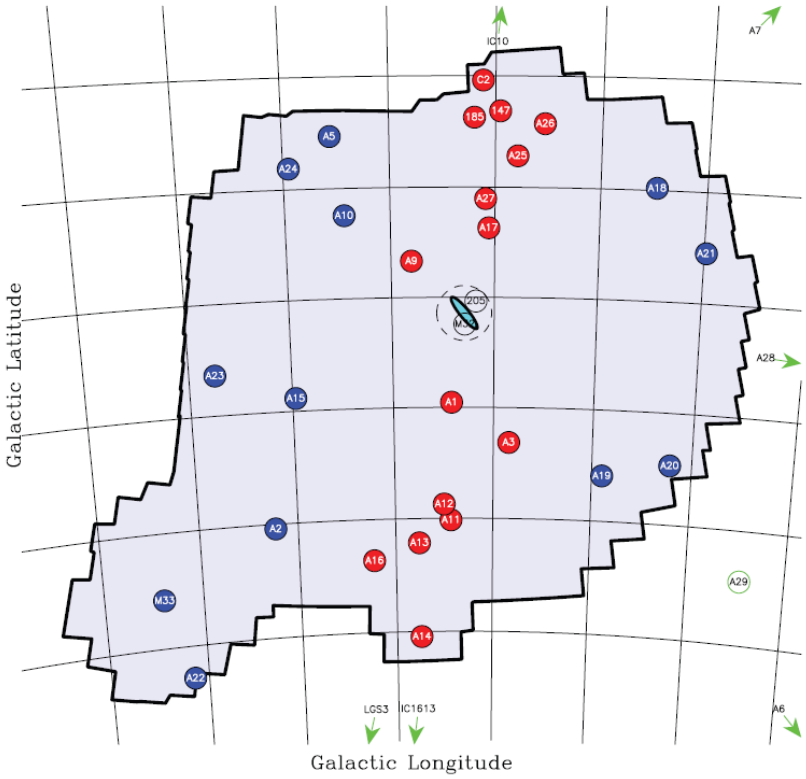
A comparison of the distribution of satellite galaxies around Andromeda and the results of ΛCDM simulations

Henning Bahl

7 August 2013

Ibata et al. (2013)



- Vast thin plane of co-rotating dwarf galaxies orbiting the Andromeda galaxy (VTPD)
- Only satellites within the PAndAS area were considered.
- 15 of 27 satellites belong to the plane
- Thickness: 12.6 ± 0.6 kpc
- 13 of the 15 satellites belonging to the plane share the same sense of rotation
- The plane is supposed to be highly statistical significant (99.998%).

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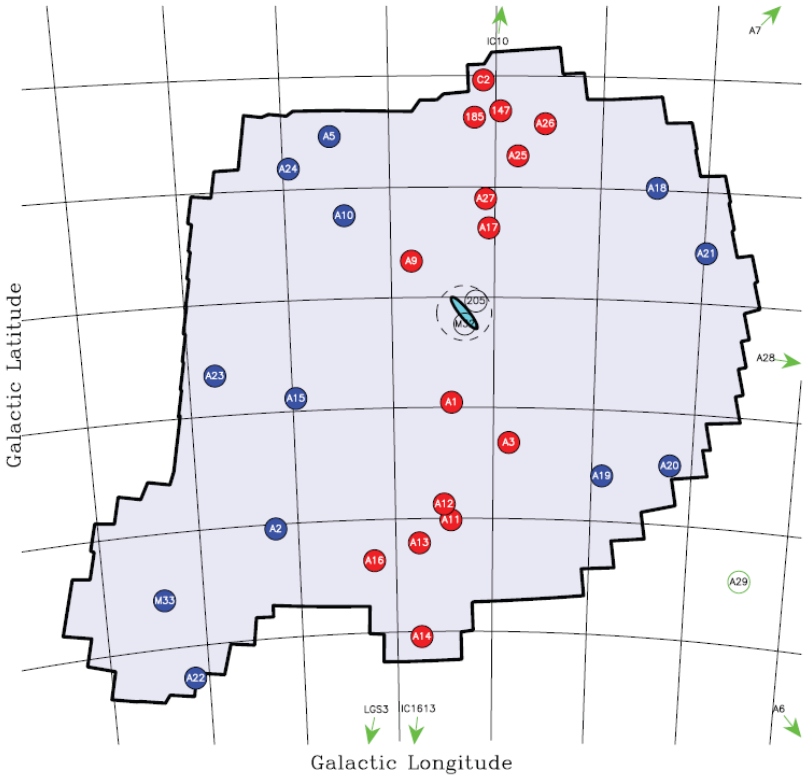

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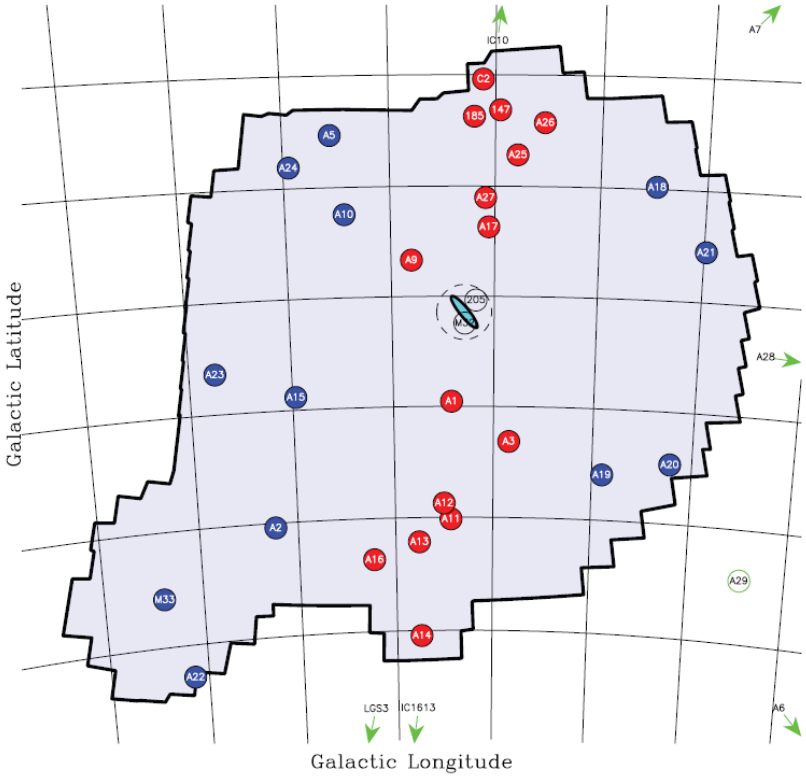

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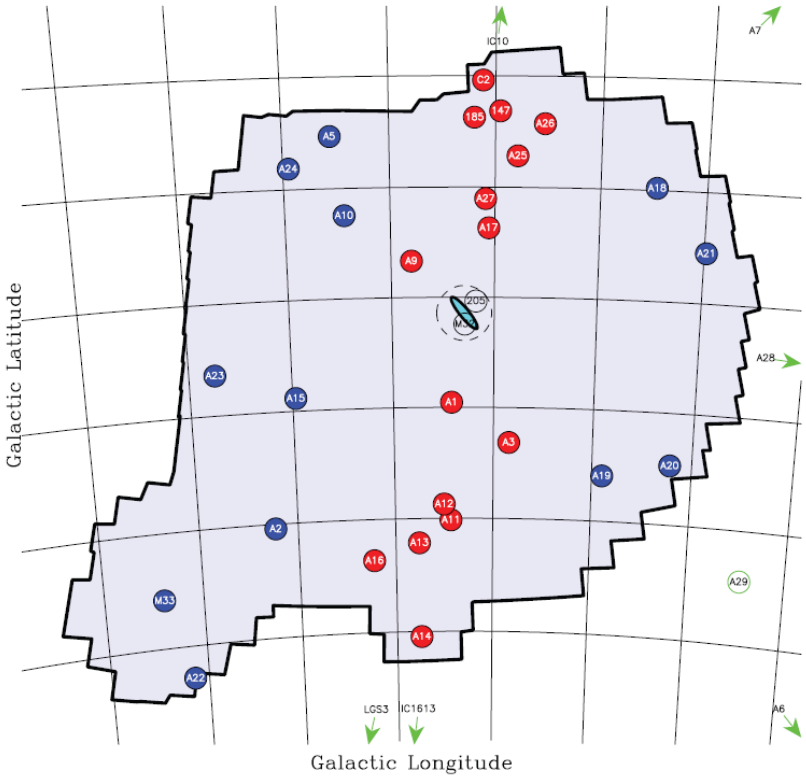

