Cold Dark Matter models of structure formation:
remarkable success or spectacular failure?

Andrey Kravtsov
Department of Astronomy & Astrophysics
Center for Cosmological Physics, University of Chicago

http://astro.uchicago.edu/~andrey
Galaxies in CDM models form in massive extended DM halos
Cold Dark Matter models are roughly two decades old but a lot of progress very recently...

Accurate and detailed predictions allow thorough model testing.

This highlighted several remarkable successes and potentially fatal problems of the CDM models...

I will focus on:

- Predictions on clustering and velocity field of galactic halos
- Mass function of halos
- Predictions on the abundance, spatial distribution, and orbital parameters of substructure in dark matter halos (i.e., halos within halos)
- Density and angular momentum structure of DM halos
- Some of the problems that CDM faces and several proposed modifications to the model
2-point correlation function of dark matter halos and bias

High - redshift galaxies are strongly biased

Adelberger et al. 1998; Giavalisco et al. 1998; Steidel et al. 1999; Adelberger 2000; Giavalisco & Dickinson 2001; Porciani & Giavalisco 2001

Bullock et al. 2002
Governato et al. 1998
2-point correlation function: LCDM vs. observations

Colin, Klypin, Kravtsov 1999

Kravtsov & Klypin 1999
2-point correlation function: excellent agreement between different methods.

- **N-body + SAM modelling**
  Benson et al. 2000

- **Gas clumps in gasdynamics simulations**
  Pearce et al. 2000
Mass dependence of halo bias

Brainerd & Villumsen 92-94; Bagla 1998; Jing 1999; Sheth & Tormen 1999

Sheth & Tormen 1999

Hu & Kravtsov 2002
Luminosity dependence of galaxy clustering
Norberg et al (2dF team) 2001, 2002; Zehavi et al. (SDSS team) 2002

Norberg et al. 2001
The origin of small-scale antibias

Kravtsov & Klypin 1999
The origin of small-scale antibias

Kravtsov & Klypin 1999
Peculiar velocities of dark matter halos

Colin, Klypin & Kravtsov 2000
Do halos trace the peculiar velocity field of matter?
3D velocity dispersion profiles of CDM clusters

Colin, Klypin & Kravtsov 2000
Galaxy clustering and bias: summary

- Correlation function of matter is not a power-law on small scales and does not match galaxy clustering at $r < 5$ Mpc.

- Halo/galaxy bias is linear (scale-independent) on large scales and is scale-dependent on small ($r < 5$ Mpc) scales. There are non-linear bias models that match simulation results extremely well.

- Predicted correlation function of galaxies is power-law over three decades in scale and matches the observed correlation function.

- Bias is a strong function of time. High-z objects are expected to be very strongly biased.

- Bias is a function of halo mass, current models reproduce luminosity and color dependence of galaxy clustering.

- Pairwise velocity dispersion of galactic halos is significantly lower than that of DM at $z=0$, and matches the observed velocity dispersion of galaxies.
Halo mass function
Sheth & Tormen 1999; Jenkins et al. 2001
Evrard et al. 2001; Hu & Kravtsov 2002; Zheng et al. 2002; White 2002

\[ \nu f(\nu) \equiv m^2 n(m, z) \frac{d\log m}{d\log v} \]

\[ \nu f(\nu) = A \left( 1 + \frac{1}{\nu^2} \right)^{1/2} e^{-\nu^2/2} \]

Sheth & Tormen 1999:

\[ f(\ln \sigma^{-1}) = \frac{M}{\bar{\rho}_m(z)} \frac{dn(< M, z)}{d \ln \sigma^{-1}} \]

\[ f(\ln \sigma^{-1}) = A \exp(-|\ln \sigma^{-1} + B|^e) \]

Jenkins et al. 2001:
Halo mass function

Can be expressed in universal form which works for different cosmologies and redshifts if (and only if) the halo mass is defined as the mass within a radius of a fixed overdensity with respect to the mean density of the universe.

