Leibniz-Institut für Astrophysik Potsdam

LCDM and MDAR in the light of cusp-core transformation. Is there a need for alternative DM models?

Arianna Di Cintio

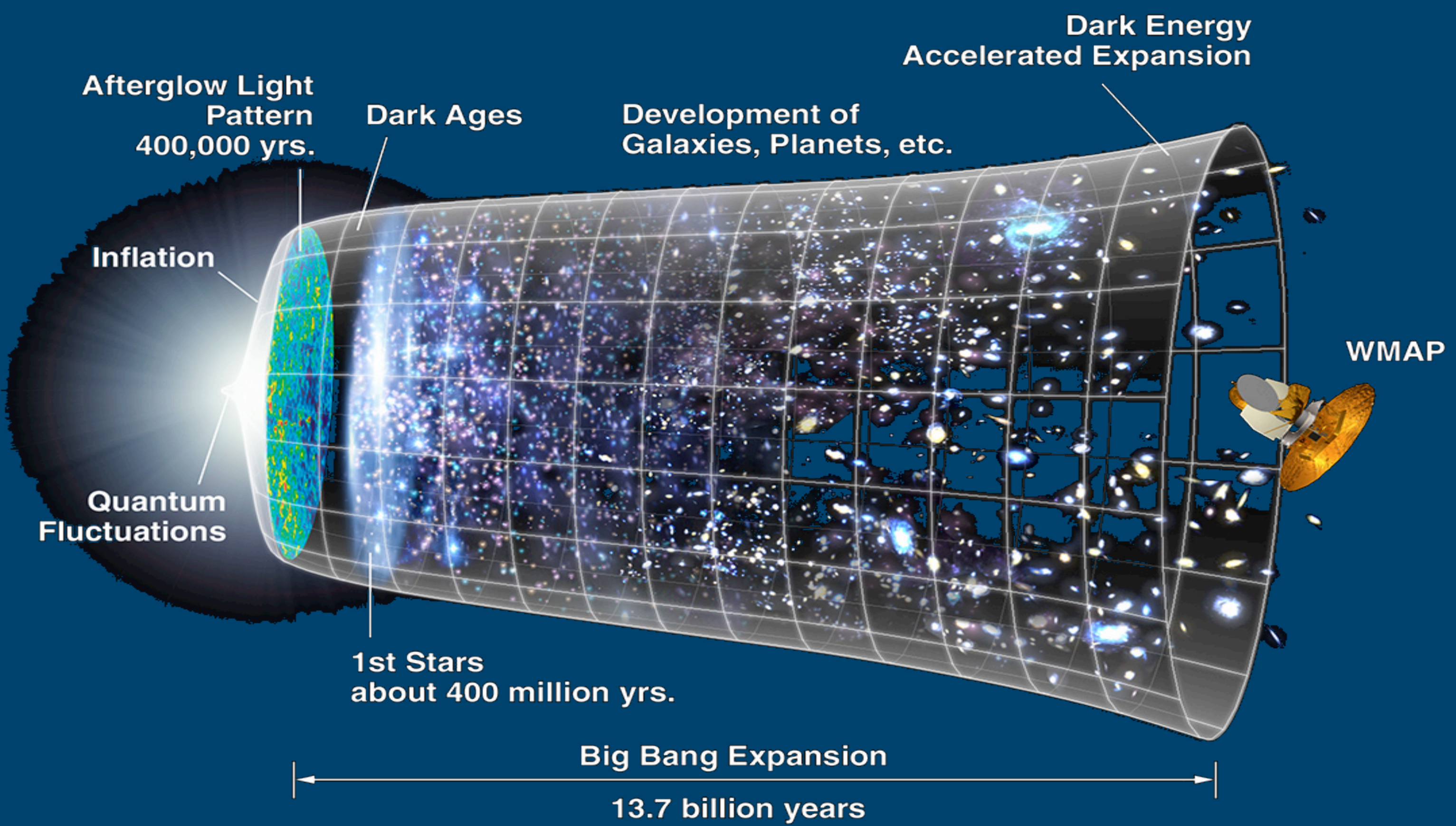
Schwarzschild fellow
@ AIP – Potsdam

Collaborators: C. B. Brook, A. V. Macciò, A. A. Dutton, I. Santos-Santos, A. Pontzen, F. Governato, M.Tremmel, J. Zavala, A. Knebe, N. Libeskind, G. S. Stinson, H. Katz, F.Lelli

Outline

- The ΛCDM small scale crisis
- Possible Solution: CDM +baryonic physics
- Cusp-cores and MDAR (RAR)
- Alternative DM models

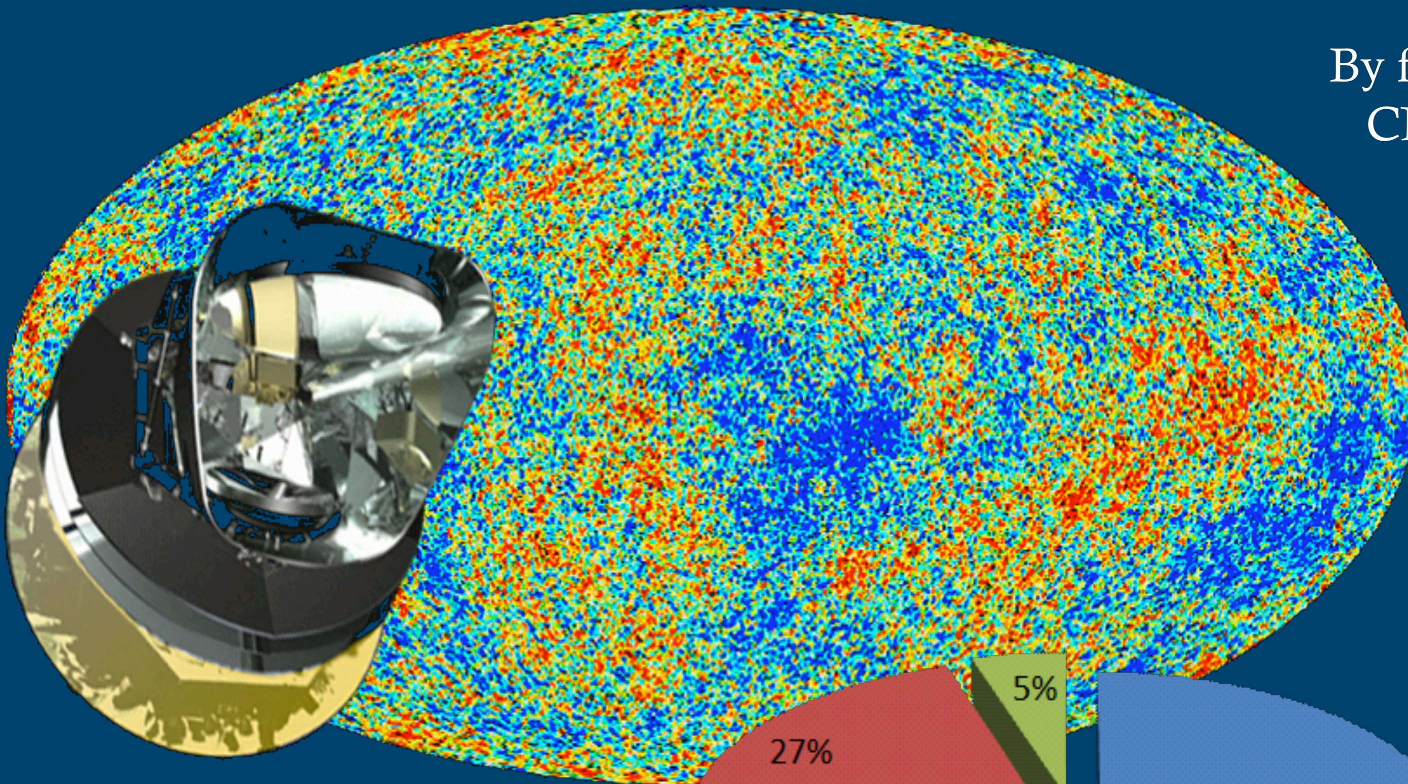
Galaxy Formation in one slide

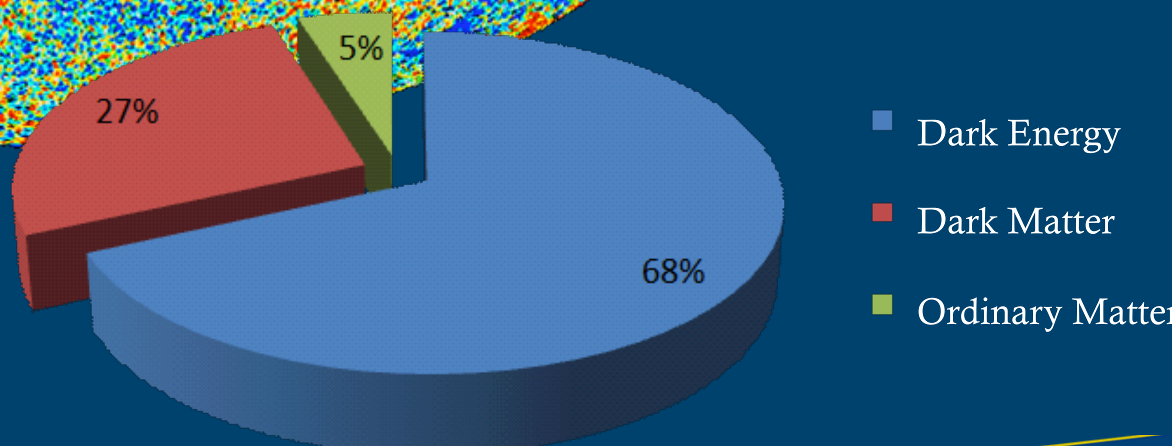


Cradit:NASA-WMAP science team

Composition of the Universe

By fitting the observed CMB power spectrum we can find the best theoretical model that describes it

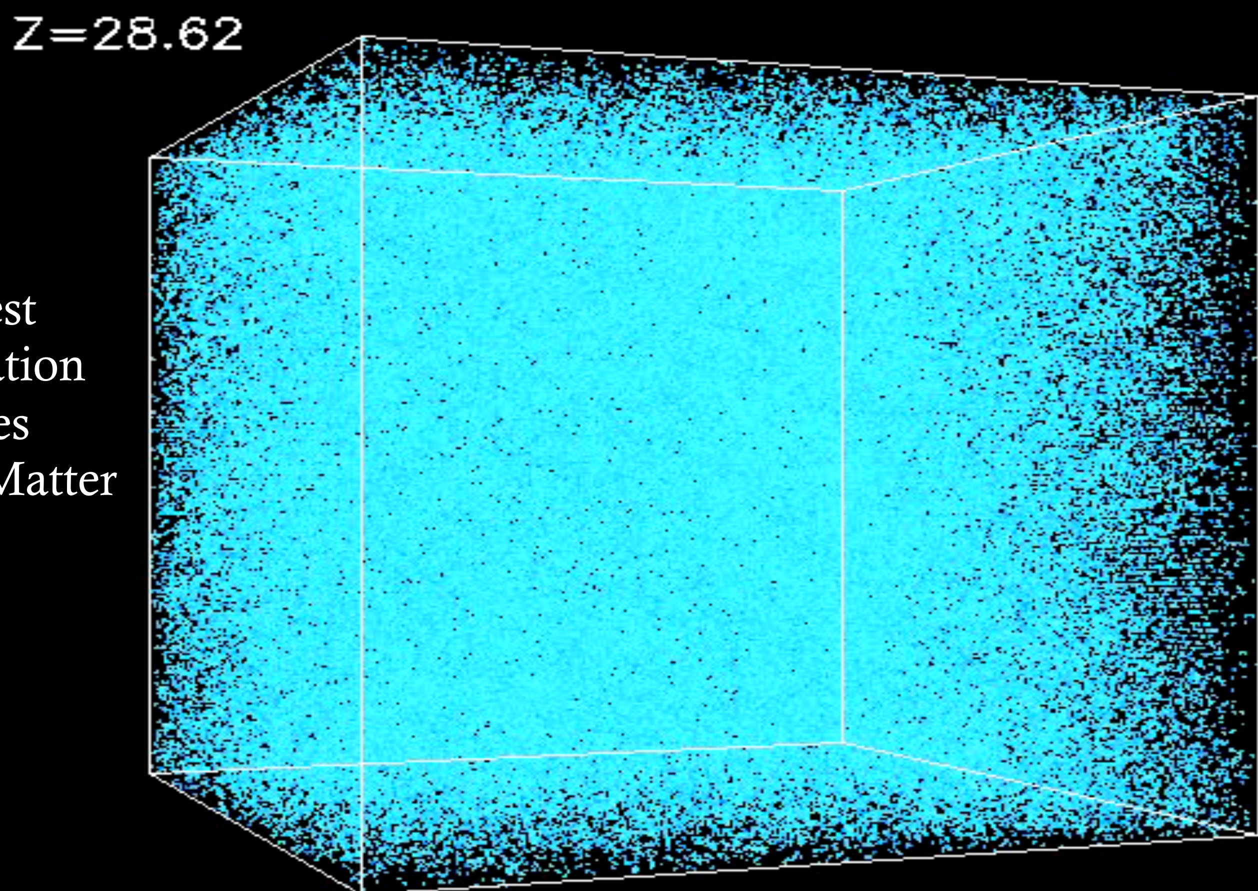




Planck Satellite (ESA)

Studying galaxy formation requires numerical simulations

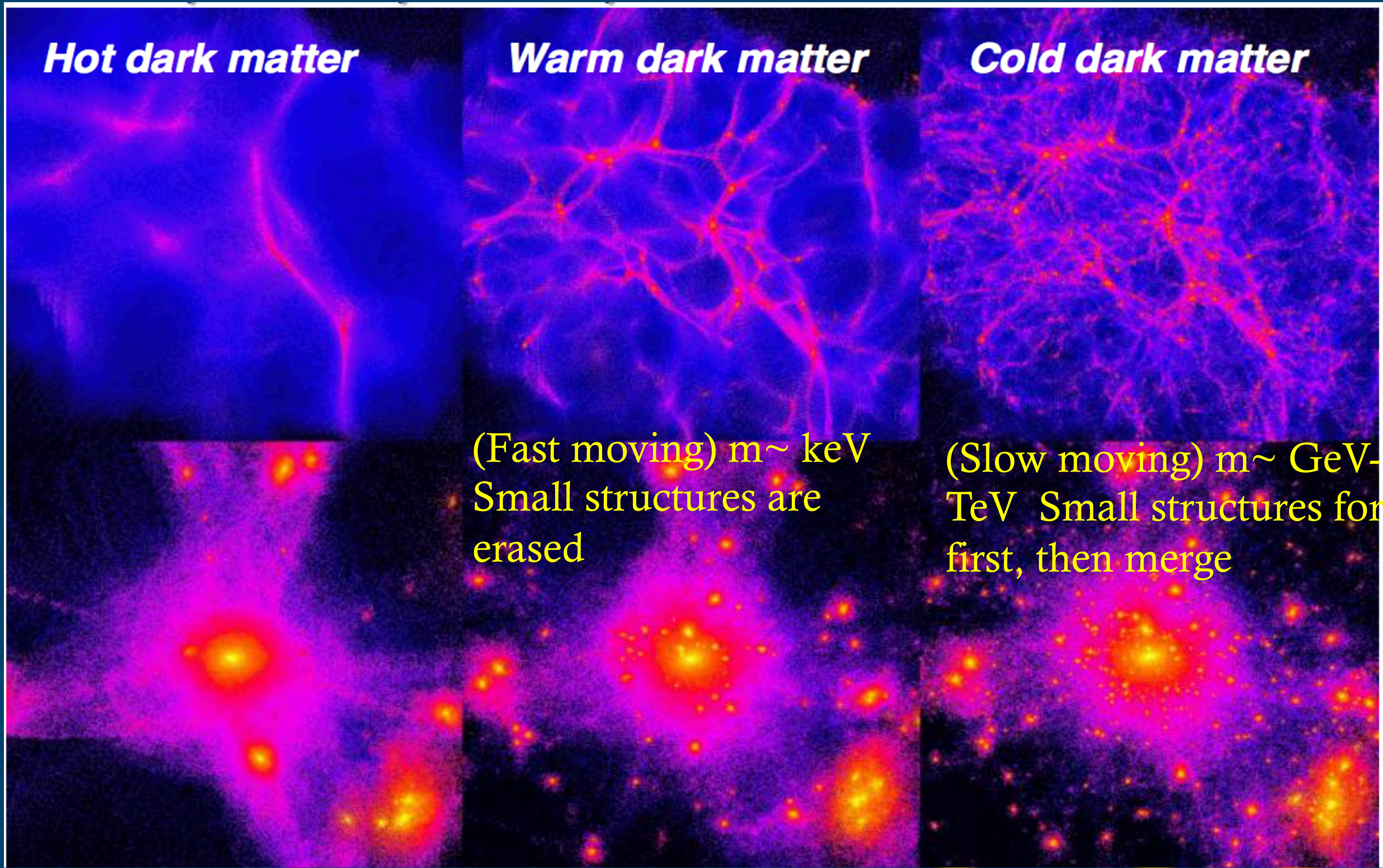
Simplest Simulation includes Dark Matter only!



