Distinguishing CDM from non standard DM models: the vital role of baryon physics

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In collaboration with

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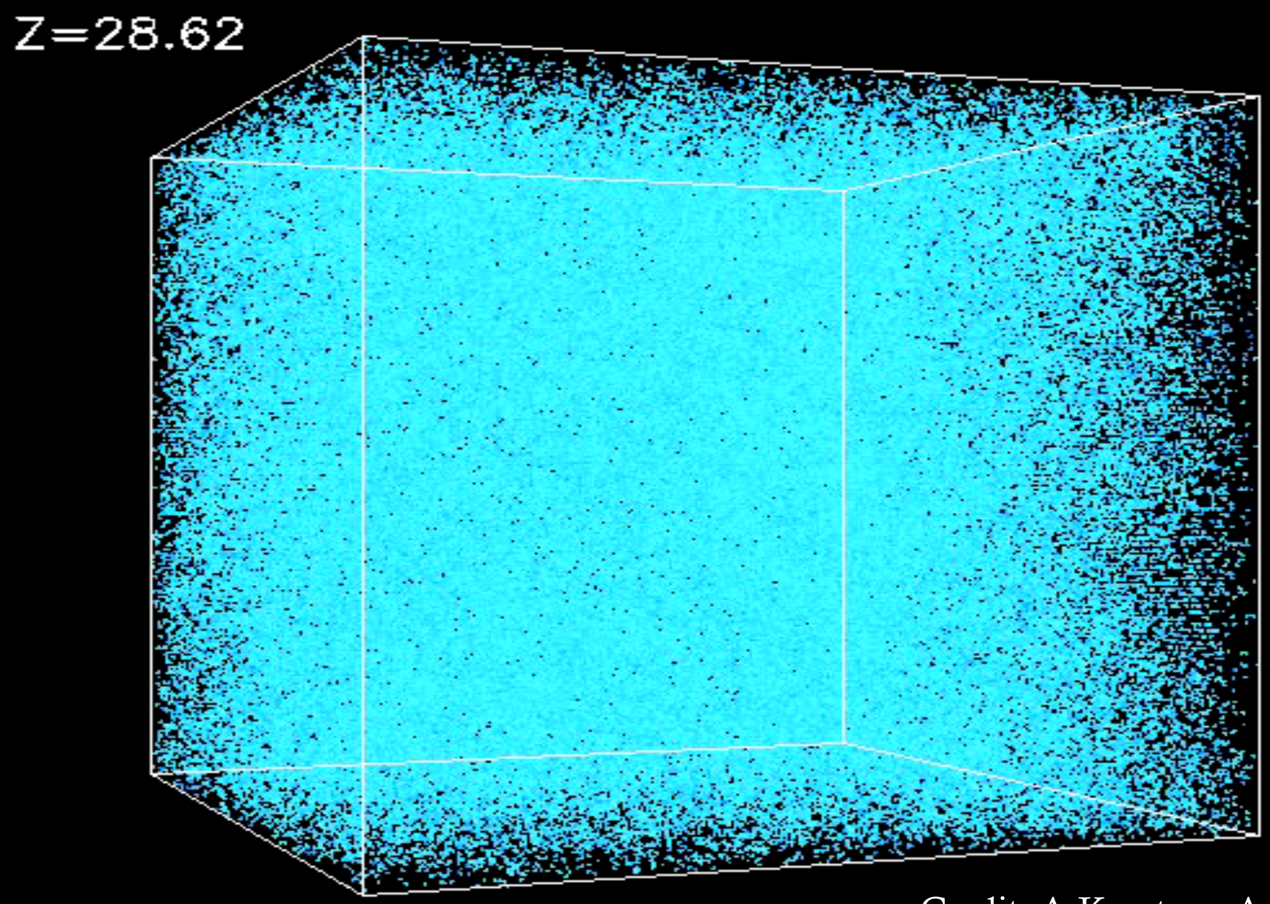
Outline

- The **L**CDM small scale crisis: tbtf-missing satellites-cusp/core-velocity function-RCs
- Solution #1: CDM +baryonic physics
- Solution #2: alternative DM models SIDM/WDM
- Solution #3: SIDM/WDM + baryonic physics
- Future perspectives

CDM N-body simulations



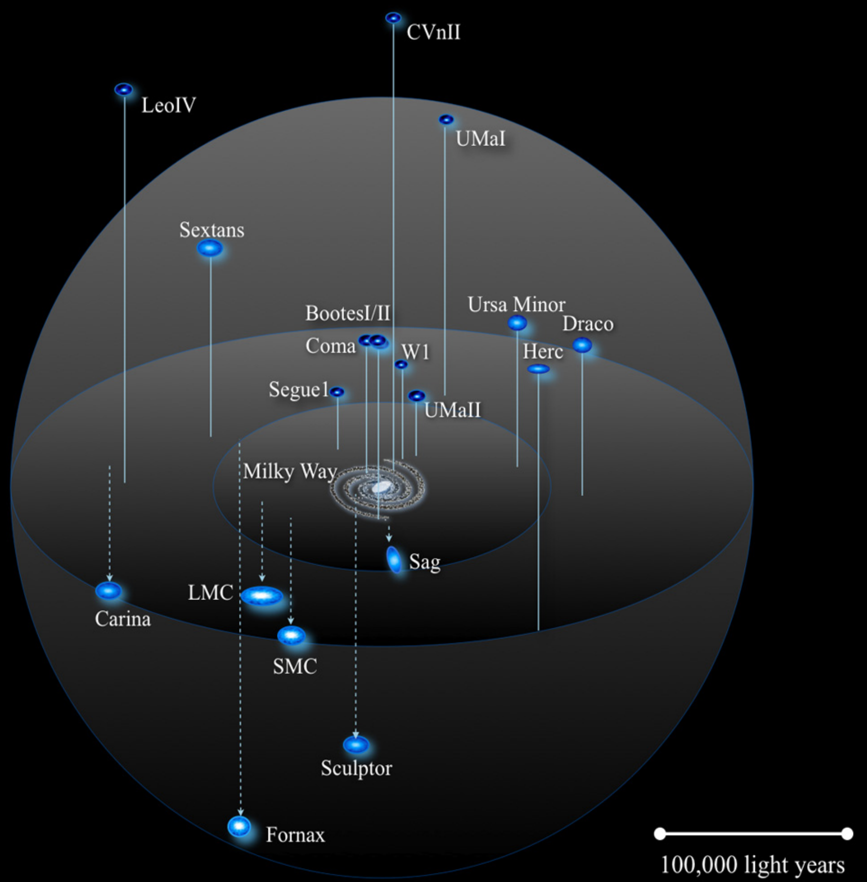
Credit: A.Kravtsov, A. Klypin

The LCDM small scale crisis

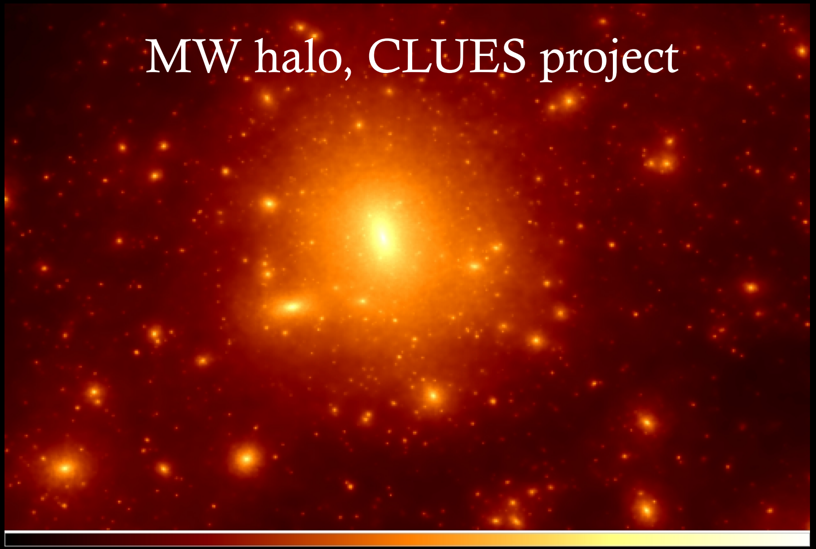
- ✓ Missing satellite problem
- ✓ "Too-big-to-fail" problem
- ✓ Cusp-core discrepancy
- ✓ Velocity function of galaxies
- ✓ Diversity of rotation curves

