The Structure of Simulated Dark Matter Haloes

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Dark Matter in the Milky Way, Mainz, May 2016

Outline

1) The Goal: Simulating the Milky Way

2) Dissipationless Cold Dark Matter simulations

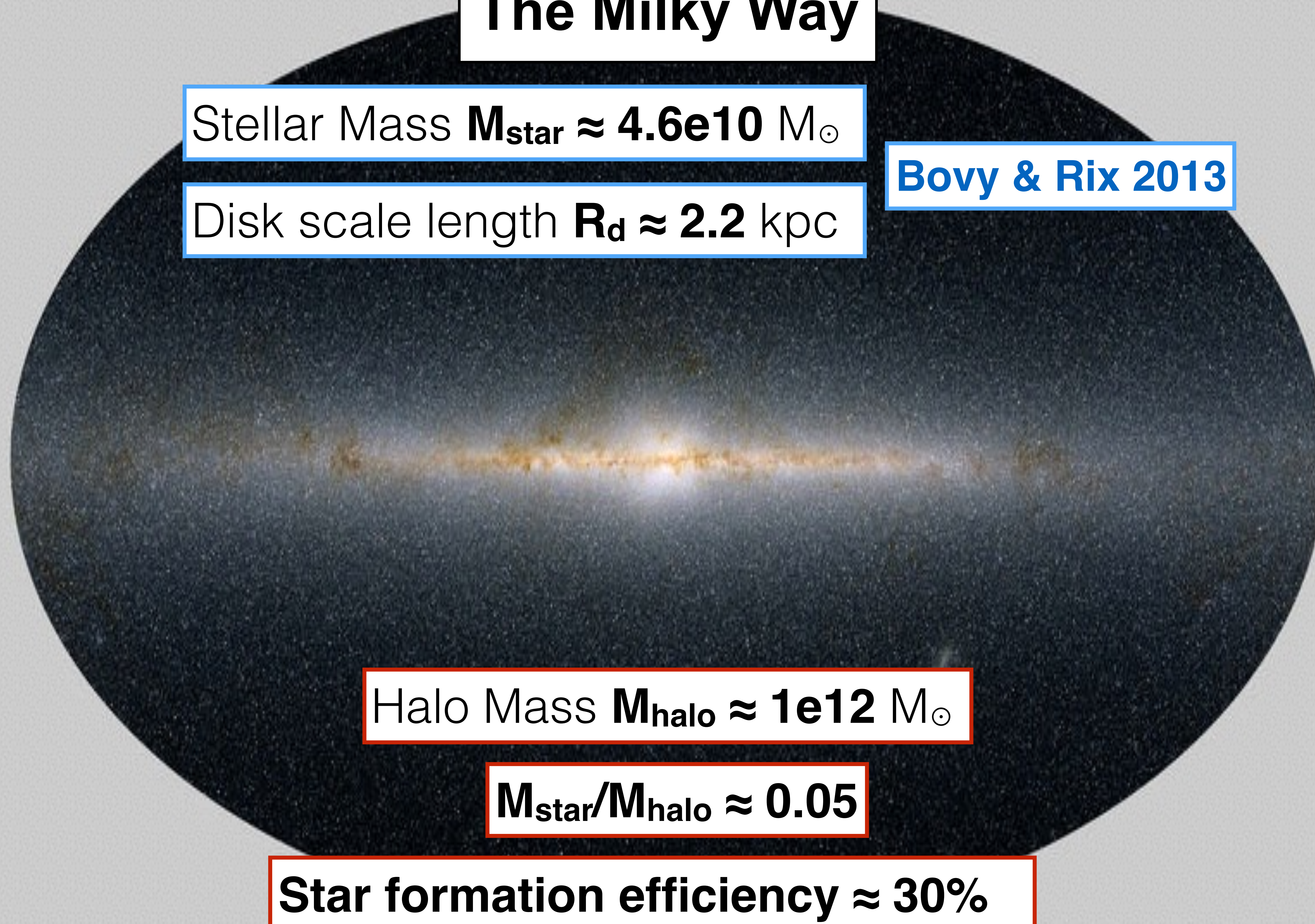
3) Hydrodynamical CDM simulations

4) Other Dark Matter models

The Milky Way

Two Micron All Sky Survey Image Mosaic: Infrared Processing and Analysis Center/Caltech & University of Massachusetts

The Milky Way



Stellar Mass $\mathbf{M_{star}} \approx \mathbf{4.6e10}\ M_\odot$

Disk scale length $\mathbf{R_d} \approx \mathbf{2.2}$ kpc

Bovy & Rix 2013

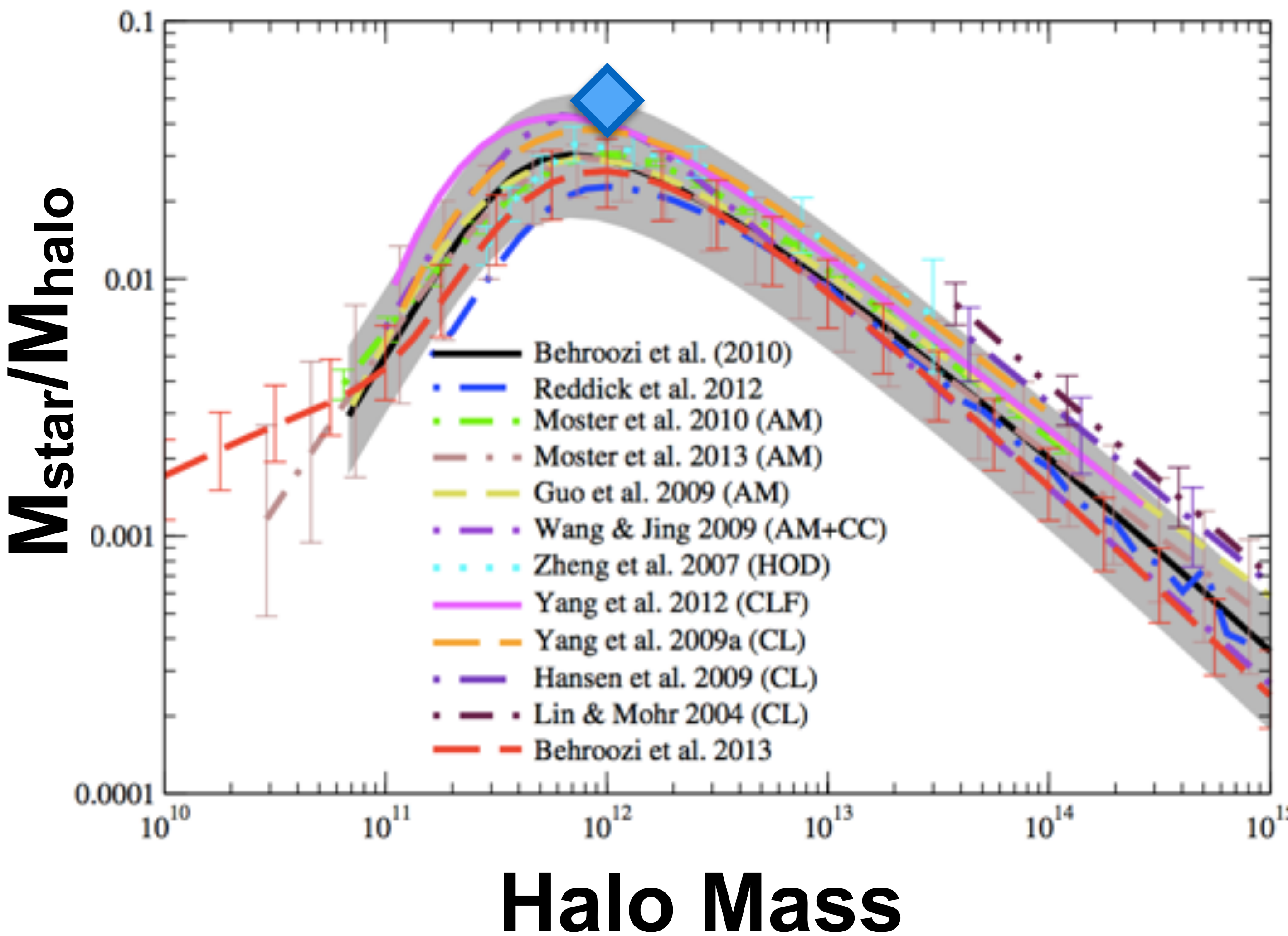
Halo Mass $\mathbf{M_{halo}} \approx \mathbf{1e12}\ M_\odot$

$\mathbf{M_{star}/M_{halo} \approx 0.05}$

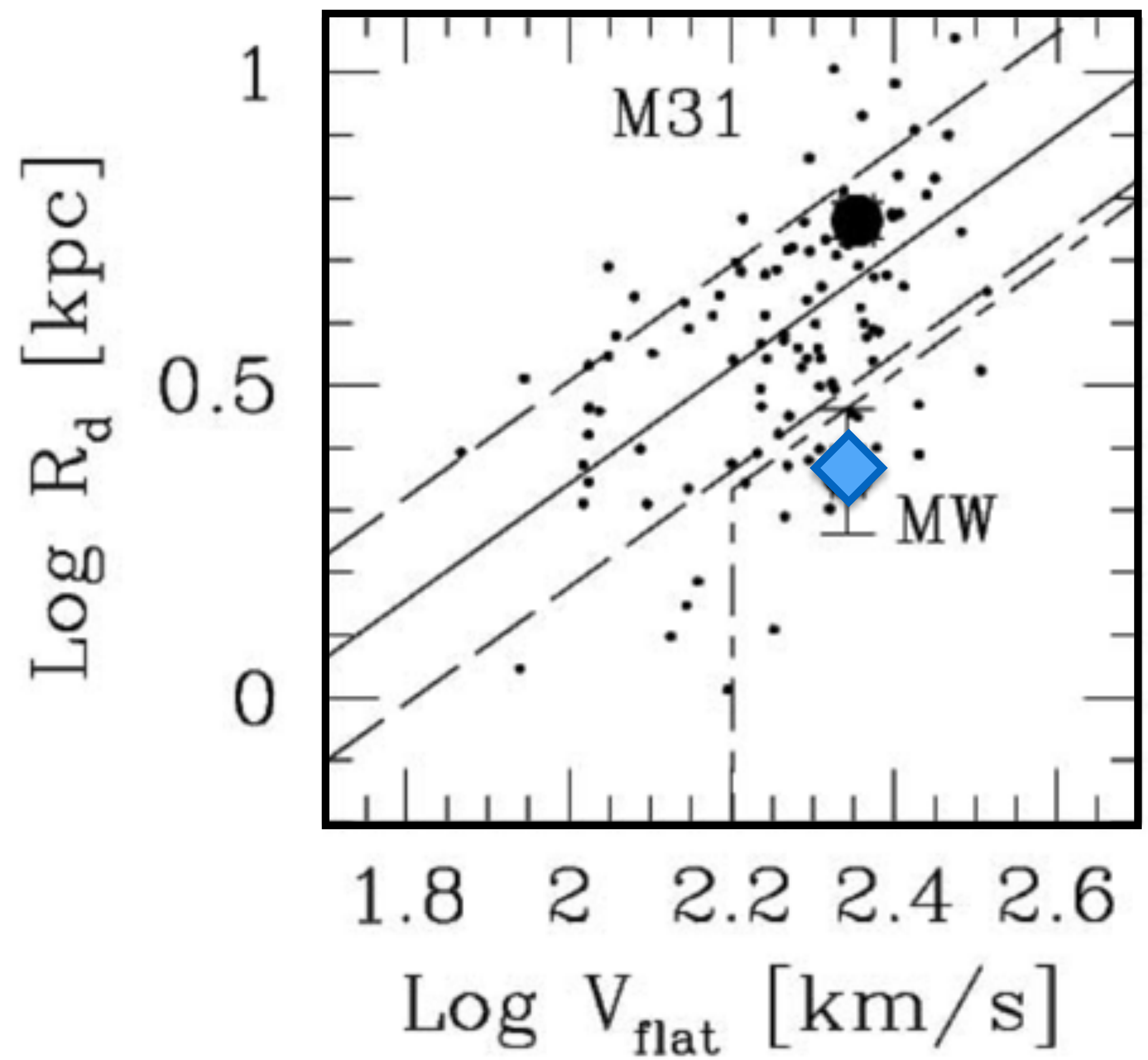
Star formation efficiency ≈ 30%

Two Micron All Sky Survey Image Mosaic: Infrared Processing and Analysis Center/Caltech & University of Massachusetts

The Milky Way is Unusually Efficient at forming stars, and smaller than typical disks



