Dark and Luminous Galactic Halos

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The Milky Way and its Dark Matter Halo
The Plan

• Short review (and new results) on the structure of Cold Dark Matter Halos
  – Central cusp
  – Halo shapes and LSB rotation curves
  – Galaxy-induced halo transformations

• Luminous (Stellar) Halos
  – Structure and application to observations
Dwarf, Galaxy, and Cluster Halos

Virial velocities range from 30 km/s to 1500 km/s
Each halo has $\sim 10^6$ particles within the virial radius and is resolved down to $r_{\text{conv}} \approx 0.01 \ r_{\text{vir}}$

Hayashi et al. 2004
The Quest for a Billion-Particle Dark Matter Halo

Science Case:

The Structure of Substructure:
- what is the spatial distribution and kinematics of substructure? (lensing flux anomaly, etc)
- what is the density profile of dSph halos?
- The phase-space distribution of DM particles

The Structure of the Central Cusp
- Is the cusp well represented by a power-law and what is its slope? (rotation curves, etc)
- what is $\int <\rho^2>/ <\rho>^2$? (annihilation flux, etc)

A semi-analytic model of the Milky Way: from the detailed structure of disk/bulge/halo to the origin of the faintest galaxies in the universe
The Central Cusp
The Universal Mass Profile of $\Lambda$CDM halos

- Properly scaled, all halos look alike: CDM halo structure appears to be approximately “universal”
- Usually characterized by a “concentration” parameter: $c = r_{\text{vir}}/r_2$

Navarro et al. 2004
An improved fitting formula

A law where the logarithmic slope of the density profile is a simple power-law of radius fits the dark halos to better than 5% at all radii.

\[
\frac{d \log \rho_\alpha}{d \log r} = -2 \left( \frac{r}{r_\alpha} \right)^\alpha
\]

Remarkably, this is the same radial behaviour (a Sersic law) of the stellar distribution in elliptical galaxies!

Navarro et al 2004
Density Profiles of CDM Halos

- Fits with a core or with a power-law inner slope $\rho \sim r^{-\gamma}$ ($r \to 0$) provide equally good fits to the data, so situation is unclear.

Merritt, Navarro et al 2005
A 45-million particle CDM halo

The largest halo simulation in our series so far.
Density Profile

Density profile and best-fit NFW profile
Velocity dispersion profile for our series, including smaller test cases, plotted down to the converged radius.
Phase-space density profile for our series, including smaller test cases, plotted down to the converged radius.

Note the remarkable power-law behaviour of this quantity, with slope identical to Bertschinger’s self-similar secondary infall solution.
‘Hydrostatic’ Isotropic Solutions to Power-Law Phase Space Density Profiles

Depending on the local ‘pressure’, there is a family of solutions, ranging from a power law to a profile resembling that of CDM halos, which corresponds to the ‘critical’ case beyond which solutions are unphysical.

CDM density profiles appear to correspond to the minimum ‘pressure’ compatible with the radial entropy stratification of the spherical collapse model. Innermost (asymptotic) slope in this case is -0.75.

Example: the singular isothermal sphere (ρ ∼ r⁻², σ = const.) may be recovered from Jeans’ equation and the power-law entropy constraint if the (isotropic) velocity dispersion is 2σ² = GM(r)/r. As σ is decreased, a family of solutions is generated.

Taylor and Navarro 2001
Maximum Innermost Slope of Central Cusp

- No obvious convergence to a power-law inner profile.

- Central cusp must be quite shallow: shallower than $r^{-1}$ but not inconsistent with $r^{-0.75}$. 
The Shapes of Galactic Halos and LSB rotation curves
Halo shapes: density vs potential

- Shapes are much easier to measure using gravitational potential rather than density

Hayashi et al. 2006
Radial Dependence of Halo Shape

- Halos become more aspherical towards the center, with a strong tendency to become prolate, in density and potential.

- Angular momentum tends to be perpendicular to major axis.
Signatures of Halo Triaxiality: Elliptical Orbits

For disks situated in the symmetry plane of a triaxial halo, closed loop orbits may be to first order approximated by ellipses.
Orbits in an m=2 perturbed NFW halo

For a perturbed potential of the form:

$$\Phi(r) = (1 + f \cos 2\theta) \Phi_{\text{NFW}}(r), \quad (f \ll 1)$$

The ellipticity of the orbit is given by:

$$\varepsilon(r) \sim f \left(v_{\text{esc}}^2/v_c^2 - 1\right)$$

which increases toward the center for an NFW potential, so that large deviations from circularity may be obtained with small perturbations.
Scaled LSB rotation curves

- Most LSB rotation curves are reasonably well fitted by CDM halos.
- The rest are like UGC5750, shown in the figure.

\[(V_{0.3}, r_{0.3})\]: where the logarithmic slope of the curve is 0.3

\[V \propto r\]

Hayashi et al 2003
Long-slit rotation curves

- Along the long axis of symmetry of the orbits, the line-of-sight velocities are gradually reduced toward the center (relative to circular) so that the rotation curve looks “solid-body”, mimicking the presence of a constant-density core.

