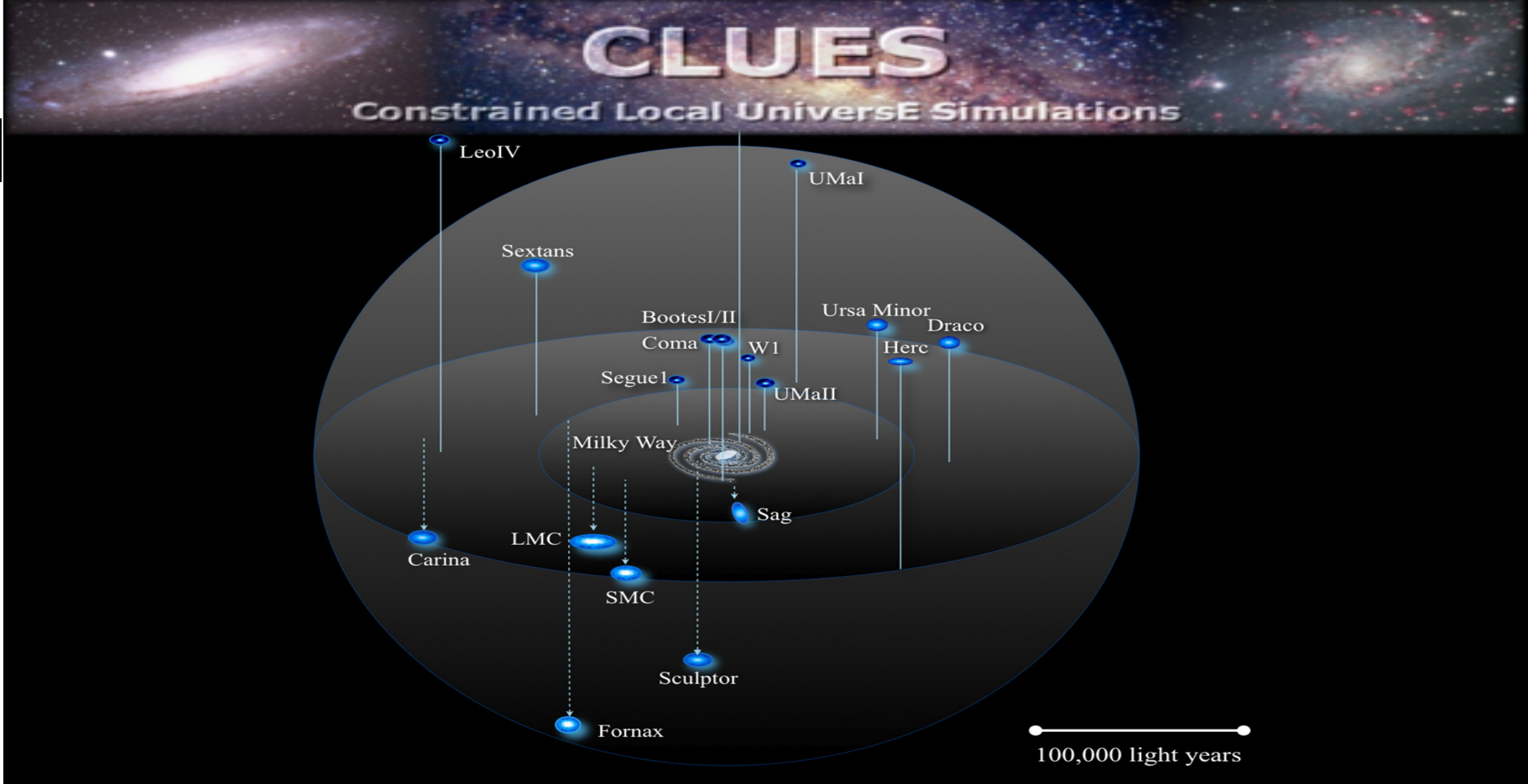

THE NON-UNIVERSAL DENSITY PROFILE OF SUBHALOS IN HYDRODYNAMICAL SIMULATIONS: IMPLICATIONS FOR THE MILKY WAY'S DSPHS

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22 June 2012 CLUES Meeting

Abstract

While the predictions of the current Cold Dark Matter (CDM) model have been widely confirmed at cosmological scales, there are still a number of discrepancies between theory and observations at galactic and subgalactic scales: one example is the well-known "missing satellite problem", which can be alleviated if the the smallest DM haloes are inefficient at forming stars. However, there is an inconsistency not only with the number, but also about the kinematics of the observed MW's dwarf spheroidals (dSphs) when compared to the velocity profiles of the most massive subhaloes found in dark matter simulations, the latter being too dense to host any of the MW' satellite galaxies. A review of previous developments on this subject will be presented, as well as our recent results based on Constrained Local UniversE Simulations (CLUES). In particular, we investigated the effects of the inclusion of baryons in hydrodynamical simulation, showing that the density profile of substructures is not universal and it is better described by an Einasto model, as opposed to the commonly used NFW profile. This finding is enough to reconcile simulations with observations if the MW mass is at the low end of current estimates, i.e. ~5-8 x 10^{11} Msun.

Outline

- The ‘massive dark matter subhaloes’ problem
- Possible solutions and past developments
- Recent results based on CLUES
- Conclusions and open questions

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Missing Satellite Problem

Klypin et al.99, Moore et al.99

- Discrepancy between the number of observed and expected satellites of our galaxy

↓

- Alleviated if the smallest dark matter halos are inefficient at forming stars

↓

- Early reionization of gas and supernovae feedback have been invoked to identify the halo mass scale where the galaxy formation starts to be inefficient (Bullock et al.00, Somerville 02, Koposov et al.09).

Too dense massive DM subhaloes

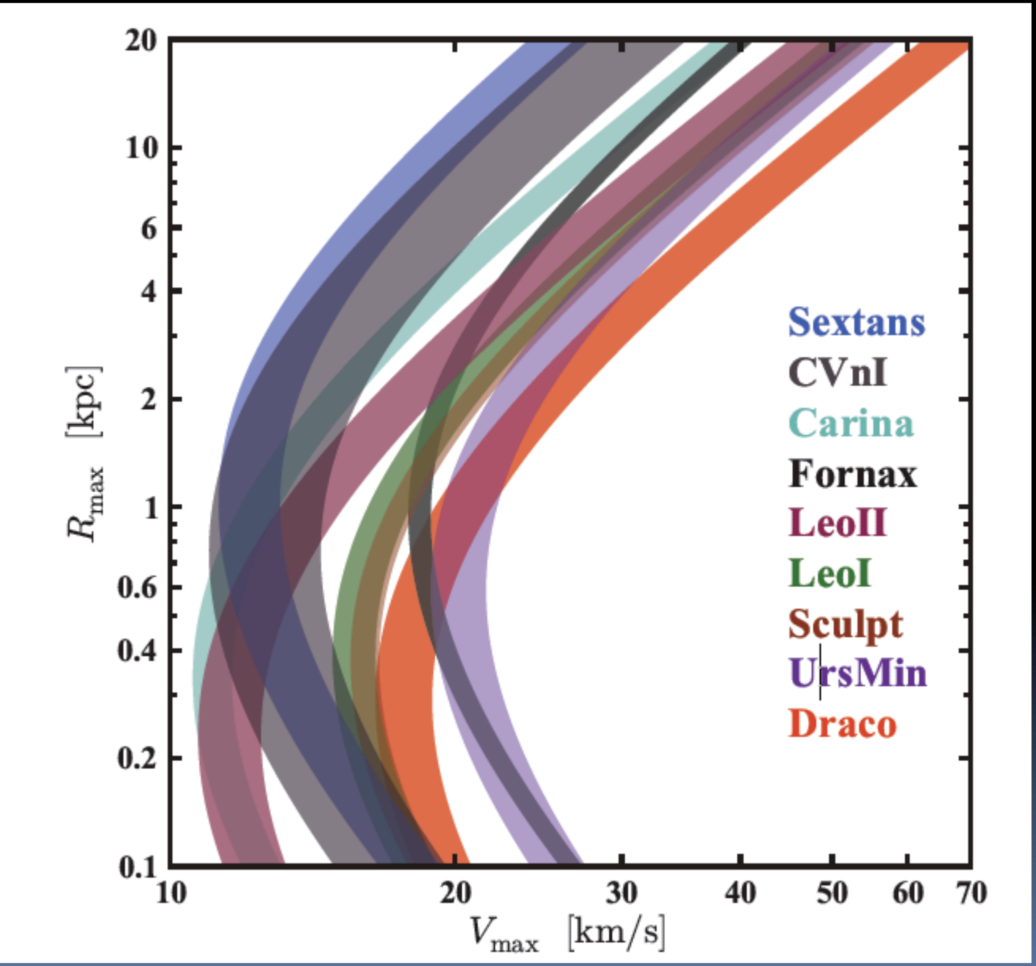
Boylan-Kolchin et al.11

- Discrepancy between the predicted and inferred distribution of max(V_{circ}) values
- Kinematic measurements of known dSphs to get M1/2 and R1/2 (Wolf et al.10)
- Assumption: the underlying subhaloes follow a NFW profile

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

Too dense massive DM subhaloes

Boylan-Kolchin et al.11



$$M(<R_{max}) = \sqrt{\frac{M_{1/2}b}{\ln(1+R_{1/2}/bR_{max}) - 1/(1+bR_{max}/R_{1/2})}}$$

$$V_{max} = \sqrt{\frac{GM(<R_{max})}{R_{max}}}$$

Possible Vmax-Rmax pairs for the 9 brightest classical dwarfs

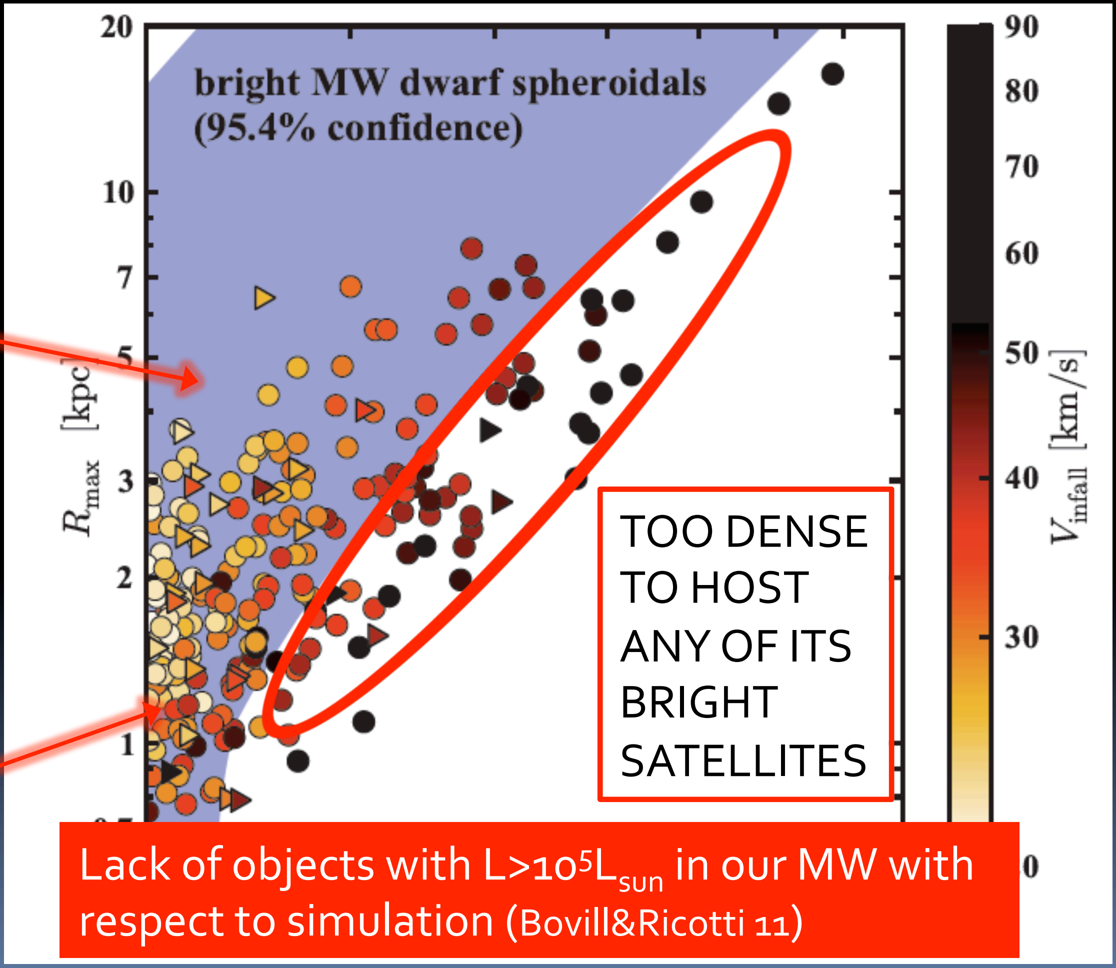
Using Aquarius (σ_8=0.9) and Via Lactea II (σ_8=0.74) simulations

