Evidence against cuspy dark matter halos in large galaxies

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Dark Matter and Weak Interactions

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FAPES
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A comment on MOND

- It is not uncommon to hear that "the problem with MOND is that it only works in galaxies."

- Actually, even for galaxies it has serious problems…

- It depends on the hypothesis of existence of a fundamental acceleration at galaxies, while the same data that was argued as a triumph for MOND [McGaugh et al PRL 2016] is not compatible with a fundamental acceleration. See [DCR et al, Nature astronomy 2018]. Standard dark matter can generate an emergent acceleration scale at galaxies.

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Absence of a fundamental acceleration scale in galaxies

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Outline

✳ In [DCR, Del Popolo, Marra, Oliveira, MNRAS 2017] we:

- develop a new estimator to the core-cusp/inner-mass-deficit issue based on the uniformity of the fitted rotation curve;

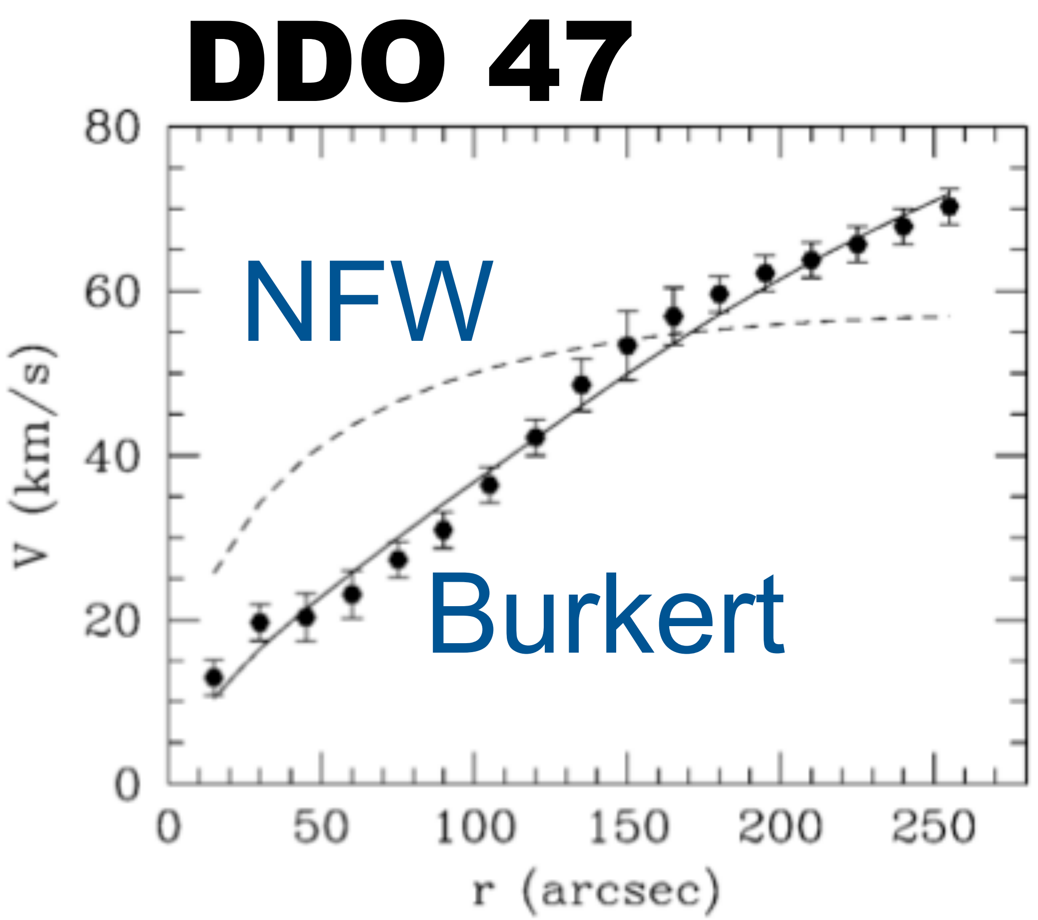
- point out that not only dwarf galaxies suffer from the issue: systematic issues with the NFW cusp also appear in large galaxies ($M_* \sim 10^{10} M_\odot$);

- we find that the Burkert profile, for some reason, has a better overall agreement with all the disk galaxies.