Problem # 1: missing satellites

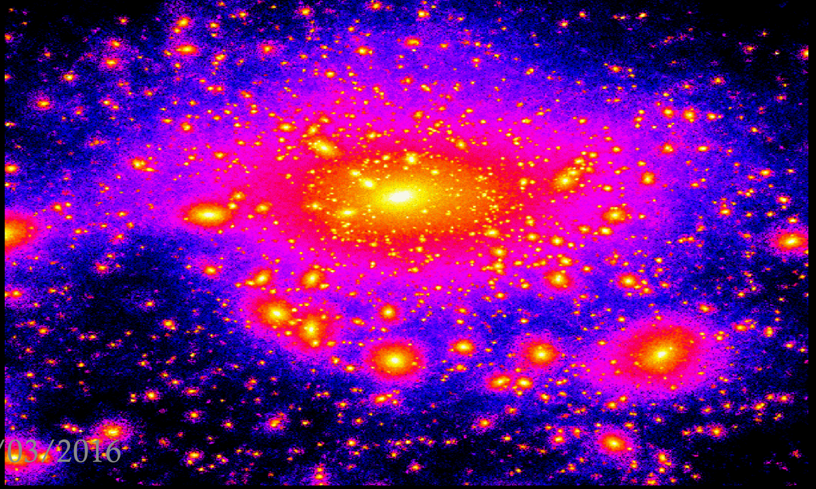
Klypin +99, Moore +99



MW halo, CLUES project

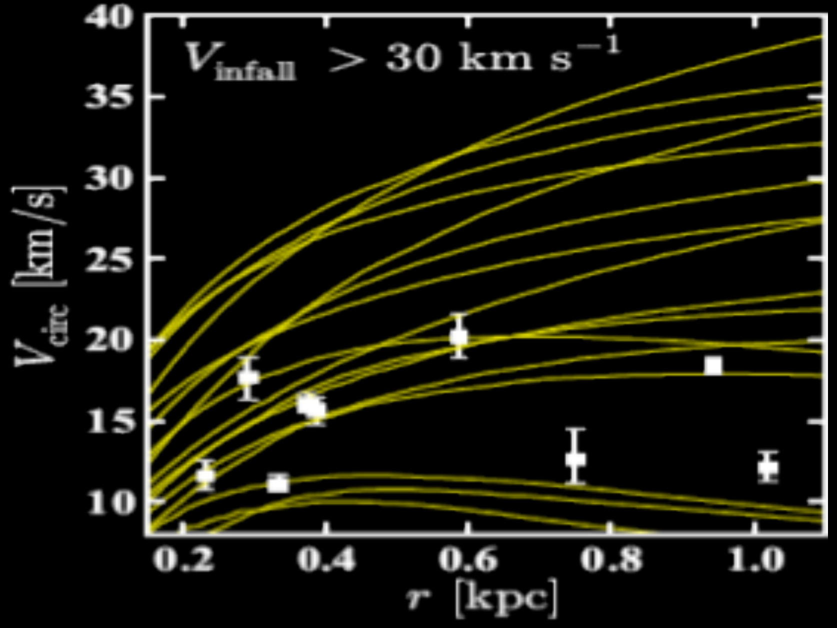


Credit: Mayer and Kazantzidis



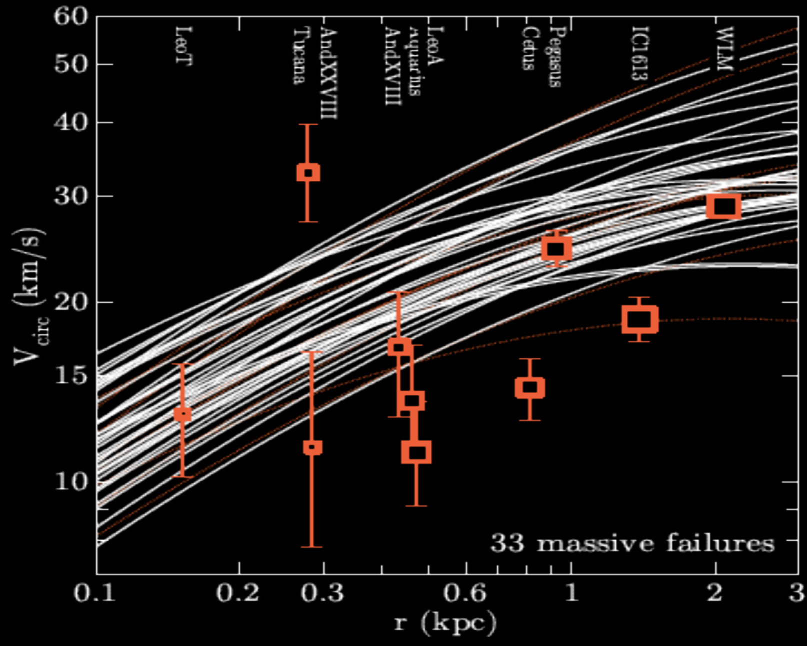
Problem #2 : TBTF in the LG

In satellite galaxies



Boylan-Kolchin +11,+12

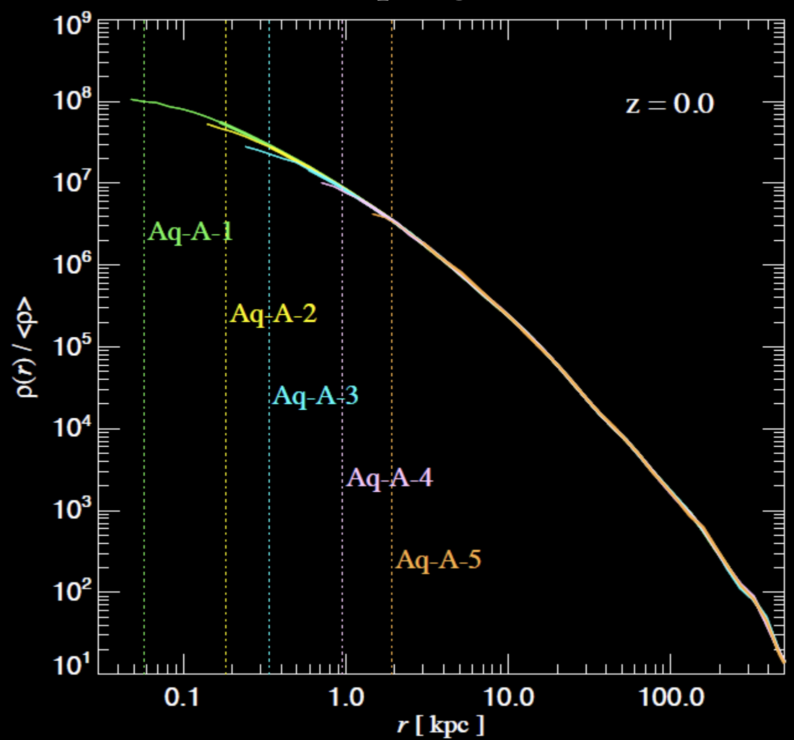
In isolated galaxies



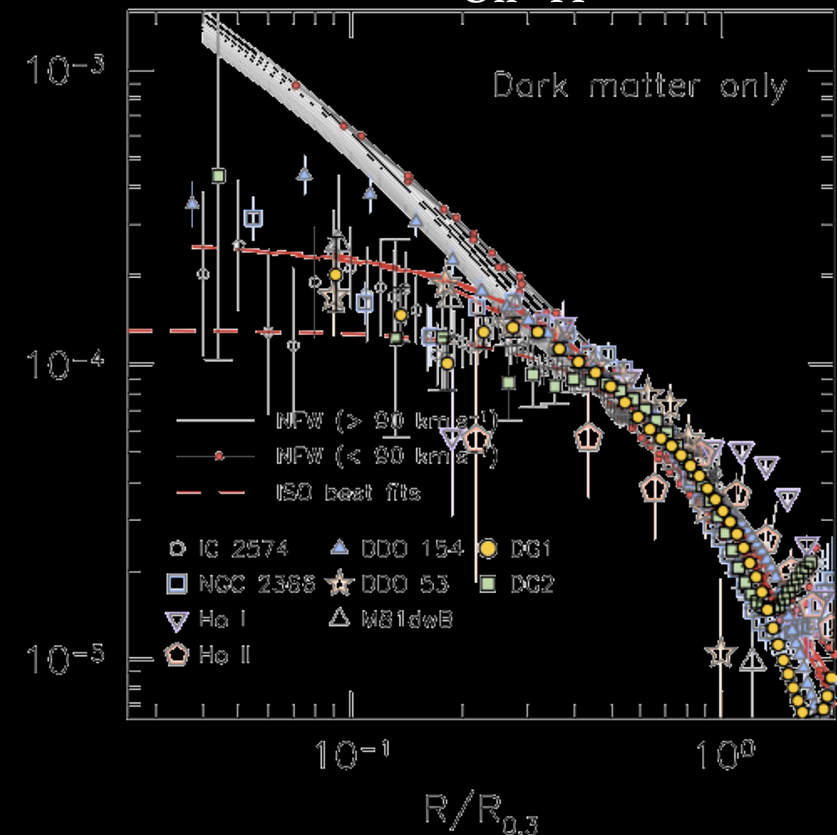
Garrison-Kimmel +14

Problem #3: CUSP-CORE discrepancy

Springel+05



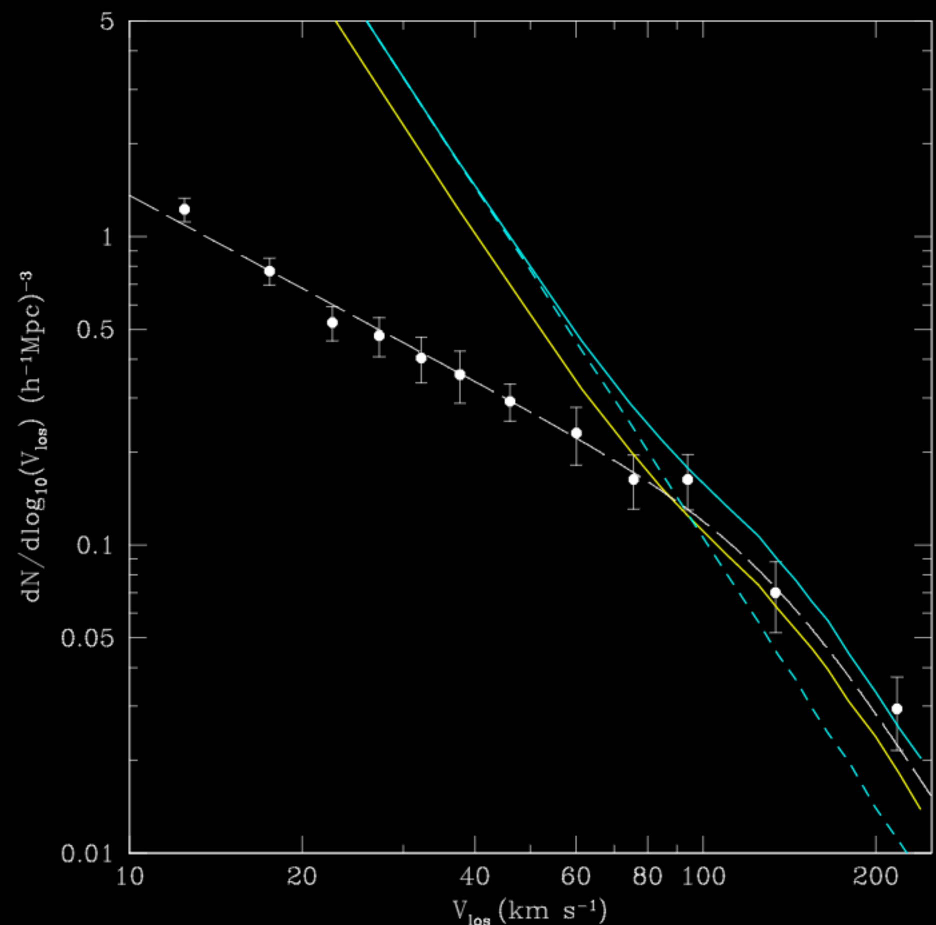
Oh+11



Simulations find 'CUSPY' profiles
Inner slope γ ≥ 1

Observations show 'CORED' profiles
Inner slope γ < 1

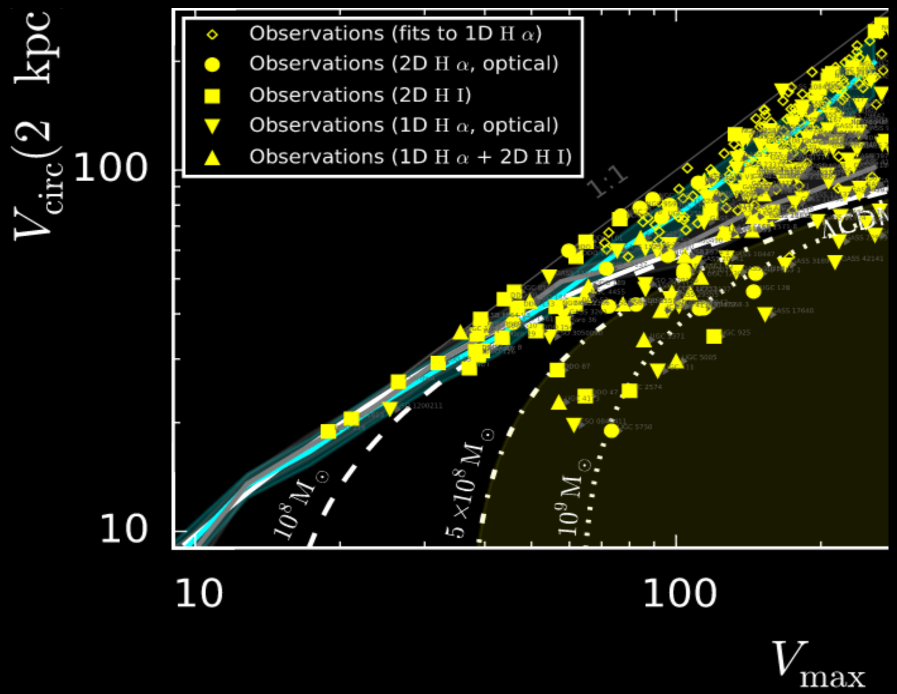
Problem #4 :Velocity function

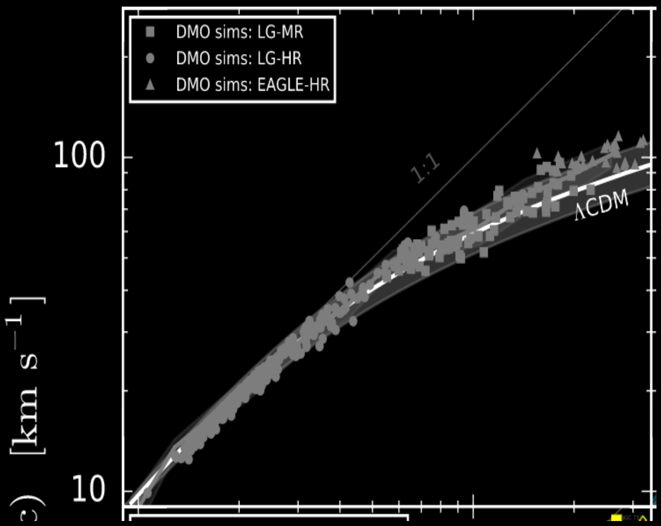


Klypin+14
Papastergis+11
Zavala+09

$$V_{rot} = \sqrt{((W50/2/sin(i))^2 - \sigma_v^2)}$$

Problem #5: Diversity of dwarfs RCs





Oman+05

Solution #1: CDM +baryonic physics

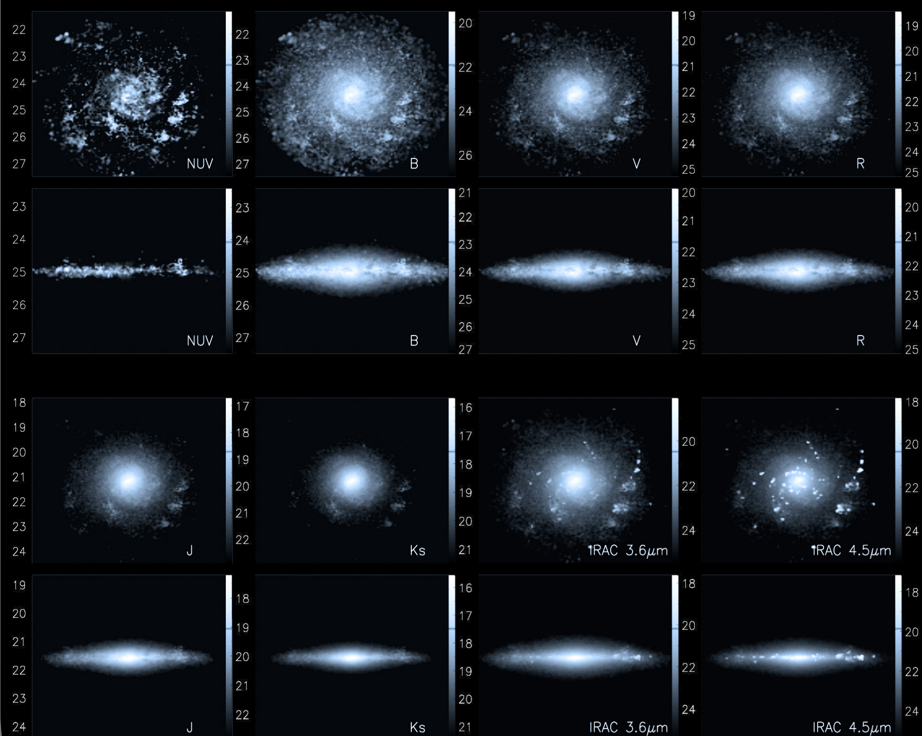
Making Galaxies in a Cosmological Context
MaGICC project

(Brook+12b, Maccio'+12, Penzo+14, Herpich+14, Kannan+14, Obreja+14 etc)
Stinson+13, Brook +12

Hydrodynamical simulations of galaxies including dark matter, gas, stars and..

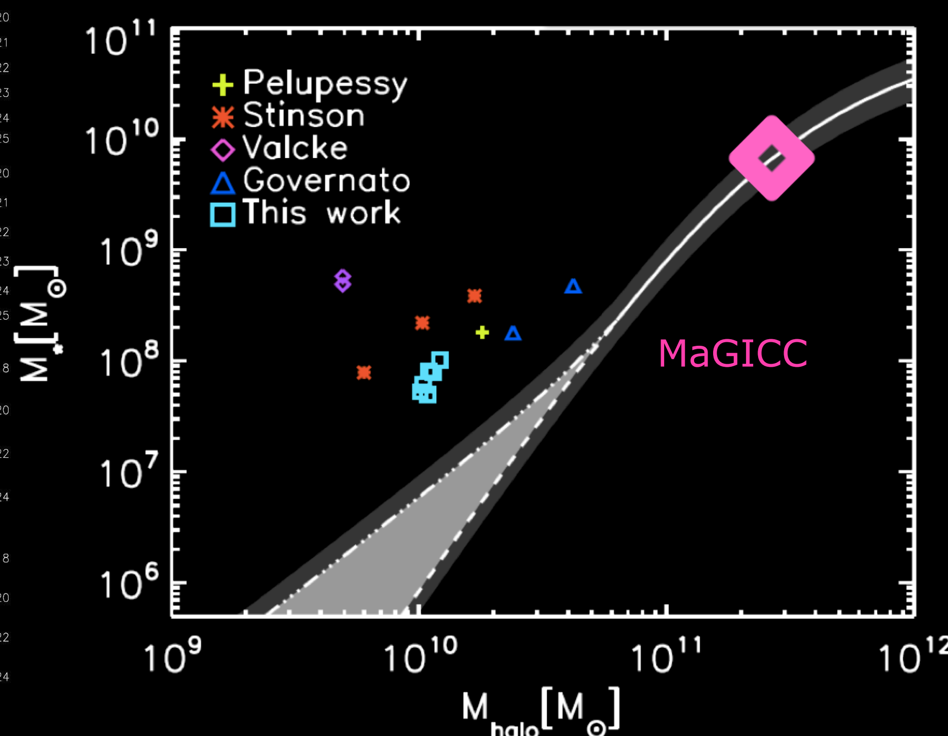
MaGICC Hydro simulations

Making Galaxies In a Cosmological Context
The MaGICC project



Credit: Dominguez-Tenreiro, Obreja+13

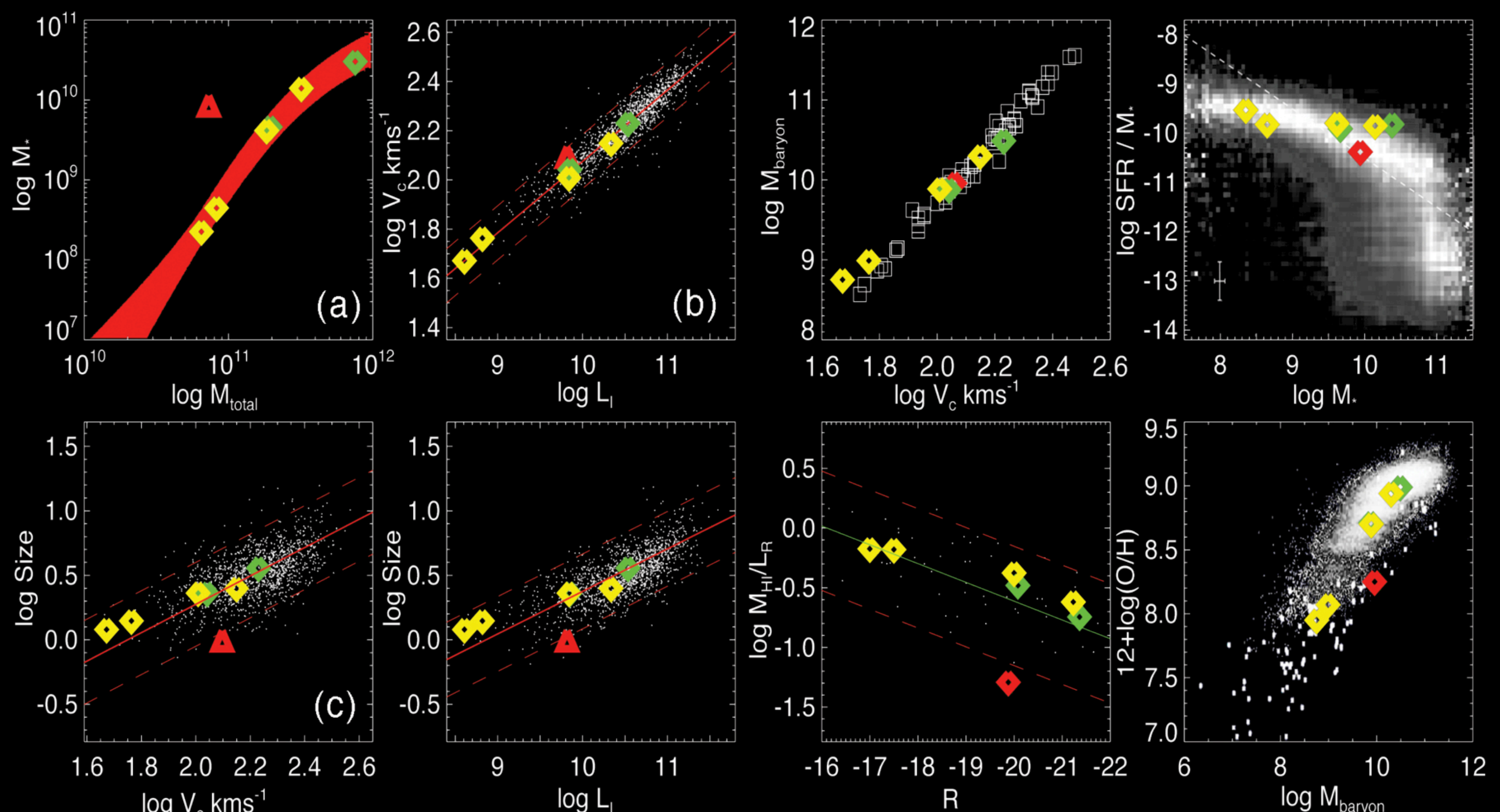
Stinson+13, Brook+12
GASOLINE N-body + SPH code Wadsley 04
SN feedback with blastwave formalism Stinson+06
Early-stellar feedback from massive stars



