Cosmic structure formation

Simon White
Max Planck Institut für Astrophysik
A Digital Sky Survey of the Northern Galactic Cap

The Grey Book
(SDSS proposal to the NSF, 1993)
Has structure grown through gravitational instability?
What are the properties/origin of the primordial fluctuations?
What is the dark matter?
What are the values of $\Omega$ and $\Lambda$?
How did galaxies form?
What physics, other than gravity, played a role?
What determines galaxy luminosity, size, color, morphology?
What is the relation between the galaxy and mass distributions?

“Because galaxies are the markers by which we trace large scale structure, we cannot address the first category of questions without simultaneously addressing the second, especially the final question about galaxies and mass.”
Grey Book Methods to achieve Science Goals

Survey Design

- Large-sky area, covering full north Galactic cap
  localised window function for P(k) measurements
- Full sampling of area both for photometry and spectroscopy
  sensitivity to morphology of large scale structure
- 5-band photometry to enable photo-z's
  increase volume and depth surveyed

Statistical tools

- Power spectra, correlation functions, redshift space distortions
- High order correlations, counts, void studies, morphology/topology
- Large scale flows
- Cluster abundance and evolution, cluster morphology
- QSO metal line clustering

MISSING!  Ly α forest, gravitational lensing
In 1993 there were no measures of CMB doppler peaks of an accelerated expansion of LBG's/Madau plots

Nevertheless, the $\Lambda$CDM model was already the de facto standard because of LSS studies

(There were also no exoplanets, star streams, Dark Energy or concordance cosmology!)
The observational case for a low-density Universe with a non-zero cosmological constant

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Observations are providing progressively tighter constraints on cosmological models advanced to explain the formation of large-scale structure in the Universe. These include recent determinations of the Hubble constant (which quantifies the present expansion rate of the Universe) and measurements of the anisotropy of the cosmic microwave background. Although the limits imposed by these diverse observations have occasionally led to suggestions that cosmology is facing a crisis, we show here that there remains a wide range of cosmological models in good concordance with these constraints. The combined observations point to models in which the matter density of the Universe falls well below the critical energy density required to halt its expansion. But they also permit a substantial contribution to the energy density from the vacuum itself (a positive ‘cosmological constant’), sufficient to recover the critical density favoured by the simplest inflationary models. The observations do not yet rule out the possibility that we live in an ever-expanding ‘open’ Universe, but a Universe having the critical energy density and a large cosmological constant appears to be favoured.
Riess et al 1998

The expansion is accelerating

COBE/DMR
Boomerang98

Netterfield et al 2002

The Universe is flat

The expansion is accelerating
The ESSENCE Survey
Wood-Vasey et al 2007

The ESSENCE Survey

- flat matter-dominated universe
- flat dark energy-dominated universe
### WMAP5

![Graph showing multipole moment vs. $l$ with data points and a red line fit.]

#### Parameter Values

<table>
<thead>
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<th>+ BAO + SNe</th>
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QuaD polarization power spectrum

\[ \chi^2_{\text{LCDM}} = 20.1 / 23, \text{ PTE 0.63} \]
\[ \chi^2_{\text{smooth}} = 50.7 / 23, \text{ PTE 0.001} \]

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Grey Book Simulations

Park & Gott 1993
PM with $N = 5.5 \times 10^7$, $\epsilon = 1 \text{ Mpc}$,
$\Omega_m = 0.4$, $\Omega_\Lambda = 0.6$, $\sigma_8 = 0.76$

Galaxy luminosities, positions and velocities from a statistical bias recipe

Figure 11.1: Slices from a simulation of the SDSS redshift survey. The upper panel (repeated from Figure 2.1.3) shows a 6 degree by 130 degree slice in redshift space – each point represents a galaxy, plotted at the distance indicated by its redshift. The lower panel shows the same slice in real space, with no peculiar velocity effects.
Galaxy luminosities, positions and velocities from simulating galaxy formation within the model
SDSS estimates “classical” clustering measures with extraordinary precision: e. g. LRG correlations....
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\[ M_*> 10^{11}M_\odot \]

\[ g - r > 0.8 \]