Behroozi et al. 2013

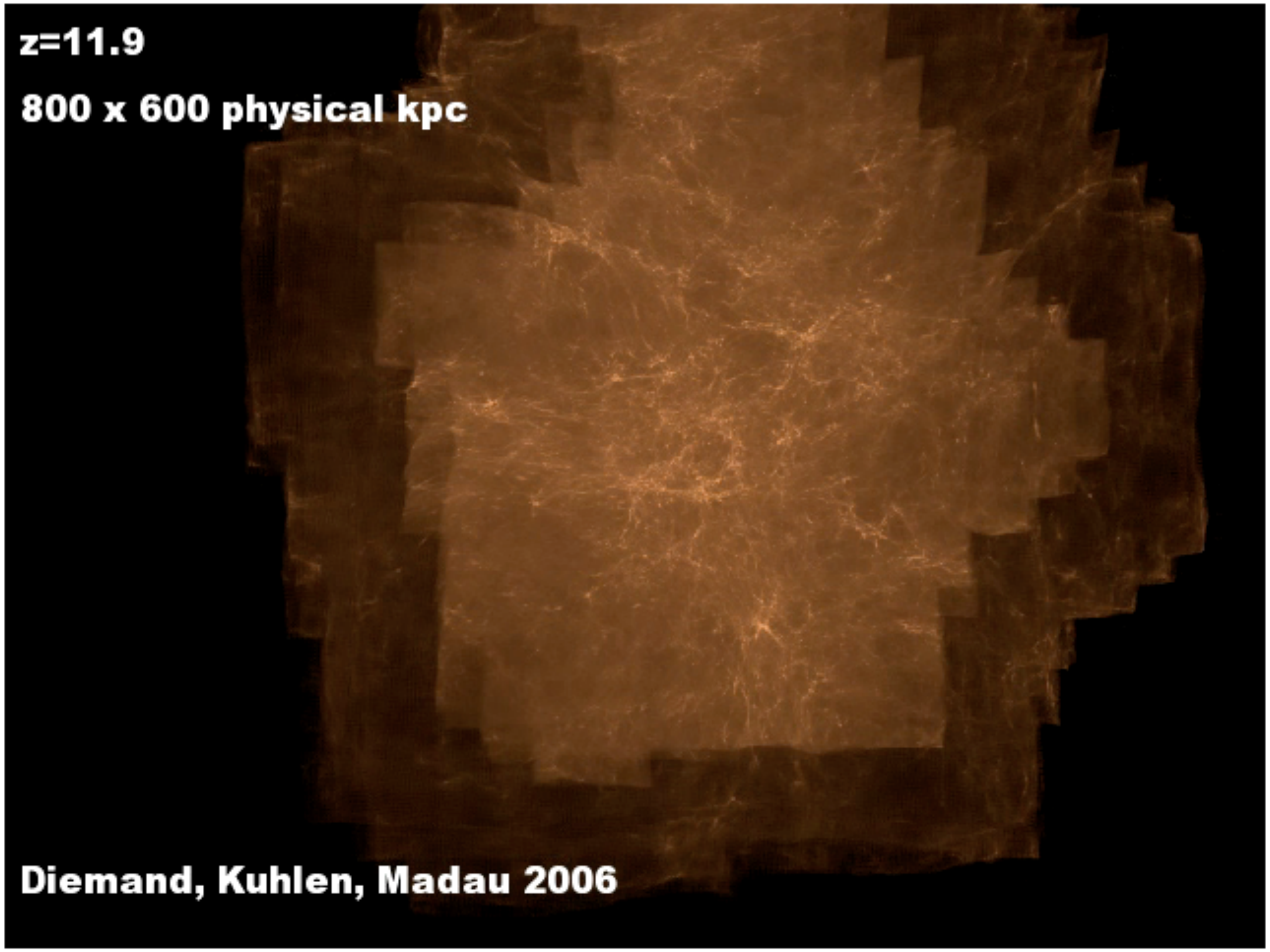


Hammer et al. 2007

The MW probably does not live in a typical DM halo

“Via Lactea” Cold Dark Matter (only)

Diemand, Kuhlen, Madau 2006



800x600 kpc

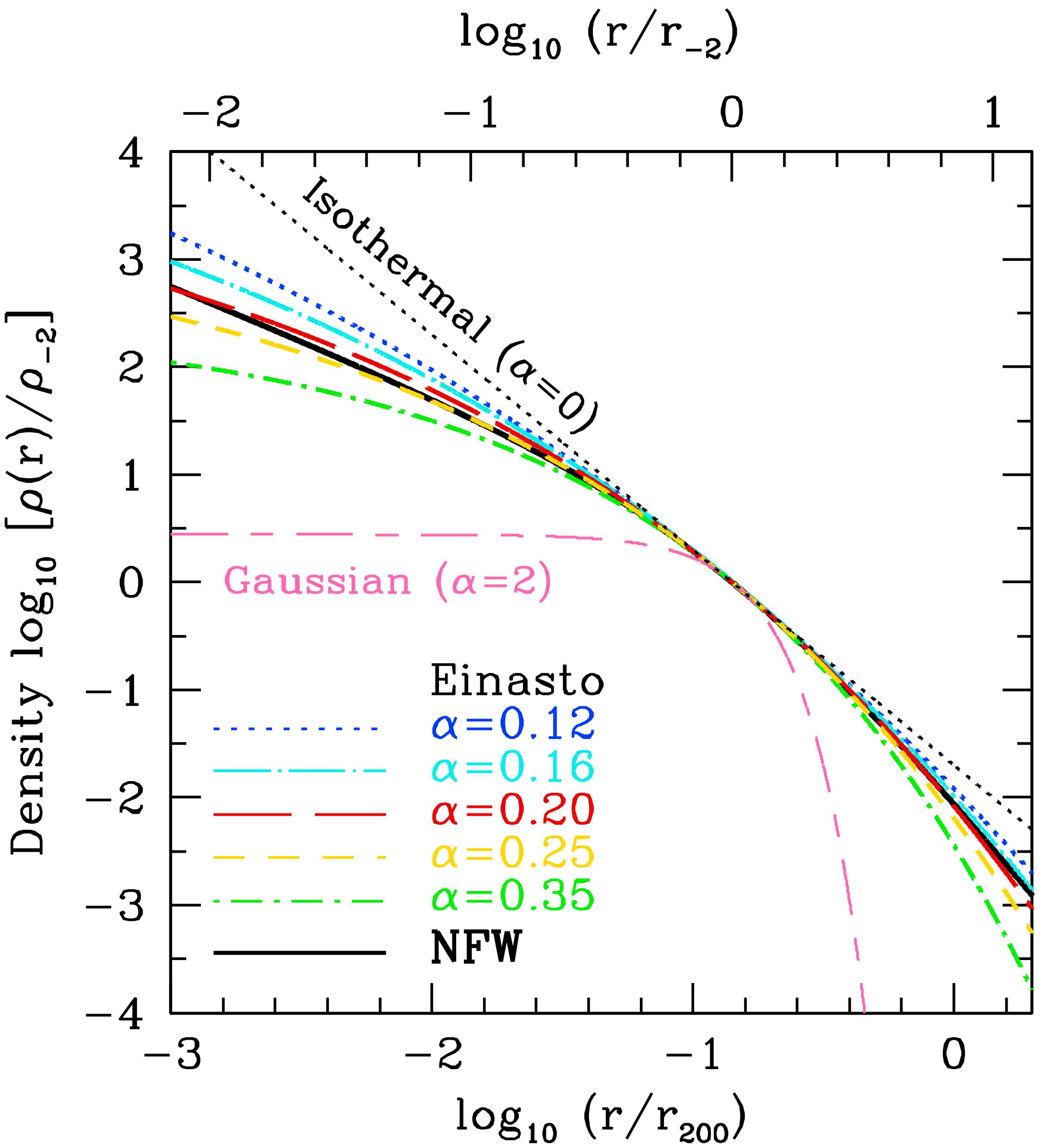
Density profile

Navarro, Frenk, White 1996

$$\frac{\rho_{\rm NFW}(r)}{\rho_{-2}} = \frac{4}{(r/r_{-2})(1+r/r_{-2})^2}$$

Einasto 1965

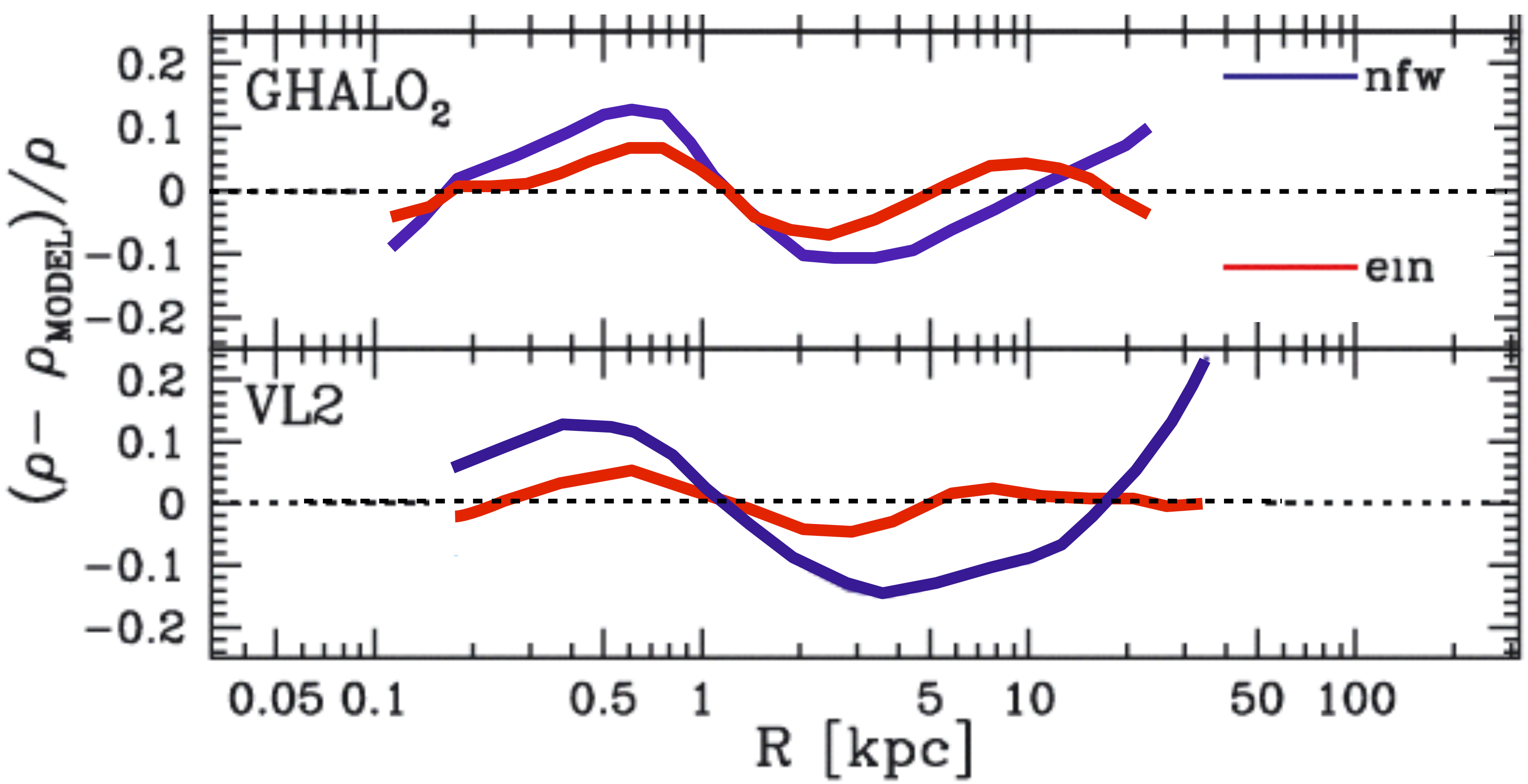
$$\frac{\rho_{\rm EIN}(r)}{\rho_{-2}} = \exp\left\{-\frac{2}{\alpha}\left[(r/r_{-2})^{\alpha}-1\right]\right\}$$



Einasto fits CDM haloes better than NFW

(Merritt et al. 2005, Gao et al. 2008; Stadel et al. 2009; Navarro et al. 2010)

