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Leibniz-Institut für
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The internal structure of DM haloes in the presence of baryons

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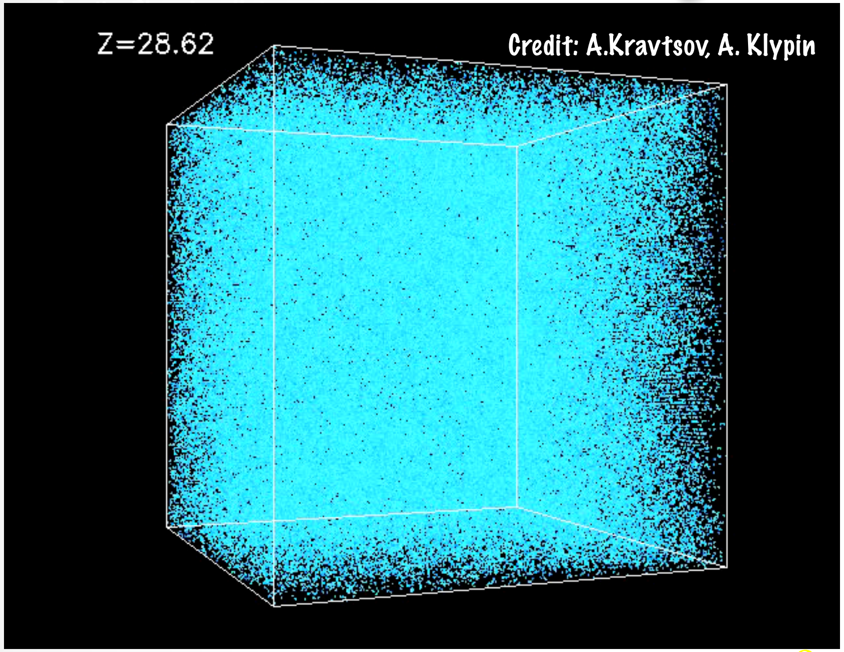
-> IAC from January 2018

Why is the inner structure of DM haloes so important?

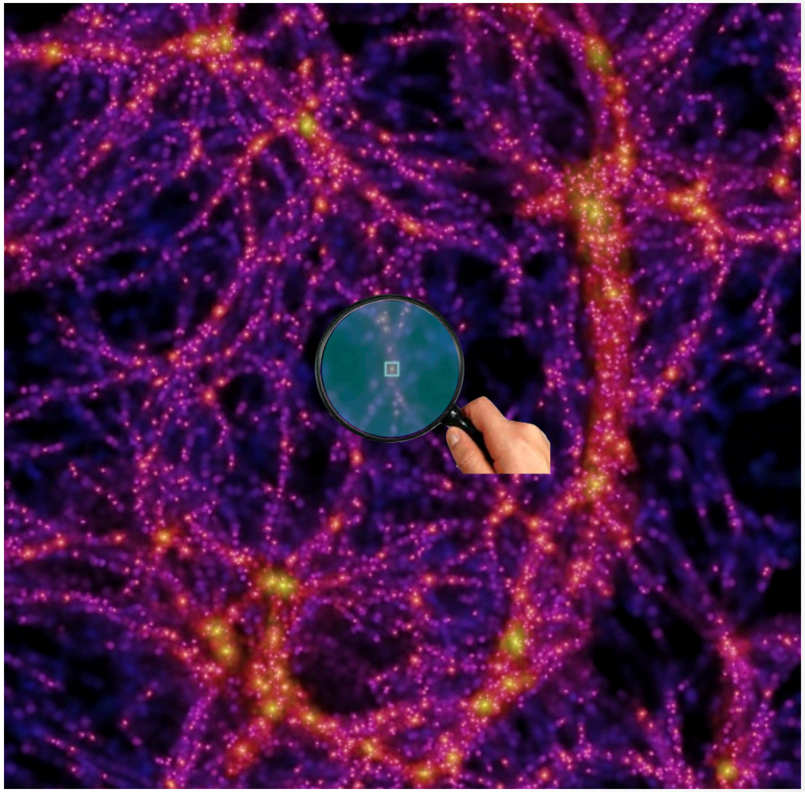
- The distribution of matter within galaxies - AKA their density profile - is a key prediction of galaxy formation happening within a cosmological framework!

- It must agree with observations, and it can potentially provide constraints about the nature of DM itself

Dark matter haloes in N-body simulations



Credit: A.Kravtsov, A. Klypin



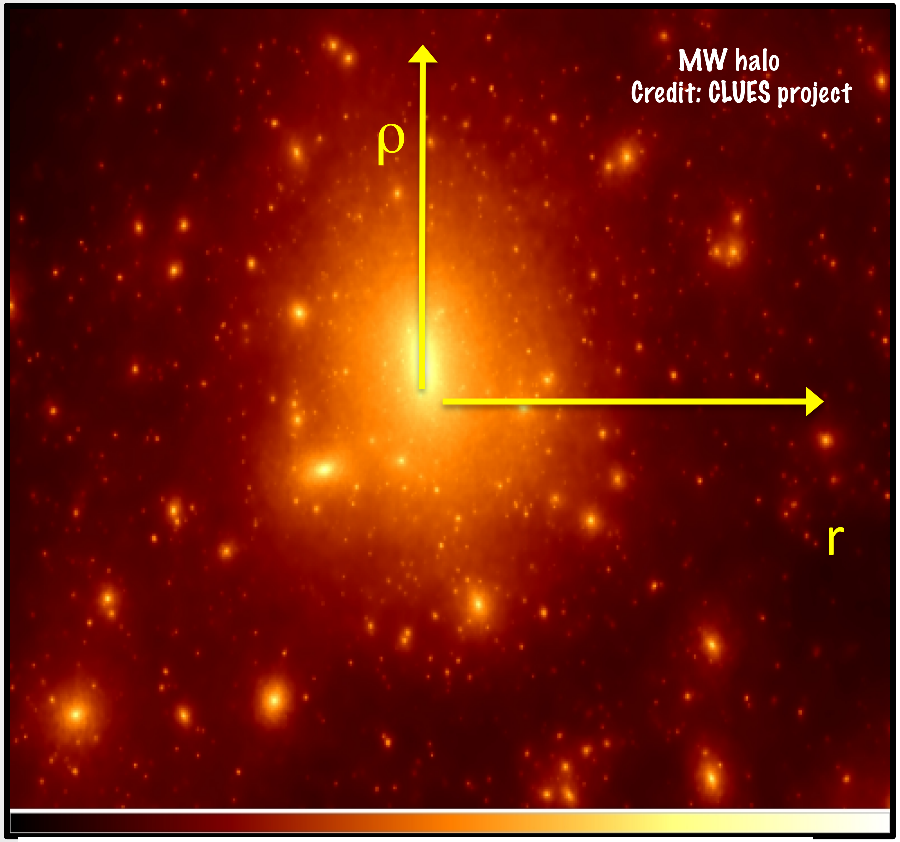
ρ

$$M_{\mathrm{halo}} = \frac{4}{3}\pi R_{vir}^{3}\Delta\rho_{crit}$$

r

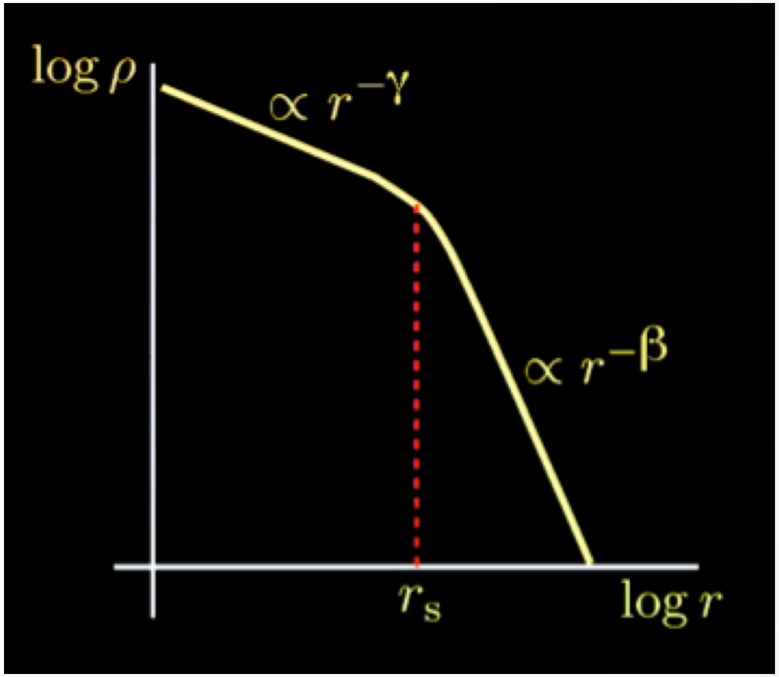
DM halo mass, Mvir=Mhalo, is the mass within a sphere of radius Rvir containing Δ times the critical density of the Universe

Density profile of DM haloes



MW halo
Credit: CLUES project

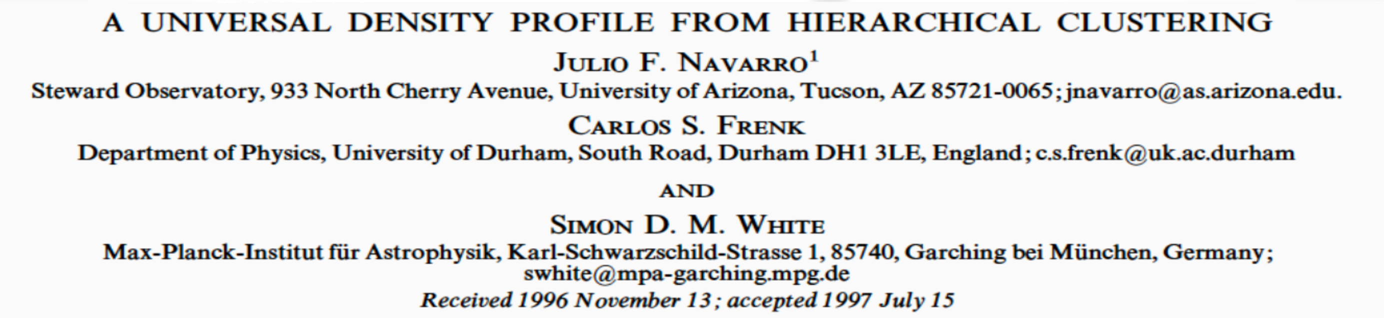
General double-power law model (Hernquist 1990; Jaffe 1983) has 5 free parameters:



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

α	Sharpness of transition
β	Outer slope
γ	Inner slope
rs	scale radius
ρ_s	scale density