Credit: A.Kravtsov, A. Klypin

Structure formation depends on DM type

LCDM is the standard cosmological model of structure formation , based on weakly Interacting massive particles (WIMPS), a.k.a. Cold dark matter (CDM)



(Fast moving) m~ keV Small structures are erased

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

Credit: Ben Moore

The LCDM small scale crisis

Missing satellite problem

Diversity of RC in dwarf galaxies

Mass discrepancy acceleration relation

Cusp-core discrepancy → rotation curves of galaxies

Large size of Ultra-Diffuse galaxies

Velocity function of galaxies

Kinematic of satellite galaxies (TBTF problem)

The LCDM small scale crisis

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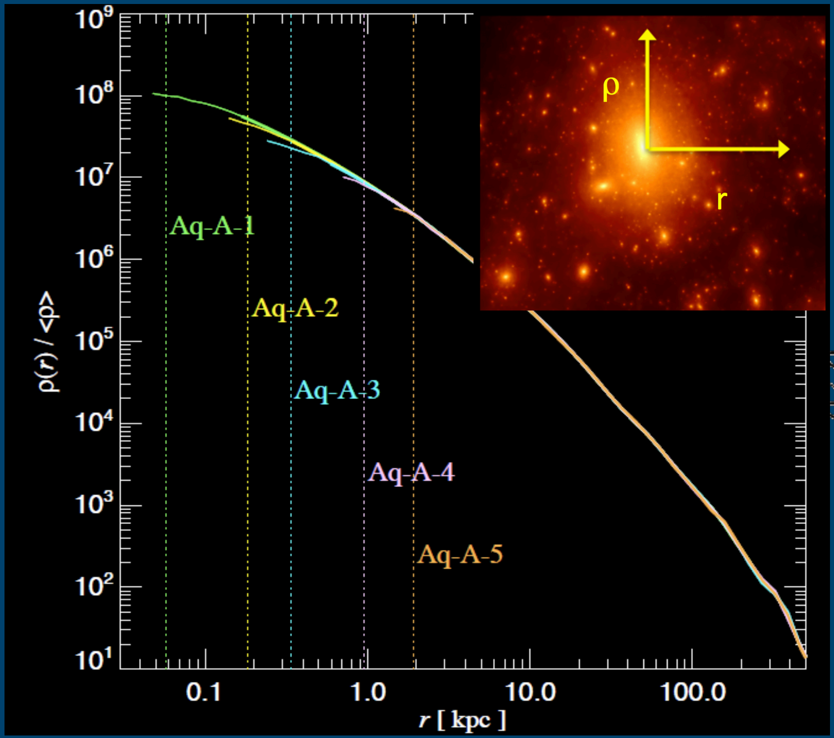
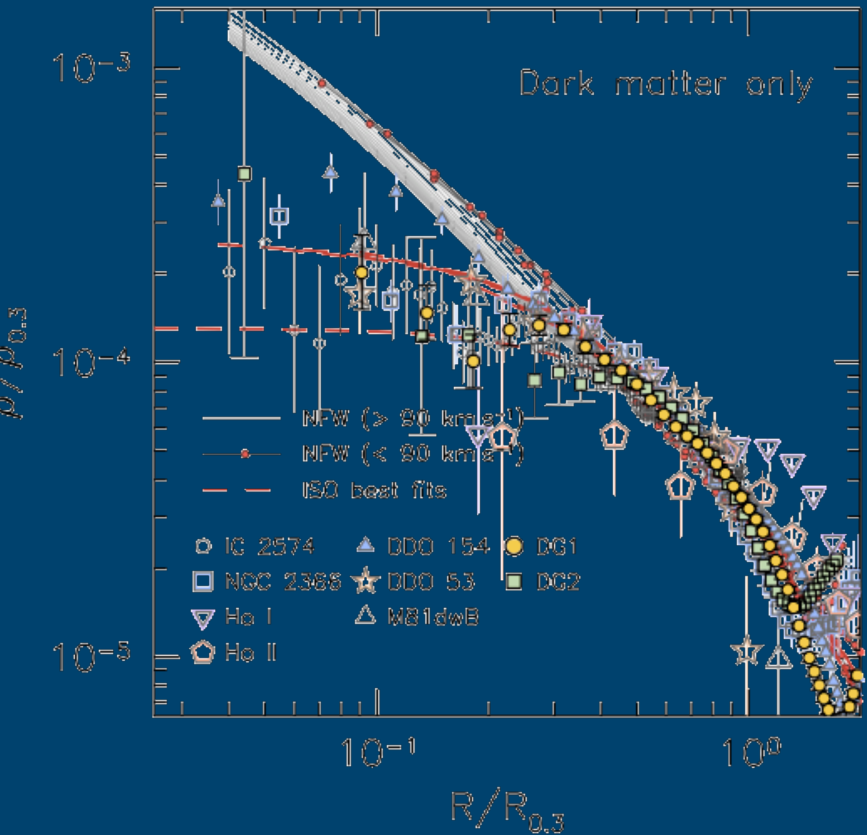
CUSP-CORE discrepancy

Springel+05



Oh+11



Simulations find 'CUSPY' profiles
Inner slope γ ≥ 1 NFW

Observations show 'CORED' profiles
Inner slope γ < 1

Possible Solution→ baryonic physics

Hydrodynamical simulations of galaxies including DM + GAS + STARS

MaGICC/NIHAO project

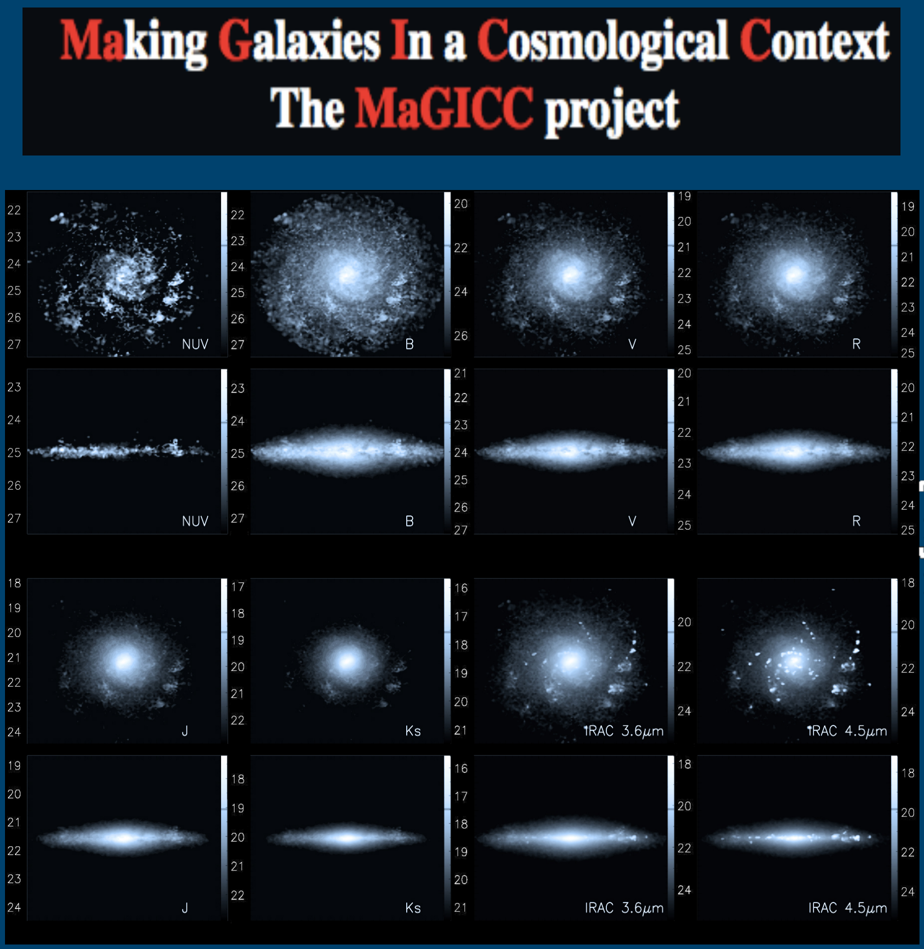
(Stinson13,Brook12,Stinson13,Di Cintio17,Wang+15,Brook+12b, Maccio'+12, Penzo+14, Herpich+14, Kannan+14, Obreja+14 etc)

Star Formation and Feedback (Stinson et al. 2006 for details) with GASOLINE (Wadlsey et al 04)

- A local Schmidt Law is assumed
- O and Fe yields from SN I & II
- Kroupa IMF
- Mass/metals loss from stellar winds included.
- Star Particles formed from cold, dense gas
- Uniform, time-dependent cosmic UV bg from Haardt & Madau

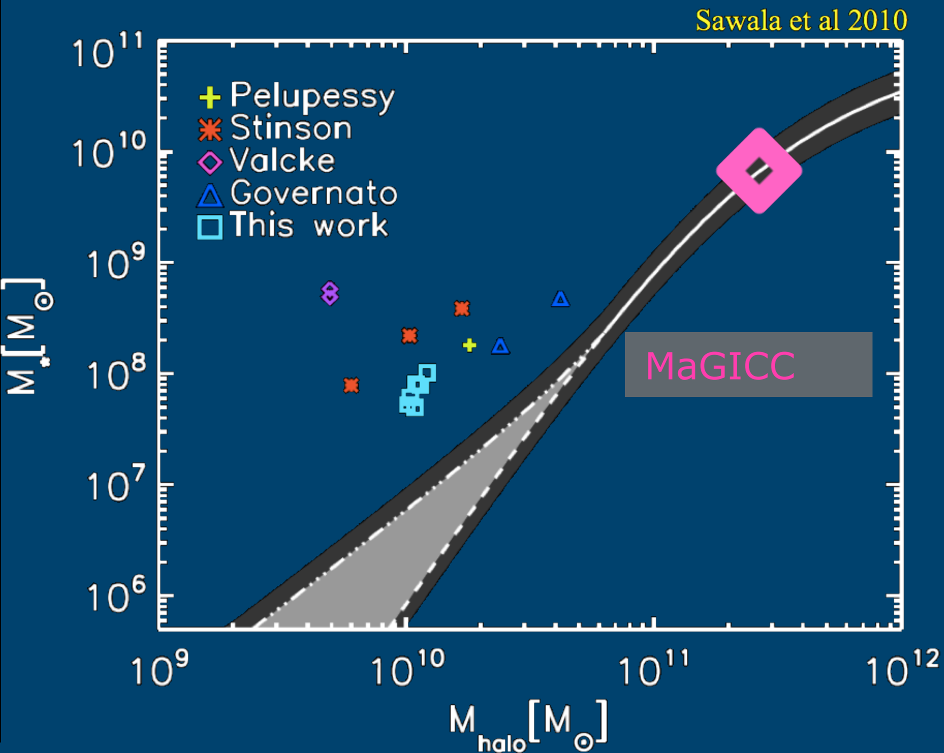
▪Supernovae Feedback with Blastwave model

MaGICC/NIHAO Hydro simulations



Credit: Dominguez-Tenreiro, Obreja+13

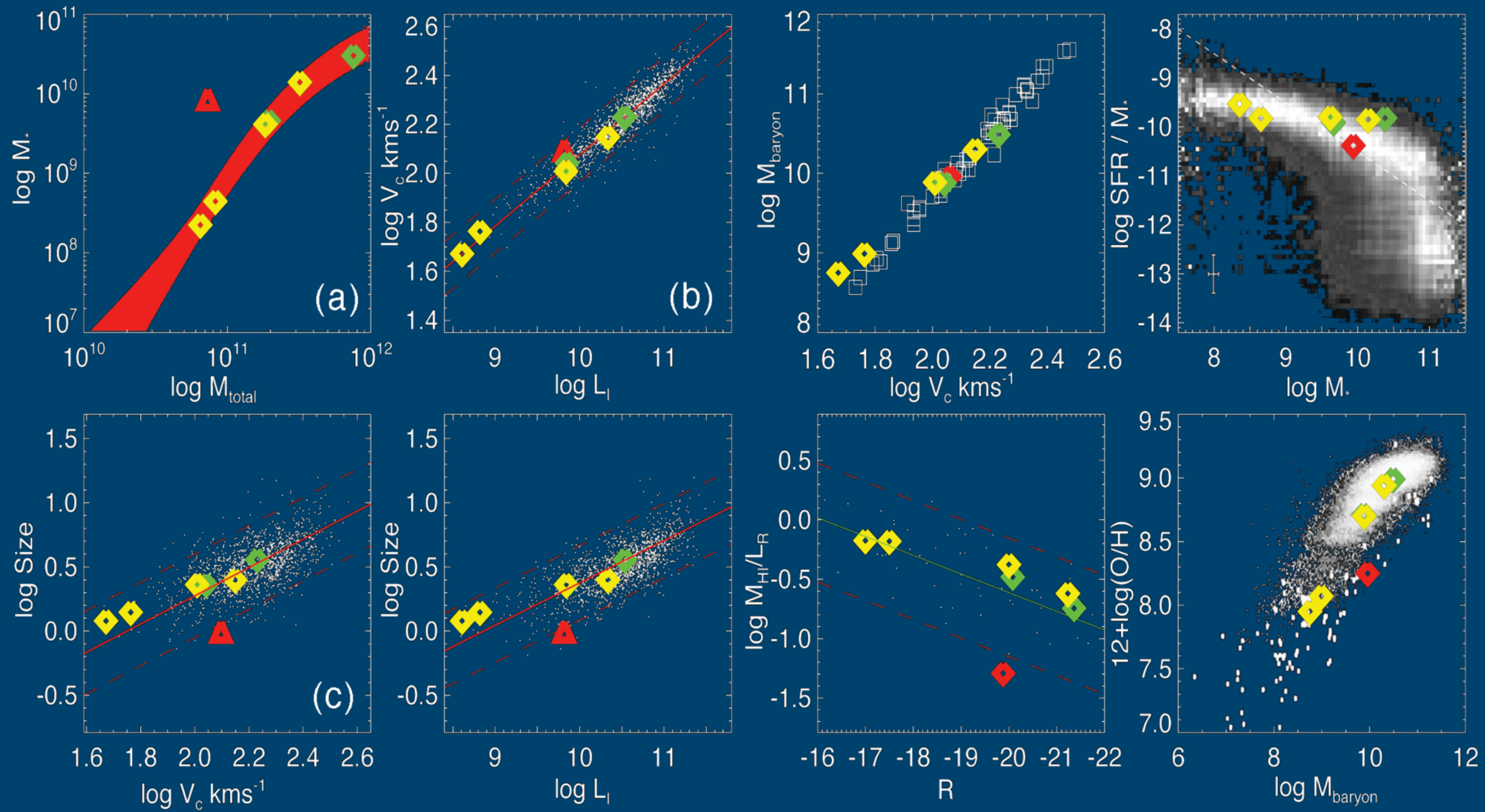
Stinson+13, Brook+12
GASOLINE N-body + SPH code Wadsley 04
SN feedback with blastwave formalism Stinson+06
Early-stellar feedback from massive stars



