similar in all galaxies

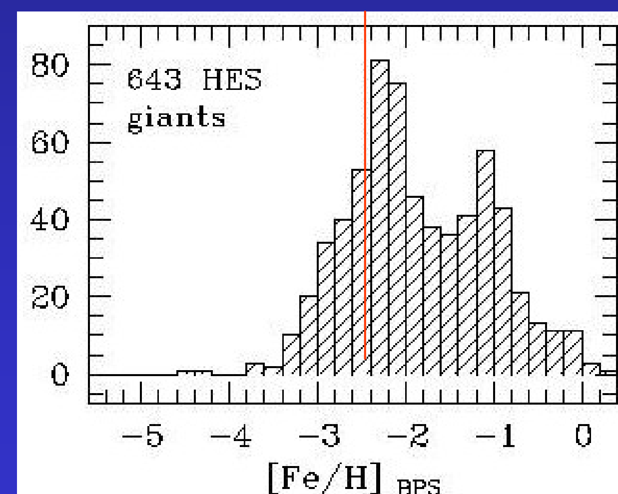
Sculptor	-2.9 ± 0.2
Sextans	-2.7 ± 0.1
Fornax	-2.7 ± 0.3
Carina	-2.7 ± 0.2

Implications and the Galactic halo

- Suggests uniform pre-enrichment across 1 Mpc^3 volume
- Lowest metallicity coincides with mean of the IGM towards QSO at z ~ 3 - 5 (corresponding to T ~ 12-13 Gyr ago)
- The Galactic halo does show very metal-poor (VMP) stars…



Ryan & Norris 1991

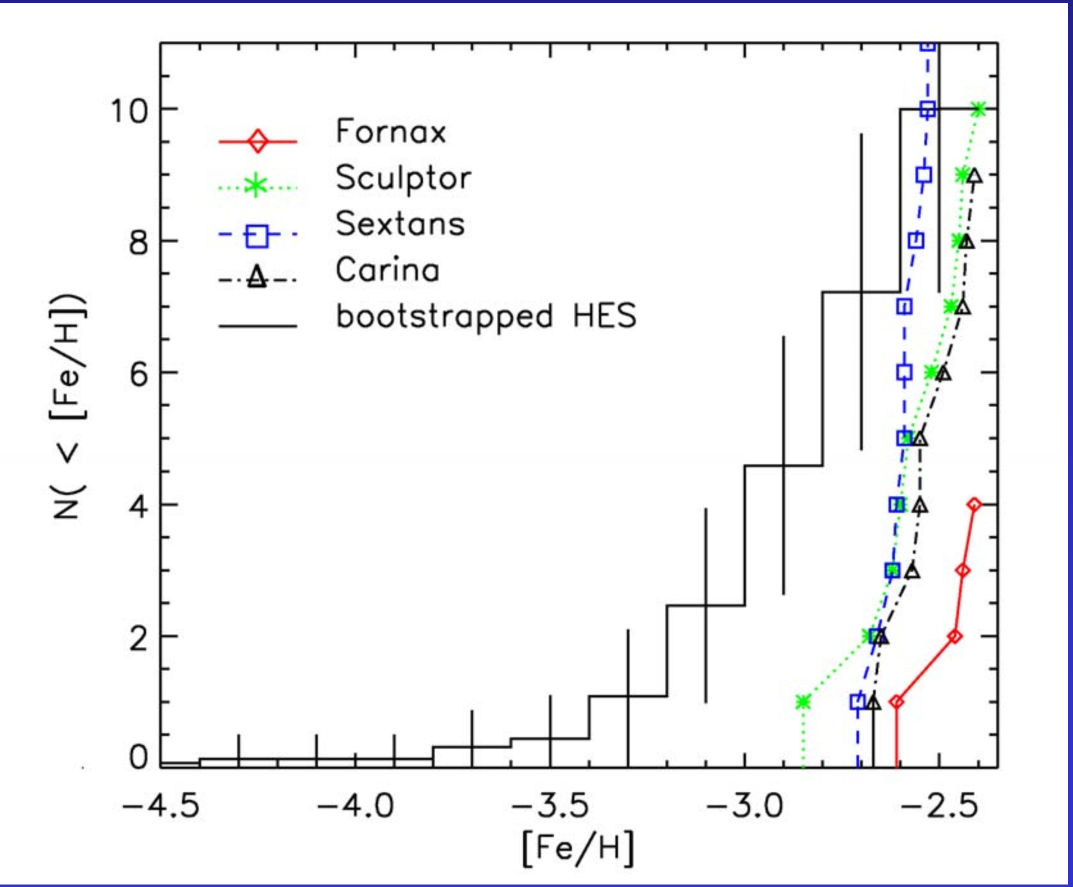


Christlieb 2004

Implications and the Galactic halo

- 130 HES giants with [Fe/H] < -2.5 dex, ~ 35 with [Fe/H] < -3 dex
- Bootstrap HES distribution to account for the different sample sizes

- Significantly different
- KS test probabilities < 10^{-3}
- If the same parent distribution, would have expected ~1/4 (i.e. 35/130) stars in the dSph < -3 dex.
- Although samples are small, we should have seen 10 stars with [Fe/H] < -3 dex.