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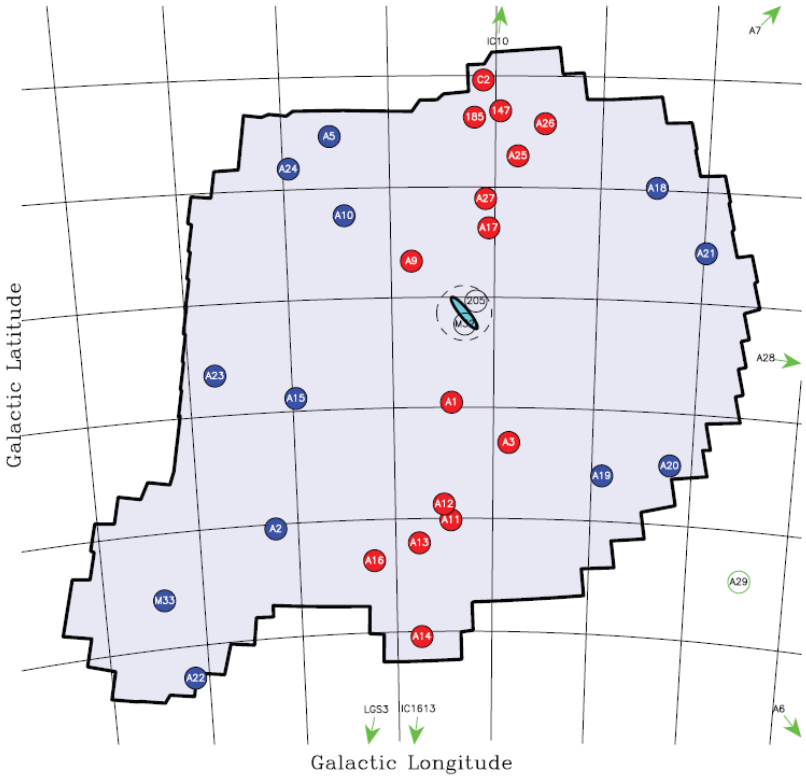

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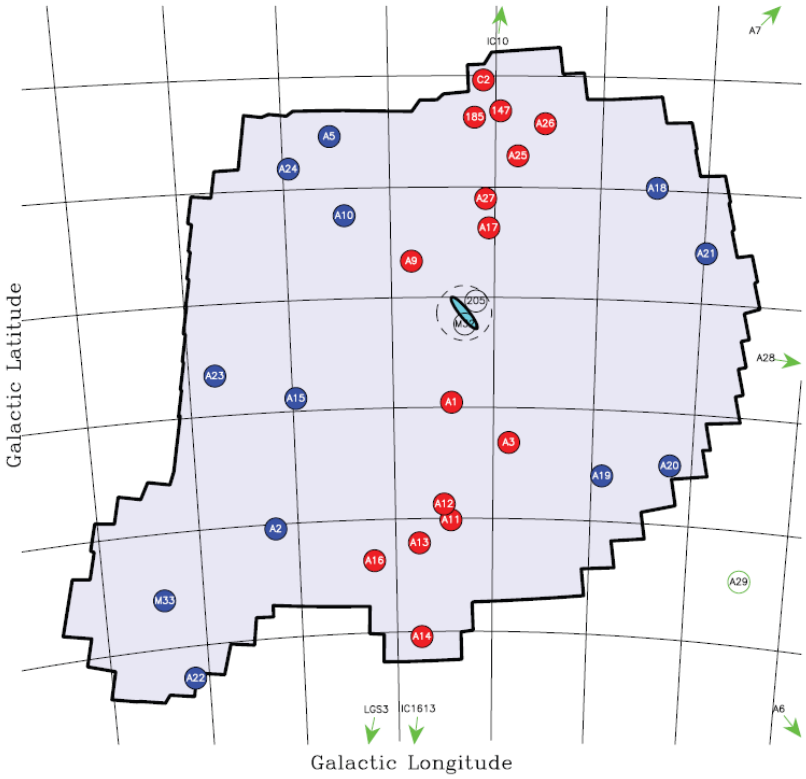

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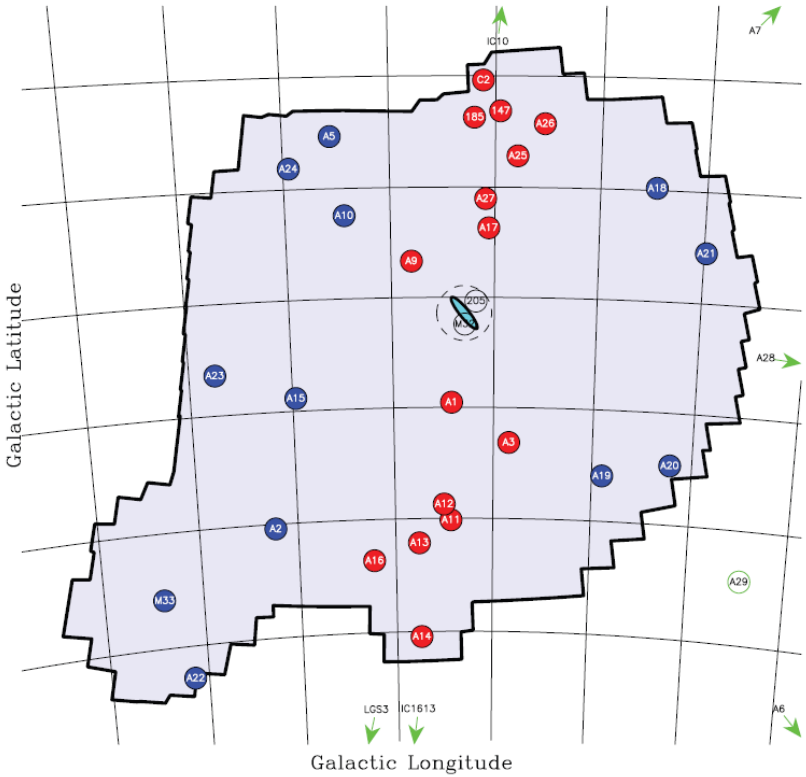

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- The satellite distribution around the Milky Way is also anisotropic. $\rightarrow$ search for similar structures in ΛCDM simulations

Basic idea

Search for VTPD like structures in large-scale cosmological simulations

Millennium II simulation data is used. Reasons:

- large sample of halos provides statistical significance
- easy query features
- original version was scaled to match WMAP7 cosmological constants (Guo et al. 2013)

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- started in box with a cube size of 104.3 Mpc/h
- contains 2160^3 particles with a mass of $8.5 \cdot 10^6$ $M_\odot/h$
- Guo et al. 2013 ran a semi-analytical galaxy formation model (Guo et al. 2011) on the simulation
- semi-analytical model follows gas infall (both cold and hot, primordial and recycled), shock heating, cooling, star formation, stellar evolution, supernova feedback, black hole growth, AGN feedback, metal enrichment, mergers and tidal and ram-pressure stripping.