Credit: Sawala +10

Feedback from Sne and massive stars

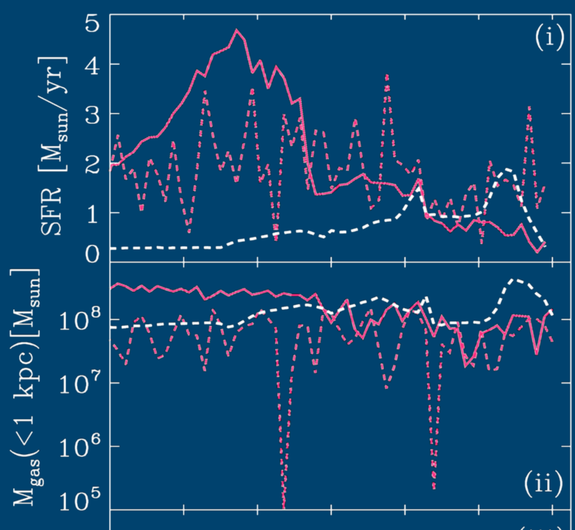
Stinson+06,+13

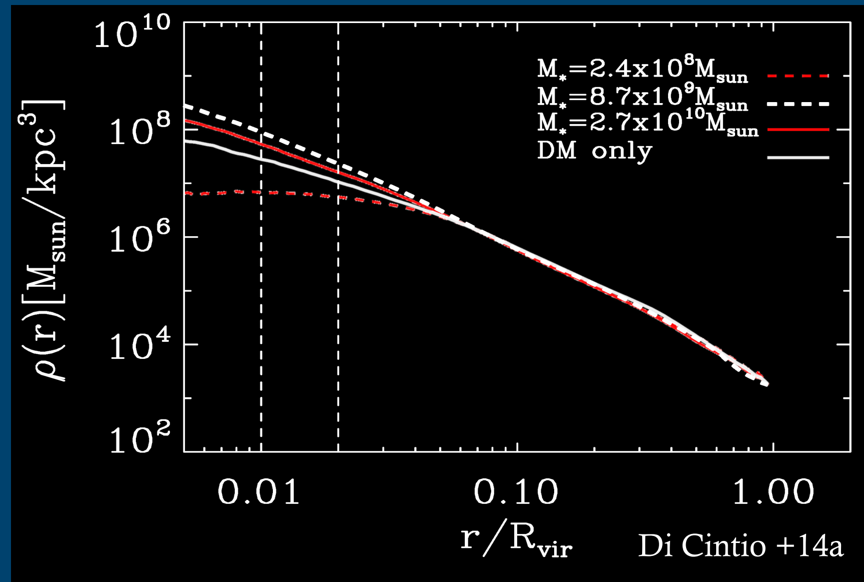


Brook +12


0.4 Gyr
Credit:Greg Stinson

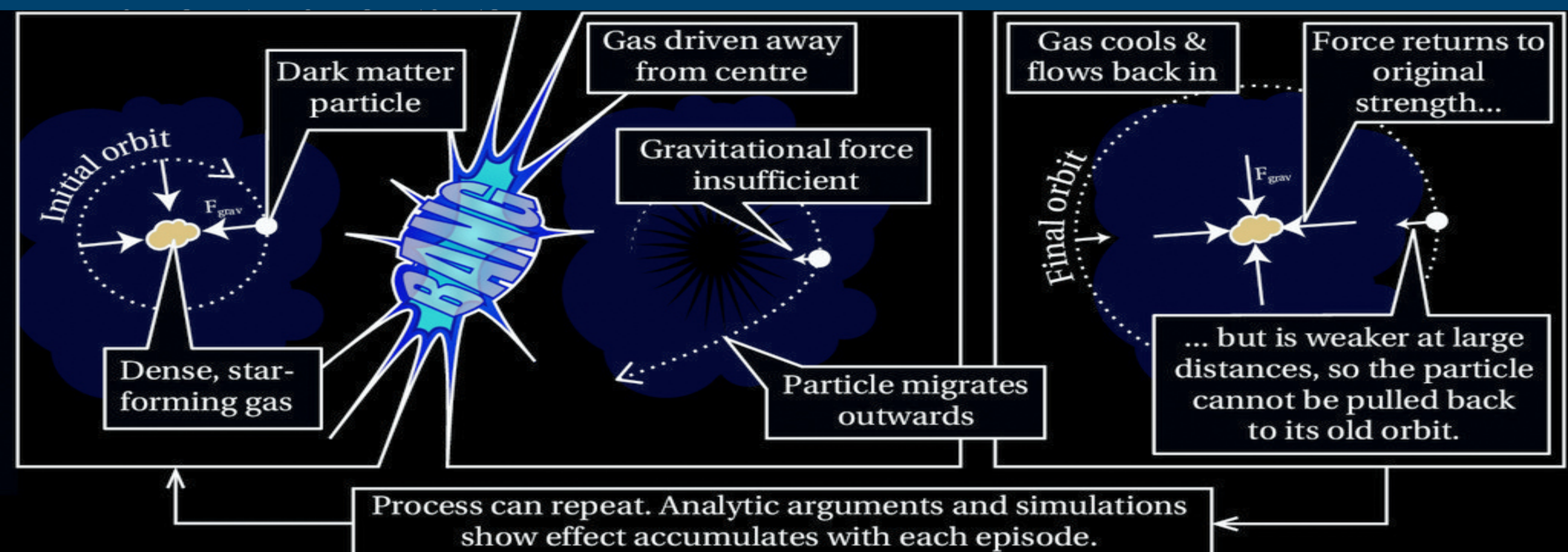
Core creation mechanism



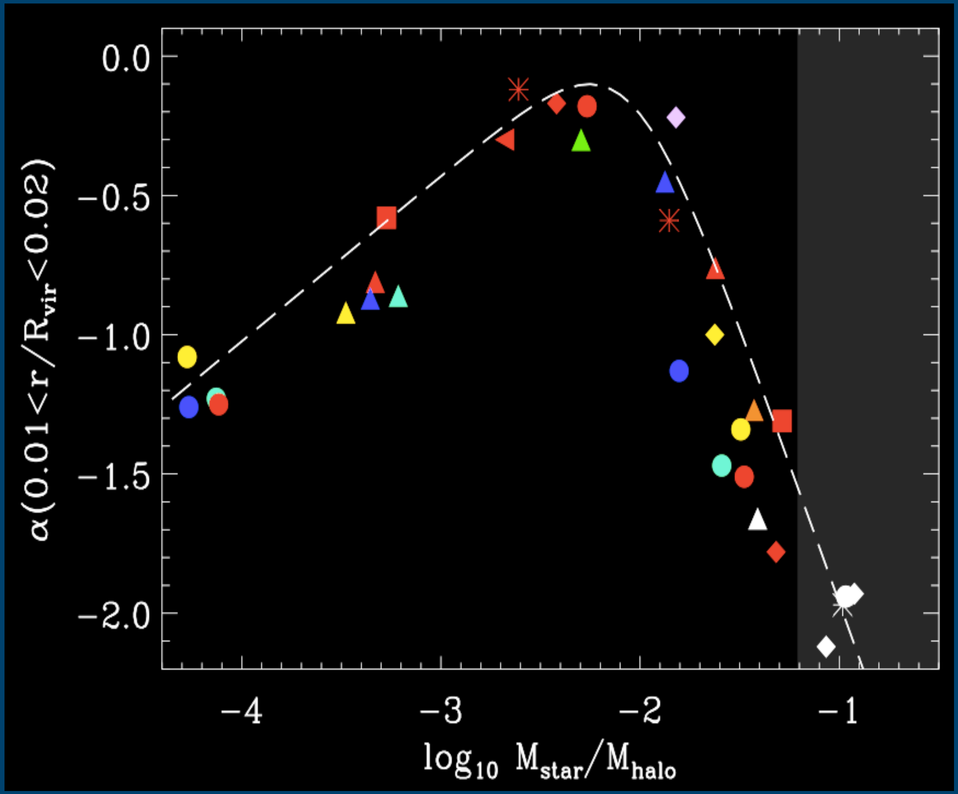


See also
Navarro +96,
Mashchenko +08,
Read & Gilmore 05
Governato+12,
PG 12

PG 14 Nature



Inner slope dependence on $M_\star/M_{halo}$



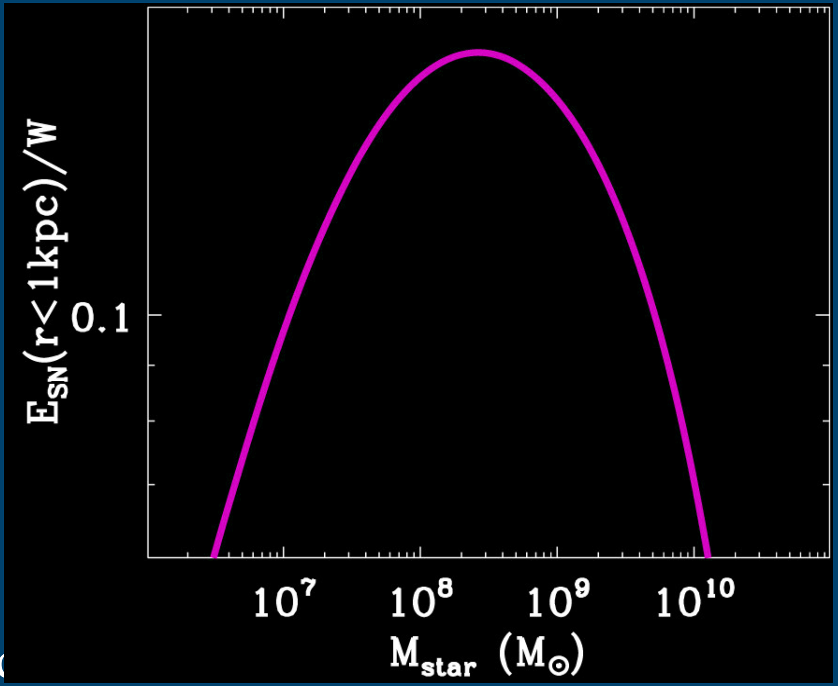
Peak in core formation for galaxies of M*~10^8.5 Msun

Dark matter profiles determined by two opposite effects: energy from Sne vs underlying gravitational potential of the DM halo

Di Cintio+14a

Peak in CORE formation efficiency

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

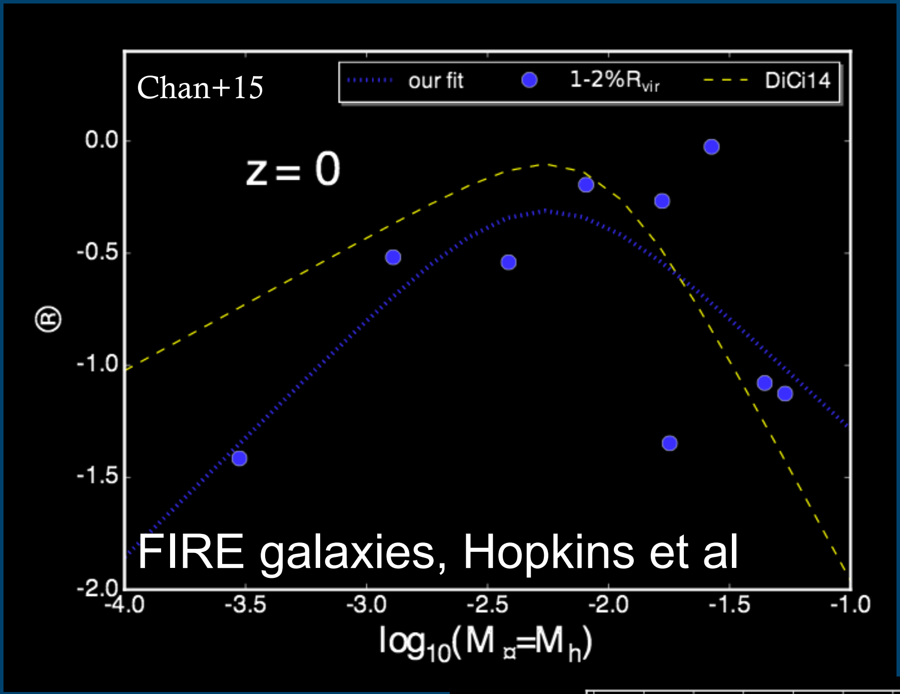


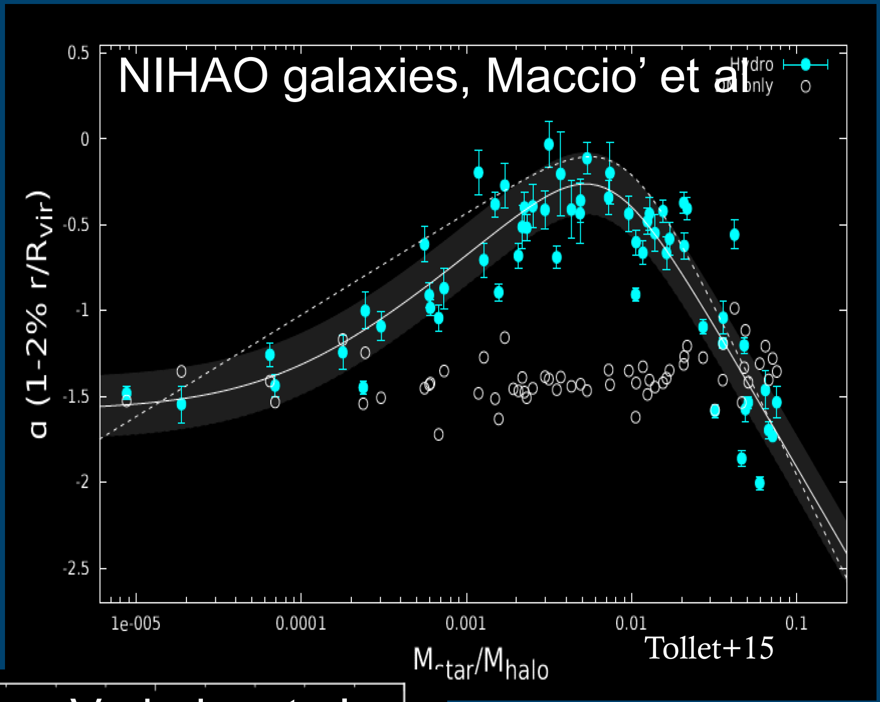
Energy balance between SNe energy and potential energy of NFW halo.
Flattest profiles expected at $M_* \sim 10^{8.5}$ $M_\odot$

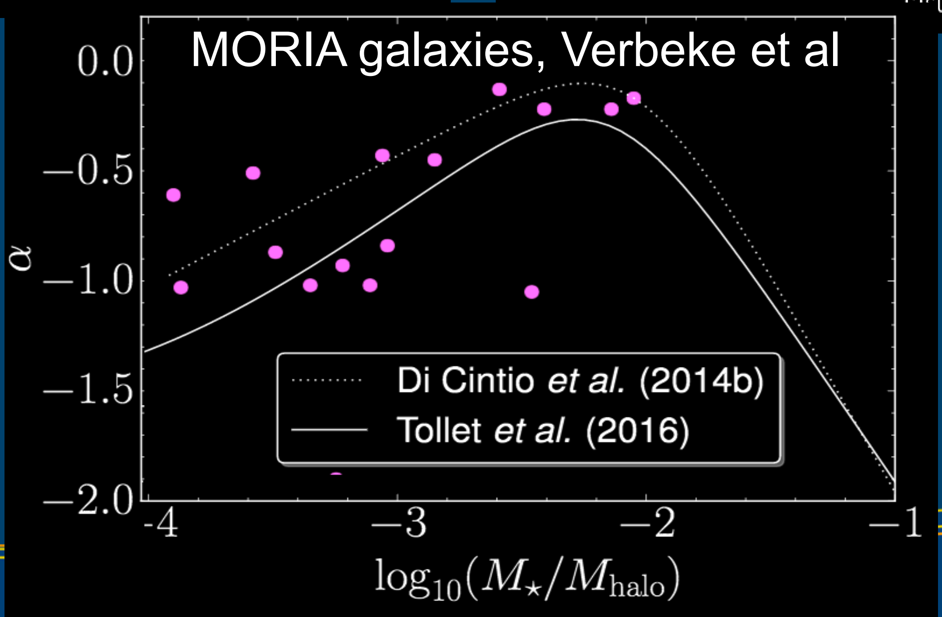
Brook & Di Cintio2015a

see also Peñarrubia+12

Result confirmed with other sims/feedback







A double power law profile

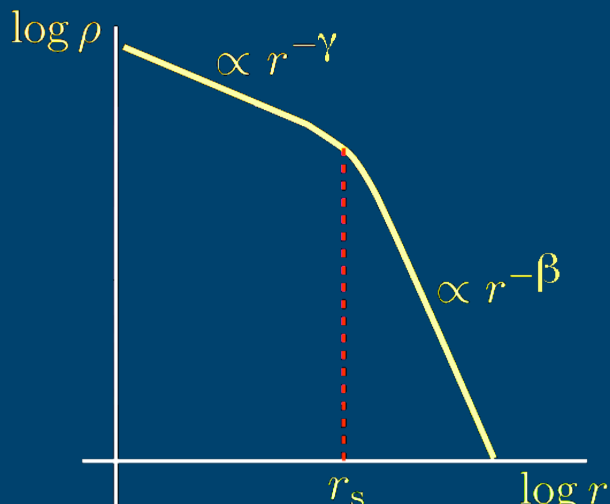
$$\rho(r) = \frac{\rho_s}{\left(\frac{r}{r_s}\right)^{\gamma}\left[1+\left(\frac{r}{r_s}\right)^{\alpha}\right]^{(\beta-\gamma)/\alpha}}$$