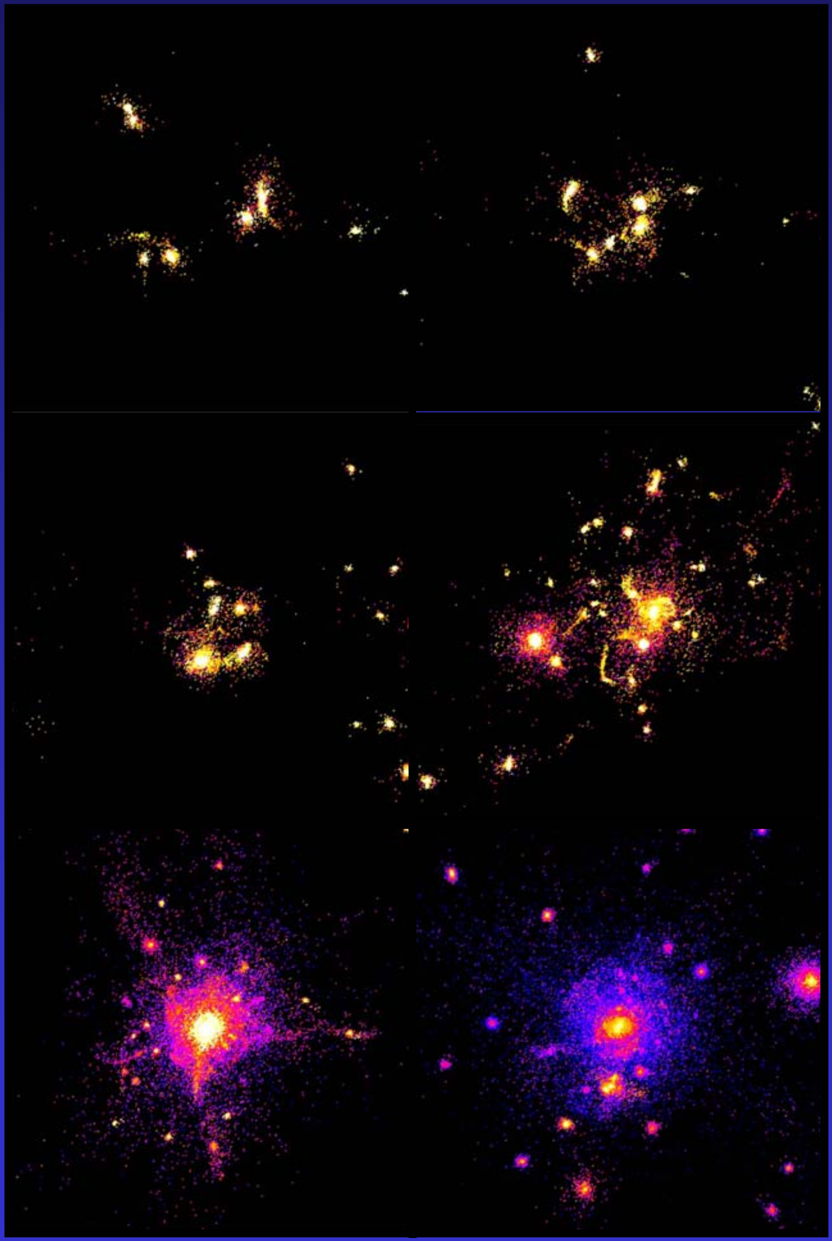


Helmi et al 2006

The puzzle

- Dwarf spheroidals lack very metal-poor stars, [Fe/H] < -3 dex, despite their low mean metal abundance.
- Comparison to Galactic halo, leads to the conclusion that the dwarfs *progenitors* not the building blocks of galaxies like the Milky Way
- Possible scenarios:
  - building blocks are high-σ peaks, dSph 1σ peaks
    - collapse earlier and enrich the IGM, from which the dwarfs (at later z) form. dSph not related to the reionization of the Universe.
  - IMF in building blocks different from dwarf spheroidals
    - First stars top heavy in dSph, but low mass stars present in building blocks (high σ peaks, e.g. Nakamura & Umemura 1999).

Hierarchical paradigm and dark-matter



How did the building blocks look like?

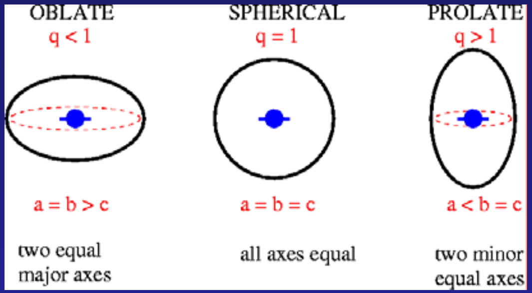
- what is the link to today's nearby small galaxies (dSph)?