Commonly used overdensity is 180 or 200. See White (2002) for comparisons of mass functions for different mass definitions.

Other mass definitions can always be easily converted to the above definition because we know the density structure of dark matter halos (see Hu & Kravtsov 2002 for useful mass conversion fitting formulae).
Substructure in CDM halos

Discussion topics

☐ Are there too many/few subhalos predicted by CDM models?

☐ Is spatial distribution of subhalos in galactic halos too extended?

☐ how about cluster halos (e.g., Virgo, Fornax)?

☐ can discrepancies be explained by ordinary physical processes (e.g., suppression of starformation in the presence of UV background)?

☐ can high-velocity clouds (HVCs) be the CDM substructure?

☐ how substructure can be used to put constraints on CDM, WDM, SIDM, etc. models?
Mass function of subhalos

Klypin et al. 1999; Moore et al. 1999; Ghigna et al. 2000

Ghigna et al. 2000
Velocity function of subhalos: overprediction of galactic satellite abundance

Klypin et al. 1999

Moore et al. 1999
VF of subhalos collapsed at $z > z_{\text{re}}$

Cumulative velocity function

Halo maximum circular velocity
Radial distribution (number density profile) of subhalos

Colin, Klypin, Kravtsov 1999

Ghigna et al. 2000
## Median galactocentric distance for satellites

<table>
<thead>
<tr>
<th>V\text{circ} &gt; 20\text{km/s}</th>
<th>V\text{circ} &gt; 15\text{km/s}</th>
<th>V\text{circ} &gt; 10\text{km/s}</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>MW/M31</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>R &lt; 200/h kpc</td>
<td>43 ± 20/h kpc</td>
<td>57 ± 16/h kpc</td>
</tr>
</tbody>
</table>

| **LCDM**                     |                              |                              |
| 118/h kpc for R < 200        | 178/h kpc for R < 500/h kpc  |

| **Reionization**             |                              |                              |
| 102/h kpc for R < 200        | 143/h kpc for R < 500/h kpc  |

| **WDM**                      |                              |                              |
| 139/h kpc for R < 200        | 217/h kpc for R < 500/h kpc  |

**Conclusion:** if this is a serious discrepancy (currently, we have only one system, out Local Group to work with) SIDM, WDM, and other modifications to CDM will not help (they will probably make this particular discrepancy worse).

Reionization model *may work*
Halo mass function: summary

- Halo mass function is currently calibrated with accuracy < 10% in amplitude for CDM cosmologies.

- The mass function can be expressed in a universal (cosmology and redshift independent form) if mass is defined in a specific way.

- Mass function of subclumps is similar in shape to that of isolated halos, but is different in normalization.

- The predicted abundance of subclumps in galactic halos greatly exceeds the observed abundance of satellites around galaxies.
Density profiles of DM halos

Dubinski 1991;
Navarro, Frenk & White (NFW) 1995-97;
Moore et al. 1999; Fukushige & Makino 1999;
Klypin et al. 2001; Bullock et al. 2001; Jing &
Suto 2001-02; Power et al. 2002

NFW 1997
Halo concentrations

NFW96,97; Jing 2000; Bullock et al. 2001

\[ \frac{\rho(r)}{\rho_{\text{crit}}} = \frac{\delta_c}{(r/r_s)(1 + r/r_s)^2}, \]

Concentration:
\[ C = r_{\text{vir}}/r_s \]

\[ n(c)dc = \frac{1}{\sqrt{2\pi} \sigma_c^2} \exp \left( -\frac{(\ln c - \ln \bar{c})^2}{2\sigma_{\ln c}^2} \right) d\ln c, \]

\[ \bar{c}(M, z) = 9(1 + z)^{-1} \left[ \frac{M}{M_*(z)} \right]^{-0.13}, \]

\[ \sigma_{\ln c} = 0.2, \]
The inner slope controversy

Fukushige & Makino 1999; Moore et al. 1999; Jing & Suto 2001; Klypin et al. 2001; Power et al. 2002
The jury is still out ...
NFW vs. Moore et al. profile