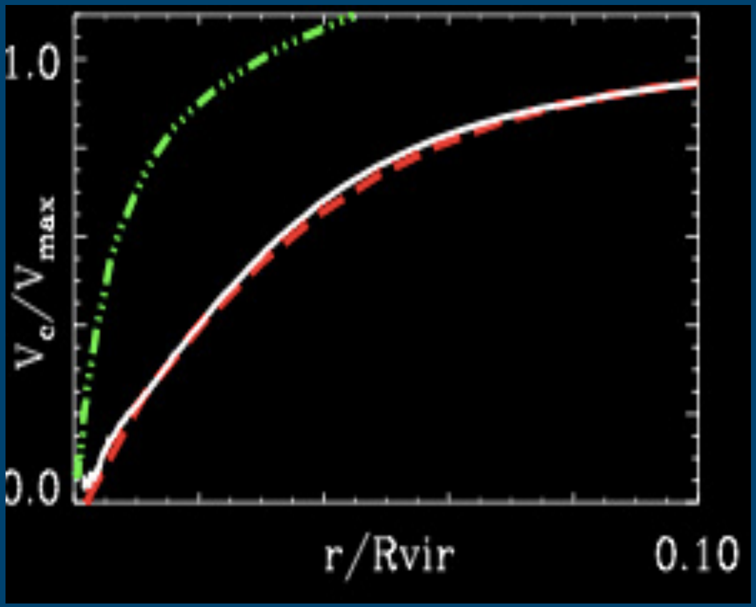
γ inner slope

β outer slope

α sharpness of transition

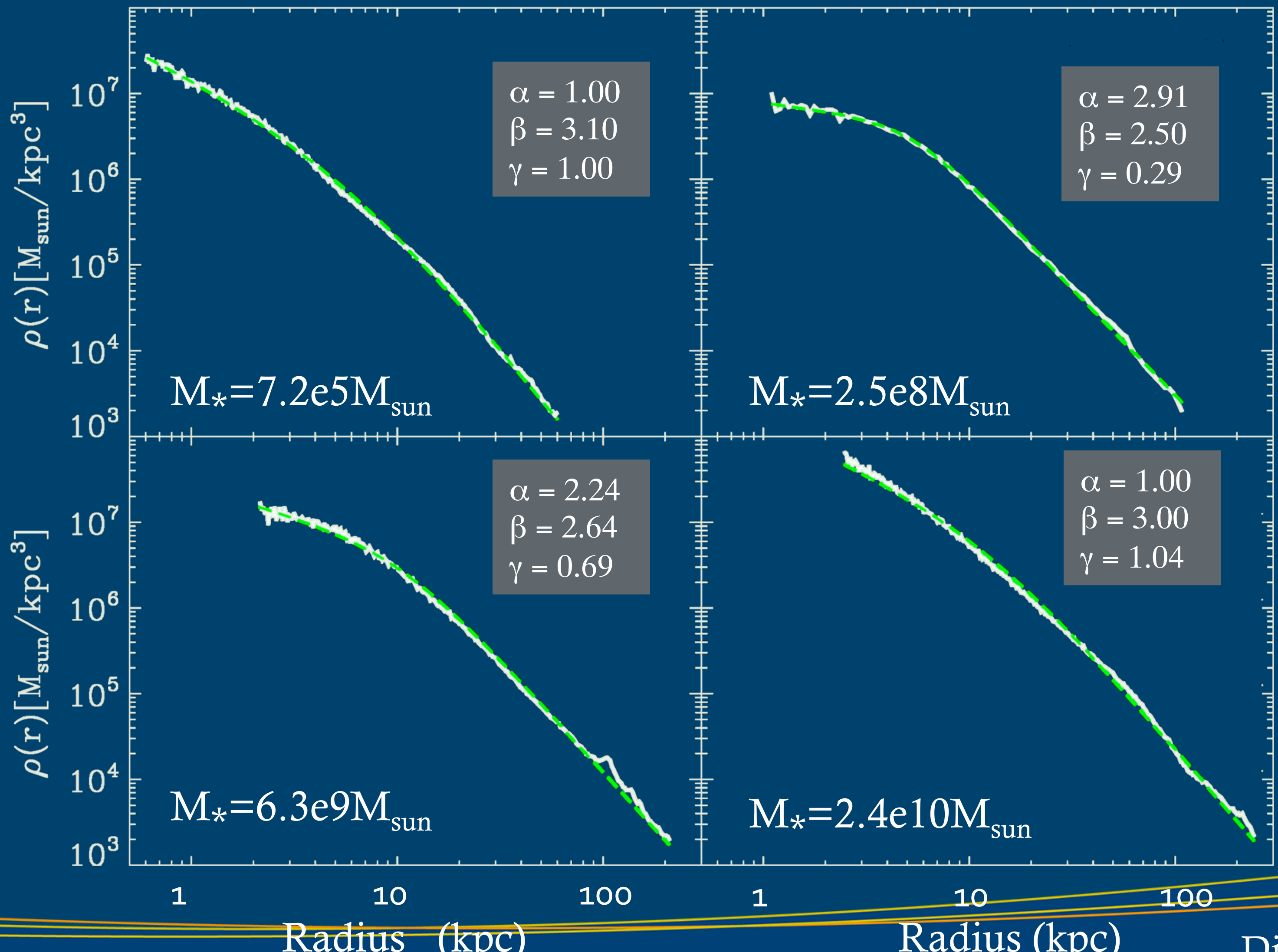
Constrained via M^*/M_{halo}





Cores→ slowly rising RCs

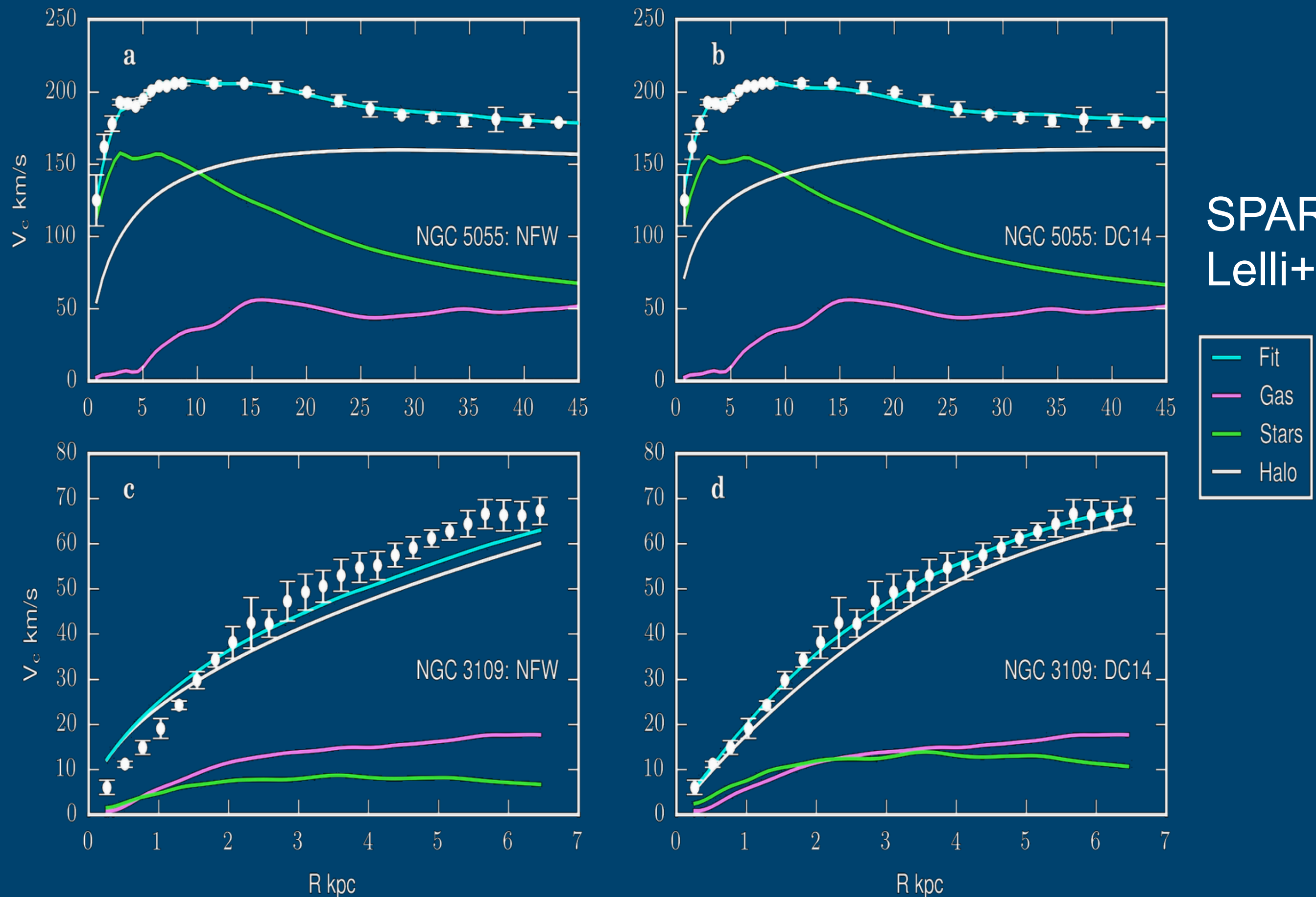
Mass dependent DM profile



Di Cintio+14b

Fit full RCs with NFW and DC14 profile

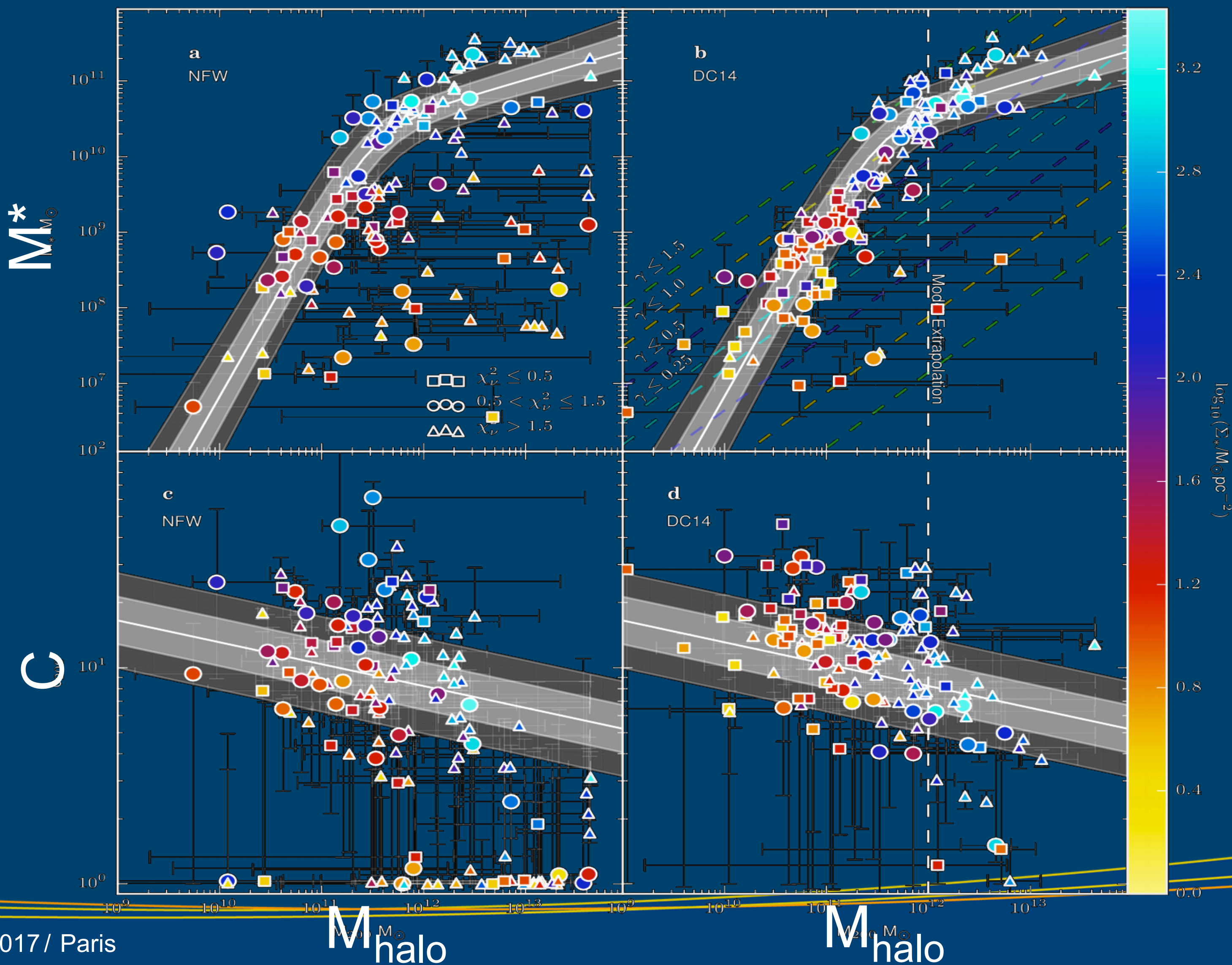
Katz, Lelli, Mc Gaugh, Di Cintio, Brook, Schombert 2017



SPARC dataset
Lelli+16

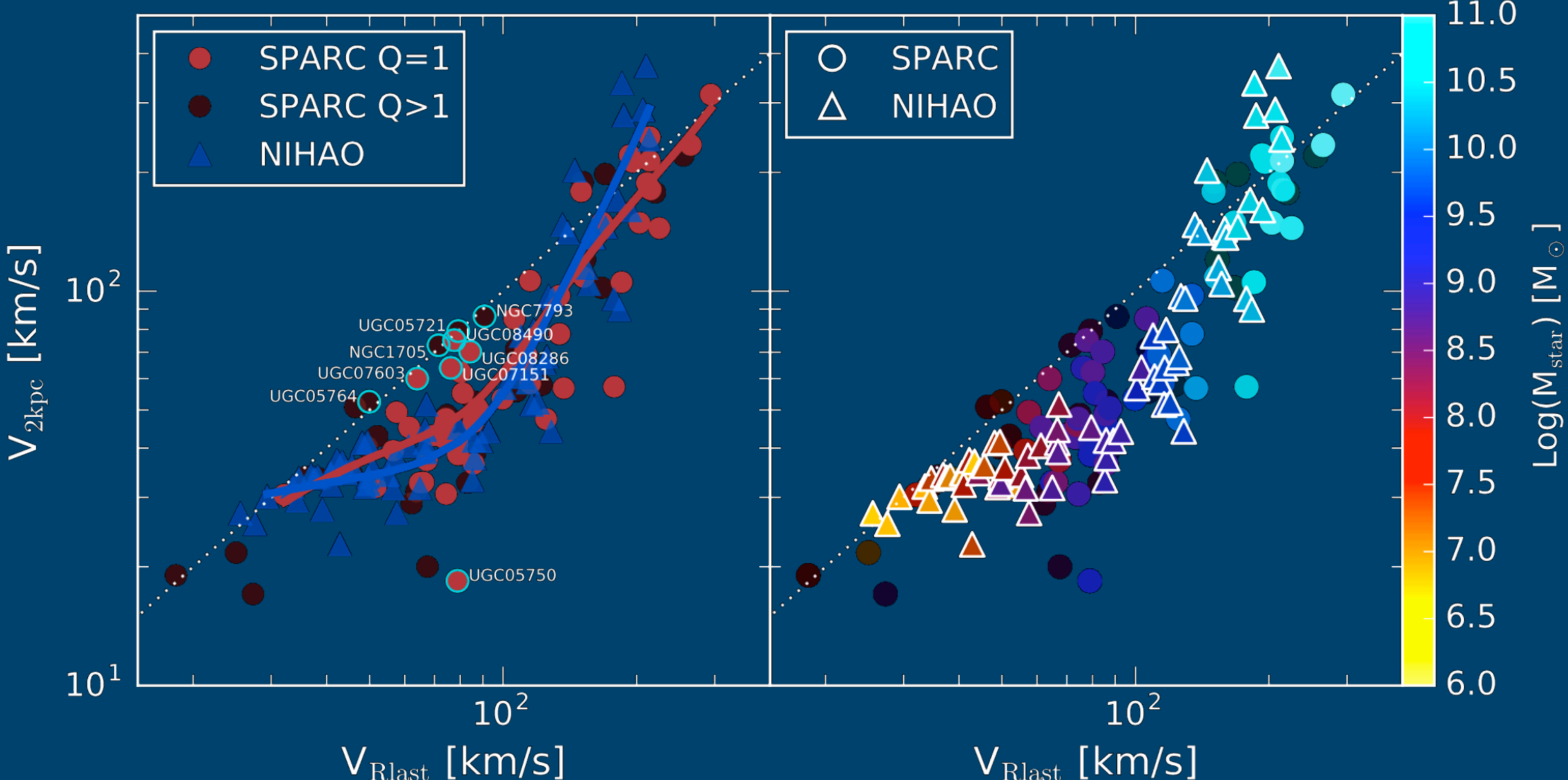
Recover M^*-M_{halo}, c-M, RCs for the DC14 profile

