Simulations of the Dark Matter Distribution

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• Quasilinear DM distribution
  -- Large-scale gravitational lensing
  -- Ly α forest
  -- high redshift 21 cm distribution

• Nonlinear DM distribution in our Galaxy
  -- Radial mass distribution in the Milky Way
  -- Substructures
  -- structure on the scale of DM detectors

• DM distribution around groups and clusters
  -- radial distribution
  -- flattening
  -- structure of substructures

Nature of DM
- neutrino contrib'n
- primordial $n$

- annihil'n signature
- direct detect signal

- Interaction with baryons
Many people are enthusiastic about Dark Matter!
• Halos extend to ~10 times the 'visible' radius of galaxies and contain ~10 times the mass in the visible regions

• Equidensity surfaces approximate triaxial ellipsoids
  -- more prolate than oblate
  -- axial ratios greater than two are common

• "Cuspy" density profiles with outwardly increasing slopes
  -- $\frac{d \ln \rho}{d \ln r} = \gamma$ with $\gamma < -2.5$ at large $r$
  \hspace{1cm} $\gamma > -1.2$ at small $r$

• Substantial numbers of self-bound substructures containing ~10% of the mass and with $d N / d M \sim M^{-1.8}$

  Most substructure mass is in the most massive subhaloes
Density profiles of dark matter halos

The average dark matter density of a dark halo depends on distance from halo centre in a very similar way in halos of all masses at all times -- a universal profile shape --

$$\frac{\rho(r)}{\langle \rho \rangle} \approx \delta \frac{r_s}{r(1 + r/r_s)^2}$$

More massive halos and halos that form earlier have higher densities (bigger $\delta$)
A high-resolution Milky Way halo

Navarro et al 2006

\[ N_{200} \sim 3 \times 10^7 \]

600 kpc
Convergence tests on density profile shape

Navarro et al 2006

DM profiles are converged to a few hundred parsecs
The inner asymptotic slope must be shallower than $-0.9$
Dark Matter Annihilation

For certain kinds of Dark Matter particles

---Self-annihilation is possible
---Annihilation products will typically include $\gamma$-rays

The luminosity density of annihilation emission is

$$\mathcal{L}(x) \propto n_{DM}(x)^2 \langle \sigma \ v \rangle$$

Thus the $\gamma$-ray luminosity of an object is

$$L \propto \langle \sigma \ v \rangle \int \rho^2 \ dV \propto \langle \sigma \ v \rangle \int \rho^2 \ r^2 \ dr$$

The critical density exponent for convergence is

$$\rho \propto r^{-1.5}$$
- $N_{200} = 2.23 \times 10^8$

- Inner slope > -1

- Annihilation mainly from region where $\gamma \sim -1.5$, $R \sim 5$ kpc

- Baryonic effects will increase the DM density and thus the emission

- Central BH may cause substantial additional effect
Image of a 'Milky Way' halo in annihilation radiation

\[ S(\theta) \propto \int \rho^2 \, dl \]

Stoehr et al 2003

270 kpc
Cumulative radial distributions of mass and light

- Half mass/light radii of the diffuse halo component are 90 kpc and 7 kpc
- Half mass/light radii of the subhalo component are both 130 kpc
- Total light from subhalo component is 25% that from the diffuse component
- The Sun is much closer to the peak of the diffuse emissivity than to a subhalo

Observed flux dominated by diffuse emission from inner Galaxy
Signal-to-noise of the simulated Milky Way as seen from the Sun's position

- Hatched area is scatter in circularly averaged signal-to-noise profiles for *wide beam* observation of 8 artificial skies assuming *uniform* background.

- Heavy lines from analytic fits to the density profile.

- Best S/N is achieved about at a radius of 10 degrees.

- At this radius simulation is secure and backgr'd is *lower* than nearer the centre.

Stoehr et al 2003
Small-scale structure in $\Lambda$CDM halos

A rich galaxy cluster halo
Springel et al 2001

A 'Milky Way' halo
Power et al 2002
Is the kinematics of the Milky Way's satellites inconsistent with $\Lambda$CDM substructure?

- Number of observed satellites was **claimed** to be $\sim 1/30$ the number of $\Lambda$CDM satellites with the same max. circular velocity $V_c = (GM/r)^{1/2}$

- But the MW data are plotted at the **incorrect** values of $V_c$ for this test!

Moore et al 1999

Klypin et al 1999

Stoehr et al 2002
Dark Matter within Satellites

- Flat stellar velocity dispersion out to the tidal radius
  - Rising $V_c$ curve
- Extended DM halos?
- High DM phase density? $WDM$
- $V_{c,\text{max}} \geq 25$ km/s?
- Critical observation: extratidal stars?
DENSITY PROFILES OF COLD DARK MATTER SUBSTRUCTURE: IMPLICATIONS FOR THE MISSING-SATELLITES PROBLEM

Stelios Kazantzidis¹, Lucio Mayer, Chiara Mastroiopetru, Jürg Diemand, Joachim Stadel, and Ben Moore

Motivated by the structure of our stripped satellites, we compare the predicted velocity dispersion profiles of Fornax and Draco to observations, assuming that they are embedded in CDM halos. We demonstrate that models with isotropic and tangentially anisotropic velocity distributions for the stellar component fit the data only if the surrounding dark matter halos have maximum circular velocities in the range 20 – 35 km s⁻¹.
Inconsistency with observed satellite kinematics?

