The dark halo-to-stellar mass ratio in S⁴G disk galaxies

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Abstract

- We use 3.6 μm photometry for disk galaxies in the S⁴G survey to obtain the stellar component of the circular velocity. By combining the disk+bulge rotation curves with H I line width measurements from the literature, we estimate the ratio of the halo-to-stellar mass within the optical disk, and compare it to the total stellar mass.
- We find the $M_{\rm halo}/M_*-M_*$ relation in good agreement with the best-fit model at $z\approx0$ in ΛCDM cosmological simulations, assuming that the dark matter halo within the optical radius comprises a constant fraction ($\sim 4\%$) of its total mass.

Context

- In the lambda cold dark matter (ΛCDM) paradigm, galaxies are formed from the cooling and condensation of gas in the center of dark matter halos (White & Rees 1978, Fall & Efstathiou 1978).
- A challenge for astronomers is to link the properties of present-day galaxies to their parent host halos with the aid of photometric and spectroscopic observations and cosmological simulations.

Sample

- We use 3.6 μm photometry for 1154 disk galaxies with inclinations $i < 65°$ (Salo et al. 2015) taken from the Spitzer Survey of Stellar Structure in Galaxies (S⁴G, Sheth et al. 2010).

Maximum rotational velocity

- We estimate the maximum circular velocities of the galaxies ($V_{\rm HI}^{\rm max}$) from the H I line widths ($W_{\rm mx}^{\rm av}$), available in the Cosmic Flows project (Courtois et al. 2009, 2013) and HyperLEDA, corrected for the disk inclination (from Salo et al. 2015):

$$V_{\rm HI}^{\rm max} = W_{\rm mx}^{\rm av}/(2\sin {\rm i}). \qquad (1)$$

Stellar contribution to the circular velocity

- Using the NIR-QB code (Salo et al. 1999, Laurikainen & Salo 2002), we inferred the gravitational potential from the deprojected S⁴G 3.6 μm photometric images (Díaz-García et al. 2016b).
- We calculated the stellar contribution to the circular velocity:

$$V_{\rm disk}(r) = V_{3.6\mu{\rm m}}(r) = \sqrt{\Upsilon_{3.6\mu{\rm m}}\,\langle F_{\rm R}(r)\rangle\, r}, \qquad (2)$$

where r is the galactocentric radius, $F_{\rm R}$ corresponds to the radial force obtained for $M/L=1$, and $\Upsilon_{3.6\mu{\rm m}} = 0.53$ is the mass-to-light ratio at 3.6 μm obtained by Eskew et al. (2012).