The NFW profile



A UNIVERSAL DENSITY PROFILE FROM HIERARCHICAL CLUSTERING

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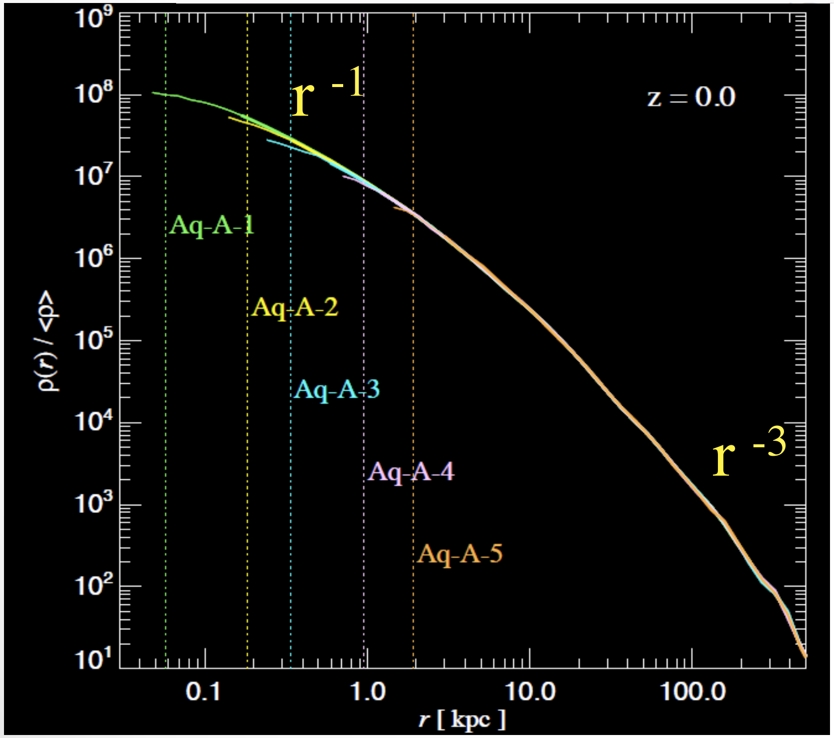


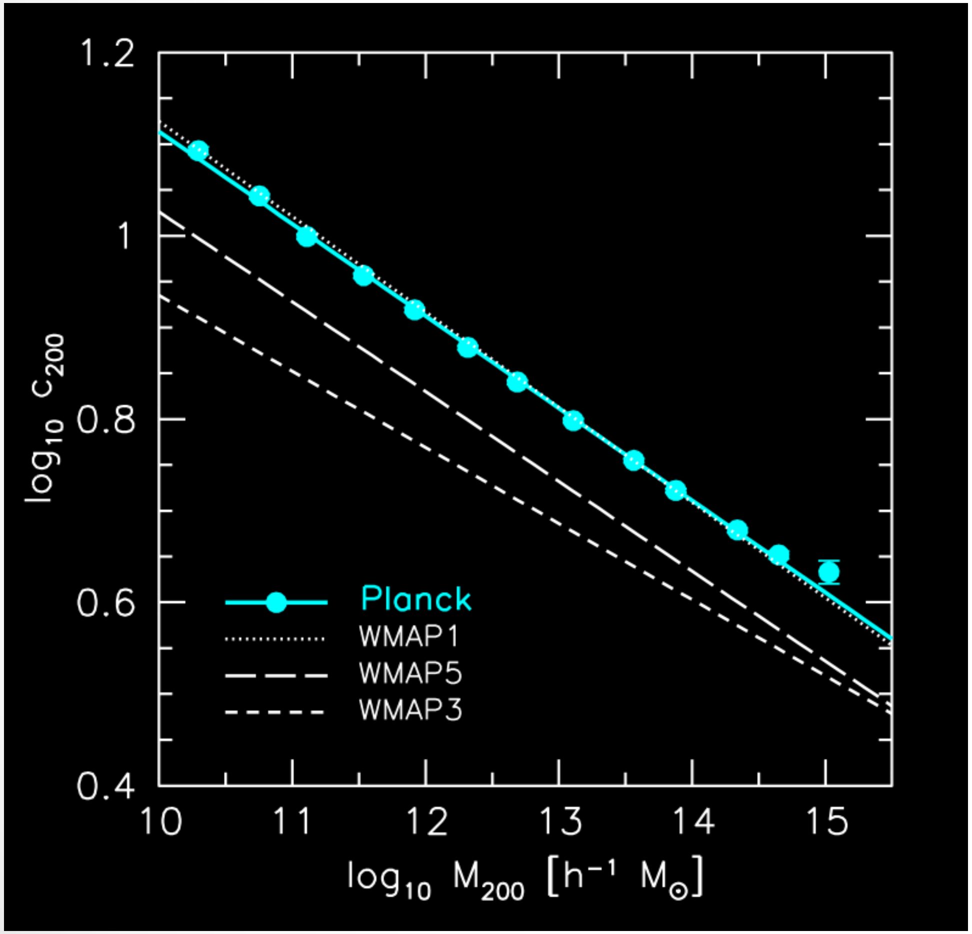
Aquarius simulations

- Navarro, Frenk & White 1997 CDM haloes in N-body simulations have a universal density profile
- NFW has logarithmic inner slope γ=-1 and outer one of β=-3 NFW profile (α,β,γ)=(1,3,1)

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

Concentration-Mass relation

$$R_{\rm vir} = cR_s$$



Dutton&Maccio'14

- The mass and concentration are correlated, with a shallow slope ($c \sim M^{-0.1}$ and small scatter ($\sigma\log c \sim 0.1$), so the structure of CDM haloes is almost scale free
- Small changes in cosmological parameters have a non-negligible effect on the structure of CDM haloes.

$$c(M_{\rm vir}) = 10\left(\frac{M_{\rm vir}}{10^{12}\,M_{\odot}}\right)^{-0.1}$$

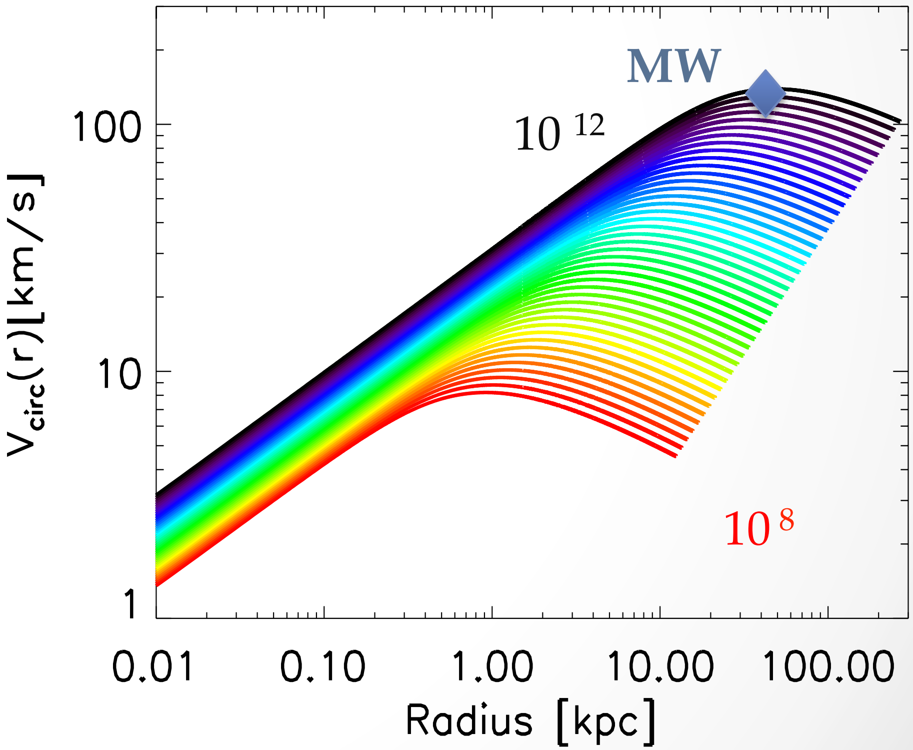
Mass/Velocity of a NFW halo

$$R_{\rm vir} = cR_s$$

$$M = \int_0^{R_{\rm vir}} 4\pi r^2 \rho(r)\, dr = 4\pi\rho_0 R_s^3 \left[\ln(1+c) - \frac{c}{1+c}\right]$$

$$v_{\rm c}^2(r) =-r\frac{\partial\Phi}{\partial r} = r|\vec{F}| = \frac{GM(r)}{r}.$$

$$v_{\rm c}^2(r) = v_{200}^2\frac{1}{x}\frac{\ln(1+cx)-(cx)/(1+cx)}{\ln(1+c)-c/(1+c)}$$



Steep central density translate into a fast-rising rotation curve!

NFW has a maximum at Vmax=2.16Rs

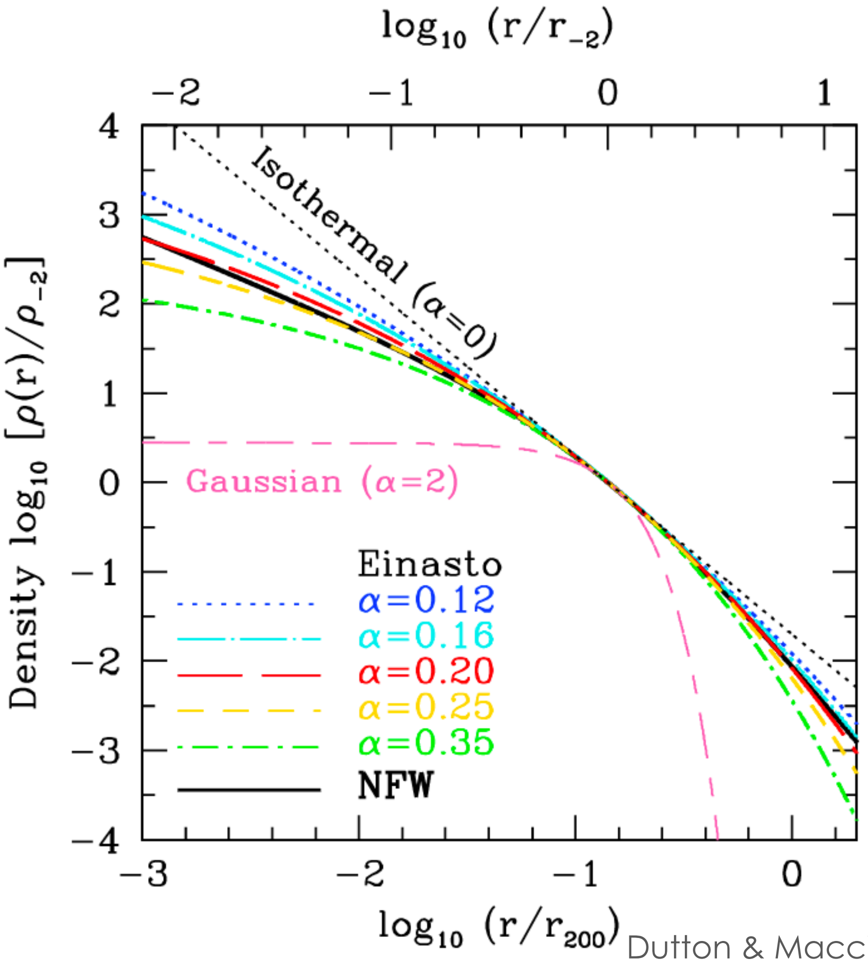
The Einasto profile

$$\frac{\rho_{\rm EIN}(r)}{\rho_{-2}} = \exp\left\{-\frac{2}{\alpha}\left[(r/r_{-2})^{\alpha} - 1\right]\right\}$$

$$\rho_{-2} = \rho_s/4.$$

- Einasto shape parameter α~0.17 resembles a NFW profile

The Einasto profile has a finite central density unlike the NFW profile which has a divergent inner density.