- For this configuration, the velocity field is symmetric and orbits are indistinguishable from circular.
The imprint of halo triaxiality on disk velocity fields

- Lines of constant speed are asymmetric, and show characteristic "kinks".
- Iso-velocity contours are (anti)symmetric in diagonally opposite quadrants, but differ in contiguous ones.
- The effect becomes gradually more pronounced toward the centre.
LSBs with 2D Velocity Field Data: NGC 2976

NGC 2976: an LSB disk without obvious bulge or bar components.

“...independent of any assumptions about the stellar disk or the functional form of the density profile, NGC 2976 does not contain a cuspy dark matter halo”

Simon et al 2004
The Velocity Field of NGC 2976

Velocity field is quite asymmetric, with “kinks” similar to those seen in projection for disks in triaxial halos.

Simon et al. 2004
Simon et al (2004) choose to model such deviations by tilted concentric rings with rotation, as well as “radial” (i.e. expansion or contraction) velocities.

Good fits are obtained, but this treatment may mask the presence of elliptical motions and may hide a cusp.
Galaxy-Induced Transformations of Cold Dark Matter Halos

- Set of simulations including **only** the effects of radiative cooling and of an UV background.

- A total of 13 simulations of ~200 km/s halos with a reasonably “quiet” assembly history, i.e. no major mergers since $z=2$.

- Disks and satellites are well resolved; typically $N_{\text{disk}} \sim 50,000$

Yellow = cold gas  
Red = dark matter
Changes in Shape: Density

Dark Matter only

Dark Matter + Baryons

Zoom: x1

x2

x4
Changes in Shape: Potential

Dark Matter only

Dark Matter + Baryons

Zoom: x1  x2  x4
Changes in Shape: Potential

• Dark halo becomes much more spherical as a result of the assembly of the galaxy

• Nearly prolate halos may become oblate, an effect that extends well beyond the luminous galaxy

• Minor axis roughly coincides with the rotation axis of the disk

• Disk angular momentum is well aligned with that of the halo.
Alignment between Disk and Dark Matter

- Dark halo becomes much more spherical as a result of the assembly of the galaxy.
- Nearly prolate halos may become oblate, an effect that extends well beyond the luminous galaxy.
- Minor axis roughly coincides with the rotation axis of the disk.
- Disk angular momentum is well aligned with that of the halo.

\[ \Theta = \text{angle between } J_{\text{disk}} \text{ and minor axis (or } J_{\text{DM}} \)
Changes in Dark Mass Profile

The dark matter responds to the assembly of the galaxy by becoming more centrally concentrated.

The response, however, is weaker than expected from simple models based on adiabatic invariant approximations.
Halo Contraction in Response to Galaxy Assembly

The halo response is weaker than expected from the traditional adiabatic contraction formula.

This has interesting implications for reconciling the Tully-Fisher relation with the abundance of galaxy-sized LCDM halos.
The majority of galaxies assembled in a CDM-dominated universe have gone through a period of intense merging activity.
Essentially all stars beyond the traditional luminous radius of a galaxy (and not in satellites) originate in past accretion events.

The outer luminous halo of a galaxy holds important clues to the merging history of a galaxy.

Abadi, Navarro & Steinmetz 2005.
The Outer Surface Brightness Profile of Galaxies

- Outer halos appear as an “excess” of light over extrapolations of the inner surface brightness profile of a galaxy.

- The outer halo is well approximated by a Sersic law.

- The same law describes very well the profile of all accreted stars.

Abadi, Navarro & Steinmetz 2005.
Globular clusters: Tracers of accreted stars?

- The number density profile of globular clusters around M31 and the Milky Way is consistent with the density profile of accreted stars in our simulations.
- Curves in the figure are *not* fits, they just show a Sersic law with parameters of the accreted stars.
- Majority of GCs might be relicts of accretion events? (Searle & Zinn 1978)
Such outer halos have been detected around edge-on, isolated spirals (Zibetti et al 2004) and M31 (see also Irwin et al 2005).

- The outer spheroid may be used to estimate the total number of accreted stars in a galaxy!

The velocity dispersion tensor of stars in the outer halo is remarkably anisotropic:

\[ \sigma_r^2 \sim 4 \sigma_t^2 \]

Abadi, Navarro & Steinmetz 2005.
The velocity dispersion of halo tracers drops significantly in the outer regions of the Milky Way.

Traditional modeling of such data favors truncated dark matter halos.
The Mass of the Milky Way

- Combining our model for stellar halo with these data suggests that circular velocity of the Milky Way drops in the outer regions ($V_{\text{vir}} \sim 110 \text{ km/s}$)

- The Milky Way halo might be much less massive than commonly assumed!
  - $(7-8 \times 10^{11} M_{\odot})$

- How can we test this? ➔ Escape velocity

Abadi, Navarro & Steinmetz 2005
The End