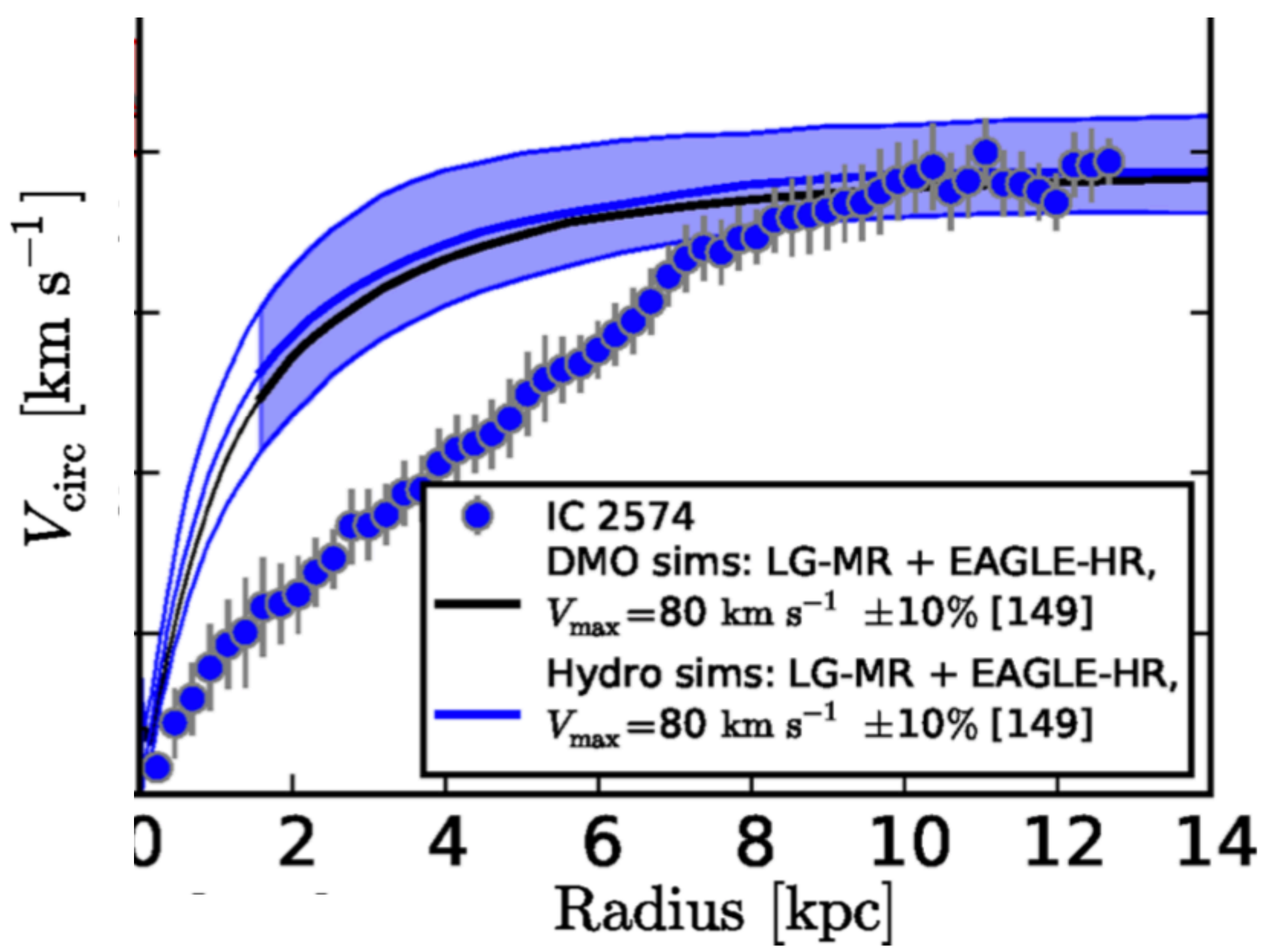
Introduction: The core-cusp issue

- The core-cusp issue refers to a possible conflict between observations and simulations, it is one of the main and most persistent small scale issues of LCDM [e.g., Moore et al, Nature 1994; de Blok, Adv.Astron. 2009].

- Currently, it is commonly considered to be related to a diversity problem and an inner mass deficit, instead of a universal slope issue. [Oman et al, MNRAS 2015].



[Gentile et al ApJ (2005)]



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- Three main aspects that are relevant to the issue:

  i) observational data reduction (e.g., issues with noncircular motions...),

  ii) baryonic feedback modeling in the hydro simulations (e.g., the stellar/SN feedback…),

  iii) physics beyond CDM (e.g., self-interacting DM, ultralight DM…).

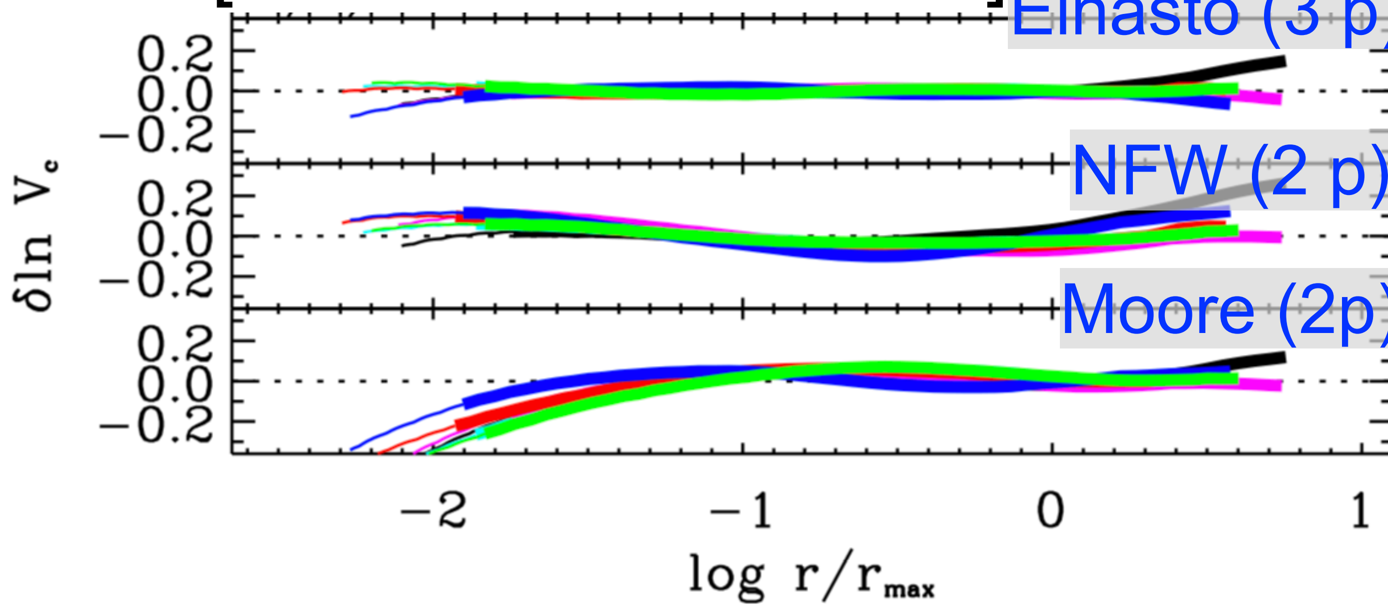
- The core-cusp issue may serve as a window towards DM physics or to improving our modeling of baryonic astrophysics.

Dark Matter Only simulations: NFW-like profile

- Dark matter only (DMO) simulations lead to NFW-like halos for galaxies [Navarro et al ApJ 1996, 1997, MNRAS 2010]:

$$\rho_{\rm NFW}(r) = \frac{\rho_s}{\frac{r}{r_s}\left(1+\frac{r}{r_s}\right)^2}$$

[Navarro et al MNRAS 2010]



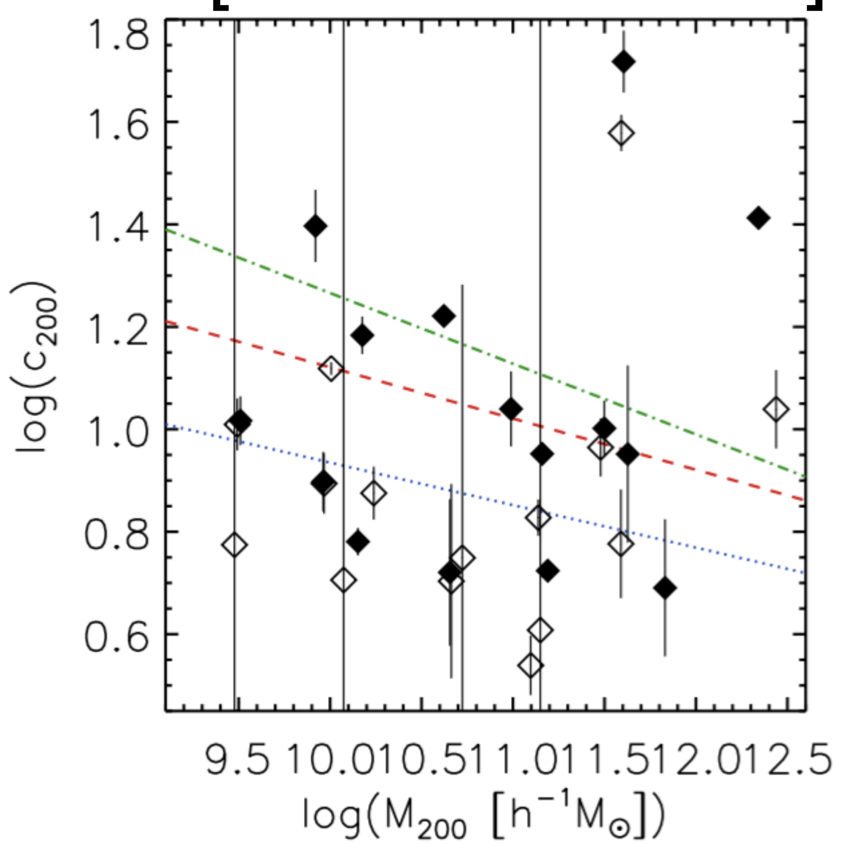
- Two parameters halo.

