The Effects of Baryons on Dark Matter Halos: A Brief Summary

Andrew R. Zentner
University of Pittsburgh
1. Overview of Structure Formation
   1.1. Dark Matter Halos and Halo Structure
   1.2. Galaxies and Galaxy Formation
2. Baryonic Influences on Dark Matter Halos
   2.1. Halo Contraction
   2.2. Halo Shapes
   2.3. Halo Substructure (Subhalos)
3. Effect on Dark Energy Measurements
4. Summary & Future
Why Care?

1. Contraction affects tests of dark matter on a variety of scales, using a variety of techniques

   1.1. Rotation Curve Measurements
   1.2. Gravitational Lensing Tests
   1.3. Direct DM Search Signal Predictions
   1.4. Abundance of Halo Substructure (subhalos)
   1.5. Halo Shape Tests for DM Self-Interactions
   1.6. DM Annihilation Luminosities & Morphologies
Halo Structure
Dark Matter Halos

- **Halos are “building blocks” of Nonlinear structure**
- **Virialized “Halos” have masses and radii...**

\[ M_{\text{vir}} = \frac{4\pi}{3} \Delta \langle \rho \rangle R_{\text{vir}}^3 \]

\[ \Delta \sim 200 \]
Dark Matter Halos

- Halos have spherically-averaged density structures...

- The concentration parameter “c” specifies how centrally concentrated the dark matter is at fixed overall, $M_{\text{vir}}$

\[
\rho(r) \propto \left( c \frac{r}{R_{\text{vir}}} \right)^{-1} \left( 1 + c \frac{r}{R_{\text{vir}}} \right)^{-2}
\]
“Subhalos” are the self-bound, smaller clumps that lie within the “Virialized” regions of larger “Halos.” Subhalos are, to rough approximation, much like smaller, denser halos.
Dark Matter Halos
Galaxies Form in Halos
Galaxy Formation & Halo Contraction
Halo

Well-mixed, baryonic gas
“Spiral Galaxy”

Energy "Feedback" by a central quasar?
Adiabatic Contraction

\[ r \; M(<r) \] is an adiabatic invariant for circular orbits

Steigman et al. 1978; Zel'Dovich et al. 1980; Blumenthal et al. 1986
Use $r \times M(< \langle r \rangle )$ as an invariant to account for noncircular orbits.

Fit, $\langle r \rangle = A r_{\text{vir}} \left( \frac{r}{r_{\text{vir}}} \right)^w$ to particle orbits.

Gnedin et al. 2005
Halos in galaxy forming simulations look have steeper profiles.

- Rudd et al. 2008
- Rasia et al. 2008
- Guillet et al. 2009
- Casarini et al. 2010

\[ \frac{\rho(r) - \rho_{DM}}{\rho_{DM}} \]

\[ \frac{\rho(r)}{\rho(r_{500c})} \]

- galaxy formation
- non-radiative Gas
- dissipationless n-body
Halos with Galaxies

Rudd et al. 2008

- Modified Halo Concentration Relation
  Relative to the Standard N-Body Result
The goodness-of-fit measure combination can reproduce the range of DM haloes, indicating (dashed), and G04 with our best-fit parameter values (solid).

Figure 12.

- **Weak Feedback**
  - \( \Delta M_{\text{vir}} = 7.2 \times 10^{13} \) c_{\text{vir}} = 5.3 \( \beta = -1.5 \) DMONLY
  - \( M_{\text{vir}} = 7.2 \times 10^{13} \) c_{\text{vir}} = 5.5 \( \beta = -1.7 \) ZC_WFB

- **Strong Feedback**
  - \( \Delta M_{\text{vir}} = 7.2 \times 10^{13} \) c_{\text{vir}} = 5.3 \( \beta = -1.5 \) DMONLY
  - \( M_{\text{vir}} = 7.1 \times 10^{13} \) c_{\text{vir}} = 5.4 \( \beta = -1.6 \) ZC_SFB

See also: Gnedin+04; Gustafsson+06; Romano-Diaz+08; Kazantzidis+08; Pedrosa+09; Tissera+10; Wang+10
CONTRACTION MODEL RESIDUALS

WANG ET AL. 2010

Blumenthal et al 1986 :  
Gnedin et al 2004 :  

\( \frac{ \rho_{AC} - \rho_{\text{simulation}} }{ \rho_{\text{simulation}} } \)

Similar: Gustafsson+06; Pedrosa+09; Tissera+10; Duffy+10
Is there evidence for contraction?
Yes?

Dark matter contribution to mass based on velocity dispersions & stellar population modeling

Mass implied by weak lensing on large scales & NFW assumption for halo

Schulz et al. 2010
Also: Gnedin et al. 2006; Sand et al. 2008; Simon et al. 2008; Trachternach et al. 2008; de Blok et al. 2010...
Can the simple model be “Corrected”?
Adiabatic Contraction

Use $r \times M(<\langle r \rangle)$ as an invariant to account for noncircular orbits.