Fundamental ingredient of the model: dark-matter

- how is it distributed?
  - density profile
  - shape
- what are its properties?

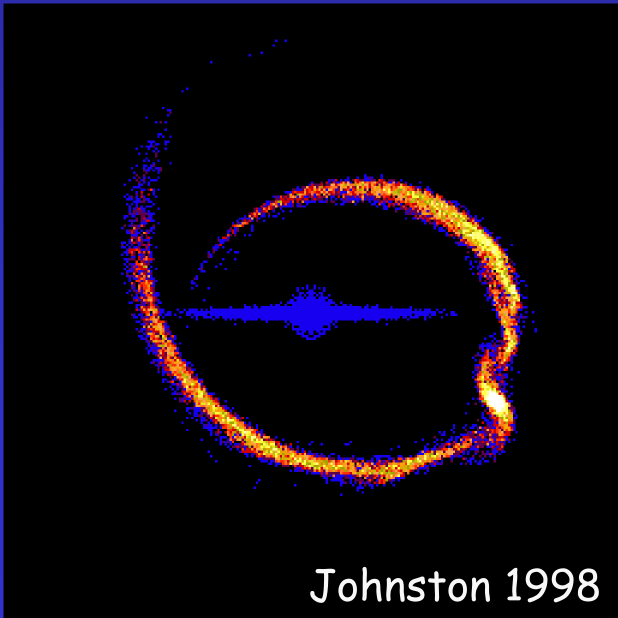
The Milky Way's dark halo shape

- Insight on nature of dark matter:
  - CDM: oblate, prolate, triaxial. <q> ~ 0.6 – 0.8 (Dubinski 1994; Bullock 2002; Allgood et al 2005).
  - HDM: spherical (Mayer et al. 2002)
  - SI: close to spherical (Dave 2002)



- Streams in halo excellent probes:
  - stars on parallel orbits moving under influence of the dark halo potential

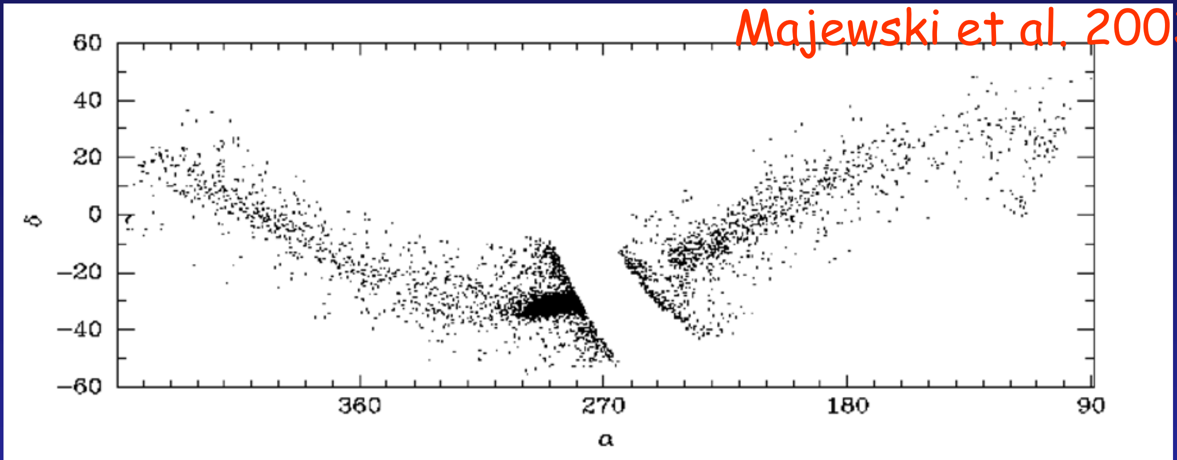
- Simple test
  - Spherical halo -> motion in a plane
  - Non-spherical -> plane precesses