- Inconsistency is much less dramatic when one uses the *limiting* circular velocity inferred from the velocity dispersion profiles.
- The *maximum* of the DM circular velocity profile may be outside the visible galaxy and still larger (plots show shift to $V_{\text{max}} = 30 \text{ km/s}$).
$N_{200} = 2.23 \times 10^8$

$>30,000$ subhalos

$8\%$ of mass within $R_{200}$ in subhalos

Total subhalo mass (weakly) convergent as $m_{\text{sub}} \rightarrow 0$
- Circular velocity curves for 9 of the 30 most massive subhalos
- The 'main halo' curve is scaled to the \((r_m, V_m)\) of largest subhalo
- The maximum circular velocities are at radii outside observed satellites
- Shape inside \(r_m\) is similar to that of main halo
- Inner core *still* not well enough resolved to predict total annihilation radiation
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All but one of 11 well observed satellites could be in these subhalos
For effectively collisionless DM:  \( \frac{D}{Dt} f(x, v, t) = 0 \)

i.e. phase-space density preserved along orbit of each particle

Initial phase-space density is effectively 3-dimensional

→ current DM distribution is a superposition of 3-d “sheets”
in local \((x, v)\) space near the Sun

3-d density of each sheet decreases with time as \( \sim (1 + t / t_{orb})^{-3} \)

→ up to \(10^5\) sheets near the Sun

→ a Schwarzschild-like distribution
weak caustics
Mean density profiles of halos of given $M_{200}$ are well fit down to overdensities of 10 by the fitting formula of Navarro et al (2004).
Density profile shapes at large radii

Hayashi et al 2007

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- At lower overdensities they are well fit by the linear mass correlation function with bias from Sheth, Mo, Tormen (2001)
Mean density profiles of halos of given $M_{200}$ are well fit down to overdensities of 10 by the fitting formula of Navarro et al (2004).

At lower overdensities they are well fit by the linear mass correlation function with bias from Sheth, Mo, Tormen (2001).
Galaxy-mass cross-correlations are directly measurable through galaxy-galaxy lensing.

They can be predicted from an HOD model and mean halo mass profiles.

Here they are predicted with the Croton et al gal. formation simulation.

On large scale they follow the nonlinear $\xi_{mm}$.
Weak lensing measures of halo mass profiles

Seljak et al 2004: from SDSS

\[ \Delta \Sigma \sim M_{\text{sun}} / r^2 \]

- **L3: \([-20, -19]\)**
  - \(M = 2.2 \pm 0.6\)
  - \(\alpha = 0.12 \pm 0.06\)

- **L4: \([-21, -20]\)**
  - \(M = 6.0 \pm 0.8\)
  - \(\alpha = 0.13 \pm 0.01\)

- **L5: \([-22, -21]\)**
  - \(M = 25 \pm 2\)
  - \(\alpha = 0.15 \pm 0.02\)

- **L6: \([-23, -22]\)**
  - \(M = 213 \pm 34\)
  - \(\alpha = 0.33 \pm 0.09\)
High redshift with strong lensing

$\sigma_{\text{clus}} = 1034 \pm 46$

from measured redshifts
\[ \bar{z}_{\text{source}} = 1.2 \]

\[ \theta_{\text{res}} = 30'' \]

100 gals/squ.arcmin

reconstruction noise included
\[ \overline{z}_{\text{source}} = 1.2 \]

\[ \theta_{\text{res}} = 30'' \]

100 gals/
squ.arcmin

reconstruction
noise excluded
15 arcmin square

\[ z_{\text{source}} = 15 \]

\[ \theta_{\text{res}} = 30'' \]

SKA 21cm survey

reconstruction noise included
$z_{\text{source}} = 15$

$\theta_{\text{res}} = 30''$

SKA 21cm survey reconstruction noise excluded
$z_{\text{source}} = 15$

$\theta_{\text{res}} = 30''$

“super”-SKA 21cm survey

reconstruction noise included
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“super”-SKA 21cm survey

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CONCLUSIONS

- The observed properties of Galactic satellites are not in conflict with the substructure predicted in CDM models.
- Dark matter should be smoothly distributed on small scales with a Schwarzschild-like (multivariate gaussian) velocity distribution.
- Substructures and caustics should be subdominant sources of annihilation radiation.
- Annihilation radiation should be most easily detected over a large area ~10° away from the Galactic Centre and at high latitude.
- Galaxy-galaxy lensing can (by stacking signal) detect the mean shapes and profiles predicted for DM halos.
- Lensing of 21cm from prerecombination HI could image the DM distribution over the whole sky with high fidelity and resolution.