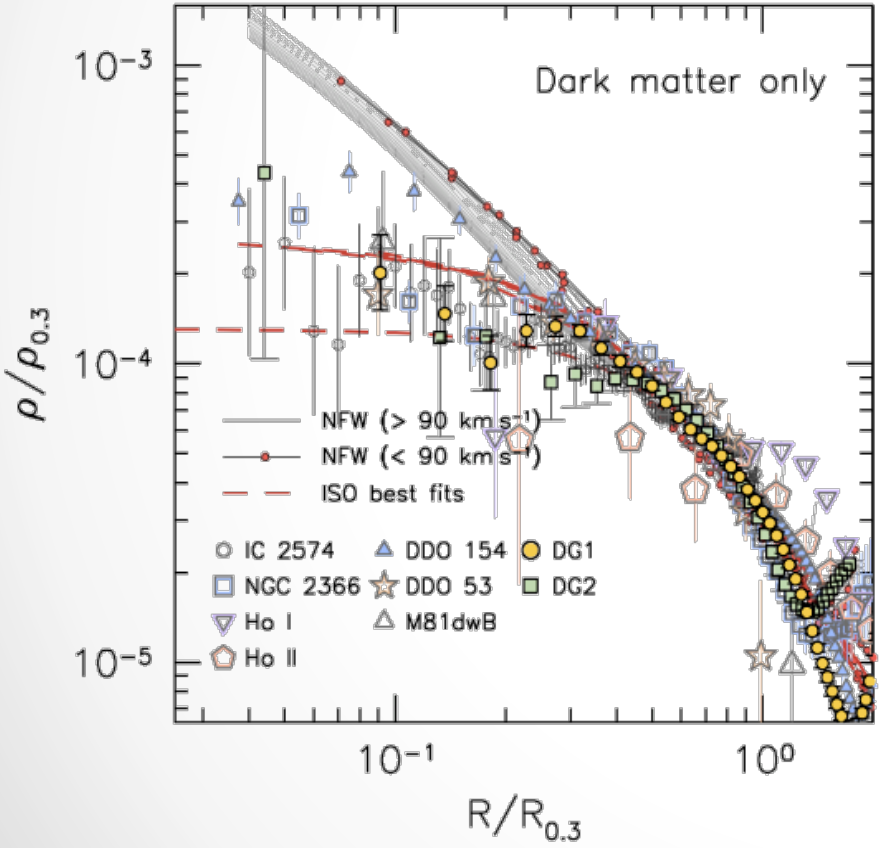


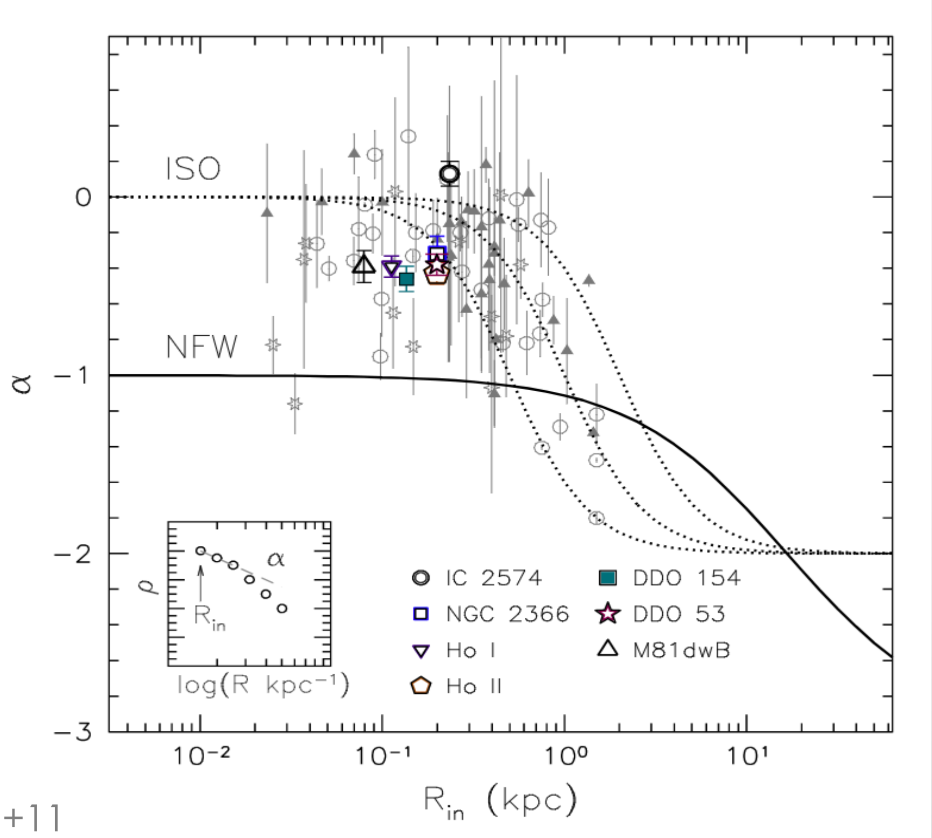
Dutton & Maccio'14

The `cusp-core’ discrepancy

Simulations find ‘CUSPY’ profiles
Inner slope γ <= -1 NFW

Observations of dwarfs and LSB
show ‘CORED’ profiles
Inner slope 0> γ > -1

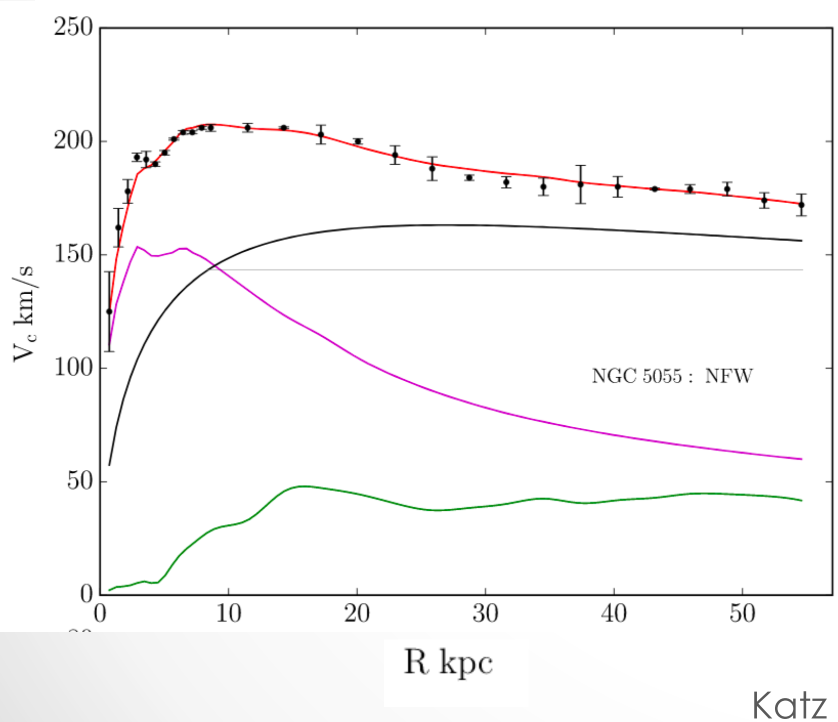


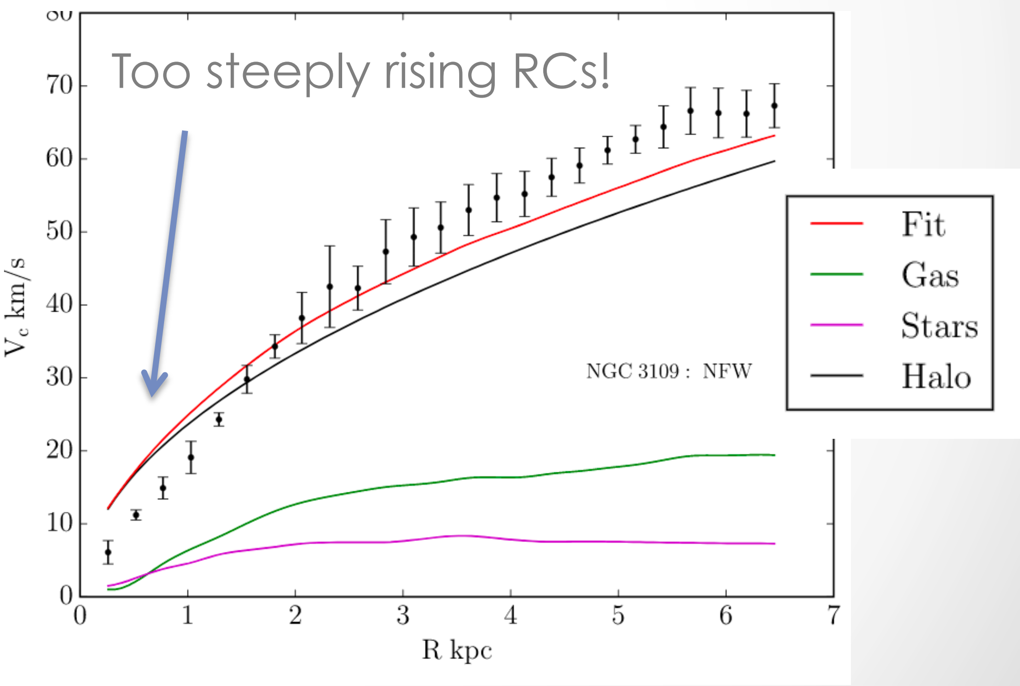


Oh+11

Cusp-core issue arising in galaxy rotation curves

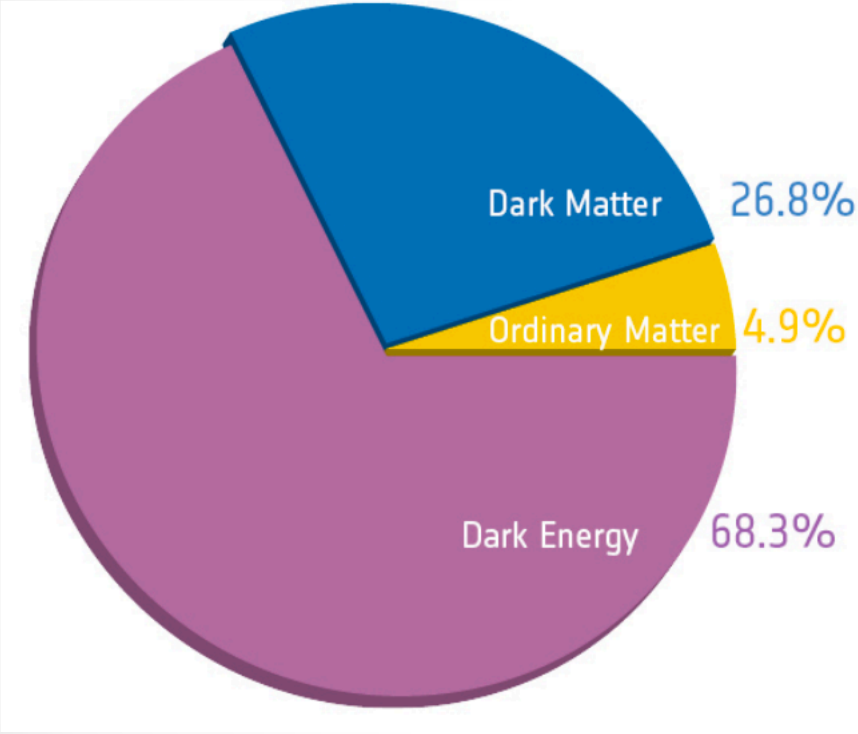
$$V_c(r) = \sqrt{V_{DM}(r)^2 + V_{gas}(r)^2 + (M_*/L)V_{stars}(r)^2}$$




Too steeply rising RCs!