Katz, Lelli, Mc Gaugh, Di Cintio, Brook, Schombert 2017



Diversity of RC shapes explained by cores

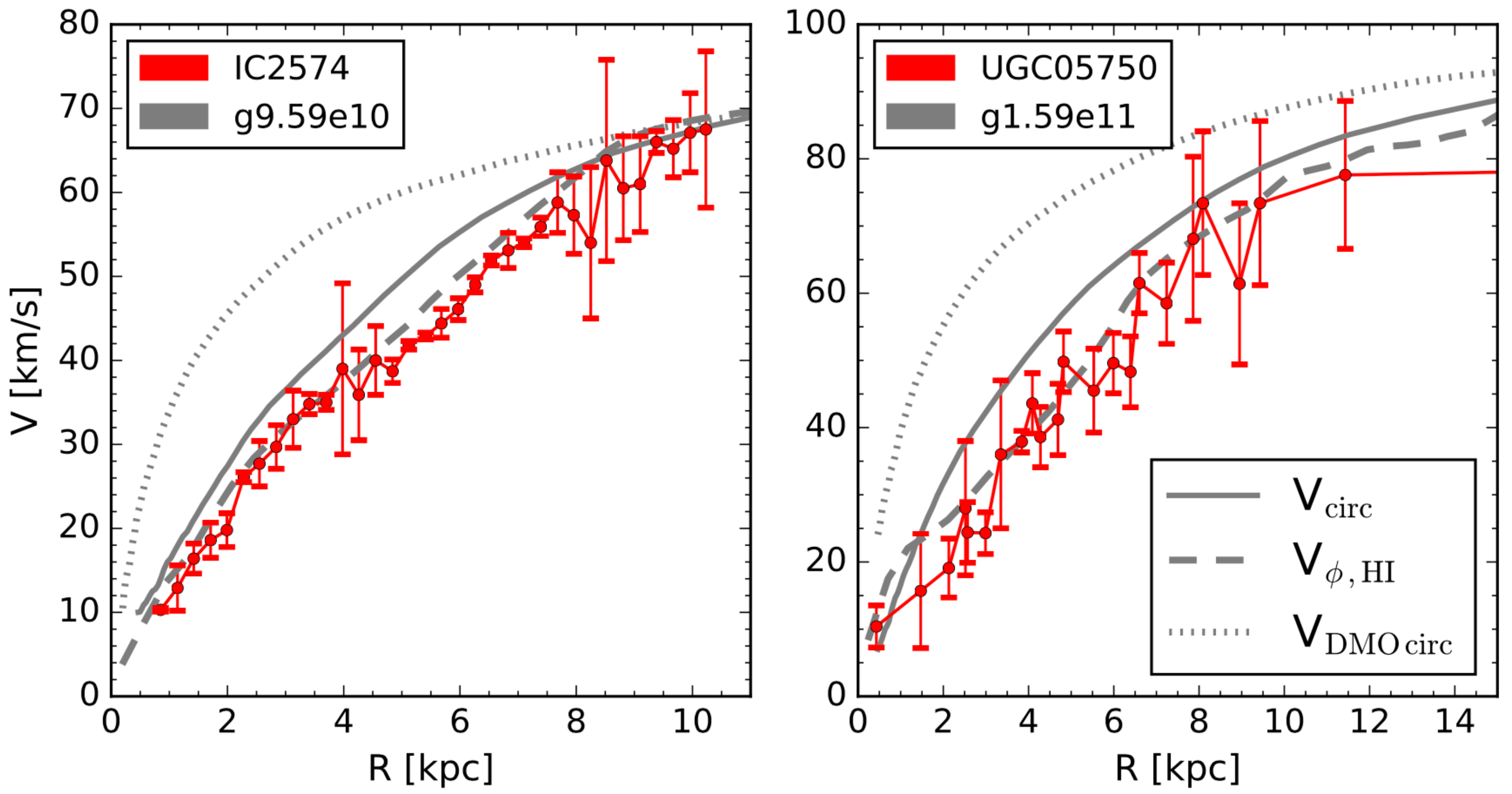
Santos-Santos, Di Cintio et al 2017 submitted



For DM cores not be "real', there must be some conspiracy for which observational errors mimic the presence of a DM core exactly in the range where we expect DM cores from theoretical models.

Diversity of RC shapes explained by cores

Santos-Santos, Di Cintio et al 2017 submitted



The mass discrepancy acceleration relation in a ΛCDM context

Arianna Di Cintio[1*] & Federico Lelli[2]
[1]*Dark Cosmology Centre, Niels Bohr Institute, University of Copenhagen, Juliane Maries Vej 30, DK-2100 Copenhagen, Denmark*
[2]*Astronomy Department, Case Western Reserve University, 10900 Euclid Avenue, Cleveland, OH 44106, USA*

Accepted 2015 November 19. Received 2015 November 19; in original form 2015 October 23

Take a distribution of haloes. — Mhalo
Assign a stellar mass using abundance matching relations. — M*
Assume 2 density profiles for DM haloes : NFW and DC14 — $\rho(r)$

$$\log_{10}(c_{200}) = 0.905 - 0.101\log_{10}(M_{200}/[10^{12}h^{-1}M_\odot])$$

$$\log_{10}(M_{HI}/M^\star) = -0.43\log_{10}(M^\star) + 3.75$$

$$R_{eff} = 0.13(M^\star)^{0.14}\left(1.0 + \frac{M^\star}{14.03\times10^{10}M_\odot}\right)^{0.77}$$

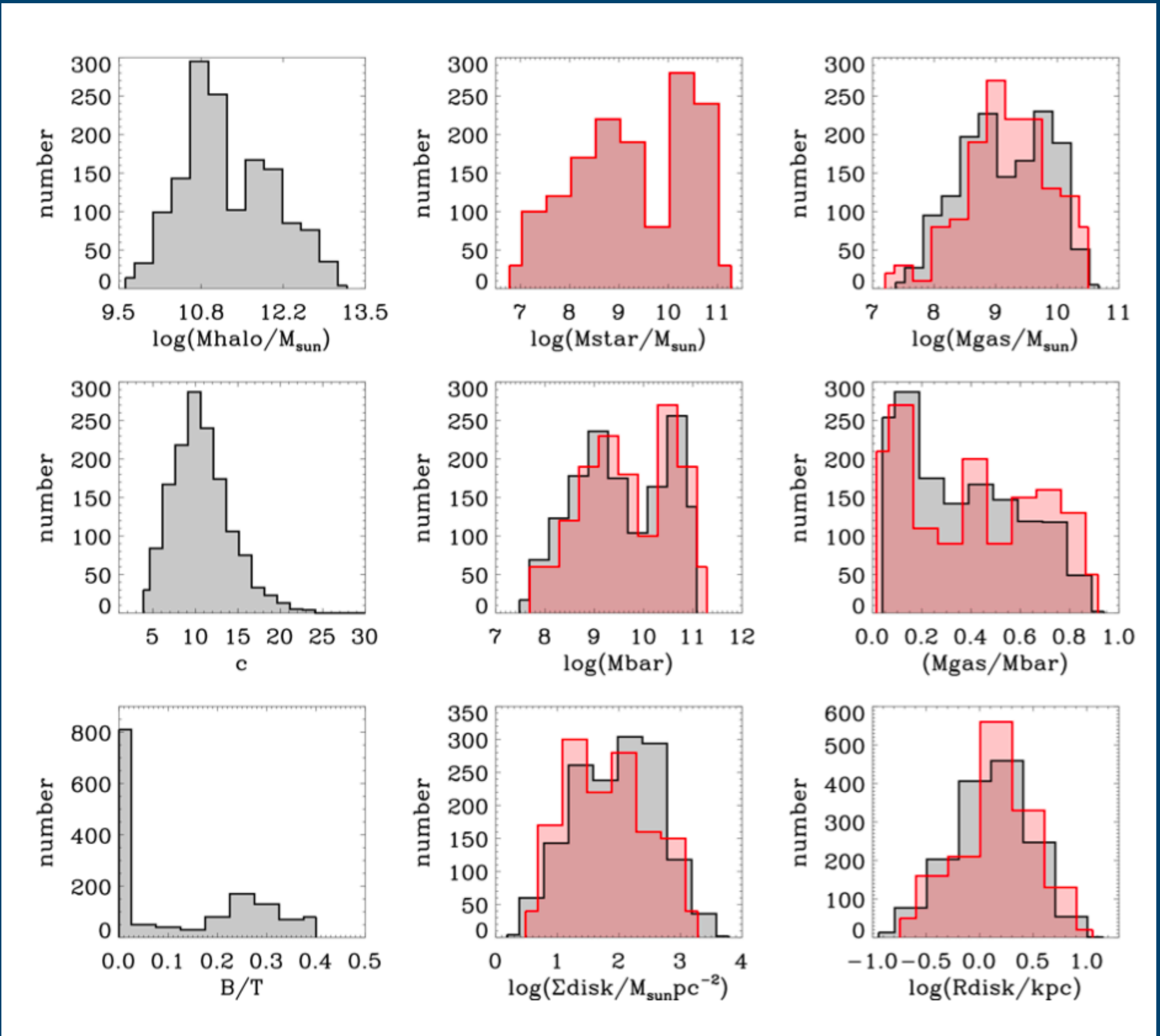
$$M_{bulge}/M^\star = (\log_{10}(M^\star) - 9.5)/4.2$$

C
MHI
Reff
Mbulge

Include scatter in the
Various relations

Obtain a very good
Match of observed
And modeled galaxies

Let's now compute
the MDAR



Di Cintio & Lelli 15

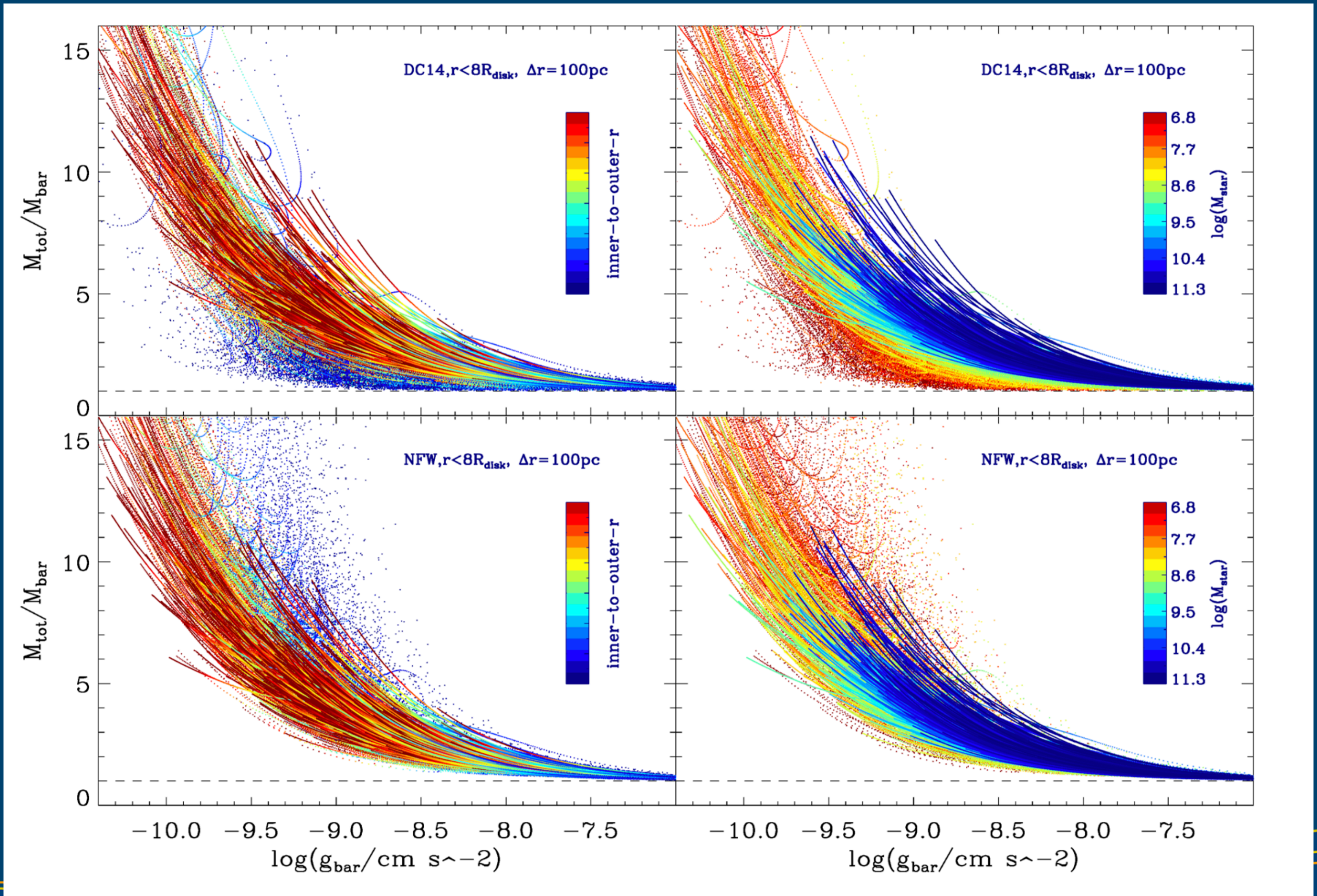
$$V^2_{obs}(r)/V^2_{bar}(r)=M_{tot}(r)/M_{bar}(r)$$

$$g_{bar}=V^2_{bar}(r)/r$$

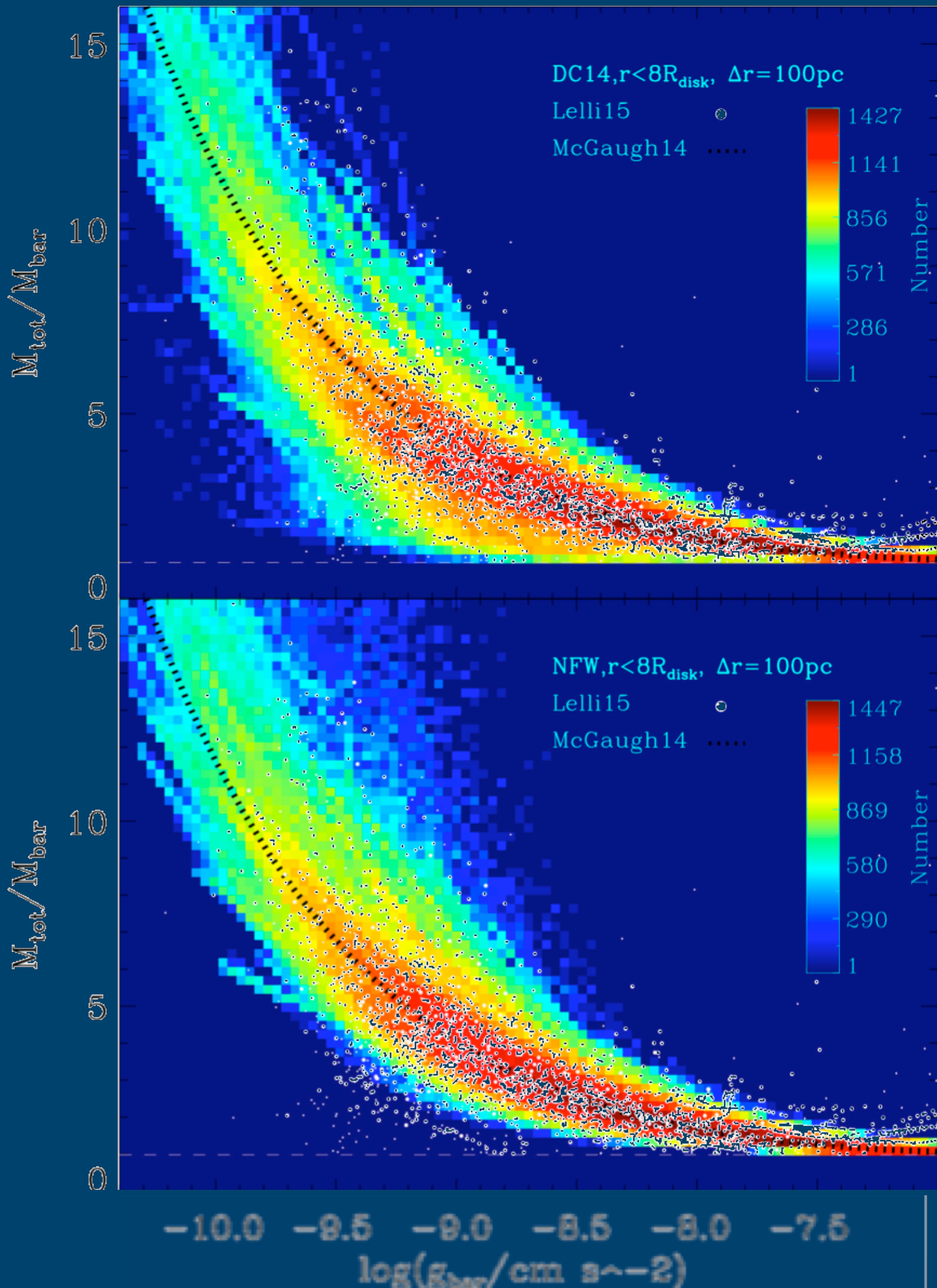
$$V^2_{disk}(r) = \frac{GM_{disk}}{R_{disk}} 2y^2[I_0(y)K_0(y) - I_1(y)K_1(y)]$$