Observations from 2MASS

Approx. thousand M giants, debris from Sgr

Distances and radial velocities available

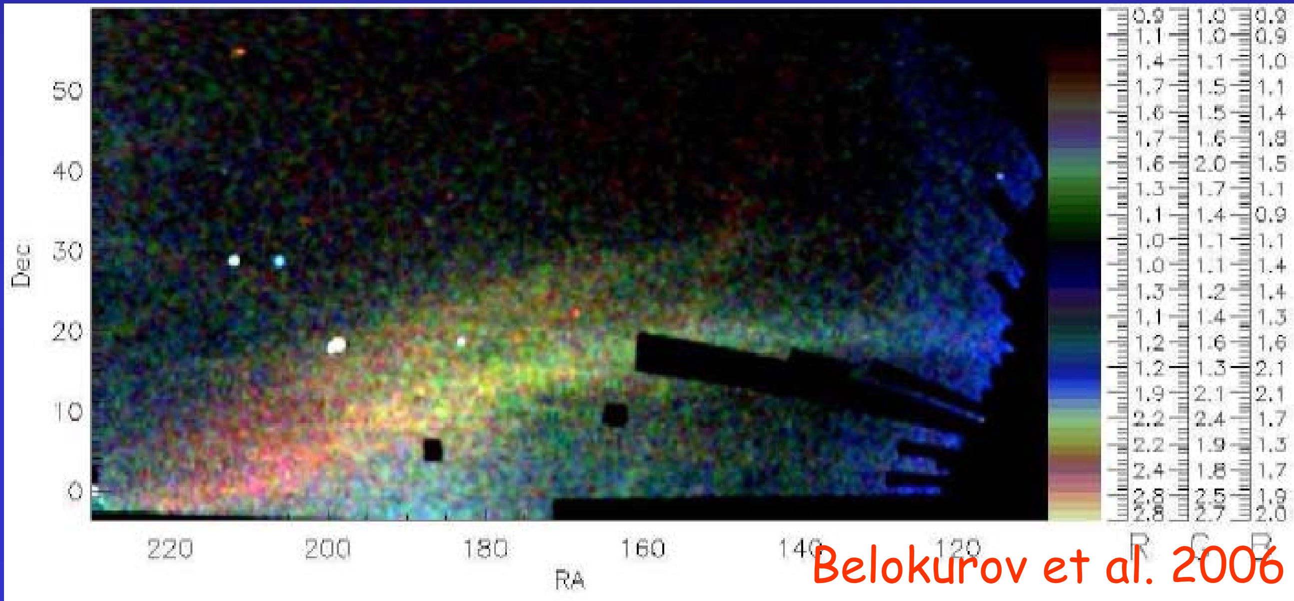


Majewski et al. 2003

SDSS view

stars with g-r < 0.4

towards north galactic cap



Belokurov et al. 2006

Modelling the streams

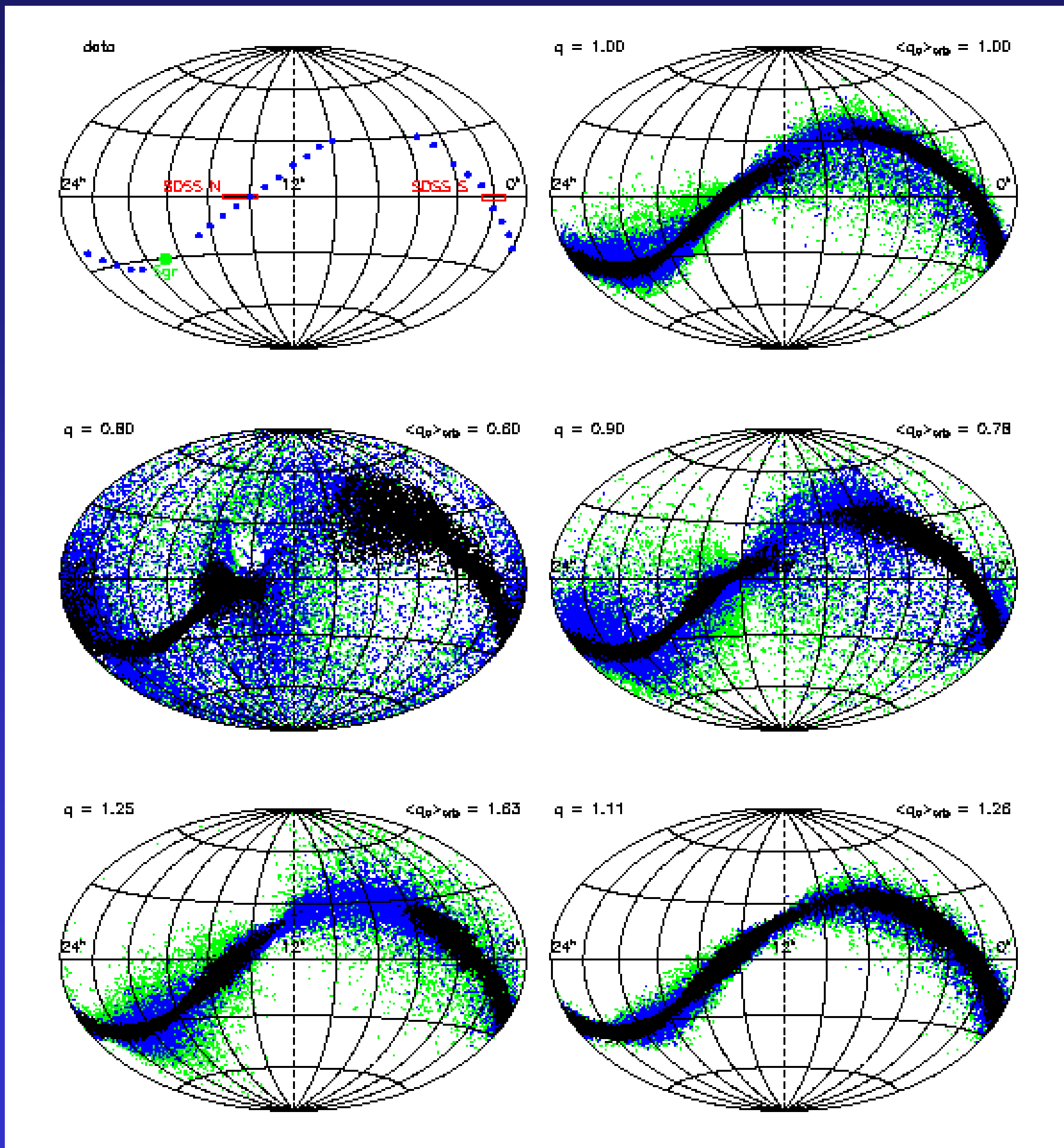
- N-body experiments of the evolution of Sgr in Galactic potentials with halo of varying shape: from oblate to prolate

