The influence of halo evolution on galaxy structure

Simon White
Max Planck Institut für Astrophysik
The *WMAP* of the whole CMB sky
Dunkley et al 2010

![Graph showing C_l vs multipole moment l with different curves and labels such as WMAP 7yr, ACT 148 GHz, and uncertainty bars.]

<table>
<thead>
<tr>
<th>Primary</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>LCDM</td>
<td>$100\Omega_b h^2$</td>
<td>$2.214 \pm 0.050$</td>
</tr>
<tr>
<td></td>
<td>$\Omega_c h^2$</td>
<td>$0.1127 \pm 0.0054$</td>
</tr>
<tr>
<td></td>
<td>$\Omega_\Lambda$</td>
<td>$0.721 \pm 0.030$</td>
</tr>
<tr>
<td></td>
<td>$n_s$</td>
<td>$0.962 \pm 0.013$</td>
</tr>
<tr>
<td></td>
<td>$\tau$</td>
<td>$0.087 \pm 0.014$</td>
</tr>
<tr>
<td></td>
<td>$10^9 \Delta^2 R$</td>
<td>$2.47 \pm 0.11$</td>
</tr>
<tr>
<td>Derived</td>
<td>$\sigma_8$</td>
<td>$0.813 \pm 0.028$</td>
</tr>
<tr>
<td></td>
<td>$\Omega_m$</td>
<td>$0.279 \pm 0.030$</td>
</tr>
<tr>
<td></td>
<td>$H_0$</td>
<td>$69.7 \pm 2.5$</td>
</tr>
</tbody>
</table>

---

*a 20σ detection of DM!*
At an age of 400,000 years, the mass-energy content of the Universe was dominated by a nonrelativistic, nonuniform component which interacts purely gravitationally with the baryon-photon fluid.

This could not consist of neutrinos or any other known elementary particle.

The structure seen in the CMB agrees with that predicted by the concordance $\Lambda$CDM model down to scales corresponding to today's groups and clusters of galaxies.
Diffuse intergalactic gas at “high” redshift can be observed through its Ly α absorption in QSO spectra. Structure in the absorption is due to fluctuations in the density and gravitationally induced velocities.

Data - 3300 SDSS quasars

Model - ΛCDM
At redshifts between 4 and 2 the density and velocity perturbations in the diffuse pregalactic baryons are a close match to those expected for Dark-Matter-driven quasilinear growth from the structure seen at \(z=1000\).

This structure in the Ly-\(\alpha\) forest agrees with the predictions of the concordance model down to scales corresponding to the masses of small dwarf galaxies.
Mean halo profiles from gravitational lensing

\[ \log \frac{M^*}{M_\odot} = 10.5 \]

\[ \log \frac{M^*}{M_\odot} = 10.8 \]

\[ \log \frac{M^*}{M_\odot} = 11.0 \]

\[ \log \frac{M^*}{M_\odot} = 11.3 \]

\[ \log \frac{M^*}{M_\odot} = 11.6 \]

Mean mass profiles around galaxies of given stellar mass compared to CDM predictions

Mandelbaum et al 2006
The mean $z = 0$ mass profiles of galaxies of given stellar mass are a good match to the $\Lambda$CDM predictions for evolution from the linear initial conditions observed in the CMB at $z = 1000$ and in the Ly $\alpha$ forest at $z = 2.5$

This comparison has, in essence, no free parameters because the assignment of galaxies to model halos can be made by matching the observed abundance of galaxies, without reference to the lensing results.

Overall, dark matter is thus the dominant component of galaxies, and is comparable in mass to the stars in the inner visible regions.

DM is likely to be a significant repository of energy and angular momentum during secular evolution, which may also be forced by evolution and non-steady behaviour of the DM halo.
The fine-scale structure of a dark matter halo
For halos with virial mass $M_{200} \sim 4 \times 10^{12} M_\odot$ the typical offset between potential minimum and barycentre is $0.03 \, r_{200} \sim 10$ kpc.

10% are offset by $0.09 \, r_{200} \sim 30$ kpc

More massive halos are proportionately more asymmetric.
Velocity offset of “centre” from barycentre

For halos with virial mass $M_{200} \sim 4 \times 10^{12} \, M_\odot$ the typical velocity offset between potential minimum and barycentre is $\sim 15$ km/s.