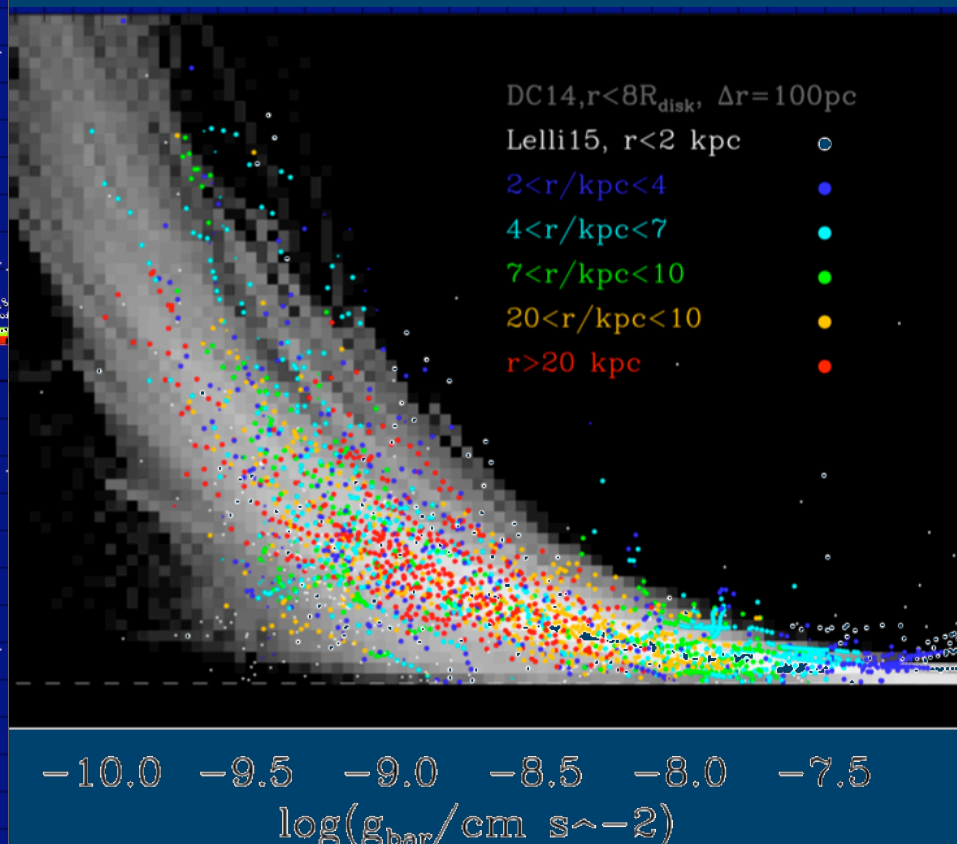
$$V^2_{tot}(r) = V^2_{disk,g}(r) + V^2_{disk,\star}(r) + V^2_{bulge}(r) + V^2_{DM}(r) \quad (6)$$

where V_{DM} has been multiplied by a factor $\sqrt{1 - f_b} = \sqrt{0.842}$



Di Cintio & Lelli 15

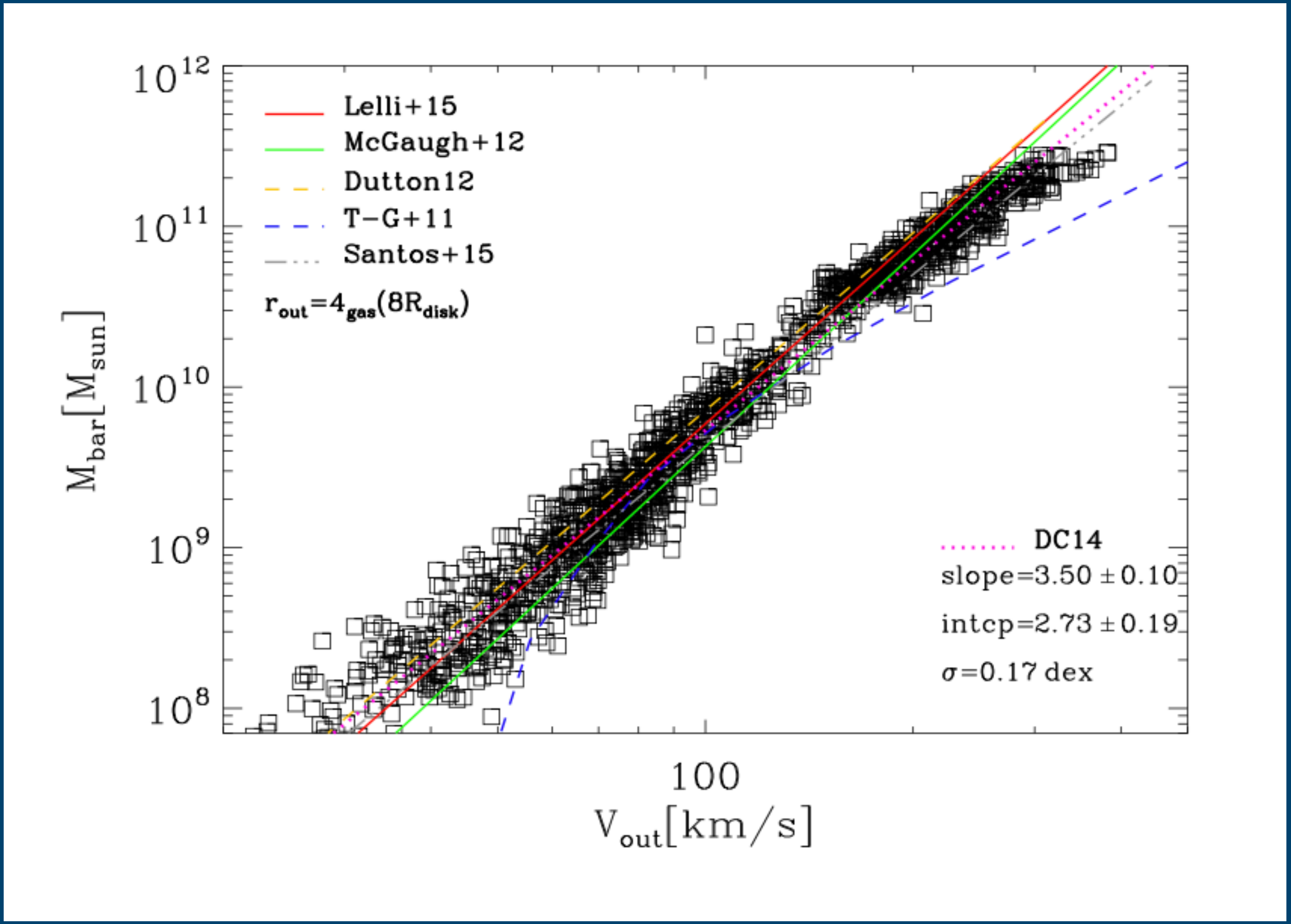




NFW can not explain this region of the observed MDAR => CORED galaxies

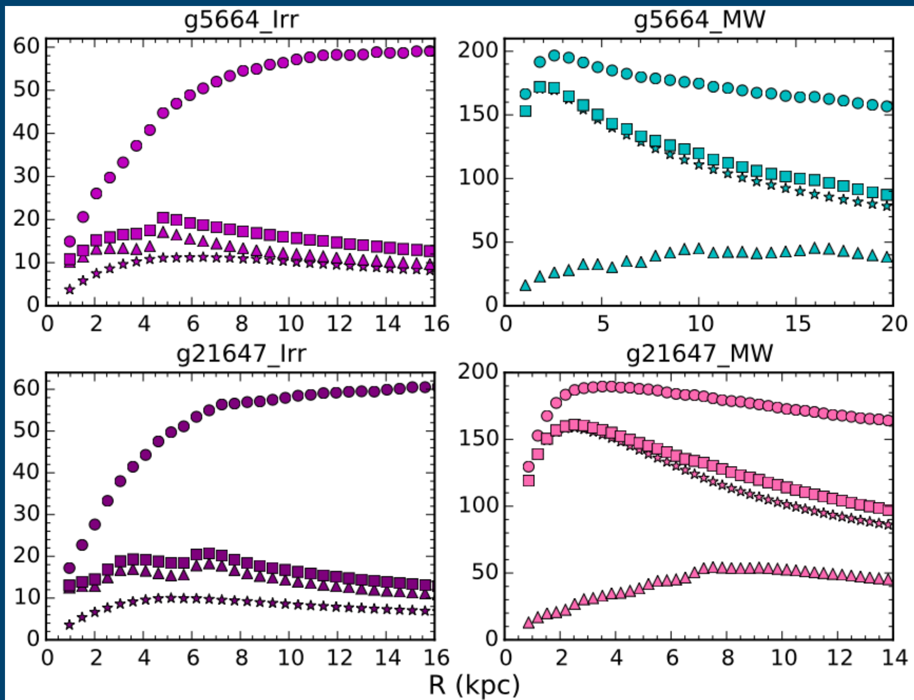
Di Cintio & Lelli 15

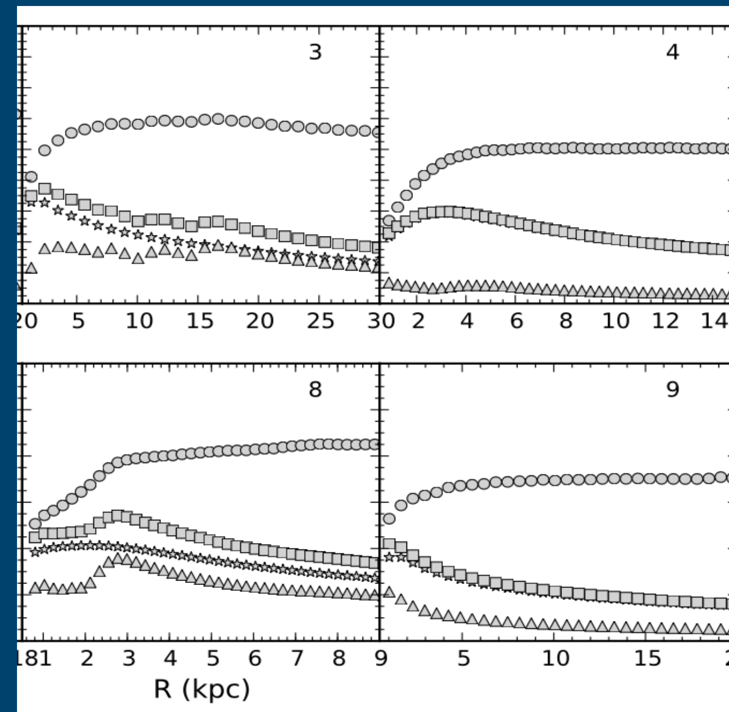
By rank ordering DM haloes (abundance matching technique), we get the correct BTFR for free -> success of LCDM model



Di Cintio & Lelli 15

Result derived with semi-empirical model, was already found in Hydro simulations that produce DM cores!





MaGICC galaxies, produce cores at a mass range M*~10^8-9Msun
=> Well described by DC14 profile

CLUES galaxies, They all have a NFW profile

Santos-Santos+15

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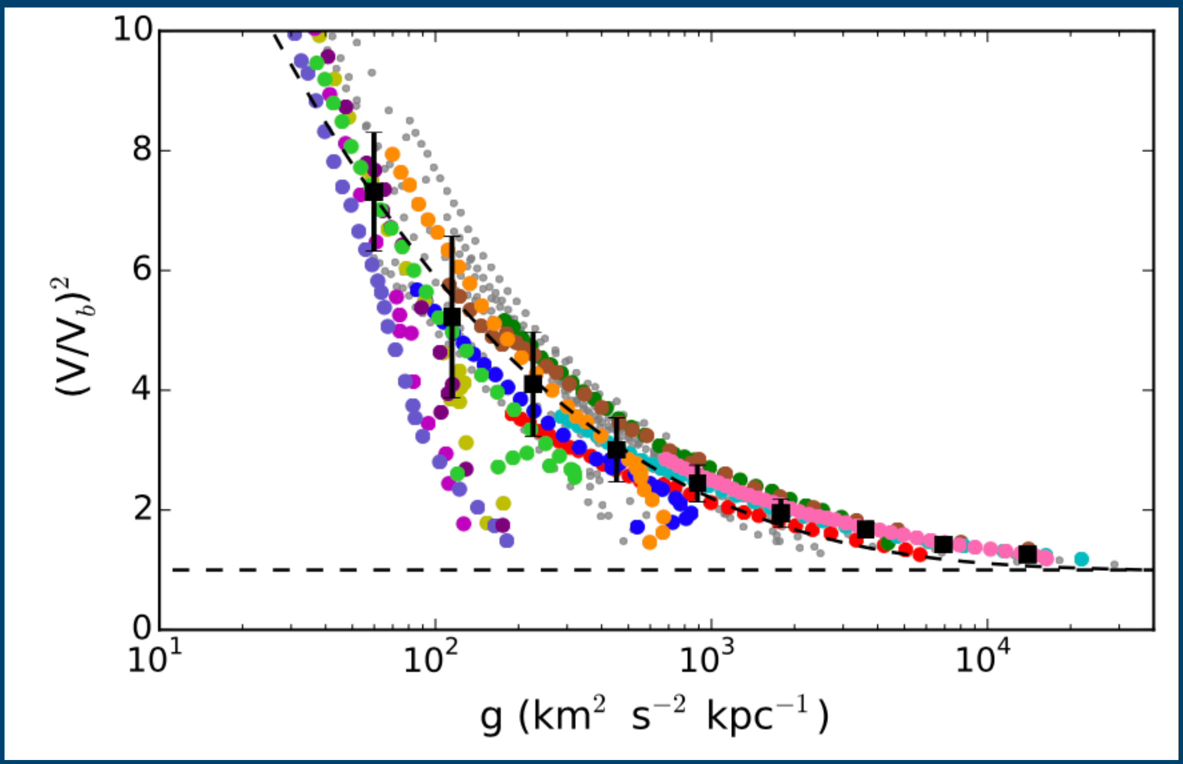
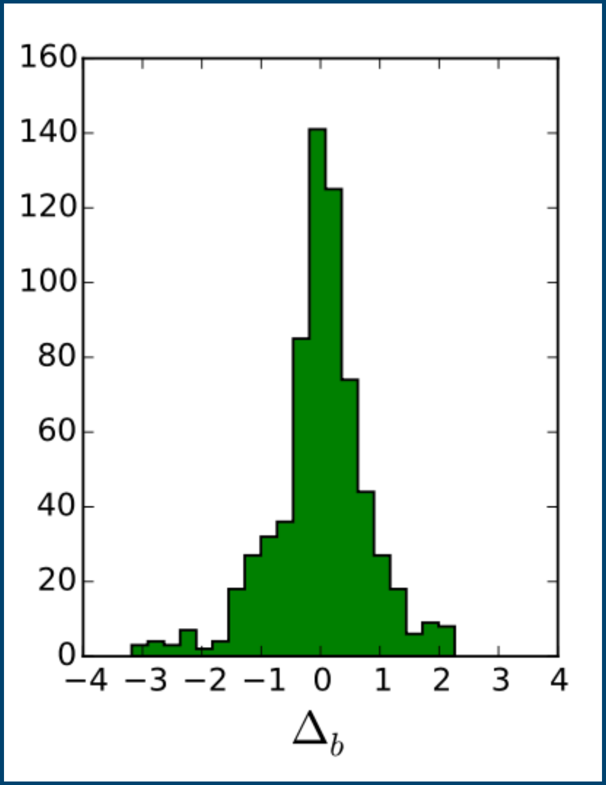
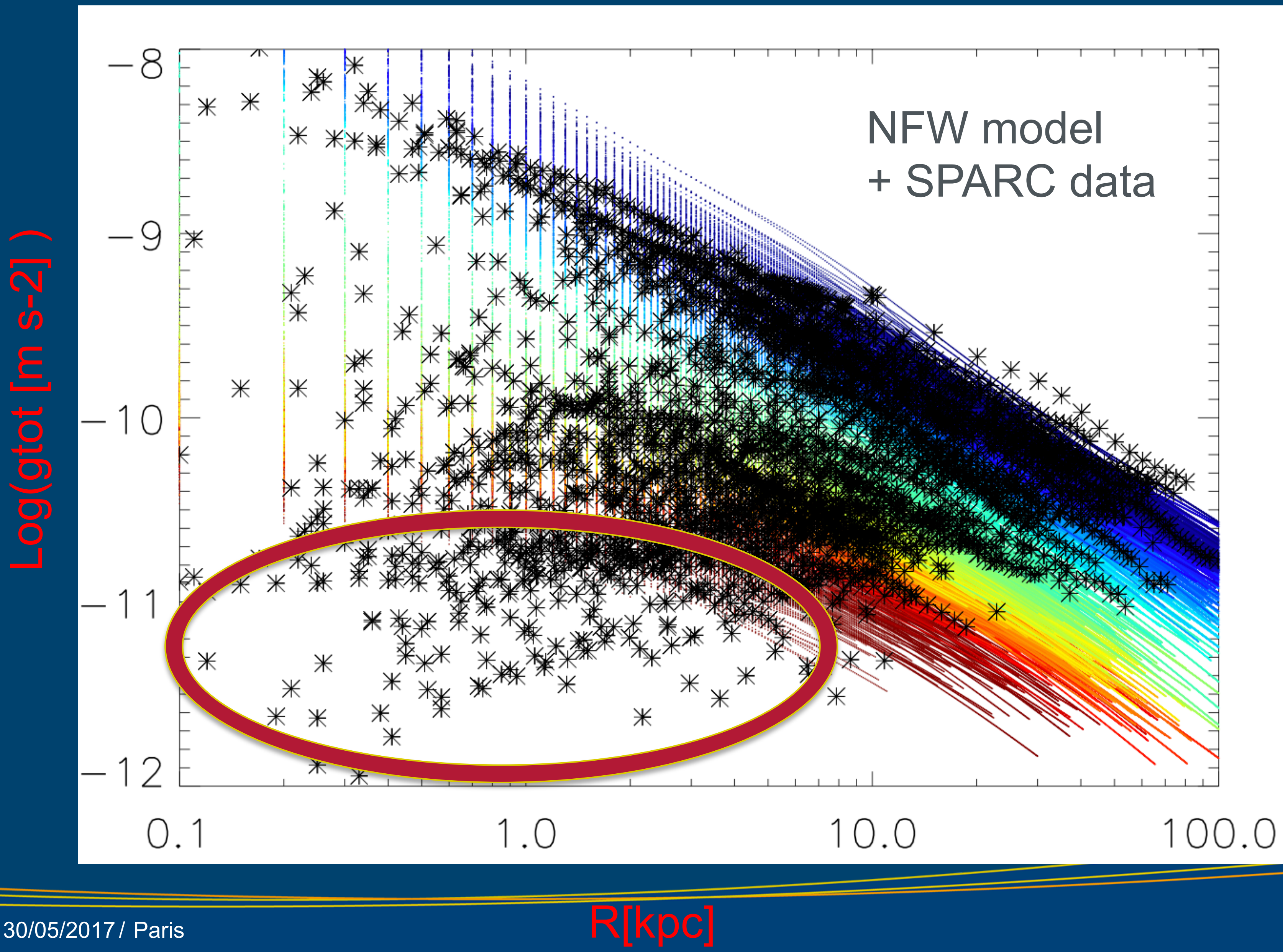