Credit: Sawala +10

Feedback from Sne and massive stars

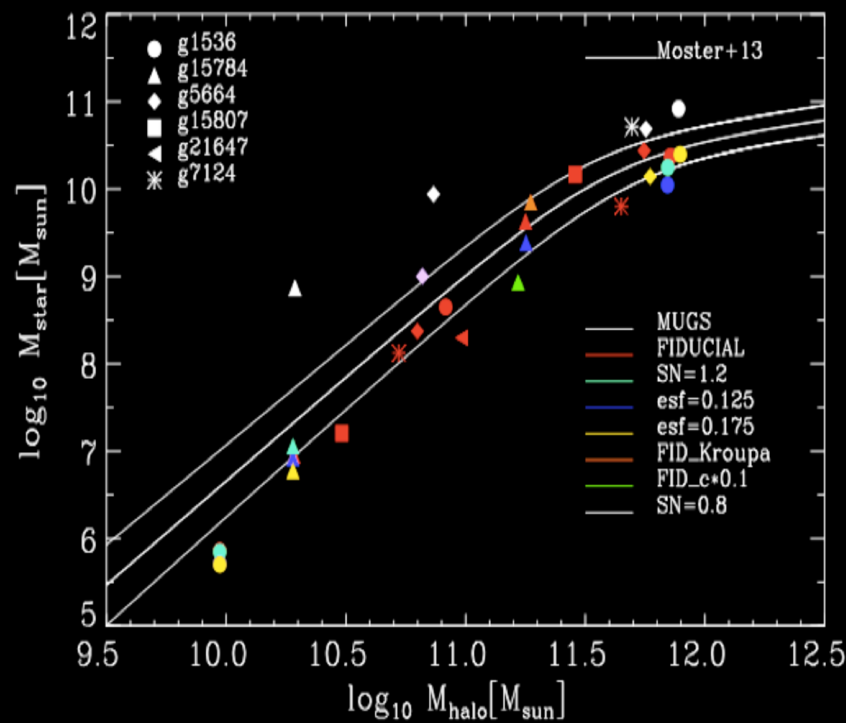
Stinson+06,+13

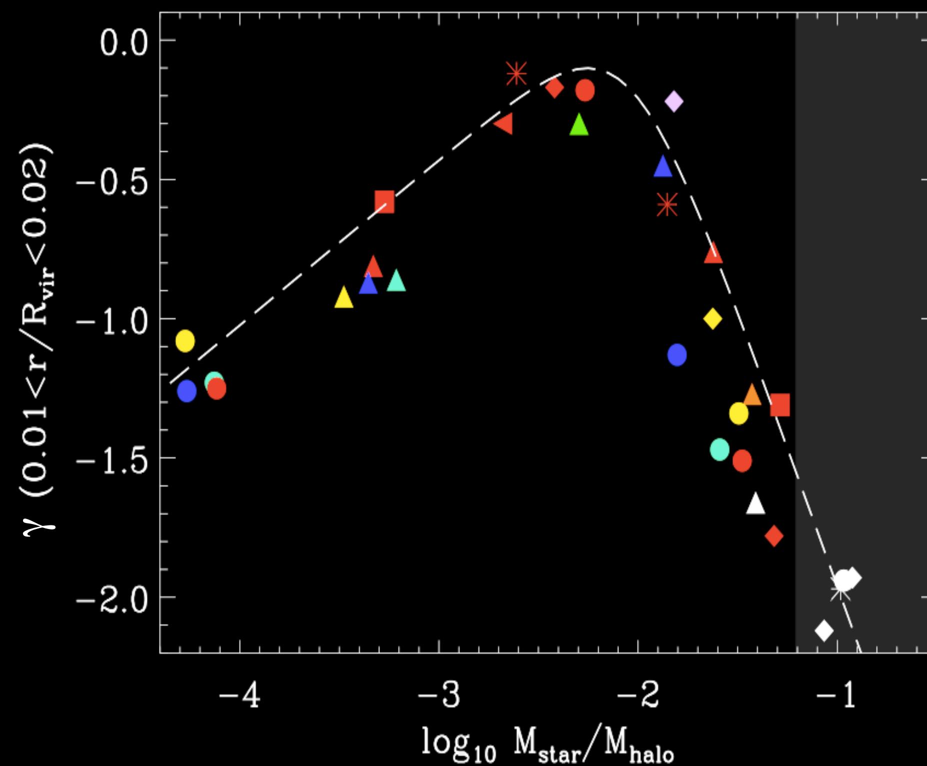


Brook +12

Credit:Greg Stinson

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





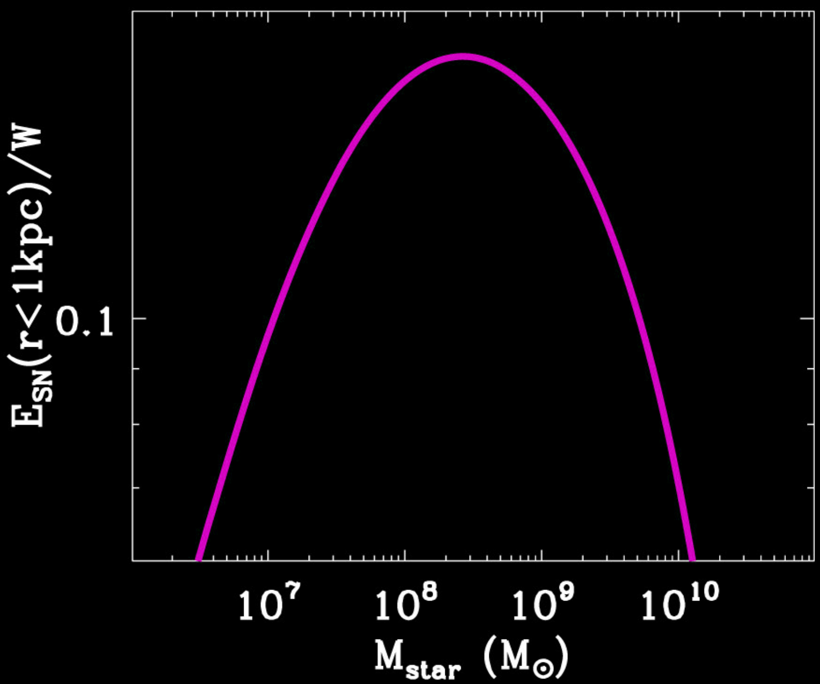
Dark matter profiles determined by two opposite effects: energy from Sne vs Increasing gravitational potential

$$\gamma(X) = n - \log_{10}\left[\left(\frac{X}{x_0}\right)^{-\beta} + \left(\frac{X}{x_0}\right)^{\kappa}\right]$$

Di Cintio+14a

Peak in CORE formation efficiency

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

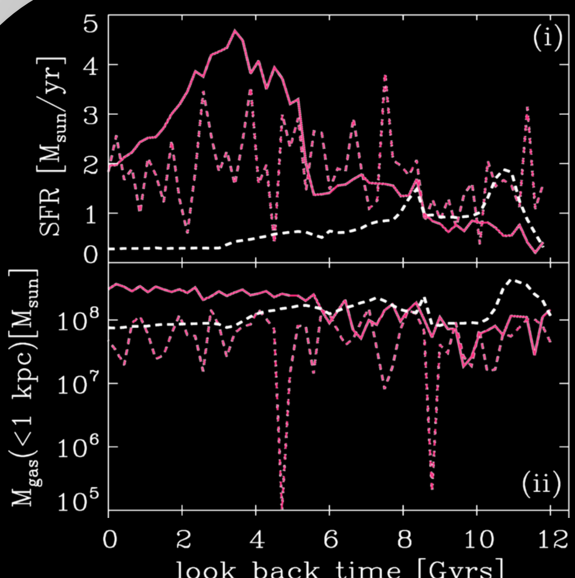


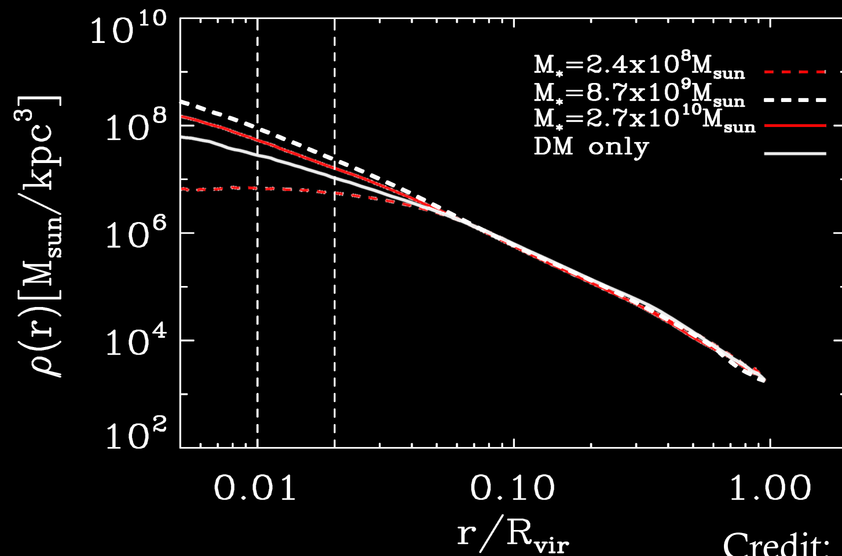
Energy balance between SNe energy and potential energy of NFW halo.
Flattest profiles expected at $M_* \sim 10^{8.5} M_\odot$

