Dark Matter Halos

A. Klypin (NMSU)
A. Kravtsov (Chicago)
D. Ceverino (NMSU)

O. Valenzuela (U. Washington)
G. Rhee (UNLV)
F. Governato, T. Quinn, G. Stinson (U. Washington)
J. Wadsley (McMaster, Canada)
Major codes:

- N-body
- Hydro
- Cooling/Heating/SF
- Metal enrichment
- Radiative transfer
- Multistepping/Multiple masses

<table>
<thead>
<tr>
<th>Code</th>
<th>Authors</th>
</tr>
</thead>
<tbody>
<tr>
<td>GADET</td>
<td>Springel, SDM White</td>
</tr>
<tr>
<td>PKDGRAV - GASOLINE</td>
<td>Quinn, Steidel, Wadsley, Governato, Moore</td>
</tr>
<tr>
<td>ART</td>
<td>Kravtsov, Klypin, N.Gnedin, Gottlober</td>
</tr>
<tr>
<td>ENZO</td>
<td>Bryan, Norman</td>
</tr>
</tbody>
</table>
Mass function of distinct halos
Mass function of distinct halos

• It started long ago: 32 years to be precise
• Now we live through 5th generation of this.
Mass function of distinct halos

Warren et al. 2005: 13 sims each with 1G particles
Mass function of distinct halos

Warren et al. 2005: 13 sims each with 1G particles

**Fig. 2.** Shown are the residuals from the binned simulation data to the fit presented in this work as square data points of different colors per simulation. The Jenkins fit is the solid (purple) line, ST original fit the dashed (dark gray) line, the ST fit with parameters $A, a, p$ free with dot-dashed line (red), and the ST fit with $a, p$ free and amplitude $A$ set to require all dark matter in halos as a triple-dot-dashed line (light gray). The binned mass function from the Virgo Hubble Volume simulation are the asterisk points with errors (pink).
Subhalo mass function

Gao et al 2004

Halos are not self-similar: Large halos have more substructure. Yet the effect is very weak.
Cusps: simulations

Diemand et al. 2004

![Graph showing density profiles and logarithmic relationships]

- Graph a) displays the density profiles $\rho / \rho(<r_{vc max})$ against $r / r_{vc max}$.
- Graph b) shows the derivative of the logarithm of density $d \log \rho / d \log r$.
Tasitsiomi et al. 2004

Slope gets shallower with decreasing radius, but it does not go below -1

Consistent with what other groups found
Profiles are NOT NFW

$$\rho(r) = \rho_0 \exp(-2nr^{1/n}) + \langle \rho \rangle$$

n=6-8  3D Sersic

Navarro et al. 2004
Merritt, Navarro 2004
Prada et al. 2005
Average profiles of Milky Way-size halos
Infall velocities on halos of different mass

Prada et al 2005
Very small scales

Cusps and rotation curves
DDO 47:

Vmax = 80km/s
Distance = 4Mpc
HI is very lumpy
Stellar light does not align with HI
Observations:

- A large fraction of dwarf Galaxies in the central 1kpc has a maximal disk: stellar populations with observed colors.
- Signs of a weak bar are frequent.
- ISM is very clumpy.
DM in central regions of galaxies: Can cusps be destroyed?

- bars (Weinberg & Katz 2002).
  - Answer **no**: Colin et al 2005: DM density increases as bars form

- baryons:

<table>
<thead>
<tr>
<th>Study</th>
</tr>
</thead>
<tbody>
<tr>
<td>El-Zant, Shlosman, Hoffman (2001)</td>
</tr>
<tr>
<td>Gnedin &amp; Zhao (2002)</td>
</tr>
<tr>
<td>Mashchenko, Couchman, Wadsley (2006)</td>
</tr>
</tbody>
</table>

- Very artificial and unrealistic setup
- Real N-body+Hydro sims (**30pc** resolution) show **increase in DM density**
Cosmological Simulations: feedback, high resolution …

20 x 6.5 Kpc. Blue = Gas  Red = Stars

LMC HI distribution Venn+Stavely Smith 2003)

Multiphase ISM is nicely reproduced

Governato 2004
Cosmological Simulations: feedback, high resolution ...