Katz et al.17

Role of baryonic physics



baryons for astrophysicists

Baryonic physics processes modeled in hydrodynamical simulations:

- Gas inflowing and cooling
- Star formation
- Feedback (mechanical, thermal, kinetic, radiation pressure) from SNae, massive stars, AGNs

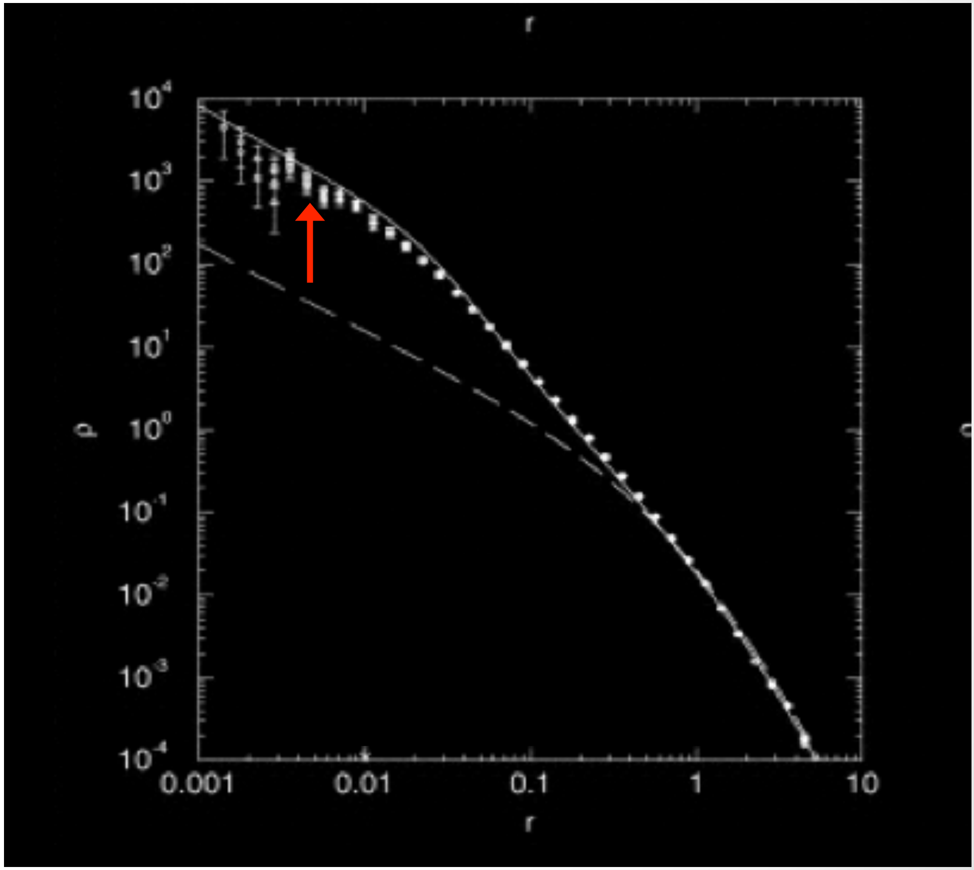
Role of baryons #1 adiabatic contraction

Contraction of a dark matter halo in response to condensation of baryons in its center.

Blumenthal+84, Gnedin+04

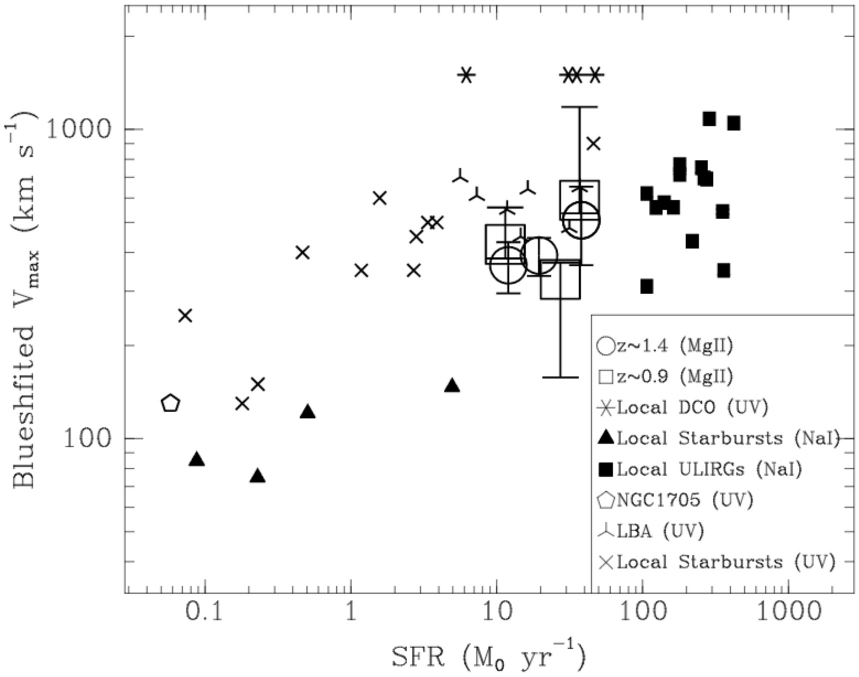
Since the timescale of the baryonic infall is very slow, longer than the local dynamical timescale, dm is pulled it inward

Inner slope > -1!!



Adiabatic approximation may not be valid in reality

Fast Outflowing gas is ubiquitous around galaxies Martin +12



Outflows necessary to solve the angular momentum catastrophe Brook +11

Role of baryons #2
SNae feedback and outflows

- KEY ingredients:

high initial density for star forming gas, similar to molecular cloud formation in our Galaxy n=10-100 mhcm^{-3}

- RESULT:

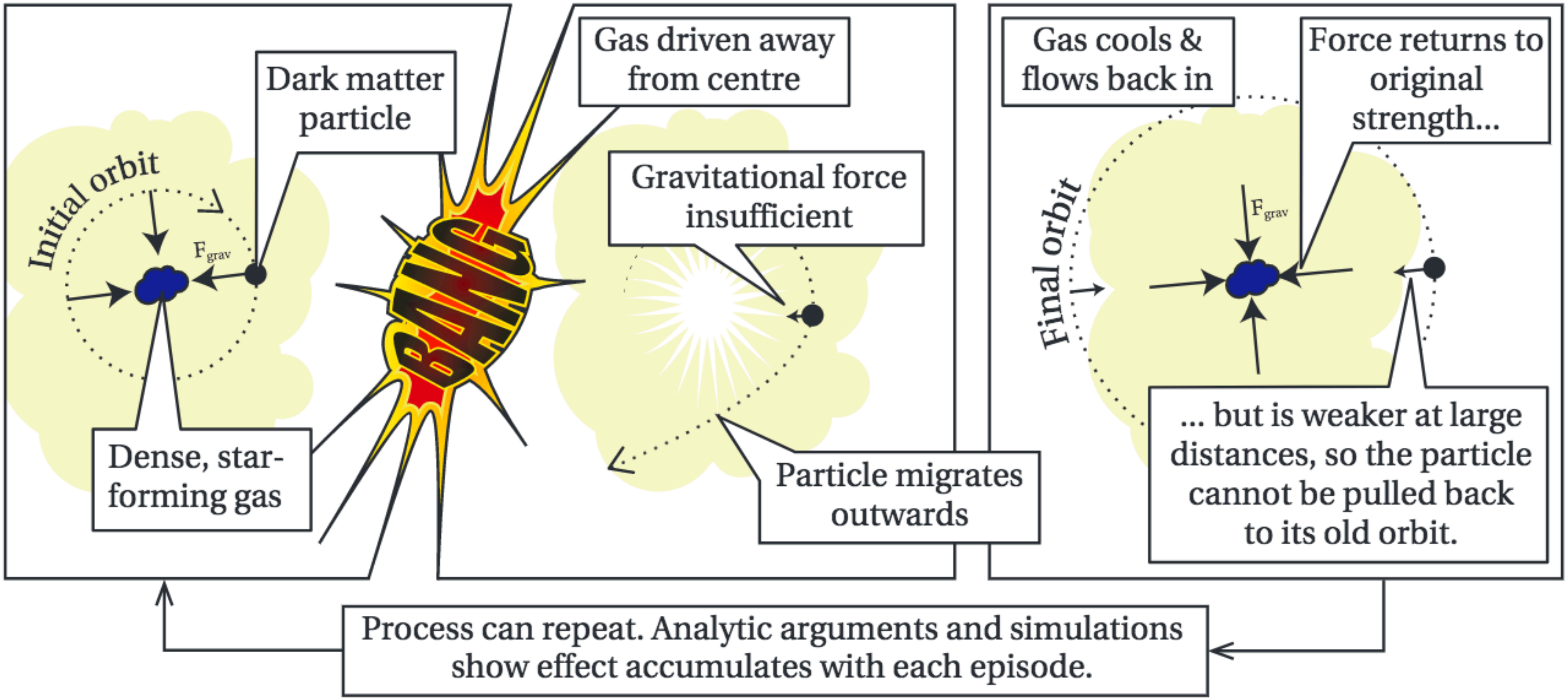
stars form efficiently in small, isolated regions, energy is dumped into the gas which heats to much higher temperatures, gas is overpressurized and expands rapidlly: galactic scales outflows are launched at speeds greater than local circular velocity

- FEATURE: the process is cumulative

credit: A. Pontzen & F. Governato

Credit:A. Dutton, NIHAO simulations

From gas outflows to DM ‘cores’



Dark matter particle

Dense, star-forming gas

Gas driven away from centre

Gravitational force insufficient

Particle migrates outwards

Gas cools & flows back in

Force returns to original strength...

... but is weaker at large distances, so the particle cannot be pulled back to its old orbit.

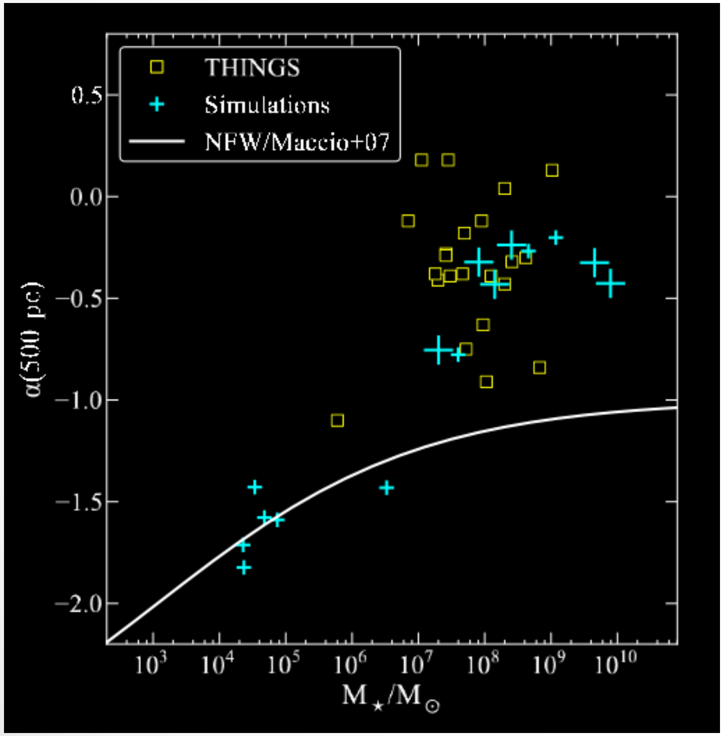
Process can repeat. Analytic arguments and simulations show effect accumulates with each episode.