- Simulations also indicate a correlation between them.

- Sometimes the correlation is strongly assumed to write a 1-parameter NFW halo. And from this case the strongest discrepancies are found with observational data. [e.g., Gentile et al ApJ (2005)].

- Galaxy data have tensions with such correlations [e.g., Chemin et al AJ 2011].

[Chemin et al AJ 2011]



✳ Proposed on phenomenological grounds [Burkert ApJ 1995]

$$\rho_B = \frac{\rho_0}{\left(1 + \frac{r}{r_0}\right)\left(1 + \frac{r^2}{r_0^2}\right)}$$

It has a finite density at the center (a core with radius r_0), and it decays for large radii just like NFW.

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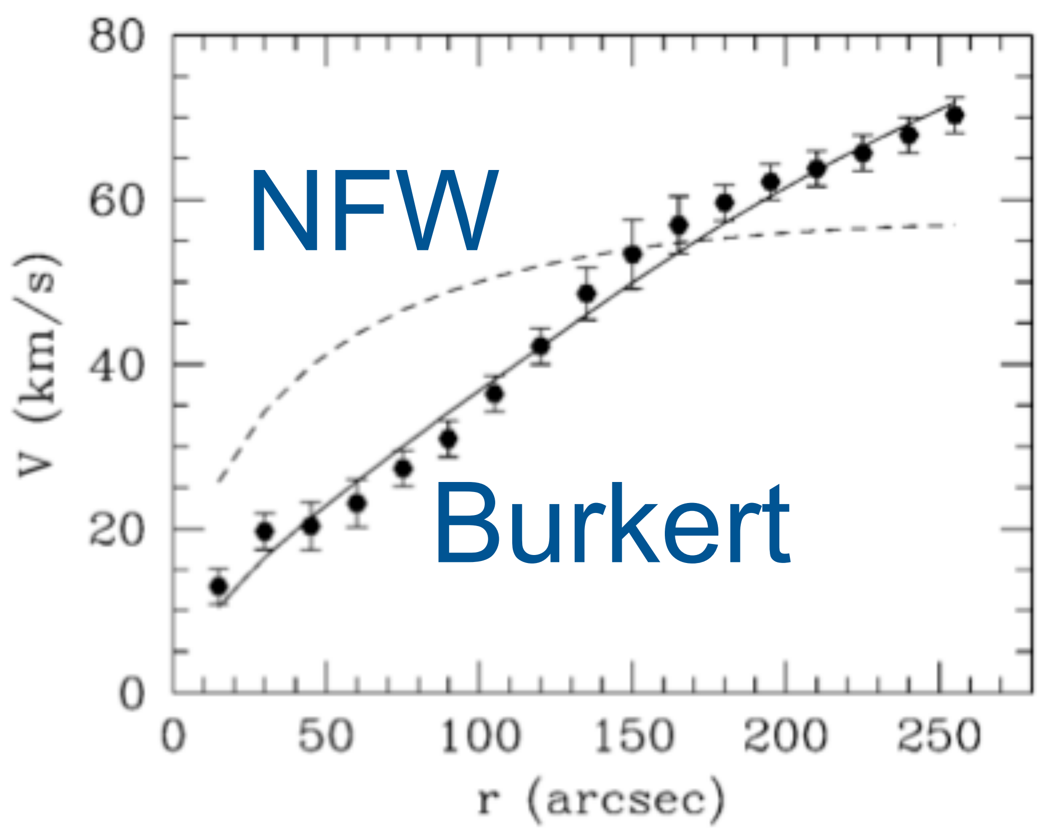
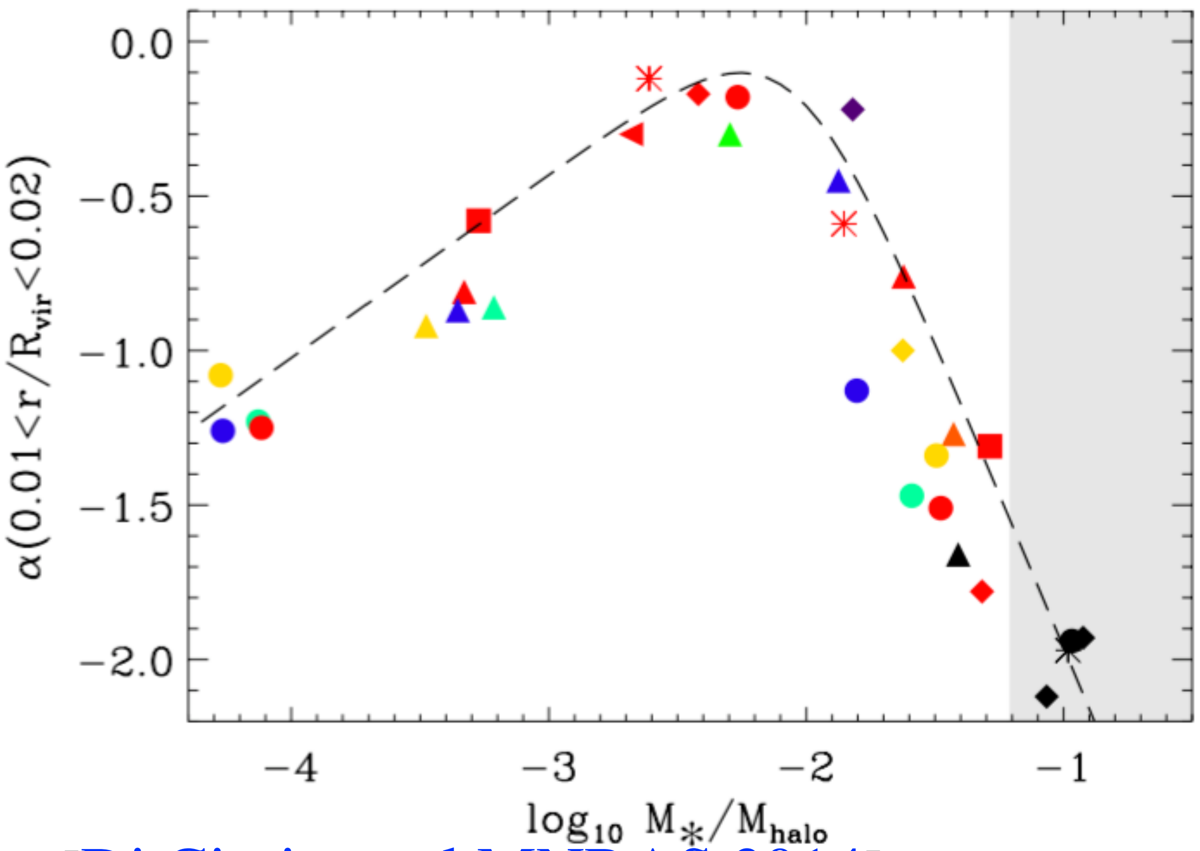
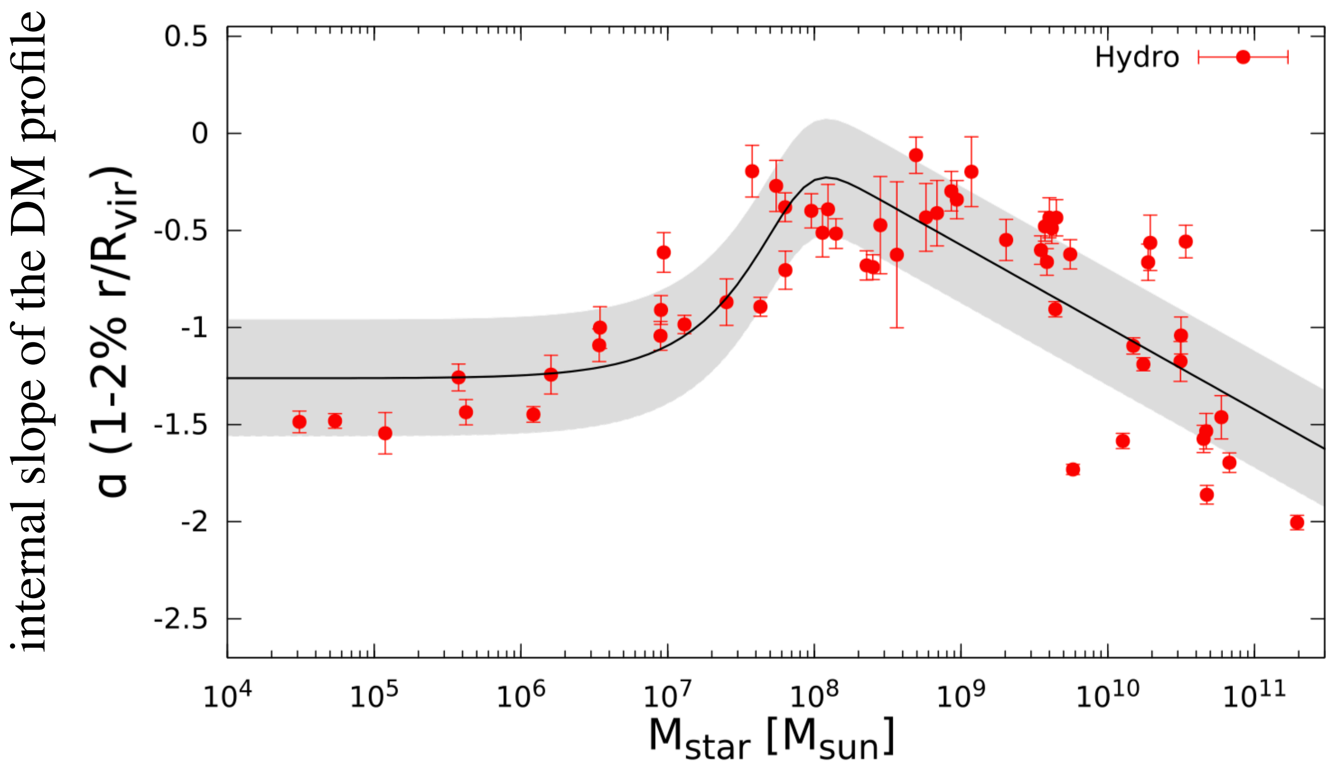