Brook & Di Cintio2015a

see also Peñarrubia+12

Core creation mechanism

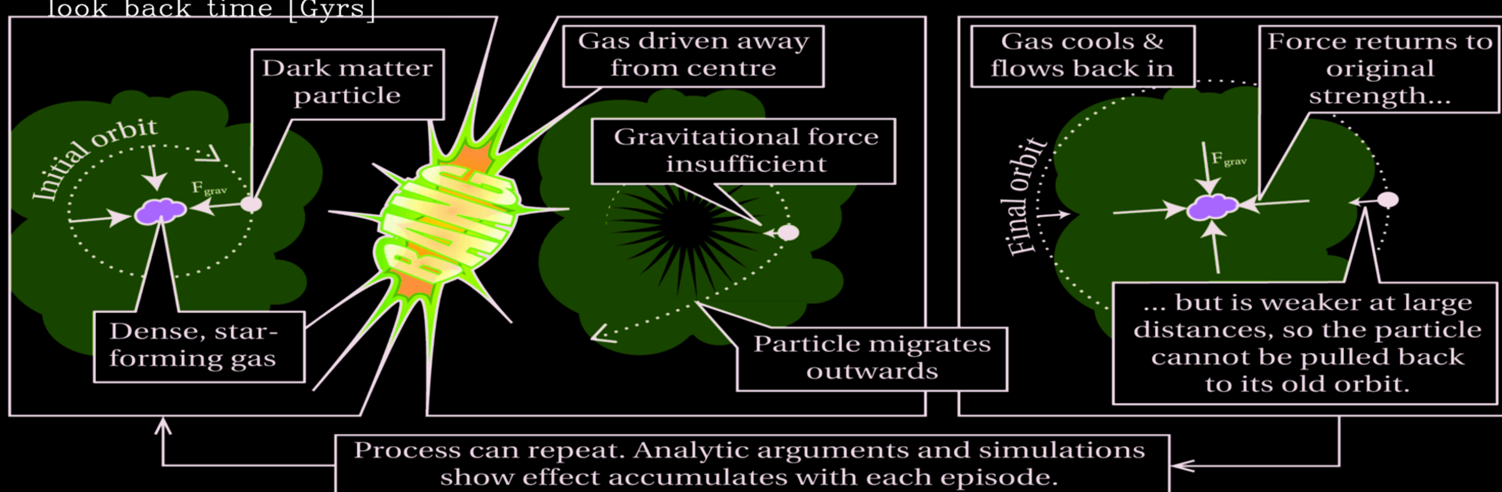




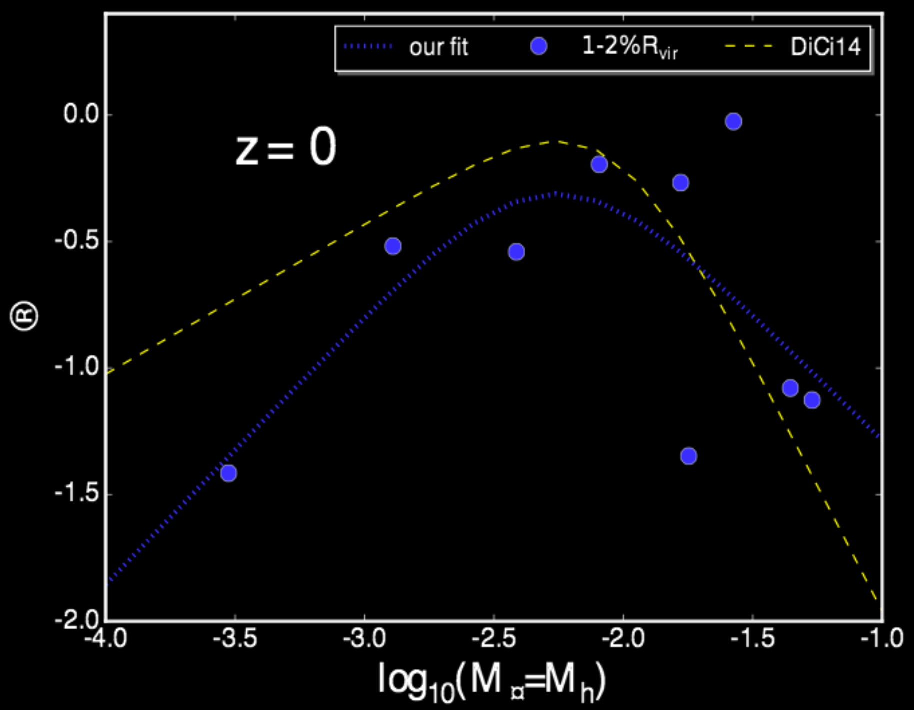
Di Cintio +14a

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

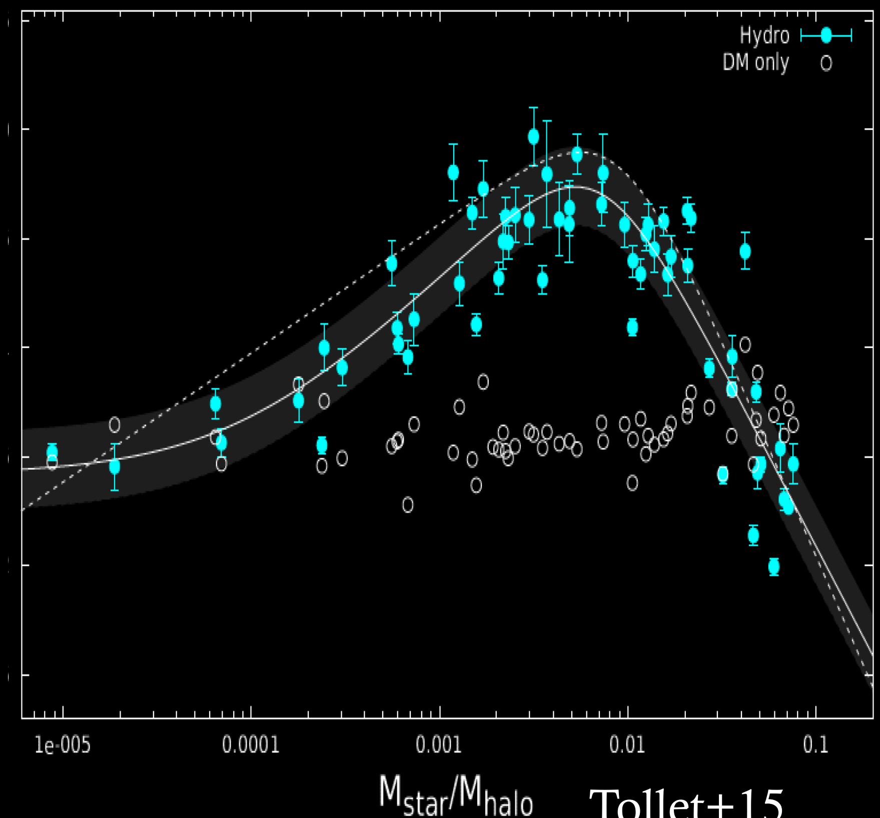
Credit: Pontzen & Governato 14



Result confirmed with other sims/ feedback implementations

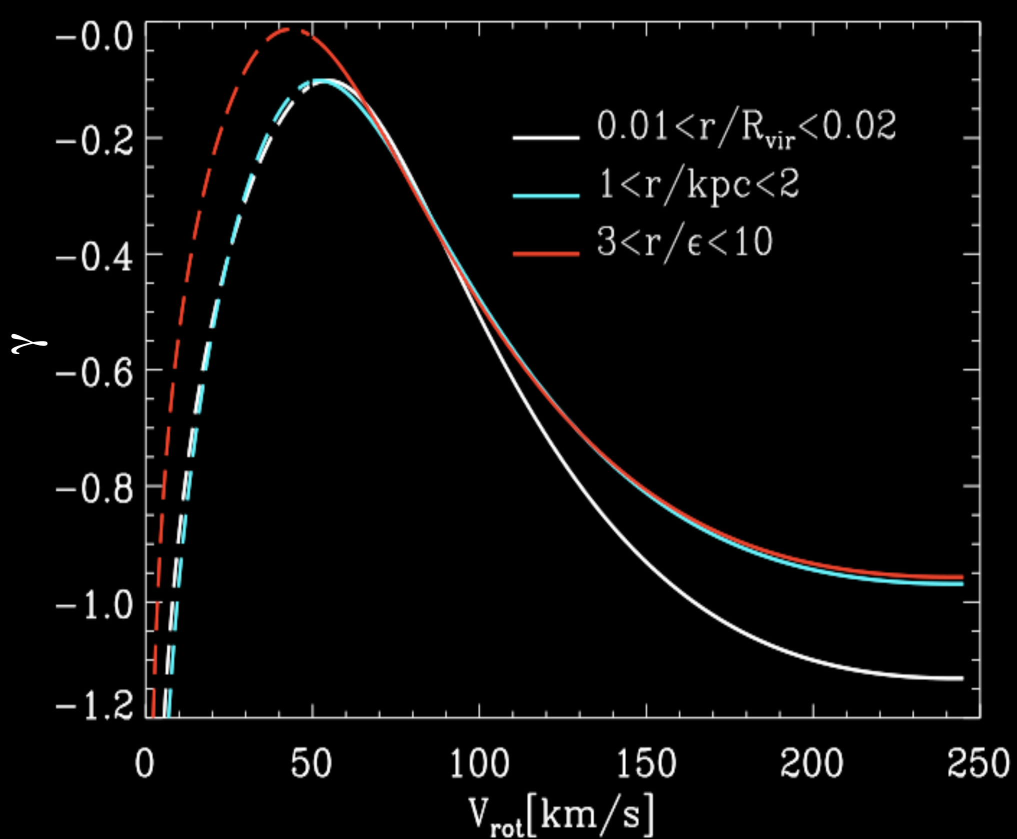


Chan+15



Tollet+15

Predictions for observed galaxies



THINGS galaxy survey $10^7<M^*/M_\odot<10^9$, provides mean γ=-0.3 (Oh+08, Oh+11)
Flattest profiles in galaxies with V_{rot}~50km/s
Clear observations of cores in LSB galaxies with **V_{rot}< 100km/s** (de Blok+08, Kuzio de Naray +08,+09)

Di Cintio+14a

TF from Dutton+10

A double power law profile

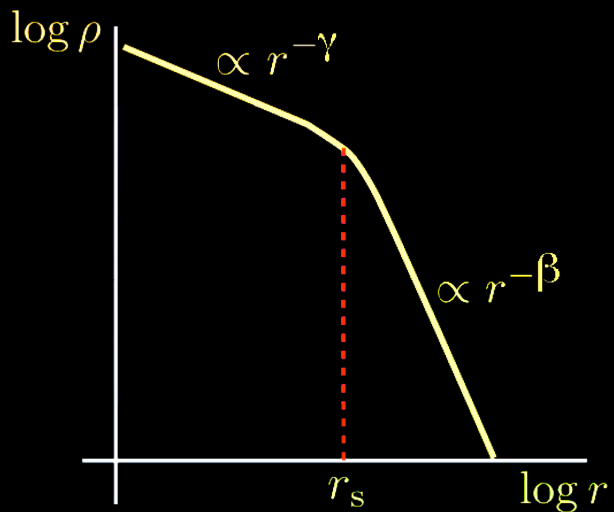
$$\rho(r) = \frac{\rho_s}{\left(\frac{r}{r_s}\right)^{\gamma}\left[1+\left(\frac{r}{r_s}\right)^{\alpha}\right]^{(\beta-\gamma)/\alpha}}$$

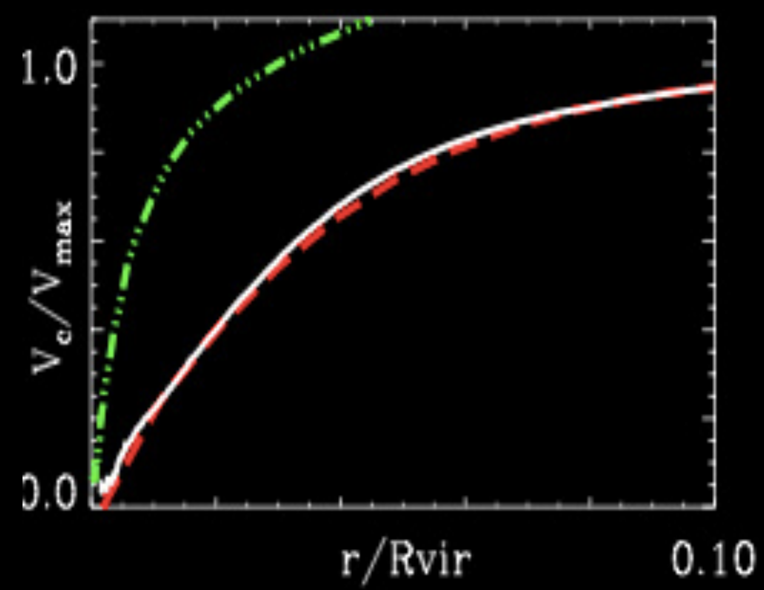
γ inner slope

β outer slope

α sharpness of transition

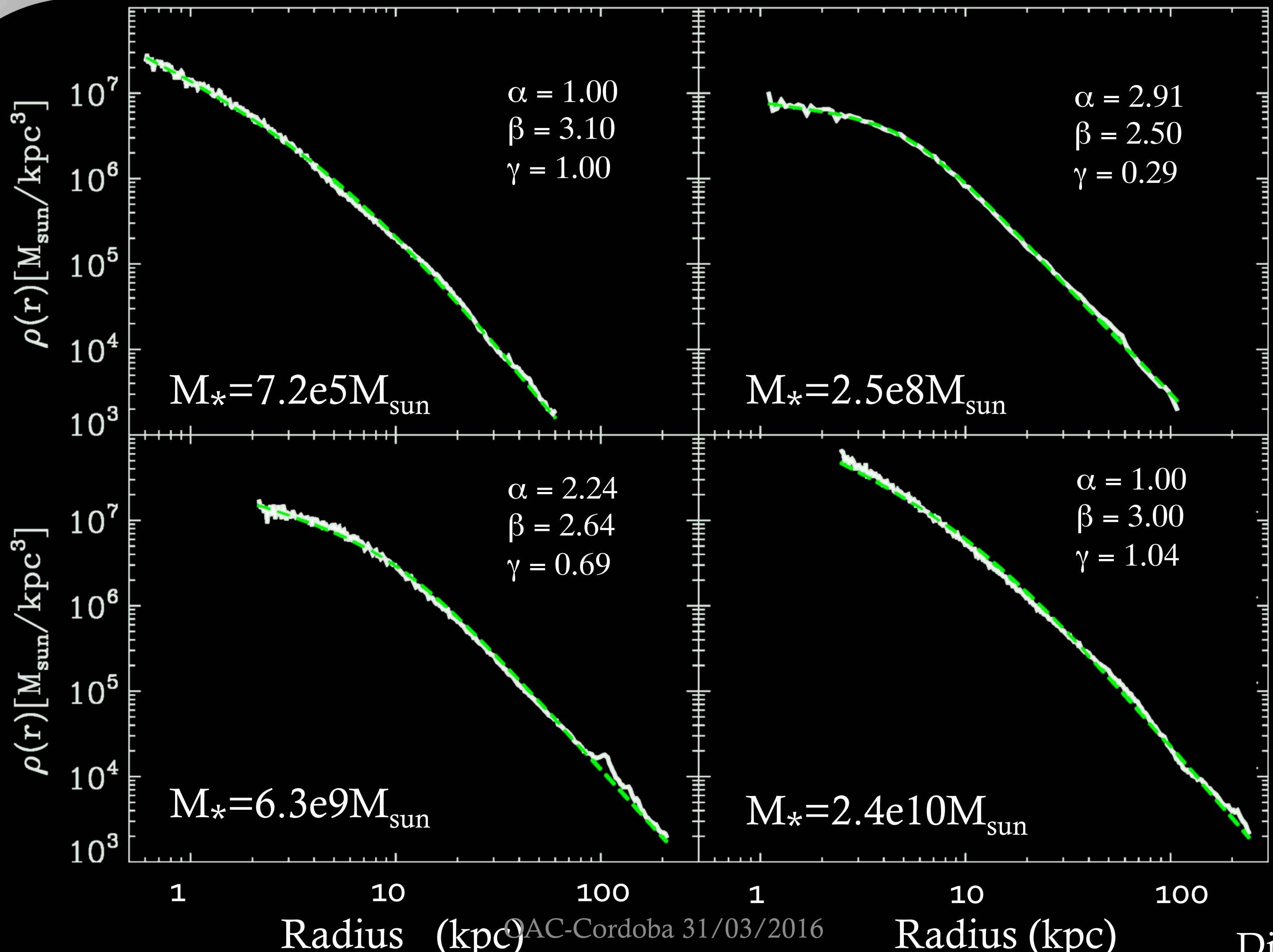
Constrained via M^*/M_{halo}





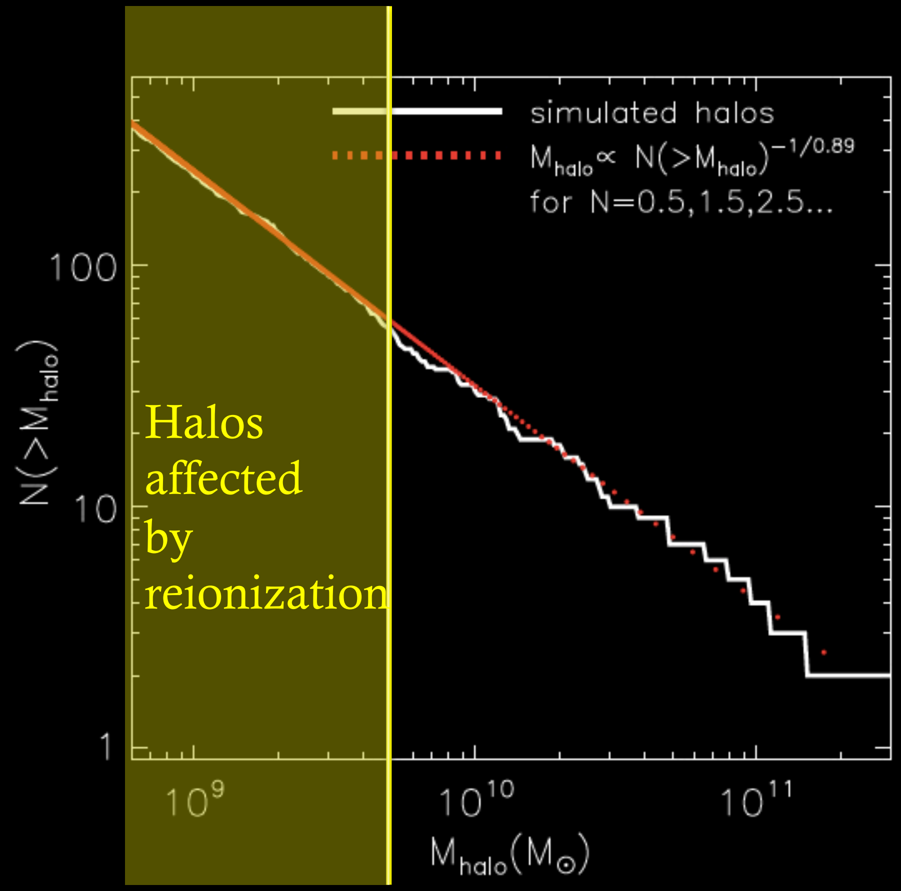
Cores→ slowly rising RCs

Mass dependent DM profile



Di Cintio+14b

Mass function of the Local Group



LG simulations

CLUES-Gottloeber +10

ELVIS-Garrison-Kimmel +14

LG analogue-Sawala+14

$N(>M_{halo})$ is a well defined power law

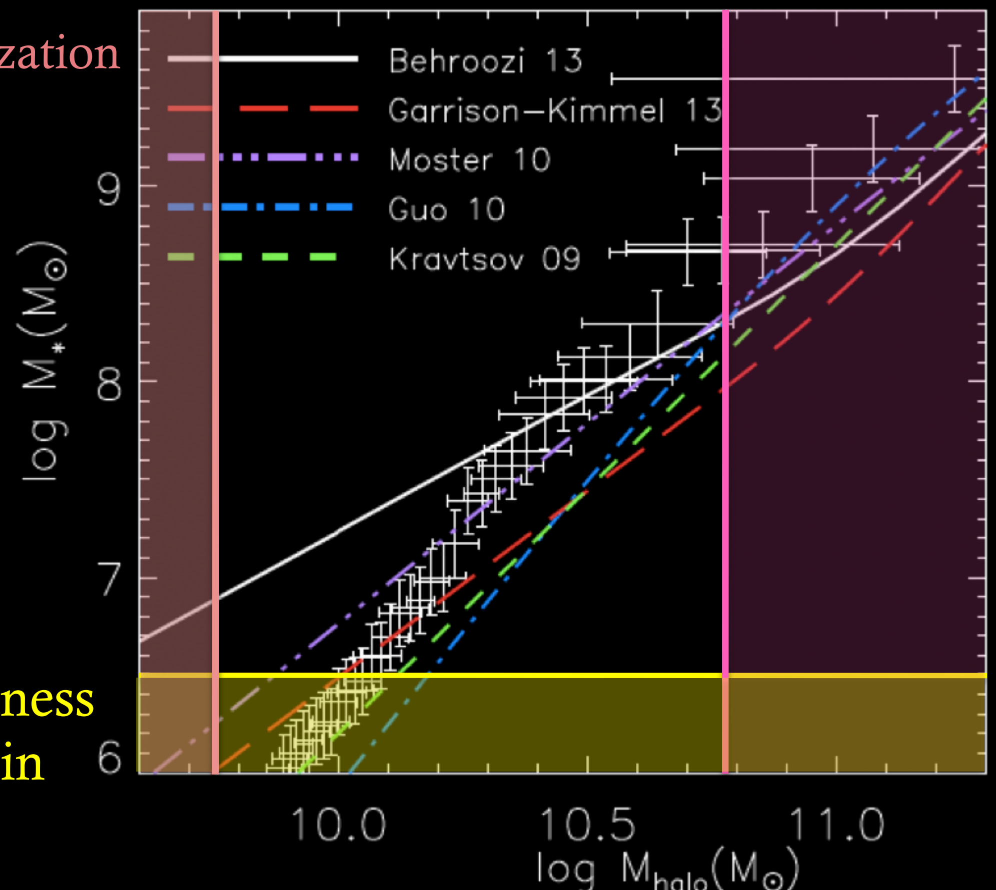
There are 40-50 halos bigger than 7*10^9 M_{sun} a region where ALL halos have been shown to form stars in simulations