Boylan-Kolchin et al.11

MW-haloes masses
(0.95-2.2)10^{12} M_{sun}

2σ confidence interval for possible hosts of the bright MW dwarf spheroidals

Subhalos within 300 Kpc from the host centre, with Vmax > 10 Km/s



Lack of objects with $L>10^5L_{sun}$ in our MW with respect to simulation (Bovill&Ricotti 11)

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- Density profile of subhaloes is not NFW
- Alternative hypothesis for the nature of dark matter
- Atypical satellites distribution in the MW
- Photo-ionization feedback inhibit galaxy formation
- Baryonic processes lower the concentration of massive subhalos
- The MW mass is at the low end of current estimates
- Stochastic galaxy formation at scale V_{max}<50 km/s
- LCDM is wrong

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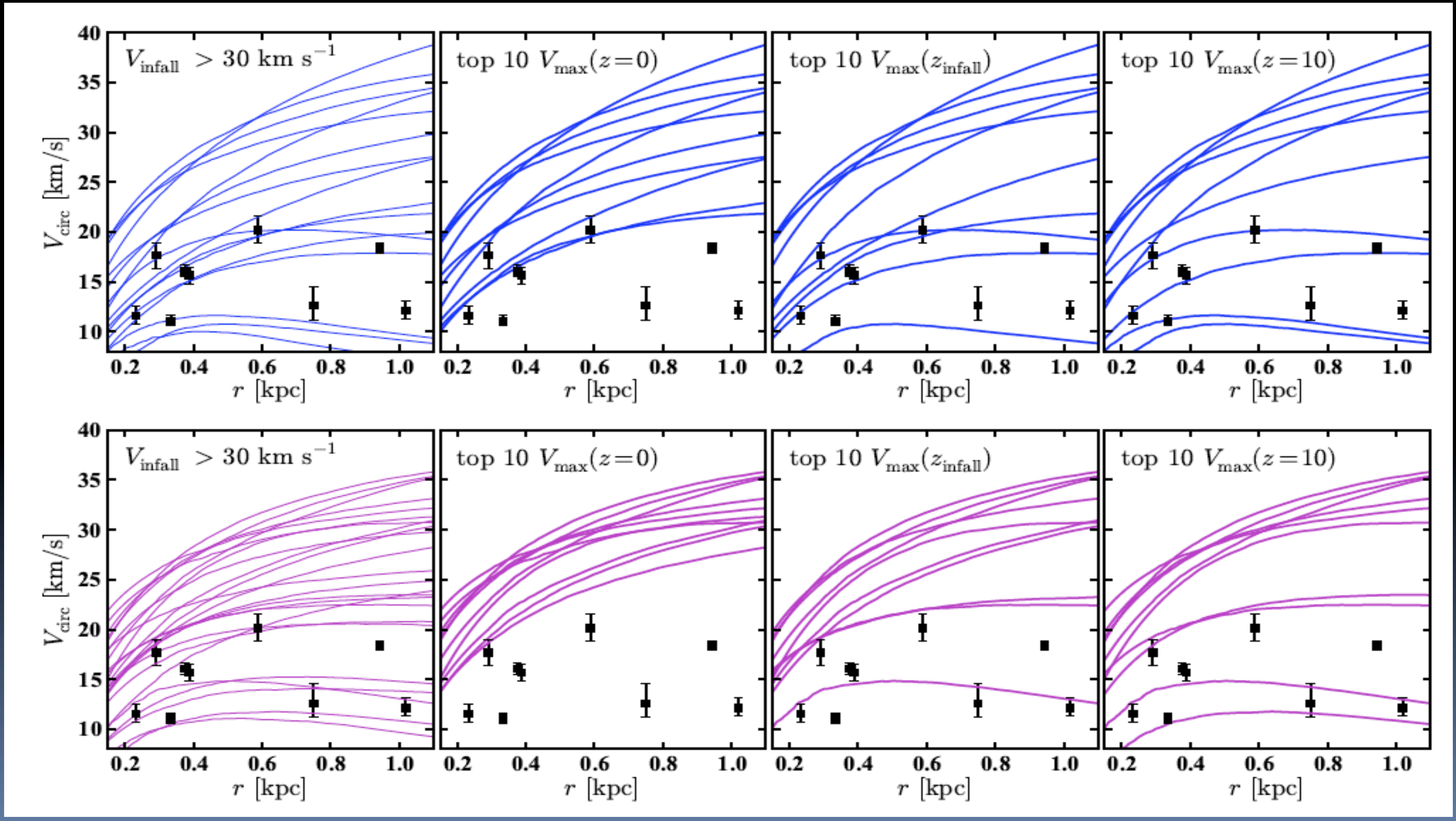
Uncertainty on the subhaloes density profile Boylan-Kolchin et al.12 (see also Di Cintio et al.12, Vera-Ciro et al.12)

Using the raw particle data directly there is a number of massive subhaloes which are more massive that any dwarf at z=0, z=10 and z=infall. Top ->Mvir = 9,5 10^{11} M_{sun} Bottom ->Mvir = 1,4 10^{12} M_{sun}



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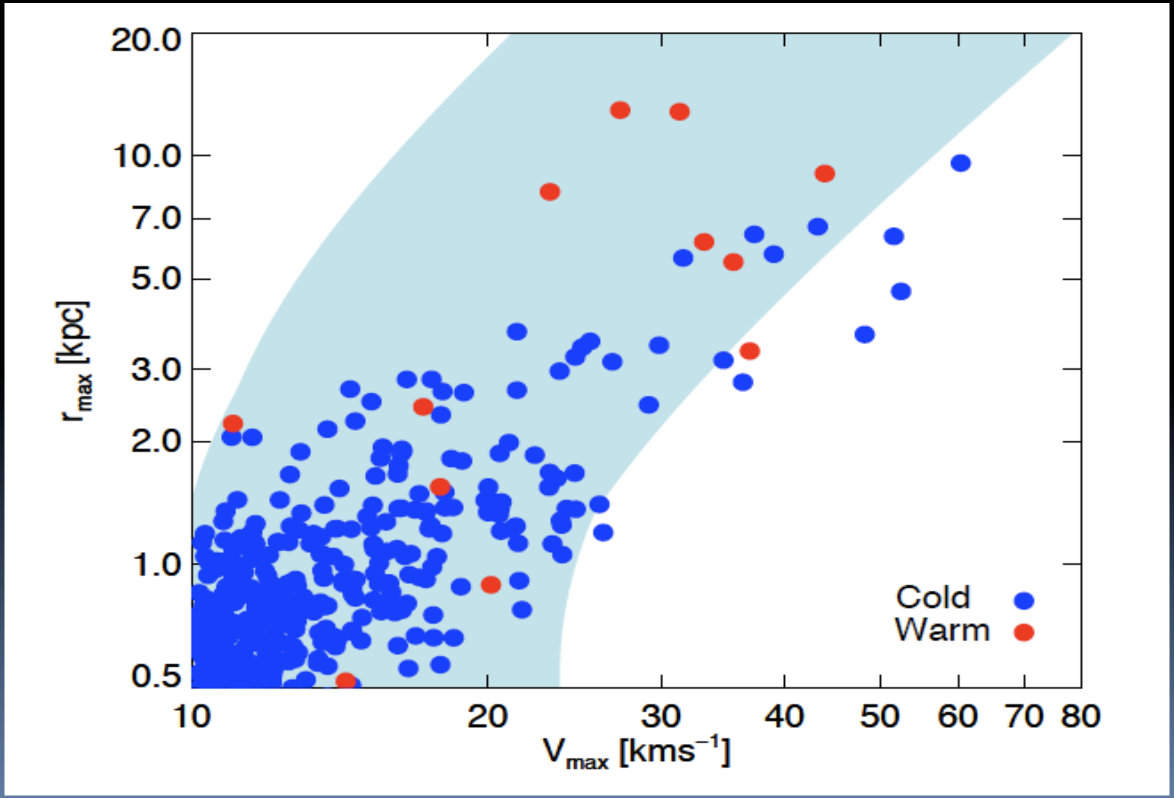
WDM model ~2keV particle

Lovell et al.11

Resimulation of one of the Aquarius haloes with the power spectrum corresponding to a ~ 2keV neutrino particle. The small scale power in these simulations is greatly reduced -> less substructures

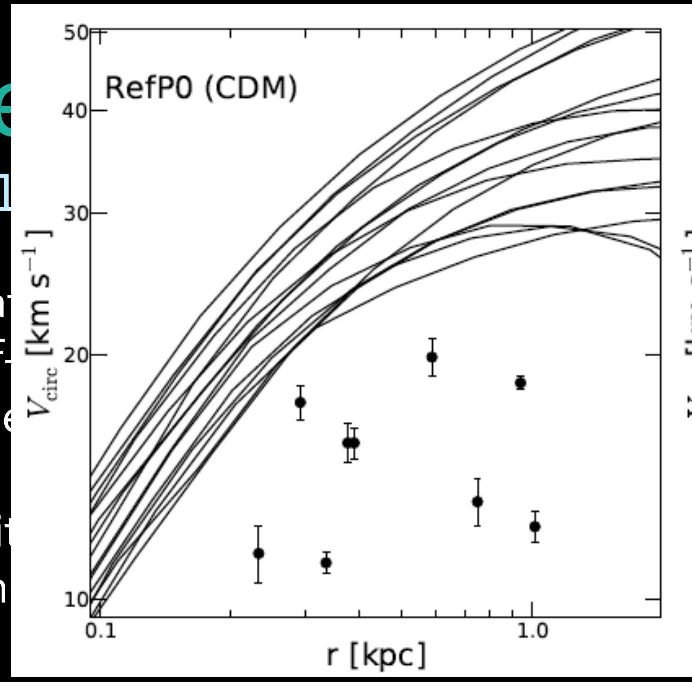
The formation of the haloes that will end up hosting the satellites is delayed -> this lowers their concentration compared to that of the corresponding CDM haloes