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



Stadel et al. 2009

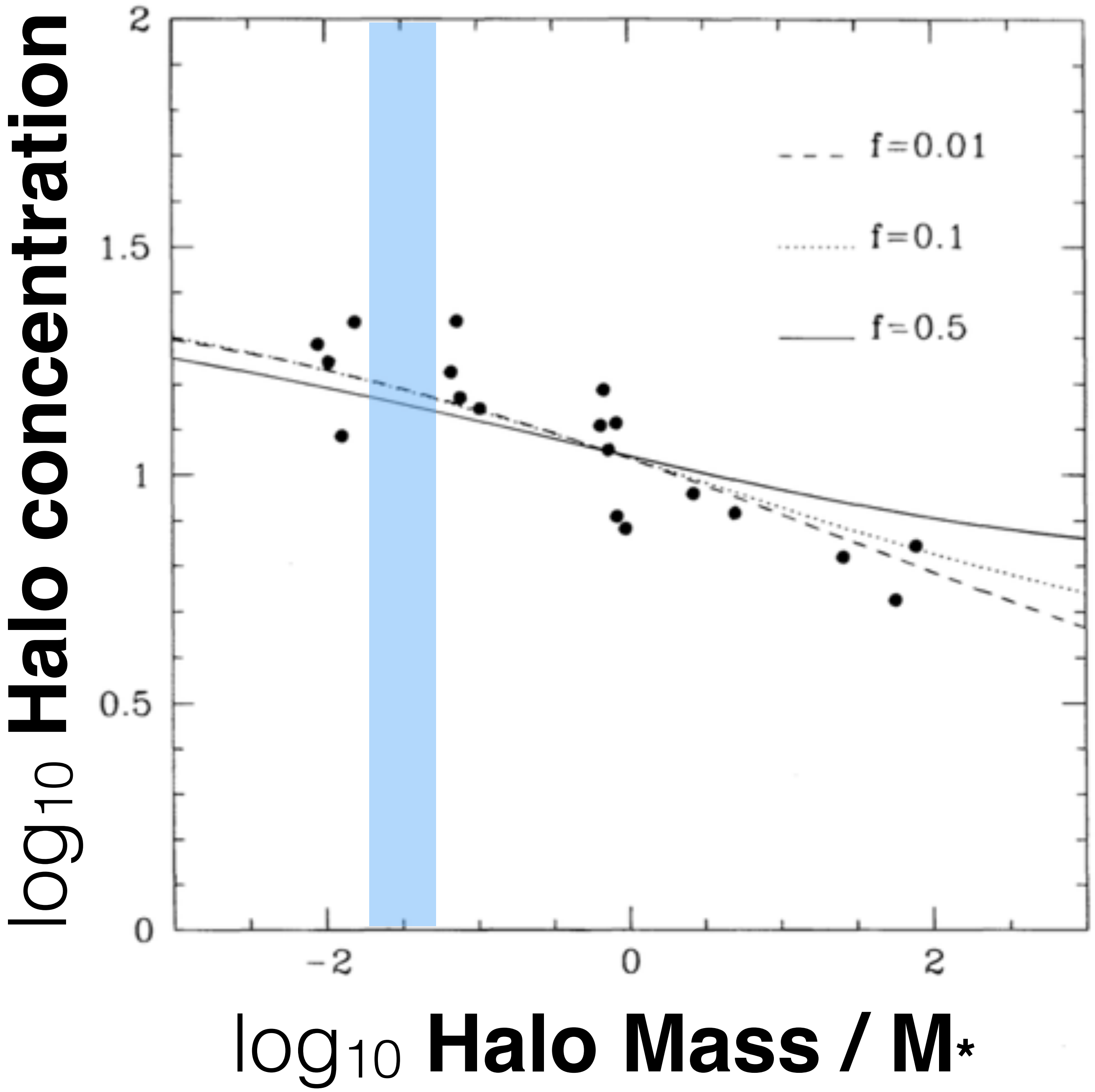
3 billion particles

ghalo

$c = R_{vir}/r_{-2}$

Concentration vs Mass

Navarro, Frenk, White 1996



Lower mass haloes are (slightly) denser

Lower mass haloes form earlier

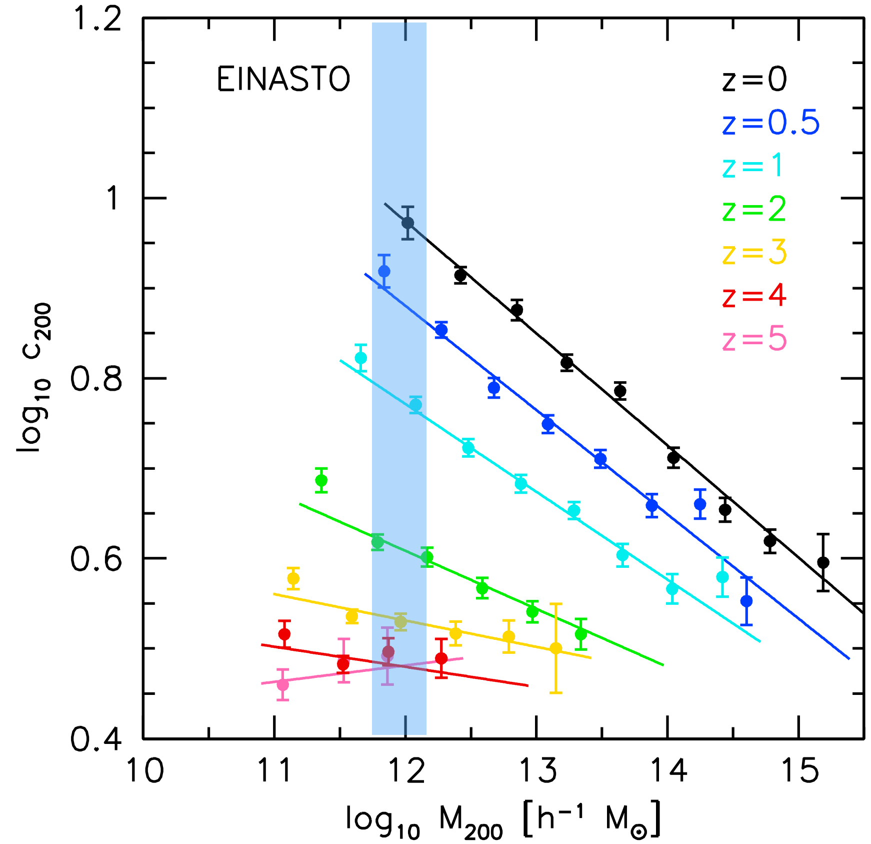
The universe was denser when they collapsed