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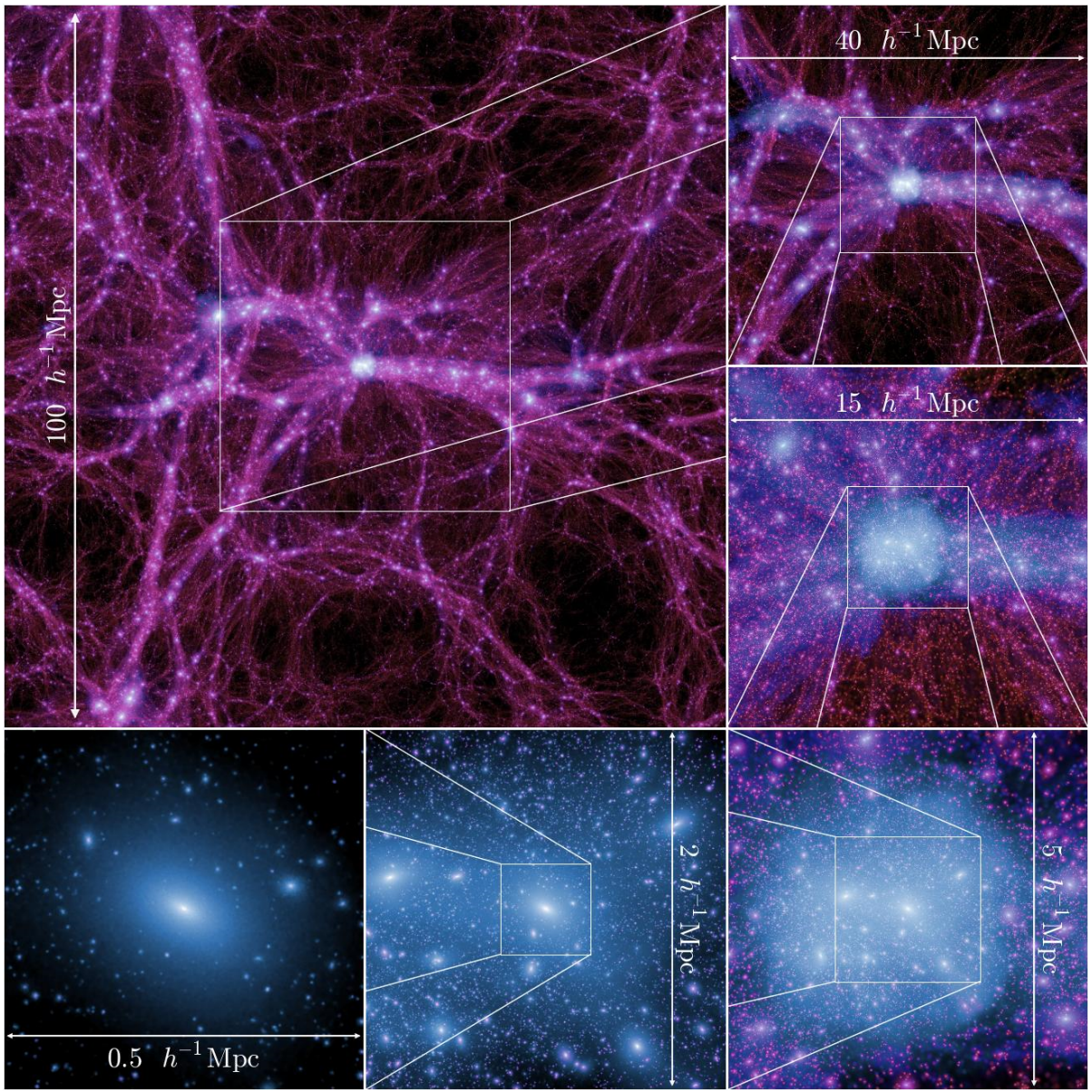
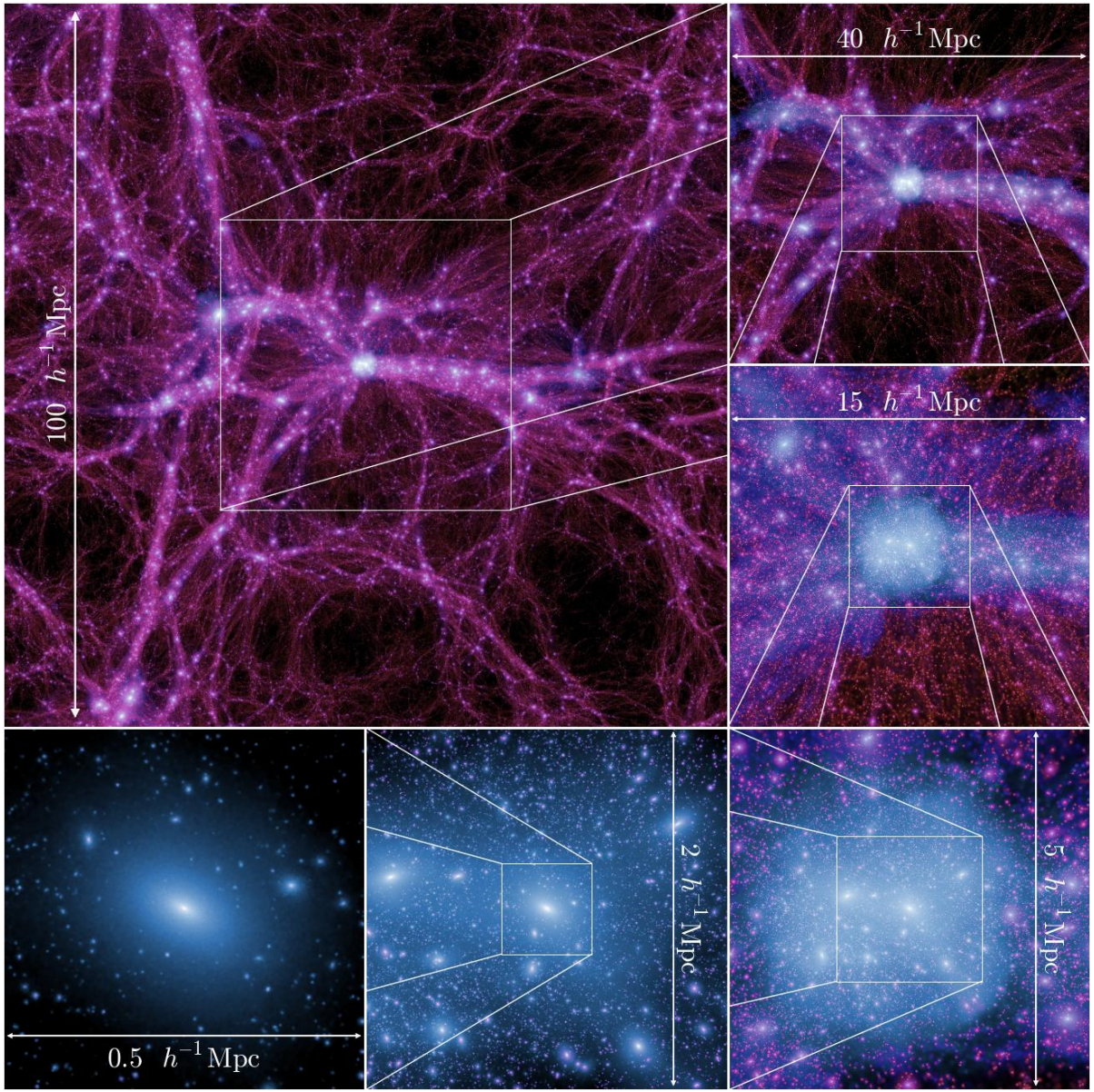


Cosmological parameters (WMAP7)

- $\Omega_m = 0.272$
- $\Omega_b = 0.045$
- $\Omega_\Lambda = 0.728$
- $h = 0.704$
- $n_s = 0.961$
- $\sigma_8 = 0.807$