$$\Phi = v_h^2 \log(R^2 + z^2/q^2 + d^2)$$

- Orbital initial conditions: set by current position, and motion of the dwarf, and orbit to pass close to SDSS detections
- Final dwarf is the same -> differences in streams properties due differences in the halo flattening

- Explore how the debris is distributed on the sky, as function of distance, and the radial velocity trends

Debris sky distribution



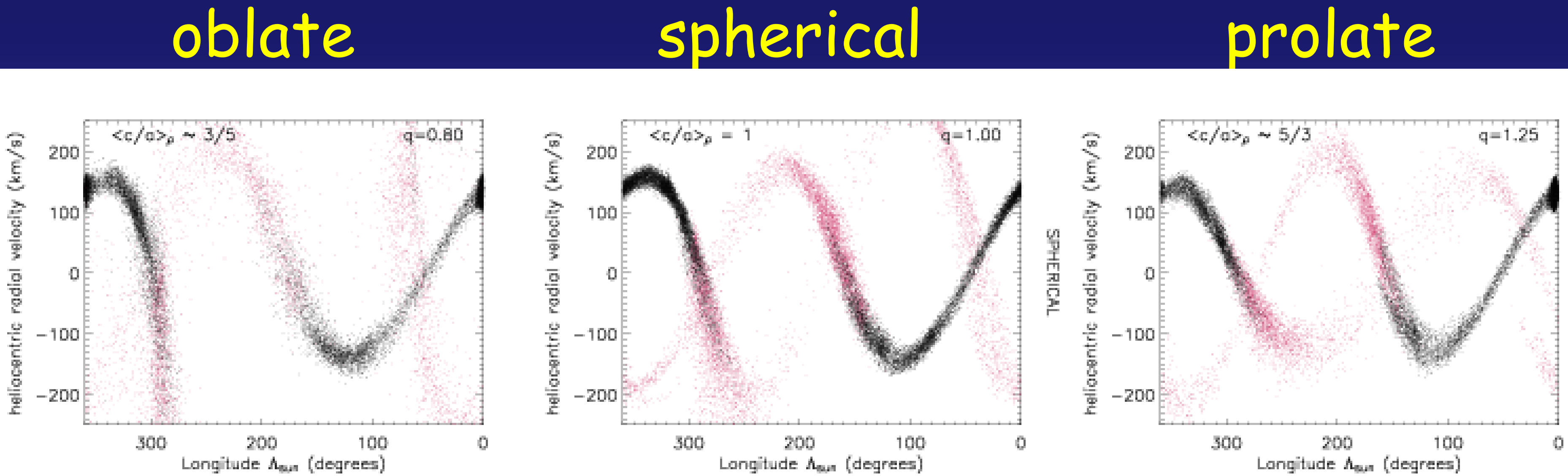
- Appearance depends on the dynamical age of the streams

- Youngest streams in black (< 3 Gyr), have very similar distributions for all halo flattening/shapes

