MDAR in the context of LCDM

Alejandro Benítez-Llambay

LCDM, Modified Gravity or new Dark Matter models?, 30th May 2017, Paris

In Collaboration with

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- Julio Navarro (Canada)
- Carlos Frenk (Durham)
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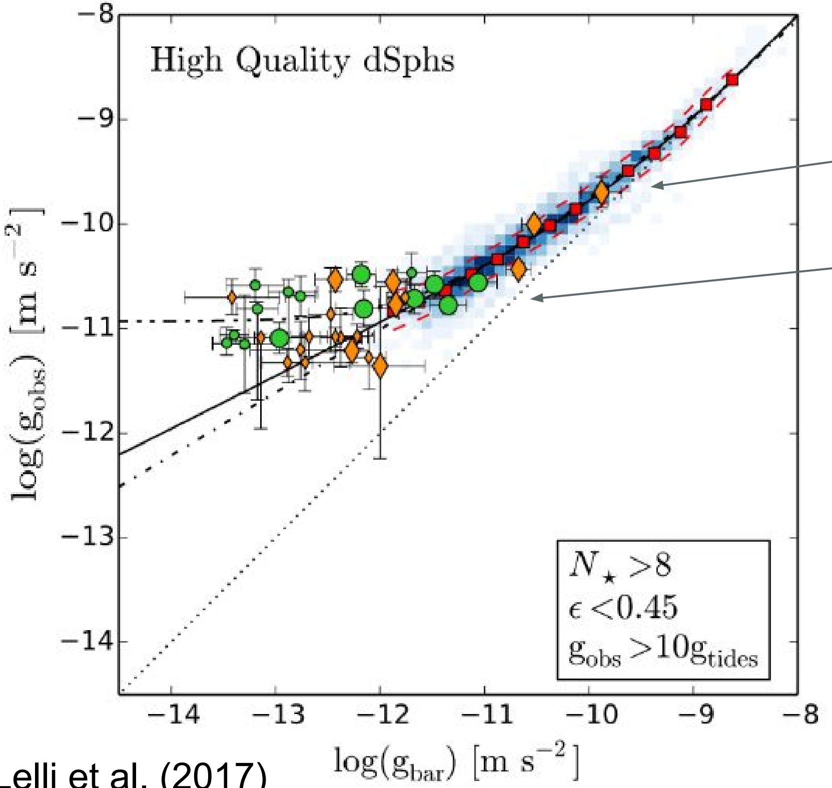
- Matthieu Schaller (Durham)
- Joop Schaye (Leiden)
- Tom Theuns (Durham)
- Rob Crain (Liverpool)
- Richard Bower (Durham)
- et al.

Aim of the talk



Lelli et al. (2017)

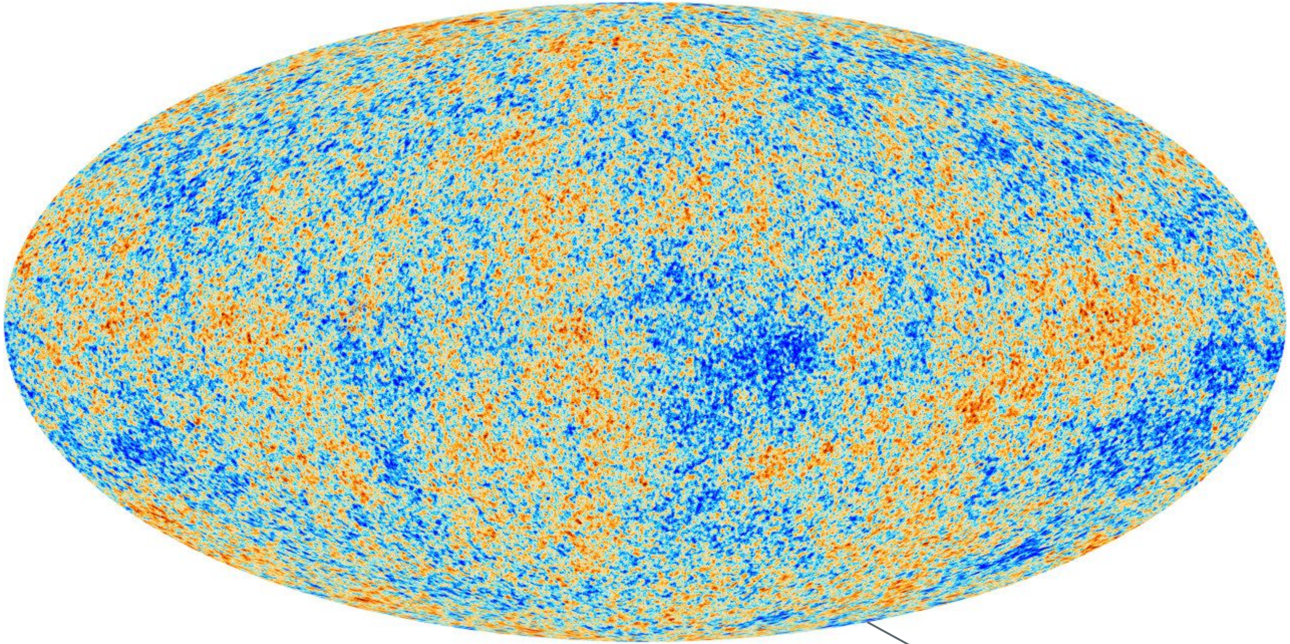
Implication of MDAR for rotationally supported galaxies:

1. Few, if any, galaxies are dark matter dominated at accelerations exceeding $a_0 \sim 10^{-10}$ m/s^2
2. Few, if any, galaxies probe accelerations below a lower limit of $a_{min} \sim 10^{-11}$ m/s^2

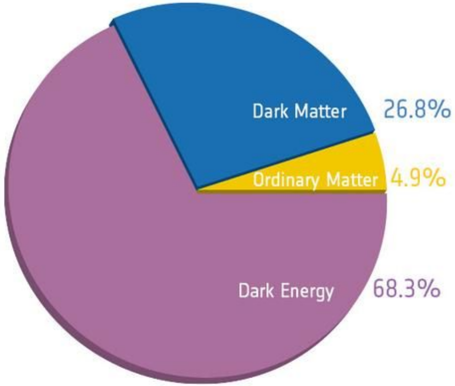
In the context of LCDM, MDAR arises as a consequence of the scaling relations between the size and the mass of galaxies and dark matter halos (see e.g., Di Cintio & Lelli 2016; Keller & Wadsley 2016; Ludlow et al. (2016); Desmond 2016).

I will try to convince you that this is indeed the case.

The Standard Model of Cosmology



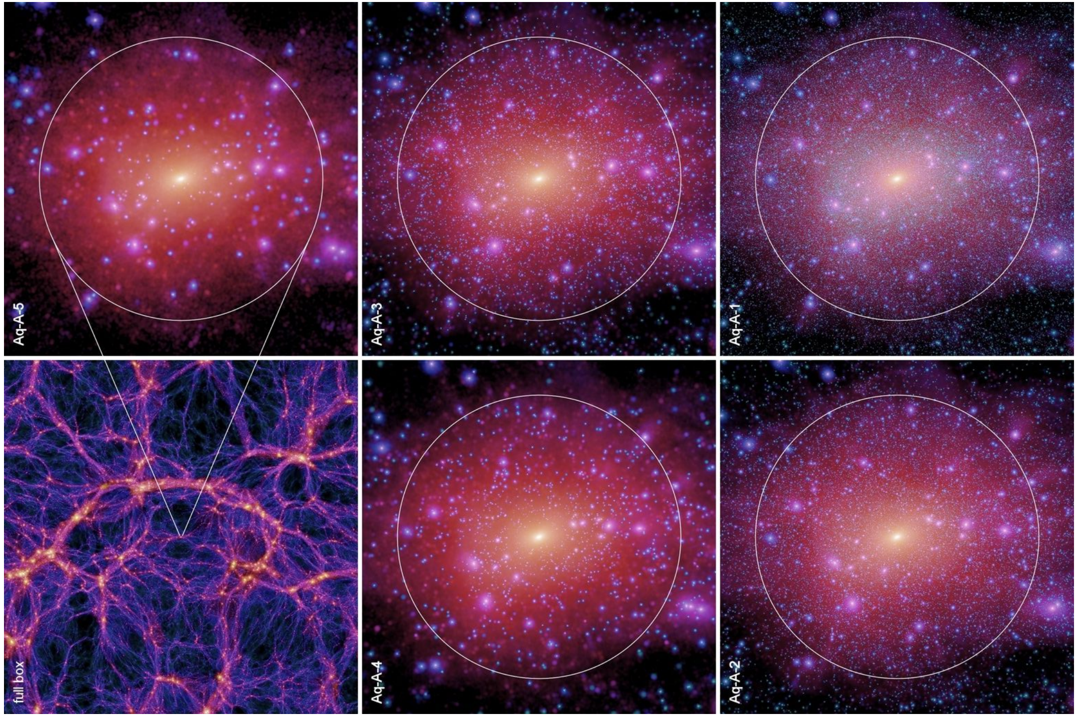
Planck Collaboration (2016)



Cosmological parameters are now known with exquisite precision.

Give us the framework to construct a model of the evolution of the Universe, assuming that the main driver of structure formation is gravity.

Structure formation



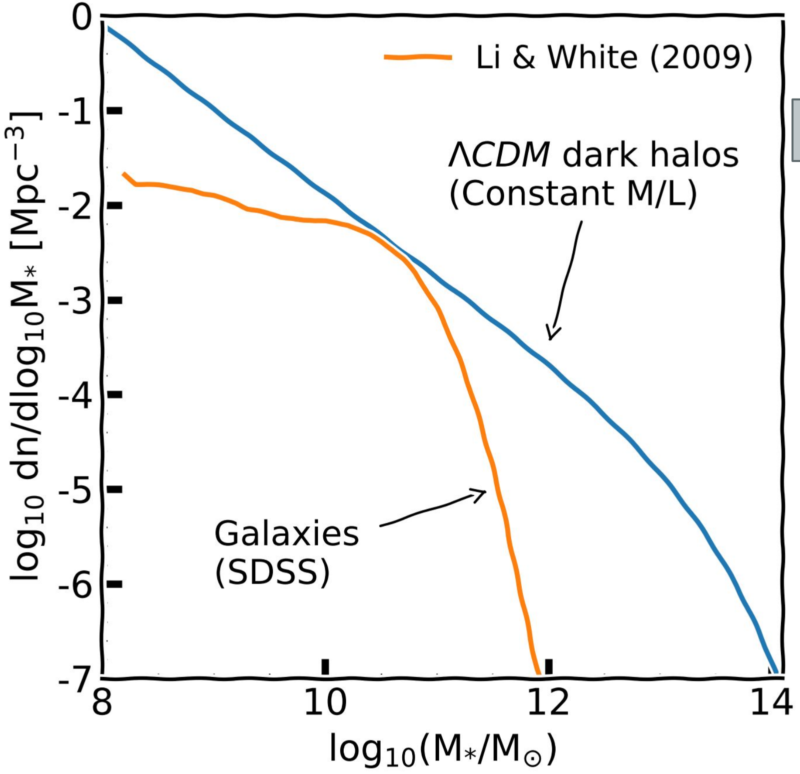
Given the cosmological parameters, there is no much freedom. Galaxies should form in the potential wells of dark matter halos, which are now well understood.