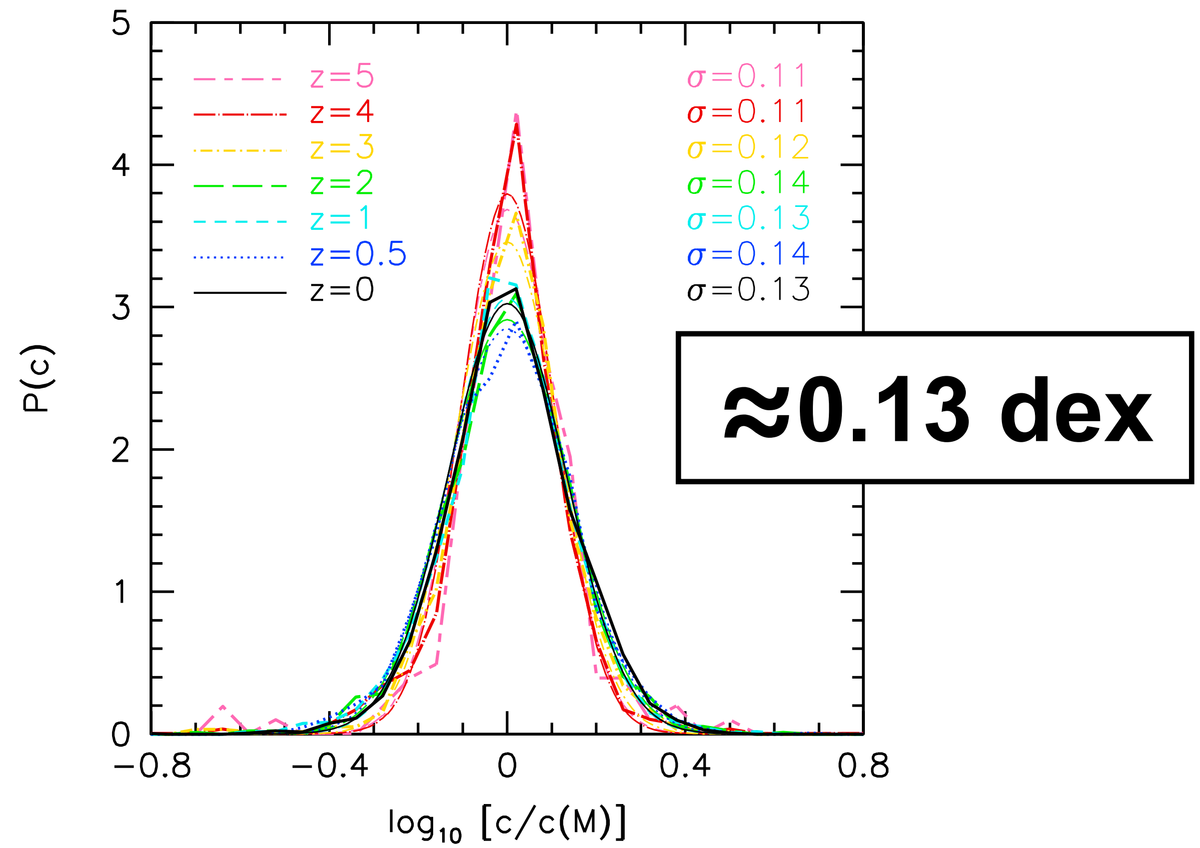
$M_* = 3.3 \times 10^{13}\ M_\odot$

Einasto structural parameters Planck 2014 Cosmology

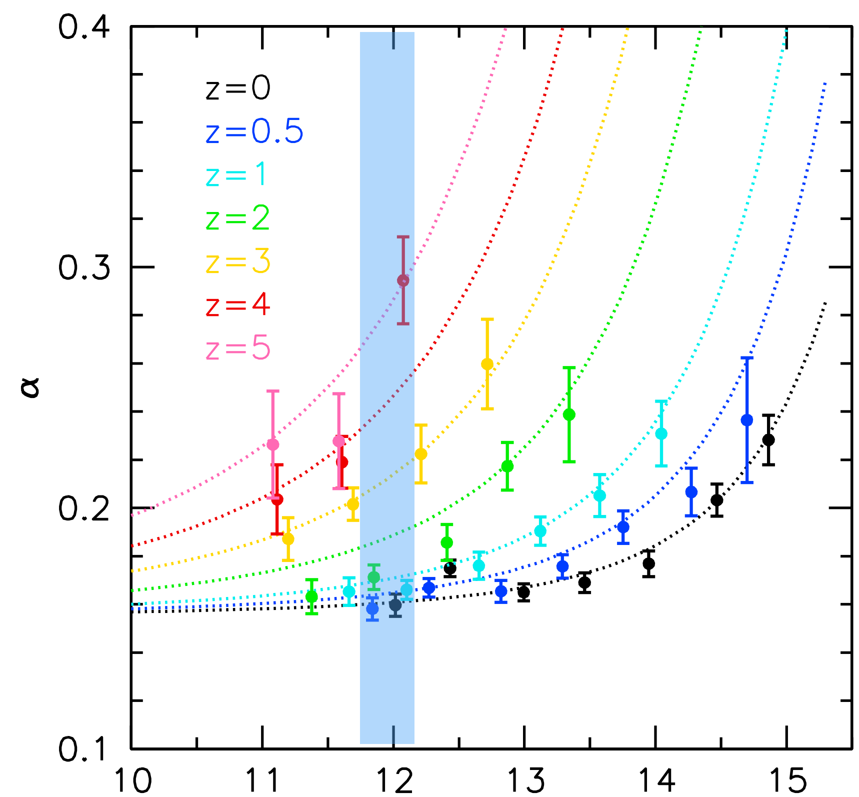
Dutton & Maccio 2014

Halo concentration

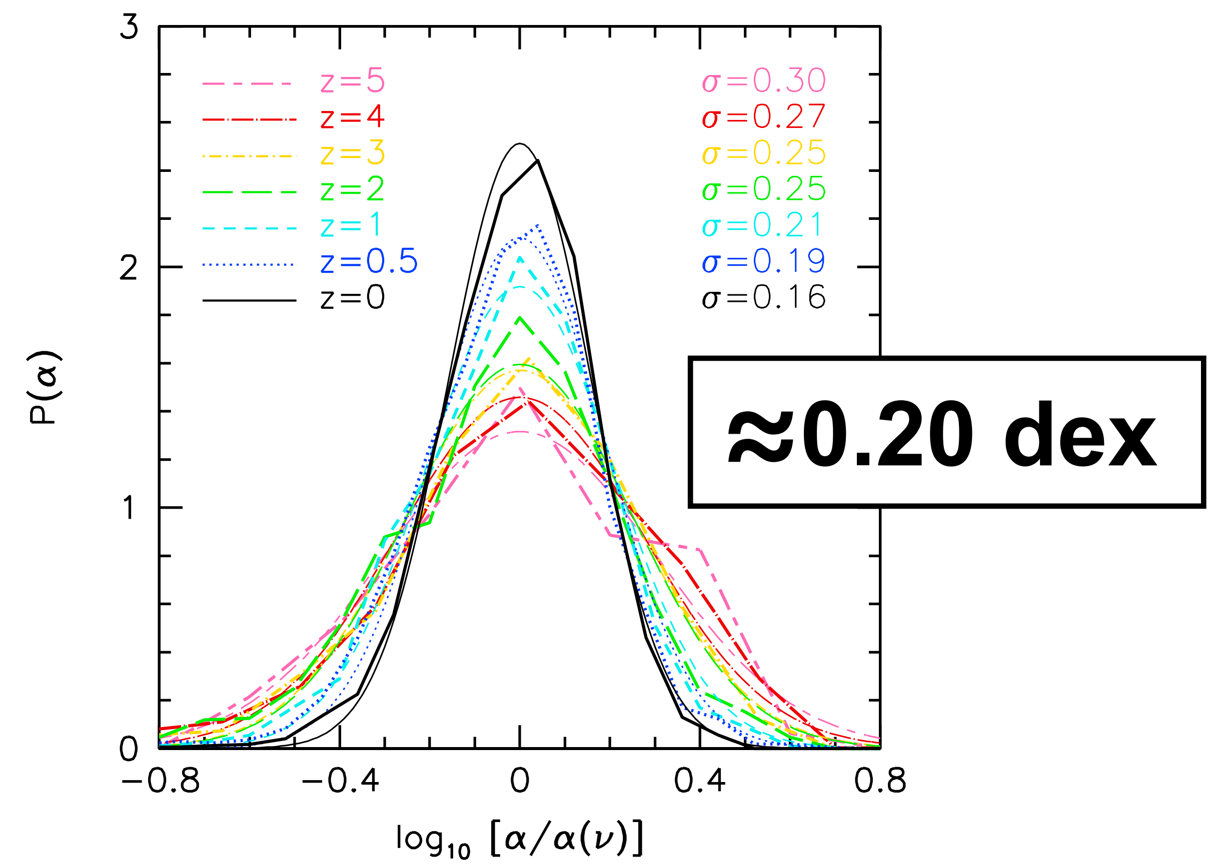




Einasto Shape

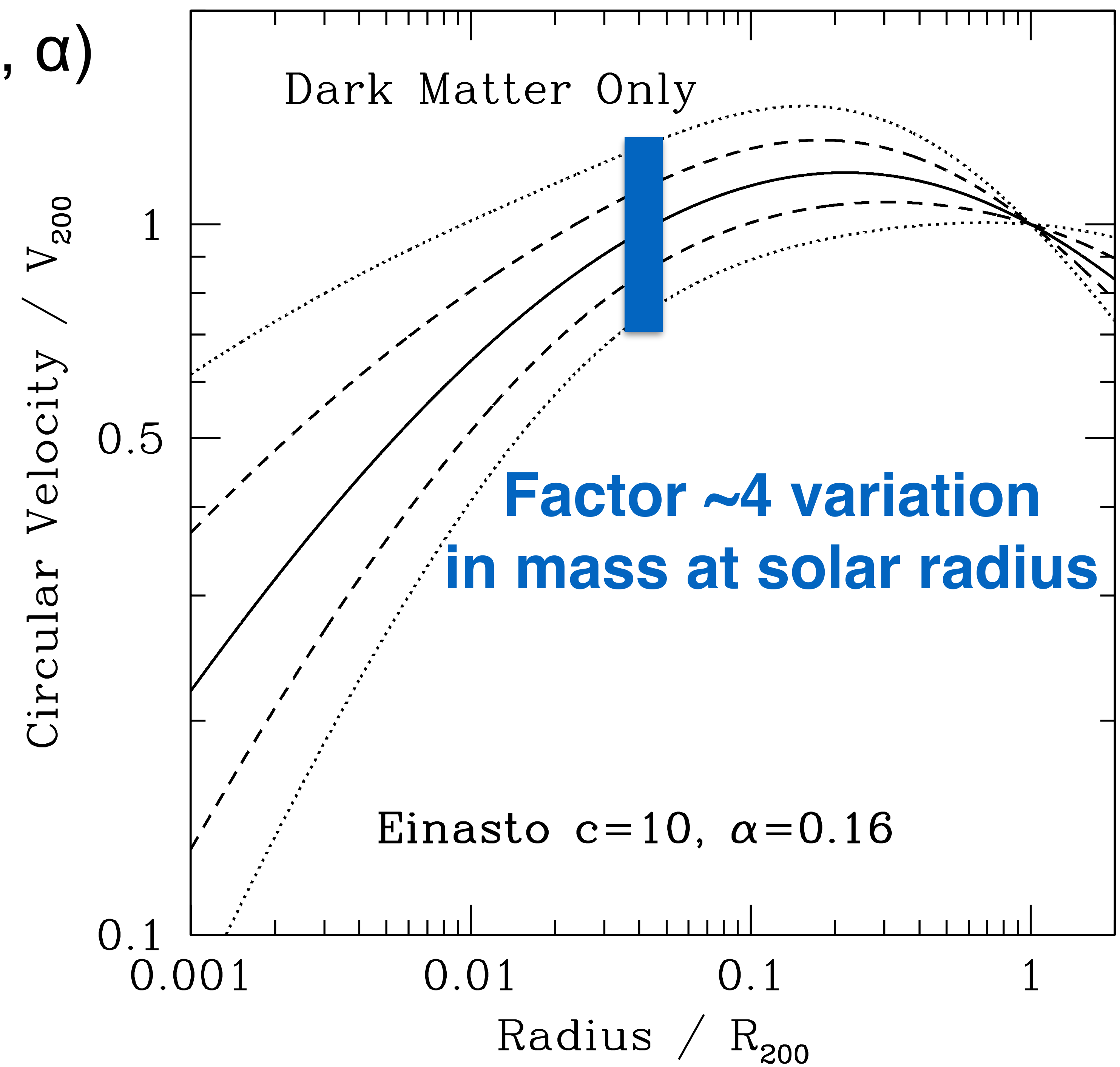


Halo Mass



Summary of Dissipationless CDM Simulations

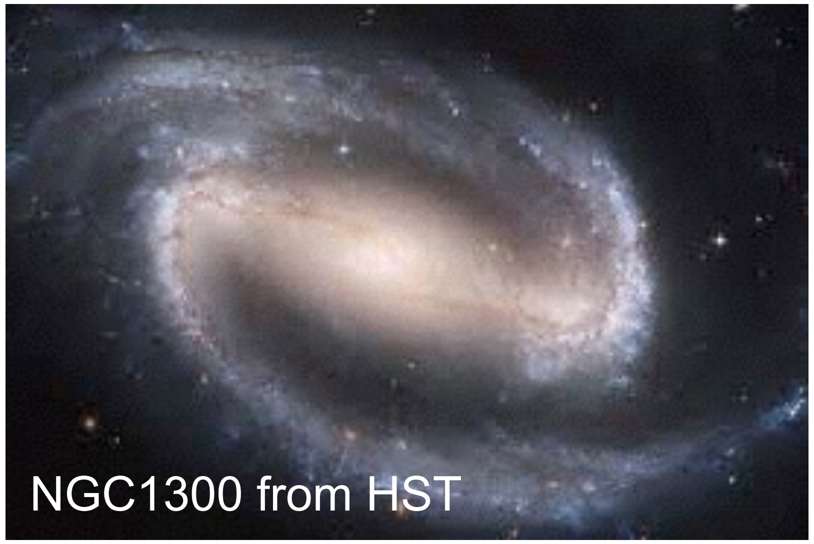
- **Einasto profile** (M_{200}, c, α)
- $M_{200} \approx 10^{12}\ M_\odot$
- c ≈ 6 - 18 (2σ)
- α ≈ 0.08 - 0.32 (2σ)



Several physical process can modify the structure of DM haloes

- **Smooth and Slow Accretion: “Adiabatic Contraction”**
  - **r M(r) = const.** **(Blumenthal et al. 1986, Gnedin et al. 2004)**

- **Dynamical Friction: Expansion**
  - Satellite/clumpy accretion
    (e.g., El-Zant et al. 2001; Johansson et al. 2009)
  - Galactic bars
    (Weinberg & Katz 2002)

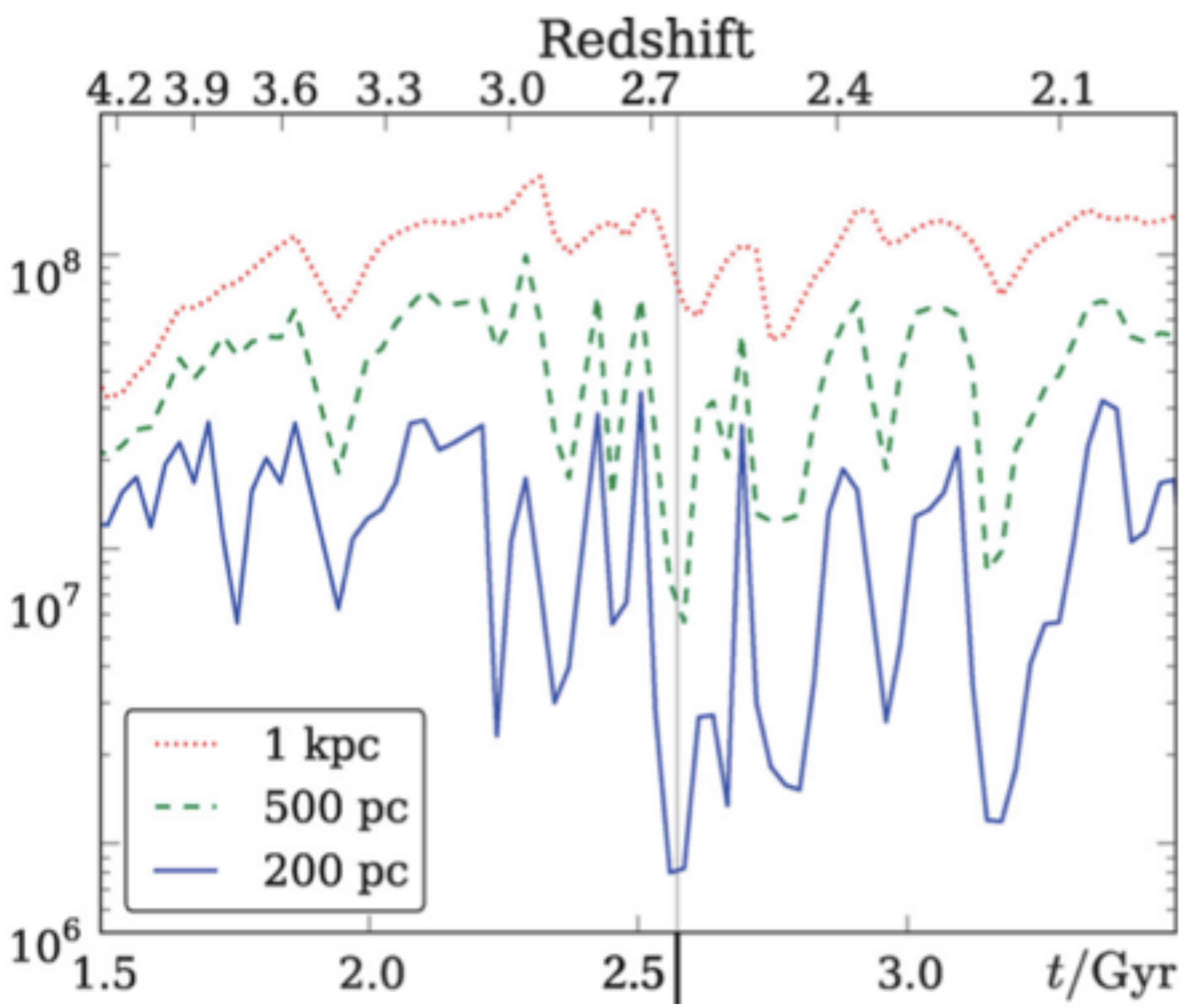


- **Gas Outflows: Expansion**
  - Strong mass outflows
    (e.g., Navarro et al. 1996; Read & Gilmore 2005)
  - Rapid Perturbations to potential
    (e.g., Pontzen & Governato 2012)

Halo expansion driven by SN feedback

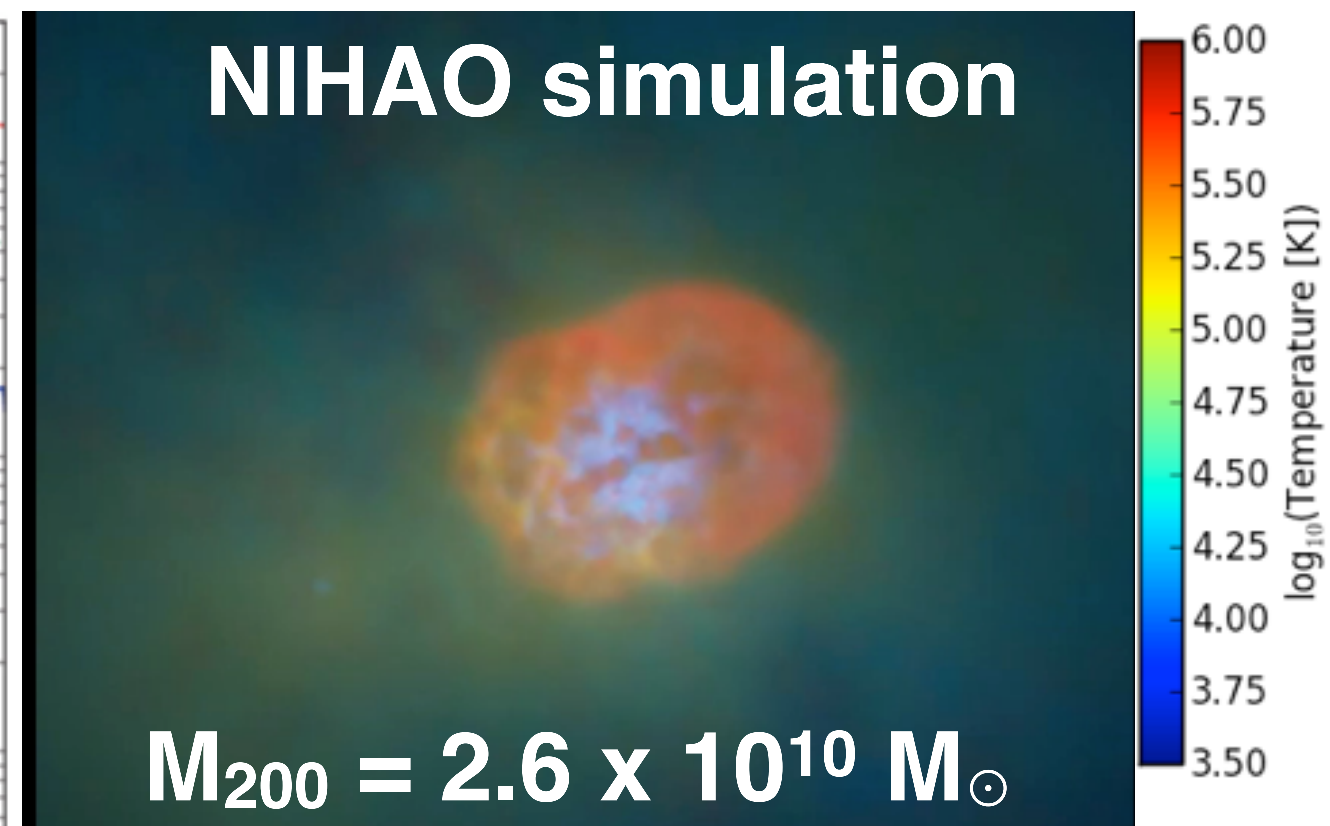
particles moving in a rapidly fluctuating potential gain energy

Pontzen & Governato 2012



M_{baryon} (<r) [M⊙]

Time [Gyr]



60 kpc/h comoving

(see also Navarro, Eke, Frenk 1996; Read & Gilmore 2005; Mashchenko et al. 2008)