Log. slope

$C_{\text{vir}} = 17$ ("galaxy")

Overdensity

$C_{\text{vir}} = R_{\text{vir}} / R_{2}$

$C_{\text{vir}} = 7$ ("cluster")
It is possible that there is scatter in central slopes, just like there is scatter in halo concentrations.
Triaxiality of dark matter halos

Bullock et al. 2001; Jing & Suto 2002

<p>| | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Jing & Suto 2002
Distribution of axis ratios

Warren et al. 1992; Bullock et al. 2001; Jing & Suto 2002

$\Omega_m = 0.3, \Lambda = 0.7, \sigma_8 = 0.9$

$0.2 < a/c \leq 0.3$

$0.3 < a/c \leq 0.4$

$0.4 < a/c \leq 0.5$

$0.5 < a/c \leq 0.6$

$0.6 < a/c \leq 0.7$

$0.7 < a/c \leq 0.8$

$p(a/b | a/c)$

$z = 0$

$z = 0.5$

$z = 1.0$

Jing & Suto 2002
Triaxial density profiles

Jing & Suto 2002

$$R^2(\rho_s) = \frac{X^2}{a^2(\rho_s)} + \frac{Y^2}{b^2(\rho_s)} + \frac{Z^2}{c^2(\rho_s)}.$$
Specific angular momentum distribution of DM halos

Bullock et al. 2001

see also Bullock, Kravtsov & Colin 2002; van den Bosch et al. 2002; Chen & Jing 2002

\[ M(<j) = M_{\text{tot}} \left[ 1 - \left( \frac{j}{j_{\text{max}}} \right)^{3/2} \right], \]

\[ M(<j) = M_0 \left( \frac{\mu j}{j_0 + j} \right), \quad \mu > 1. \]
Specific angular momentum: spatial structure

Bullock et al. 2001

\[
M(<j) = M_{\text{tot}} \left[ 1 - (1 - j/j_{\text{max}})^{3/2} \right], \\
M(<j) = M_v \frac{\mu j}{j_0 + j}, \quad \mu > 1.
\]
Distribution of specific angular momentum: dark matter - gas connection

van den Bosch et al. 2002
Specific angular momentum: halo-disk connection
Bullock et al. 2001
van den Bosch et al. 2001

\[ M(<j) = M_{\text{tot}} \left[ 1 - \left(1 - j/j_{\text{max}} \right)^{3/2} \right], \]

\[ M(<j) = M_v \left( \frac{\mu j}{j_0 + j} \right), \quad \mu > 1. \]
Formation of galactic disks in CDM halos

Simulations qualitatively reproduce general morphology of disk galaxies

Navarro & Steinmetz 2002
Formation of galactic disks in CDM halos: angular momentum problem

Navarro & Steinmetz 1997-2000

Governato et al. 2002
Modifications to CDM

- Self-interacting DM (SIDM)
  Spergel & Steinhardt (1999); and followup by
  Hannestad (1999); Miralda-Escude (2000); Mo
  Hogan & Dalcanton (2000); Yoshida et al. (2001)
  Firmani et al. (2000); Mo & Mao (2000); Kochanek
  Colin et al (2000-02)
Modifications to CDM

- Self-interacting DM (SIDM)
  Spergel & Steinhardt (1999); M. Hannestad (1999); M. Hogan & Dalcanton (2000); C. Firmani et al. (2000); C. Colin et al. (2000-02)

- Warm dark matter (WDM)
  Sommer-Larsen & Dalcanton (2001); Kamionkowski & Lidz (2001)
  Knebe et al. (2001)
Modifications to CDM

• Self-interacting DM (SIDM)
  Spergel & Steinhardt (1999); and followup by Ostriker (1999);
  Hannestad (1999); Miraída-Escude (2000); Moore et al. (2000);
  Hogan & Dalcanton (2000); Yoshida et al. (2000a,b); Burkert (2000);
  Firmani et al. (2000); Mo & Mao (2000); Kochanek & White (2000);
  Colin et al. (2000-02)