Brook, Di Cintio +14

Abundance matching in the LG

Reionization regime

Local Group Galaxies



SDSS limit

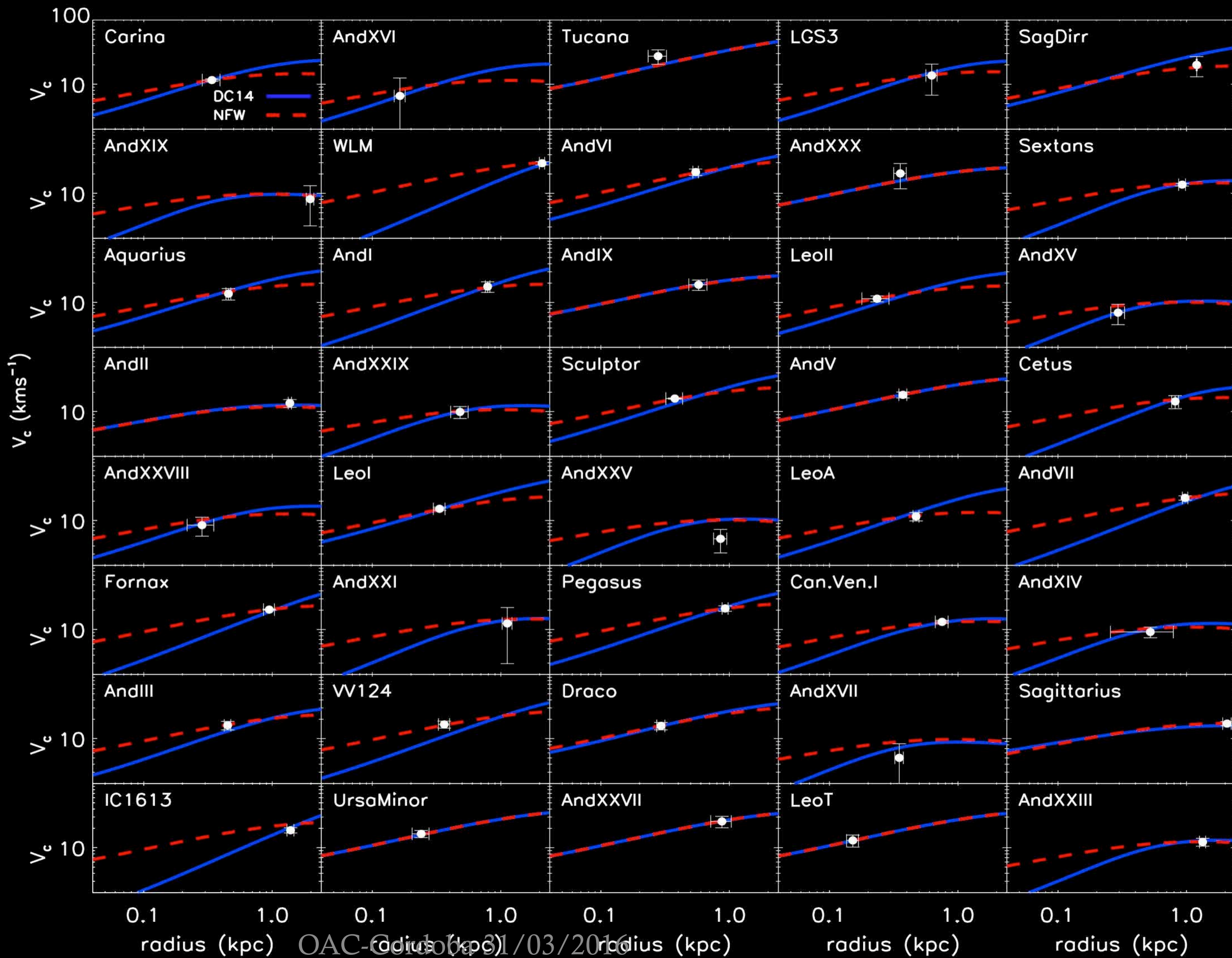
Completeness limit within 1.8 Mpc

Brook, Di Cintio +14

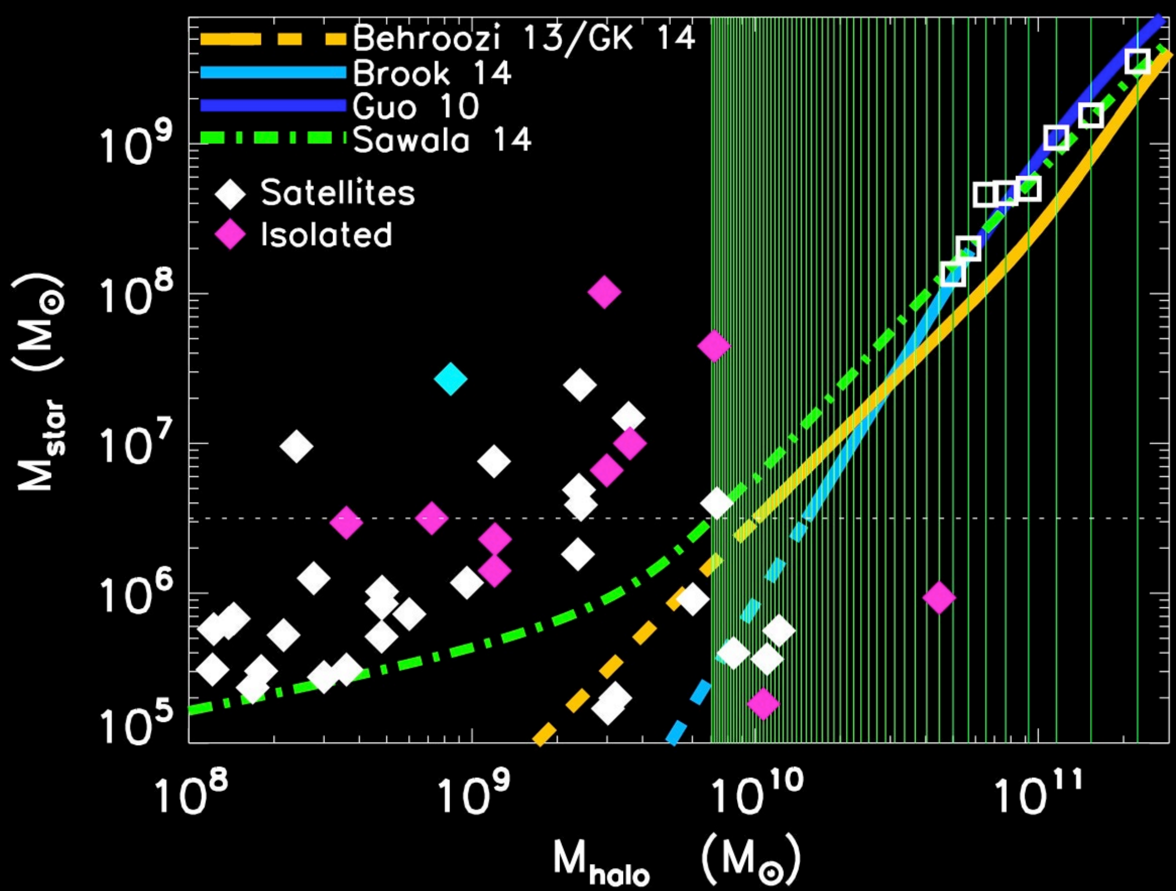
$M_\star/M_{halo}$ in the LG

Kirby+14
Tollerud+14
Wolf+10

Brook &
Di Cintio 2015a



$M_\star/M_{halo}$ in the LG with NFW



Too big to fail haloes

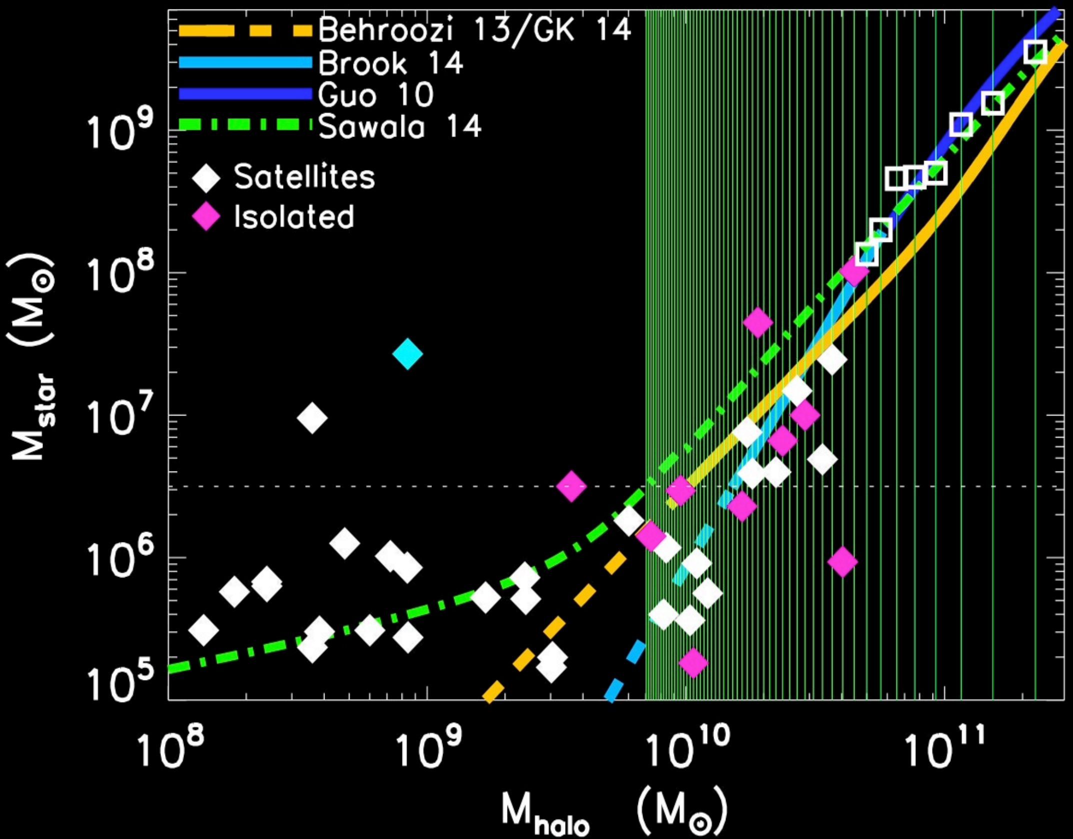
see also
TBTF in the
Local Group

Garrison-Kimmel
+14
Kirby+14
Tollerud+14

Brook & Di Cintio 2015a

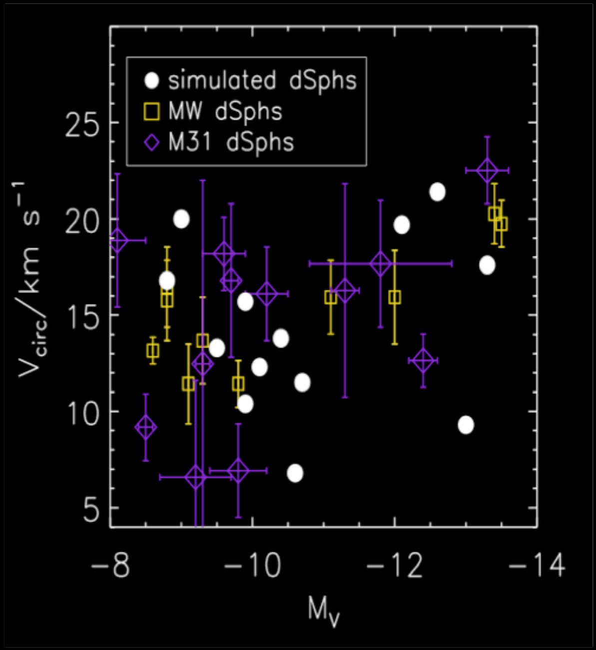
$M_\star/M_{halo}$ in the LG with DC14 profile

Too big to fail haloes



Brook & Di Cintio 2015a

Brooks & Zolotov2014



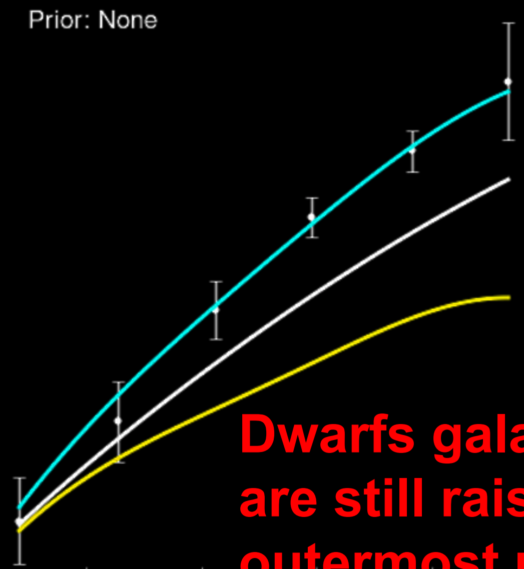
Galaxy velocity function

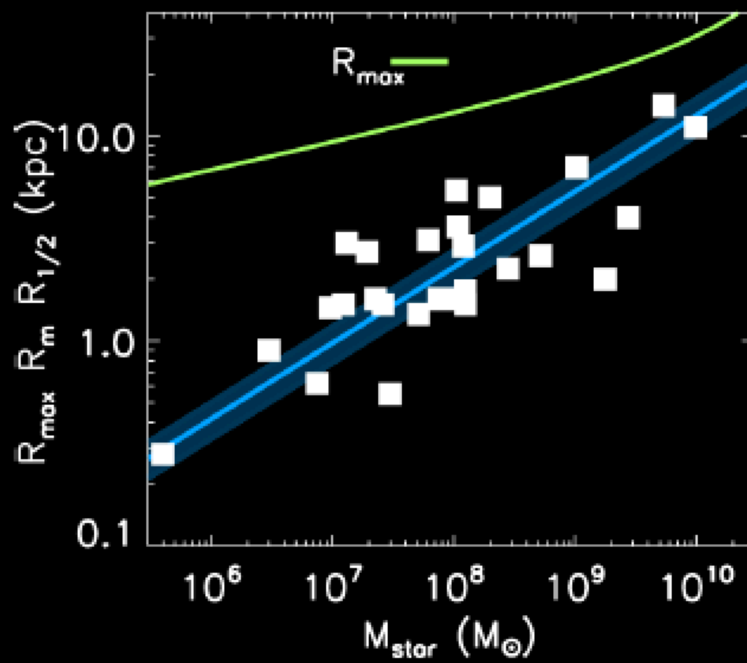
Zavala+09
Papastergis+11
TG+11
Klypin+14

Brook & Di Cintio 2015b

Measurement radius counts!