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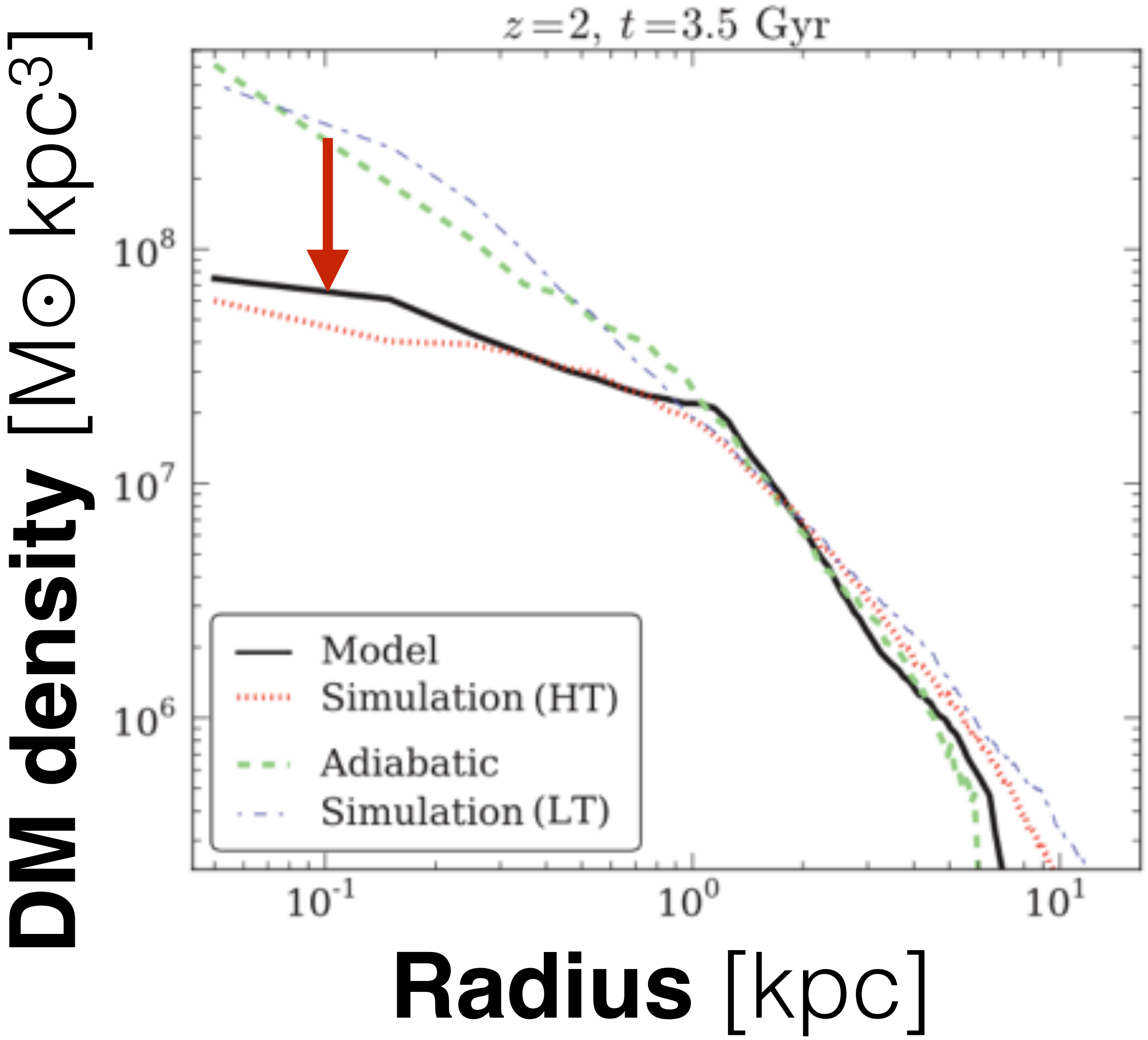
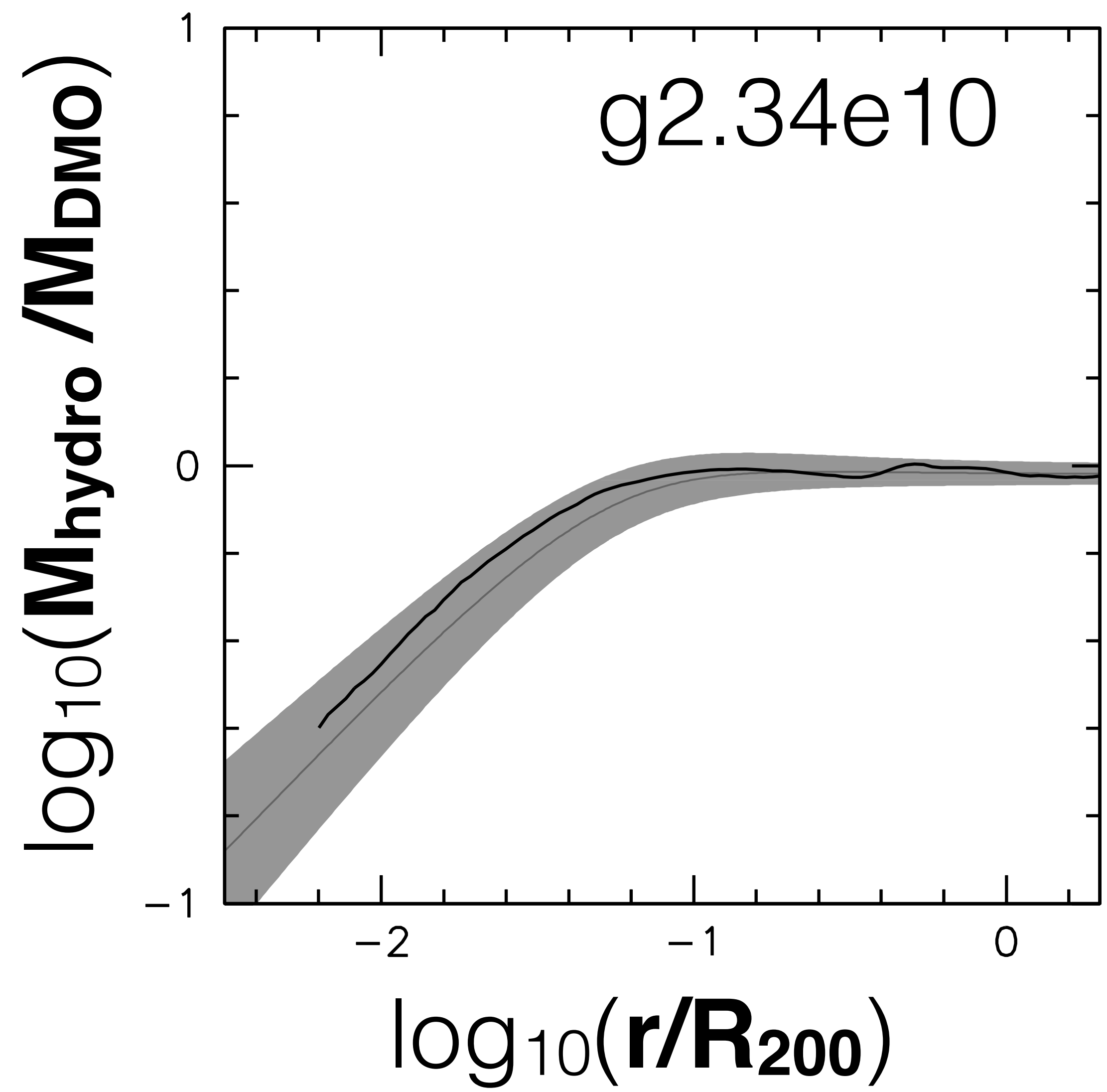


Dutton et al. in prep

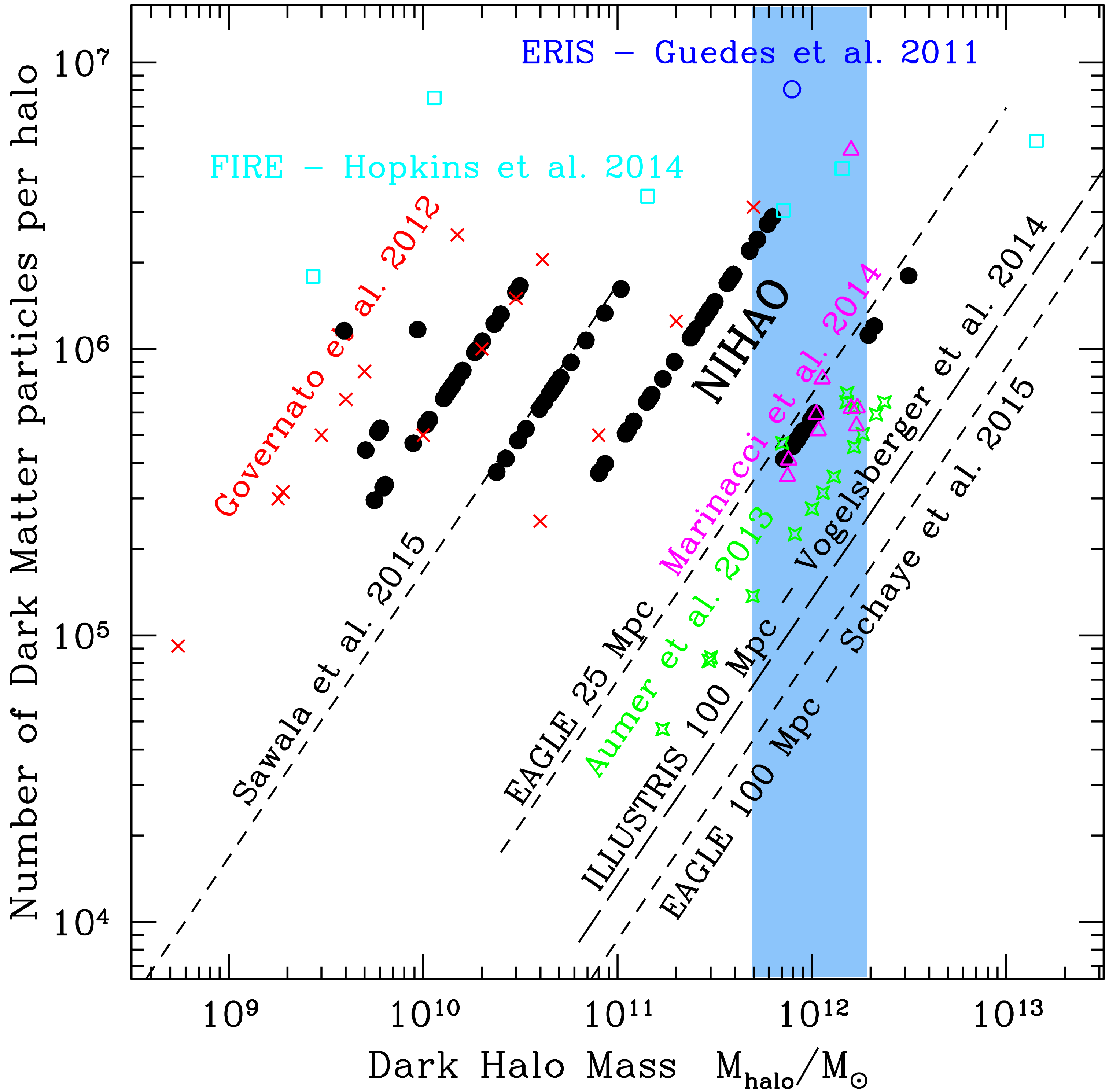


(see also Navarro, Eke, Frenk 1996; Read & Gilmore 2005; Mashchenko et al. 2008)

Different hydro codes and subgrid models

name	code	n_{th} / [cm^{-3}]	feedback
FIRE	GIZMO	100	thermal+
MaGICC/NIHAO	GASOLINE	10	thermal blastwave
Illustris	AREPO	0.13	kinetic
EAGLE	GADGET-3	~0.1	thermal stocastic

Dark Matter Mass Resolution



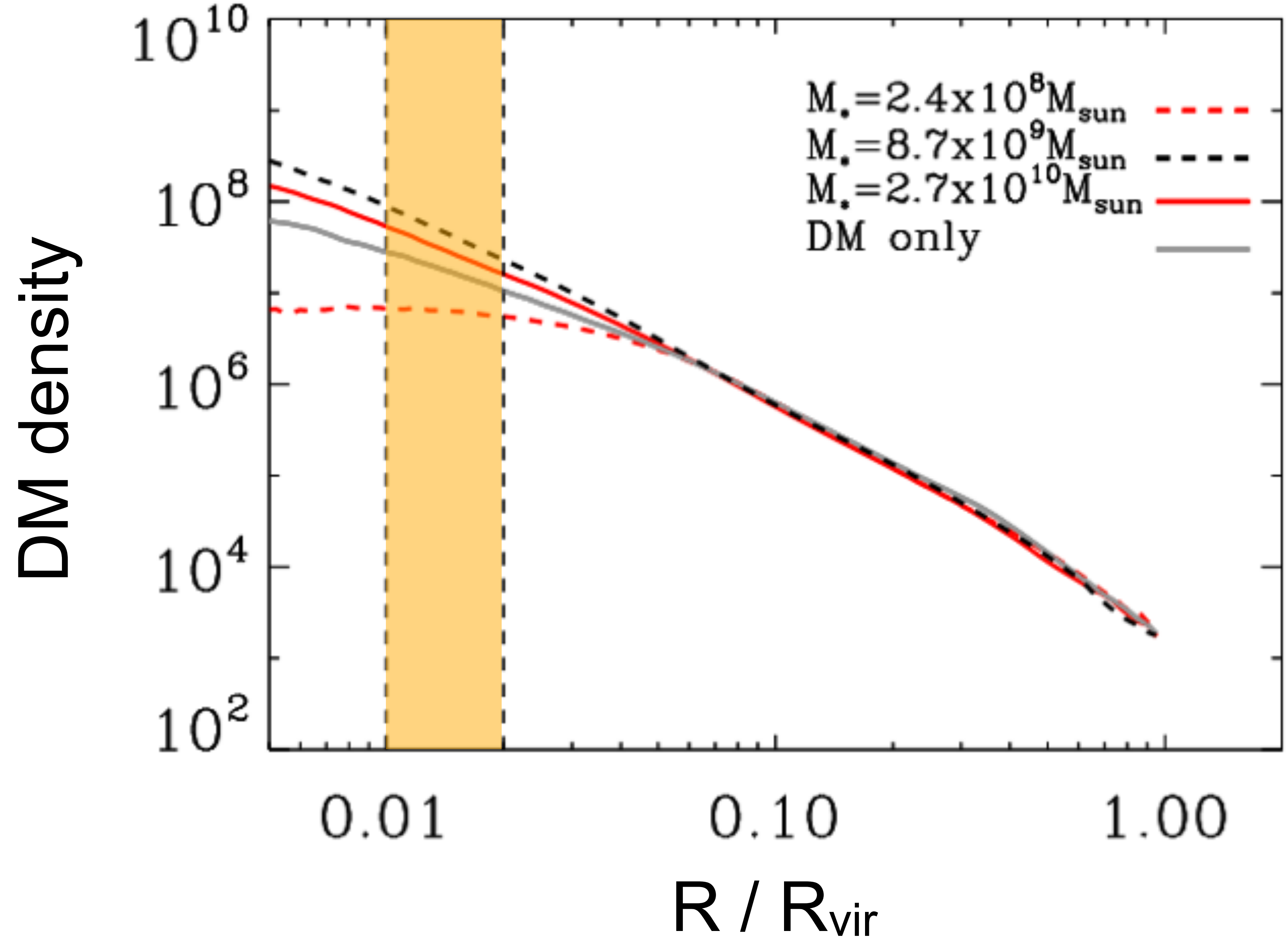
Other factors:

What gas scales are resolved?

Is the ISM correctly modeled on these scales?