[Gentile et al ApJ (2005)]

Can the inner DM slope change significantly due to stellar feedback?



[Di Cintio et al MNRAS 2014]



[Tollet et al MNRAS 2016]

The case above lead to the DC14 profile

$$\rho(r) = \frac{\rho_s}{\left(\frac{r}{r_s}\right)^{\gamma}\left[1+\left(\frac{r}{r_s}\right)^{\alpha}\right]^{(\beta-\gamma)/\alpha}}$$

$$\alpha = 2.94 - \log_{10}[(10^{X+2.33})^{-1.08} + (10^{X+2.33})^{2.29}]$$
$$\beta = 4.23 + 1.34X + 0.26X^2$$
$$\gamma = -0.06 + \log_{10}[(10^{X+2.56})^{-0.68} + (10^{X+2.56})]$$

where $X = \log_{10}(M_\star/M_{\rm halo})$.

In [Katz et al MNRAS 2017] it is shown that the DC14 profile has better overall results than the NFW profile, specially for dwarf galaxies.

For $M_* \sim 10^{10} M_\odot$, the DC14 profile becomes a NFW profile.

Notation on χ^2

- Observational data table of the following form:

Radius (R_i)	Velocity (V_i)	Velocity error (σ_i)

As usual, rotation curve fits are performed by minimising a χ^2 quantity,

$$\chi^2(p_j) \equiv \sum_{i=1}^{N} \left(\frac{V_{\text{model}}(R_i, p_j) - V_i}{\sigma_i} \right)^2 ,$$

where N is the total number of data points and p_j are model parameters. The values of the latter that minimise χ^2.

The values of p_j that minimize χ^2 are denoted $\bar{p}_j$.

$$\chi^2(\bar{p}_j) = \chi^2_{\min}$$

To evaluate the uniformity of the fits: χ^2_R

A truncation on $\chi^2_{\min}$ considering data up to the radius R is given by

$$\chi^2_R \equiv \sum_{i=1}^{N(R)} \left(\frac{V_{\text{model}}(R_i, \bar{p}_j) - V_i}{\sigma_i} \right)^2 .$$

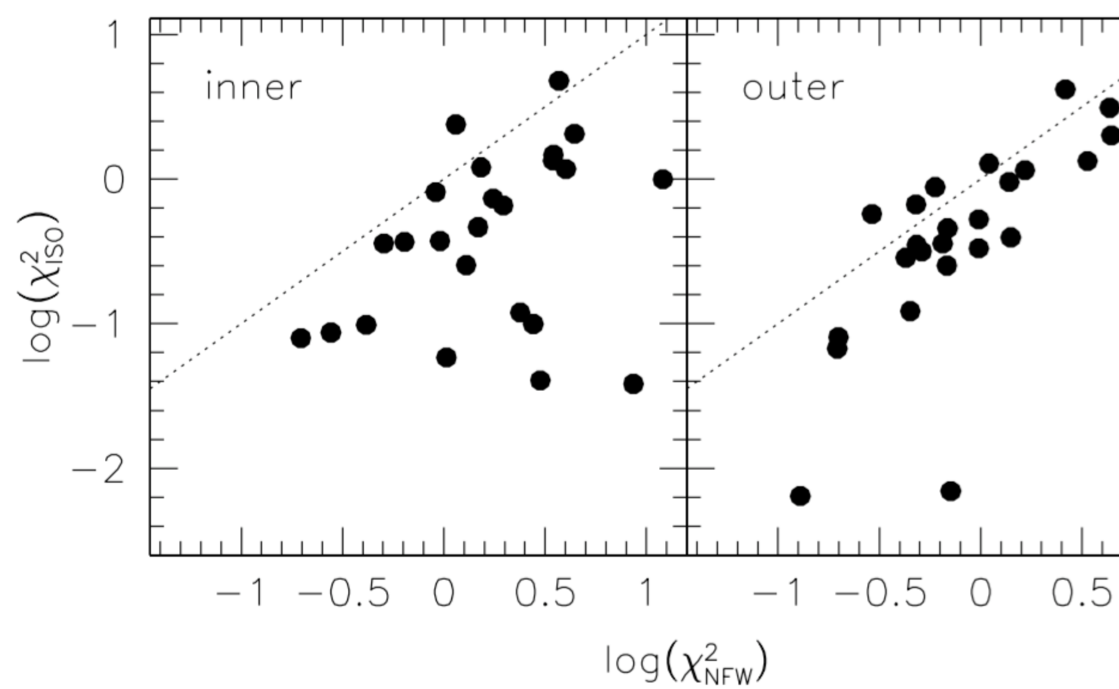
Number of points up to the radius R.