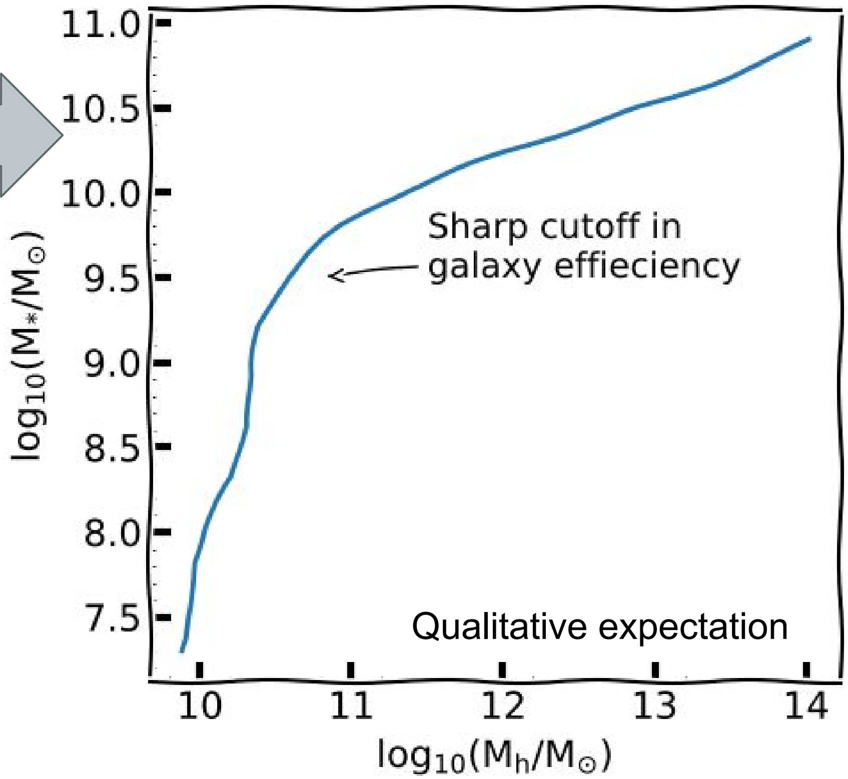
Simulations have enabled a full characterization of the clustering of cold dark matter on all astrophysically-relevant scales: from scales smaller than any observed galaxy, to scales larger than any observed galaxy cluster

$$\rho(r) = \frac{\rho_0}{\frac{r}{R_s}\left(1 + \frac{r}{R_s}\right)^2}$$ (NFW profile)

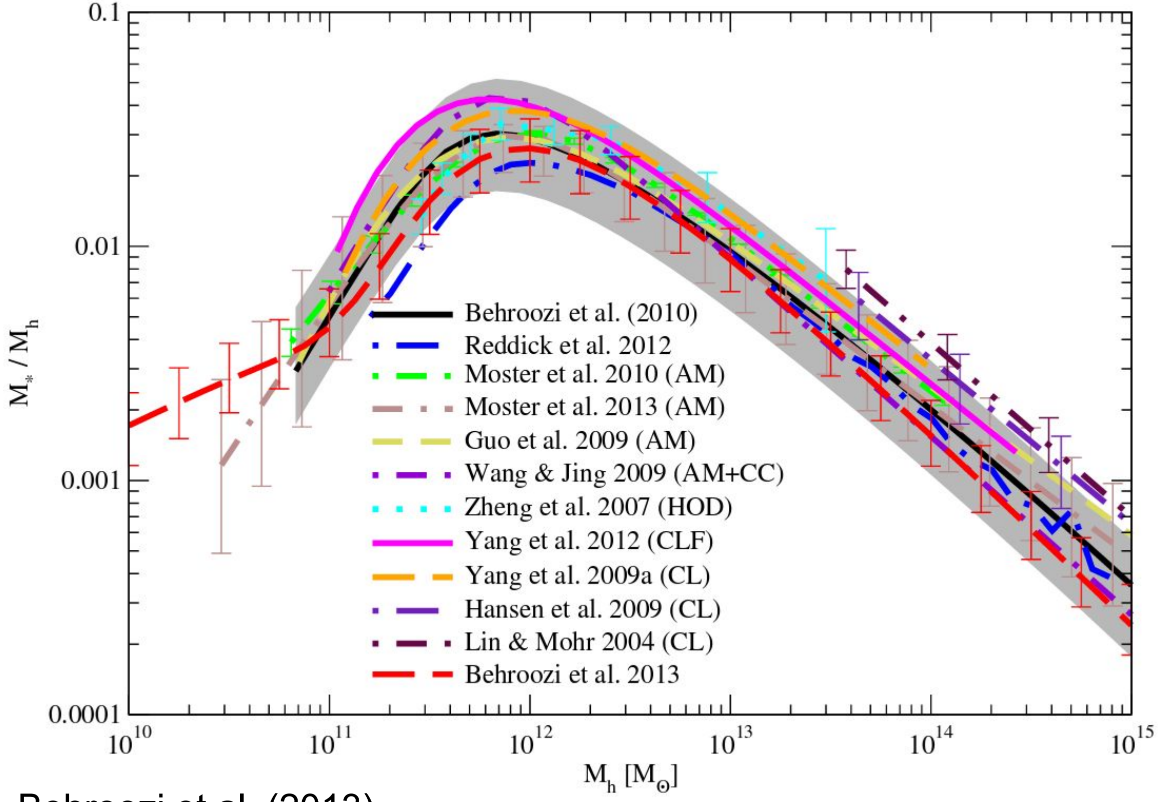
Aquarius project - Springel et al. (2008)

Galaxy-halo connection





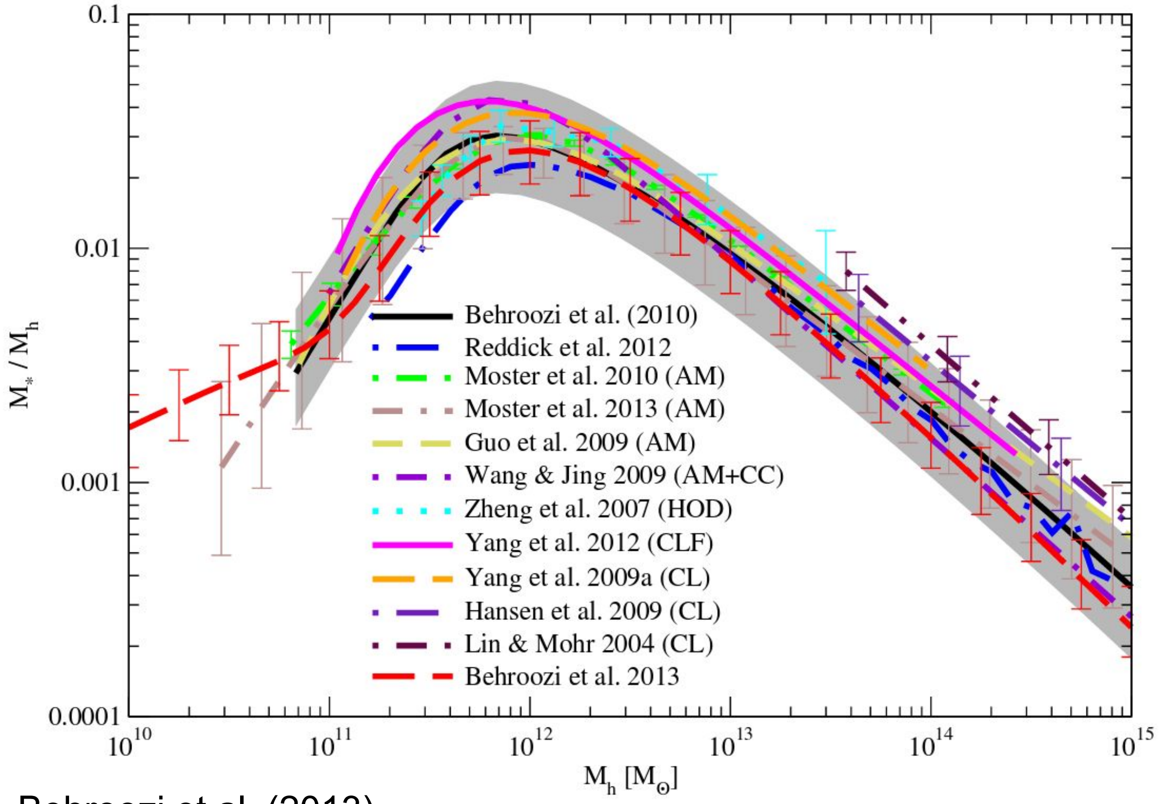
Galaxy-halo connection



Behroozi et al. (2013)

Less than 20% of the available baryons in the Universe condense to form a galaxy in the potential wells of dark matter halos. The efficiency is reduced further at low/high masses.

Galaxy-halo connection

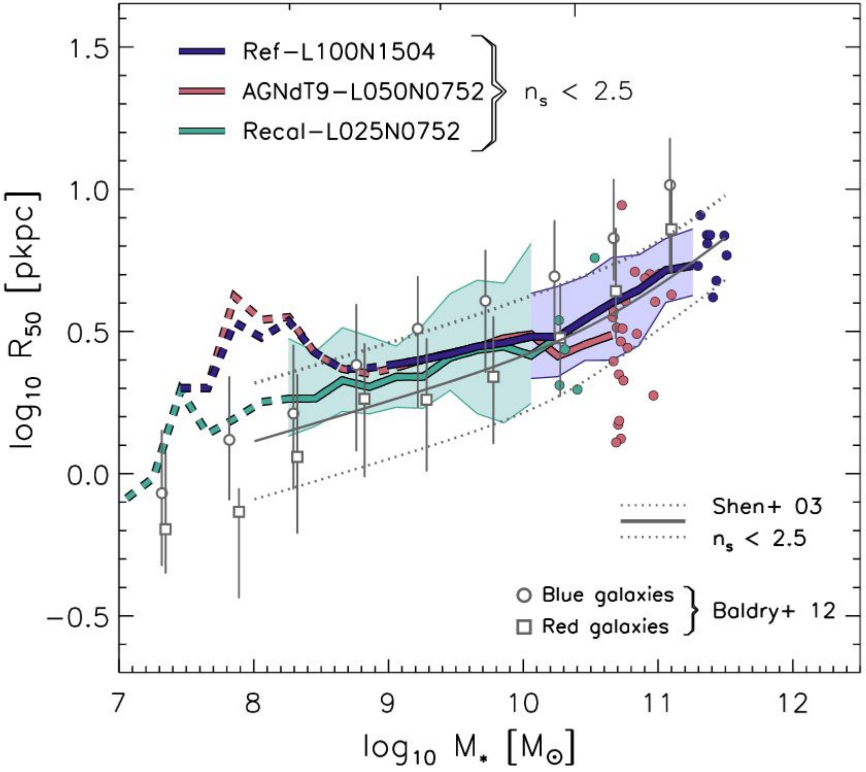


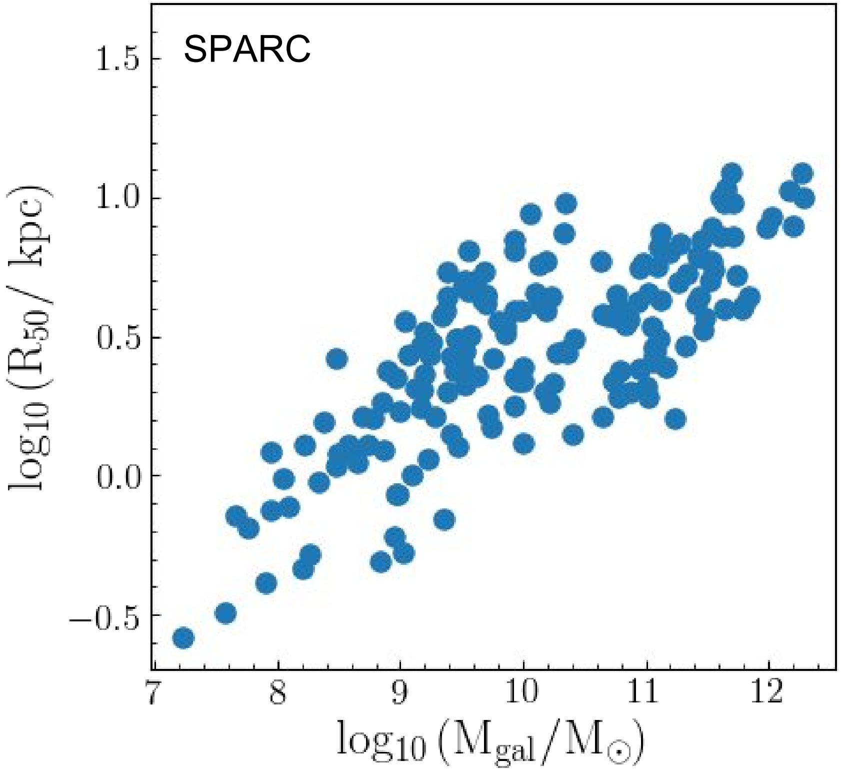
Behroozi et al. (2013)

Less than 20% of the available baryons in the Universe condense to form a galaxy in the potential wells of dark matter halos. The efficiency is reduced further at low/high masses.