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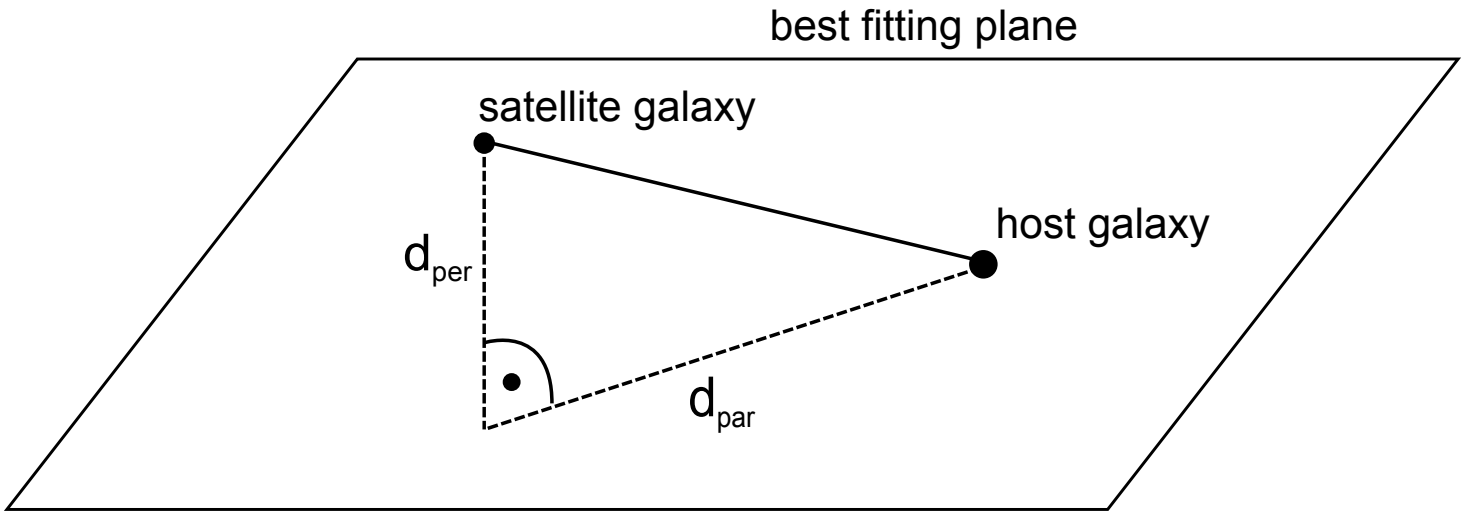
Two different ways to measure the distance of galaxies from a plane:



- The root mean square distance of the satellites to the best fitting plane

$$r_{per} = \sqrt{\frac{1}{15}\sum_{i=1}^{15} d_{per,i}^2}$$

- The root mean square distance to the host halo of the satellites projected in the best fitting plane

$$r_{par} = \sqrt{\frac{1}{15}\sum_{i=1}^{15} d_{par,i}^2}$$

Only the 15 satellites which minimize r_{per} are considered in the calculation of r_{per} and r_{par}.

- Best fitting plane is calculated by minimizing r_{per} (considering the 15 satellites closest to the plane)

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Selection criteria for host halos:

- Virial mass between $1.1 \cdot 10^{12} M_\odot$ and $1.7 \cdot 10^{12} M_\odot$
- Mass weighted age less than 10 Gyr
- Host halos which have a satellite galaxy with a baryonic mass higher than $7 \cdot 10^{10} M_\odot$ within 500 kpc are rejected.

$\rightarrow$ 1825 halos fulfil these requirements

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- The simulation predicts a too high number of satellite galaxies $\rightarrow$ missing satellite problem

$\Rightarrow$ The number of satellites has to be restricted to 27 satellites to avoid bias.
(more satellites $\Rightarrow$ thin planes consisting of 15 satellites are more likely)

Selection criteria for satellites:

- Three-dimensional distance cuts: Only satellites within a distance of 500 kpc and beyond a distance of 60 kpc to the host halo are considered.
- Approximation of the PAndAS area as a sphere with a radius of 250 kpc

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- Exclusion of all satellites within a projected distance of 32 kpc to respect effects of a luminous disk
- If less than 27 satellites remain, a new line of sight is chosen until enough satellites remain (max. 3 times).
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- Exclusion of small cluster of dwarf galaxies (3 or more galaxies within a sphere with a radius of 5 kpc)
- Finally: selection of the 27 satellites with the highest baryonic mass

$\Rightarrow$ Satellite samples comparable to the one considered by Ibata et al. (2013)

- Additional second data set in which all young satellites (age < 10 Gyr) are excluded to see how the formation time affects the final results.

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To learn about the formation and further evolution of thin planes all halos with an r_{per} value lower than 14 kpc and with 13 or more co-rotating satellites are selected.

- The scaled version of the Millennium II simulation does not stop at $z = 0$ but at $z \sim -0.29$.
- The 15 satellites belonging to the best fitting plane are traced back to $z \sim 0.5$ by querying their first progenitors. The further evolution is followed by pursuing their descendants to $z \sim -0.29$.
- r_{per} is calculated for each snapshot considering only the 15 first progenitors/descendants.
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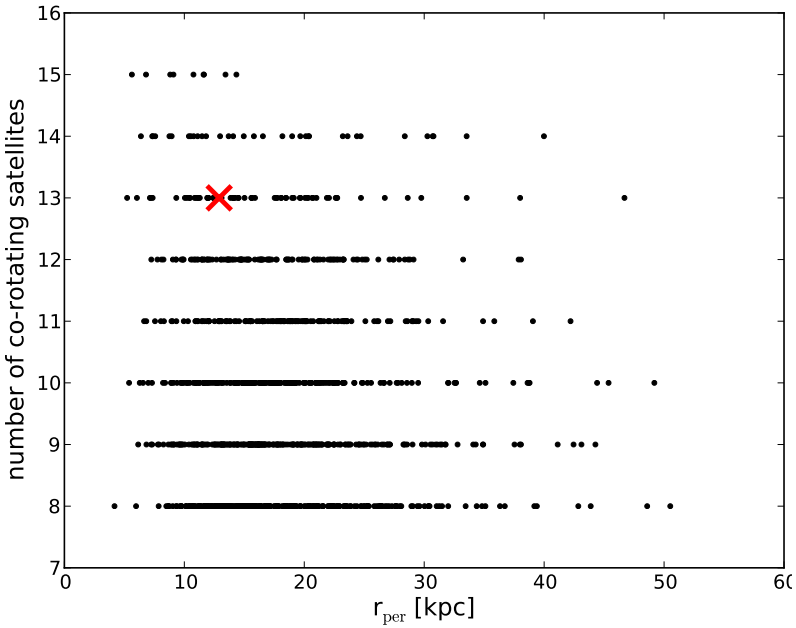
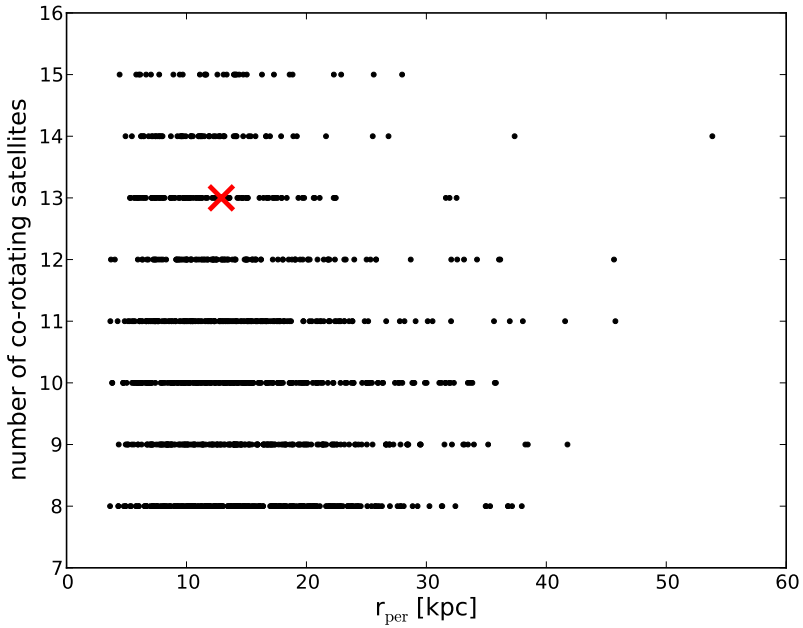
r_{per} plotted against the number of co-rotating satellites



without age cut (1120 halos)



with age cut (1187 halos)

Without age cut

- $r_{per} < 12.9$ kpc for 22% of all halos
- $r_{per} < 12.9$ kpc and ≥ 13 co-rotating satellites for 3% of all halos

With age cut

- $r_{per} < 12.9$ kpc for 45% of all halos
- $r_{per} < 12.9$ kpc and ≥ 13 co-rotating satellites for 7% of all halos

r_{per} is assumed to be equal 12.9 kpc for the Andromeda satellite system.