* This quantity was used in [de Blok, Bosma A&A (2002)].

* In that reference, $R_{\max}$ plays a central It divides galaxies in inner and outer ha

$$\chi^2_{\text{inner}} = \chi^2_{\frac{R_{\max}}{2}}$$

$$\chi^2_{\text{outer}} = \chi^2_{\min} - \chi^2_{\frac{R_{\max}}{2}}$$



* One may use quantities like $\chi^2_{1\text{kpc}}, \chi^2_{5\text{kpc}} \cdots$, but these are not correlated with galaxy properties.

The distance scale

- If a model has systematic problems to fit the "inner region" of galaxies, there is an issue that needs to be solved.
- One needs to use a natural *distance scale* to defined the “inner region”.
- Recently, some papers are considering a fixed radius at 2 kpc to evaluate the core-cusp/diversity issue [e.g., Santos-Santos et al MNRAS 2018].
- However, galaxies have an emergent distance scale that changes from galaxy to galaxy (and whose median value is about ~2 kpc): *the disc scale length (h),* which we consider as providing a natural distance proxy.

The quantities χ^2_{nh} and $\xi(m,n)$

✳ From [DCR, Del Popolo, Marra, Olivera, MNRAS 2017] (see also [DCR et al MNRAS 2014])

In order to evaluate the uniformity of the fits along the galaxy radius, we introduce the following quantity

$$\xi(m,n) \equiv \frac{\chi^2_{mh}}{\chi^2_{nh}}$$

m and n are distances measured in units of h.

For an ideal set of galaxies, and for an ideal model with no bias towards any radius,

$$\langle \xi(m,n) \rangle \approx \frac{m}{n}.$$

$\langle\ \rangle$ designates the median.

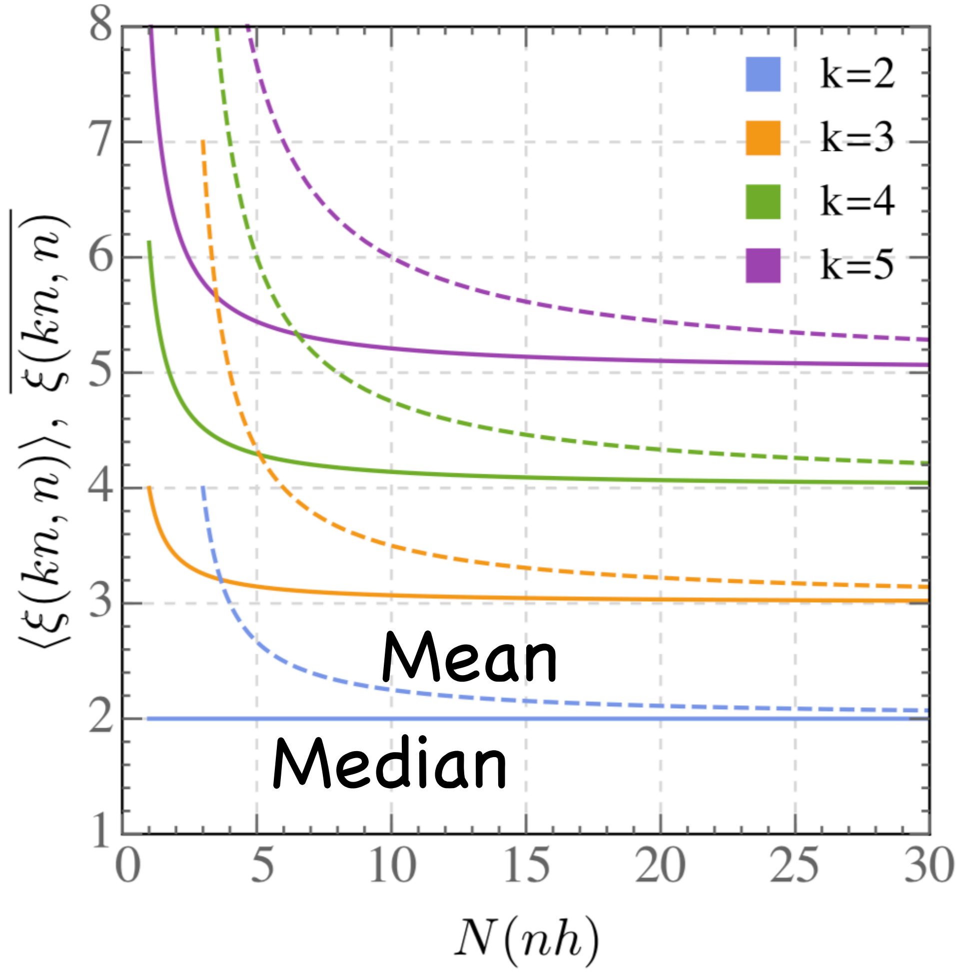
For arbitrary n and m values, with m > n,

$$\langle \xi(kn,n) \rangle = \frac{1}{I^{-1}_{\left(1,-\frac{1}{2}\right)}\left[\frac{N(nh)}{2}, (k-1)\frac{N(nh)}{2}\right]}$$

I is the generalized regularized incomplete beta function.

$$\langle \xi(2n,n) \rangle = 2$$

The case m = 2 n (i.e., k = 2) has no dependence on N.



The quantity $\zeta(m,n)$

✳ Real galaxy sets are not ideal, and there may be systematics on the data itself:

- The RC data points need not to be evenly spaced.
- The error bars need not to be constant on average along the galaxy radius.

✳ To quantify the homogeneity of the data set, we introduce

$$\zeta(m,n) \equiv \frac{\Sigma(mh)}{\Sigma(nh)},$$

with $\Sigma(mh) \equiv \sum_{i=1}^{N(mh)} \frac{1}{\sigma_i^2}$.