Pontzen & Governatp 14

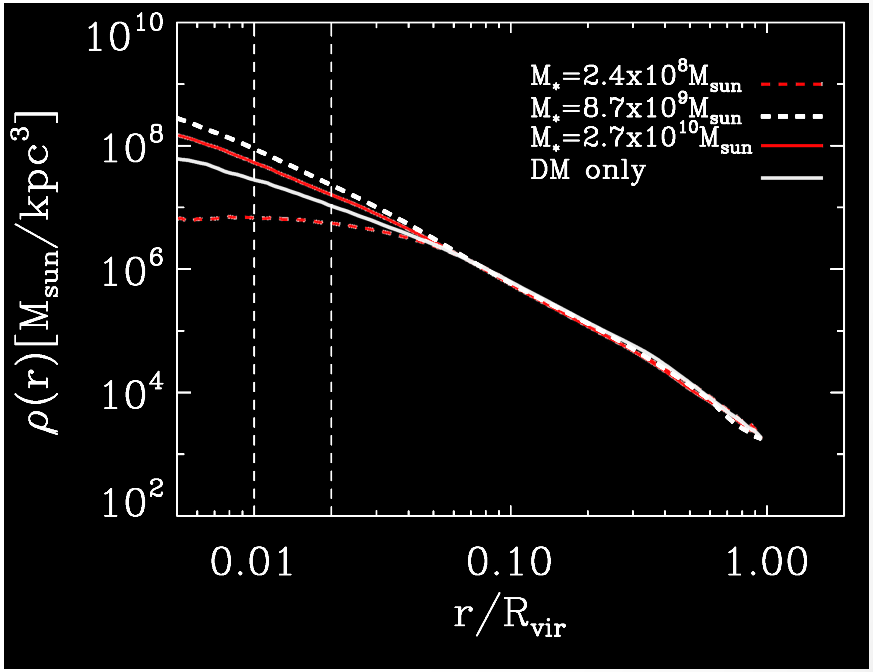
Core formation mechanism -> outflows driven by SNae feedback
Core created during starburst events that launch powerful gas outflows

The role of SNae-driven gas outflows in creating 'cores'

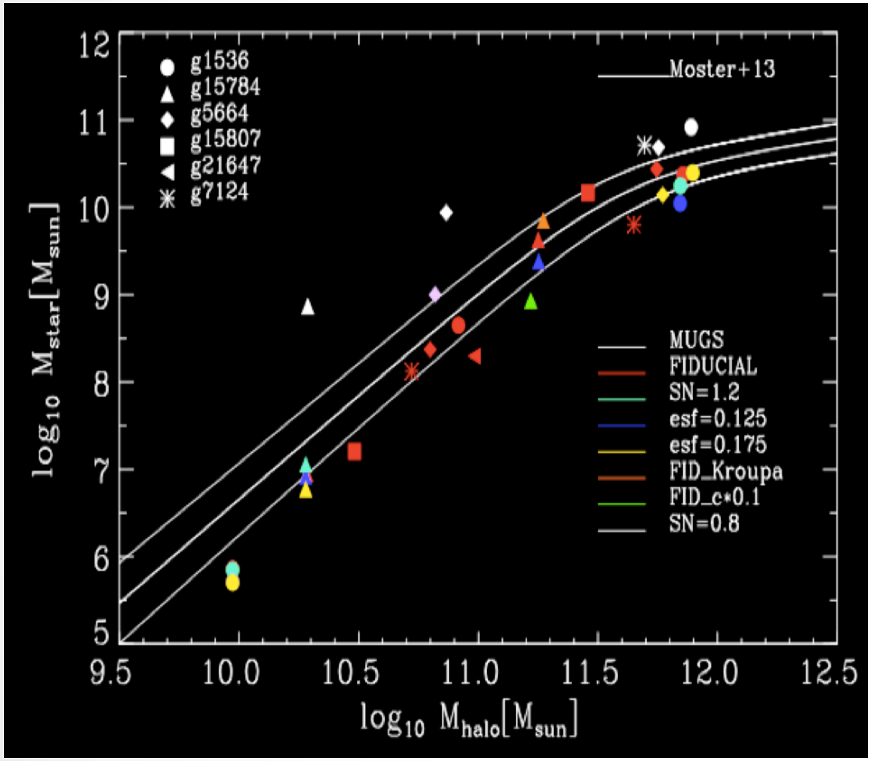
Governato +12   nth=10=100 mh cm-3

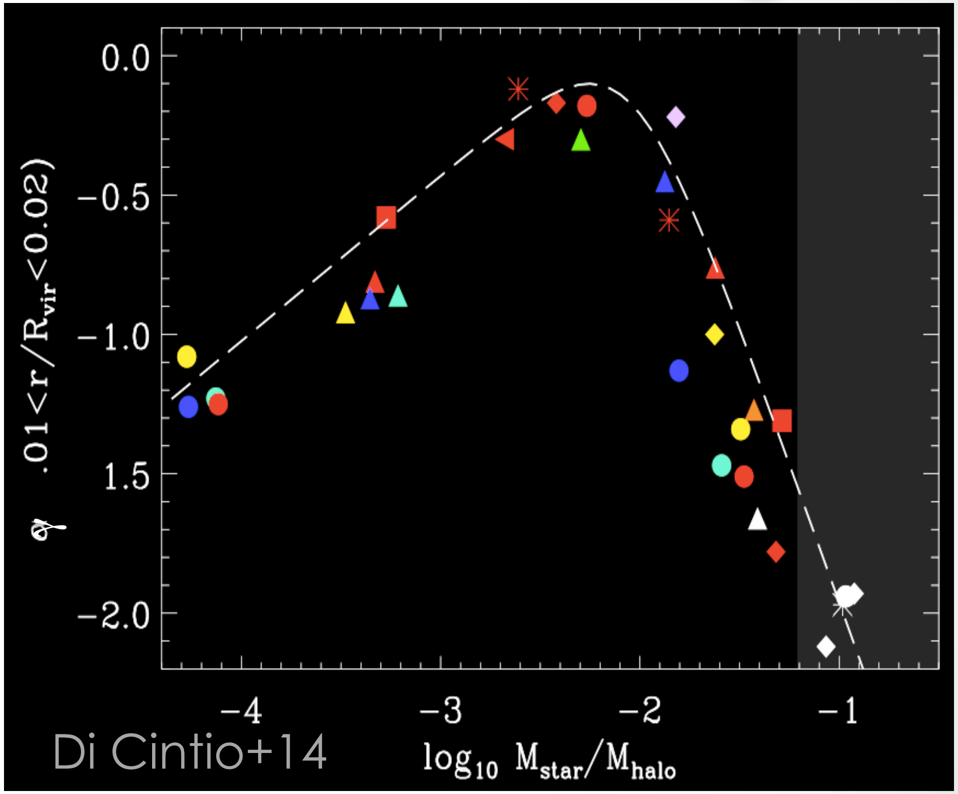


Di Cintio +14a



Cores are created in a particular M*/Mhalo range



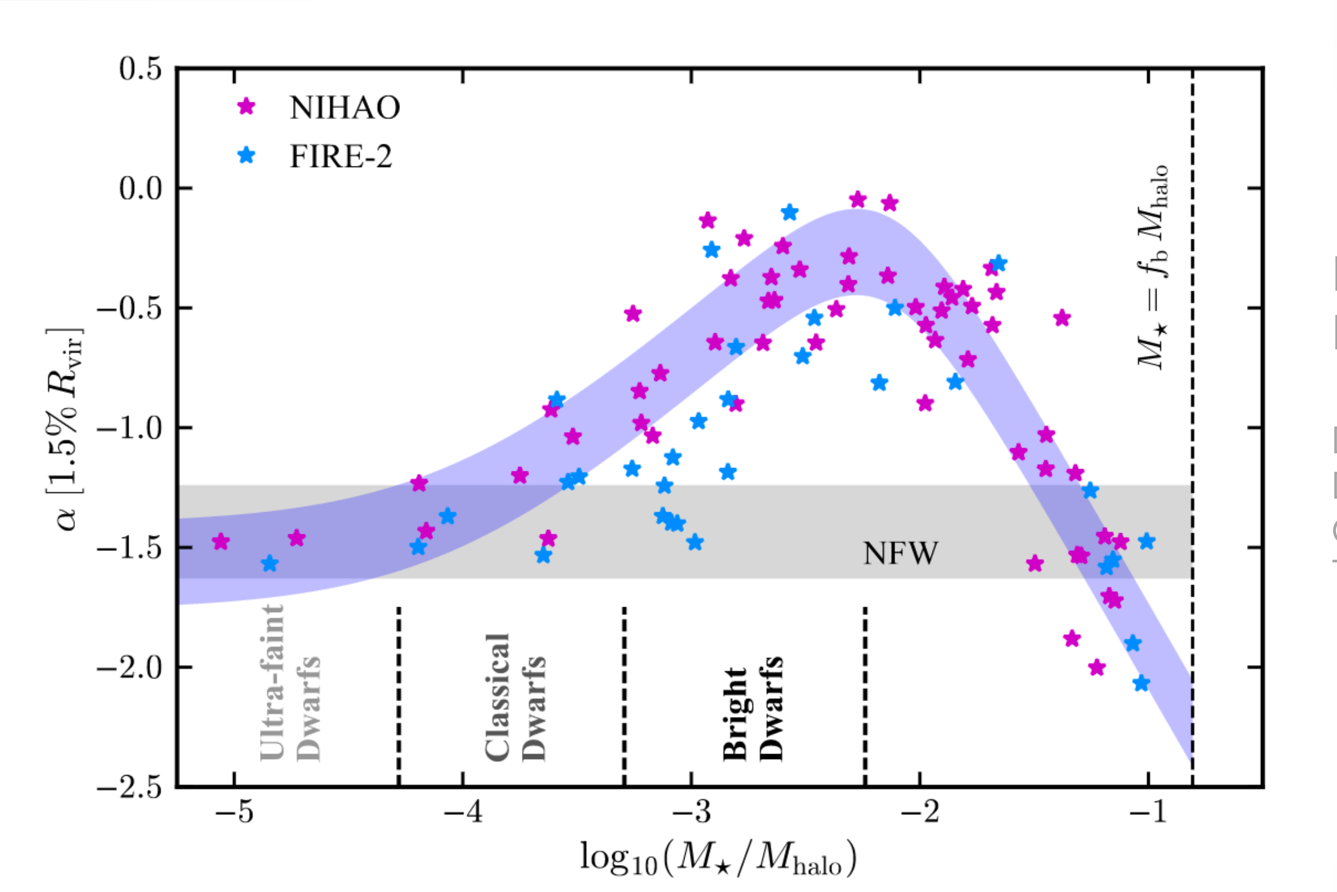


Di Cintio+14

Peak of core formation at log(M*/Mhalo)~-2.4 → M*~$10^{8.5}$ Msun

Dark matter profiles determined by two opposite effects: energy from Sne vs Increasing gravitational potential (see also Governato+12,Read+16,Onorbe+15,Brooks&Zolotov12)