We know “how” to populate halos with galaxies.

Empirical galaxy mass-size relation

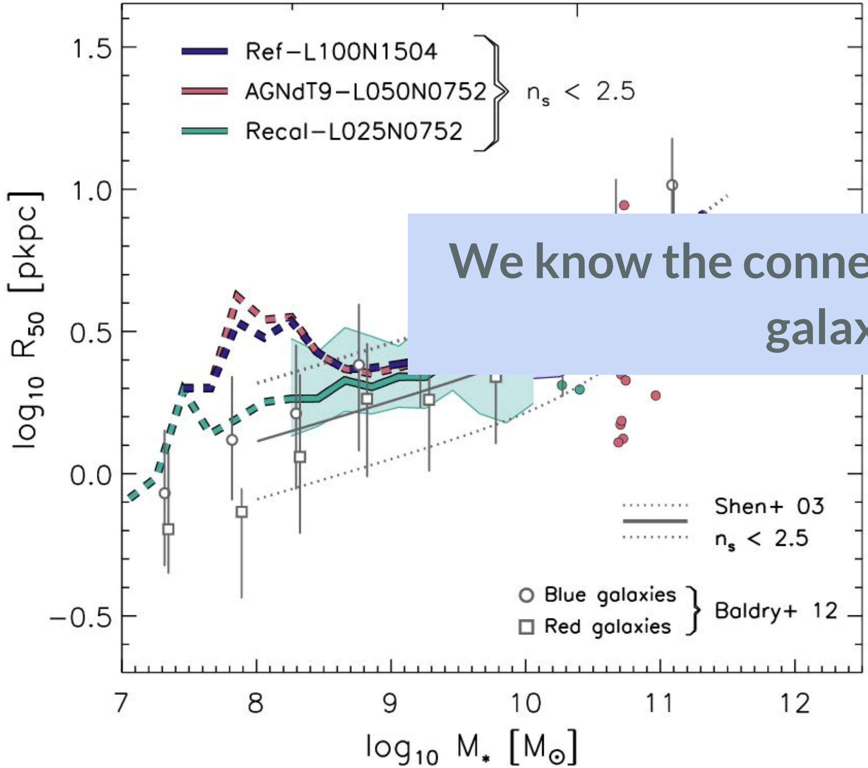




Schaye et al. (2015)

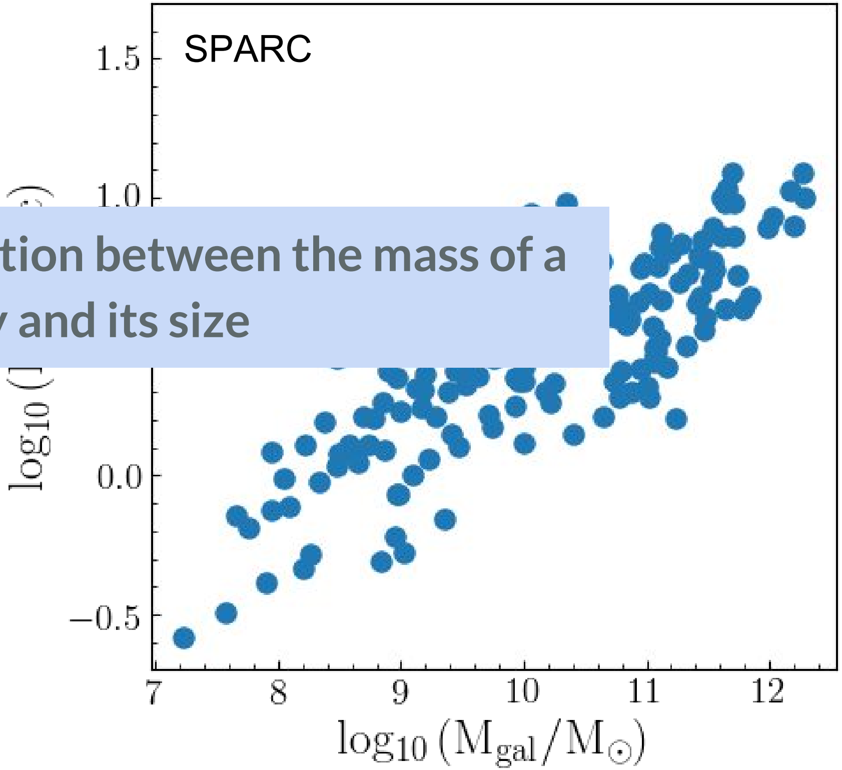
Lelli et al. (2016)

Empirical galaxy mass-size relation



Schaye et al. (2015)

We know the connection between the mass of a galaxy and its size



Lelli et al. (2016)

Mass distribution

Dark matter halos are well described by the Navarro, Frenk & White profile (Navarro et al. 1996,1997)

$$\rho(r) = \frac{\rho_0}{\frac{r}{R_s}\left(1 + \frac{r}{R_s}\right)^2}$$

Disk galaxies are well described by exponential profiles (e.g., Freeman 1970, Boroson 1981; Bland-Hawthorn et al. 2005, and references therein).

$$\Sigma(R) = \Sigma_0 e^{-R/R_d}$$

$$\Sigma_0 = \frac{M_{gal}}{2\pi R_d^2} \qquad R_{50} = 1.678 \times R_d$$

Properties of NFW halos

$$M(x) = M_{200} \frac{\ln(1+cx) - cx/(1+cx)}{\ln(1+c) - c/(1+c)}$$

(Enclosed mass)

$$x = \frac{r}{r_{200}}$$

$$g(x) = V_{200}^2 \frac{1}{x^2} \frac{\ln(1+cx) - cx/(1+cx)}{\ln(1+c) - c/(1+c)}$$

(Acceleration profile)

$$\lim_{x \to 0} g(x) = g_{dm}^{\max} = \frac{V_{200}^2}{2} \frac{c^2}{\ln(1+c) - c/(1+c)}$$

(Maximum central acceleration reached by a NFW halo)

Note that the only freedom here is the halo mass. The concentration parameter is a well-known function of the halo mass / power spectrum (e.g., Ludlow et al. 2016).

Properties of NFW halos

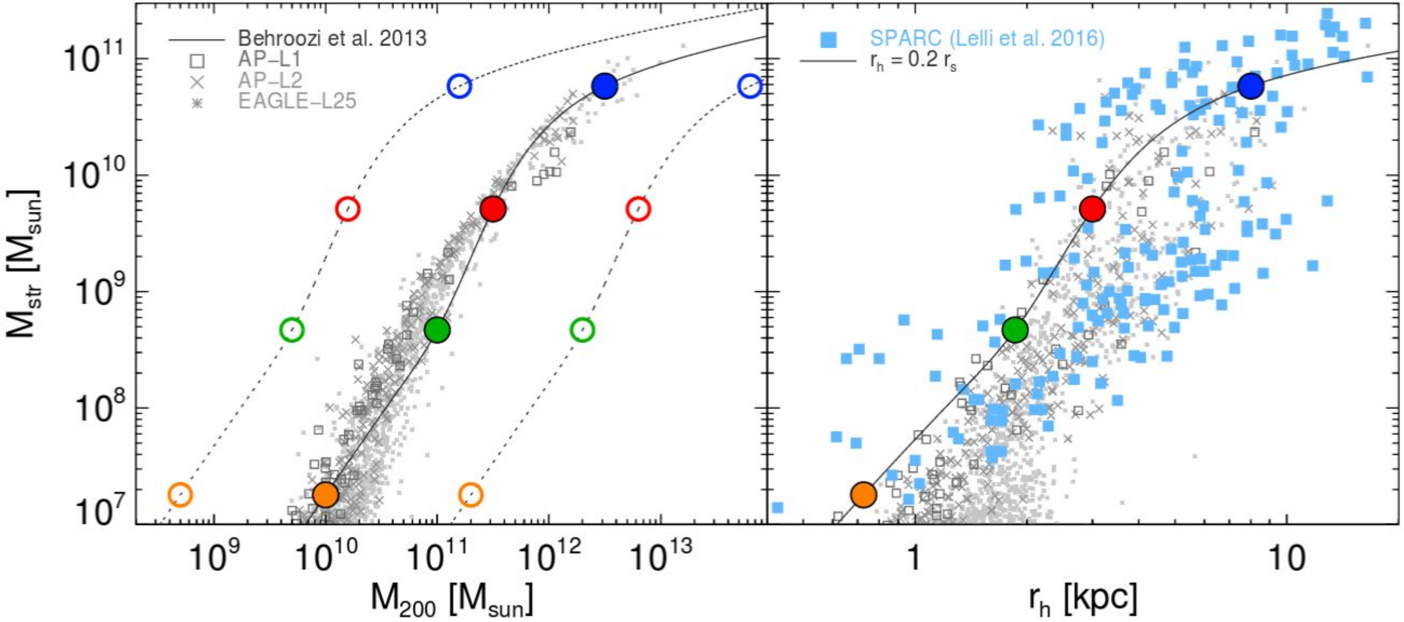
$$M(x) = M_{200}\frac{\ln(1+cx) - cx/(1+cx)}{\ln(1+c) - c/(1+c)}$$ (Enclosed mass) $$x = \frac{r}{r_{200}}$$

$$g(x) = V_{200}^2\frac{1}{x^2}\frac{\ln(1+cx) - cx/(1+cx)}{\ln(1+c) - c/(1+c)}$$ (Acceleration profile)

$$\lim_{x\to 0} g(x) = g_{dm}^{\max} = \frac{V_{200}^2}{2}\frac{c^2}{\ln(1+c) - c/(1+c)}$$ (Maximum central acceleration reached by a NFW halo)

$$\boxed{g_{\rm dm}^{\max} \approx 1.15 \times 10^{10}\left(\frac{m}{s^2}\right)\left(\frac{M_{200}}{10^{12}M_\odot}\right)^{1/3}\left(\frac{f(c)}{35}\right)}$$