$<r> = A r_{vir} (r/r_{vir})^w$

fit $A$ & $w$ to get better contraction model!

Gustafsson+06; Wang+10; Duffy+10
Orbit Correction?

“Weak” Feedback

“Strong” Feedback

1. “Best” model does not reflect particle orbits!
2. “Best” model depends upon baryonic feedback and assembly history: complicated!

Similar: Gustafsson+06; Wang+10
1. Residuals depend upon dark matter halo properties
Halo Shapes
HALO
Halo

well-mixed, baryonic gas

Halo

WELL-MIXED, BARYONIC GAS
Halo

Galaxy
\[ q = \frac{b}{a} \]
\[ s = \frac{c}{a} \]
• Halos in DM-Only simulations typically are not round, $q \approx 0.65$ & $s \approx 0.6$

• However, many inferences drawn from local group data suggest a nearly spherical MW halo (Olling+00; Ibata+01; Majewski+03; Helmi+04; Johnston+07; Majewski+08; Smith+10)

• Distant galaxy halos as well... (Dubinski+91; Olling+00; Buote +02; Hoekstra+04; Mandelbaum +08; Buote+09)
1. Halos become significantly more spherical when baryons cool and form galaxies
• Baryonic cooling in simulations gives dramatic changes in halo shape (but not velocity anisotropy; Tissera+2010)

• Changes as large as $\Delta(c/a) \approx 0.2$ are typical
Testing This

- Mock X-ray maps of simulated clusters

No Baryon cooling

With Baryon cooling

Lau et al. 2010
• Mock X-ray maps of simulated clusters compared to data...

• Elliptical shapes of cluster suggest minimal shape transformation (and minimal cooling?)
Locally

- Shape of halo may have interesting consequences for direct and indirect search results locally...

- Stellar disk enhances DM density in the plane (compared to measures that average spherically to derive DM density)
- Deviations from axial symmetry lead to time-dependent density along the Sun’s orbit.

Pato et al. 2010
Halo Substructure with Baryons
Disk “Heating”

Galaxy

Subhalo

Orbit
Disk “Heating”

Accelerations of Particles on Halo Outskirts

Galaxy

Subhalo

Orbit
The disk is heated and disk “features” are generated...

Figure 2. Density maps of disk stars illustrating the global morphological evolution of a galactic disk subject to a $\Lambda$CDM-motivated satellite accretion history. The left panel shows the initial disk assuming that the sequence of satellite-disk interactions initiates at $z=1$, while the right panel depicts the disk after the last satellite passage, evolved in isolation for additional $\sim 4$ Gyr, so that the evolution of disk stars is followed from $z=1$ to $z=0$. The edge-on (upper panels) and face-on (bottom panels) views of the disk are displayed in each frame and the local density is calculated using an SPH smoothing kernel of 32 particles. Satellite-disk interactions produce several distinctive signatures in galactic disks: long-lived, low-surface brightness, ring-like features in the outskirts; conspicuous flares; bars; faint filamentary structures above the disk plane that (spuriously) resemble tidal streams in configuration space; and a complex vertical morphology that is well-described by the commonly adopted “thin-thick” disk decomposition analysis. These morphological features are similar to those being discovered in the Milky Way, M31, and other disk galaxies.

Figure 2 depicts the transformation of the global structure of a thin galactic disk subject to repeated subhalo impacts. This figure shows face-on and edge-on views of the initial and final distributions of disk stars. Particles are color-coded on a logarithmic scale with brighter colors in regions of higher stellar density.

3. Global Disk Morphology

The “final” disk discussed in the next sections has experienced all six subhalo impacts and was evolved in isolation for $\sim 4$ Gyr after the last interaction. This ensures that all of the resultant morphological features are long-lived rather than transient. Consequently, our results are relevant to systems that exhibit no obvious, ongoing encounters. Finally, we compute all properties of the disk and show all visualizations of the disk morphology after centering the disk to its center of mass and rotating it to a new coordinate frame defined by the three principal axes of the total disk inertia tensor.
Subhalo Consequences

- The disk “heats” substructure and serves to destroy them more efficiently than N-body only simulations.
Dark Energy?
Modified Halo Concentration Relation Relative to the Standard N-Body Result
Parameter Biases

Parameter Bias Relative to Statistical Uncertainty

$\delta(w_0) / \sigma_{\text{stat}}(w_0)$

$\delta(w_a) / \sigma_{\text{STD}}(w_a)$

$\ell_{\text{max}}$

LSST
SNAP
DES

AZ, Rudd, & Hu 2008

Maximum Multipole
Under Consideration
“Conclusions”

1. Some Halo Contraction Likely Happens, but it is hard to assess the degree and it depends upon messy details of galaxy formation.

2. Baryonic Contraction likely makes halos rounder (altering, in principle, constraints on SIDM), but the degree is again hard to assess.

3. The presence of galaxies should reduce the prevalence of substructure, but the degree is hard to assess.