Multiphase ISM is nicely reproduced

Governato 2004
Valenzuela et al 05

Isolated Galaxy:
NFW halo 1-2M particles
Exponential disk 200K particles
Gas 100K
Resolution 60 pc
Star formation, feedback ….

Cold gas in central 2kpc region

simulations:

dwarf: 70km/s

Code: GASOLINE
Simulation: dwarf 5
Resolution: 60pc

Valenzuela, Rhee, Klypin, Governato et al. 2005
Models of NGC3109 and NGC6822
Simulation: dwarf 5
Resolution: 60pc

Valenzuela, Rhee, Klypin, Governato et al. 2005

Models of NGC3109 and NGC6822
Simulation: dwarf 5
Resolution: 60pc

Valenzuela, Rhee, Klypin, Governato et al. 2005
Models of NGC3109 and NGC6822
True and recovered density profiles

$V_{\text{rot}}(r) \Rightarrow \rho(r)$

True slope: -1.8  
Recovered: -0.5
True and recovered density profiles

Vrot(r) ⇒ ρ(r)

True slope: -1.8
Recovered: -0.5
NGC 6822

Magellanic-type
dwarf irregular

0.5Mpc from Milky
Way
NGC 6822

Magellanic-type dwarf irregular

0.5Mpc from Milky Way

Observations

$V_{\text{circ}}$ (total)
Cusps are not destroyed by baryons
Cores are ‘observed’ where there is a real cusp.
Observations are compatible with cuspy DM profiles
Adiabatic Compression

- Old prescription (Blumenthal et al) over predicts density of DM by a factor of 2
$V_{\text{rms}}(\text{km/s})$ vs $R(\text{kpc/h})$ with different mass values:

- $M_{\text{vir}} = 8 \times 10^{11}$
- $1.5 \times 10^{12}$
- $3.8 \times 10^{12} M_\odot$

Isolation: 1Mpc. Clusters: 5Mpc out.
Clustering: all effects combined

Conroy, Wechsler, Kravtsov (2005): N-body only
- Get all halos from high-res simulation
- Use maximum circular velocity (NOT mass)
- For subhalos use $V_{\text{max}}$ before they became subhalos
- Every halo (sub or not) is a galaxy
- Every halo has luminosity: LF is as in SDSS
- No cooling or major mergers and such. Only DM halos

Young etal, Berrier etal(2005): Halo occupation distribution

Reproduces most of the observed clustering of galaxies
**SDSS: z=0**

- **DM galaxies**
- **DM**
- **SDSS**
DEEP: \( z=1 \)
Dark Matter and Galaxies
Dark Matter and Galaxies

- **Central** DM closely correlates with $L$: Tully-Fisher, Faber-Jackson
Dark Matter and Galaxies

- **Central** DM closely correlates with L: Tully-Fisher, Faber-Jackson
Dark Matter and Galaxies

- **Central** DM closely correlates with L: Tully-Fisher, Faber-Jackson

- Morphology-density relation: morphology is mostly defined by halo mass.
Dark Matter and Galaxies

- **Central** DM closely correlates with L: Tully-Fisher, Faber-Jackson

- Morphology-density relation: morphology is mostly defined by halo mass.
- Environment (how many neighbors) is just an indicator of halo mass
Stars

Young Stars
T<0.5 Gyrs

Hot Gas
T=1e5 K

Cold Gas
T<1.5e4

Stars
Young Stars
$T < 0.5$ Gyrs

Stars

Hot Gas
$T = 1 \times 10^5$ K

Cold Gas
$T < 1.5 \times 10^4$
• Cold gas hardly shows any traces of the bar.
• Filaments and lumps of cold gas
• Large bubbles filled by $10^5$K gas
• Stellar feedback feeds the multiphase ISM
Rotation Curves:
Cold and Hot gas
Little difference
Asymmetric drift (aka random motions) cannot help to explain why gas rotates too slow.

Rms Velocities < 20km/s
Recovering total density

$\rho (M_\odot / pc^3)$

$V (km/s)$

$R (kpc)$
Cold Gas density in the central 2kpc region:

Clear signs of multiphase medium
Cold/Hot Gas: density

Cold Gas: velocity

Stars
Voids

Patiri et al 2006: SDSS and Millennium Run
$R_{\text{void}} \text{ [Mpc/h]} > 13.0$

$10.0 < R_{\text{void}} \text{ [Mpc/h]} < 13.0$