See also Brook & Shankar 2015
Sales+2016





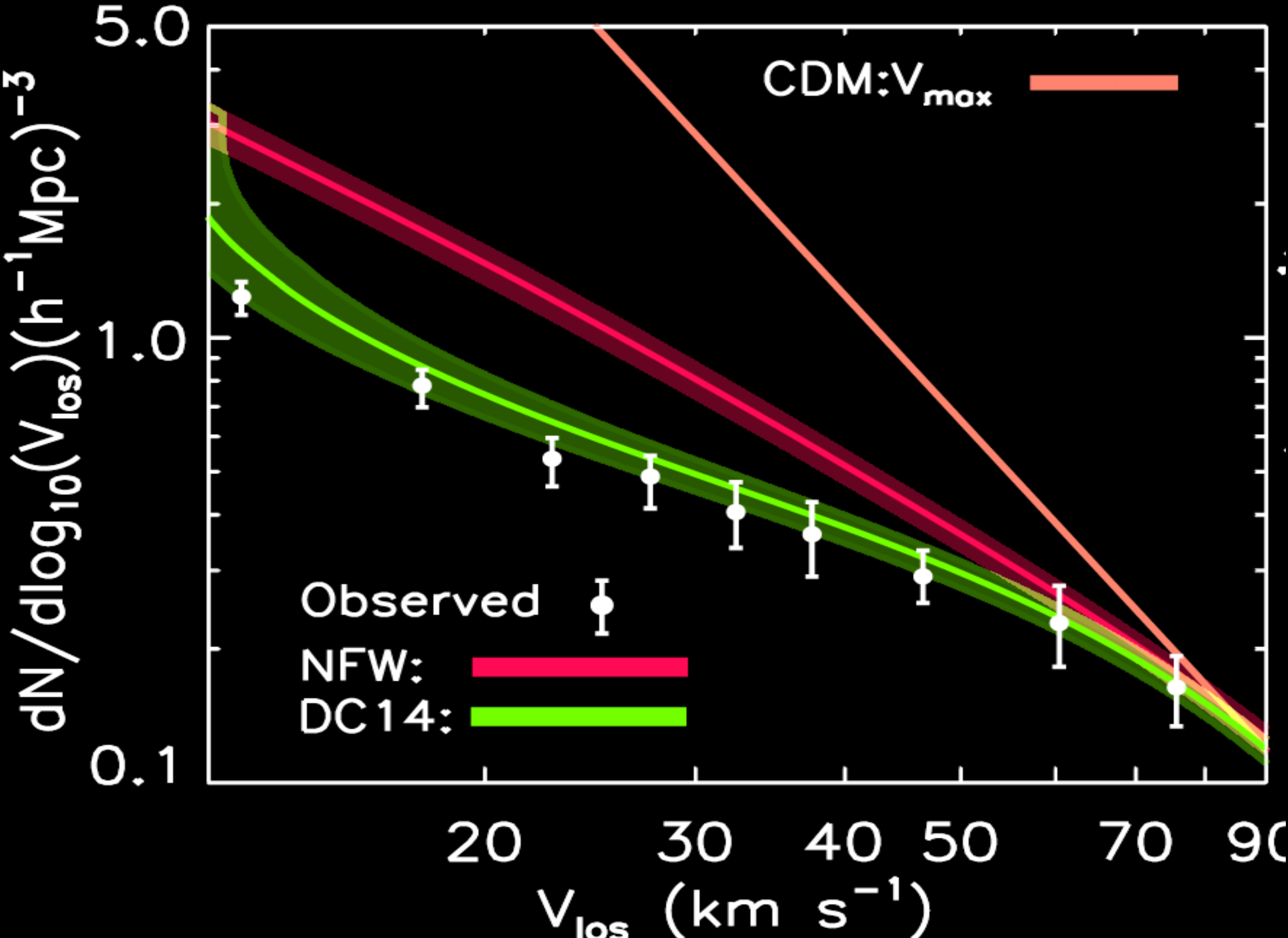
Dwarfs galaxies RCs are still raising at the outermost measured radius→ can NOT ASSUME they are tracking Vmax

W50 → Vrot
RCs → Vrot (r)
→W50 (r)

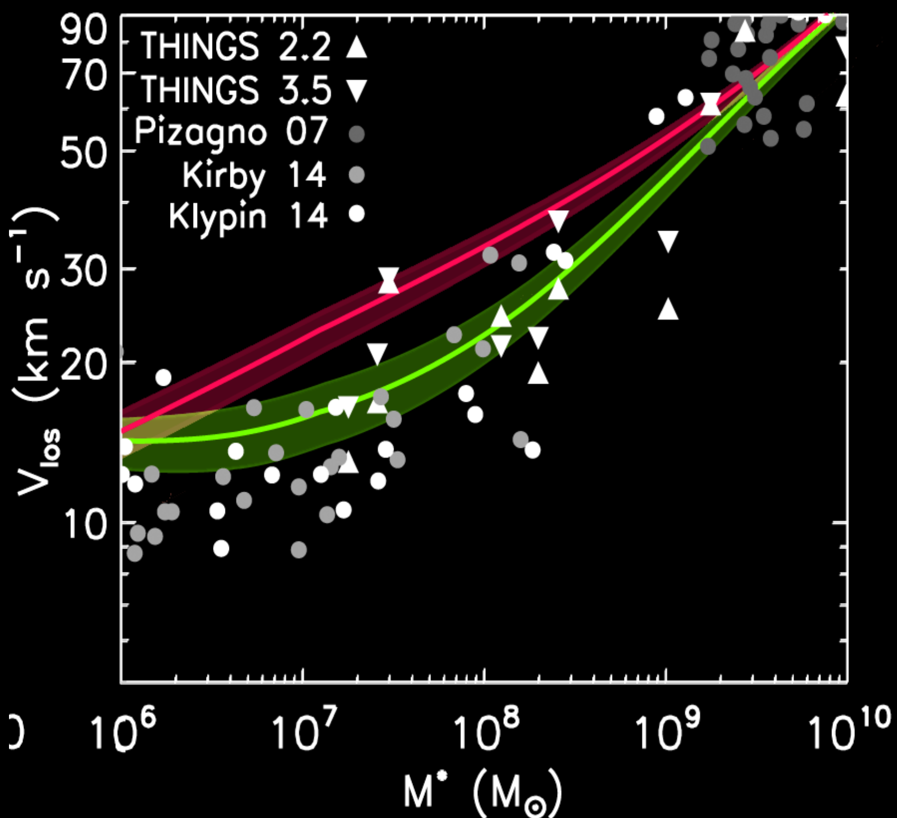
Galaxy velocity function

See also Papastergis +2015

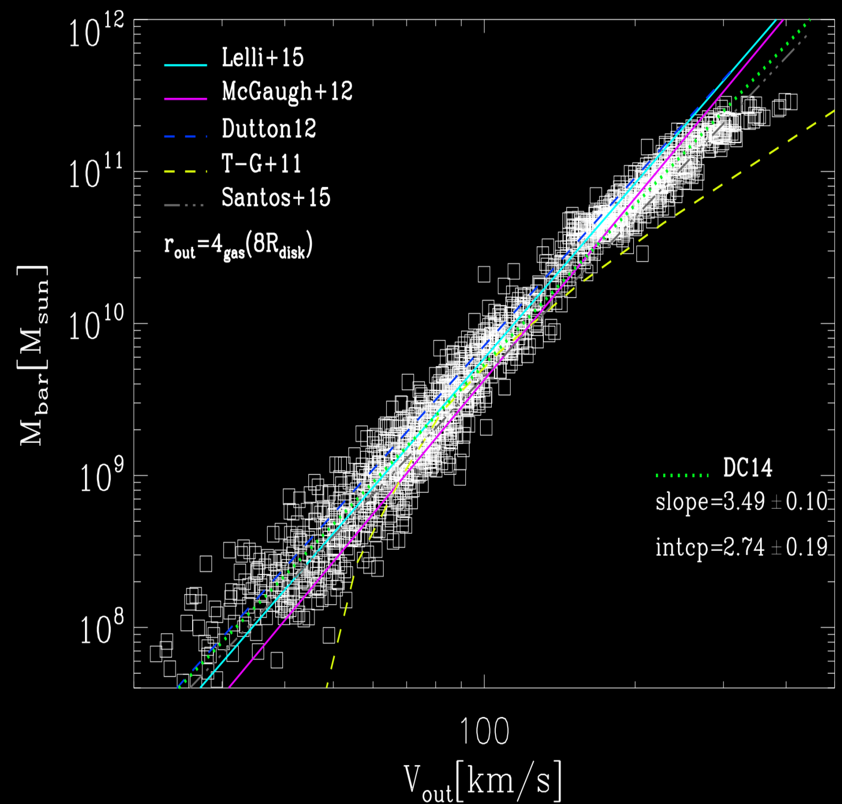
Brook & Di Cintio 2015b



TF and BTF relation



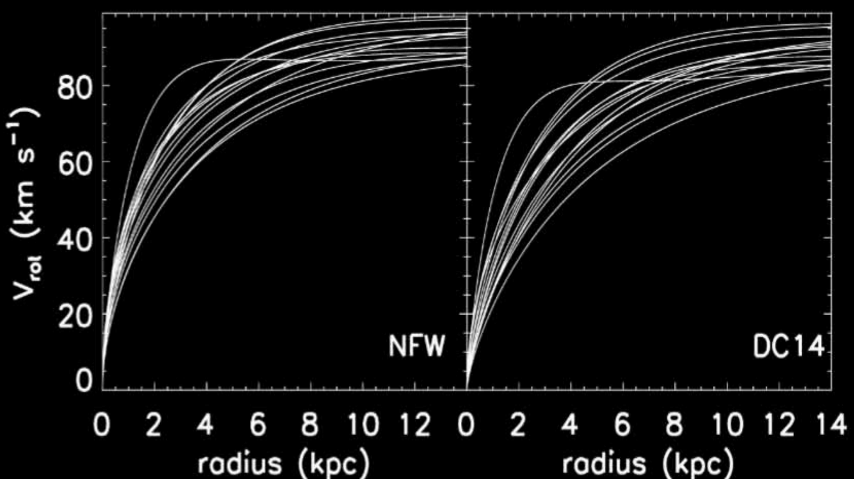
Brook & Di Cintio 2015b

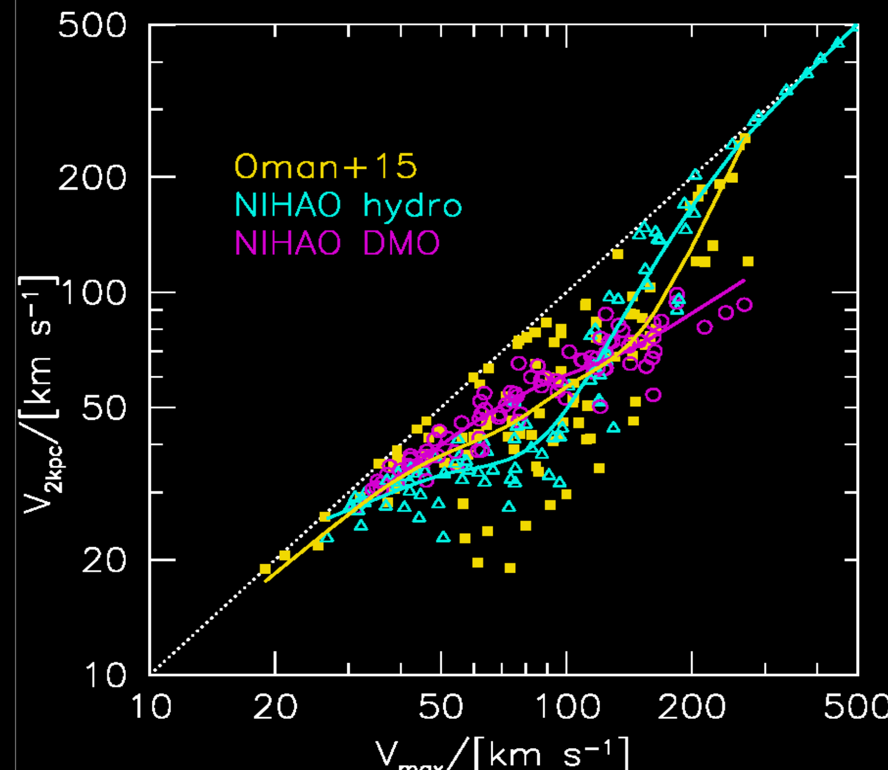


Di Cintio & Lelli 2016

Diversity of RCs explained by core formation

Dwarf galaxies RCs diversity: is it really a problem for LCDM? (Oman+2015)