MDAR in the context of ΛCDM



$$\Sigma(R) = \Sigma_0 e^{-R/R_d}$$

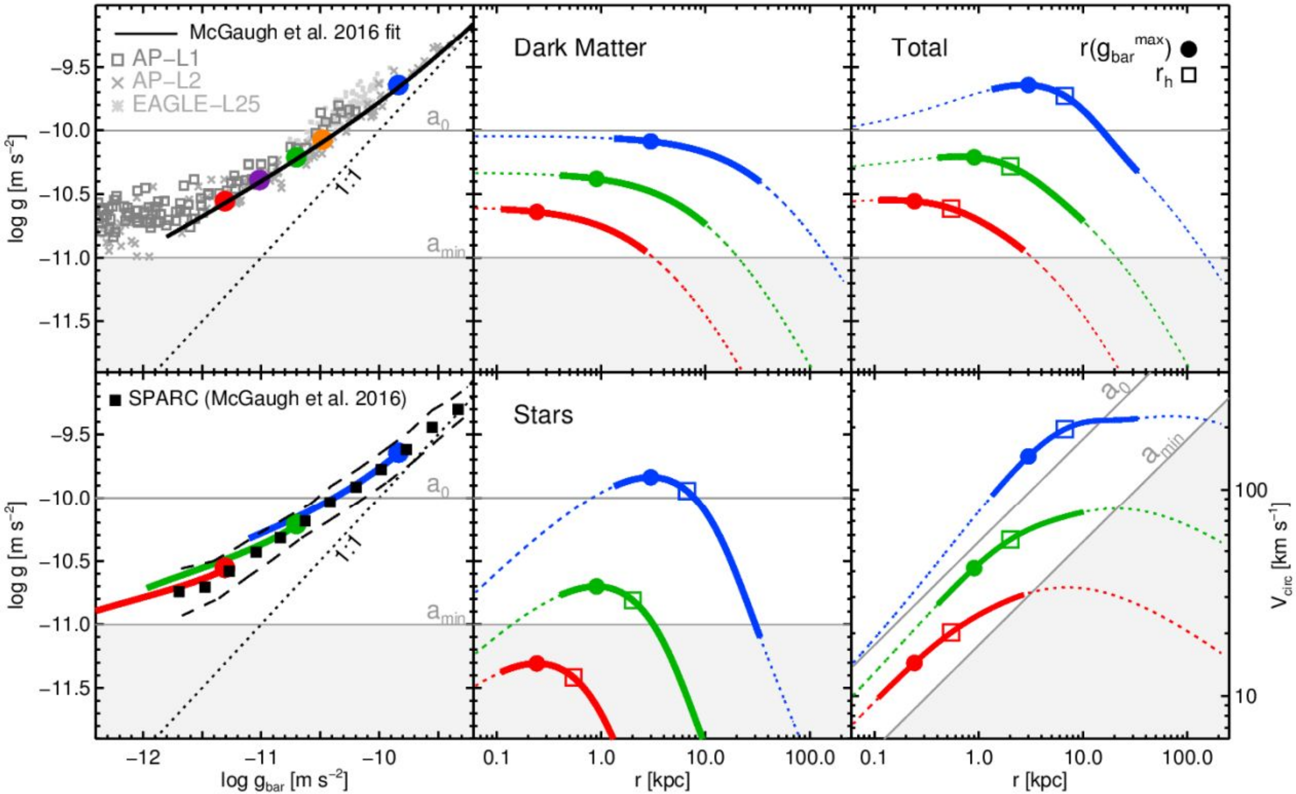
$$\Sigma_0 = \frac{M_{gal}}{2\pi R_d^2}$$

$$R_{50} = 1.678 \times R_d$$

$$R_{50} = 0.2 r_s = 0.2 \frac{R_{200}}{c}$$

Navarro et al. (2016)

MDAR in the context of ΛCDM

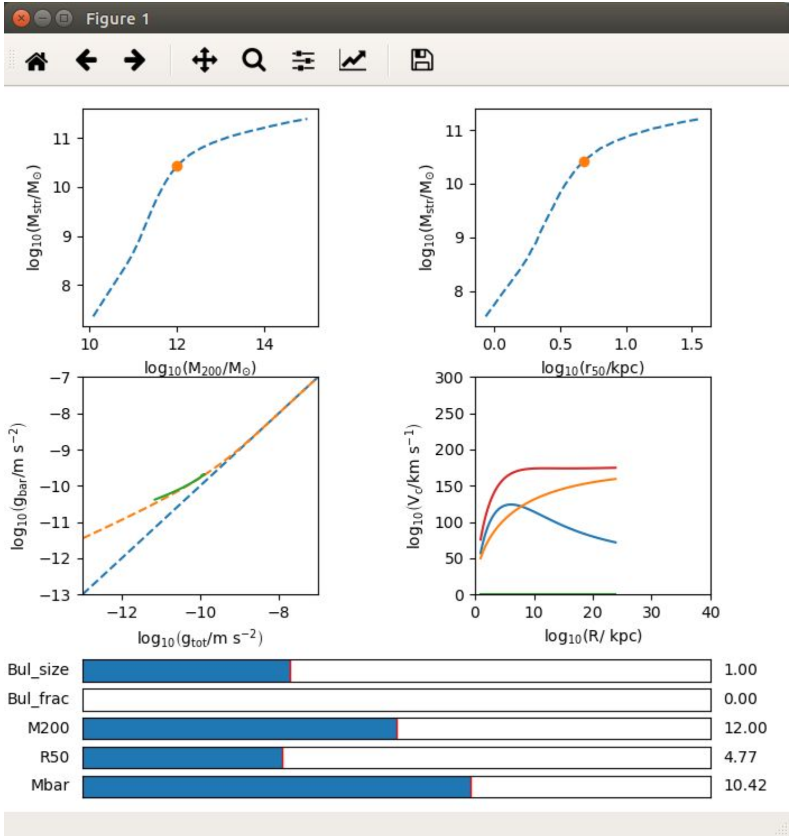


Halo masses change two orders of magnitude, and the central acceleration of the halo changes a factor of 3 (middle top).

Grey solid regions show accelerations below 10-11, which are forbidden for isolated galaxies in this simple model of galaxy formation.

Navarro et al. (2016)

Ipython notebook to explore this further



https://github.com/alejandrobll/Model_MDAR

Clone the repository and run:

python MDAR_mpl.py

MDAR in more realistic ΛCDM simulations?

The EAGLE/APOSTLE suit of cosmological simulations

APOSTLE

Zoom-in simulations of Local Groups.

Simulations at high resolution (stellar particle mass of ~ 5x10^3 M_o).

They match the stellar mass function over 4 decades in stellar mass; the shape of disk galaxy rotation curves; the zero-poin, slope, and scatter of the Tully-Fished relation.

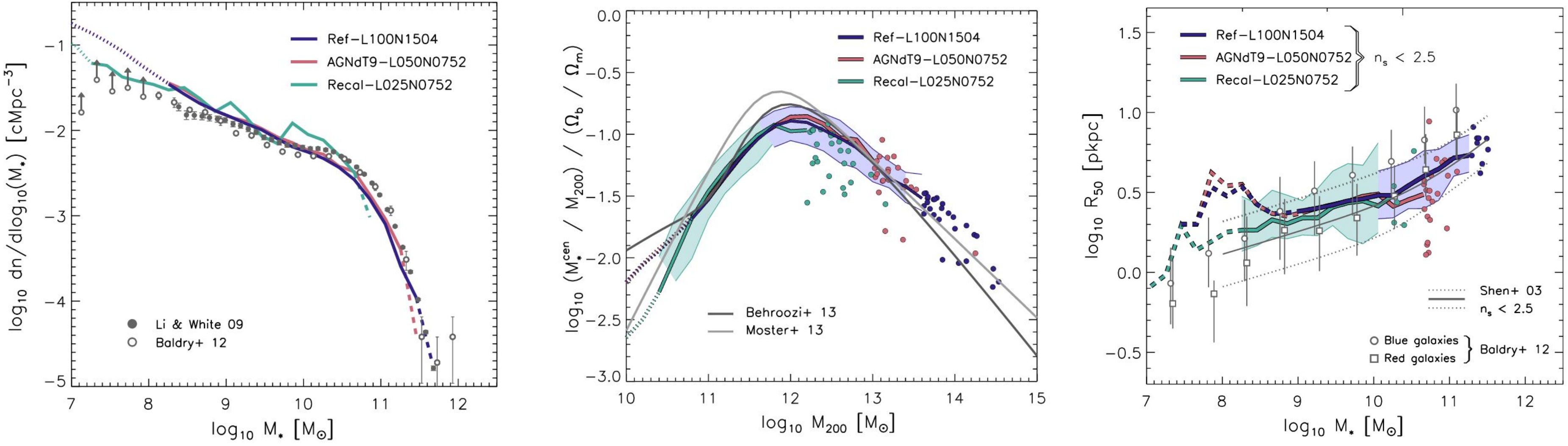
EAGLE

Hydrodynamical simulations that follow the formation of galaxies in cosmologically representative volumes.

Name	L (cMpc)	N	m_g $(M_\odot)$	m_{dm} $(M_\odot)$	ϵ_{com} (comoving kpc)	ϵ_{prop} (pkpc)
L025N0376	25	376^3	1.81×10^6	9.70×10^6	2.66	0.70
L025N0752	25	752^3	2.26×10^5	1.21×10^6	1.33	0.35
L050N0752	50	752^3	1.81×10^6	9.70×10^6	2.66	0.70
L100N1504	100	1504^3	1.81×10^6	9.70×10^6	2.66	0.70

The EAGLE/APOSTLE suit of cosmological simulations

Eagle simulation was calibrated to reproduce the current stellar mass function, and galaxy sizes. The freedom during the calibration process is in the parameters of stellar feedback. Note, however, that the shape of a galaxy profile is an outcome of the simulation.

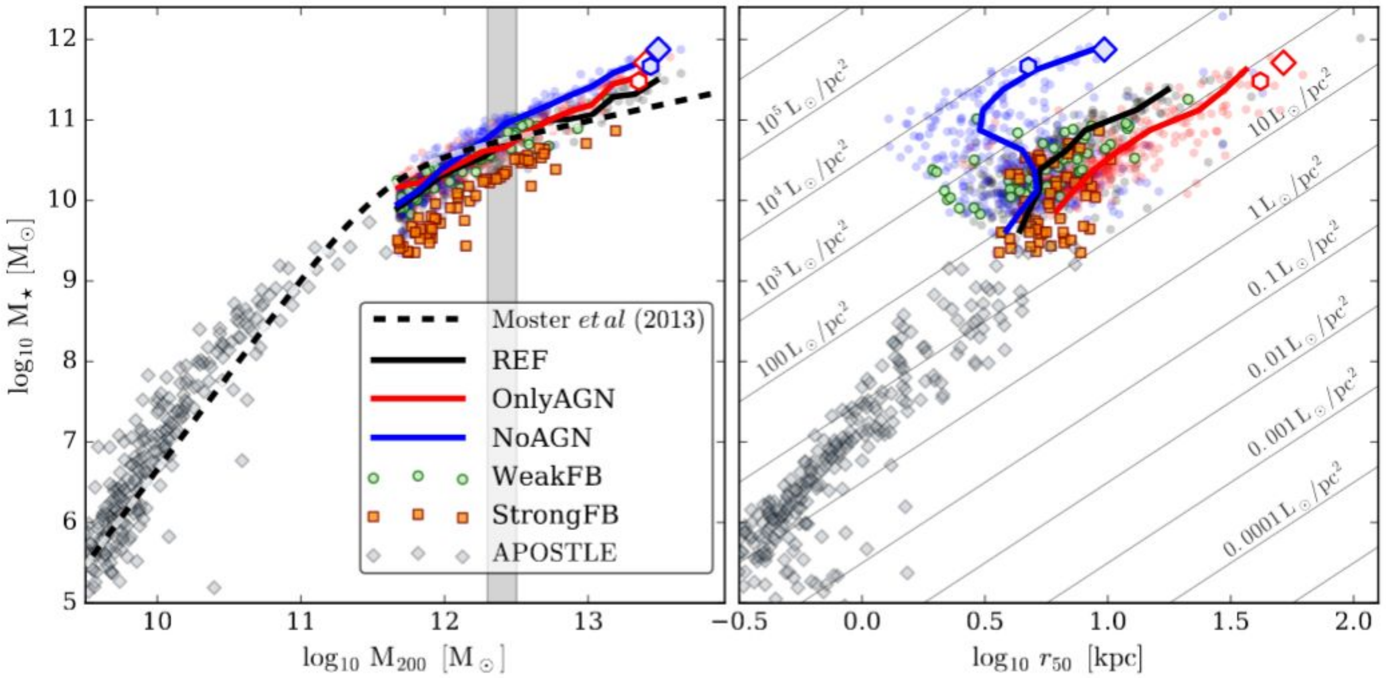


Schaye et al. (2015)