0% are offset by $0.25 \, V_{200} \sim 60$ km/s.

More massive halos are proportionately more asymmetric.
10% velocity offsets are 60 km/s w.r.t. mass within 300 kpc
40 km/s w.r.t. mass within 150 kpc
23 km/s w.r.t. mass within 75 kpc

The inner regions tend to move together
The cores of dark halos where galaxies reside are relatively symmetrically located and move quite slowly with respect to the bulk of the halo mass in the majority of objects.

Asymmetries tend to be concentrated in the outer regions. Oscillations forced purely by the DM halo are of modest amplitude in most objects and so do not seem likely, of themselves, to explain lop-sidedness statistics or warps.
The inner halo (defined as the most bound $10^{11} \, M_\odot$) has accreted at least 10% of its final mass since $z=3$ in 80% of all halos.

Since $z=0.5$, only 12% of inner halos have gained this much mass.

About half of all halos have gained a third of their inner mass since $z=3$, but only 4% since $z=0.5$. 
In the great majority of galaxy halos, most of the DM mass in the inner regions has been in place since high redshift.

Mergers which substantially affect the mass in the regions where galaxies lie are quite uncommon and affect a small fraction of present-day objects.
Although the mass fraction in subhalos is \(~10\%\) for galaxy halos as a whole, at \(r=10\ \text{kpc}\) subhalos account for only \(~10^{-3}\) of the local dark matter density.

DM subhalos have only a weak effect on the stellar dynamics of galaxies.
Stellar disks evolving in \( \Lambda \) CDM halos

DeBuehr, Ma & White 2012

Equilibrium exponential disks are inserted adiabatically into 4 Aquarius halos (with \( J \) parallel to inner major or minor axis) and allowed to evolve from \( z=1 \) to \( z=0 \)

Radial surface density profiles remain fairly stable...
..but the disks all form bars which are strong enough in 6 cases for buckling to produce an X-shape bulge

Notice the substantial out-of-plane material in many of the cases
The bar instability can be removed by replacing 40% of the stars by non-radiative gas or by reducing the disk mass.

The stellar disks satisfy the ELN82 criterion for stability quite well:

$$\frac{V_{\text{max}}}{(G M_d / R_d)^{0.5}} > 1.1$$
Stellar disks evolving in $\Lambda$CDM halos

DeBuehr, Ma & White 2012

In almost all cases the inner disk ($r < 5$ kpc) changes orientation by large angles between $z=0$ and $z=1$.

During these shifts it remains aligned with the principal axes of the inner dark halo.
Stellar disks evolving in ΛCDM halos

The outer disks do not follow these shifts but are “left behind” leading to strong “fossil” warps.

Note that these are not formed by late infall or by satellite perturbation.

DeBuhr, Ma & White 2012
Simulate disk formation in Aquarius halos starting at $z=1.3$ with a smooth, spherical, equilibrium gas distribution with $\rho \propto 1/r$ rotating at constant $V$.

Vary cooling law and orientation of $J$ vector.

Here, the reference model, with $J$ parallel to $J_{DM}$ (close to the minor axis).
Disks forming in ΛCDM halos from cooling gas

The orientation of $\mathbf{J}$ for the baryons (stars+gas) changes with time in a way which depends on its initial orientation.

The change is small when the initial $\mathbf{J}$ is aligned with $\mathbf{J}_{DM}$ (in this particular halo).

The change depends on the sign of the initial $\mathbf{J}$. 

Aumer & White 2012
A variety of final orientations are possible

Most are close to that found for a realistic cosmological gas treatment

Final orientation does not depend *only* on initial orientation
Disks forming in $\Lambda$CDM halos from cooling gas

Different halos behave differently

Here most end up close to the cosmological case
Live $Λ$CDM halos affect visible galaxies through

(i) providing a sink for energy and angular momentum, thus affecting disk and bar evolution

(ii) bombardment by substructures (relatively weak - only 0.1% of inner halo mass is in substructure)

(iii) addition of mass through infall/merging (also weak – most of the mass added at late times stays at large radius)

(iv) variation of shape and orientation of the potential, leading to substantial orientation changes in the disk and causing “fossil warps” and disk heating