Sweet spot of core formation



Review by
Bullock & MBK 2017

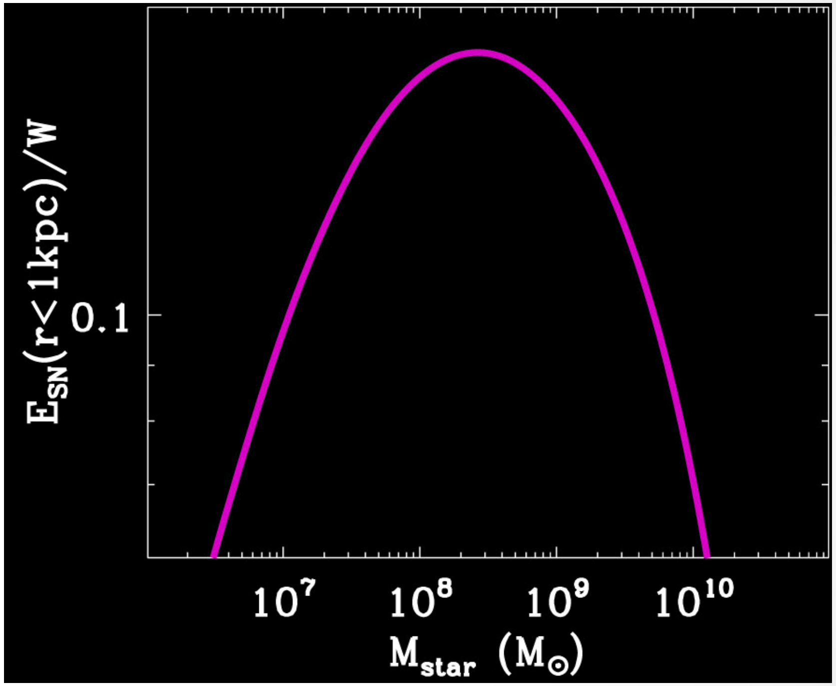
Data from
Di Cintio+14,
Chan +15,
Tollet+16

Small dwarfs not enough energy from stellar feedback to modify NFW halo
Intermediate dwarfs/LSBs correct amount of energy from Snae
Large spirals can not ‘win’ the large grav potential of 10^{12} halo with SNae alone

Energetic of core formation

$$\frac{E_{SN}}{W} = \frac{M^{\star}(<1Kpc) \times f_{SN}/\bar{m} \times 10^{51} erg \times \epsilon}{-4\pi G \int_0^{rvir} \rho(r) M(r) r dr}$$

Energy balance between SNe energy and potential energy of NFW halo.
Flattest profiles expected at
$M_{*} \sim 10^{8.5}\, M_{\odot}$.



Brook & Di Cintio2015a
(see also Penarrubia +2012)

see also Peñarrubia+12

A mass dependent profile

A mass dependent density profile that takes into account the impact of baryons on DM haloes (Di Cintio, Brook +14a,b)

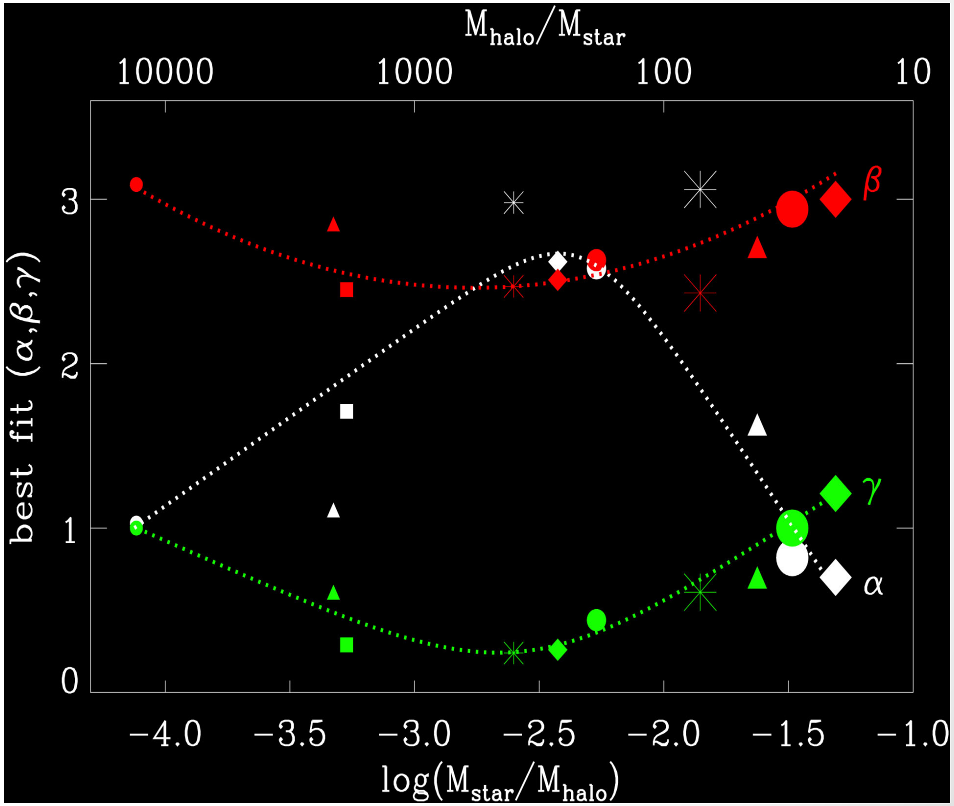
$$\rho_{\rm DC14}(r) = \frac{\rho_{\rm s}}{\left(\frac{r}{r_{\rm s}}\right)^{\gamma}\left[1+\left(\frac{r}{r_{\rm s}}\right)^{\alpha}\right]^{(\beta-\gamma)/\alpha}}$$

γ inner slope

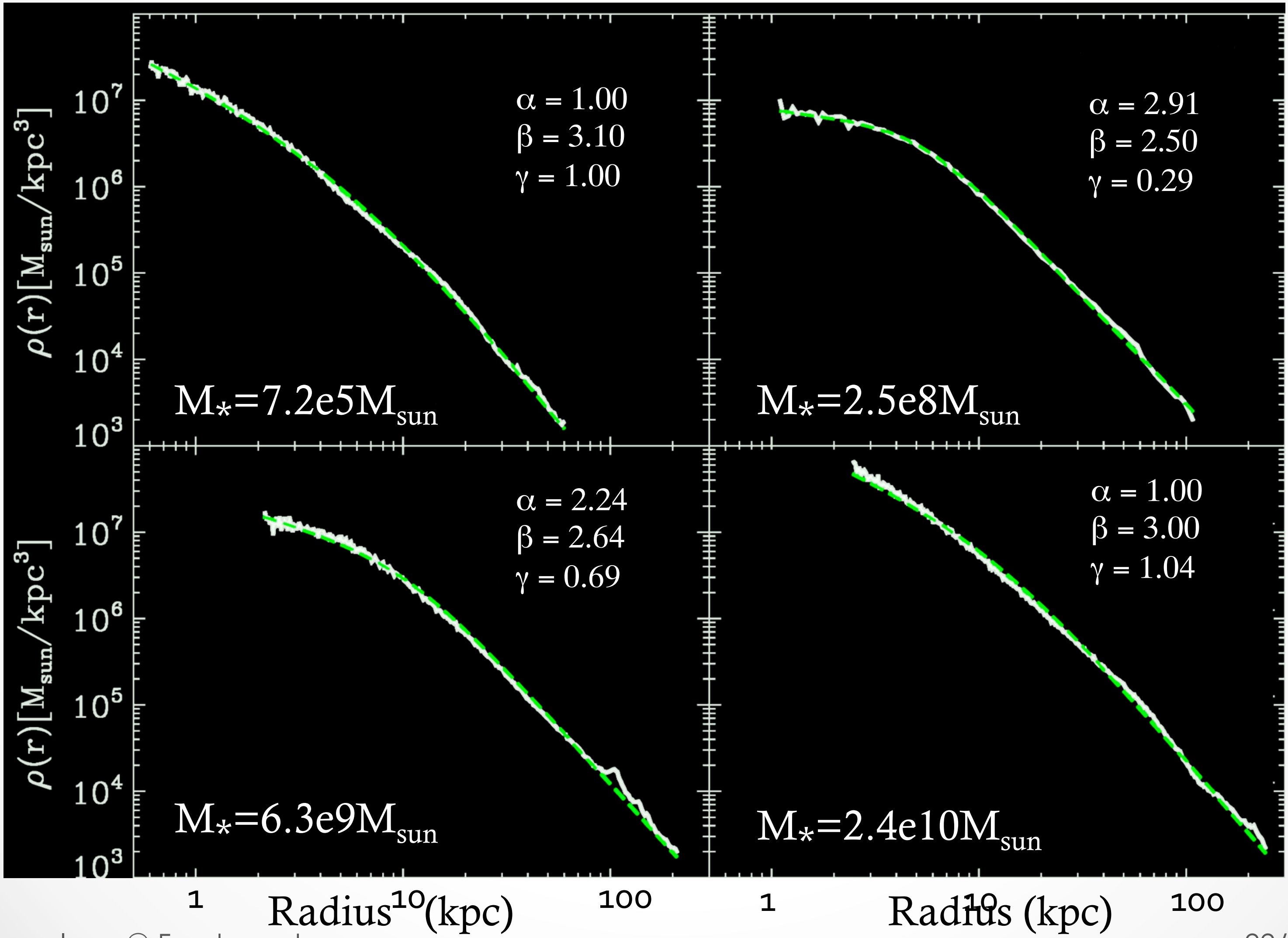
β outer slope

α sharpness of transition

constrained via X=log$_{10}$(M$_\star$/M$_{\rm halo}$)



From cusps to cores to cusps



Di Cintio +14

Mass/Velocity of a DC14 halo

Once α,β,γ are specified by the M*/M$_{\rm halo}$ value, the profile reduces to a 2 free parameters one, just like the NFW

$$\alpha = 2.94 - \log_{10}[(10^{X+2.33})^{-1.08} + (10^{X+2.33})^{2.29}]$$

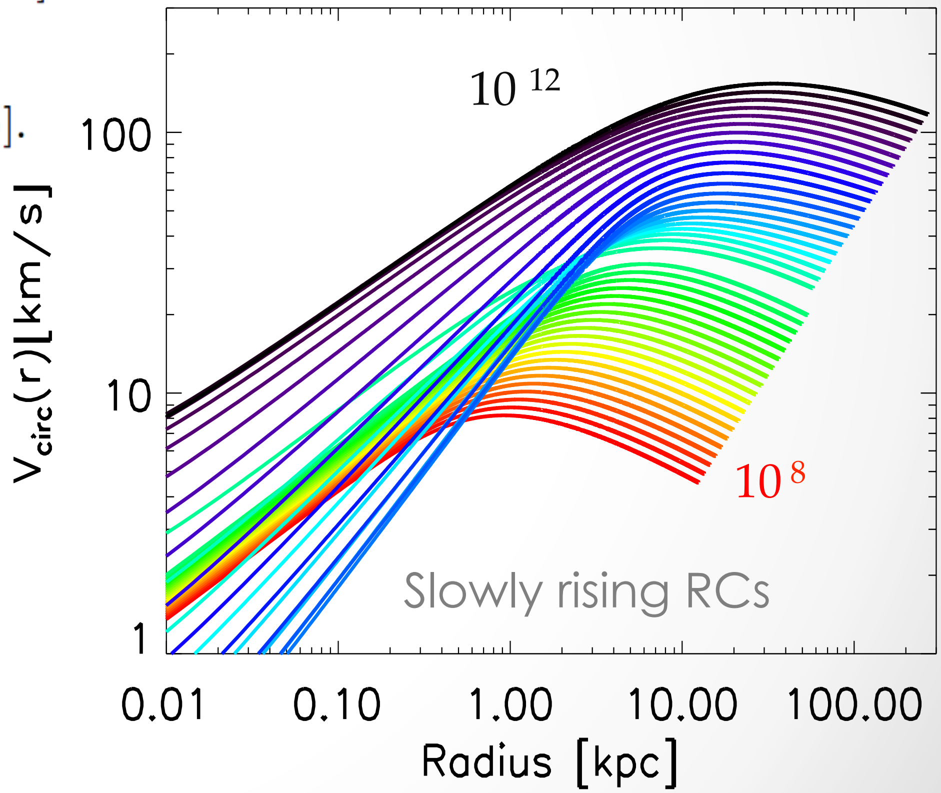
$$\beta = 4.23 + 1.34X + 0.26X^2$$

$$\gamma = -0.06 - \log_{10}[(10^{X+2.56})^{-0.68} + (10^{X+2.56})].$$

$$r_{-2} = \left(\frac{2-\gamma}{\beta-2}\right)^{1/\alpha} r_s.$$

$$M(r) = 4\pi\rho_s \int_0^r \frac{r'^2}{\left(\frac{r'}{r_s}\right)^{\gamma}\left[1+\left(\frac{r'}{r_s}\right)^{\alpha}\right]^{(\beta-\gamma)/\alpha}} dr'$$