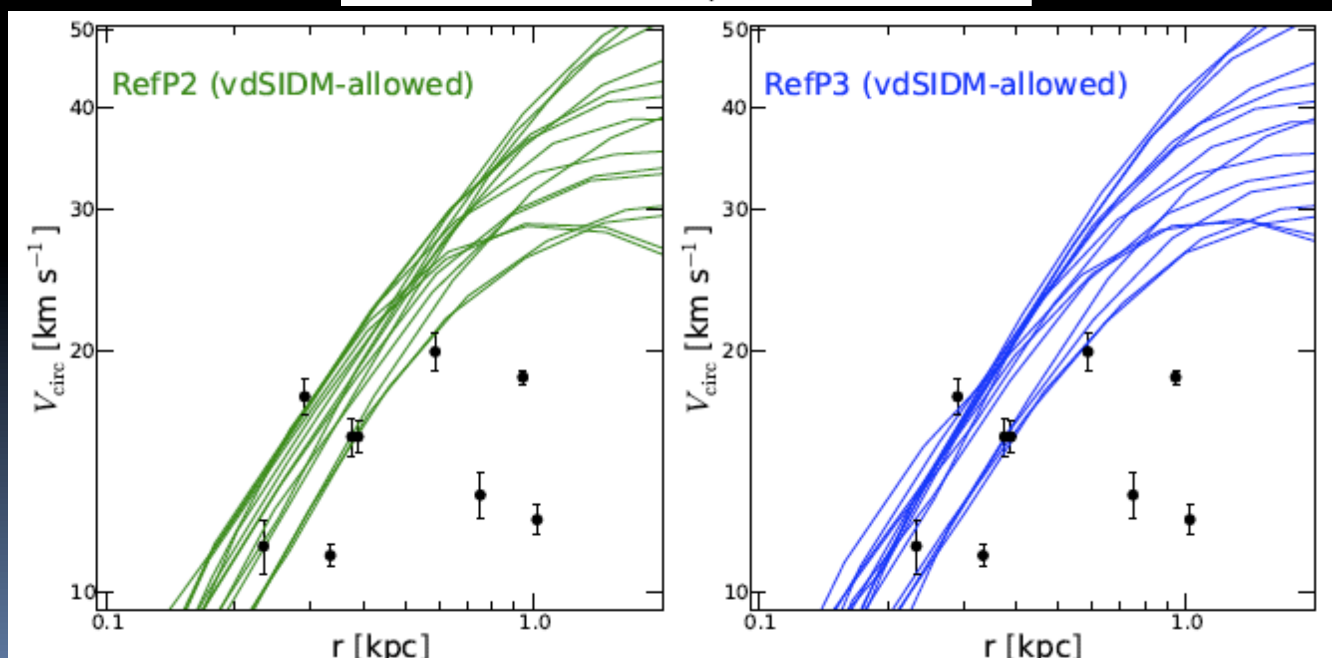


Self-inte … aloes

Vogelsberger et al

Milky Way-like dark ma … roject re-simulated with velocity-dependent self- … SIDM) .
Significant change in the … es resulting in the formation of a large density core.
The inner circular velocit … aloes is compatible with the observational data of th … vdSIDM.





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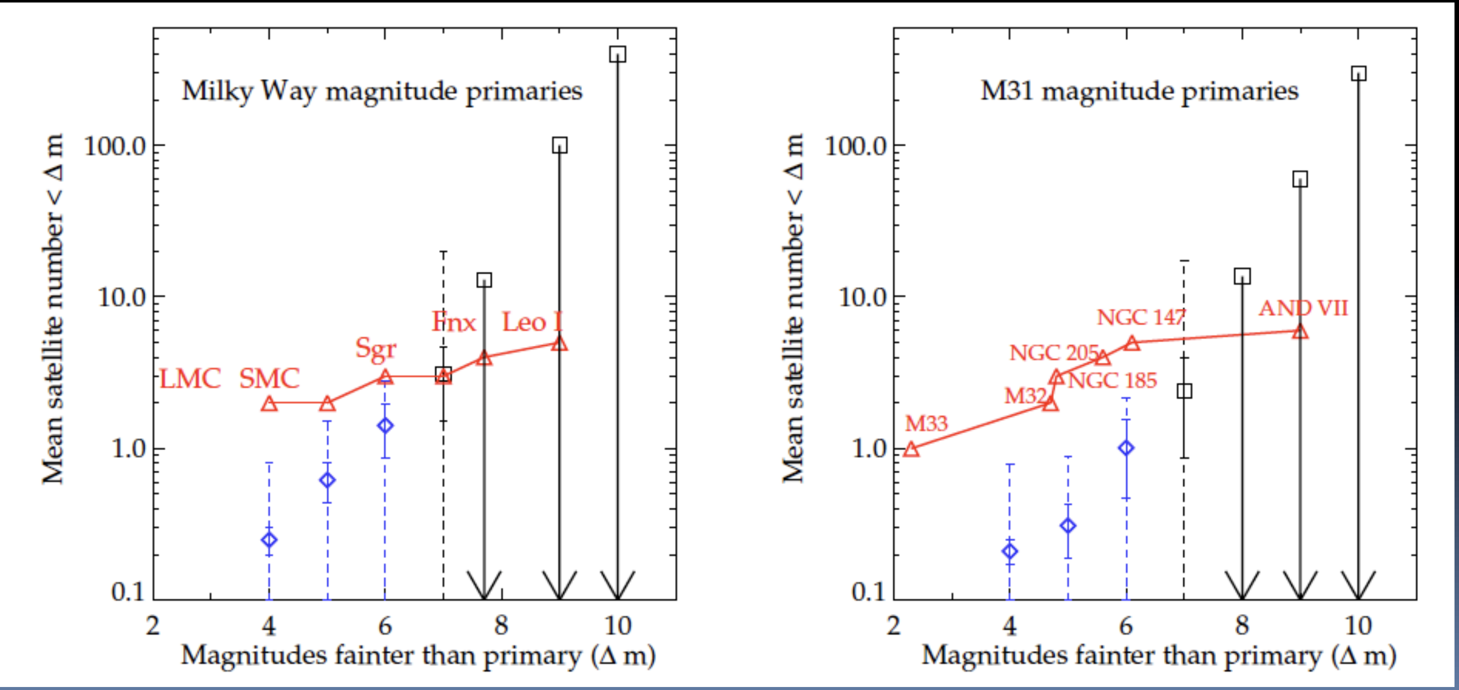
Cosmic abundance of classical MW satellites Strigari&Wechsler 12

DR8 photometric redshift data form the SDSS to limit the number of satellites around MW-analog galaxies down to 10 mag fainter than the MW.

Down to the scale of Sagittarius the MW is NOT a statistical outlier in its number of classical satellites.

At the 90% c.l. there are, on average, <13 satellites brighter than Fornax and a mean of 2 objects brighter than Sagittarius.



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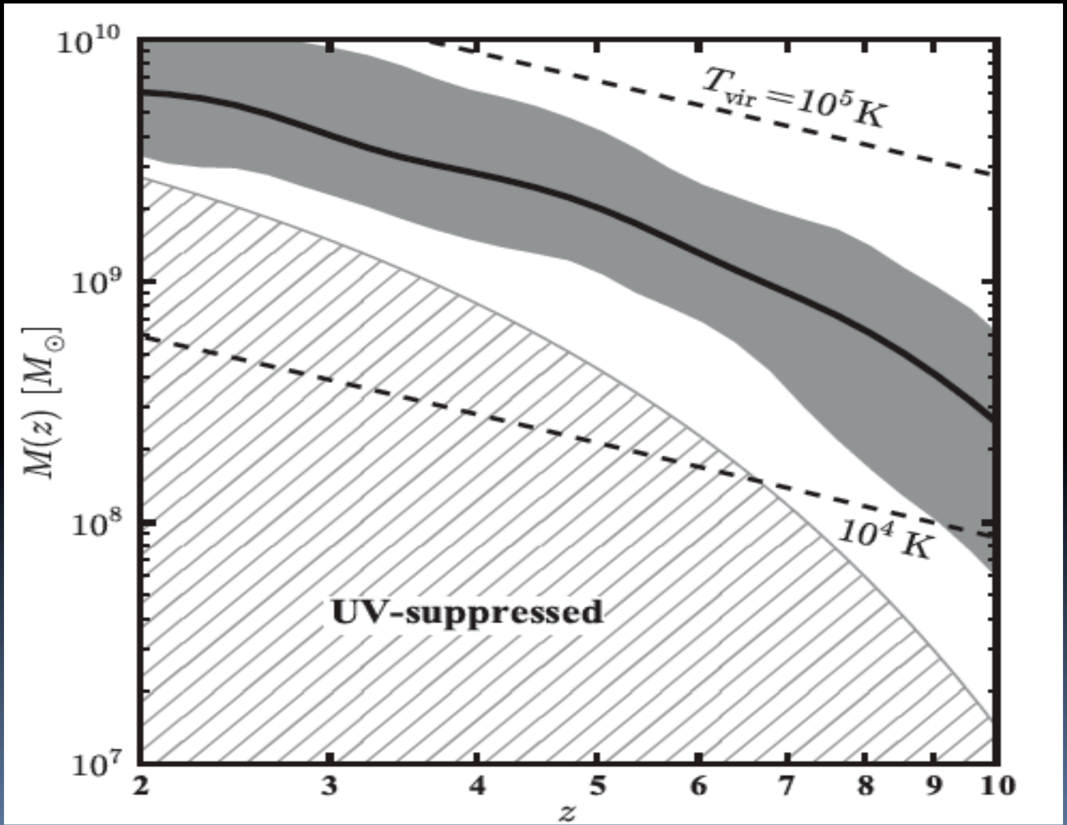
The impact of reionization

Boylan-Kolchin et al.12

Looking at the the evolution of the progenitors of all subhalos with $V_{inf} > 30$km/s and at the mass $M_{UV}(z)$ below which at least half of a halo's baryons have been removed by photo-heating from the UV background => the "massive failure" are too massive for photo-ionization feedback to be an explanation of why they do not have stars