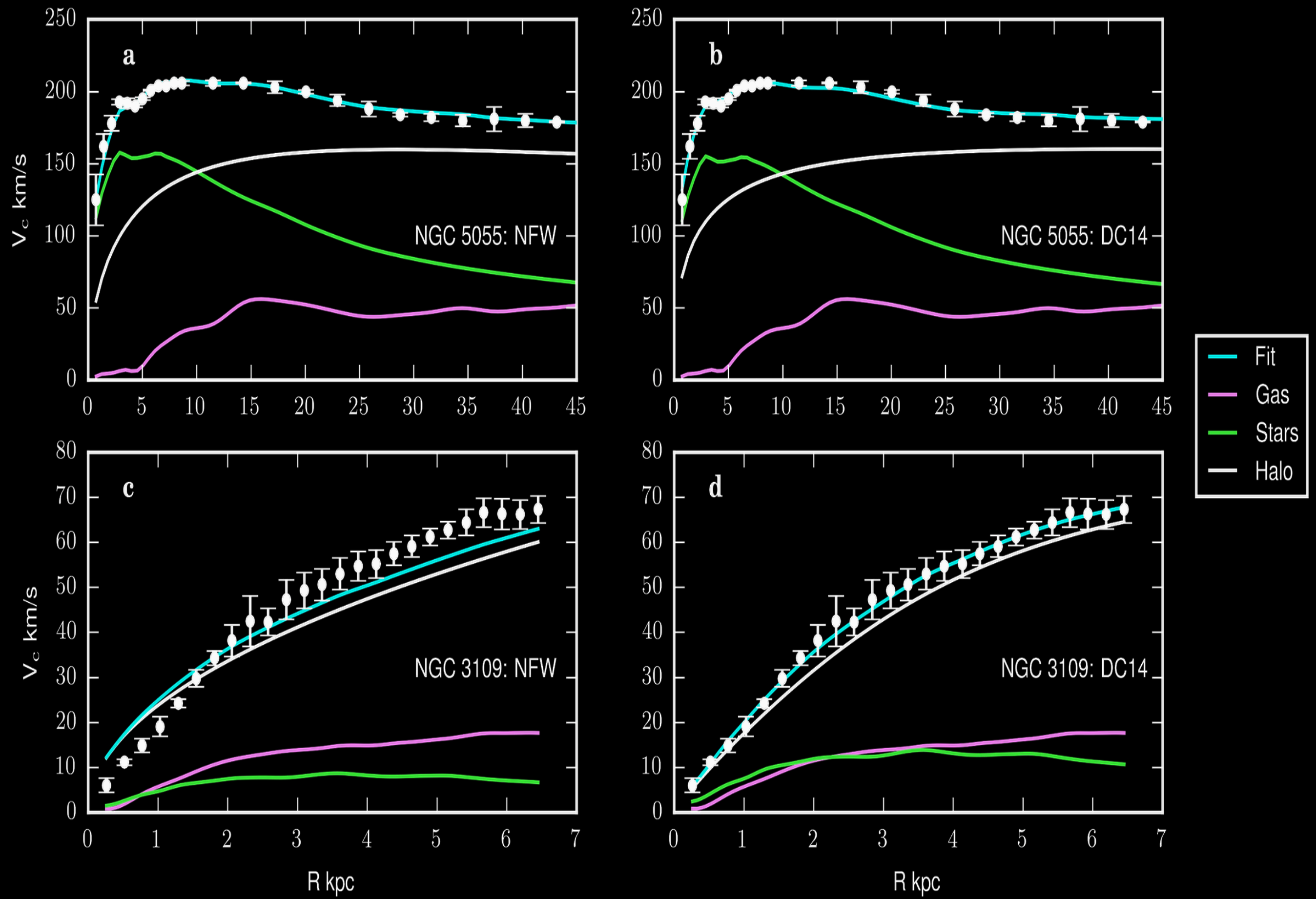


see also Brook 2015,
Read+2016

NIHAO collaboration in prep

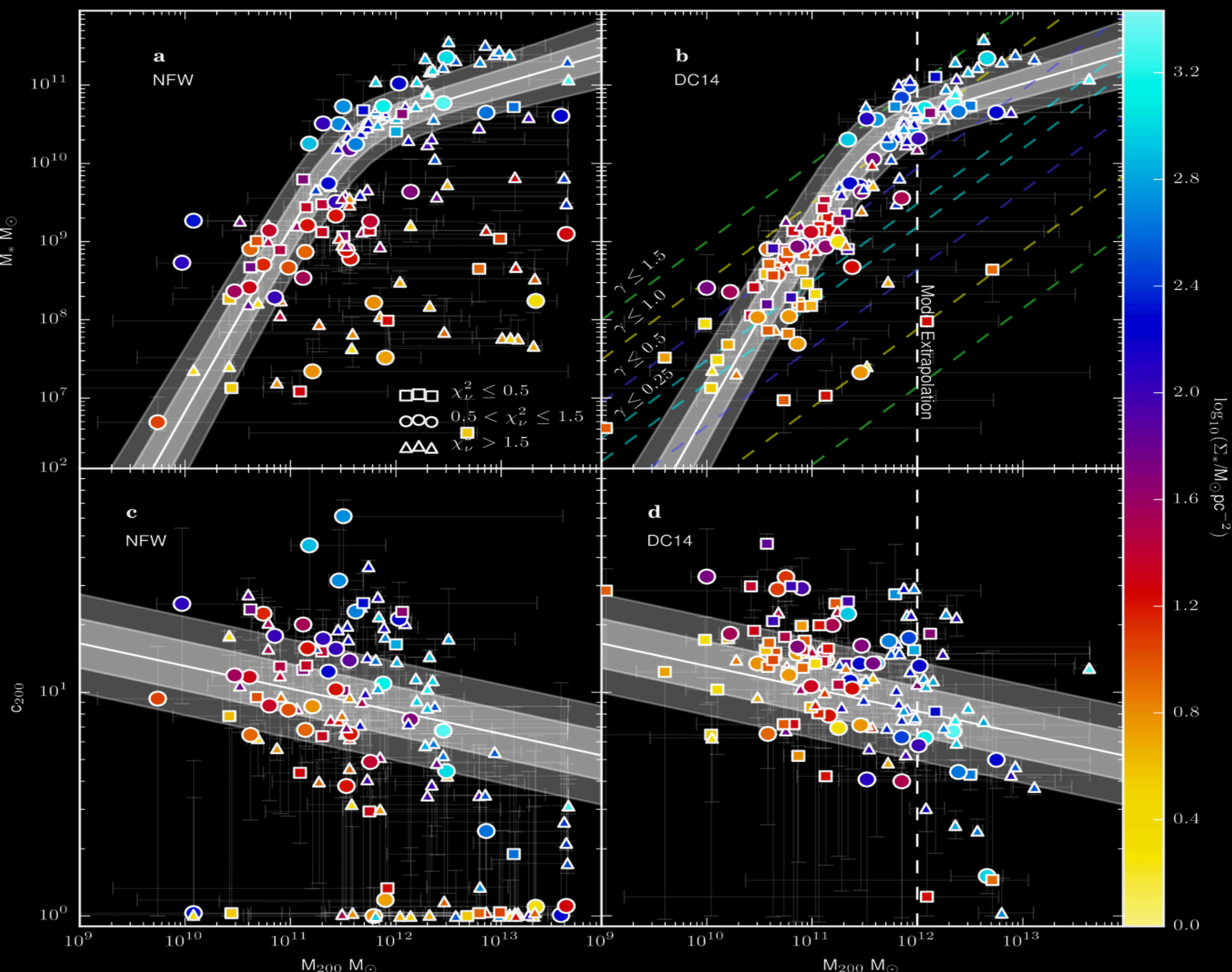
Fit full RCs with NFW and DC14 profile

Katz, Lelli, Mc Gaugh, Di Cintio, Brook, Schombert 2015, submitted



Self consistent results M*-M_{halo}, c-M, RCs for the DC14 profile

Katz, Lelli, Mc Gaugh, Di Cintio, Brook, Schombert 2015, submitted



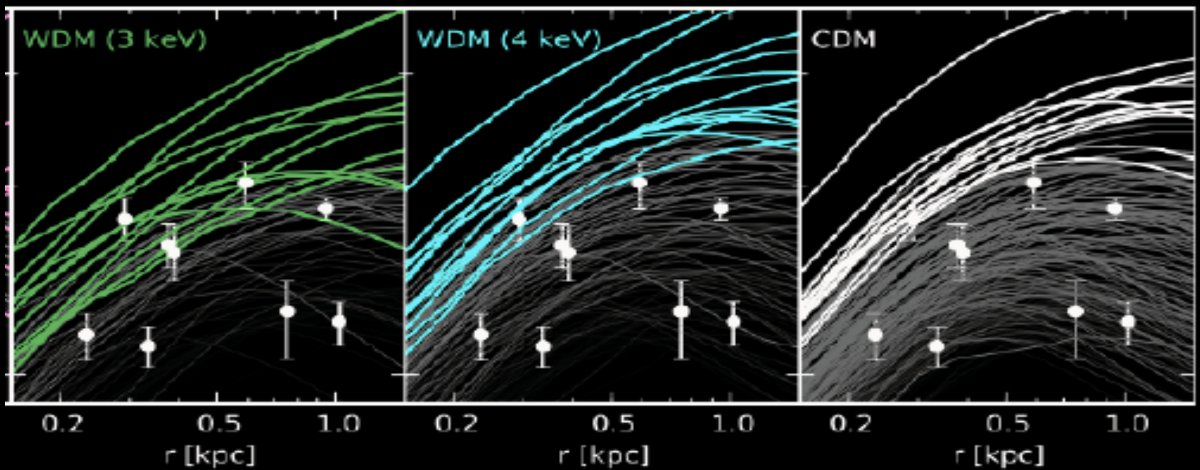
To self-consistently explain TBTF, RCs shape, M*-Mhalo, RCs diversity, Velocity Function etc…

ONE NEEDS CORES IN LCDM with a particular mass dependence

Solution #2:Alternative DM models

TBTF in Warm Dark Matter

Schneider +15



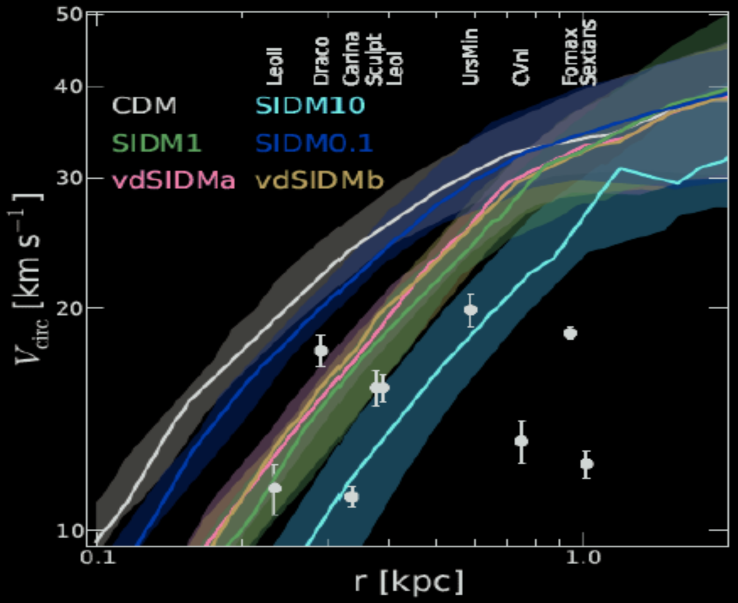
To solve the TBTF problem with WDM we need to create cores of ~Kpc size, which requires a thermal candidate with a mass below 0.1 keV, ruled out by all large scale structure constraints (see Schneider +15, Maccio'+15)

Solution #2: Alternative DM models

TBTF in Self Interacting Dark Matter

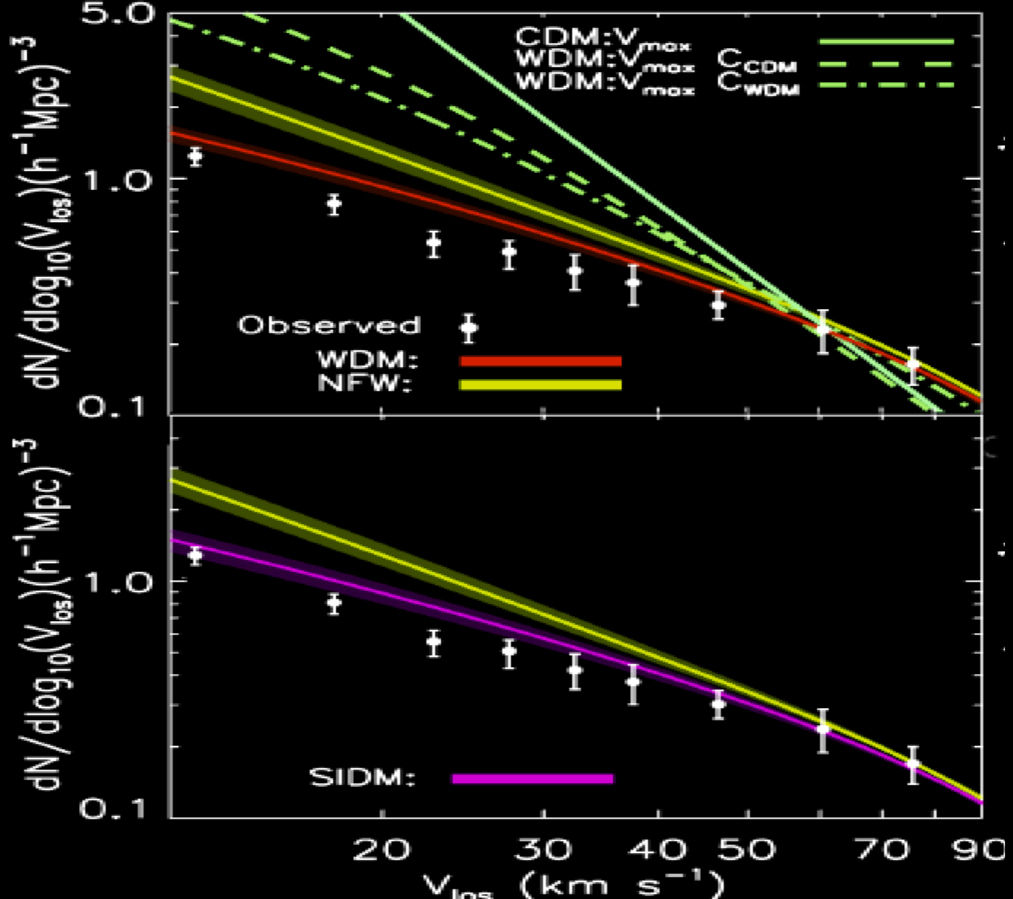
Self-interactions lower the central density alleviating TBTF problem
Vogelsberger+12, Zavala+13, Rocha+12

Zavala+13



Solution #2: Alternative DM models

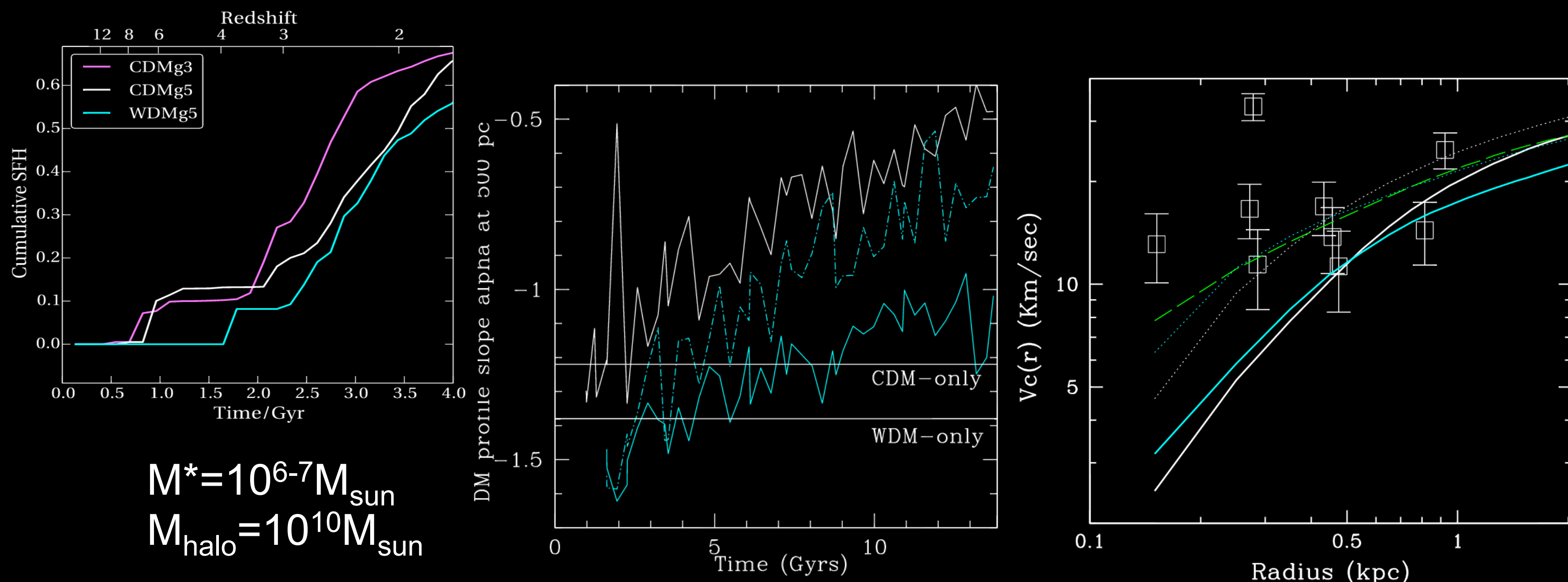
Velocity Functions and TF relation in 2 keV WDM and vdSIDM model



Brook & Di Cintio 15

Solution #3: WDM+baryons

SF in WDM-2 keV- model is reduced and delayed by 1–2 Gyr due to delay in halo assembly. Central DM density more affected by baryonic physics than WDM physics→ Same Vcirc distribution in CDM and WDM that solves TBTF