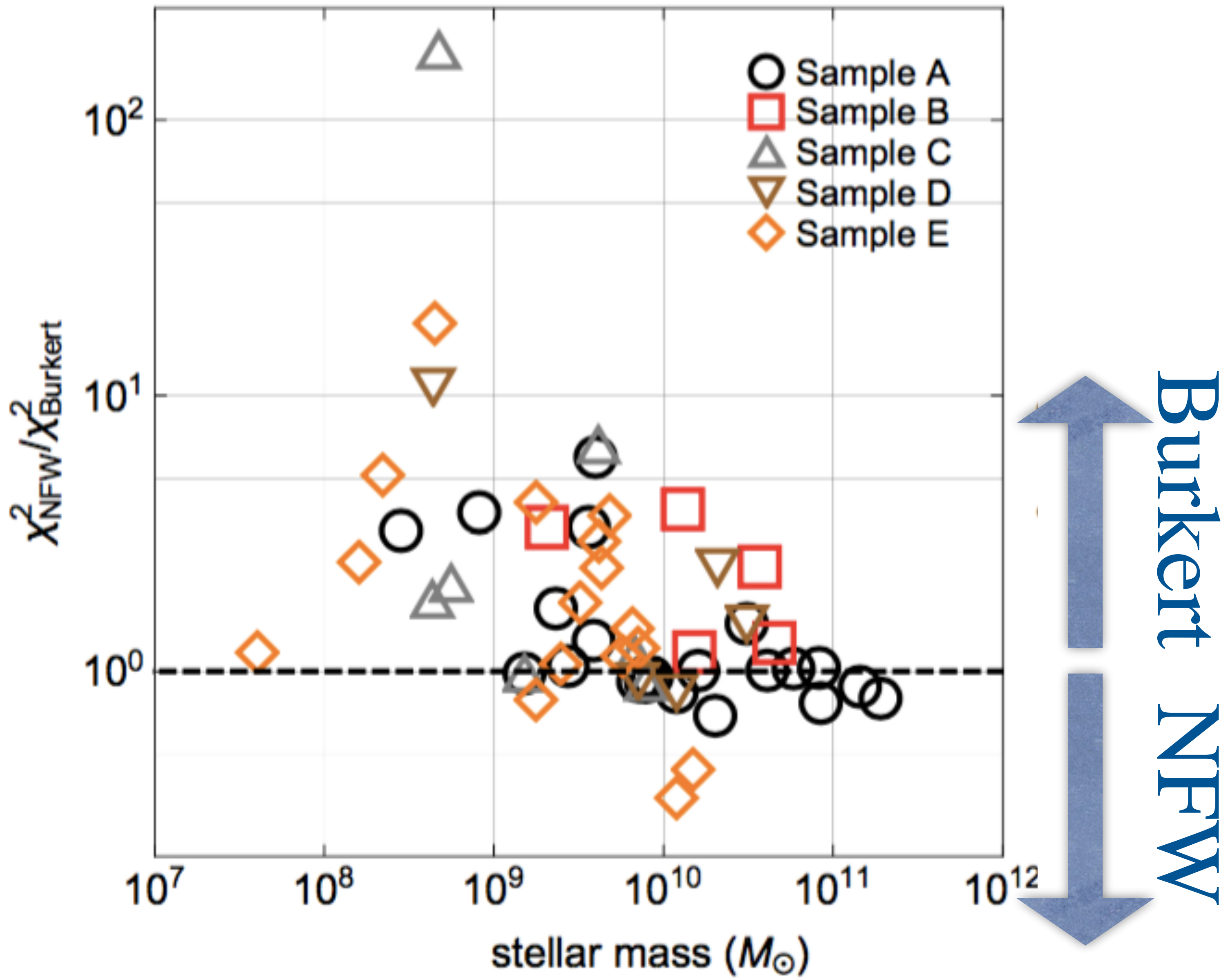
✳ For a model with no bias towards a particular radius,

$$\langle \xi(m,n) - \zeta(m,n) \rangle \equiv \langle \Delta\xi(m,n) \rangle \approx 0.$$

The samples used to perform the tests

Sample name (arbitrary order)	N. of Galaxies	Main ref. of the sample
A	19	de Blok et al, AJ (2008) (THINGS)
B	5	Gentile et al, MNRAS (2004)
C	12	de Blok & Bosma, A&A (2002)
D	8	de Blok, McGaugh, Rubin, AJ (2001)
E	18	Swaters et al, ApJ (2011) (WHISP)
	62	

The quality of the NFW fits and the stellar mass correlation

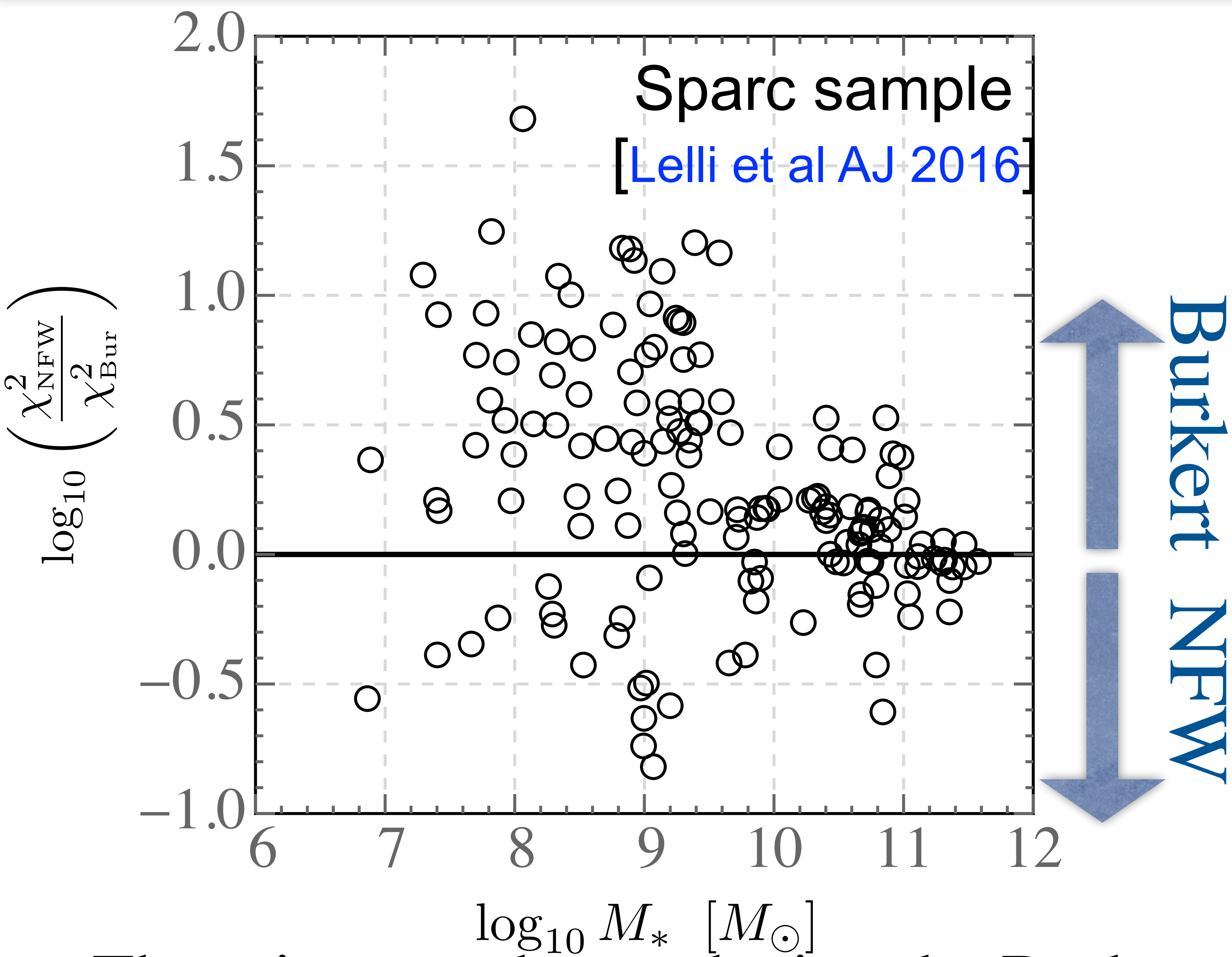


Of 62 galaxies, only13 fits better with NFW.