Inner Dark Matter density slopes

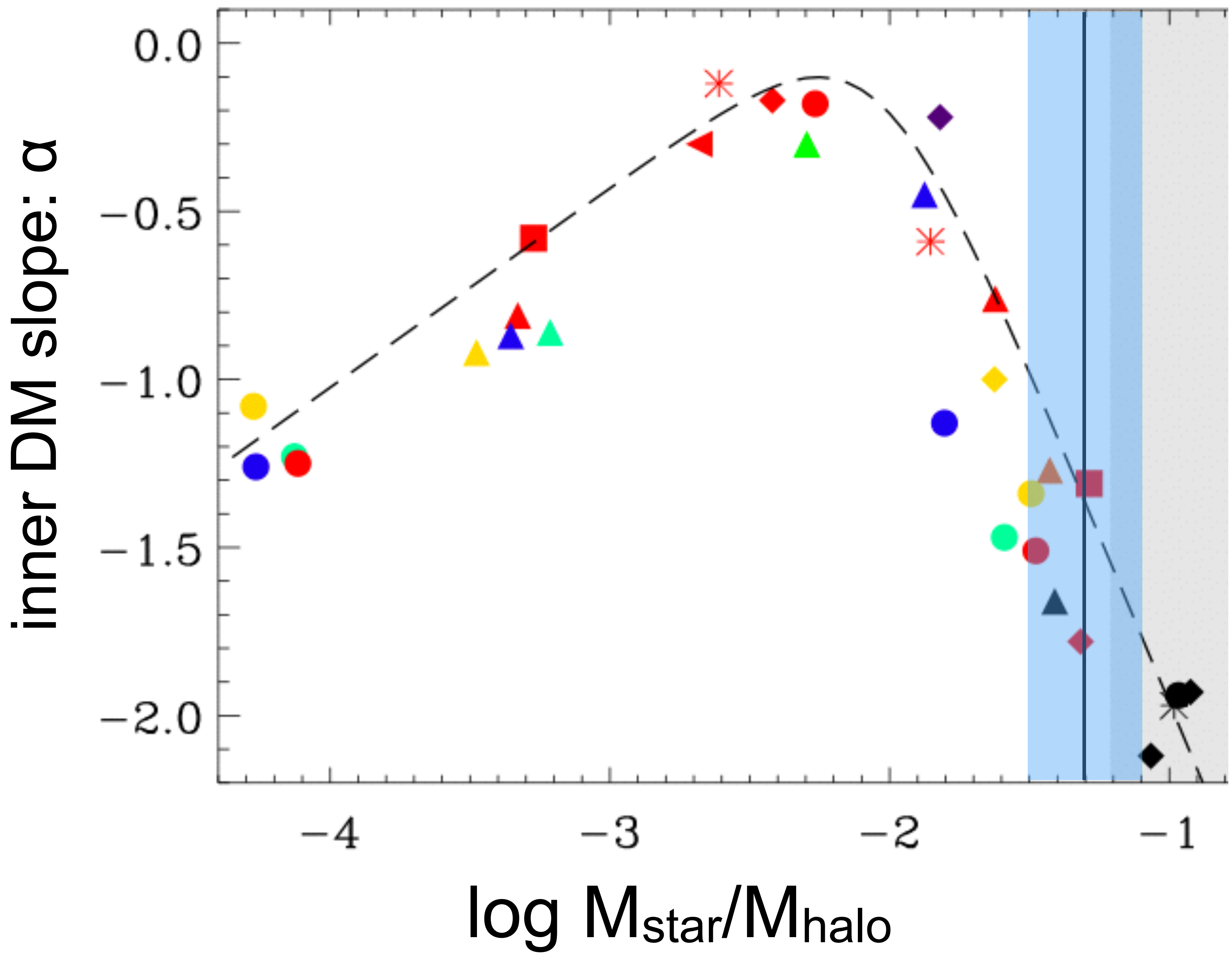
Fit for power-law slope, α, between 1 and 2% of R_{vir}



Di Cintio et al. 2014a, MNRAS, 437, 415

DM slope correlates with star formation efficiency

Di Cintio et al. 2014a, MaGICC simulations (Stinson et al. 2013)

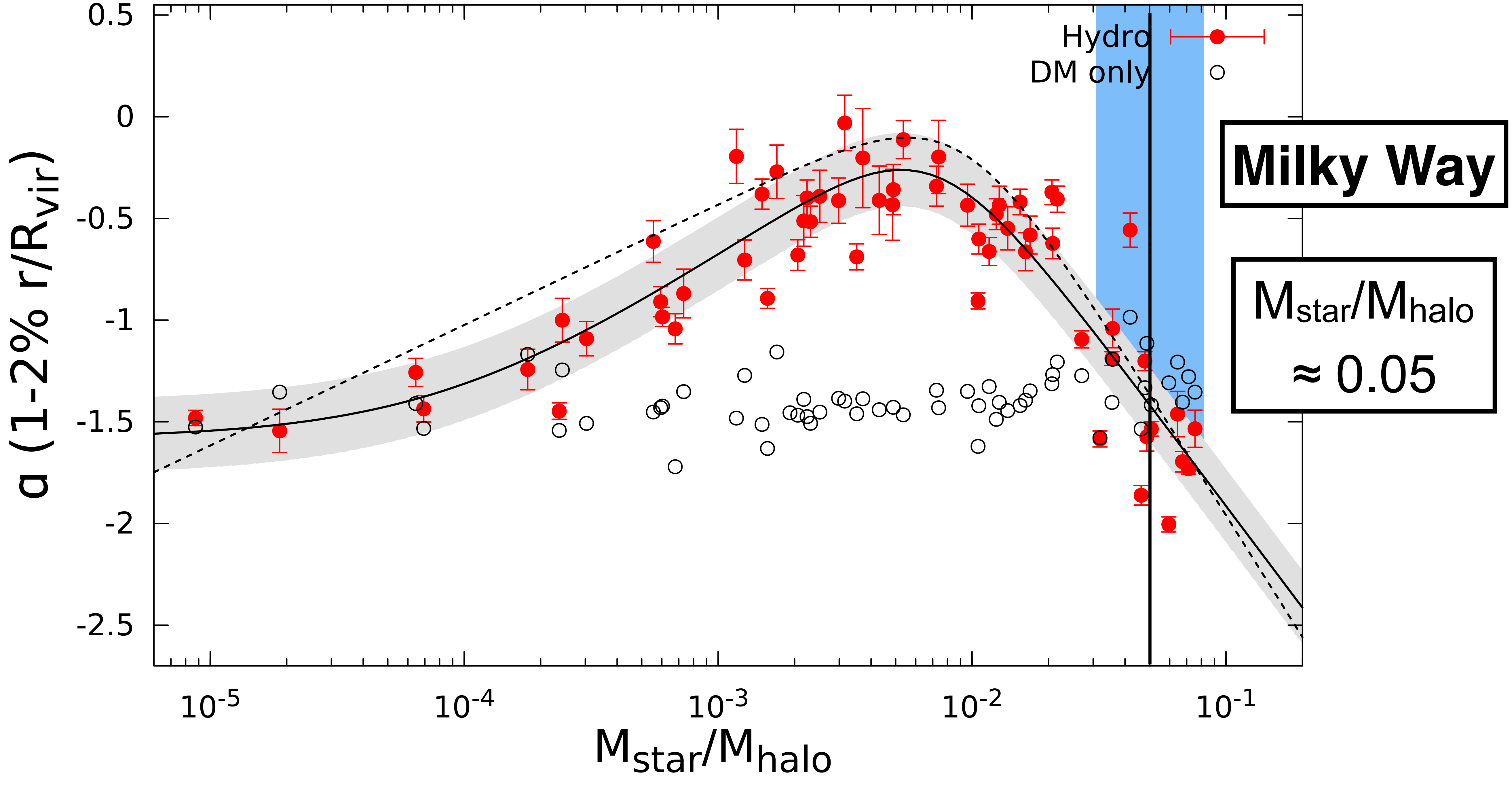


Milky Way

$M_{star}/M_{halo} \approx 0.05$

NIHAO (upgrade to MaGICC)

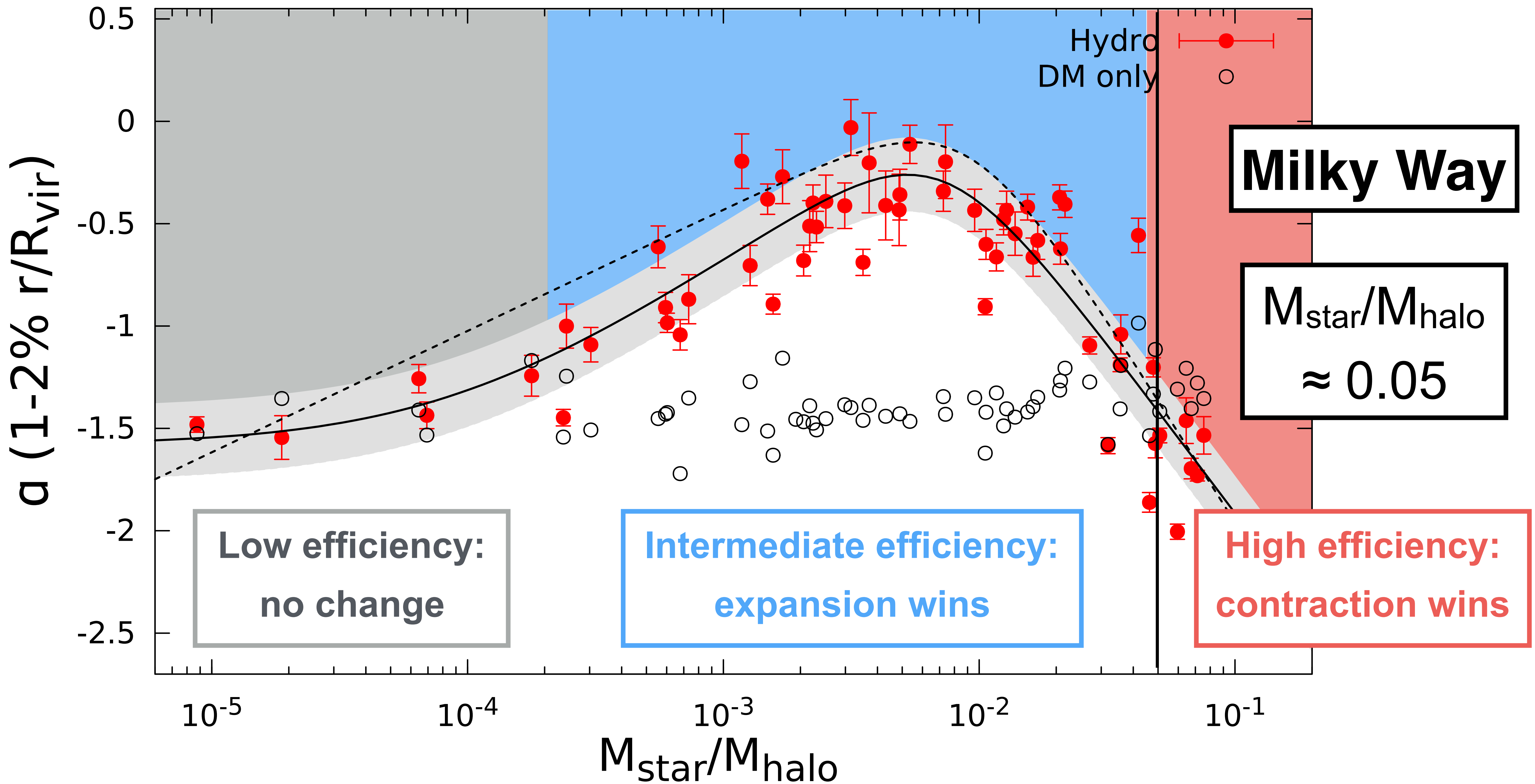
Wang, Dutton, Stinson, Macciò et al. 2015, MNRAS, 454, 83



Tollet et al. 2016, MNRAS, 456, 3542

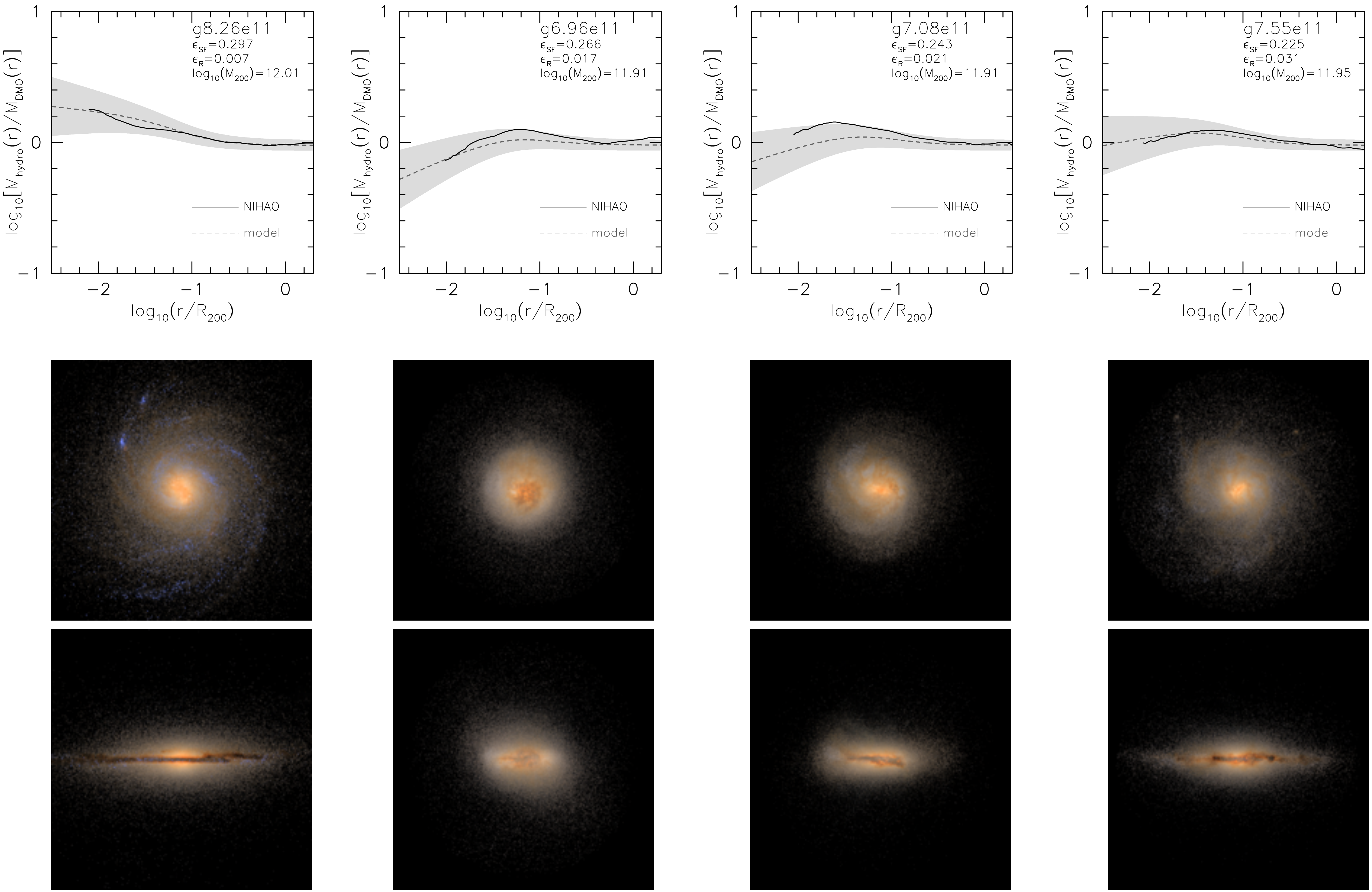
NIHAO (upgrade to MaGICC)