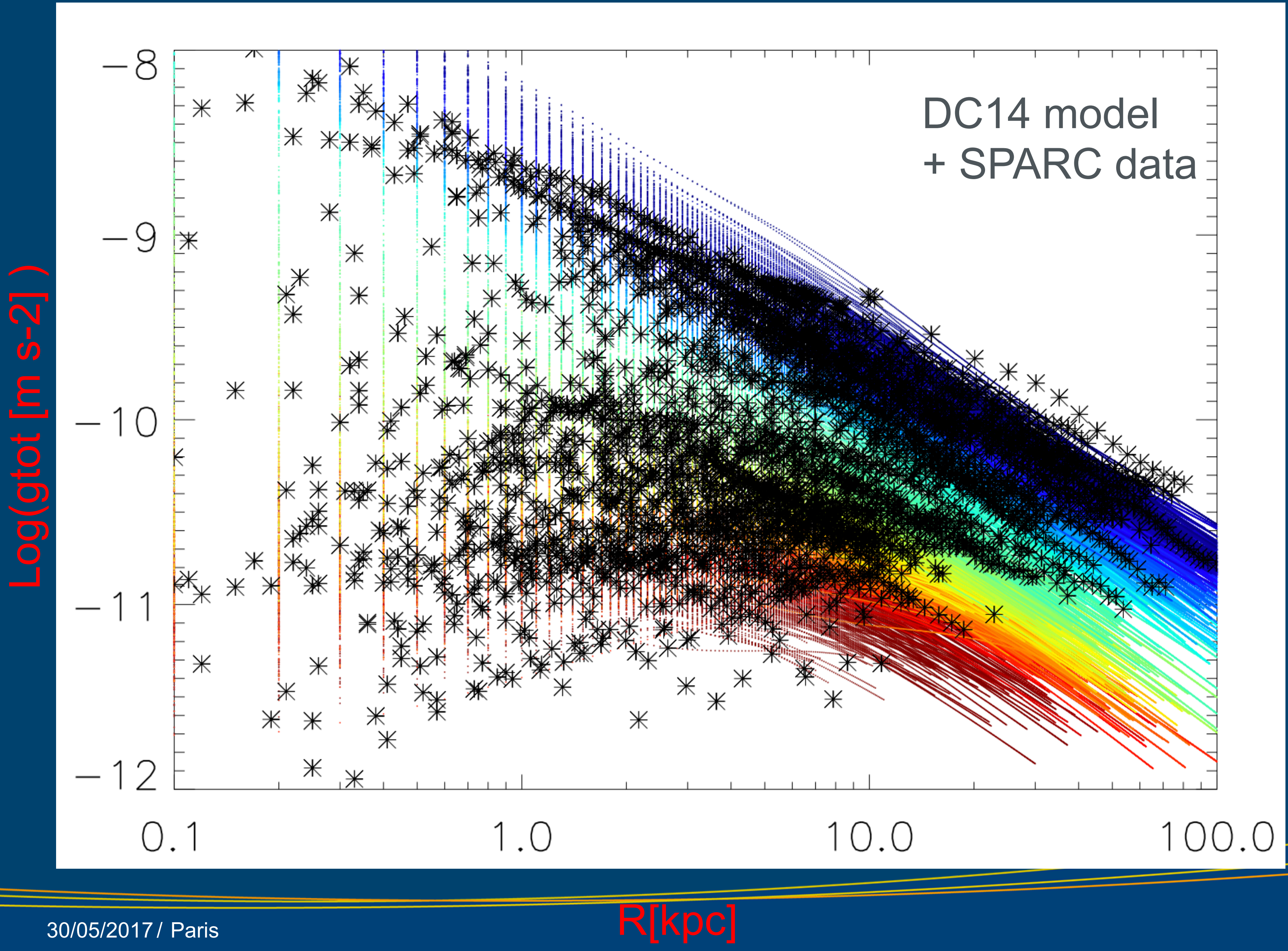


Santos-Santos+15

Can we explain the MDAR(i.e. the acceleration profiles of Galaxies) without DM cores?...not really.. gtot CAN be < 10^{-11}



Can we explain the the acceleration profiles of Galaxies with DM cores?
Much better!



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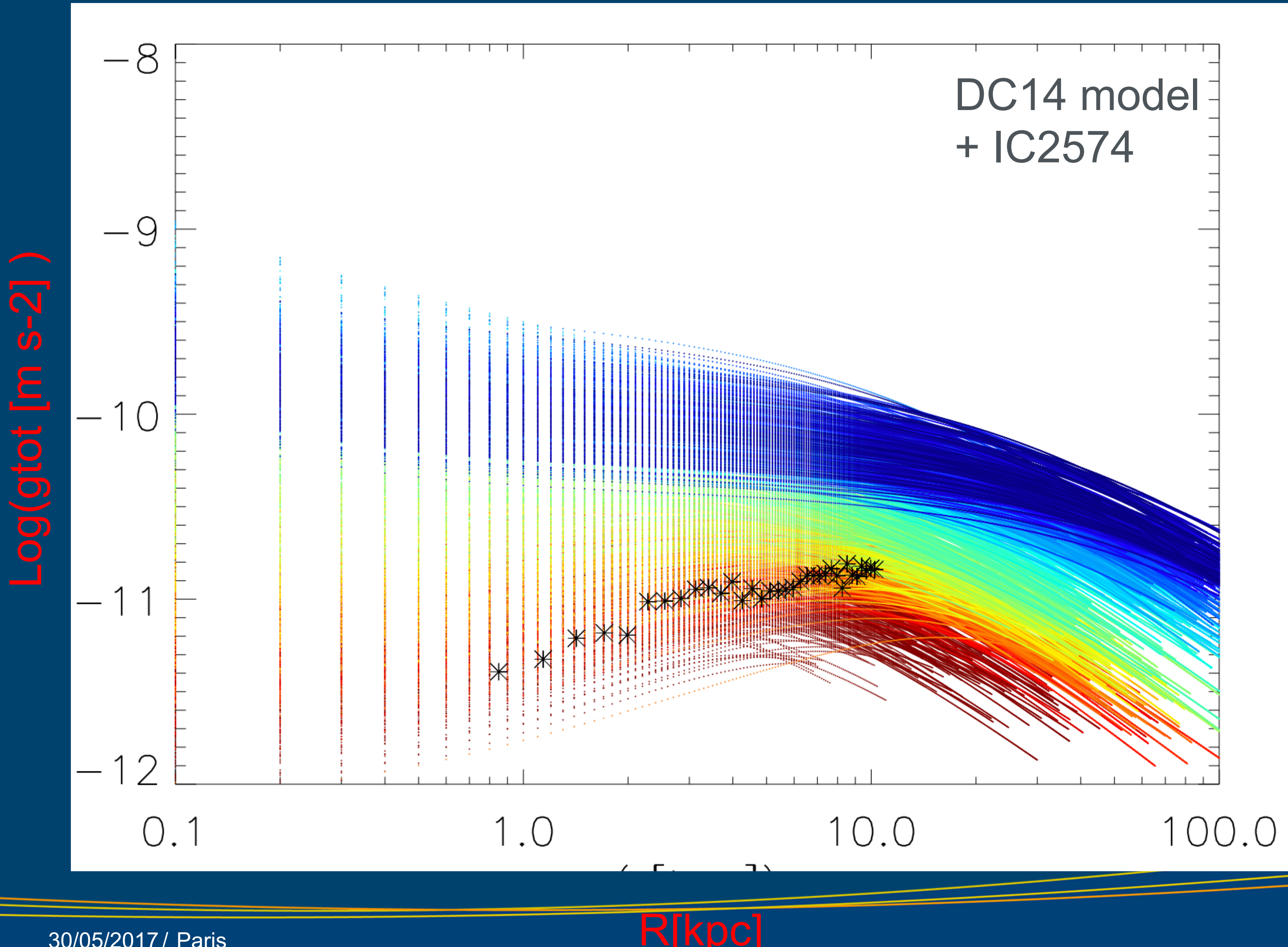


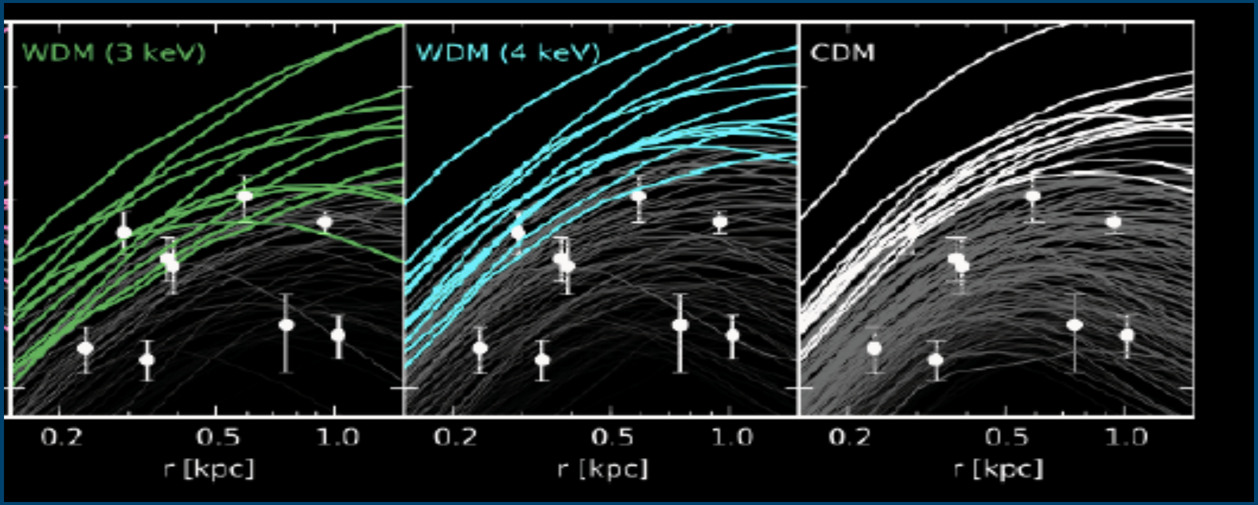
Thoughts on MDAR (RAR):

- We can reproduce its normalization and slope in LCDM simulations -> just by assuming a M*-Mhalo and a Rdisk-M* relation
- We need to form DM cores in order to recover the MDAR of (some) dwarf galaxy, and their acceleration profile
- The scatter is not well defined at low g: there may still be observational bias, and the scatter could increase significantly at low accelerations (once we include UGDs, for instance)

Alternative DM models: WDM

TBTF in Warm Dark Matter

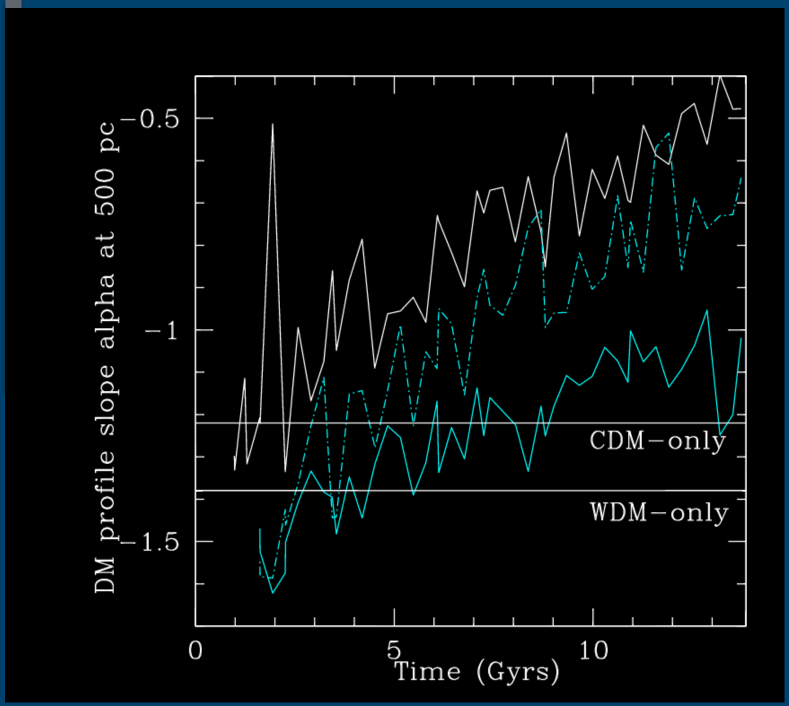
Schneider +15

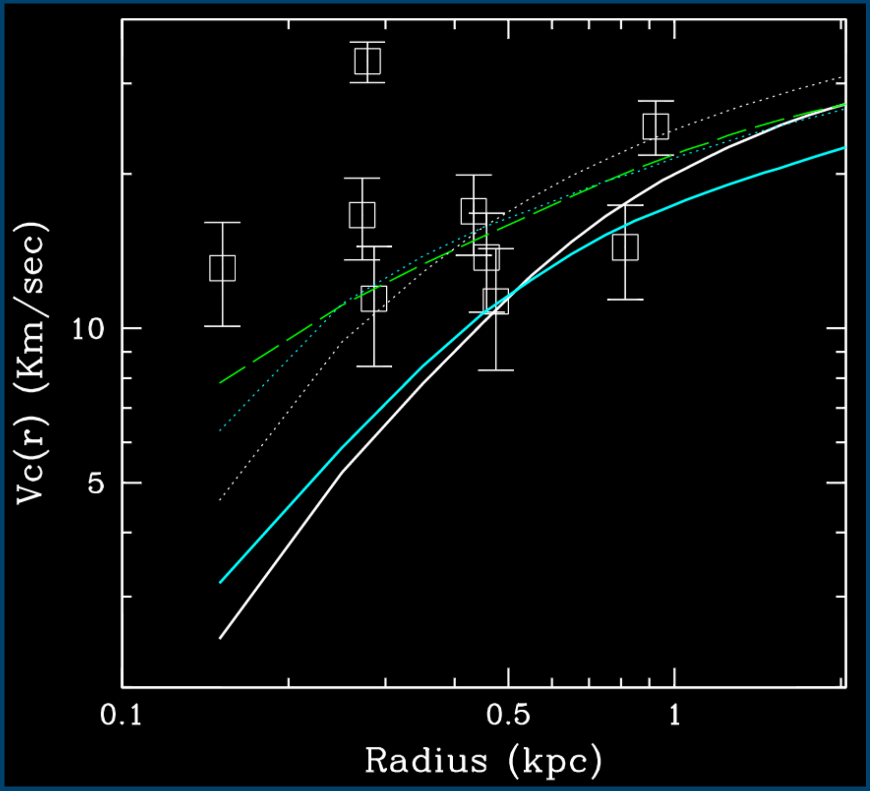


To solve the TBTF problem with WDM we need to create cores of ~Kpc size, which requires a thermal candidate with a mass below 0.1 keV, ruled out by all large scale structure constraints (see Schneider+15, Maccio'+15)