- We have only observed the youngest streams

Helmi 2004, MN

Kinematics of stream stars

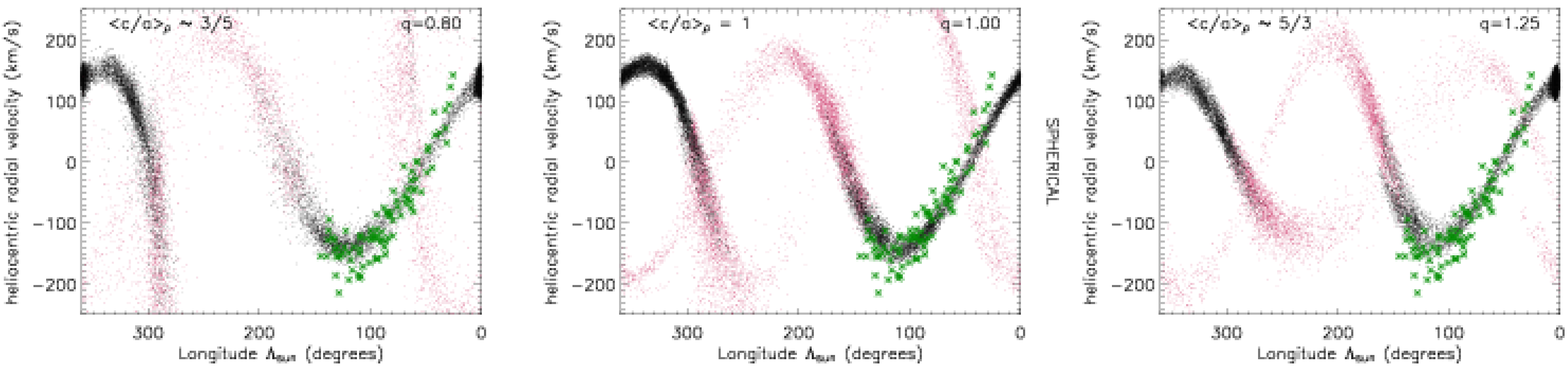


Black: particles released in the last 1.5 Gyr
(models not distinguishable)

Magenta: released between 1.5 and 4 Gyr ago
Noticeable differences
$\Lambda \sim 200$ deg (trailing) and $\Lambda \sim 280$ deg (leading)

Kinematics of stream stars

oblate spherical prolate

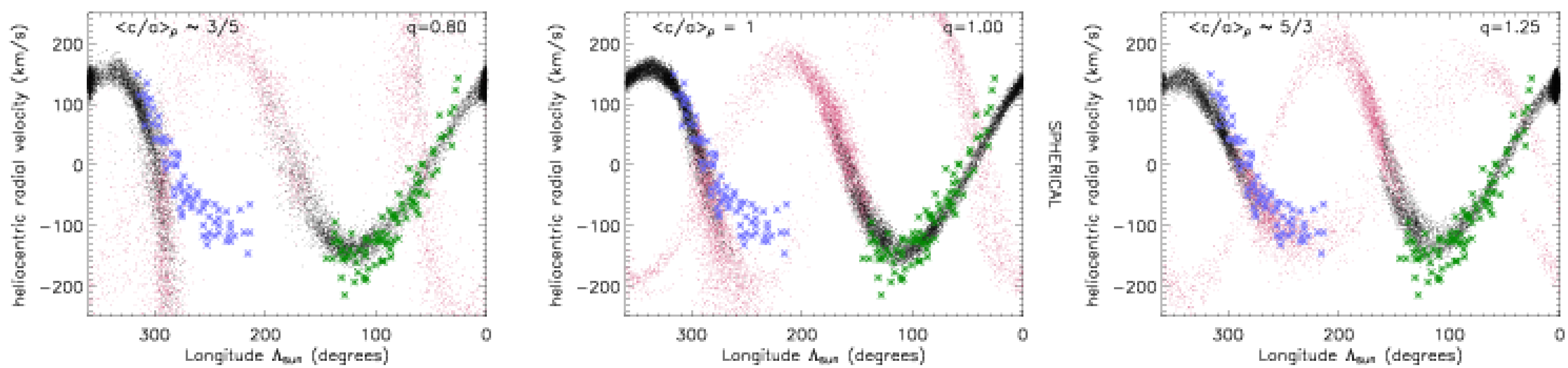


Radial velocities from Majewski et al. (2004)

Measured kinematics of trailing streams: do not provide strong constraints

Kinematics of stream stars

oblate spherical prolate



Helmi 2004, ApJL

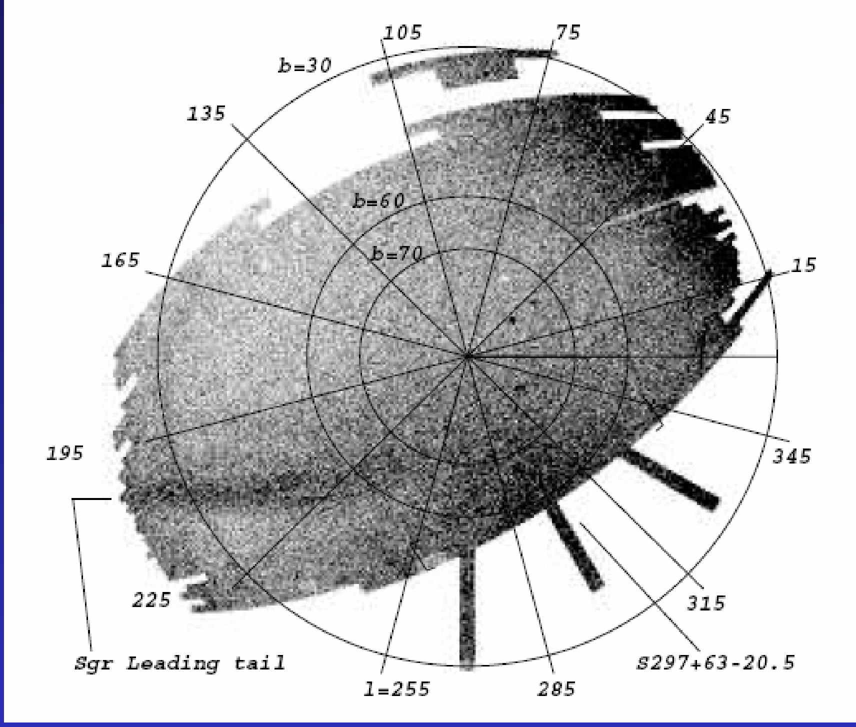
Leading stream velocities from Law et al. (2003)