The underestimation of the galaxy luminosity function at the knee (left) has a noticeable impact in the halo mass - galaxy mass relation (middle)

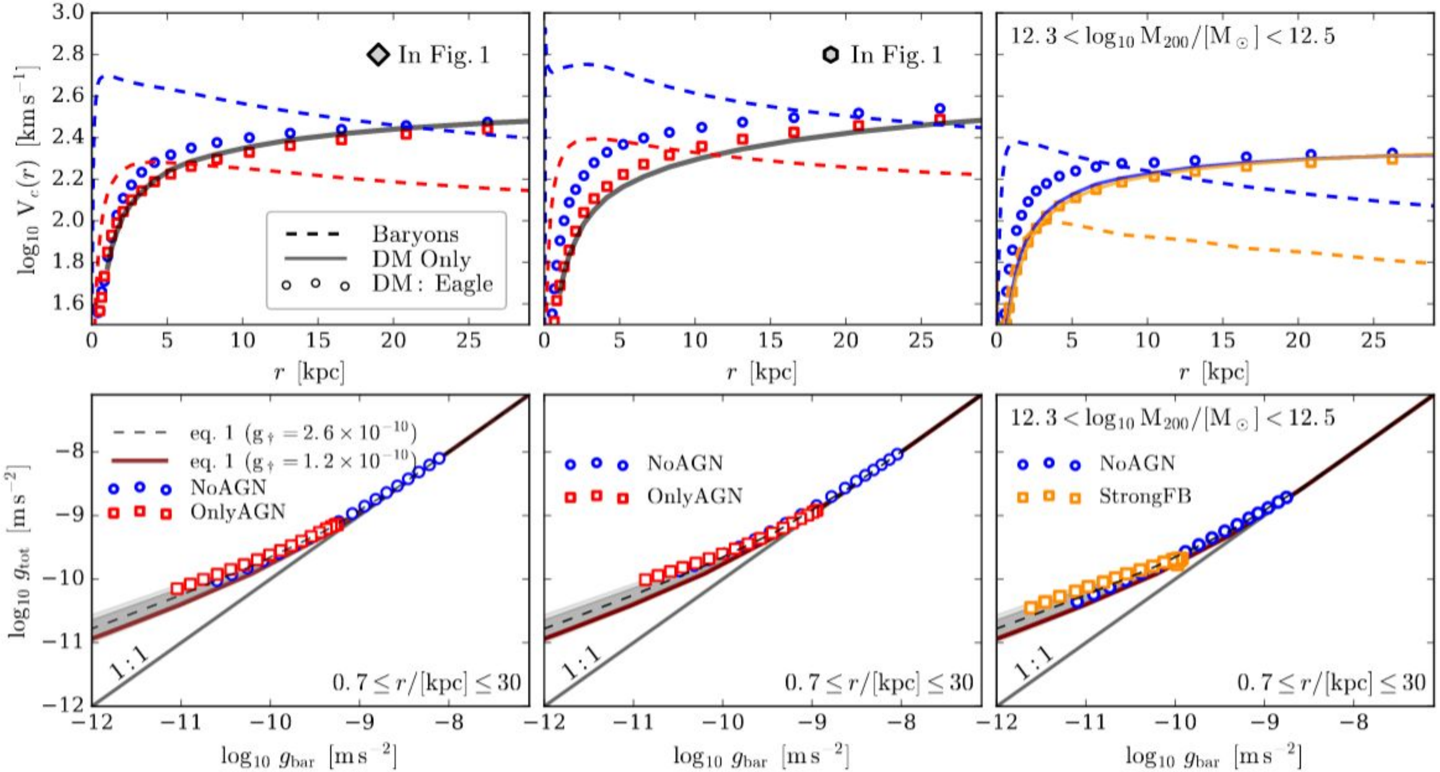
Galaxy properties in EAGLE/APOSTLE

Galaxy stellar mass vs halo mass (left) and vs galaxy size (right)

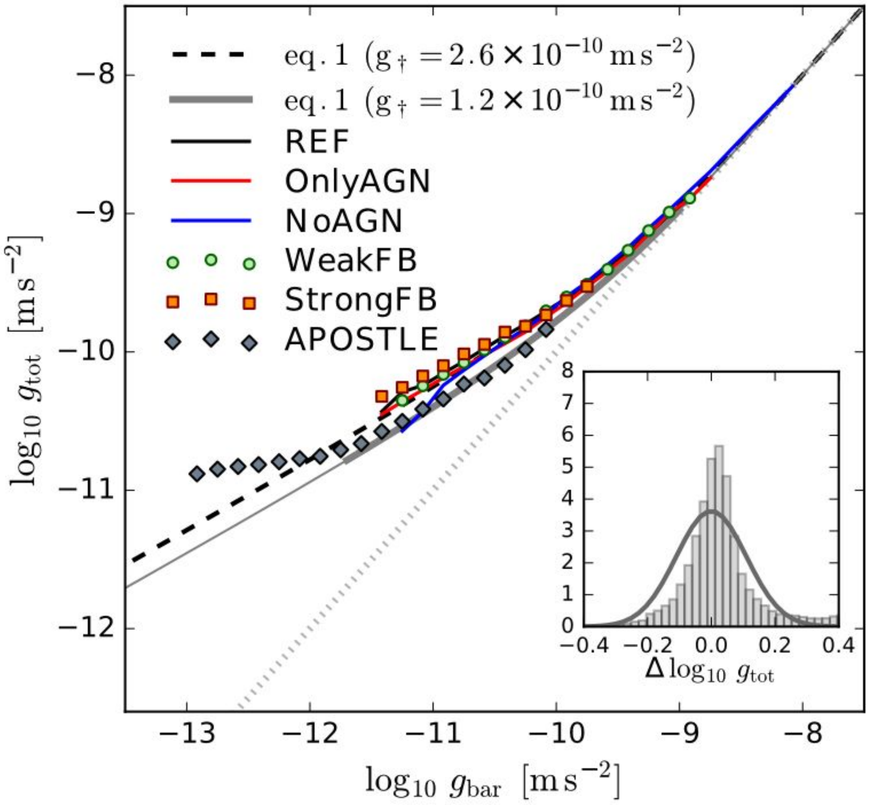


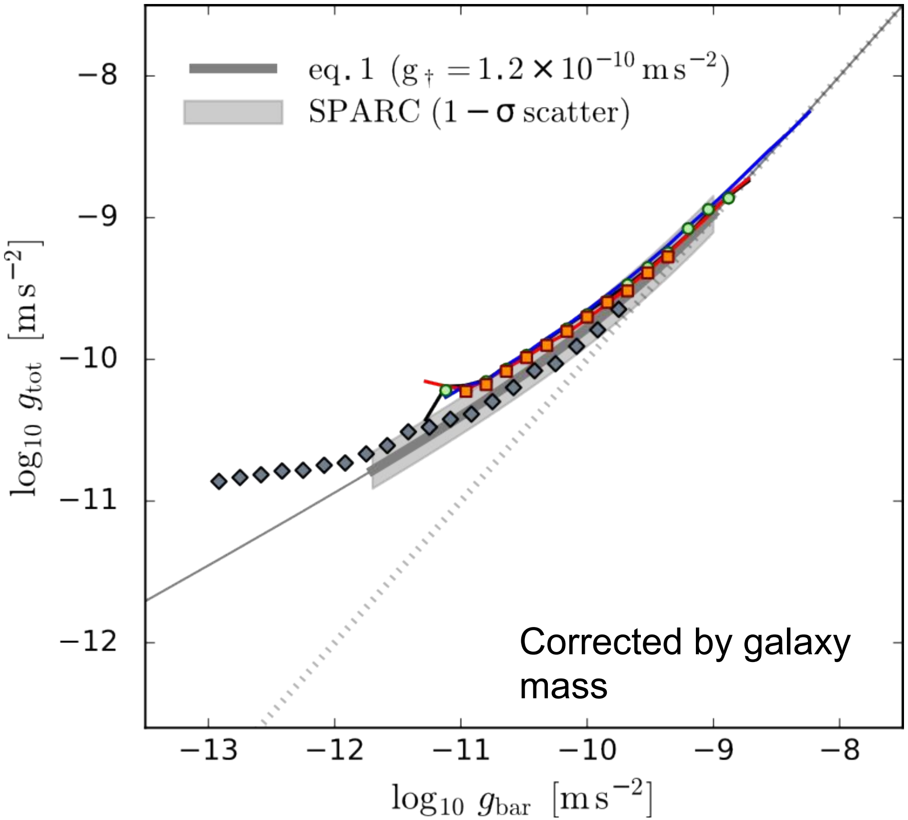
Ludlow et al. (2017)

Rotation curves



MDAR relation in EAGLE





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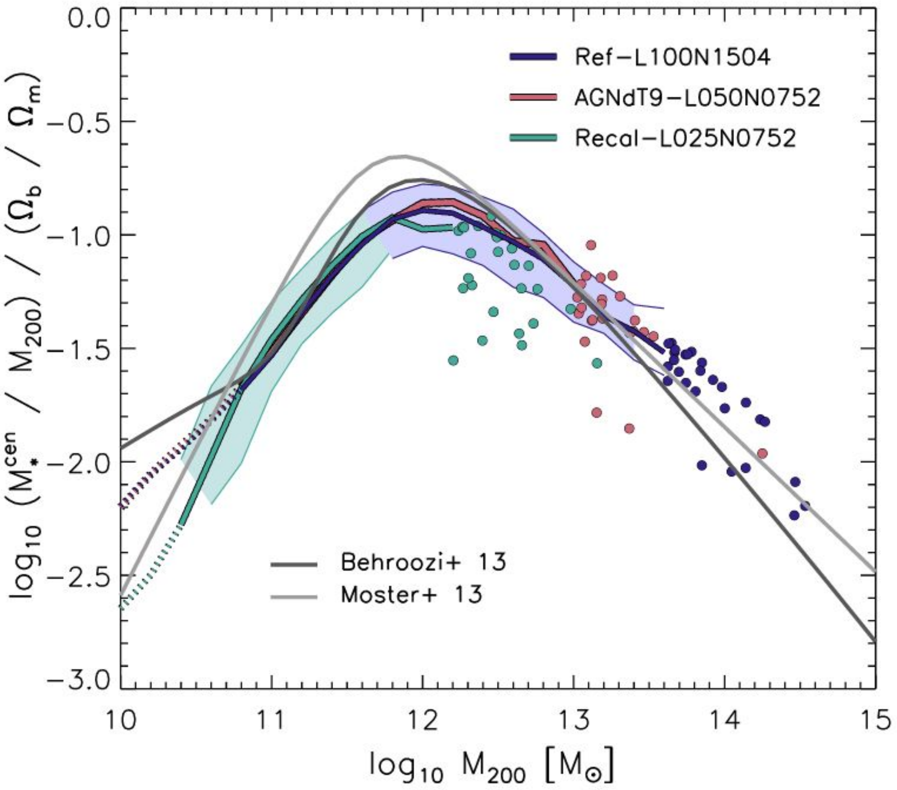
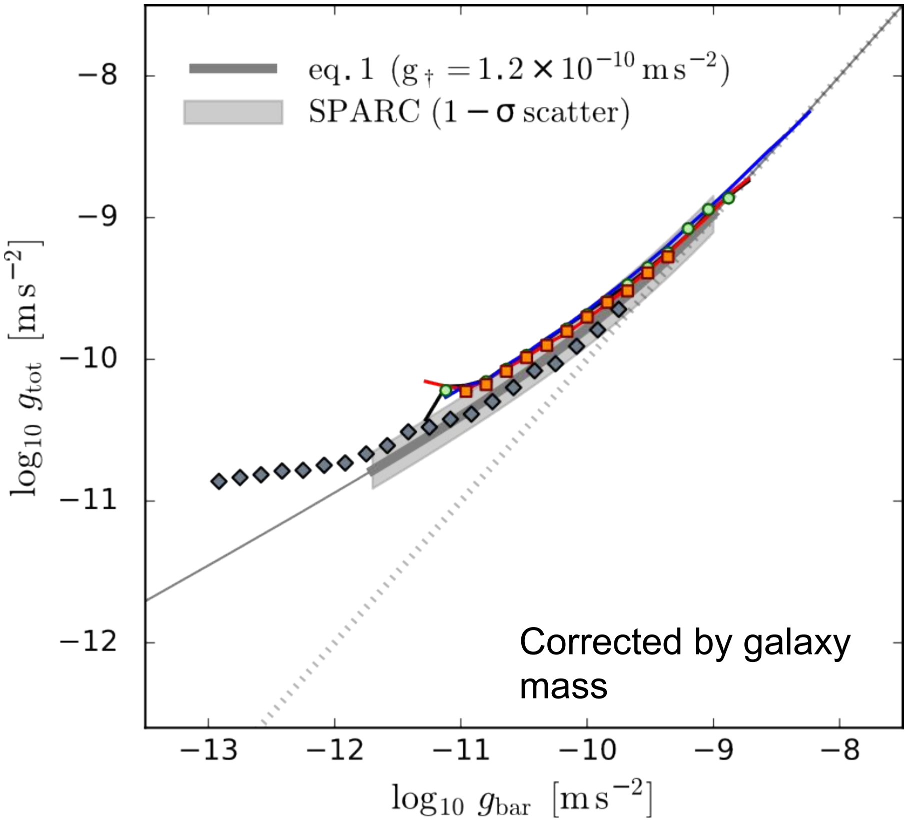