There is a trend on reducing the Burkert advantage for high M_*.

But the NFW fits become better than the Burkert ones only for $M_* \gtrsim 10^{11} M_\odot$. —Ten times the Di Cintio et al MNRAS 2014 results.

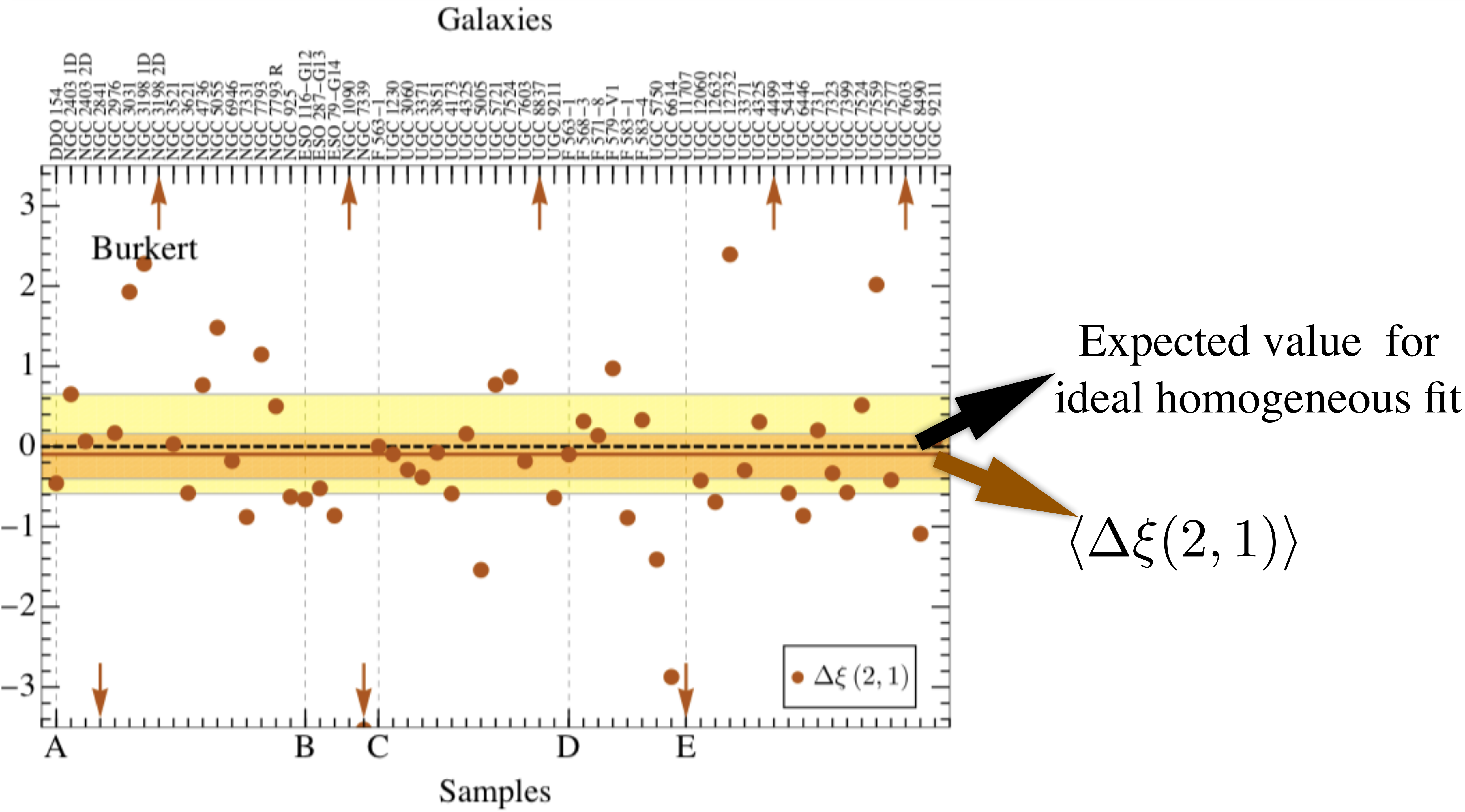
The quality of the NFW fits and the stellar mass correlation



Of 153 galaxies, only 46 fits better with NFW.

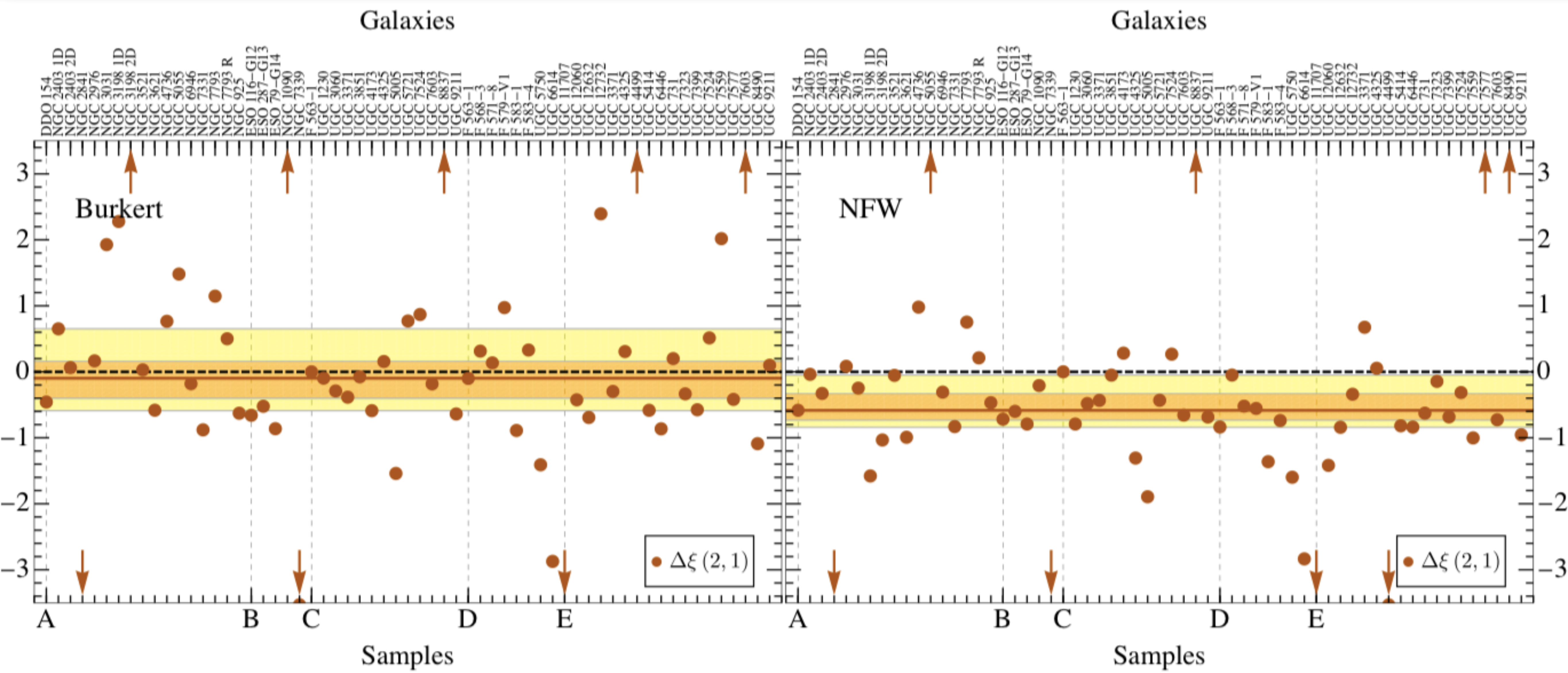
There is a trend on reducing the Burkert advantage for high M_*.