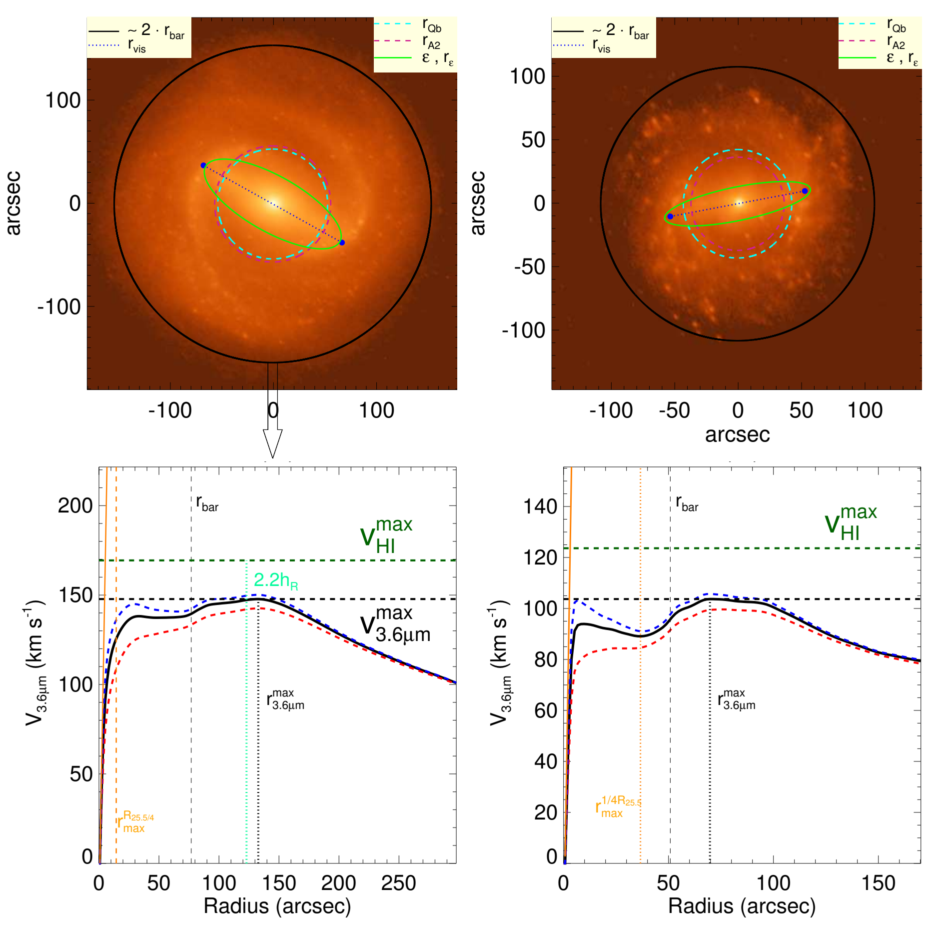

Fig 1. *S⁴G 3.6 μm images (upper panels) and the stellar component of the circular velocity (lower panels) inferred from the gravitational potential for the barred spiral galaxies NGC 4548 (left) and NGC 4123 (right).*

Estimate of halo-to-stellar mass ratio

- We obtained a first-order estimate of the halo-to-stellar mass ratio ($M_{\rm h}/M_*$) within the optical radius ($R_{\rm opt} \sim 3.2 h_{\rm R}$) using Eqs. 1-2 under the following assumptions:

  1. The gas contribution to the rotation curve is modest at the optical radius (e.g. Verheijen 1997).
  2. The circular velocity at $R_{\rm opt}$ is approximately the observed maximum velocity:

  $$(V_{\rm HI}^{\rm max})^2 \approx V_{3.6\mu{\rm m}}^2(R_{\rm opt}) + V_{\rm halo}^2(R_{\rm opt}), \qquad (3)$$

  3. The disks are exponential.

- We derive:

$$M_{\rm h}/M_*(<R_{\rm opt}) \approx F\cdot\left(\frac{(V_{\rm HI}^{\rm max})^2}{V_{3.6\mu{\rm m}}^2(R_{\rm opt})} - 1\right), \qquad (4)$$

where F corresponds to the ratio between the mass contained by a spherical distribution and that enclosed by an exponential disk yielding a similar radial force at $R_{\rm opt}$ (Binney & Tremaine 1987). In the range $2 \le r/h_{\rm R} \le 4$, $F \approx 1.34$ (see Fig. 2).

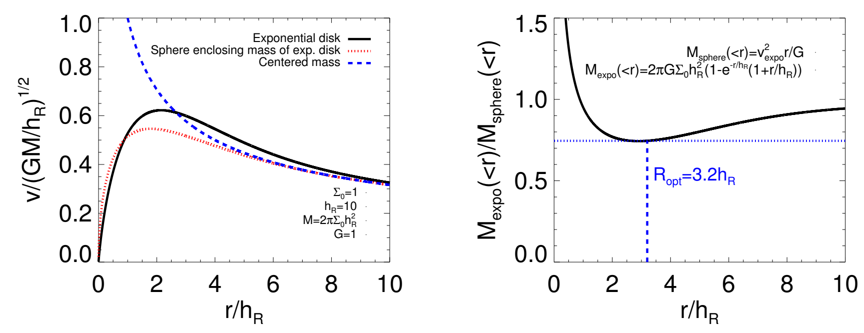

Fig 2. *Left: Circular velocity of an exponential disk (Freeman 1970) as a function of galactocentric radius, normalized to the disk scalelength ($h_{\rm R}$). Right: Ratio of the mass contained by a spherical mass distribution and that enclosed by an exponential disk.*

The $M_{\rm halo}/M_* - M_*$ relation

- We show the halo-to-stellar mass ratio within $R_{\rm opt}$ as a function of total stellar mass, and compare this to various estimates in the literature for this relation based on abundance matching and halo occupation distribution methods (e.g. Moster et al. 2010).

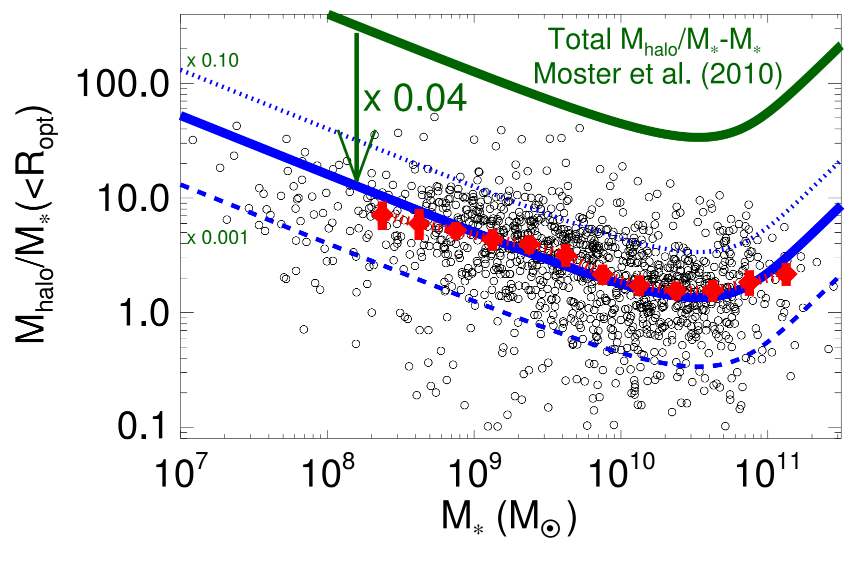

Fig 3. *Halo-to-stellar mass ratio within the optical disk versus total stellar mass (circles, reproduced from Díaz-García et al. 2016b). Red dots represent the running median. $R_{\rm opt} \sim 3.2 h_{\rm R}$ is taken from Salo et al. (2015) and total stellar masses are from Muñoz-Mateos et al. (2015).*