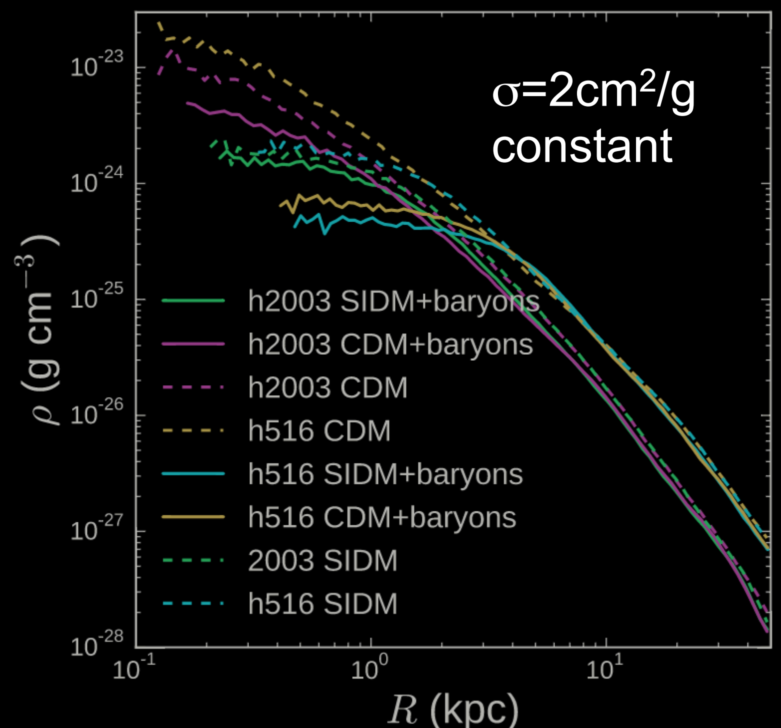


$M^*=10^{6\text{-}7}M_{sun}$
$M_{halo}=10^{10}M_{sun}$

Governato +15

Solution #3: SIDM+baryons

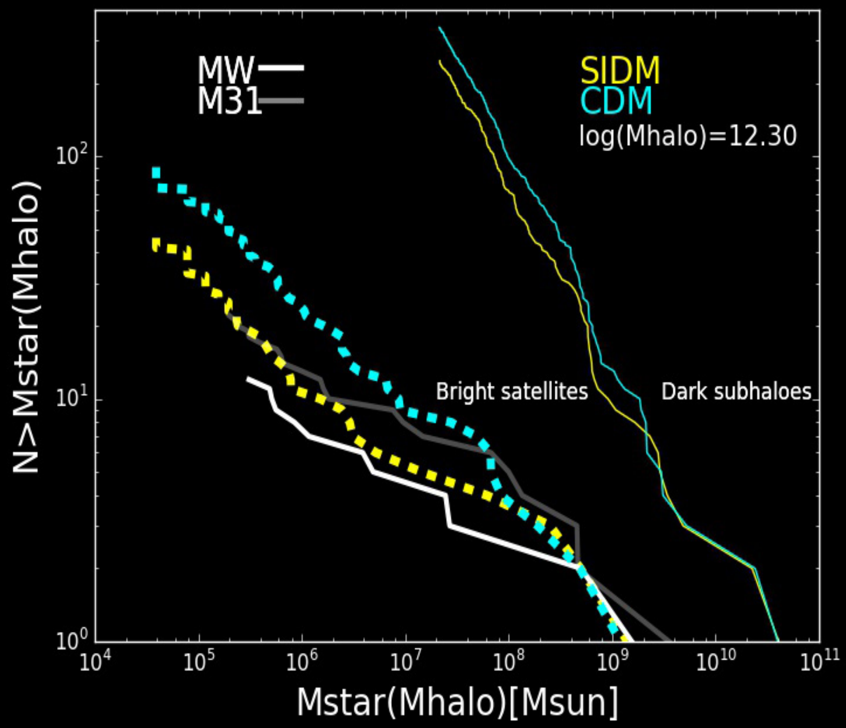
SF and resulting feedback dominates over SI: dm inner slope, SFH, star and gas content are indistinguishable between CDM and SIDM+baryons



Bastidas-Fry, Governato +15

Current and future work

SIDM+baryons with constant σ=10 cm^2/g vs CDM+ baryons
BH physics and SNae feedback included, focus on massive galaxies

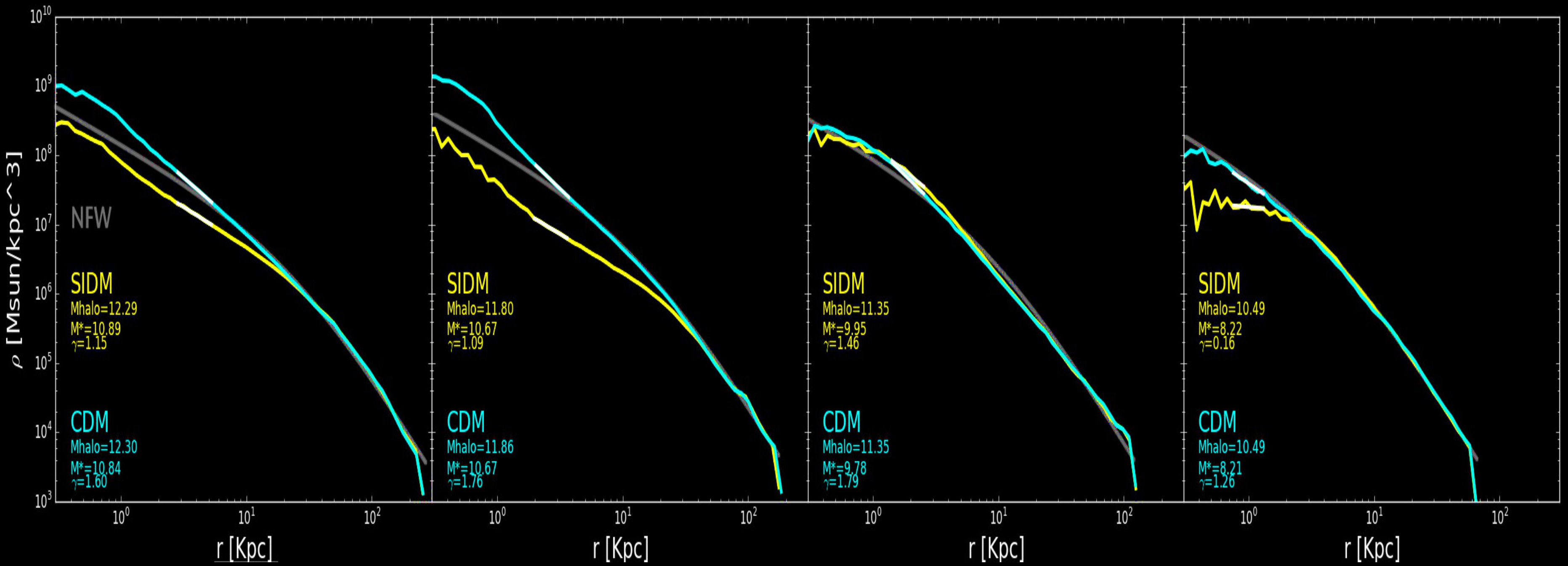


Effect of subhalo evaporation in SDIM is not strong, relaxing the constraint on constant σ (see also Rocha+12)→
Sat luminosity function well within observational constraints

Di Cintio, Tremmel, Governato + in prep.

Current and future work

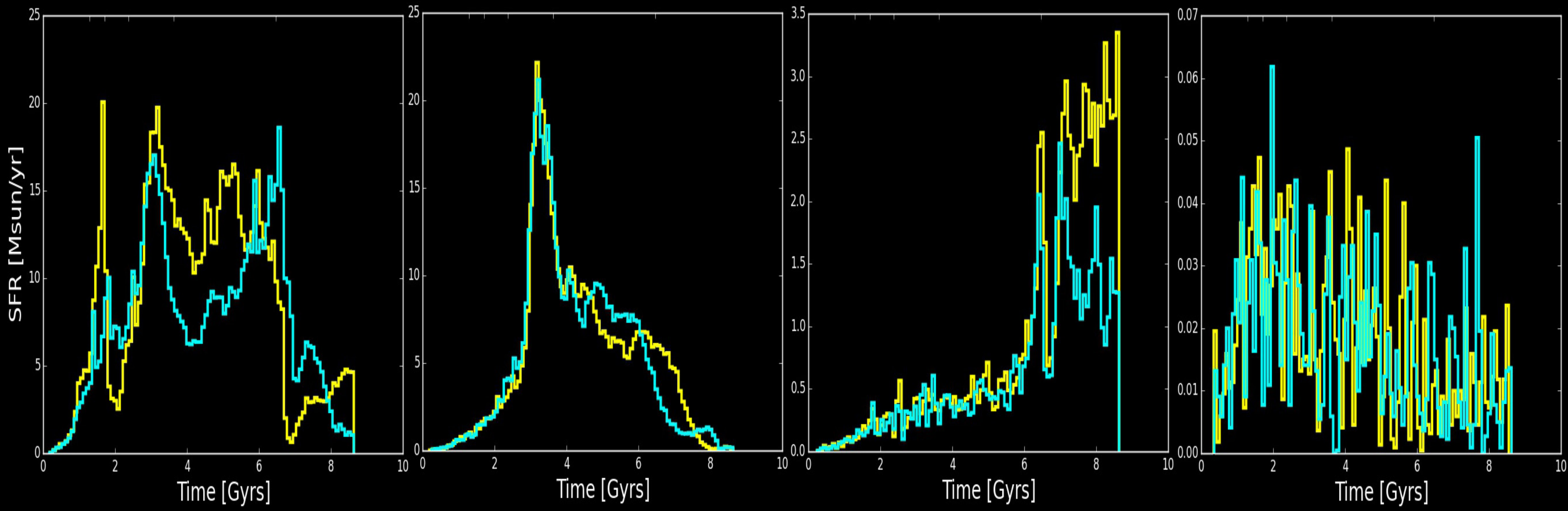
SIDM cores wins over adiabatic contraction in MW size galaxies
Massive spirals have a lower DM density in SIDM already at 20 kpc!



Di Cintio, Tremmel, Governato + in prep.

Current and future work

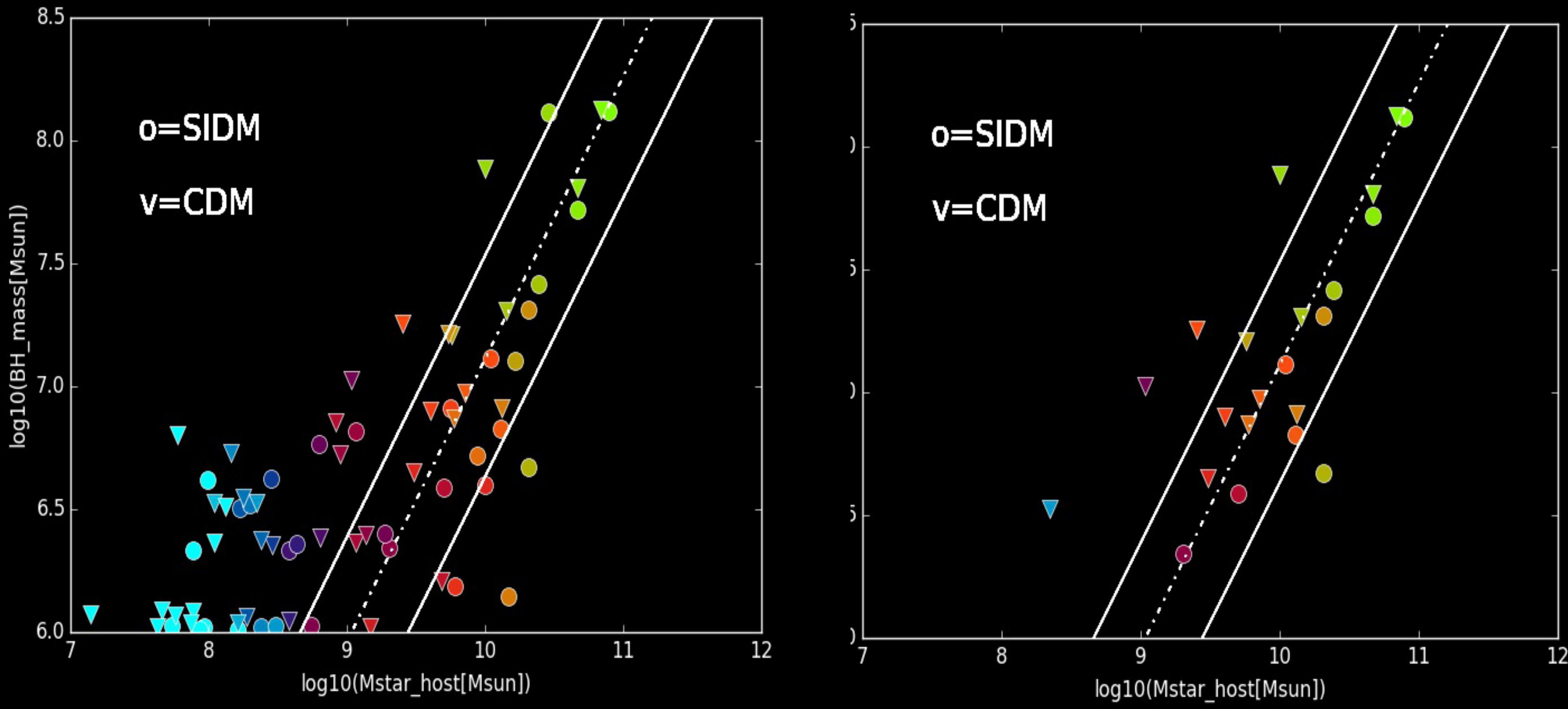
BH feedback regulate SF in the massive MW ->allows SIDM to win
In smaller systems, BH feedback is not sufficient to quench SF-> adiabatic contraction wins
Dwarfs have similar SF in CDM and SIDM,low SF efficiency and "usual" SIDM core



Di Cintio, Tremmel, Governato + in prep.

Current and future work

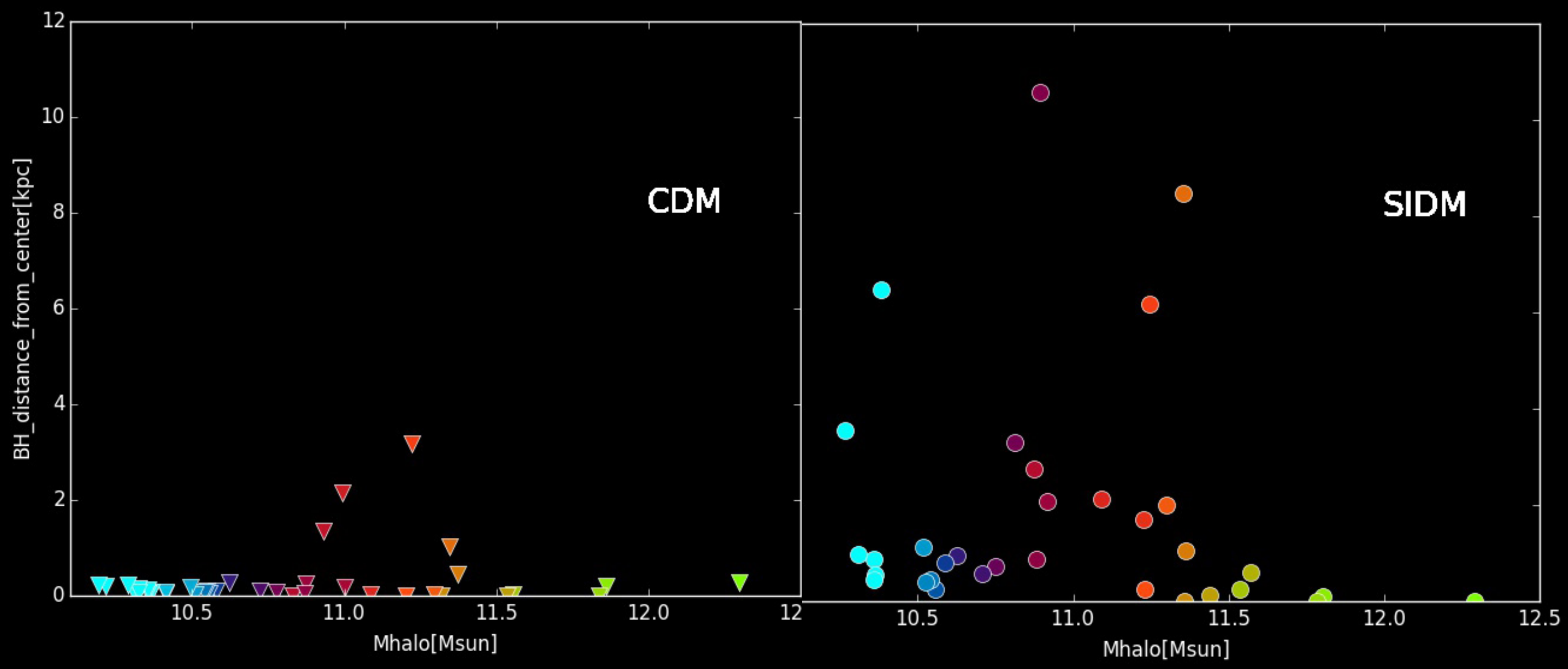
Realistic M_{BH}-M* relation → only few ACTIVE ($L>10^{42}$erg/s) BHs at z=0.5



Di Cintio, Tremmel, Governato + in prep.

Current and future work

Off-centered BHs in SIDM galaxies :
High M_{BH}→fast sinking to the center
Low central density→ longer dynamical friction timescales



Di Cintio, Tremmel, Governato + in prep.

Conclusions

✓Baryonic physic affects dark matter profiles in galaxies: CDM has a peak in core formation efficiency at $M_* \approx 10^{8.5}\, M_\odot$

✓ Looking at global properties of galaxies to get the mass dependence of core formation → will help disentangle the DM models?