The LCDM paradigm: successes and challenges on scales of galaxies

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• DM profiles, concentrations, ...
• Clustering of galaxies: $P(k)$ and correlation functions
• Satellites: abundance, number-density profiles
• Galaxies and Dark Matter: abundances
Scales of galaxies

Dwarfs. Not all halos may be bright

10 km/s

5×10⁹ M☉

10⁸ M☉

Normal galaxies. Normal Halos: all are bright

50 km/s

2×10¹⁰ M☉

170 km/s

10¹² M☉
Lots of statistics can be now predicted with very high accuracy
Halo Mass function

Full: Sheth&Tormen
Symbols: N-body Bolshoi, Spherical overdensity

Correction factor for Sheth&Tormen:

\[ F(\delta) = \frac{(5.501\delta)^4}{1 + (5.500\delta)^4} \]

Bolshoi: Klypin et al 2010
Tinker 2008: z=0-2.5
Accurate predictions for Velocity function of distinct halos
**Abundance of satellites**

Aquarius simulation. Springel et al 2008. WMAP-1

\[ n(> V) = AV^{-3} \]

Fig. 18.— Comparison of satellite velocity functions in Via Lactea II and Bolshoi simulations for halos with \( V_{\text{circ}} = 200 \) kms/s and \( M_{\text{vir}} \approx 1.3 \times 10^{12} h^{-1} M_\odot \). The dashed line is a power law with the slope \(-3\), which provides excellent fit to Bolshoi and ViaLactea II. Klypin et al 2010. WMAP-7
Concentrations of Clusters of galaxies

Prada et al 2011
Median Concentrations

Maccio et al 2008

Probing 100kpc scales
The Observed Power Spectrum

(Tegmark et al.)
Baryonic acoustic oscillations: Power spectrum

Figure 2. BAOs in power spectra calculated from (a) the combined SDSS and 2dFGRS main galaxies, (b) the SDSS DR5 LRG sample, and (c) the combination of these two samples (solid symbols with 1σ errors). The data are correlated and the errors are calculated from the diagonal terms in the covariance matrix. A standard ΛCDM distance–redshift relation was assumed to calculate the power spectra with $\Omega_m = 0.25$, $\Omega_\Lambda = 0.75$. The power spec-
Correlation function on large scales: baryonic oscillations

SDSS (Eisenstein et al.)
THE CLUSTERING OF MASSIVE GALAXIES AT $z \sim 0.5$ FROM THE FIRST SEMESTER OF BOSS DATA

M. White et al 2010
Redshift-space correlation function. Full = theory

Real space correlation function. Dot-dash = theory
Matching Galaxies with Dark Matter Halos

10-50 kpc scales:

Trujillo-Gomez et al 2010
Abundance matching: correlation function of galaxies
The probability distribution for the abundance of Magellanic Clouds-like satellites around Milky Way-mass hosts in simulations (colored diamonds).

Observations - LCDM: just enough Magellanic Clouds

Observations

LCDM
Vmax > 50 km/s

Busha et al 2010
Dark matter profiles: standard LCDM

Aquarius simulation. Springel et al 2008. WMAP-1

Central slope is very close to -1
For normal galaxies it does not matter: baryons dominate

Stadel et al 2009
Adiabatic compression

Red line NFW - compare with black squares. Duffy et al 2010

Adiabatic compression is always present. Do not forget to use it.

compare red lines. Gnedin et al 2004

Early explanation for the discrepancy was photoionization.

Tidal stripping: luminous satellites were much larger in the past. The small halos were photo evaporated.

Kravtsov, Gnedin, Klypin 2004
SDSS: new satellites

Classic satellites: about 10

SDSS: about 12 new satellites
only 20% of the sky
Correcting for sky coverage: 60
Correcting for distance incompleteness: 300 - 600

Koposov et al 2009
Tollerud et al 2008

Newly discovered satellites are very small stellar rms velocities 5-10 km/s
How to suppress formation of a galaxy

• Star-formation/Supernovae. Dekel & Silk (1985)
• Photoionization/heating (Bullock et al. 2000)

How to kill of a galaxy

\[ V_{\text{crit}} = 30-40 \text{ km/s} \]

Is there a limit on mass of galaxy?
The model is constrained to match a wide range of properties of the present day galaxy population as a whole, but at high redshift it requires an escape fraction of UV photons near unity in order completely to reionize the universe by redshift $z > 8$. In the most successful model the local sources photoionize the pre-galactic region completely by $z \approx 10$.

In addition to the luminosity function of Milky Way satellites, the model matches their observed luminosity-metallicity relation, their radial distribution and the inferred values of the mass within 300 pc.
Very small scales: cusps and cores

Cusps and rotation curves: too much of DM in central parts of galaxies?

McGaugh et al 2002
Simon et al. 04

NGC 4605  $V_{\text{max}} = 100 \text{km/s}$

-- Usual problems with NFW.

-- Disk is important: normal $M/L_R = 1$  $M/L_K = 0.5$

1 arcmin

Simon et al.
Example:
UGC8508
Distance 2.5 Mpc
$M_B = -12.9$

Russian 6m telescope
HI data

GMRT: India
Velocity of rotation:
Observed: 25-30 km/s
Theory: 40-50 km/s

Theory predicts too large circular velocity
fully consistent with ΛCDM expectations and do not require cored dark matter distributions.
Too big to fail? The puzzling darkness of massive Milky Way subhalos

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Figure 1. Constraints on the $V_{\text{max}} - R_{\text{max}}$ values (assuming NFW profiles) of the hosts of the nine bright ($L_V > 10^5 L_\odot$) MW dwarf spheroidal galaxies. The colored bands show 1σ confidence.

Figure 2. Subhalos from all six Aquarius simulations (circles) and Via Lactea II (triangles), color-coded according to $V_{\text{infall}}$. The shaded blue region shows the 95.4% confidence interval for brightness.

We show that dissipationless $\Lambda$CDM simulations predict that the majority of the most massive subhalos of the Milky Way are too dense to host any of its bright satellites ($L_V > 10^5 L_\odot$). These dark subhalos have circular velocities at infall of
Number of galaxies with $V_{\text{circ}}$: observations vs LCDM

Overabundance of dwarf galaxies with $V_{\text{circ}} = 50 \text{ km/s}$

This is a different and much worse problem as compared with the ‘satellites’ overabundance.
Conclusions

• Very accurate estimates for numerous statistics
• Tests down to 10 kpc: LCDM is doing fine
• Not clear what happens on smaller scales