Competition: inflows (contraction) vs **outflows** (expansion)



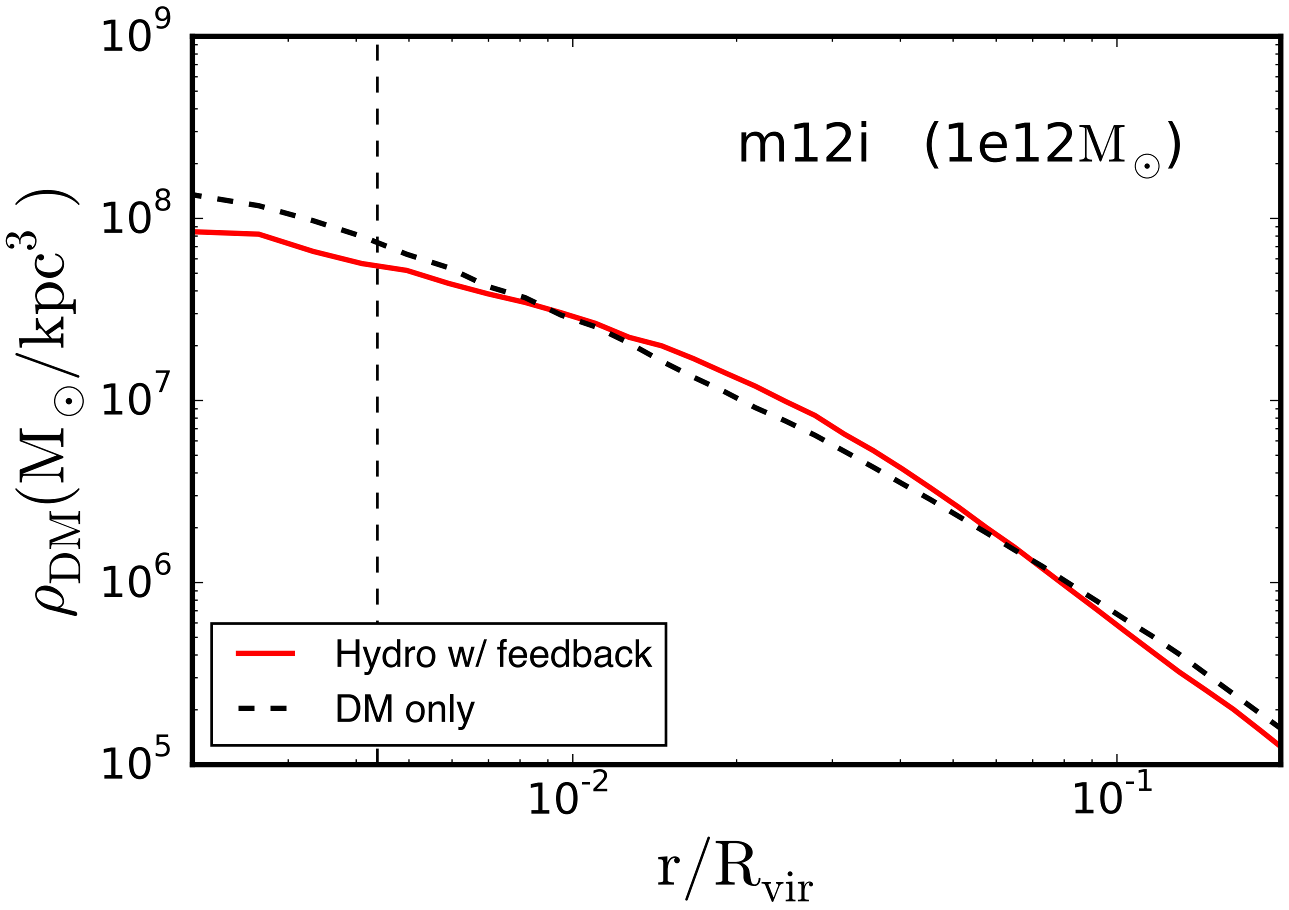
Tollet et al. 2016, MNRAS, 456, 3542

NIHAO Milky Way analogues

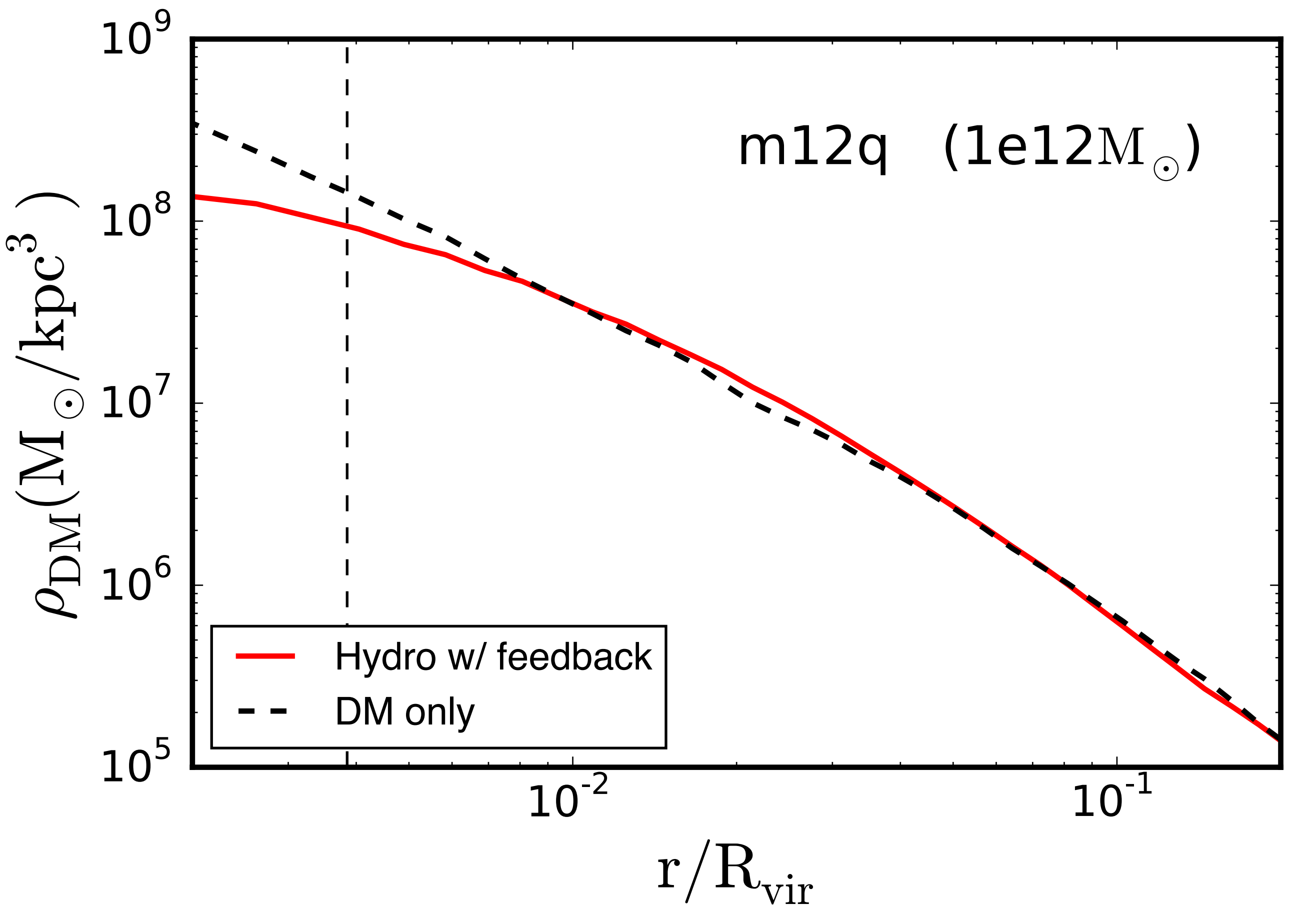


FIRE simulations

M_{star}=6.1e10 $M_\odot$, R_{star}=4.3 kpc



M_{star}=2.1e10 $M_\odot$, R_{star}=3.6 kpc



Chan, Keres, Oñorbe, Hopkins, Muratov, Faucher-Giguère, Quataert, 2015, MNRAS, 454, 2981

FIRE simulations

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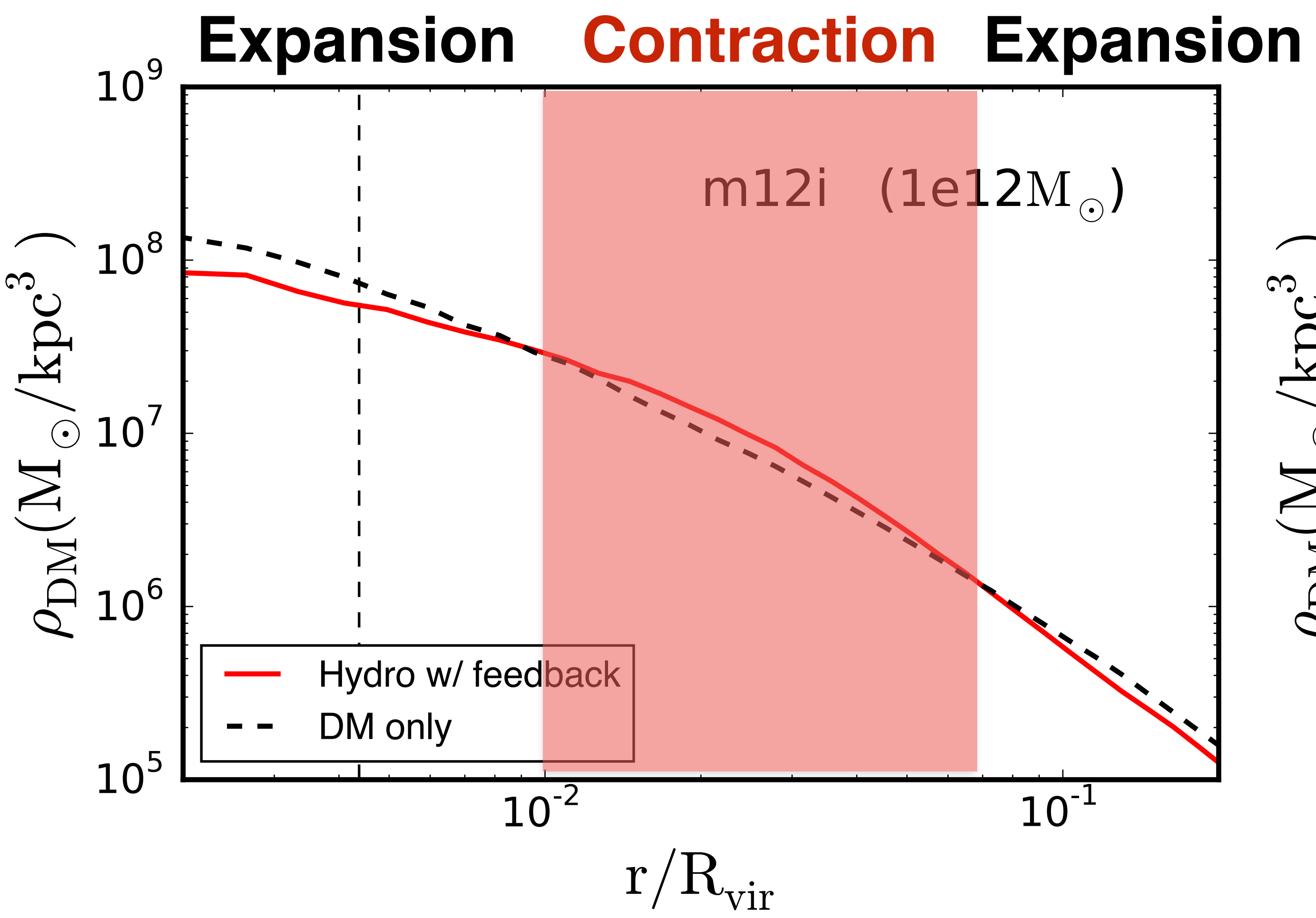