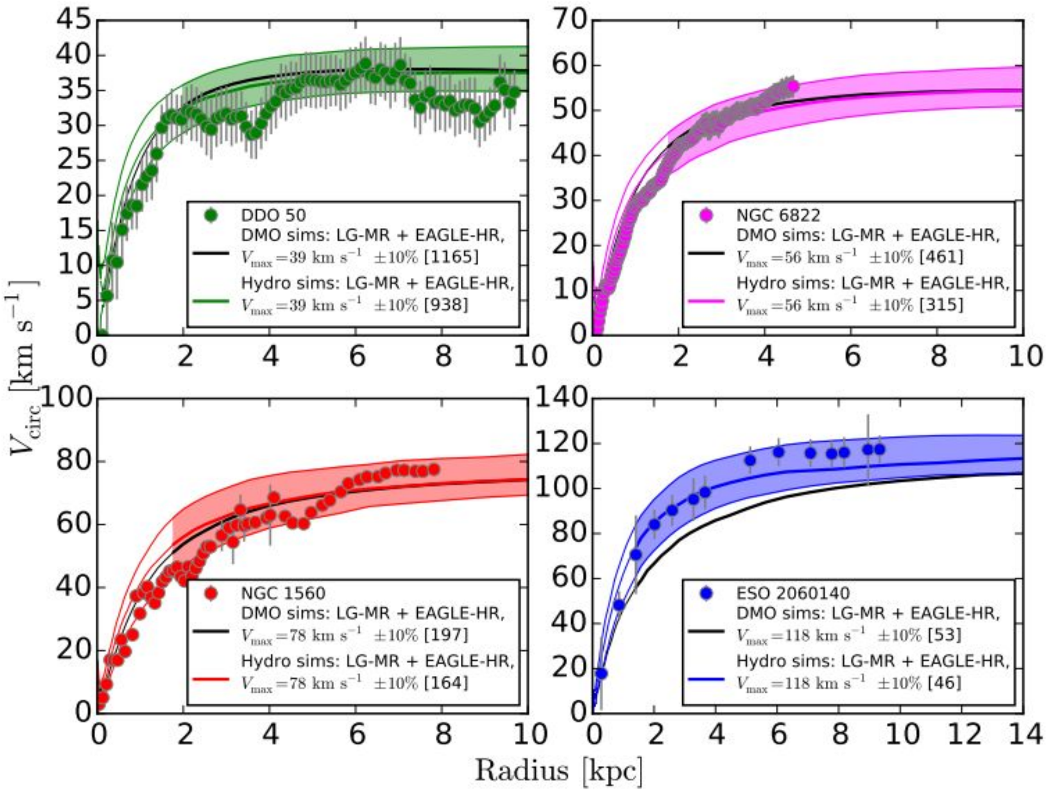
Corrected by galaxy mass

Lessons from ΛCDM+EAGLE/APOSTLE

- Disk galaxies in ΛCDM form at the centre of dark matter halos.
- Simulations are able to simulate a realistic population of galaxies, provided the "unresolved" physical processes are calibrated.
- The radial acceleration relation is very forgiving: only *large* departures from any sensible galaxy-halo scaling relations lead to noticeable systematics.
- The total baryonic acceleration depends *slightly but systematically* on the subgrid model. The differences are, however, small compared to the observational scatter.
- Galaxies with the right scaling relations are consistent with the empirical MDAR.

Challenges for ΛCDM

$$V_{circ} = \sqrt{\frac{GM}{r}}$$



Four rotation curves that are well fit by hydrodynamical ΛCDM, from dwarfs to L_*

Oman et al. (2015)

Challenges for ΛCDM

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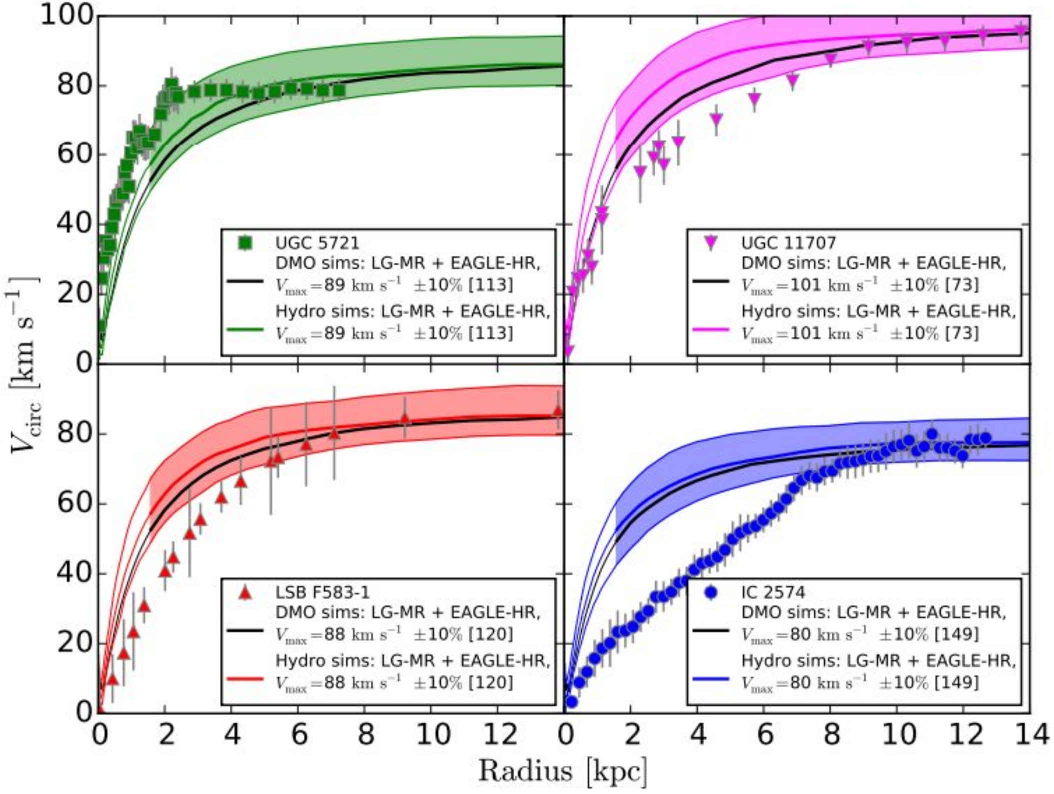
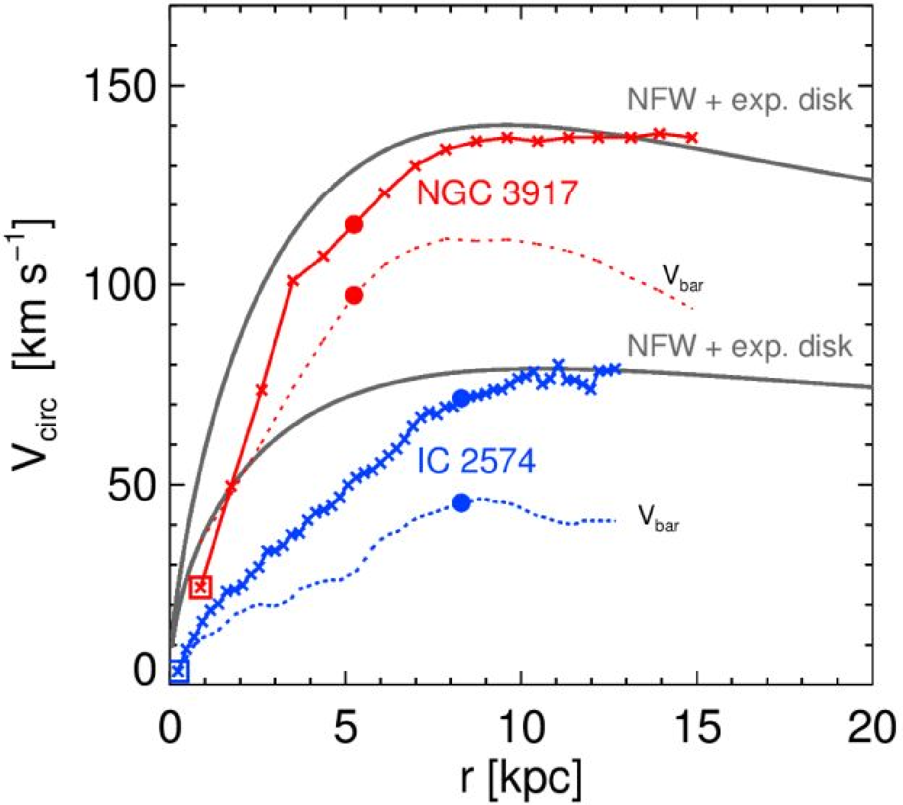
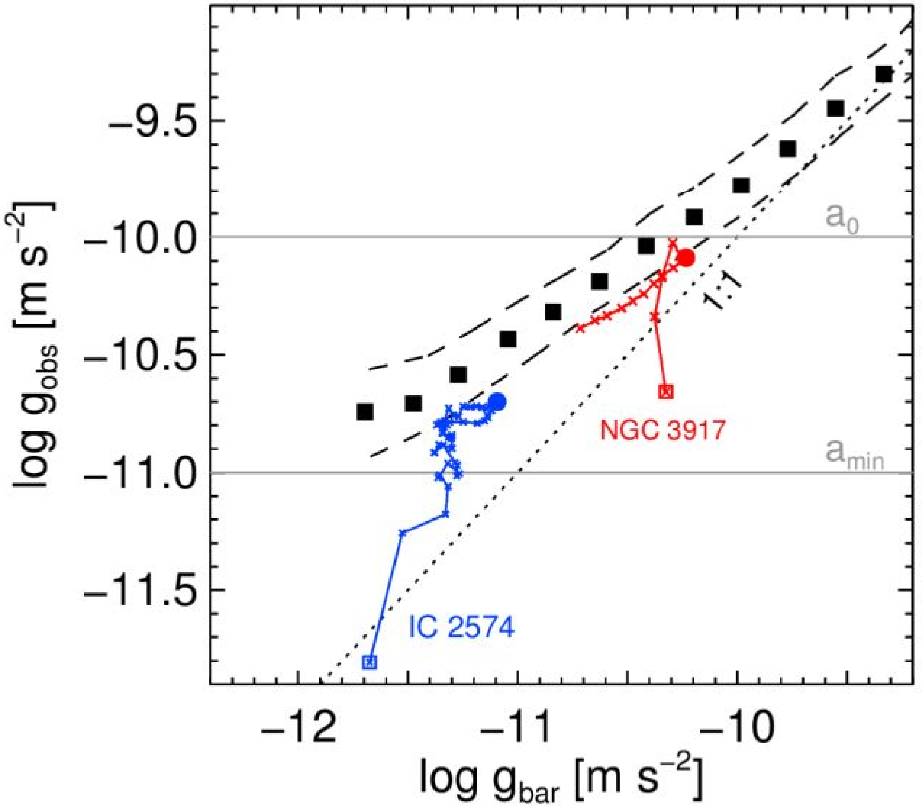