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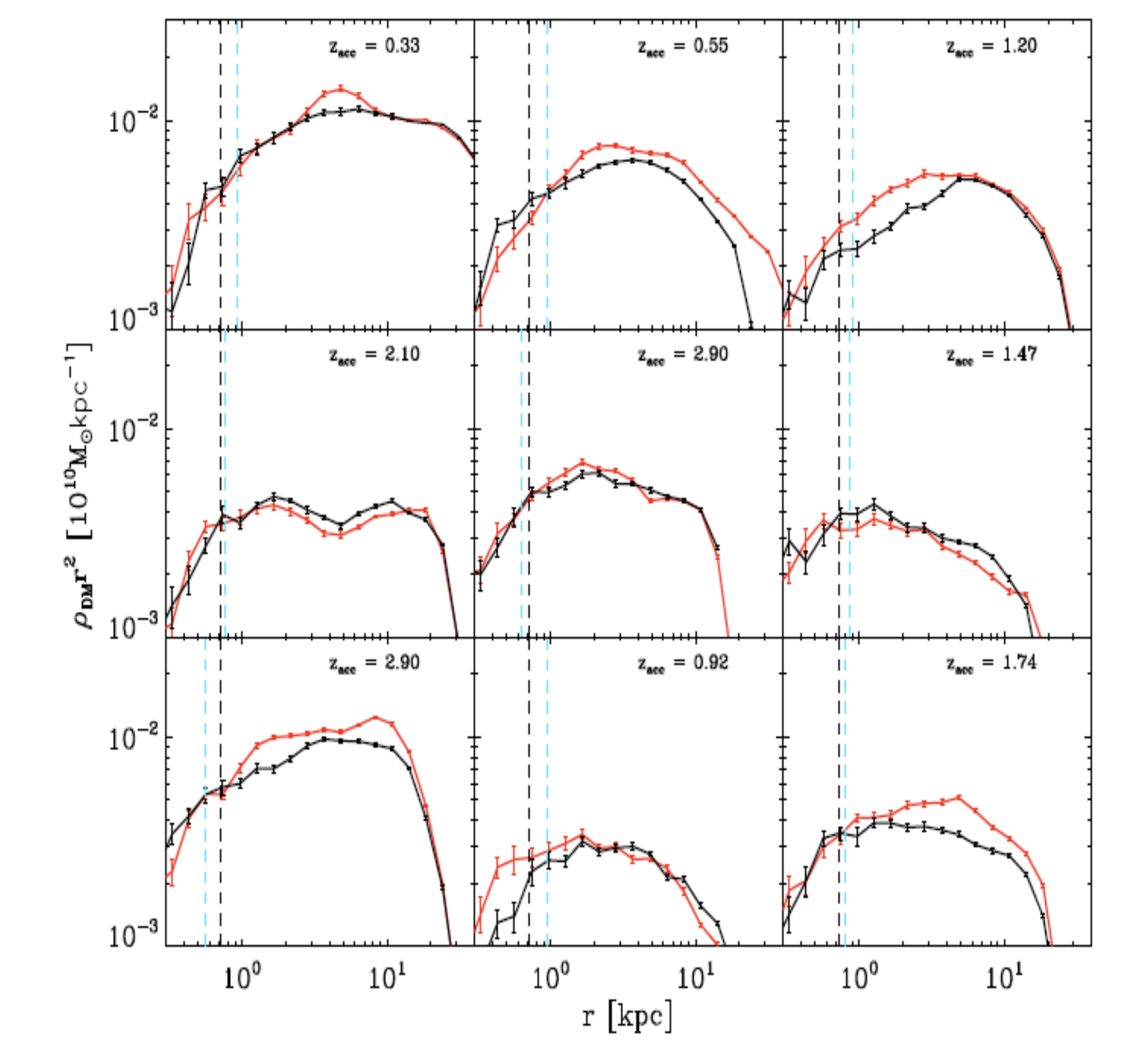
Aquarius SPH run

Parry et al.11 (see also Di Cintio et al.11)



DM particle ~ $2.6 \cdot 10^5 M_{sun}$

Gas particle ~ $5.8 \cdot 10^4 M_{sun}$

Spherically averaged DM density profile for the SPH run (red) and DM only (black)

Comparison made at the redshift at which the satellite is first accreted into the halo of the main galaxy, before the orbits have had a chance to diverge

There is not a consistent trend for baryons to increase or decrease the central density of the dark matter.

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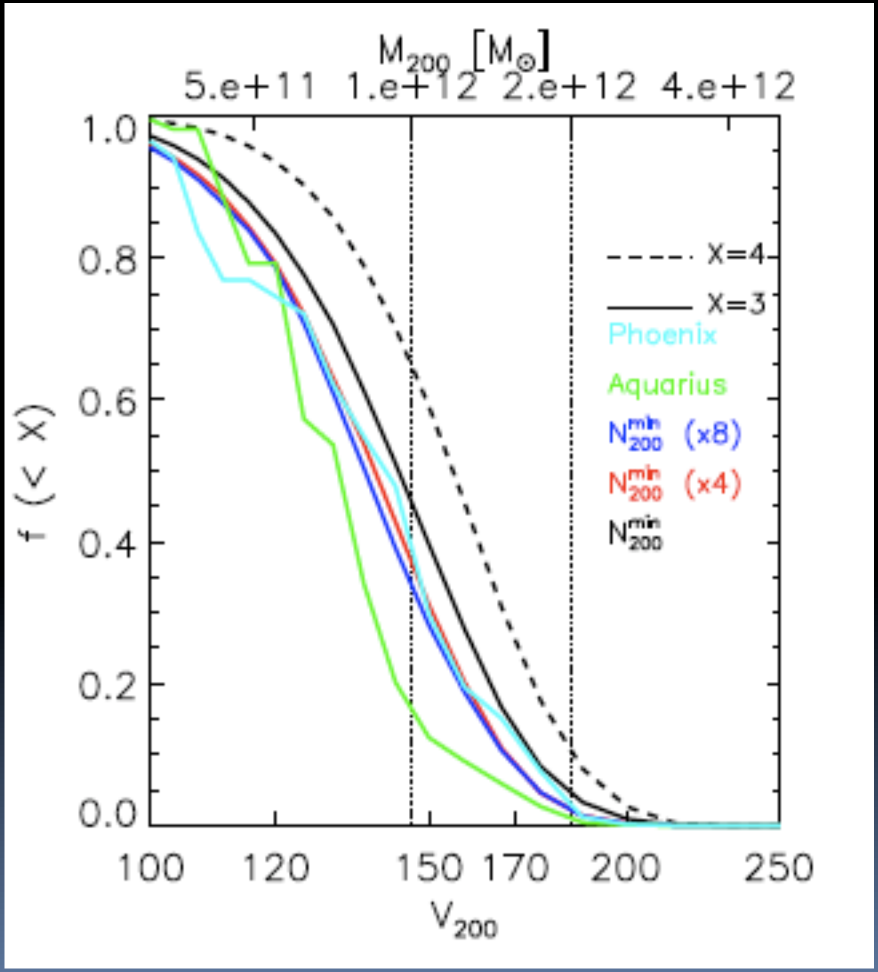
Invariance of scaled subhaloes velocity function

Wang et al.12 (see also Di Cintio et al.11, Vera-Ciro et al.12)



The number of subhaloes as a function of $v = V_{max}/V_{host}$ is independent of halo mass.

N(>v) is Poisson distributed about an average $\lambda = 10.2(v/0.15)^{-3.11}$

Probability that an halo has X or fewer subhaloes with V_{max}>30 km/s once a virial mass has been assumed for the MW

$$f(< X) = \sum_{k=0}^{X} \frac{\lambda_\nu^k}{k!} e^{-\lambda_\nu}$$

48% of haloes with $M=10^{12}$ M_{sun}
ALL haloes with $M<5x10^{11}$ M_{sun}

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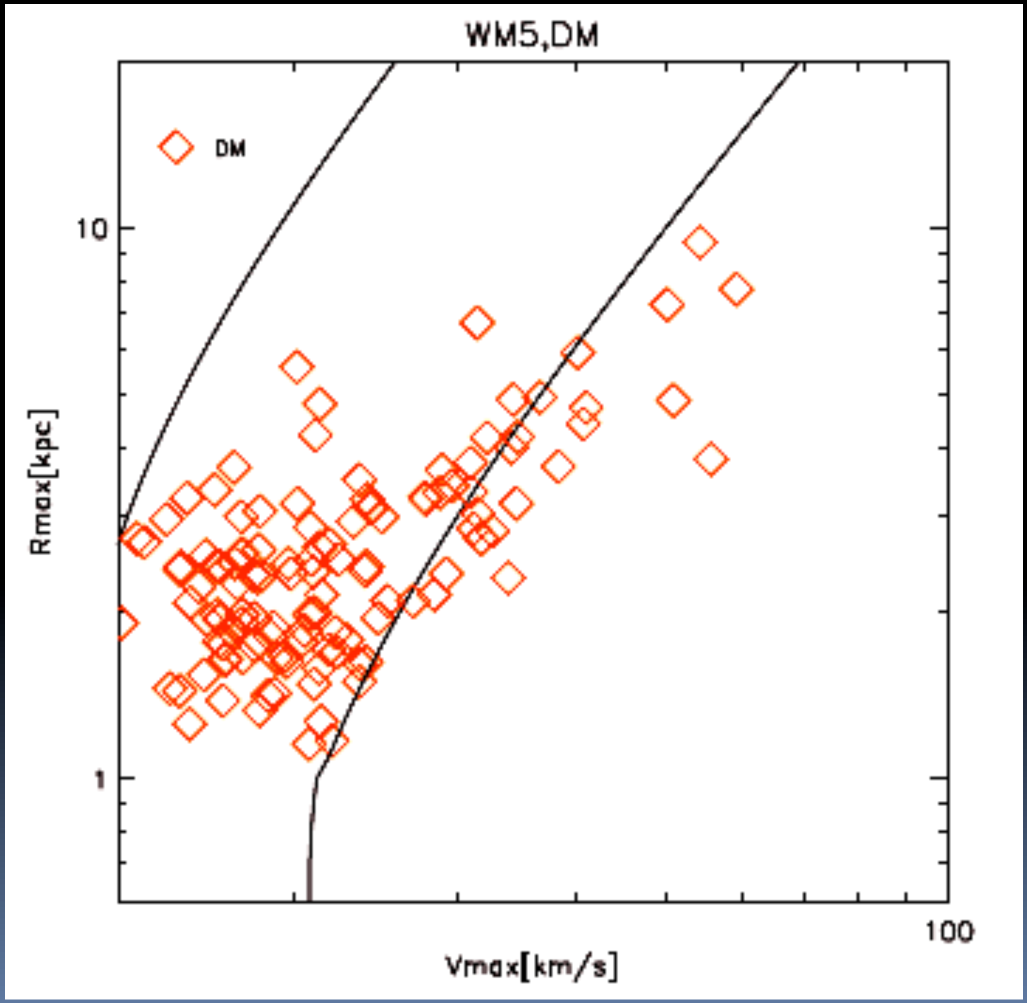
CLUES - WMAP5 – DM only

Di Cintio et al.11



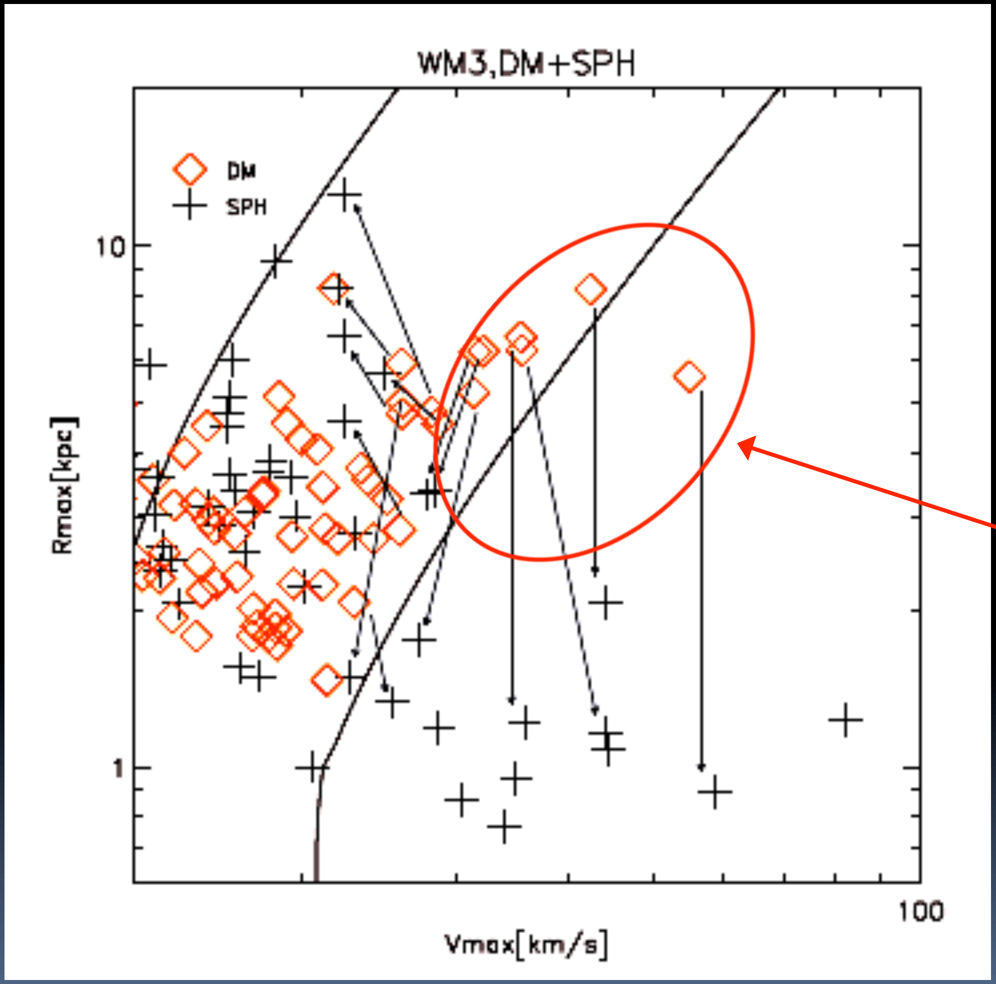
$\sigma_8 = 0.817$

m_{DM}=2.5 x $10^5 h^{-1} M_{sun}$

Subhalos of the two most massive hosts, MW and M31
r<300 Kpc from each host' centre with
M>2 x 10^8 M_{sun}