Alternative DM: WDM+baryons

Central DM density more affected by baryonic physics than WDM physics→ Same Vcirc distribution in CDM and WDM that solves TBTF





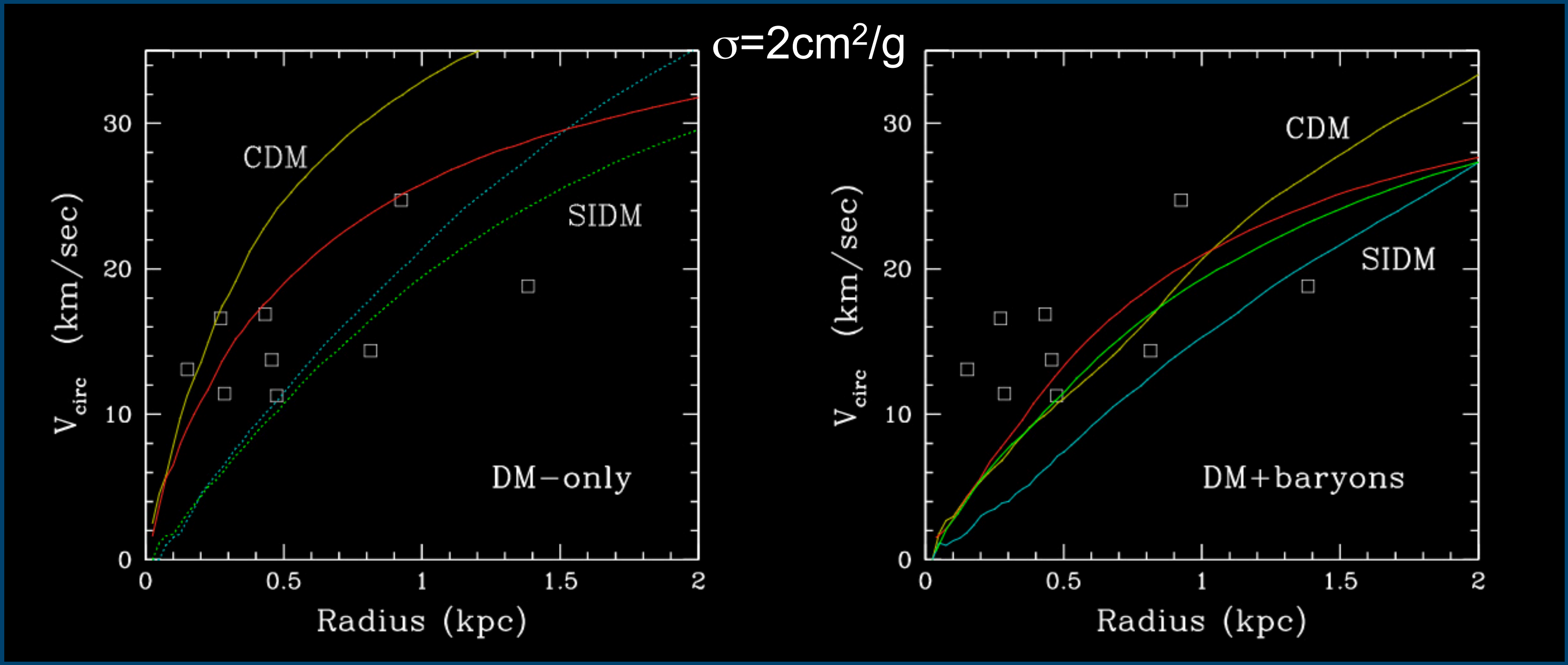
$M^* = 10^{6\text{-}7} M_{sun}$
$M_{halo} = 10^{10} M_{sun}$

Governato +15

Alternative DM: SIDM+baryons

$$\rho v \sim 1/(t\sigma)$$

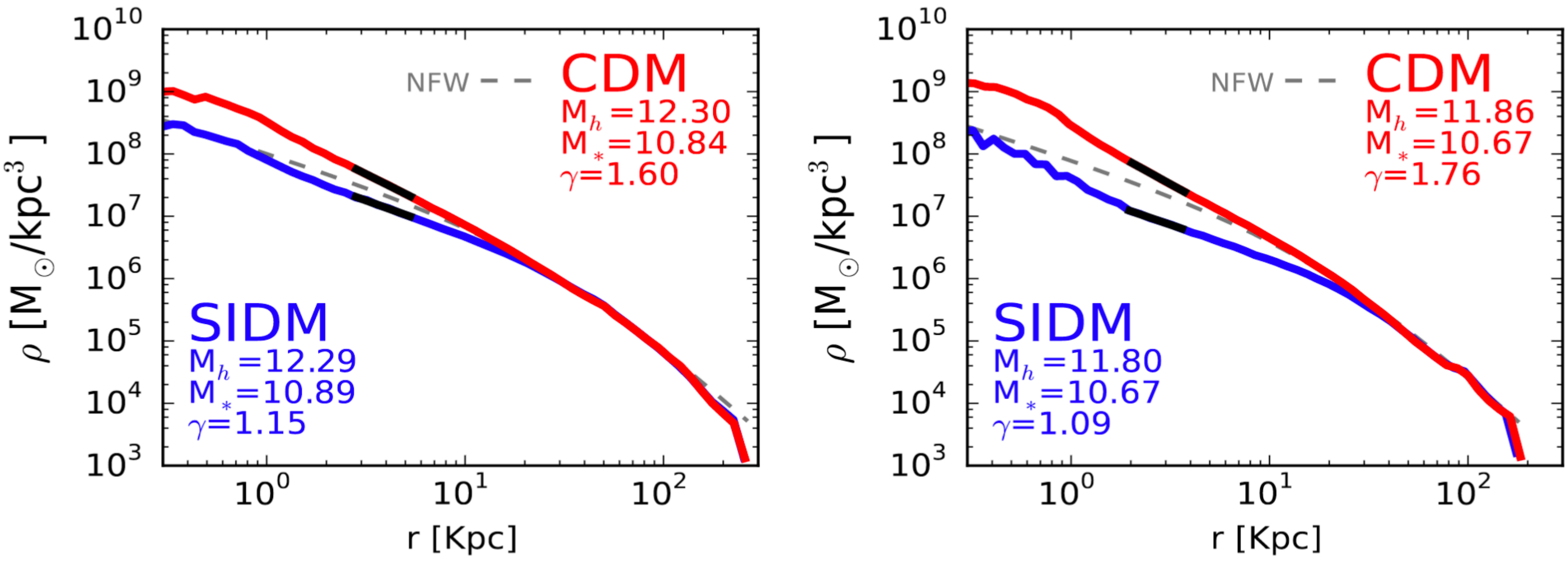
SF and resulting feedback dominates over SI: dm inner slope, SFH, star and gas content are indistinguishable between CDM and SIDM+baryons



Bastidas-Fry, Governato +15

SIDM+baryons in massive galaxies

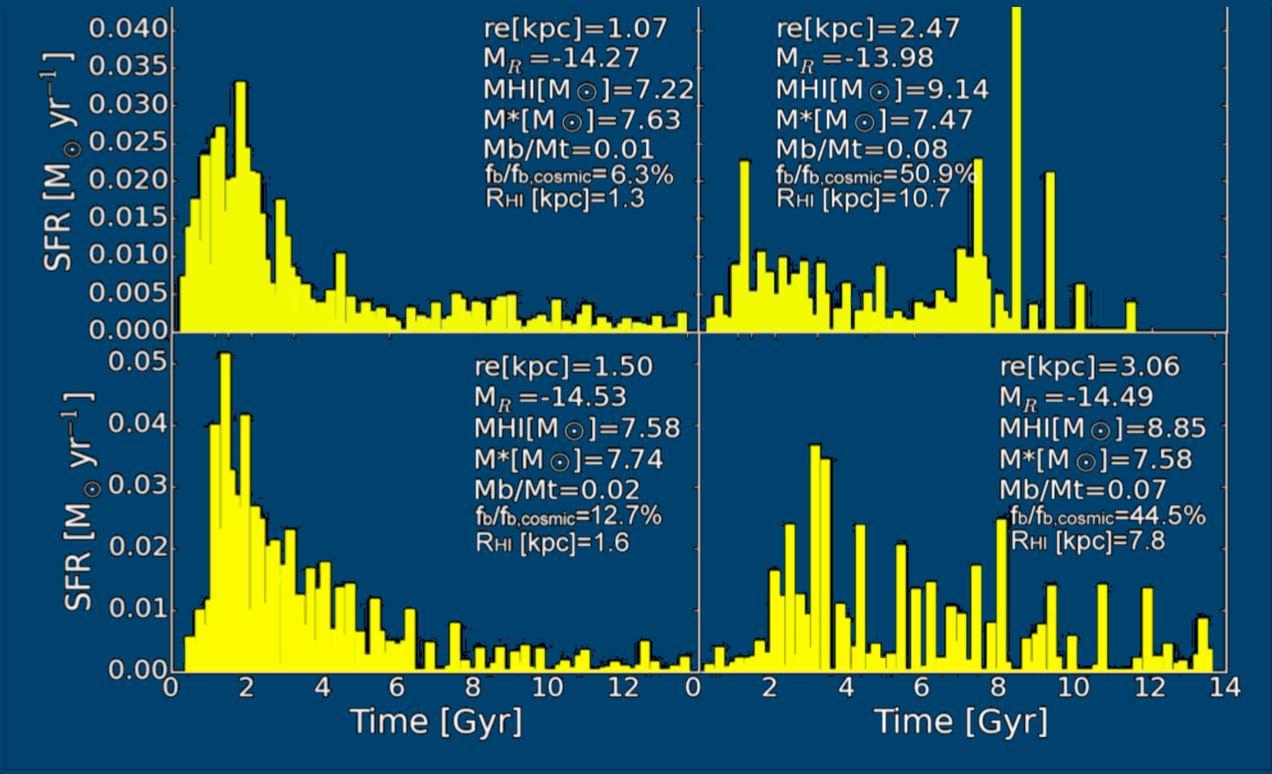
$\sigma/m=10\ cm^2/g$ => density profile in MW like galaxies is shallower than NFW



DC+17

Observational Predictions on HI content..

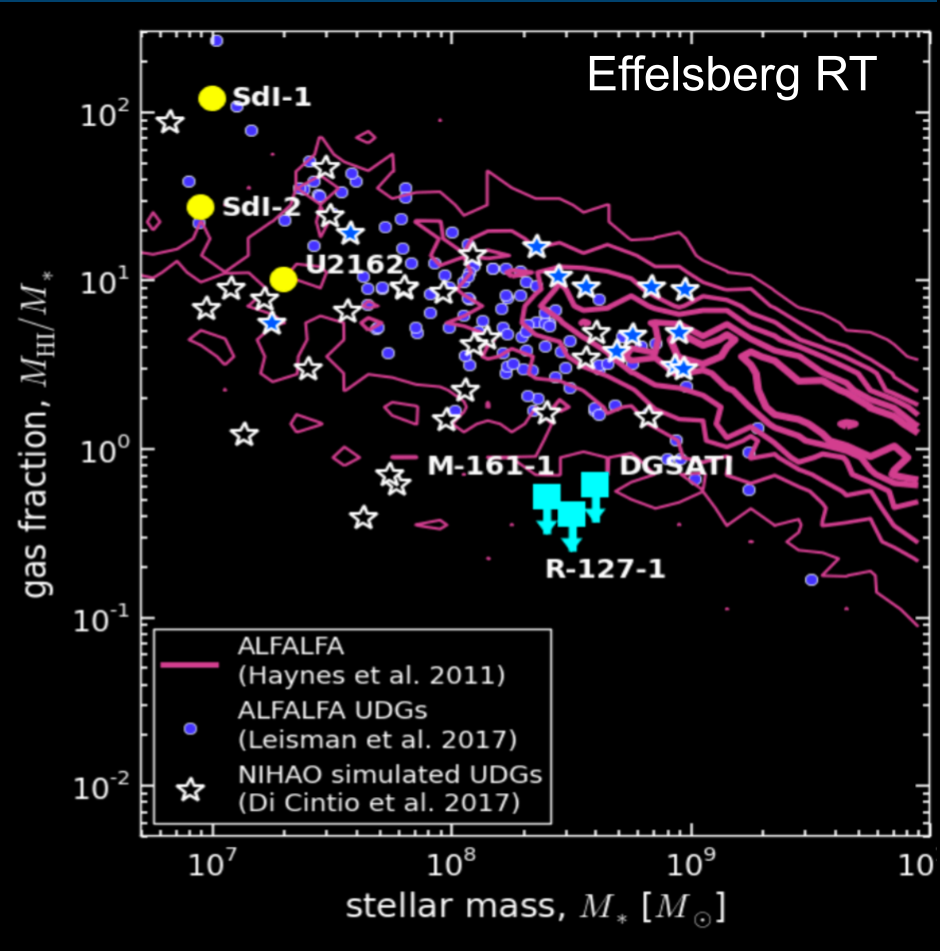
The largest isolated UDGs should contain more HI gas, have a larger baryon fraction and a more extended and *bursty* SFH than less extended dwarfs of similar M⋆

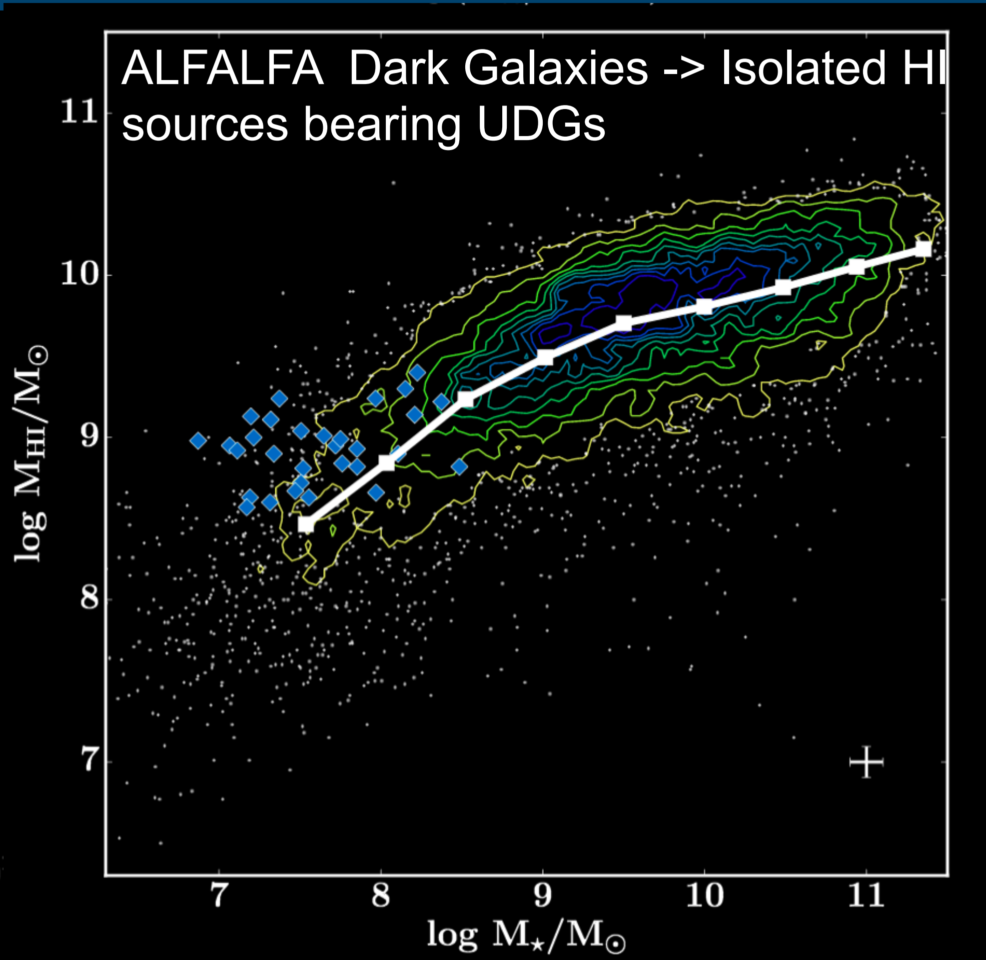


UDGs could be the *dark galaxies* of the ALFALFA survey

Di Cintio +17a

..confirmed by latest data





Papastergis+17

Leisman+17

Conclusions

- Baryonic feedback – SNae driven gas outflows - can modify both the DM and the stellar distribution within galaxies : DM core creation is most efficient in the range M*~10^7-9 Msun

- Mass-dependent DM cores in LCDM can self-consistently explain:

Rotation Curve of galaxies
MDAR relation

Emergence of Ultra-Diffuse Galaxies
Recover M*-Mhalo relation
Velocity Function in the Local Volume
Scatter in RC shapes of dwarf galaxies
Tully-Fisher and BTF relation
Kinematic of MW-M31 Satellites (TBTF problem)

- How does this picture change if the underlying DM model is different (WDM, SIDM) ? Importance of include baryonic physics!

Thank you!

Grazie!