UNIVERSAL PROPERTIES IN GALAXIES AND CORED DM PROFILES

Paolo Salucci (SISSA)


ECOLE INTERNATIONALE D. CHALONGE
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OUTLINE

- The kinematics of galaxies
- Universal Properties of DM halos: relation to LM
- The amount and distribution of DM around Spirals
- The nature of DM

The universal rotation curve of spiral galaxies - I. The dark matter connection

The universal rotation curve of spiral galaxies out the virial radius II
Central surface brightness vs magnitude

The Realm of Galaxies
15 mag range, 4 types, 16 mag arsec$^{-2}$.range
Luminosity profile is Universal.
Spirals have a length-scale
Distribution of stars: \( L(R/R_d)/LT \) independent of Luminosity
The light distribution in spirals is invariant \( I(r) = I_0 \exp[-R/R_D] \)

The mass distribution is luminosity dependent:
- TF at different radii
- The Universal profile of the RC’s
Do the RC’s probe the mass distribution of galaxies? What is the zeroth order of their mass profiles

- Radial Tully Fisher
- Inner mass distribution
The relation: magnitude vs velocity @ different radii $x_i R_D$, \( [ x_i=0.5,1,…5] \)

3 samples (600, 89, 78) $M = a_i + b_i \log V(x_i)$

No change in slope implies: i) no DM or ii) constant fraction of DM

No relationship if $V$ does not trace the mass
Radial TF relationships
Results: Slope and scatter of the TF-relations:

\[ M_B = a_i + b_i \log V(x_i) \]

The slope increases from -4 to -8
The minimum scatter 0.2 mag at 2.2 \( R_D \)

Implications:
\( V \) traces the potential
DM emerges at large radii
Modelling the very inner circular velocities: light traces the mass
The slope of the RC
The RC Slopes indicate the presence and the amount of Dark Matter.
The rotation curves

3200 coadded

Individual

C+06

PSS
ΛCDM Universal Rotation Curve from NFW profile and MMW theory

\[ \lambda = 0.04 \]
@ fixed $L$ and $X = R/R_D$, the Cosmic Variance of $V(X,L)$ is one order of magnitude smaller than:

The variations that, in each galaxy, $V(X)$ shows as $X$ varies.

The variations that, @ fixed $X$, $V(X)$ shows in galaxies of different $L$. 

The circular velocity is luminosity dependent.

\[ V(R/R_D) = F(L, R/R_D) \]
Rotation curve decomposition.

\[ V_{tot}^2 = V_{DM}^2 + V_{disk}^2 + V_{gas}^2 \]

- \( V_{disk}(R) \): from I-band photometry
- \( V_{gas}(R) \): from HI observations
- \( V_{halo}(R) \)

- dark halos with constant density cores
- dark halos with “cusps” (NFW, Moore)
- HI-scaling
- MODified Newtonian Dynamics
We can uniquely mass model a RC disk-halo components, known surf phot, reliable V(R) and dV/dR, resolution ~ 0.3 R_D
Modelling the Universal Rotation Curve

Rotation velocity

\[ V_{\text{URC}} \left( \frac{R}{R_{\text{opt}}} \right) = V(R_{\text{opt}}) \left\{ \left( 0.72 + 0.44 \log \frac{L}{L_*} \right) \left( \frac{1.97x^{1.22}}{x^2 + 0.78^2} \right)^{1.43} \right\} \]

+ \[ 1.6 \exp \left[ -0.4(L/L_*) \right] \left( \frac{x^2}{x^2 + 1.5^2 \left( \frac{L}{L_*} \right)^{0.4}} \right)^{1/2} \text{ km s}^{-1} \]

Stellar contribution

Dark matter halo contribution

Stars

Dark matter
**NFW Halos**

\[ \rho_{\text{NFW}}(r) = \frac{\rho_0}{(r/r_0)(1 + r/r_0)^2} \]

\[ c_{\text{vir}} \equiv r_{\text{vir}}/r_0 \]

\[ M_{\text{NFW}}(r) = M_{\text{vir}} \frac{A(r, r_a)}{A(c_{\text{vir}}, r_a/r_0)} \]

\[ A(x_1, x_2) \equiv \ln(1 + x_1/x_2) - (1 + x_2/x_1)^{-1} \]

**Burkert-URCH-PI Halos**

\[ \rho_B(r) = \frac{\rho_0}{(1 + r/r_0)^2 + (r/r_0)^2} \]

The profile is characterized by a density-core of extension \( r_0 \) and value \( \rho_0 \), while it resembles the NFW profile at large radii.