CLUES – WMAP3- DM + SPH run

Di Cintio et al.11



$\sigma_8 = 0.73$

m_{GAS}=4.4 x $10^4 h^{-1} M_{sun}$

"Sister" subhalos at z=0
(Libeskind et al. 2010)

High baryon fraction
f,b/f,b cosmic ~0.314

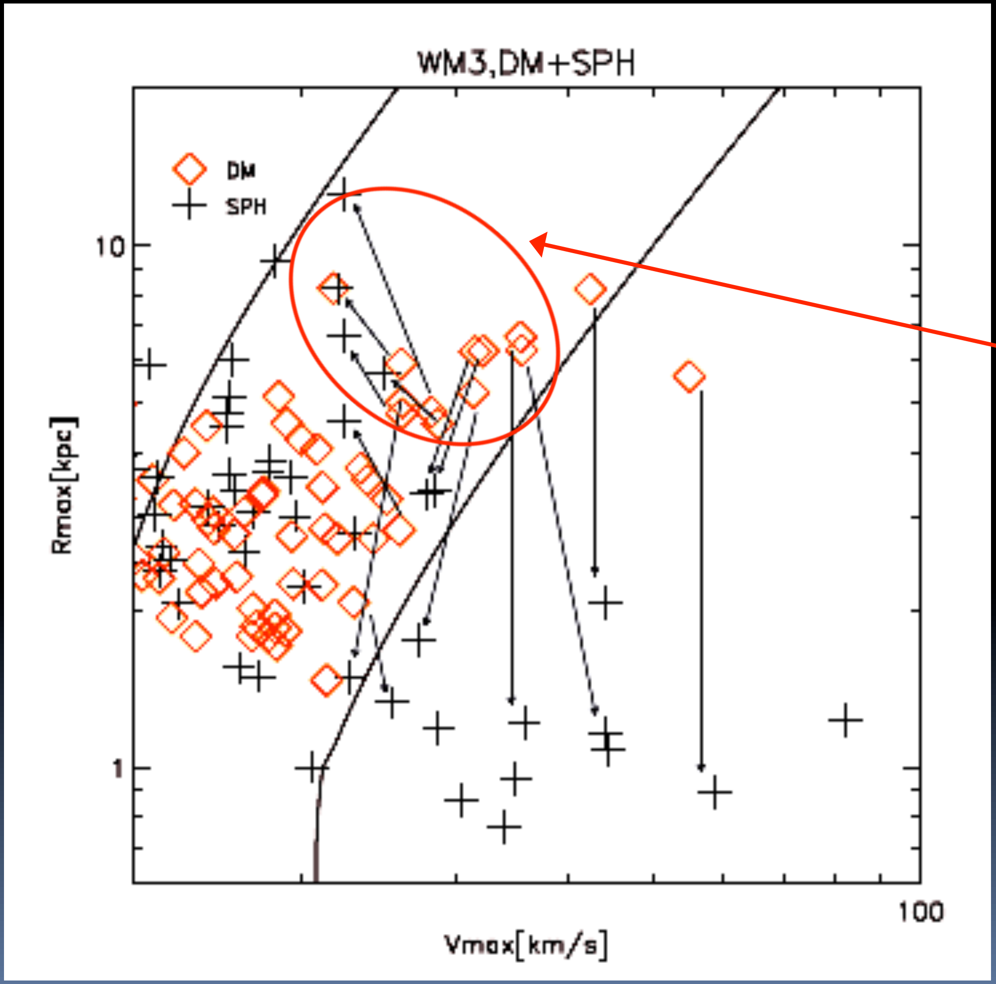
High Vmax-Rmax values

THE MOST MASSIVE SUBHALOS DO EXPERIENCE ADIABATIC CONTRACTION

CLUES – WMAP3- DM + SPH run

Di Cintio et al.11

$\sigma_8 = 0.73$



m_{GAS}=4.4 x $10^4 h^{-1} M_{sun}$

“Sister” subhalos at z=0
(Libeskind et al. 2010)

Low baryon fraction
f,b/f,b cosmic ~0.006

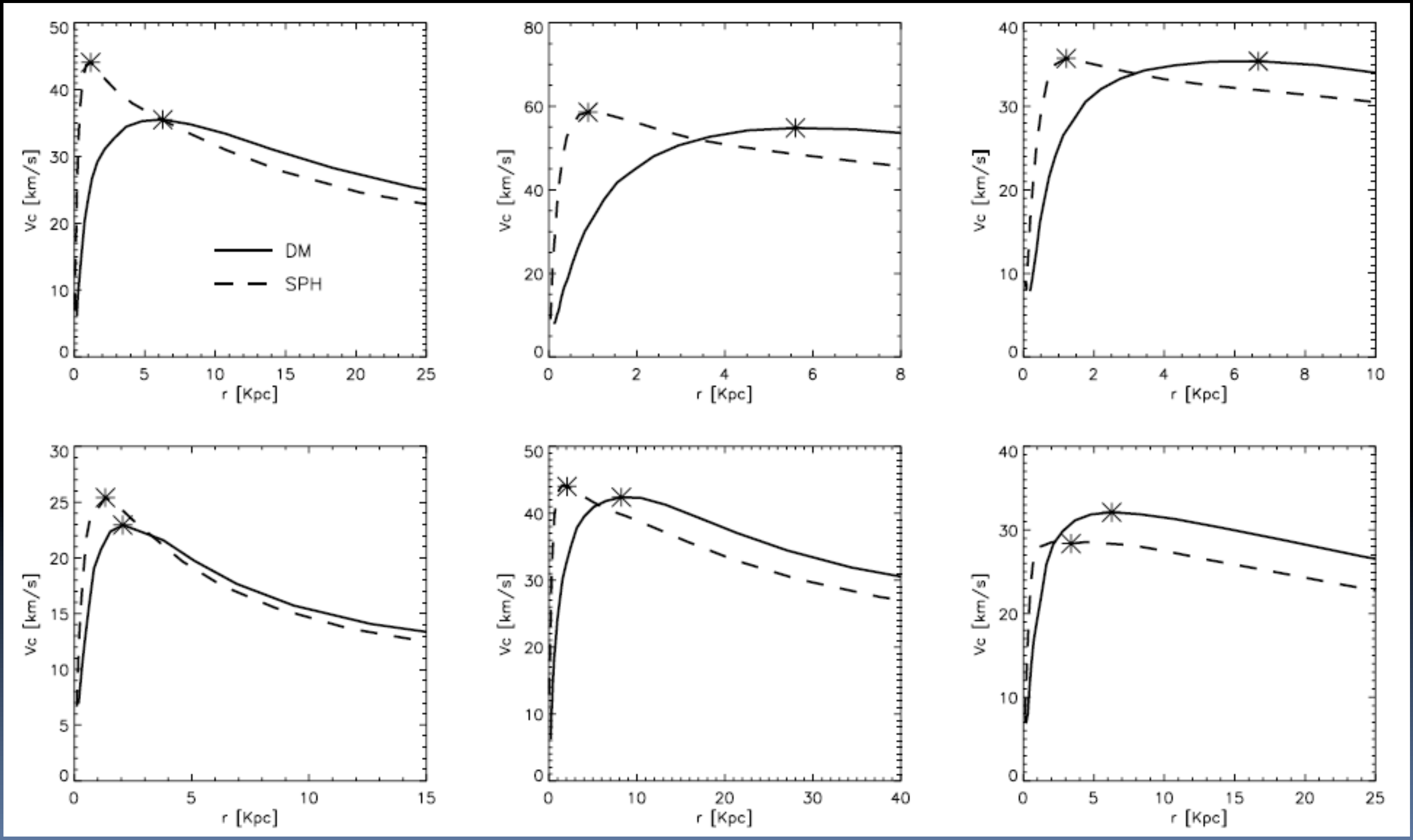
MASS OUTFLOW MODEL? Navarro96

or

RANDOM BULK MOTION OF GAS HEATS THE CENTRAL DM DISTRIBUTION?
Mashchenko06

Adiabatic Contraction
Di Cintio et al.11

Verified with the CONTRA code (Gnedin et al.04)



Why do the massive subhalos appear only in WMAP5? Di Cintio et al.11

- Vmax values of the subhaloes depend on the host mass , which is higher in WMAP5
- Scaling for each host mass eliminates the mass dependence -> the number of subhaloes above a fixed threshold is constant in both cosmologies
- $$V_{\max,sub}^{WM3} = \frac{V_{\max,host}^{WM3}}{V_{\max,host}^{WM5}} V_{\max,sub}^{WM5}$$
- Found a decrease of about 40-50% in the subhalos Vmax value
- PROPOSED SOLUTION => THE MILKY WAY MASS IS AT THE LOW MASS END OF CURRENT ESTIMATES

Density profiles of subhaloes in CLUES Di Cintio et al.12

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

$$\rho_{\mathrm{E}}(r) = \frac{\rho_{-2}}{e^{2n\left[\left(\frac{r}{r_{-2}}\right)^{\frac{1}{n}}-1\right]}}$$

$$\rho_{\mathrm{P\&S}}(r) = \frac{\rho_{-2}}{\left(\frac{r}{r_{-2}}\right)^{p} e^{n(2-p)\left[\left(\frac{r}{r_{-2}}\right)^{\frac{1}{n}}-1\right]}}$$