- The $M_{\rm h}/M_*(<R_{\rm opt})$-$M_*$ statistical trend agrees with the prediction of the best-fit model at $z\approx0$ in ΛCDM cosmological simulations, if the latter is scaled down by a factor ~ 0.04. This means that the amount of dark matter within $R_{\rm opt}$ is $\sim 4\%$ that of the total host halo.
- Fainter galaxies ($M_* \le 10^{10} M_\odot$) are more dark matter dominated within the optical radius than the more massive early-type galaxies (in agreement with Courteau & Dutton 2015).

Main bibliography

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$M_{\rm halo}/M_*$ in the Hubble sequence

- Extreme late-type galaxies (Scd-Im) show a high relative dark matter content within the optical disk (median of $\sim 3.6 \pm 0.2$), which is twice the median $M_{\rm h}/M_*(<R_{\rm opt})$ of earlier-type systems.

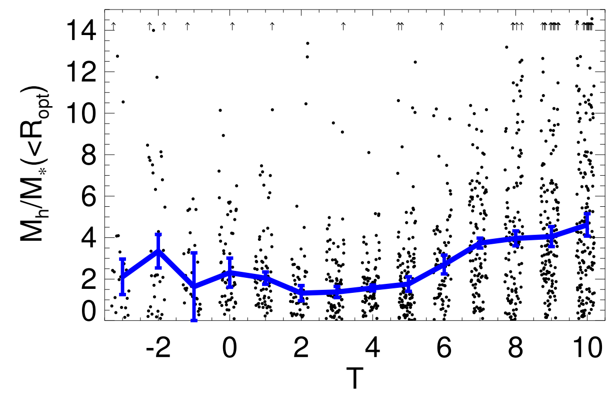

Fig 4. *$M_{\rm h}/M_*(<R_{\rm opt})$ as a function of Hubble type. The running median is overplotted in blue (error bars obtained via bootstrapping).*

Average bulge+disk component of $V_{\rm rot}$

- We show the mean disk(+bulge) component of the rotation curve in bins of M_*, obtained by averaging the individual 3.6 μm rotation curves, rescaled to a common frame in physical units.

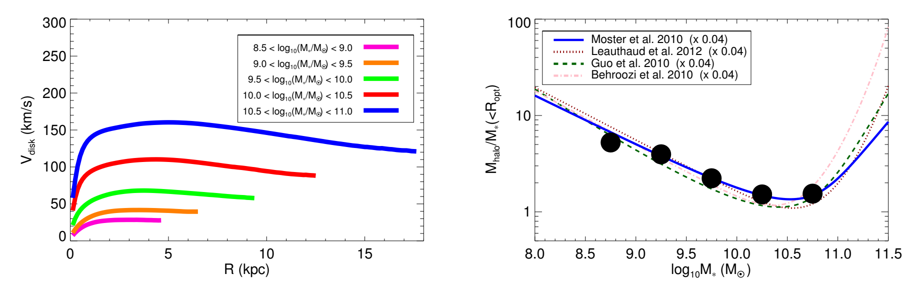

Fig 5. *Left: Mean stellar contribution to the circular velocity for different M_*-bins. Right: The central value of the M_*-bins versus the mean $M_{\rm h}/M_*(<R_{\rm opt})$. Lines correspond to estimates in cosmological simulations for the total $M_{\rm h}/M_*$ vs. M_*, scaled down by a factor 0.04.*

- From the mean $V_{\rm disk}$ rotation curves, using Eq. 4 and the mean H I velocity amplitudes, we inferred the average $M_{\rm h}/M_*(<R_{\rm opt})$. We reassess the relation between the halo-to-stellar mass ratio and M_*, successfully reproducing the slope expected from the ΛCDM cosmological simulations.

Conclusions

- We find that the amount of dark matter within the optical disk of S⁴G galaxies scales with the total stellar mass in a manner expected from the ΛCDM models (e.g. Moster et al. 2010, Behroozi et al. 2010, Guo et al. 2010, Leauthaud et al. 2012).
- Galaxies with $T \ge 5$ or $M_* \le 10^{10} M_\odot$ are found to be more dark matter dominated inside the optical disk than their early-type counterparts, on average (in agreement with Courteau & Dutton 2015 and Falcón-Barroso et al. 2015). This most likely affects their disk stability properties.

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