$$v_c^2(r) = -r\frac{\partial\Phi}{\partial r} = r|\vec{F}| = \frac{GM(r)}{r}.$$



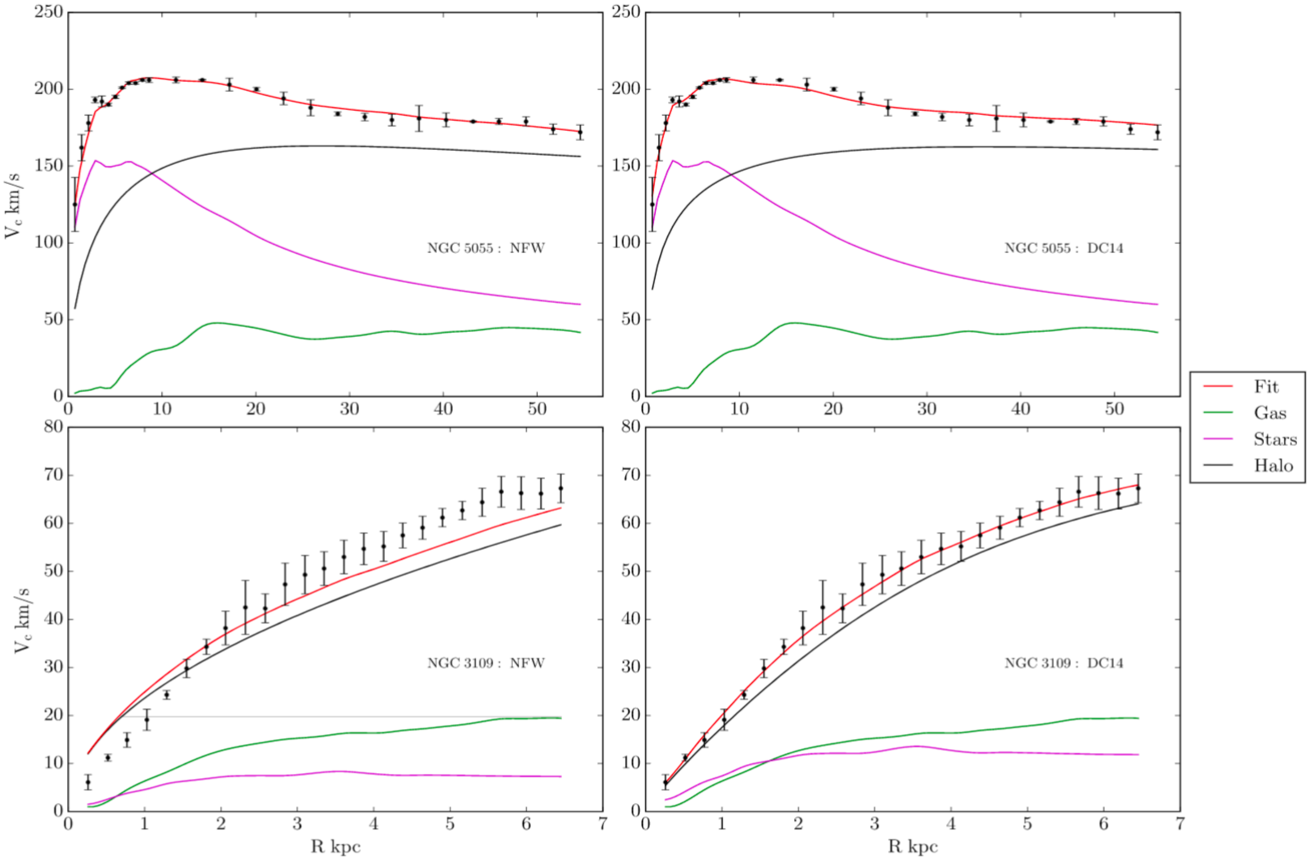
Slowly rising RCs

Testing ΛCDM with different density profiles

Take M* and V(r) from observations

MCMC fitting $V(r) = (V^2_{dm}(r)+V^2_{gas}(r)+V^2_{star}(r))^{1/2}$ with different profiles for the DM – including or not the effects of baryons

Derive M_{halo} and c and compare it with LCDM expectations



Katz, Lelli, McGaugh,Di Cintio, Brook, Schombert 2017

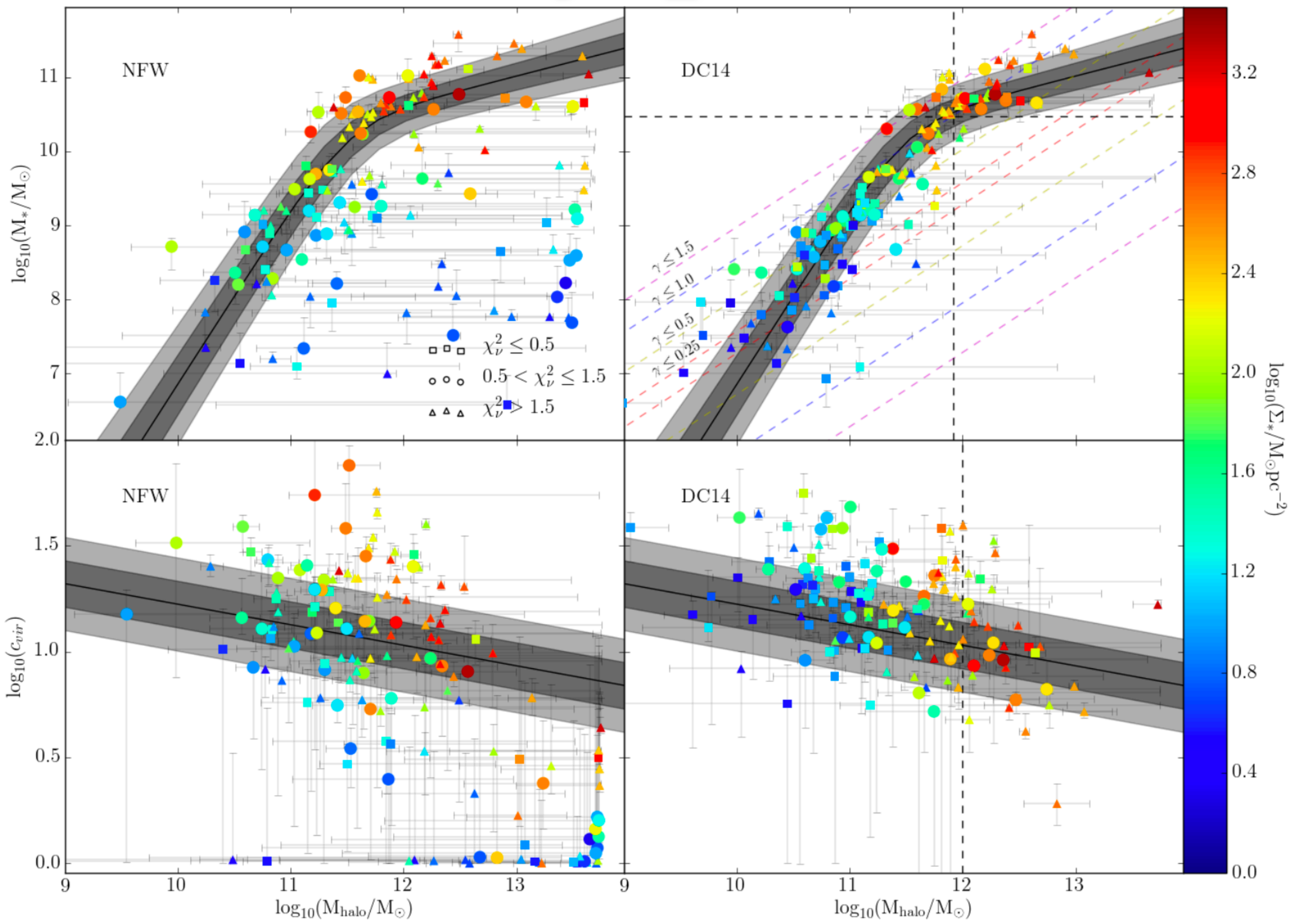
Testing ΛCDM with different density profiles

We want to reproduce both observational relations and theoretical predictions :