\[ M_B(r) = M_\star \frac{B(r, r_0)}{B(1, r_0/r_a)} \]

\[ s = r/r_0 : B(s) = 2 \ln(1+s)+\ln(1+s^{-2})-2 \arctan(s) \]
A family governed by luminosity

\[
\log \left( \frac{\rho_0}{\rho_e} \right)
\]

halo central density

\[
\log \left( \frac{1 - \beta}{\beta} \right)
\]

DM fraction

core radius \( \log(a) \)

luminosity
Halo central density vs core radius scaling

\[ \rho_0 = 10^{-23} (r_0 / \text{kpc})^{-1} \text{g/cm}^3 \]
Halo masses

\[ \text{BMF}(M_b)\,dM_b = (1.94 \times 10^{-3} \bar{M}_b^{-1.2} e^{-\bar{M}_b/1.9} + 4 \times 10^{-7} \bar{M}_b^{-2.6}) \frac{dM_b}{10^{11} M_\odot} \]

\[ \text{HMF}(M_h)\,dM_h = A M_h^{-1.84} \,dM_h \]

and

\[ \text{HMF}(M_h)\,dM_h / dM_b \,dM_b = \text{BMF}(M_b)\,dM_b \]

\[ M_h = (|\beta| - 1)/A \left(1.94 \times 10^{-3} \Gamma(-0.21, \bar{M}_b/1.9) + 2.5 \times 10^{-7} \bar{M}_b^{-1.6} + C\right)^{1/(1-|\beta|)} \]
RESULTS

DM halo density: observations vs simulations
THE UNIVERSAL VELOCITY CURVE
Dark halos from simulations

Halos form hierarchically bottom-up via gravit. amplification of initial density fluct. Most evident property: **CENTRAL CUSP**

\[
M_{\text{vir}} \equiv \frac{4\pi}{3} \Delta_{\text{vir}} \rho_u R_{\text{vir}}^3 \quad \text{\(V_{\text{vir}}^2 \equiv GM_{\text{vir}} / R_{\text{vir}}\)} \quad \text{\(c_{\text{vir}} \equiv R_{\text{vir}} / r_s \approx 9.7\left(M_{\text{vir}} / 10^{12} M_{\odot}\right)^{-0.09}\)}
\]

\[
\rho_{\text{NFW}}(r) = \frac{\rho_s}{(r/r_s)(1 + r/r_s)^2}
\]

Bullock et al., MNRAS 321, 559 (2001)
Klypin, 2010

The cusp vs core issue

cuspy NFW density profiles disagree with observed kinematics. comparison galaxy by galaxy and of coadded kinematics highlights a CDM crisis.

**NFW HALOS**
- Fit badly the RCs
- Unphysically too low stellar mass-to-light ratios
- Unphysically too high halo masses


A test case: ESO 116-G12

Cored halos the best fits
50 objects investigated
NFW inconsistent

Density vs core radius

Discrepancy points: 2σ, 3σ

<table>
<thead>
<tr>
<th>Model</th>
<th>2σ</th>
<th>3σ</th>
<th>No. of Points</th>
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<td>Burkert</td>
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<td>10</td>
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<td>3</td>
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<tr>
<td>MOND</td>
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</table>
DDO 47: Non circular motions?

Triaxial halos predictions
Results from Trieste: analysis of high quality RCs

URC fits to RCs


DDO 47


Weak lensing

With a density profile we model the tangential shear
Obtain the structural free parameters.

Same results as those obtained from RCs.
Burkert profile provides excellent fit, better than NFW.
Dwarf spheroidal galaxy kinematics and spiral scaling laws: preliminary results

Attempt to investigate whether properties of DM halos around dSphs obey to well known scaling laws found for the mass distribution of Spirals
AN INTRIGUING PROPERTY
Preliminary results

\[ \log r_0 = A \log \rho_0 + C \]

- We find similar \( \rho_0 \) and \( r_0 \) relationships independently whether the mass profiles are obtained from RCs or lensing data or from analysis of individual or coadded objects.

- dSph halos are much denser, lie on the Spiral relationship.

- Data can be reproduced by the existence of scaling relations between \( \rho_0 \) and \( r_0 \) over three orders of magnitude can rule out WDM.

- DM relations cannot arise due to self-annihilation which would predict a narrow range in \( \rho_0 \).

A matter enigma
DARK MATTER IS PRESENT IN GALAXIES

IT IS STRONGLY RELATED TO THE LUMINOUS MATTER

THERE IS A SOLID EMPIRICAL SCENARIO