Measured kinematics support prolate halo shape

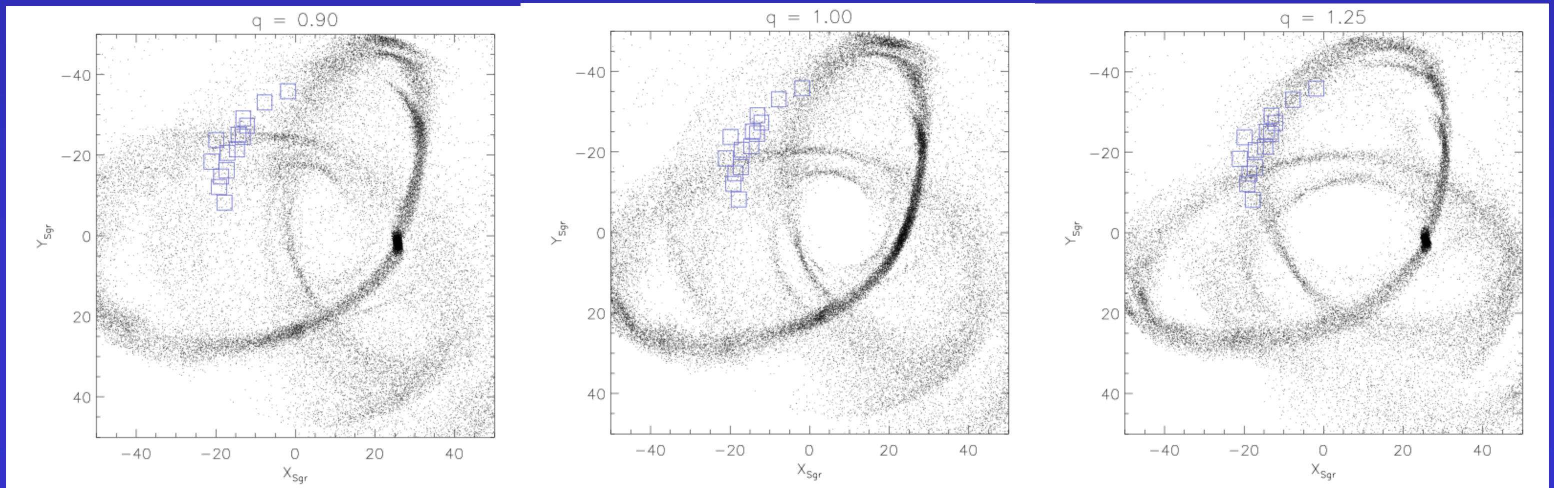
Differences greater than 100 km/s for other shapes!!

More data on Sgr

Newberg et al (2007)



- New data from SDSS shows leading stream does not pass near the Sun
- Just as expected for prolate halo
- Also consistent with recent RAVE data: no massive streams crossing the disk at the Solar neighbourhood (Seabroke et al. 2007)



Helmi (2007)

Sgr and the shape of the DM halo

- The kinematics of the stars in the streams of Sgr provide direct evidence of the prolate shape of the Galactic halo

- Favoured axis ratio: $q \sim 1.25$, or $q_\rho \sim 5{:}3$

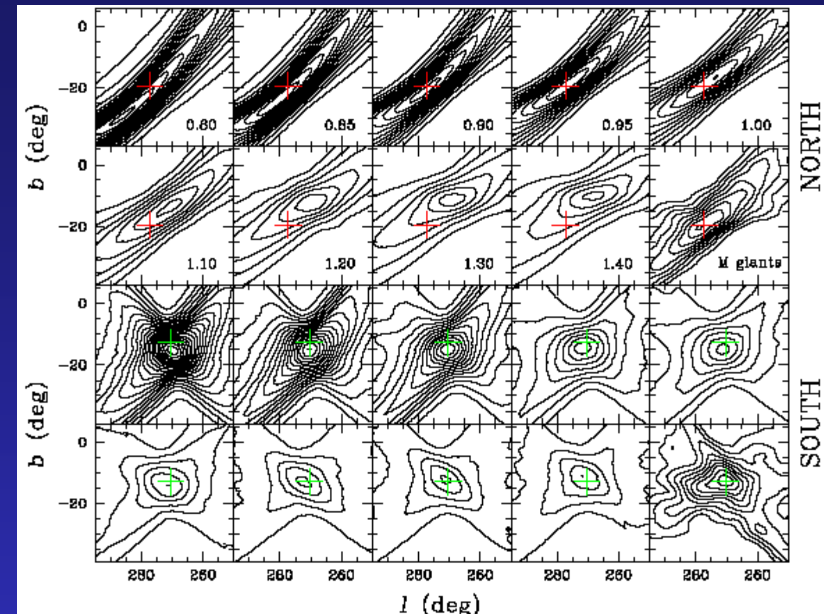
- Consistent with expectations for CDM

- Implications:
  - Smaller contribution of the dark matter density on the Galactic plane (for a fixed circular velocity)
  - Holmberg effect explained naturally: overdensity of satellites along the minor axis of disk galaxies traces DM distribution at large scales