Four rotation curves that are not well fit by hydrodynamical ΛCDM, from dwarfs to L_*

Oman et al. (2015)

Galaxies with inner mass deficit





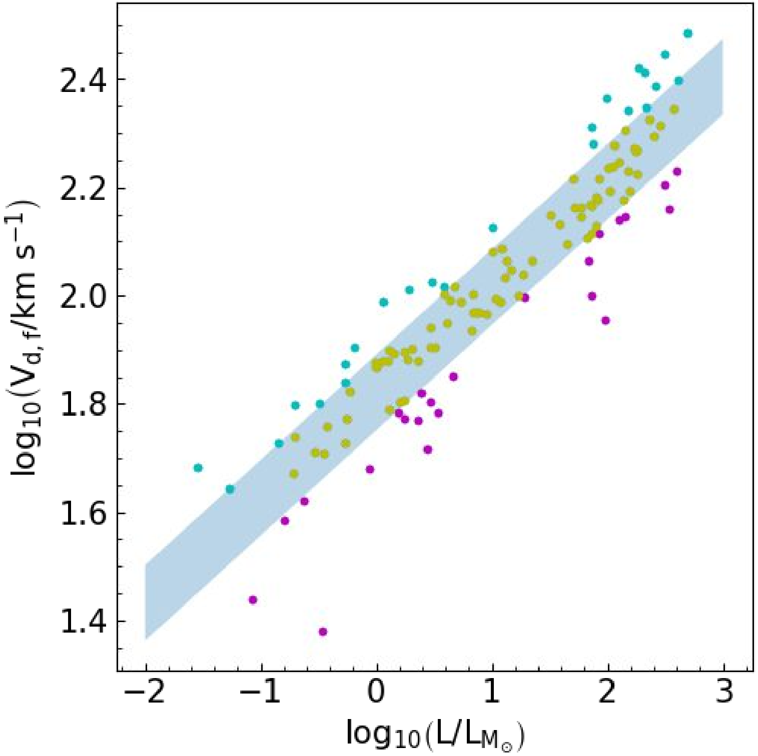
Corollaries of LCDM

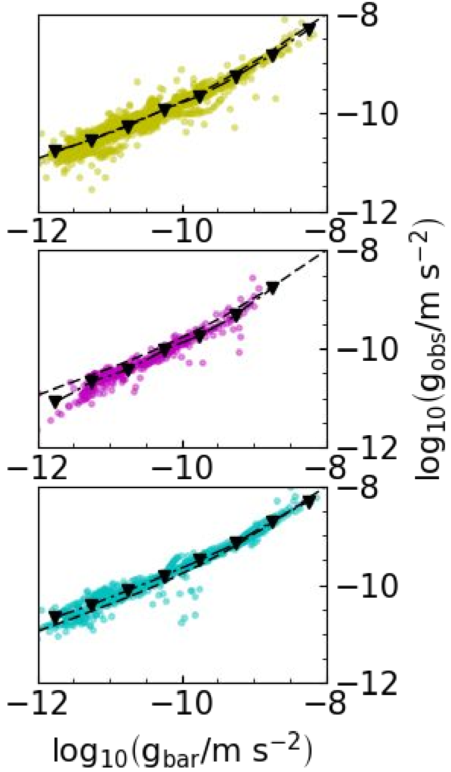
- At a given luminosity, galaxies with systematically lower/higher baryon fraction should deviate systematically from the mass discrepancy- acceleration relation: galaxies with lower/higher baryon fractions should be systematically above/below the relation. (Self-similarity of dark matter halos)

- Galaxies inhabiting high/low mass halos should also deviate from the mass discrepancy-acceleration relation, because the maximum central acceleration of a dark matter halo increases with halo mass.

Systematics in MDAR

$$V_{obs}^2(R) - V_{bar}^2(R) = V_{dm}^2(R)$$

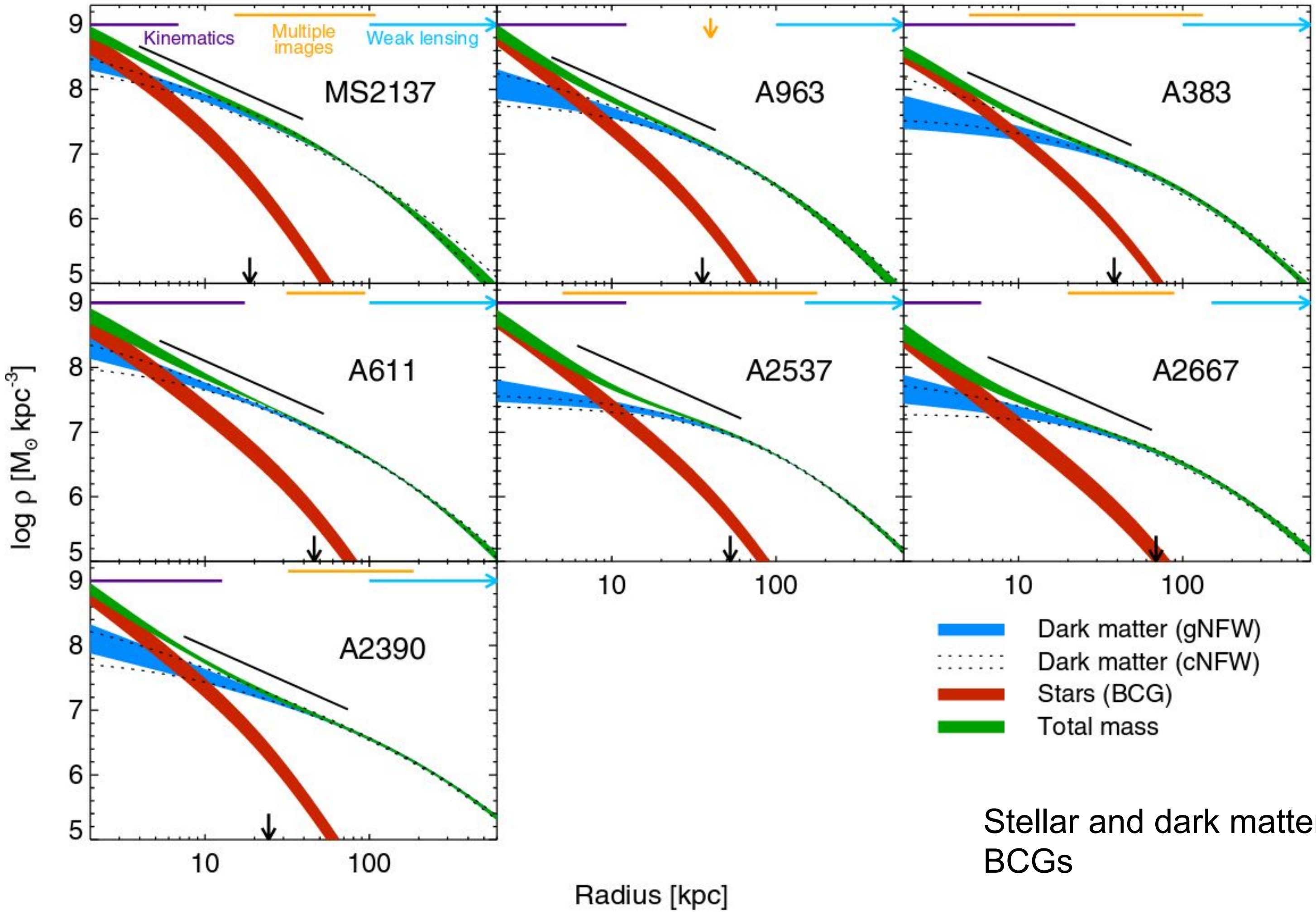




We measure the enclosed dark matter mass at R_{eff} .

Galaxies that need more/less dark matter at a given radius, need more/less dark matter at all radii. This is consistent with self-similarity of dark matter halos.

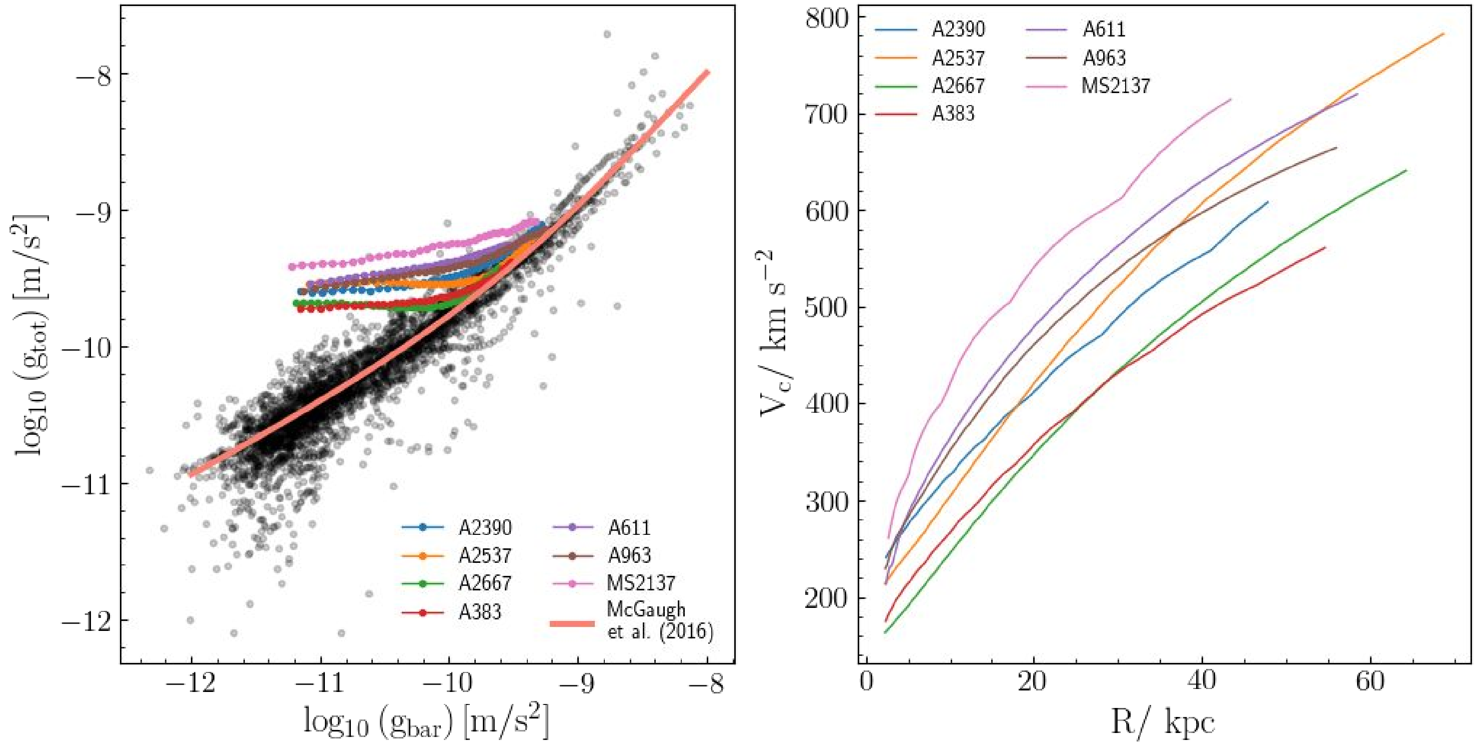
Data from SPARC (Lelli et al 2016)



