Universal properties of dark matter halos and infall model

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**Motivation**

- The flux from DM decay

\[ F_{DM} = \frac{\Gamma \Omega_{fov}}{8\pi} \int_{los} dr \rho_{DM}(r) \]

- Average DM column density

\[ S = \frac{2}{r_*^2} \int_0^{r_*} r' dr' \int dz \rho(\sqrt{r'^2 + z^2}) \]

- We can parametrize it as \( S \propto \rho_* r_* \)

- \( S \) looks to be the same, from dwarfs to clusters

- It is essentially insensitive to the choice of fitting DM profile

*Boyarsky et. al., 2006*
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Boyarsky et. al., 2006
Constant DM surface density?

Donato et al., 2009
An evidence in favour of MOND?

Gentile et al., Nature'09
Scaling of DM column density

\[ S \propto M_{\text{halo}}^{0.2} \]

Boyarsky et al., 2009
Scaling of DM column density

Napolitano et al., 2010
Infall model

Position of each particle in the halo obey

\[
\frac{d^2 r}{dt^2} = - \frac{GM(r,t)}{r^2}
\]

For initial perturbations with power-law profiles

\[
\frac{\delta M_i}{M_i} = \left( \frac{M_0}{M_i} \right)^\epsilon
\]

the halo evolves in a self-similar manner, e. g.

\[
M(r,t) = M(t)\mathcal{M}(r/R(t))
\]

\[
r(r_i, t) = R(t)\lambda(t/t_*)
\]

\[
\rho(r, t) = \frac{M(t)}{R^3(t)} \times F \left( \frac{r}{R(t)} \right)
\]
Infall model

Sikivie, Yun Wang & I.T., 1996
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Best fit: $R = 1.07 \pm 0.14$ Mpc, $h = 0.71 \pm 0.5$

G. Steigman & I. T., 1998
Diemand and Kuhlen, 2008
Infall model

\[ \nu(\epsilon, \xi)^2 ]

\[ j=0 \]

\[ \tilde{j}=0.2 \]

\( \xi = r/R \)

Sikivie, Yun Wang & I.T., 1996
\[ \rho \propto r^{-2} \] between first inner and outer caustics

\[ \rho \propto r^{-\gamma} \] inside first inner caustics, where

\[ \gamma = \frac{9\epsilon}{3\epsilon + 1} \]

\[ \gamma \approx 1.1 \quad \text{for} \quad \epsilon = 0.2 \]

*Sikivie, Yun Wang & I.T., 1996*
Qualitative understanding

- Self-similarity implies
  \[ S \propto \rho_* r_* \propto \rho_{ta} R_{ta} \]

- Infall implies
  \[ R_{ta} \propto (Gt^2 M)^{1/3} \]

- If there are deviations from self-similarity
  \[ S \propto c(M) \cdot M^{1/3} \]

- Concentration parameter
  \[ c = r_* / R_{ta} \]
  is a weak function of mass,
  \[ c \propto M^{-0.1} \]

- Therefore
  \[ S \propto \frac{M^{0.23}}{t^{4/3}} \]
Concentration parameter

\[ (M_{200}/1\text{e}17)^{-0.1} \]
Scaling of DM column density

Infall $S \propto M_{\text{halo}}^{1/3 - 0.1}$, best fit $S \propto M_{\text{halo}}^{0.2}$

Boyarsky et al., 2009
Gravity vs. cosmological expansion

Let mass $M$ creates a gravitational potential $\phi(r)$

- Turn around time

$$t_{ta} = \frac{1}{\sqrt{2}} \int_{0}^{R_{ta}} \frac{dr}{\sqrt{\phi(r) - \phi(R_{ta})}}$$

- Any gravitational potential of the form

$$\phi(r) = -\frac{GM}{r} F\left(\frac{\rho(r)}{\rho_0}\right)$$

leads to the scaling $S \propto M^{1/3}$

- Example: Schwarzschild-de Sitter potential

$$\phi(r) = -\frac{GM}{r} - \frac{\Lambda r^2}{6} = -\frac{GM}{r} F\left(\frac{\Lambda}{G\rho(r)}\right)$$
Large scale modifications of gravity

- A possible set of consistent (as a spin-2 field theory) large scale modifications of gravity is described by two parameters - scale $r_c$ and a number $0 \leq \alpha \leq 1$

- In these models (DGP, ”degravitation”)

$$\phi_\alpha(r) = -\frac{GM}{r} \pi\left(\frac{r}{r_V}\right)$$

- where the Vainshtein radius:

$$r_V = \left(2GMr_c^4(1-\alpha)\right)^{\frac{1}{1+4(1-\alpha)}}$$

- Only for $\alpha = 1/2$

$$\phi(r) = -\frac{GM}{r} F\left(\frac{\rho(r)}{\rho_0}\right)$$
Restrictions on modifications of gravity

DM column density, log_{10}[S/M_{sun} pc^{-2}]

- Clusters of galaxies
- Groups of galaxies
- Spiral galaxies
- Elliptical galaxies
- dSphs

Norm. branch, \( \alpha = 0 \); \( r_c = 150 \) Mpc
Self-acc. branch, \( \alpha = 0 \); \( r_c = 150 \) Mpc
Norm. branch, \( \alpha = 1/4 \); \( r_c = 300 \) Mpc
Self-acc. branch, \( \alpha = 1/4 \); \( r_c = 300 \) Mpc
Best-fit model \( S \propto M^{0.23} \)

Boyarsky & Ruchayskiy, 2010