• Warm dark matter (WDM)
  Sommer-Larsen & Dolgov (1999); Hogan (1999);
  Kamionkowski & Liddele (1999); Colin et al. (1999); Bode et al. (2000);
  Knebe et al. (2001)

• A combination of the above
  Hannestad & Scherrer (2000)

• Repulsive DM  Goodman (2000)

• Annihilating DM  Medvedev (2000)

• Non-CDM solutions  (e.g., MOND)

• Titled power spectra  (Zentner & Bullock 2002)
<table>
<thead>
<tr>
<th>CDM scorecard</th>
</tr>
</thead>
<tbody>
<tr>
<td>✓ Clustering/velocity field of galactic halos</td>
</tr>
<tr>
<td>✓ Halo mass function</td>
</tr>
<tr>
<td>✓ Abundance of satellites around galaxies</td>
</tr>
<tr>
<td>✓ Abundance of galaxies in clusters</td>
</tr>
<tr>
<td>✓ Density structure of galaxy clusters</td>
</tr>
<tr>
<td>✗ Density structure of galactic cores</td>
</tr>
<tr>
<td>✓ Concentrations and scatter</td>
</tr>
<tr>
<td>✓ AM distribution of DM and gas</td>
</tr>
<tr>
<td>✓ AM of galactic disks</td>
</tr>
<tr>
<td>✓ Triaxiality of DM halos</td>
</tr>
</tbody>
</table>
CDM is still a champion but its supremacy is challenged

as more and more detailed predictions are becoming available, we need
more innovative observational constraints such as precession of satellite
orbits, lensing constraints on halo density profiles and substructure, etc.

some of the new tests will be discussed at the upcoming CfCP workshop
"CDM predictions on small - scales: current and future tests" in Chicago
July 31 - Aug 2, 2002
http://cfcp.uchicago.edu/workshops/cdm2002/index.html
Velocity function of subhalos

Klypin et al. 1999

Ghigna et al. 2000
Halos in the SCDM simulation

Klypin, Kravtsov, Valenzuela & Prada 1999
Causes of overmerging

premature tidal disruption of subhalos
Intrinsic scatter in concentrations

Jing 2000; Bullock et al. 2001

\[
\frac{d\bar{n}}{dM \, dc} = \left( \frac{d\bar{n}}{dM} \right)_{ps} \rho(c),
\]

\[
\rho(c) \, dc = \frac{1}{\sqrt{2\pi} \sigma_c^2} \exp \left[ -\frac{(\ln c - \ln c_0)^2}{2\sigma_c^2} \right] \, dc,
\]
Warm Dark Matter

Bode, Ostriker & Turok 2000
Internal structure of dark matter halos

- Spherically-averaged density profiles of DM halo population can be well described by a universal functional form, although individual profiles can significantly deviate from the average.

- Density profiles of CDM halos are concentrated (e.g., compared to SIS halos) and are cuspy in the inner region.

- CDM halos are triaxial with a well-defined distribution of axis ratios.

- DM halos are not solid body rotators. The internal distribution of specific angular momentum can be described by a 'universal' distribution but again distributions of individual halos may exhibit scatter.

- Baryons and dark matter have similar angular momentum distributions.

- We have promising models of angular momentum evolution and distribution of dark matter, but not for baryons.

- How angular momentum of gas disk forming inside a halo is related to the angular momentum of the host halo and what processes are responsible for any differences remains a mystery.
CMB fluctuations at $z \sim 1000$
"Overmerging" problem

"... by no stretch of the imagination does one form "galaxies" in the current cosmological simulations: the physical model and dynamic range are inadequate to follow any but the crudest details..."

“Overmerging” no more

Klypin, Kravtsov & Gottloeber 1998
Ghigna et al. 1998
Tormen et al. 1998, 1999

Credit: B. Moore (nbody.net)