...so they constrain galaxy and structure formation strongly on both linear and nonlinear scales.
The Tegmark representation of power spectrum data (2006)
SDSS enables a good measurement of the topology of LSS

Gott et al 2008

DR4+
6 Mpc/h smoothing

Genus curve agrees well in amplitude and shape with $\Lambda$CDM predictions, but it shows a shift to negative $\nu$ whereas the simulations show a slight shift towards positive $\nu$. 
Galaxy-galaxy lensing around isolated LRGs gives the mean surface density profile of their halos: \( \Delta \Sigma = \overline{\Sigma}(r_p) - \Sigma(r_p) \)

Mandelbaum et al 2008
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Profile is a good match to $\Lambda$CDM expectation -- strong features are expected at larger radii which scale with halo mass.
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Mean $\Lambda$CDM density profiles break sharply at the 1-halo 2-halo transition -- a clear indicator of dark matter over MOND?
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Maybe – or maybe not!
...at least, a direct, high S/N measure of $M/L$ as a function of $M_{\text{halo}}$...

![Graph showing the relationship between $\Delta M_{200}$ and $N_{200}$ with error bars and a fit line.](Sheldon et al 2008)
...at least, a direct, high S/N measure of M/L as a function of $M_{\text{halo}}$ ...

\[ \Delta M_{200} \left[ h^{-1} M_\odot \right] \]

\[
\begin{array}{c}
\Delta M / \Delta L_{200} \left[ h^{-1} M_\odot / L_\odot \right] \\
N_{200}
\end{array}
\]

\[
\begin{array}{c}
\log < M / L_{185} > \\
\log [M] \left( h^{-1} M_\odot \right)
\end{array}
\]

\[ \text{Sheldon et al 2008} \]

\[ \text{Weinmann et al 2007} \]

...which agrees well with that in $\Lambda$CDM simulations of galaxy formation
(Near) future tests of the structure formation model

- Tests of gaussianity
  --- morphology, high-order correlations, cluster mass function

- Tests of gravity
  --- halo shapes and density profiles (vs MOND, or coupled models)

- Tests of the nature of dark energy
  --- BAO's, cluster abundance evolution

- Tests of the nature of dark matter
  --- Ly α forest, small-scale structure
“Milky Way” halo

$z = 1.5$

$N_{200} = 3 \times 10^6$
"Milky Way" halo

$z = 1.5$

$N_{200} = 94 \times 10^6$
“Milky Way” halo

$z = 1.5$

$N_{200} = 750 \times 10^6$
How well do density profiles converge?

Aquarius Project: Springel et al 2008

\[ z = 0 \]
How well do density profiles converge?

Aquarius Project: Springel et al 2008
How well does substructure converge?

Aquarius Project: Springel et al 2008
All mass subhalos are similarly distributed.

A small fraction of the inner mass in subhalos.

<<1% of the mass near the Sun is in subhalos.

Aquarius Project: Springel et al 2008
Conclusions from high resolution $\Lambda$CDM simulations

- The predicted DM fraction in lumps with $M > 10^{-6} M_\odot$ is:
  - $\sim 0.01$ within $r = 100$ kpc
  - $\sim 0.001$ within $r = 8$ kpc

- Small DM lumps should have negligible effect on the structure and orbits of inner halo objects.

- The (smooth) DM near the Sun should be distributed in $> 10^5$ cold streams – indistinguishable from a smooth distribution.

- DM caustics are very weak in the inner halo and have no discernible dynamical effects on observed tracers.

- Caustics and small clumps (say $< 10^5 M_\odot$) make no significant contribution to the DM annihilation flux from the inner halo ($r < 100$ kpc) of our Galaxy. The most easily detectable signal will probably be that of the main diffuse halo.
Milky Way halo seen in DM annihilation radiation

Aquarius simulation: $N_{200} = 1.1 \times 10^9$