Stellar and dark matter content within around BCGs

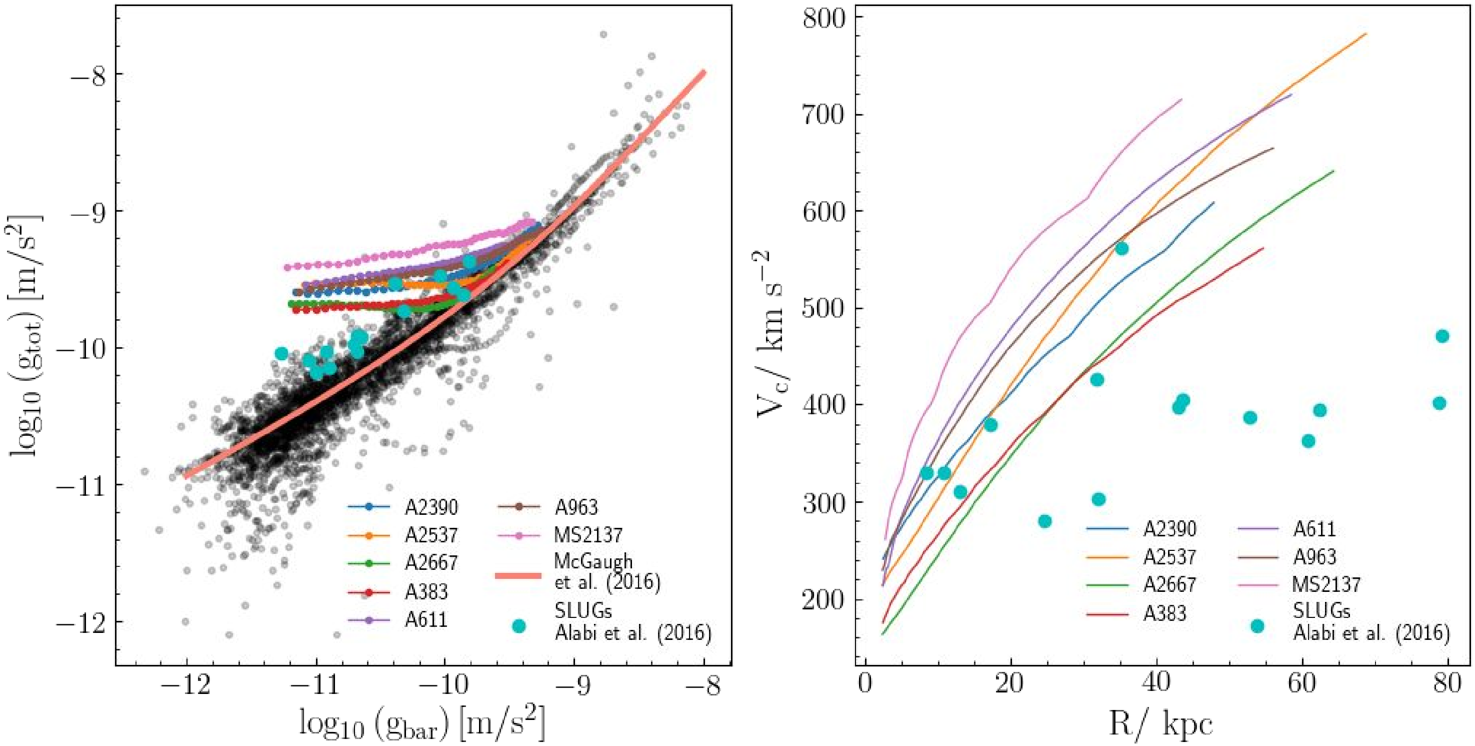
Newman et al. (2012)

Systematics in MDAR



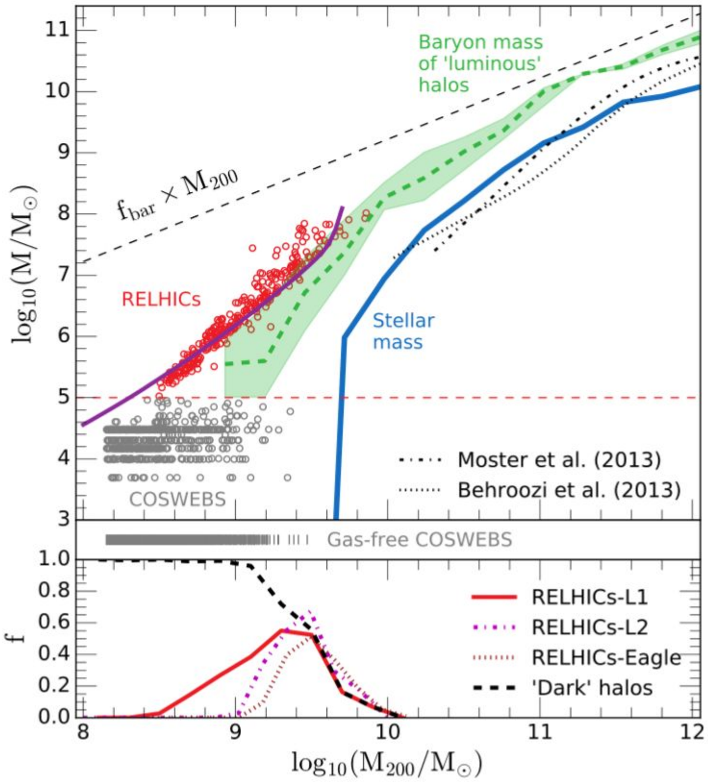
BCGs from Newman et al. (2012)

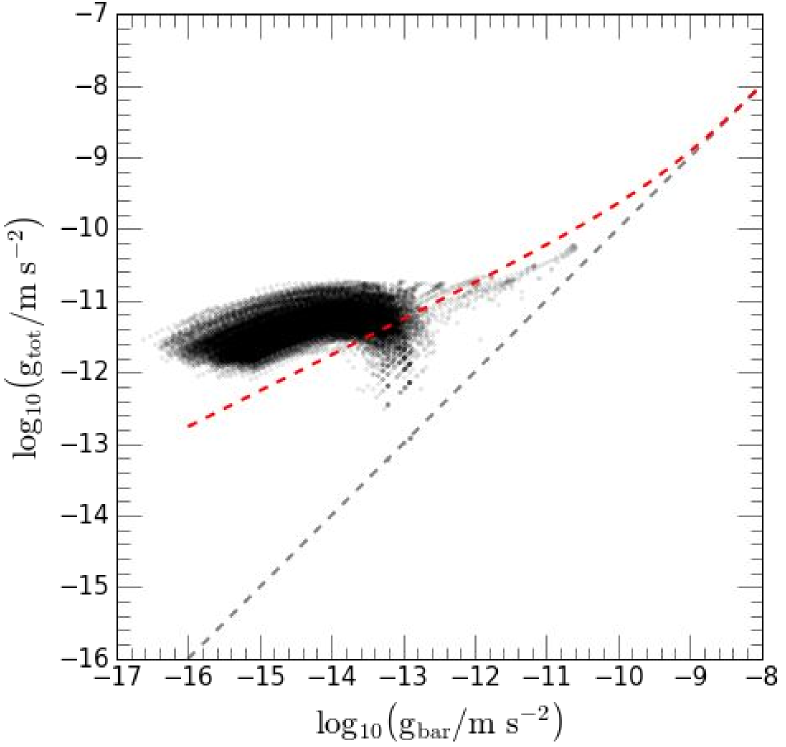
Systematics in MDAR



Early type galaxies from SLUGs (Alabi et al. 2016)

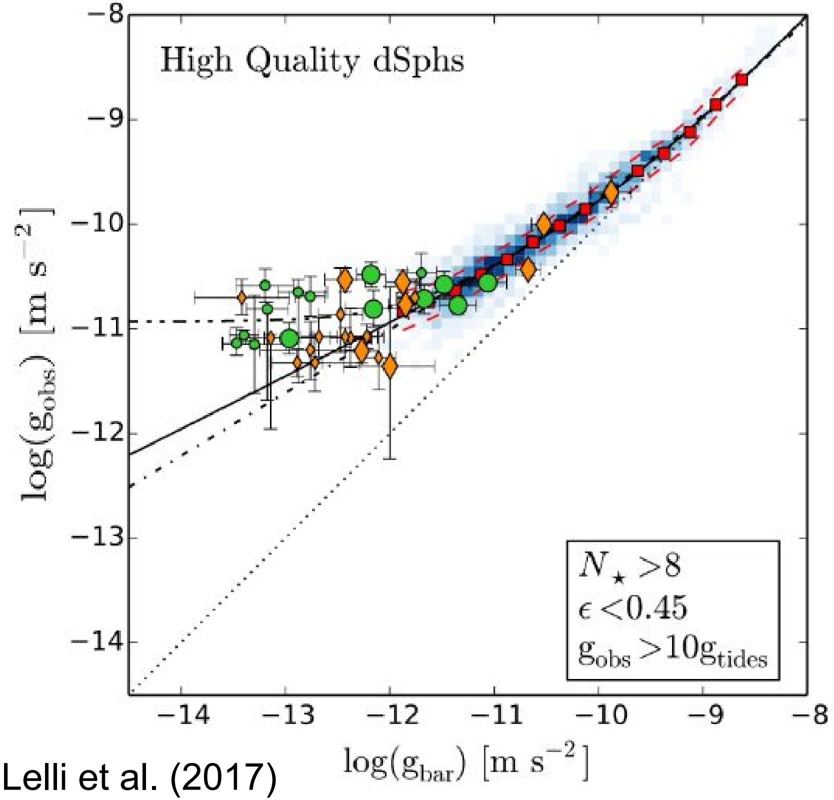
Reionization Limited HI Clouds (RELHICs)





Benitez-Llambay et al. (2017)

Observed MDAR



Lelli et al. (2017)

MDAR implies that few, if any, known galaxies:

1. probe accelerations below a lower limit of $a_{min} \sim 10^{-11}$ m/s^2
2. Are dark matter dominated at accelerations exceeding $a_0 \sim 10^{-10}$ m/s^2

(1) In the context of ΛCDM, this is because disk galaxies form at the centre of dark matter halos spanning a relatively narrow range of virial velocity (30-300 km/s)

(2) is because dark halo acceleration profiles are self-similar and have a broad maximum at the centre, reaching values bracketed precisely by a_{min} and a_0 in that mass range

(3) Halo mass and galaxy size scale relatively tightly with the baryonic mass of a galaxy

Conclusions

- Galaxies form in the potential wells of dark matter halos following very tight scaling relations, both in galaxy-halo mass and galaxy mass-size.
- The scaling relations cannot be predicted by any state-of-the-art simulation from first principles. We understand the clustering of the dark matter very well, but galaxies are the outcome of (currently unresolved) physical processes that must be modelled.
- Simulated galaxies that are realistic, and form in the right dark matter halos, will follow MDAR.
- The typical acceleration below which galaxies seem to be dark matter dominated can be understood in terms of the central broad acceleration of dark matter halos.
- Galaxies with total accelerations below ~ 10^{11} m/s^2 are difficult to accommodate within LCDM, unless they are satellites.
- Progress on our galaxy formation models must be done by focusing on challenges to the model.