(α,β,γ)=(1,3,1) Navar… 96

(α,β,γ)=(1.… …oore et al.99

2-parameter models

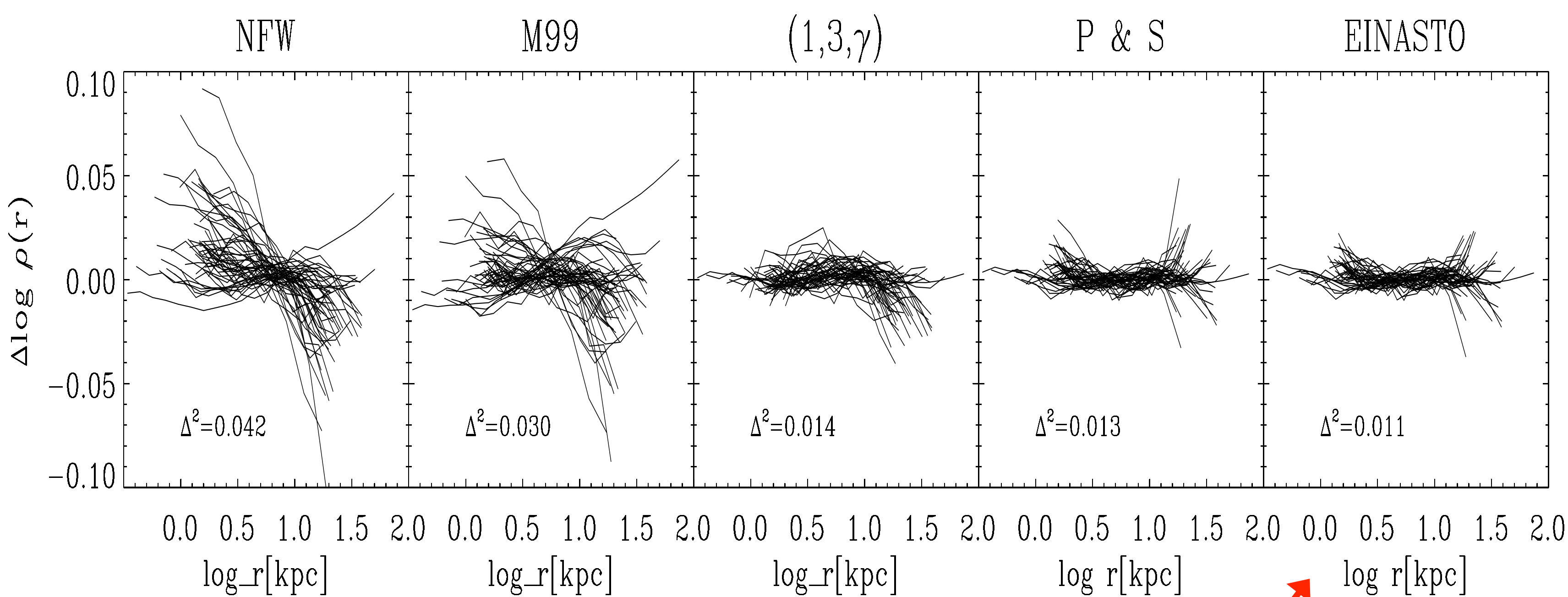
(α,β,γ)=(1,3,γ) model

Einasto 65, identical i… …onal form to the 2D Sersic …

…iel&Simien 97, approximation of the deprojected Sersic law

3-parameter models

Density profiles of subhaloes in CLUES Di Cintio et al.12



Residuals of the density profiles for different models

$$\Delta^2 = \frac{1}{N_{\rm bins}} \sum_{k=1}^{N_{\rm bins}} (\log_{10}\rho_{\rm sim,k} - \log_{10}\rho_{\rm fit,k})^2$$

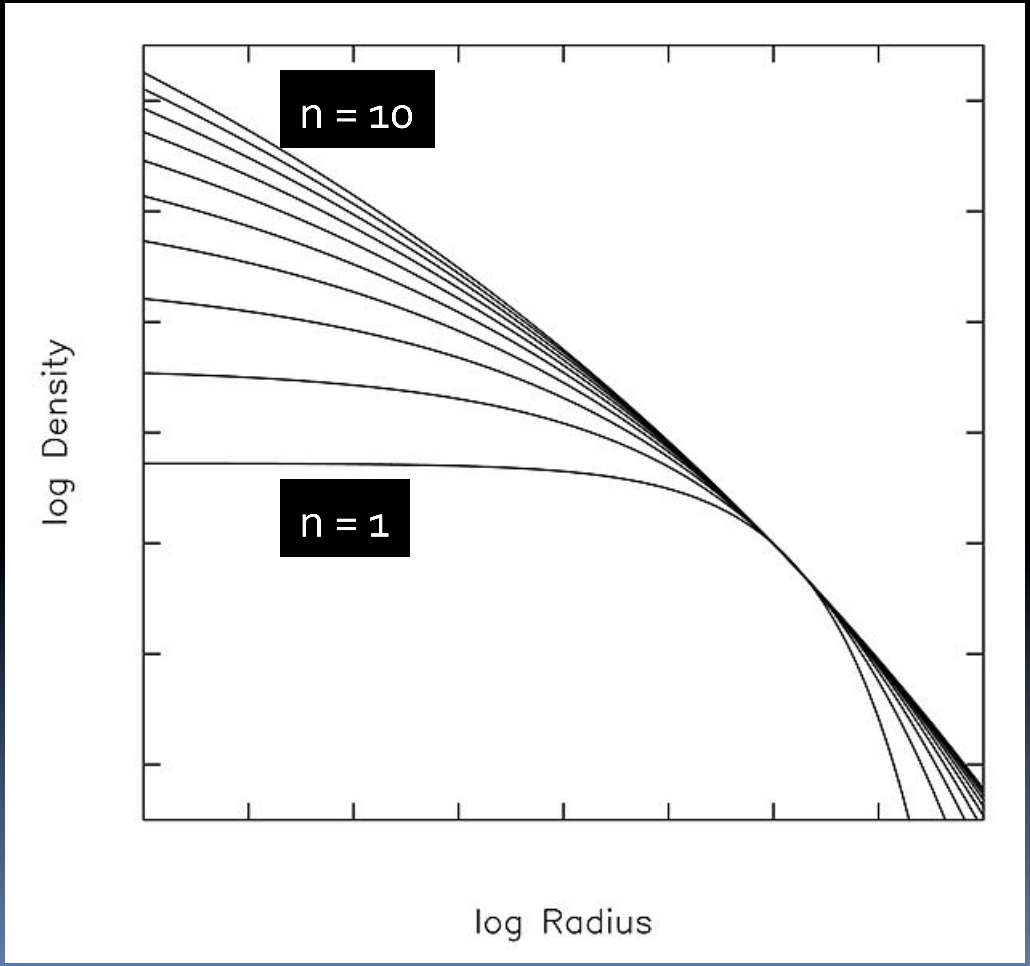
EINASTO BEST FIT AT EVERY RADIAL RANGE

Einasto profile

Einasto 65

$$\rho_E(r) = \frac{\rho_{-2}}{e^{2n\left[\left(\frac{r}{r_{-2}}\right)^{\frac{1}{n}} - 1\right]}}$$

Large shape parameter-> steep inner profile, shallow outer profile
Small shape parameter-> cored inner profile, steep outer profile



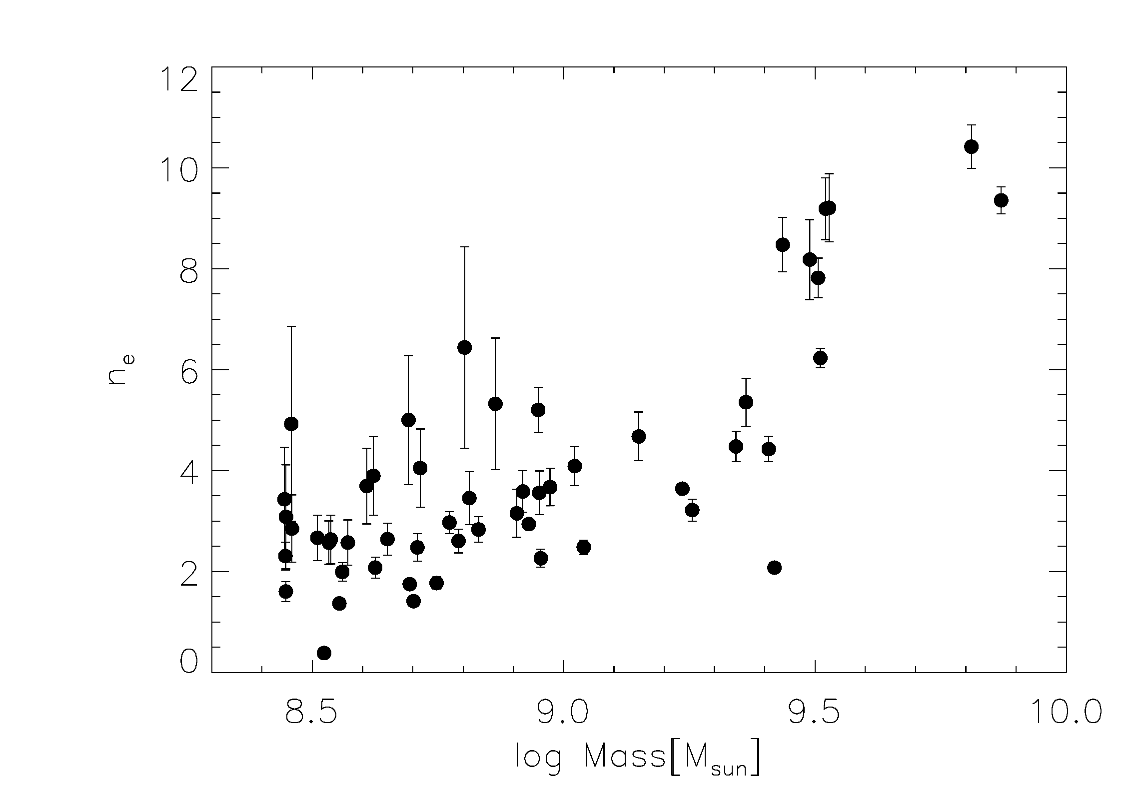
Usual values of n found in dark matter only simulations for haloes more massive than 10^{10} M_{sun} are $4 < n < 7$

In the CLUES simulations, for subhaloes with $10^8 < M/M_{sun} < 10^{10}$ we found $0.4 < n < 10.4$

Shape parameter vs mass

Di Cintio et al.12

The majority of the subhaloes has a small n, only the most massive ones have a high n. Similar conclusions from Del Popolo&Cardone 12, who used high quality rotation curves data of dwarf galaxies to show $0.29 < n_{obs} < 9.1$