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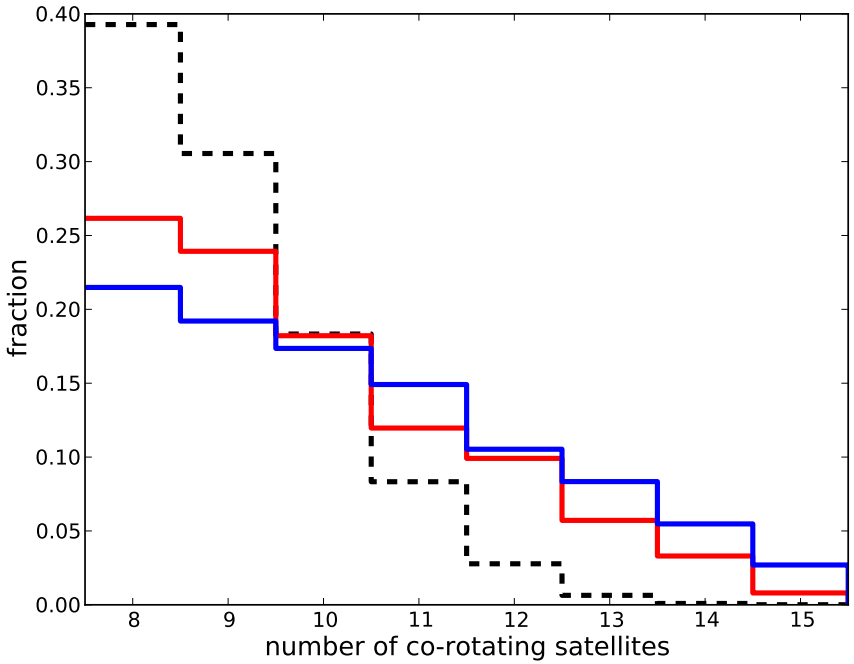
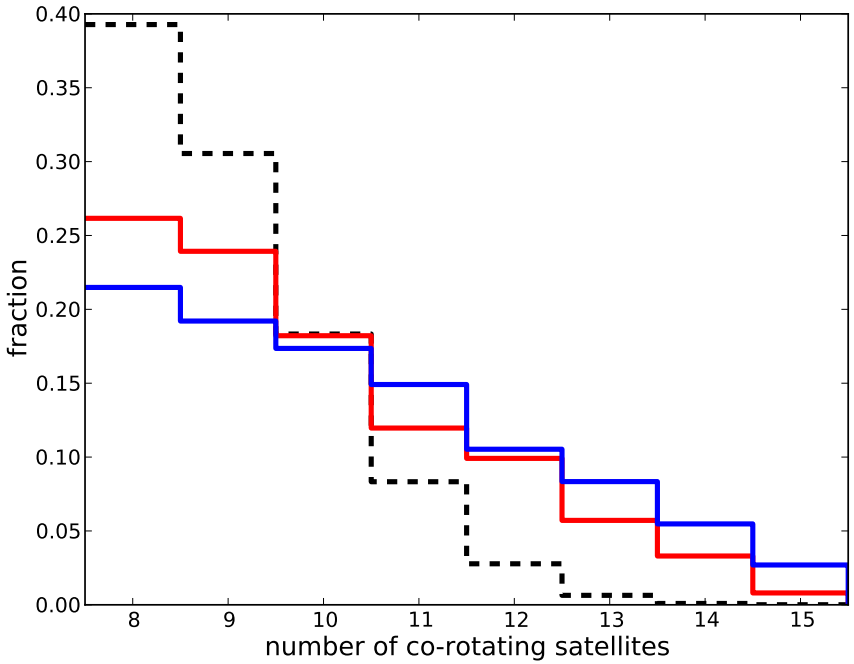


Millennium II halos without age cut
Millennium II halos with age cut

Sense of rotation is random

- The Millennium II halos have a higher number of co-rotating satellites on average as expected assuming a random sense of rotation.
- Old dwarfs co-rotate more often than young dwarfs.



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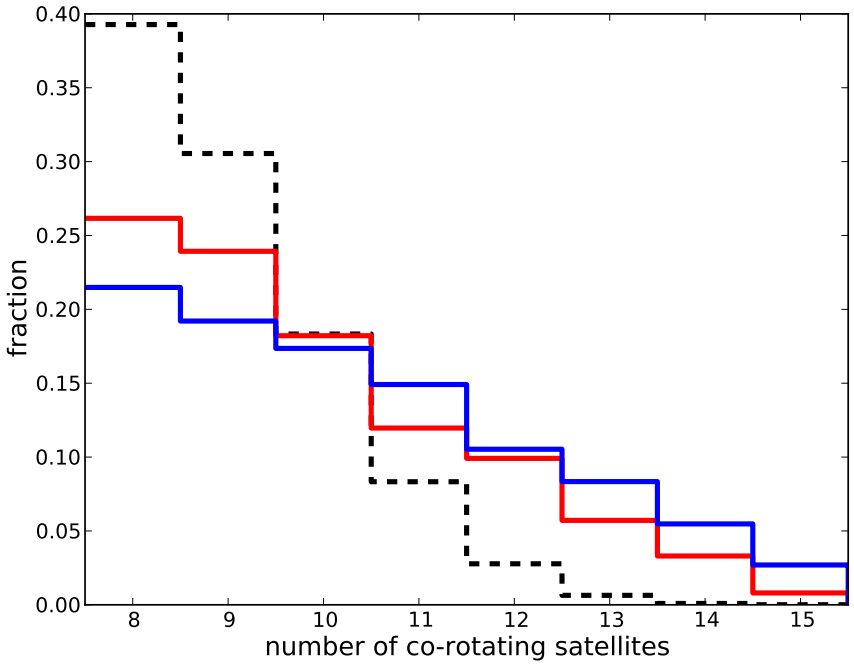

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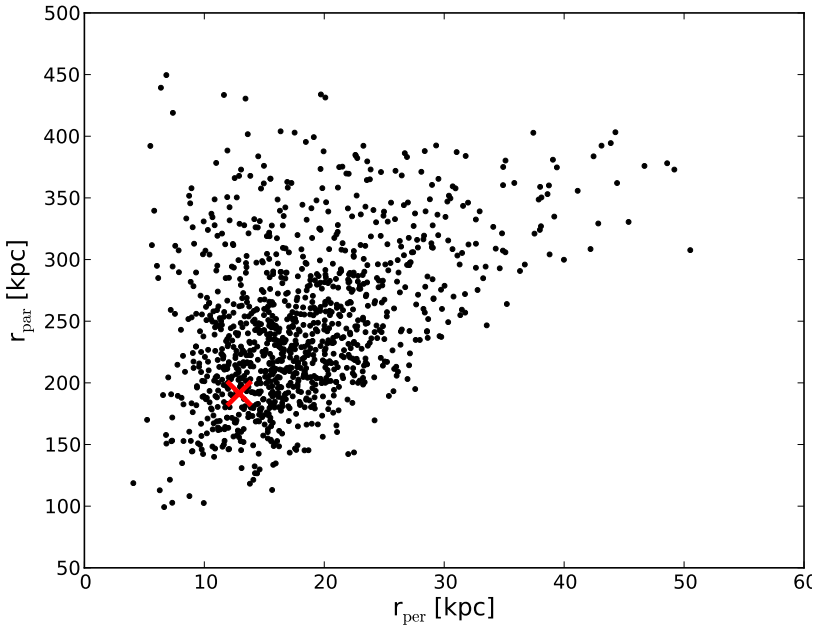
r_{per} plotted against r_{par}