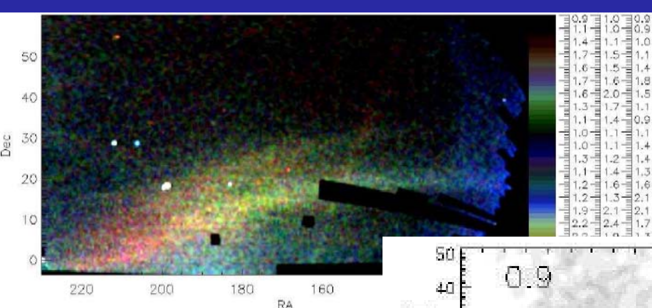
- However....

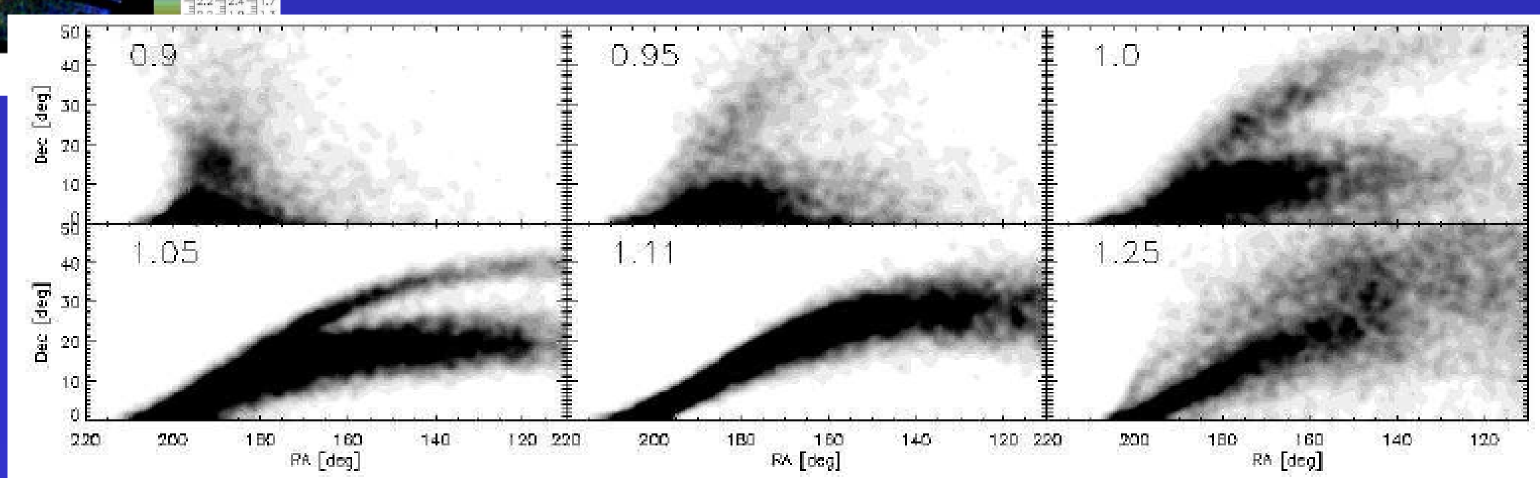
Sgr and the shape of the DM halo

- Precession of orbital plane favours oblate shape q = 0.9-0.95 (Johnston et al. 2004; q > 1.05 ruled out at 3σ)



- Biffurcation in the SDSS DR5 data favours spherical or slightly prolate





Fellhauer et al 2006

Summary and Outlook

- Milky Way ideal to test cosmological model: vast amounts of incredibly detailed data; not available for distant systems

- Concordance model tests:
  - Lots of substructure: direct evidence of mergers. How many/when?
  - (Progenitors of) dwarf galaxies are not the building blocks of large galaxies, because of lack of VMP stars. Scenario is more complex than initially believed.

  - Shape of halo: at large radii, not spherical. Motions and position of the stars of Sgr debris suggest MW prolate, precession favours oblate

Outlook

- Many surveys underway and planned for the near future
  - RAVE: radial velocity survey of 1 million stars near the Sun (1st data release containing 25,000 spectra at http://www.rave-survey.aip.de)
  - SEGUE (Sloan): radial velocities for ~ 10^5 stars (deeper than RAVE)
  - GAIA: full phase-space info + ages + [Fe/H] and [α/Fe] for 10^9 stars!
  - Push for wide-field multiplex spectrograph on 8m-class telescope; high-resolution for detailed chemical abundances studies of large numbers of stars
- There is a lot to learn about the distant universe from the fossils in our own backyard!