Rotation curves

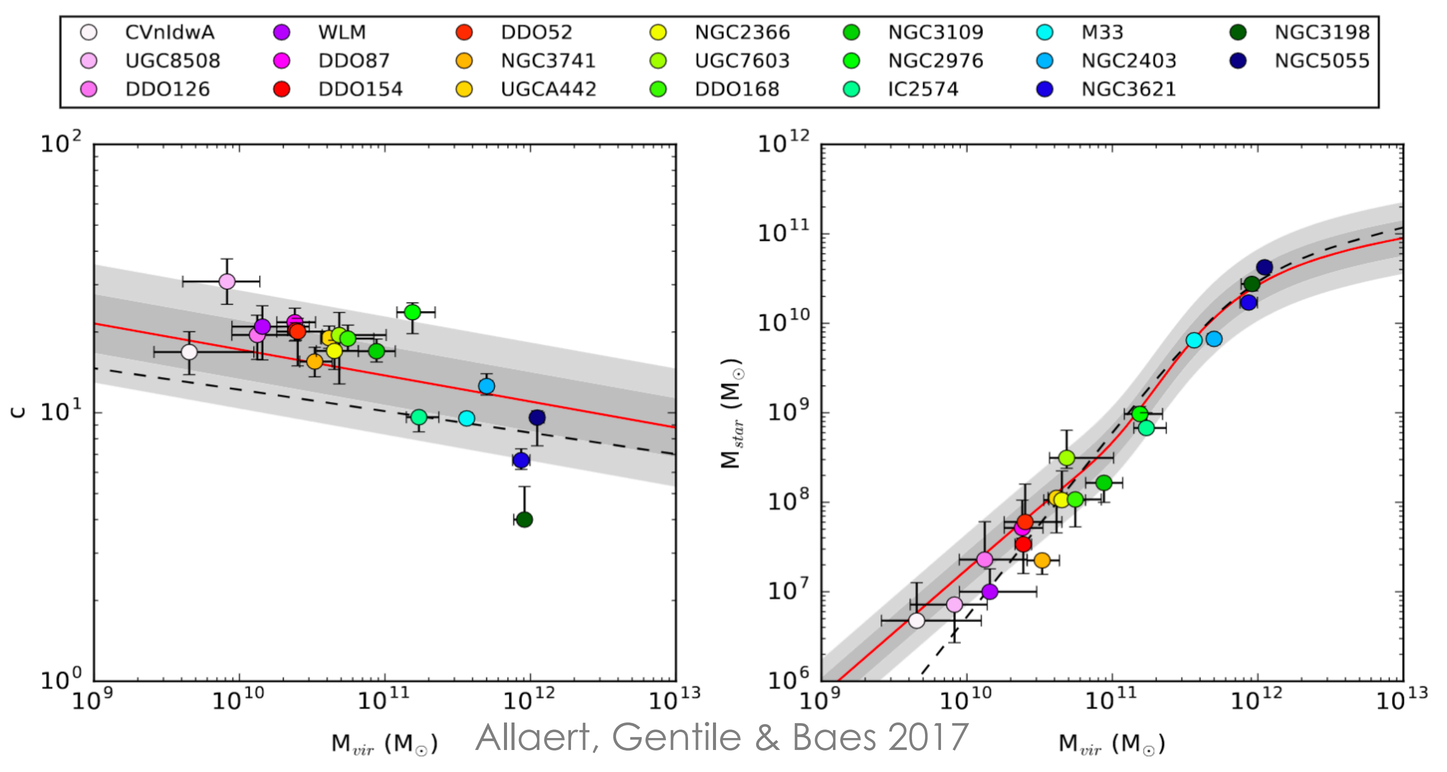
c-Mhalo

Mhalo-M*



Katz, Lelli, McGaugh,Di Cintio, Brook, Schombert 2017

Testing ΛCDM with different density profiles



Allaert, Gentile & Baes 2017

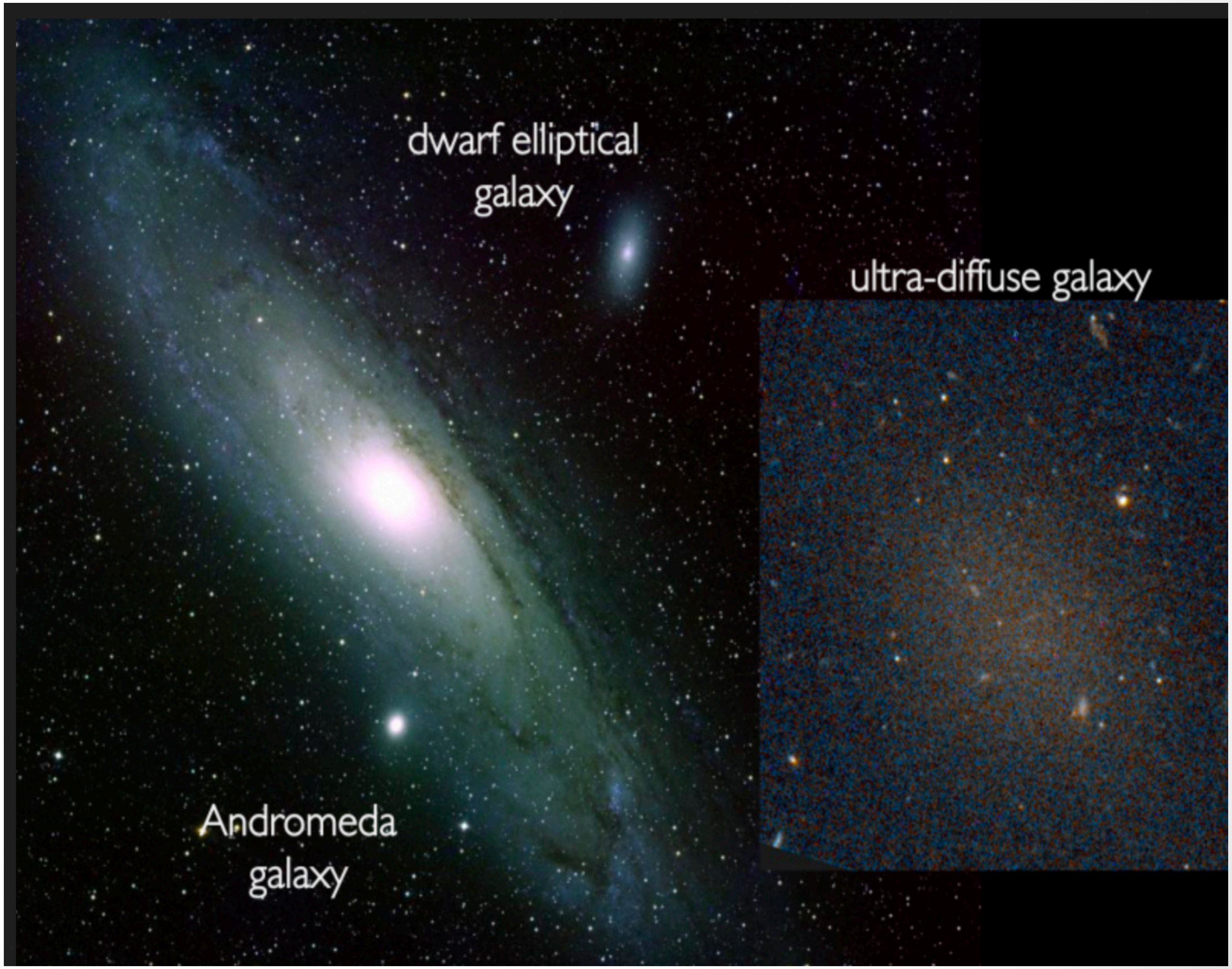
Take home point: DC14 can produce dark matter haloes that simultaneously provide good fits to the rotation curves and agree with the scaling relations C-M_{halo} and M_{halo}-M*

Outcome of core formation in LCDM => UDGs

Stellar mass of dwarf Galaxies

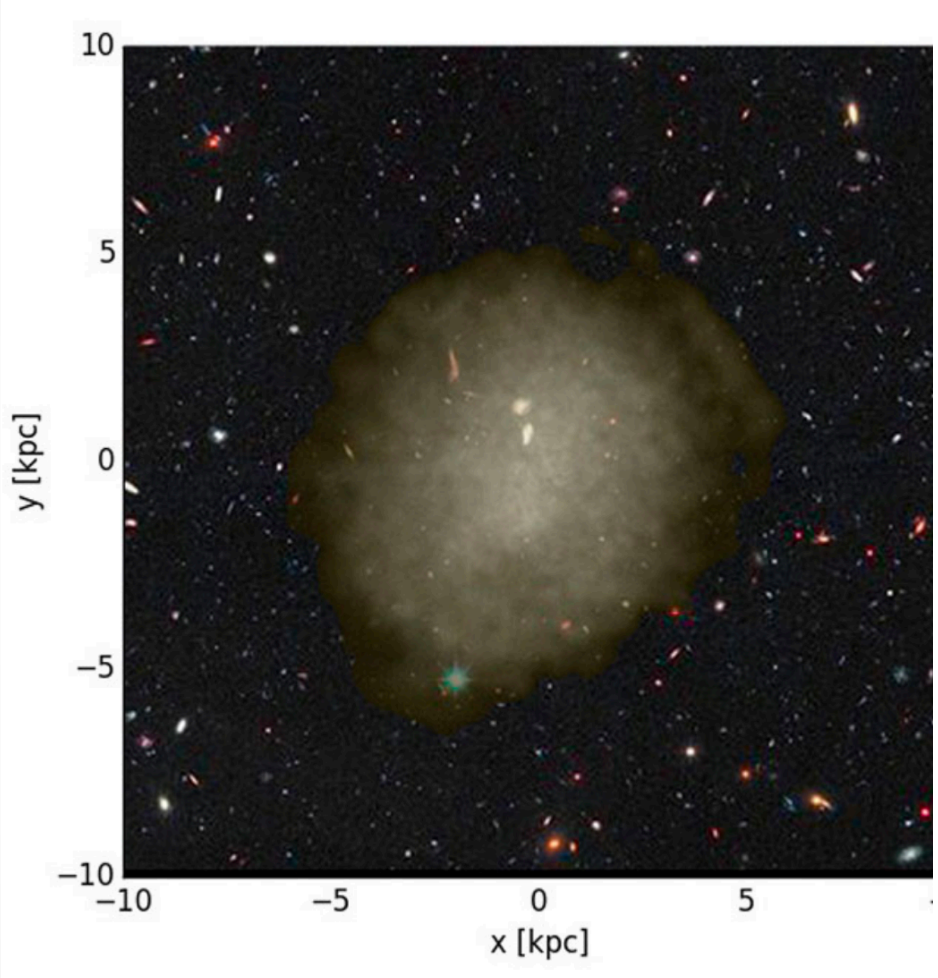
Spatial extent of large MW-like spirals

See Van Dokkum+15, Koda+15, Roman & Trujillo+16 etc..



Credit: Schoening/Harvey/van Dokkum/HST)

UDGs in simulations



UDGs are isolated dwarfs with $M_{halo} \sim 10^{10-11}$ M_{sun} and lots of gas

Stellar distribution "expanded" by the same SNae-driven outflows that expands DM distribution

Di Cintio +17b using NIHAO simulations

Take home points

◆ The inclusion of baryonic physics in simulations has a profound impact on the distribution of matter within DM haloes

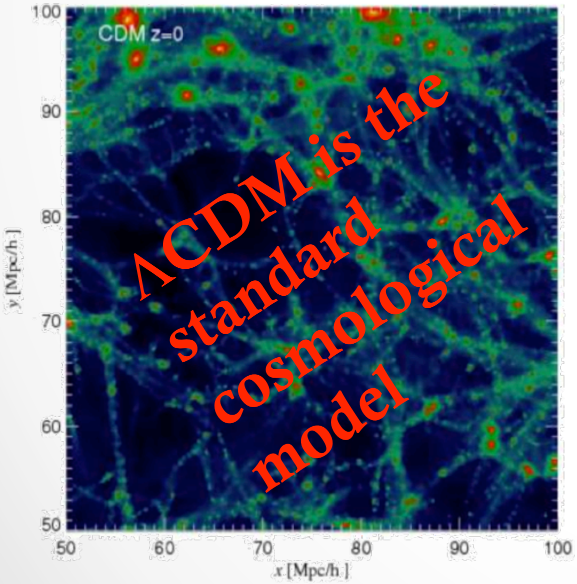
◆ Evidence that brightest dwarfs and LSB/UDG have a shallow rising rotation curves => signature of central DM core

◆ Fast gas outflows are the key mechanism to create DM cores in simulations

◆ A DM profile that takes into account core formation between $M^{*}= 10^{7-9}$ Msun can reproduce observed RCs and at the same time agree with LCDM expectations

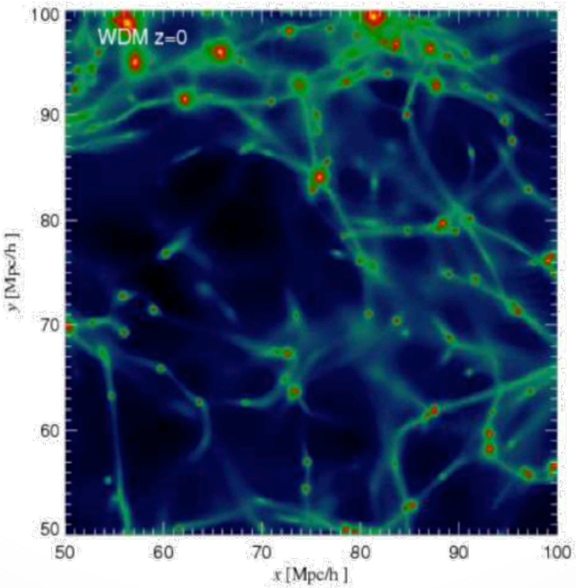
The nature of dark matter

Cold Dark Matter
(Slow moving)
m~ GeV-TeV
Small structures form first, then merge



ΛCDM is the standard cosmological model

Warm Dark Matter
(Fast moving)
m~ keV
Small structures are erased



Self-Interacting Dark Matter
Strongly interact with itself
Large scale similar to CDM,
Small galaxies are different