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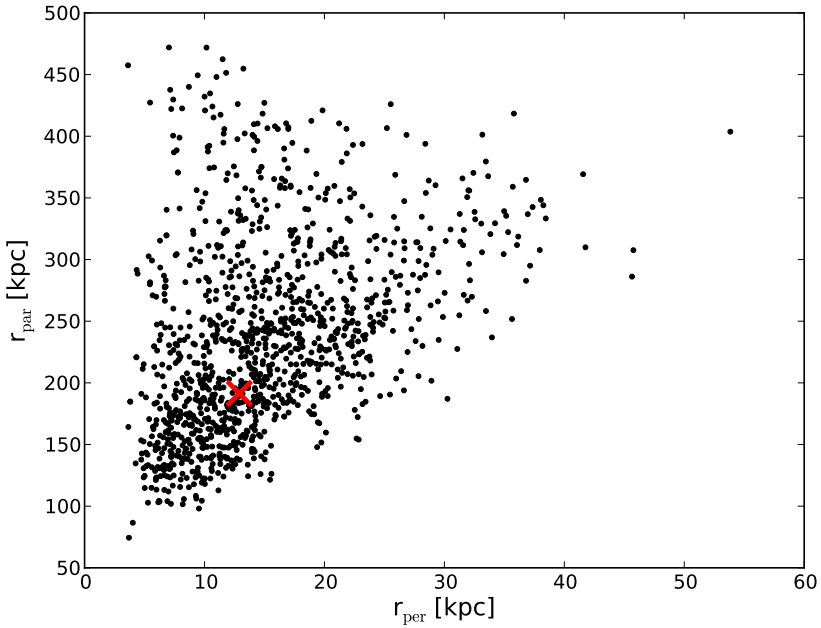

with age cut (1187 halos)

Without age cut

- $r_{per} < 12.9$ kpc and $r_{par} > 191.4$ kpc for 14% of all halos

With age cut

- $r_{per} < 12.9$ kpc and $r_{par} > 191.4$ kpc for 20% of all halos

r_{per} is assumed to be equal 12.9 kpc and r_{par} to be equal 191.4 kpc for the Andromeda satellite system.

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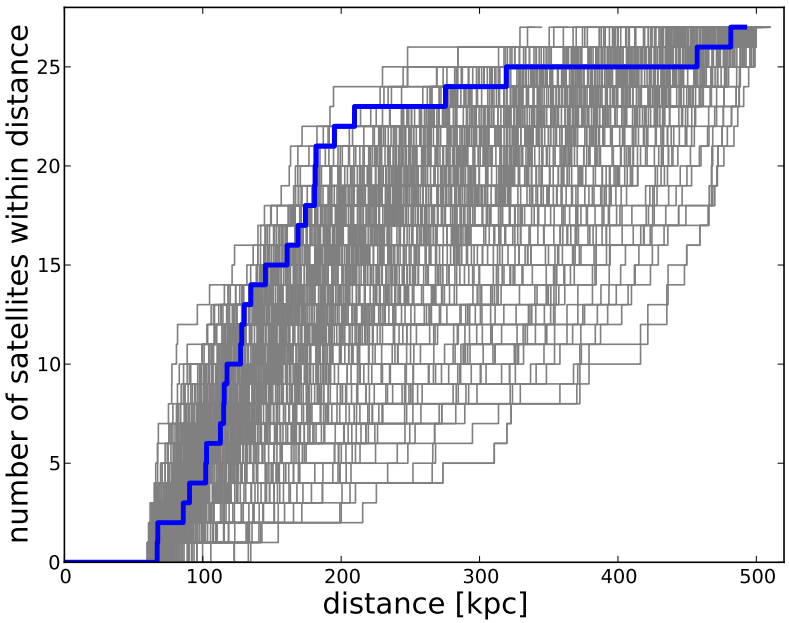
- All halos with an r_{per} value between 10.9 kpc and 14.9 kpc are selected.



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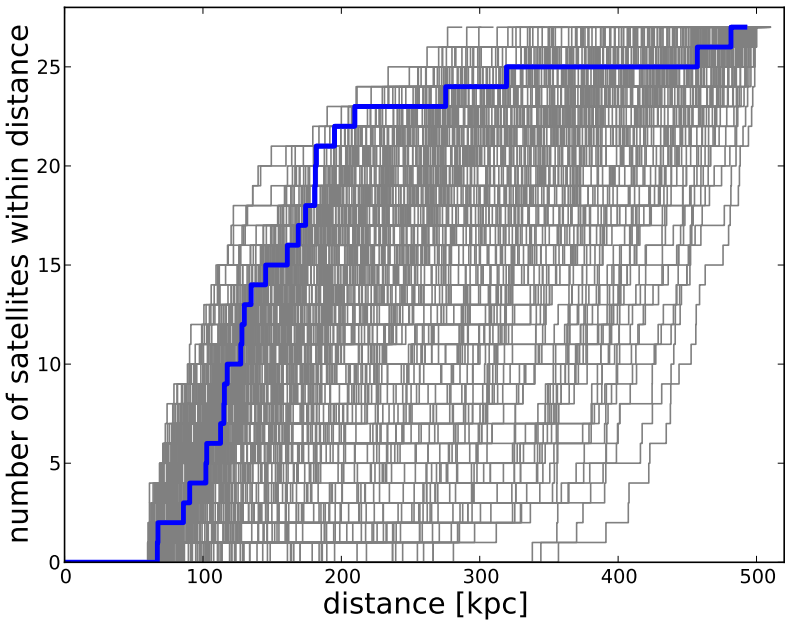

With age cut (1187 halos)

$\Rightarrow$ Radial distributions are in statistical agreement, Millennium II halos tend to be less radially concentrated.

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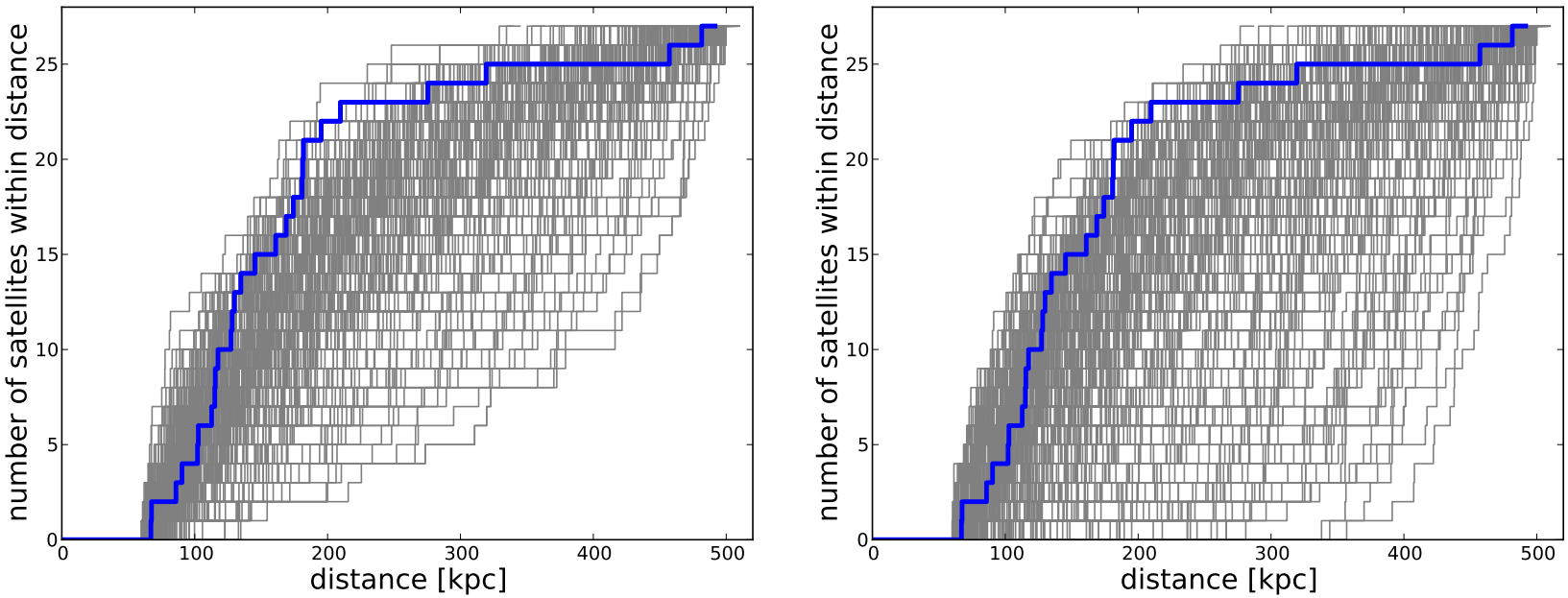