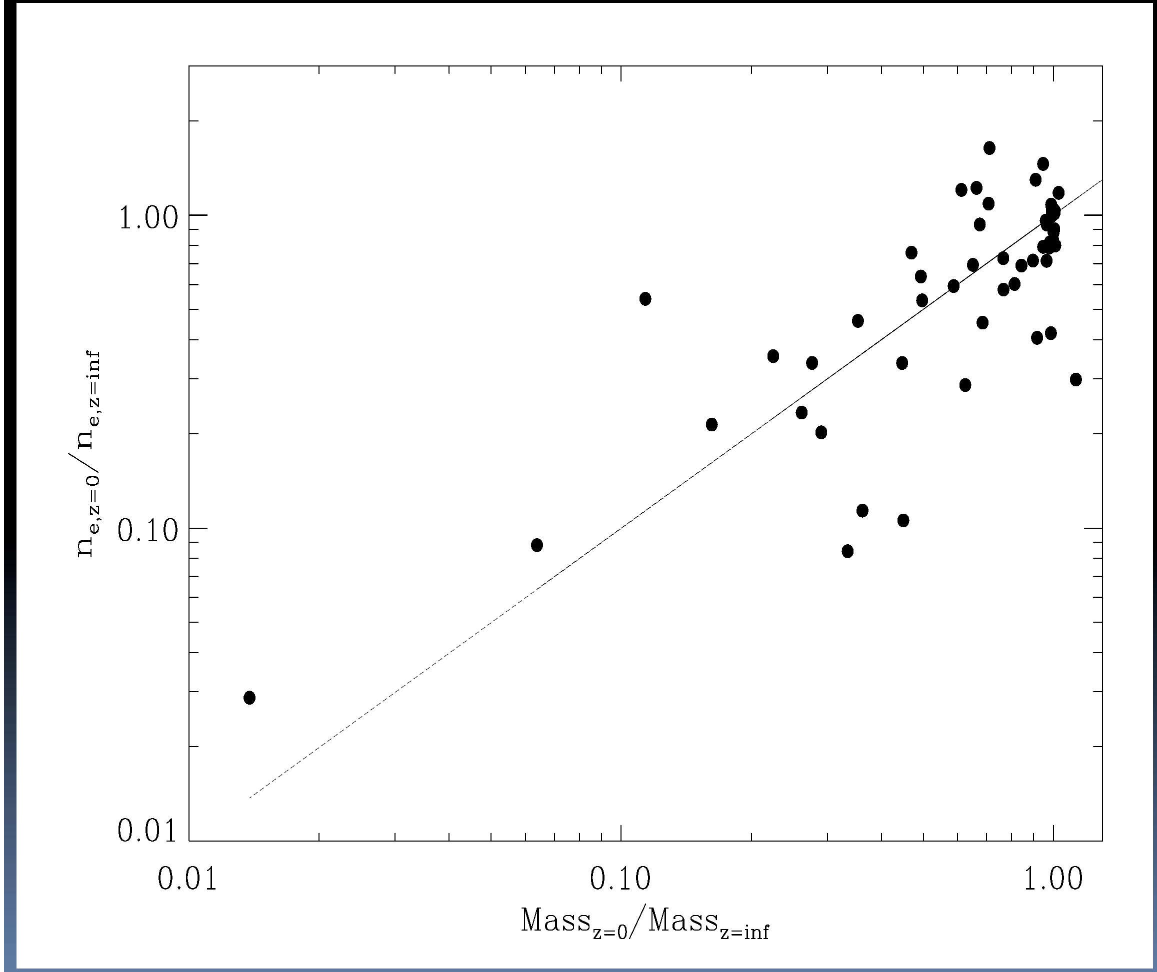


Dramatic variation of n!!
The profile of the simulated subhaloes, as well as of the observed isolated dwarf, is
NOT UNIVERSAL !!

S_r = 0,70 correlation

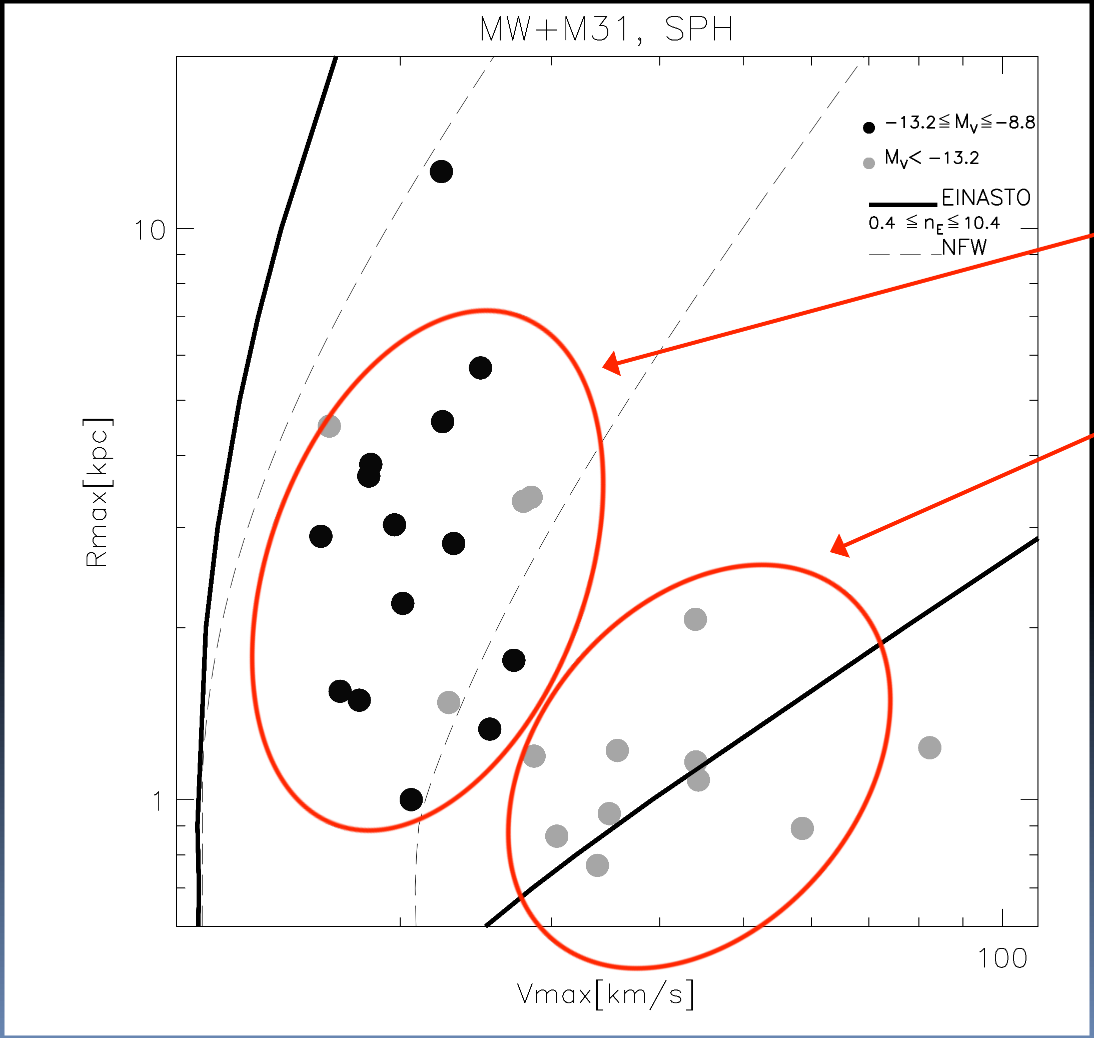
Tidal stripping affects the density profile

Di Cintio et al.12



- Subhaloes at infall are well described by both NFW and Einasto profile
- Correlation between the amount of stripped mass and the reduction of the shape parameter
- Tidal stripping not only affects the outer region, it also cause the halo to expand and the central density to decrease (Hayashi et al.03)

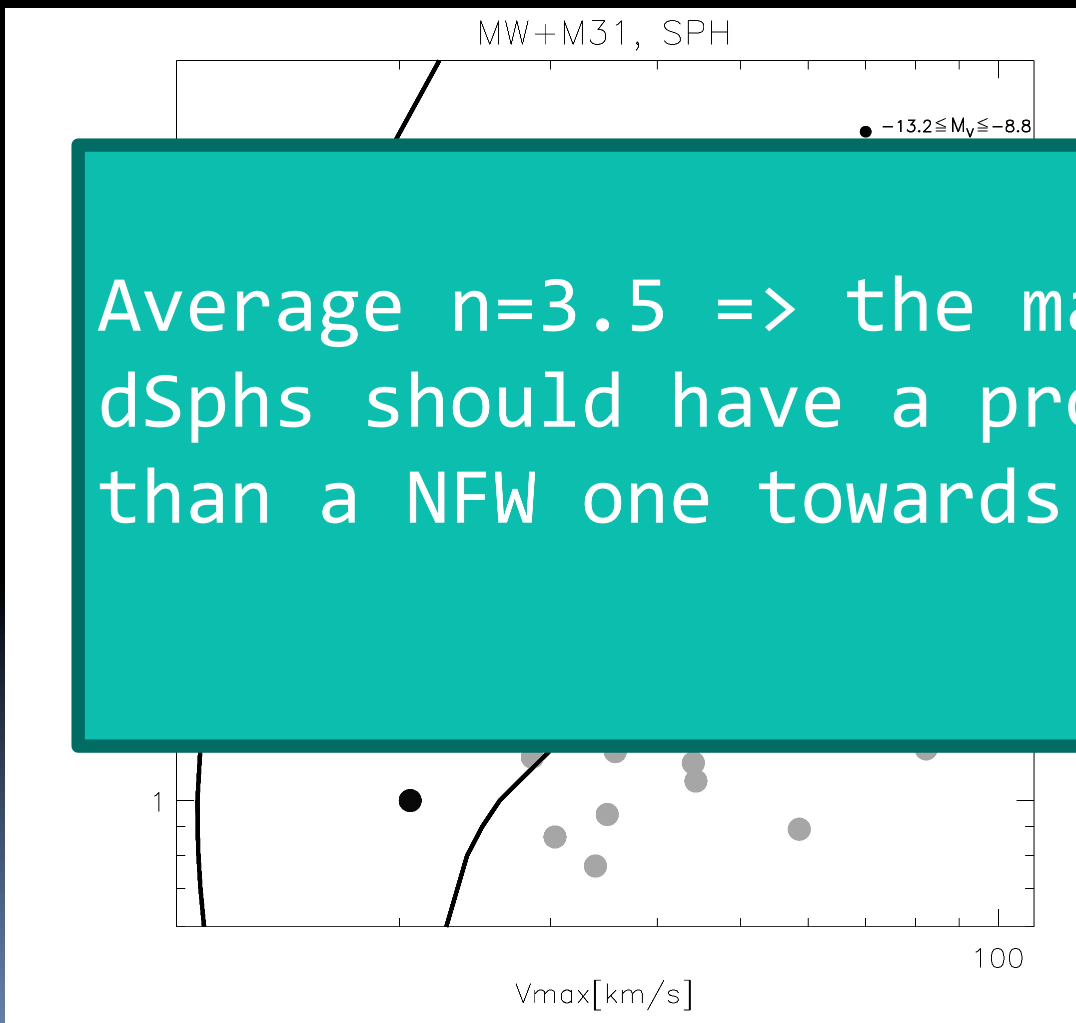
Revisited constraints for the MW'dSphs Di Cintio et al.12