But the NFW fits become better than the Burkert ones only for $M_* \gtrsim 10^{11} M_\odot$. —Ten times the Di Cintio et al MNRAS 2014 results.



Burkert results are consistent with homogeneous fit: $\langle \Delta\xi(2,1)\rangle \approx 0$

On the uniformity of the fits: the complete sample and $\Delta\xi$



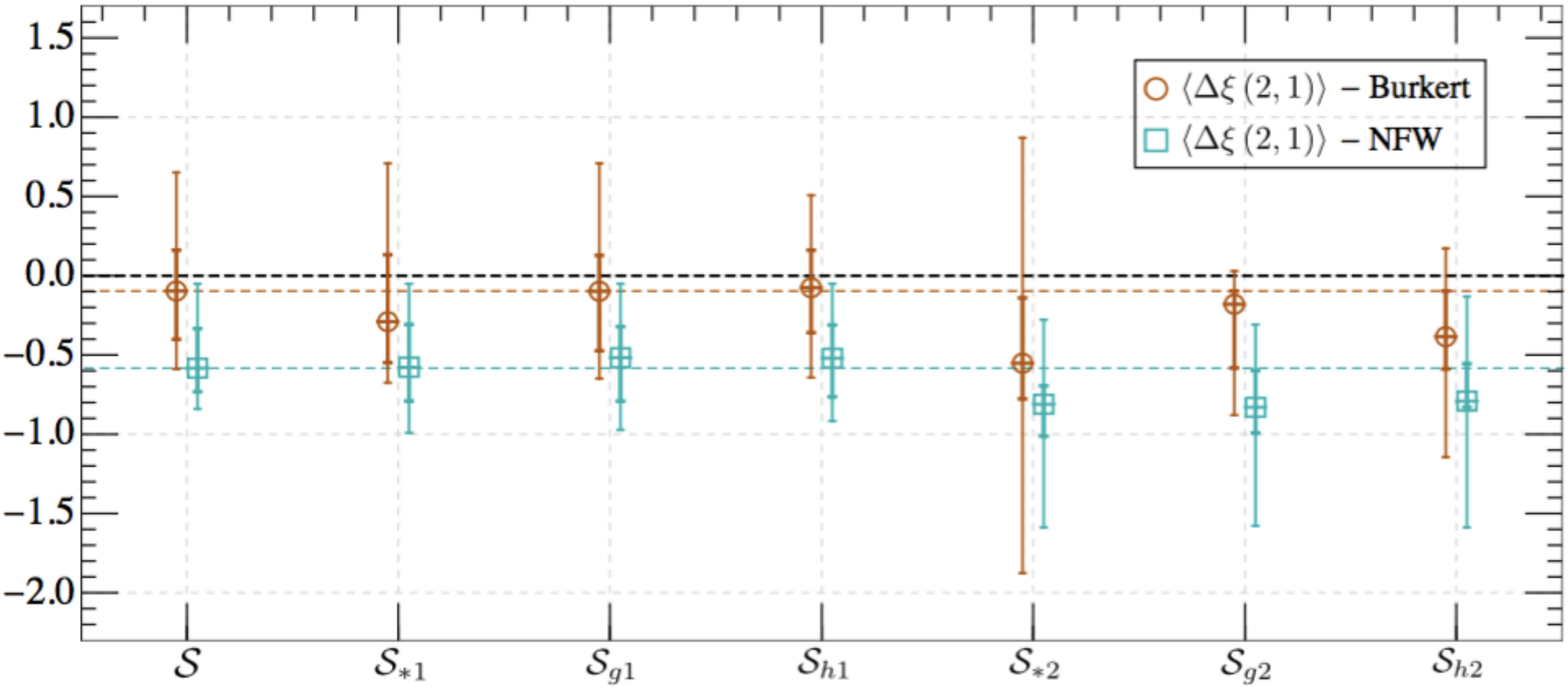
Burkert results are consistent with homogeneous fit: $\langle \Delta\xi(2,1) \rangle \approx 0$

NFW results show that, for more than 75% of the galaxies, this halo better fits the region h < R < 2h, then the region R < h.

Resampling the data using physical criteria

Sample	Criterion
S	All galaxies
S_{*1}	$M_* > 10^9 M_\odot$
S_{*2}	$M_* > 10^{10} M_\odot$
S_{g1}	$M_{gas} > 10^9 M_\odot$
S_{g2}	$M_{gas} > 5 \times 10^9 M_\odot$
S_{h1}	$h > 1.5$ kpc
S_{h2}	$h > 3.0$ kpc

On the uniformity of the fits: the subsamples



The NFW profile provides RC's with better agreement at h<R<2h than in R < h. Considering only the largest galaxies does not improves the picture.

Conclusions

* In [DCR, Del Popolo, Marra, Oliveira, MNRAS 2017] we find that the Burkert profile fits better than the NFW, even if one considers galaxies with $M_* \sim 10^{10} M_\odot$. This picture may change for $M_* \sim 10^{11} M_\odot$. Also confirmed for the SPARC sample (not published).

* NFW profile has a tendency of fitting better the region h < R < 2 h than R < h. Selecting only the largest galaxies does not improve the concordance. Burkert fits show no clear bias for a galaxy region.

* Our results point out that baryonic feedback or non-CDM models which only changes NFW for dwarf galaxies with $M_* \sim 10^8 M_\odot$ should explain why a cored profile (Burkert) commonly works for larger galaxies better than NFW.

Thanks!

Particular example

NGC 3198