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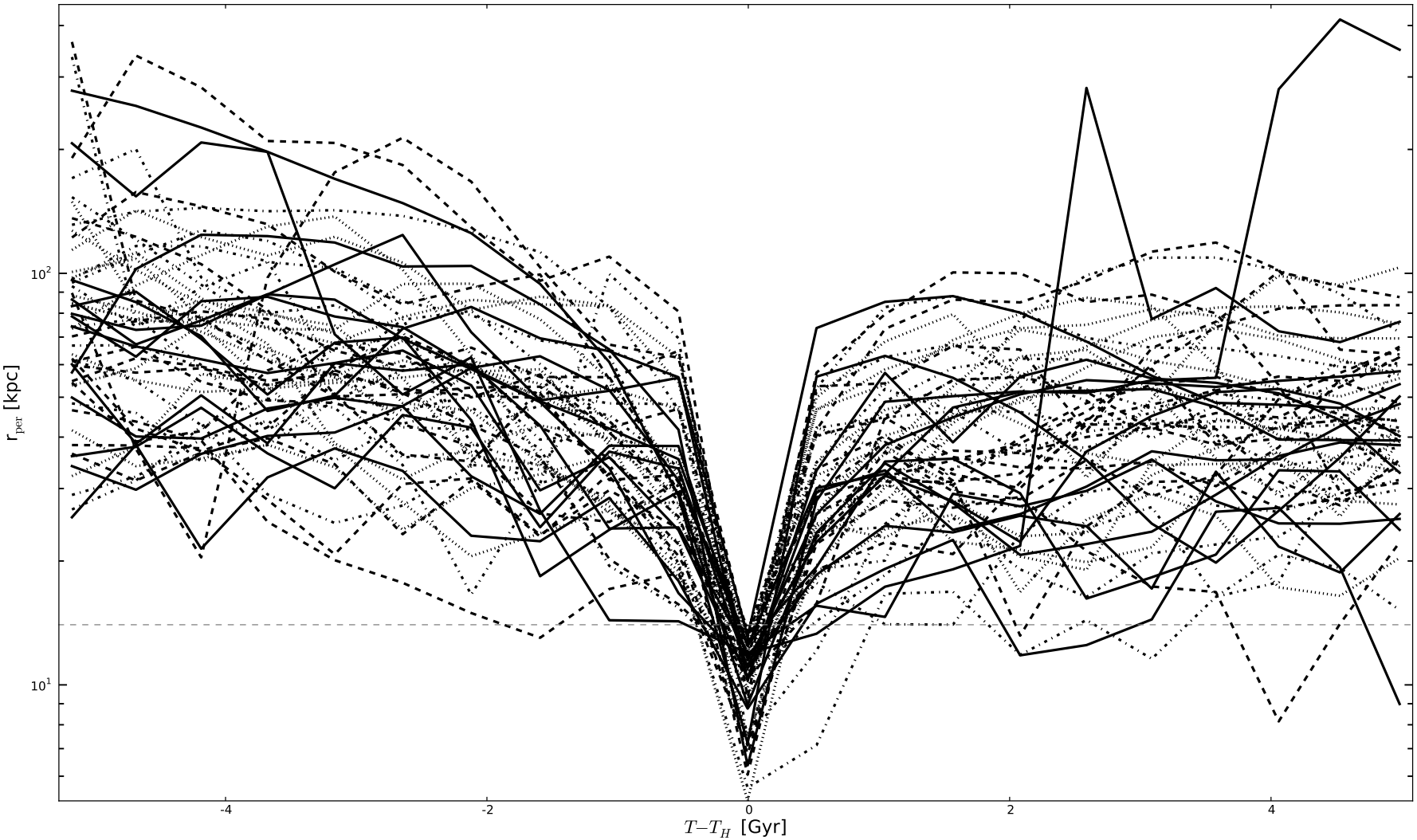
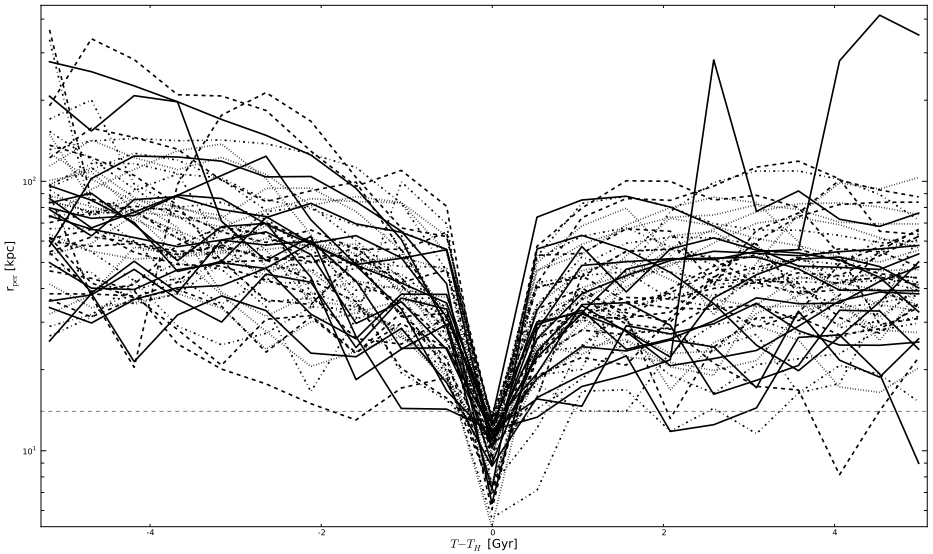
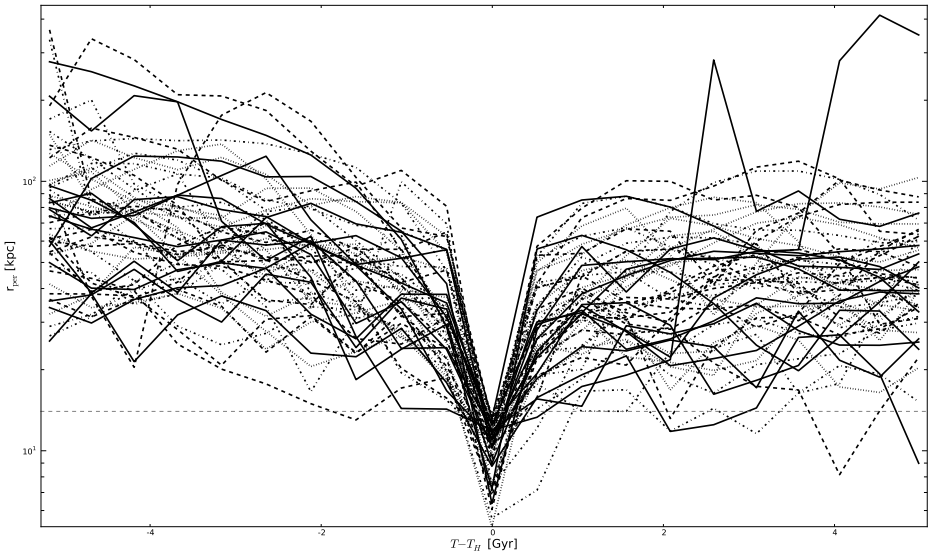
Formation history and further evolution: $T - T_H$ plotted against r_{per}





- r_{per} decreases slightly from $r_{per} \sim 80$ kpc to $r_{per} \sim 30$ kpc.
- r_{per} drops below 14 kpc and increases again within ± 0.5 Gyr.
- Afterwards the r_{per} values are roughly constant.
- Individual values fluctuate heavily.