Magnitude compatible with the one of the classical dSphs

Brighter than the classical dwarfs

Revisited constraints for the MW' dSphs Di Cintio et al.12

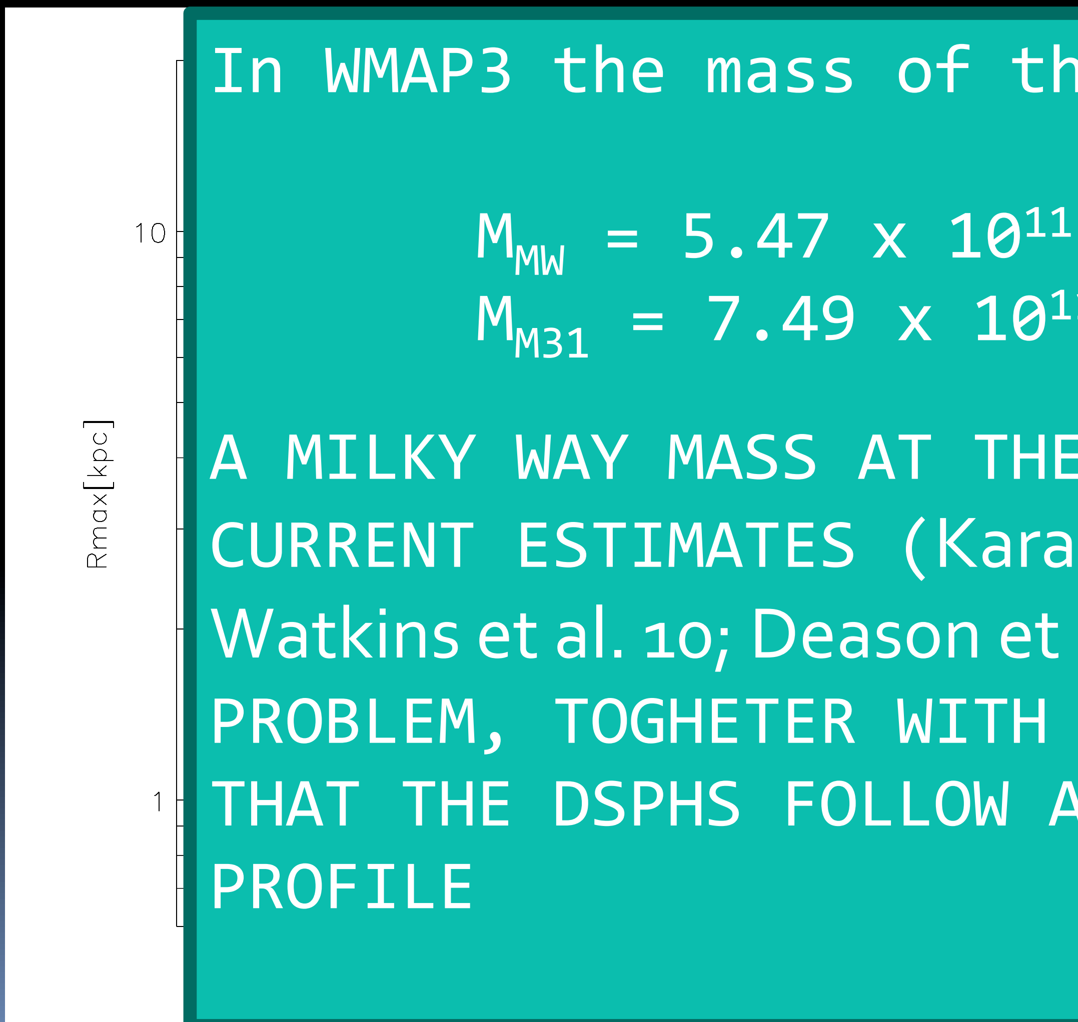


Using only the subhaloes with $-13.2<M_V<-8.8$

Average n=3.5 => the majority of the dSphs should have a profile shallower than a NFW one towards the center

dSphs favor a cuspy inner profile, others a cored central density

Revisited constraints for the MW' dSphs Di Cintio et al.12



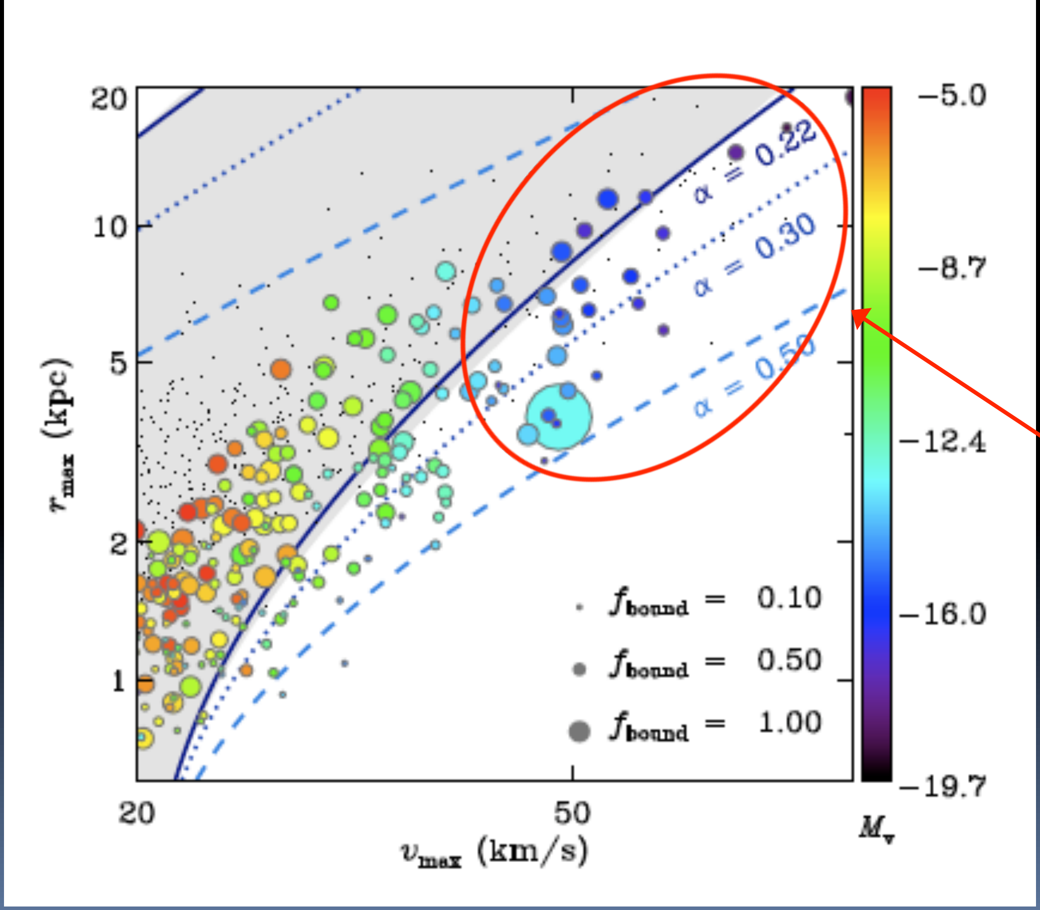
In WMAP3 the mass of the hosts are

$$M_{MW} = 5.47 \times 10^{11} M_{sun}$$
$$M_{M31} = 7.49 \times 10^{11} M_{sun}$$

A MILKY WAY MASS AT THE LOW END OF CURRENT ESTIMATES (Karachentsev et al.06; Watkins et al. 10; Deason et al.12) SOLVES THE PROBLEM, TOGHETER WITH THE ASSUMPTION THAT THE DSPHS FOLLOW AN EINASTO PROFILE

Semi-analytic galaxy formation model + Einasto profile

Vera-Ciro et al.12



Shape parameter n=2 to completely explain the Vmax-Rmax pairs of subhaloes

Different position of the most bright objects with respect to the hydro sims

Milky Way mass ~$8.2 \times 10^{11} M_{sun}$ => number of satellites per luminosity bin & their velocities consistent with observations

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CONCLUSIONS

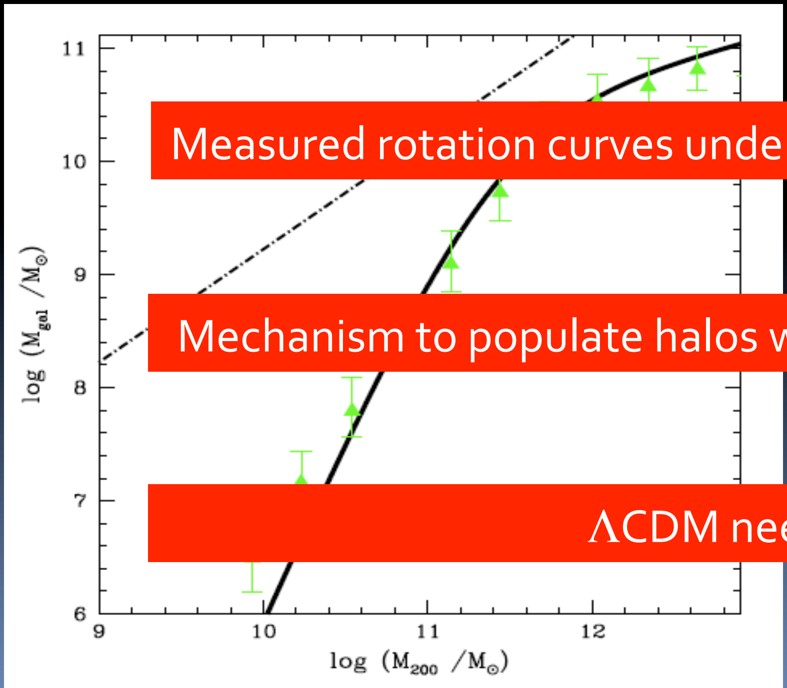
- The kinematic of the CLUES simulated subhaloes tells us that the density profile of dSphs is not universal (Di Cintio et al.12).
- Well described by an Einasto model with varying n: some dwarfs have shallow cores, some others cuspy inner profiles (consistent with Wolf&Bullock 12).
- Observations show that isolated dwarfs follow an Einasto profile as well, with a broad range for n (Del Popolo&Cardone 12).

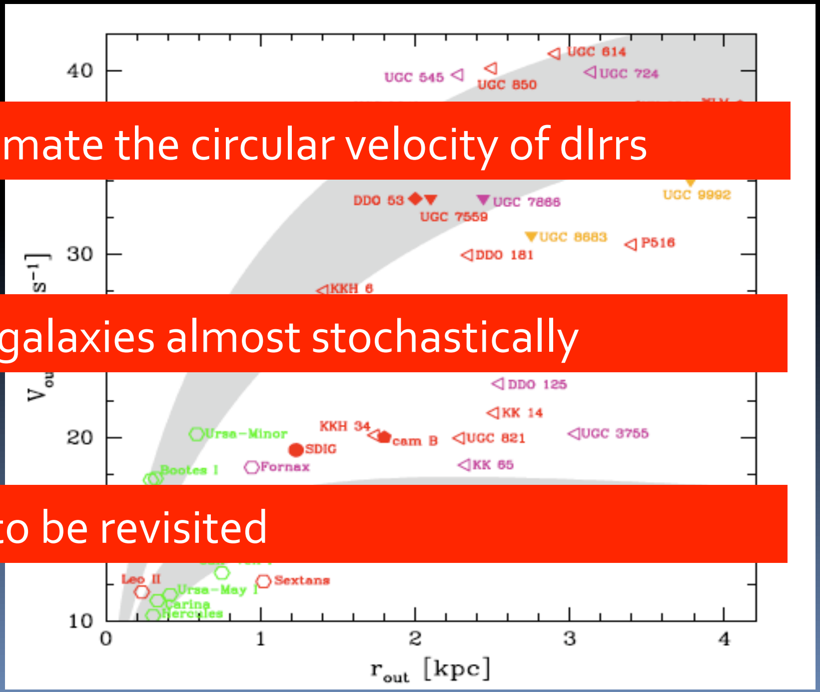
CONCLUSIONS

- The mass of the MW can be $<10^{12}M_{sun}$: this would solve the problem of the missing massive subhaloes (Boylan-Kolchin et al.12, Vera-Ciro et al.12, Wang et al.12, Di Cintio et al.12).
- A mass of $\sim 5\text{-}8\times10^{11}M_{sun}$ is in agreement with recent studies (Battaglia et al.05, 06, Smith et al.07, Xue et al.08, Watkins et al.10, Karachentsev et al.06).
- According to the model of Wang et al.12, it will give a 84%(66%) probability to find only 3 satellites with Vmax>30 km/s.
- However, this mass will lower the probability that the MW hosts two satellites as bright as the LMC and SMC.
- A MW like system is rare anyway, only 5%, as the SDSS DR7 indicates (Liu et al.11, Guo et al.11, Lares et al.11, Tollerud et al.11)

OPEN QUESTIONS..

- Lowering the mass of the MW still do not explain why many isolated dwarf galaxies, with spatially-resolved rotation curves,seem to live in haloes with $M<10^{10}M_{sun}$ (Ferrero et al.12)
- Abundance matching (Guo et al.10) suggests that circular velocity should lie on or above the $10^{10}M_{sun}$ shaded area
- If there is a minimum halo mass for galaxy formation, it's around $\sim 5x10^{8}M_{sun}$





Measured rotation curves underestimate the circular velocity of dIrrs

Mechanism to populate halos with galaxies almost stochastically

ΛCDM needs to be revisited