$\Rightarrow$ The thin planes are most likely only a statistical fluctuation of an underlying more spherical galaxy distribution



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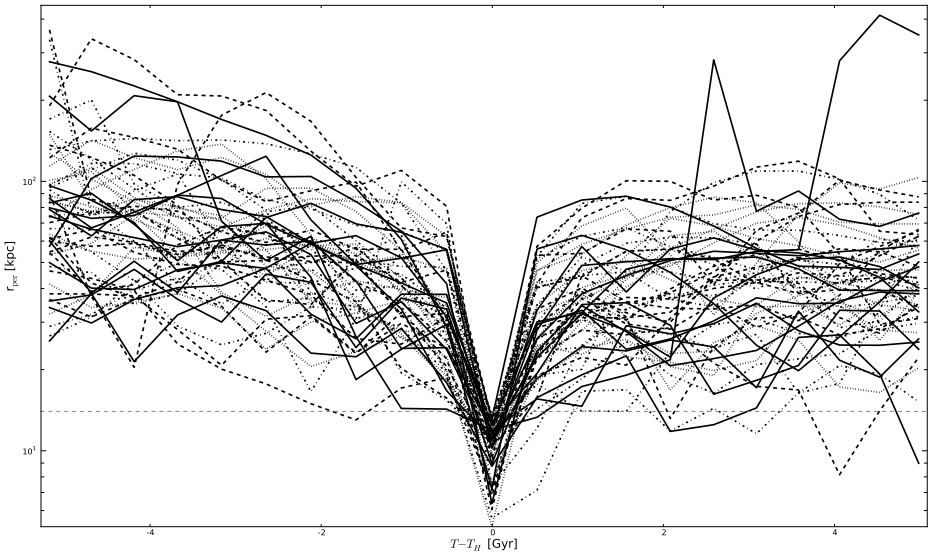

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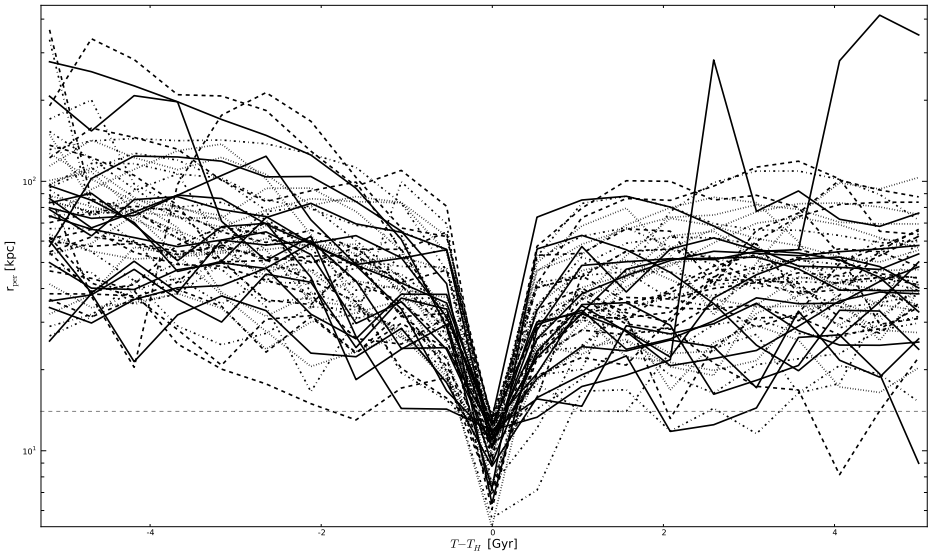

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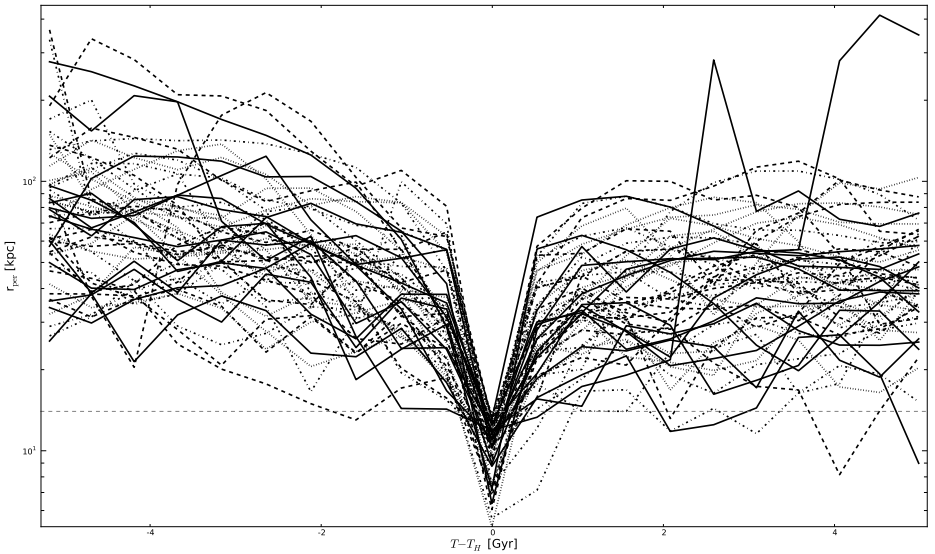

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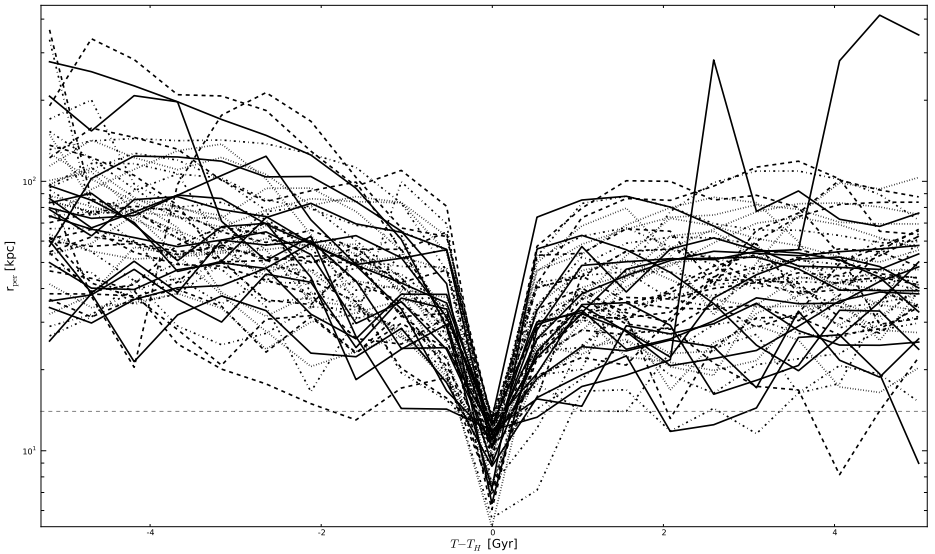

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- Thin planes of satellite galaxies are common in Millennium II halos ($\sim 22\%$).
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Main result

The vast thin plane of co-rotating dwarf galaxies (VTPD) is not in conflict with the standard cosmological paradigm.

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- Analysis strongly depends on the semi-analytical galaxy formation model.
- Low resolution:

  → 'Orphan' galaxies: galaxies without dark matter halo; only one dark matter particle is associated with the galaxy

  → None of the Millennium II halos is in agreement with the Andromeda satellite system, if 'orphan' galaxies are excluded.

- Selection criteria can be questioned.
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