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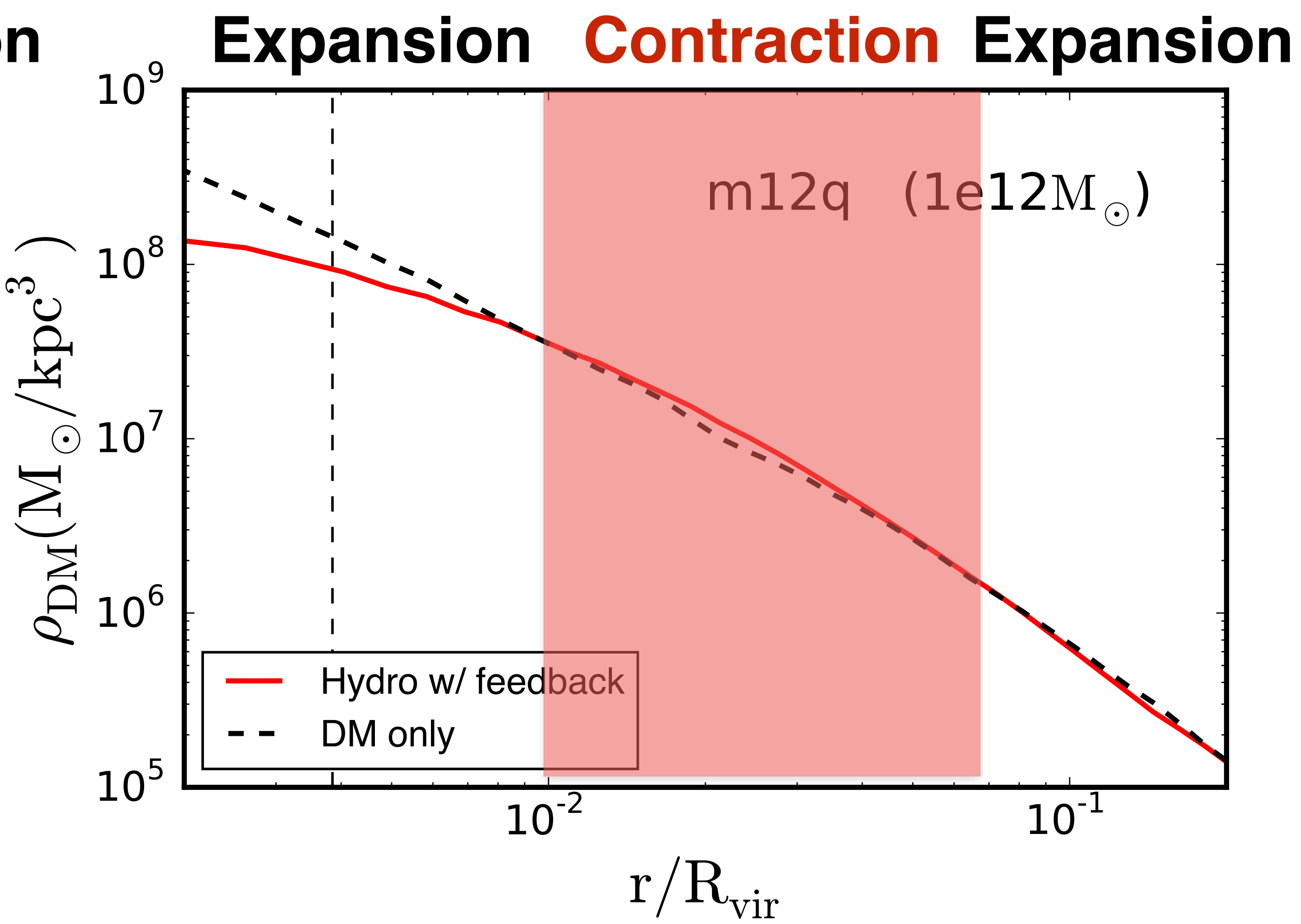

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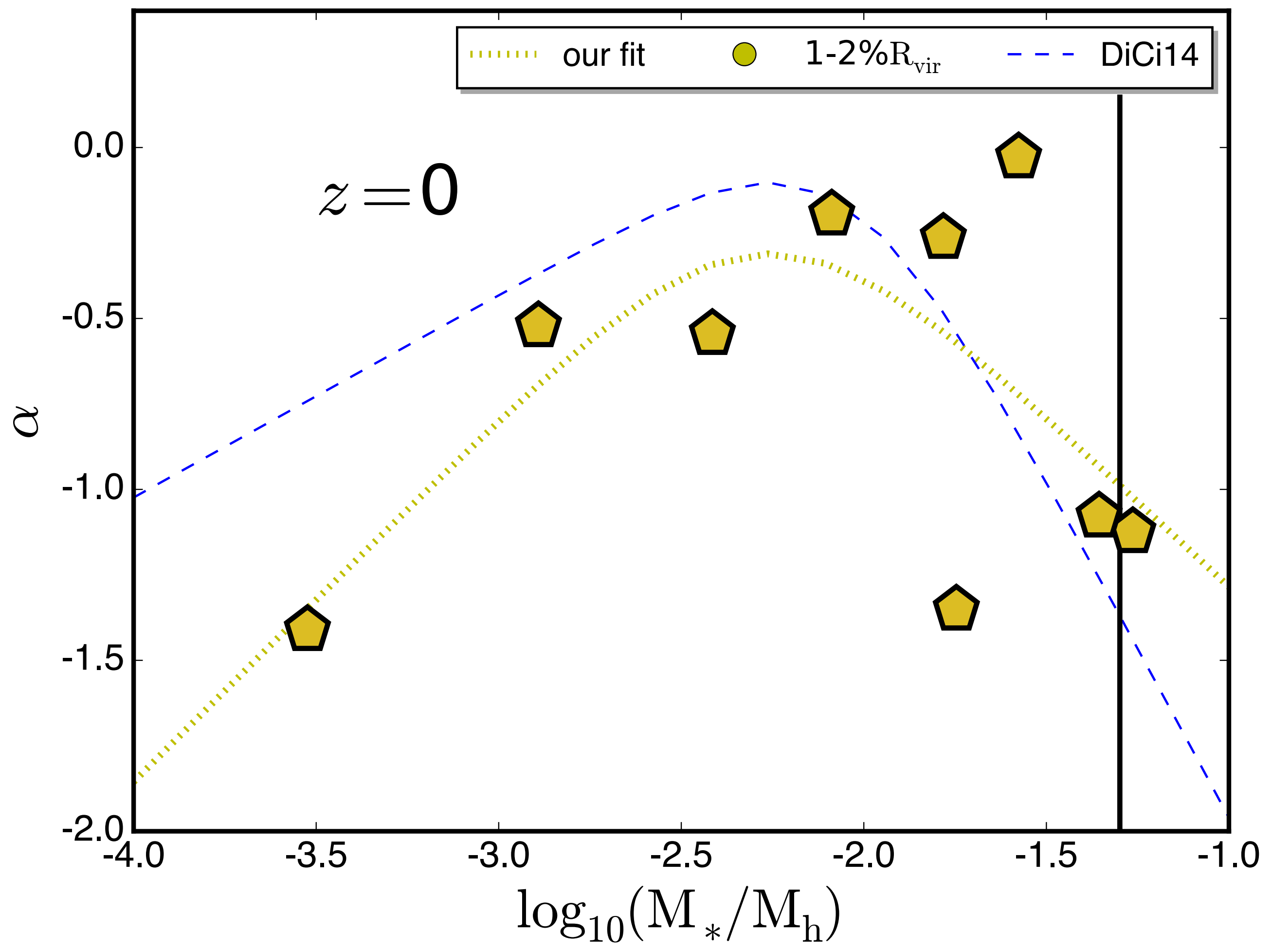
FIRE simulations



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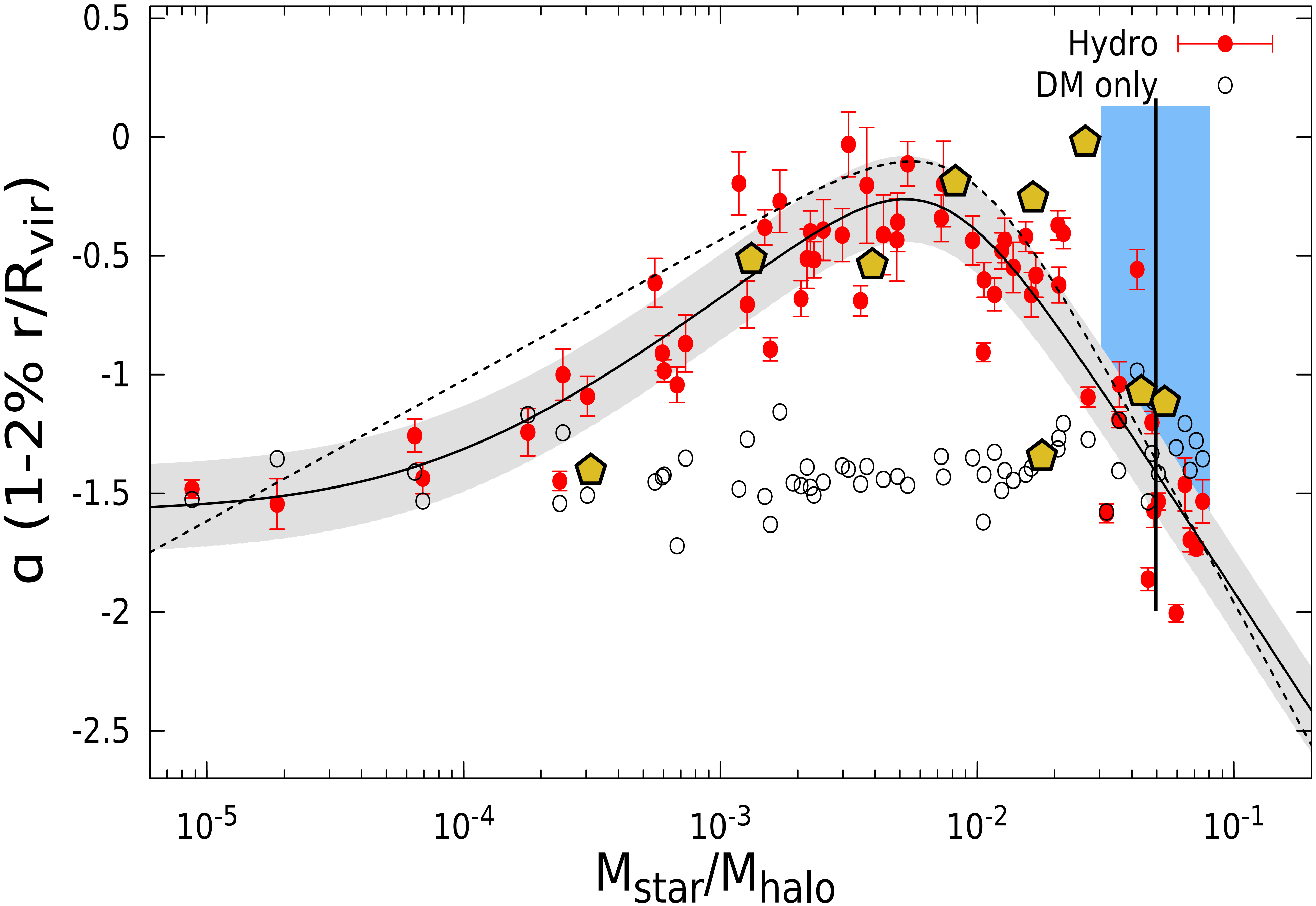
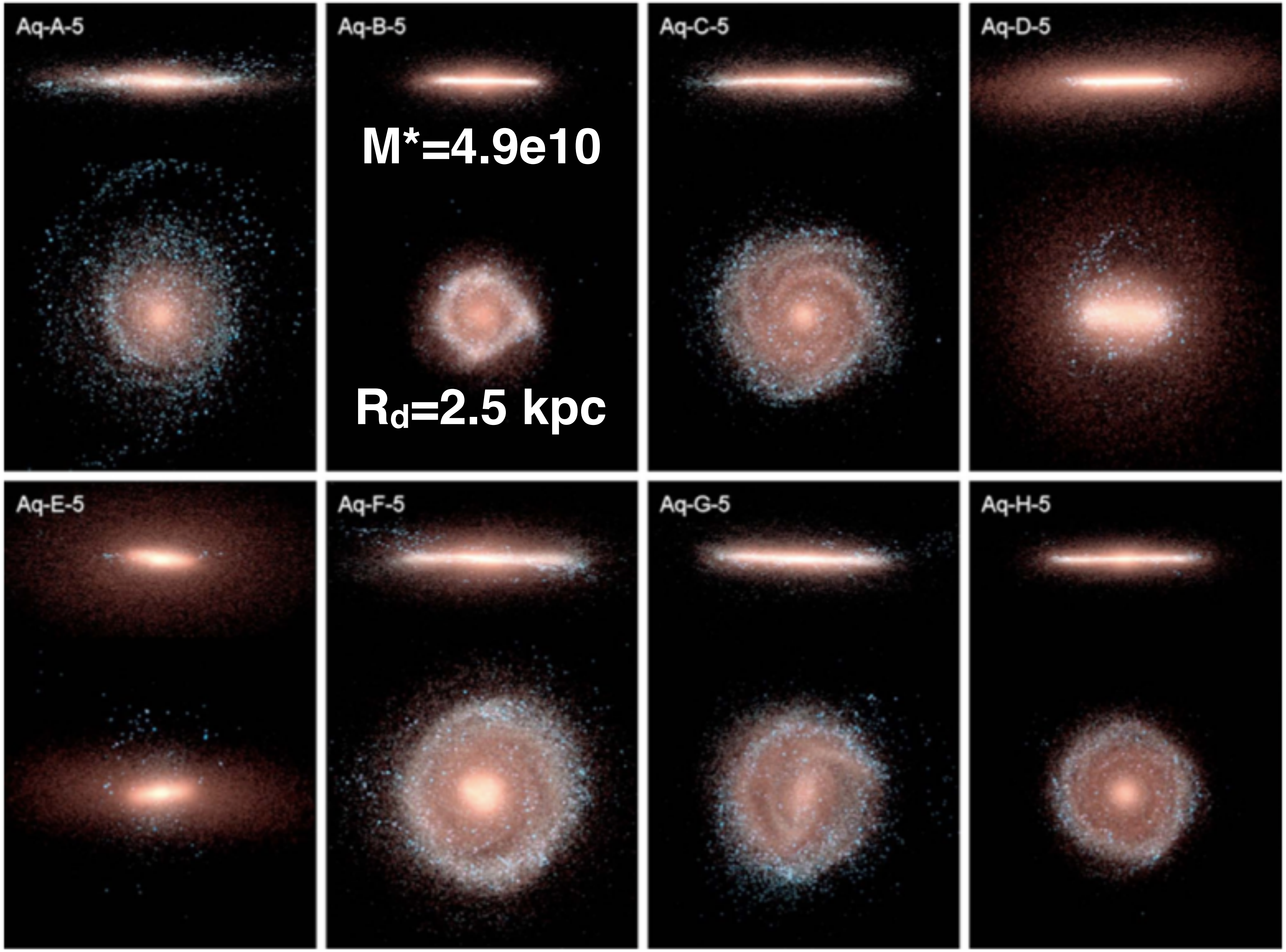


AREPO

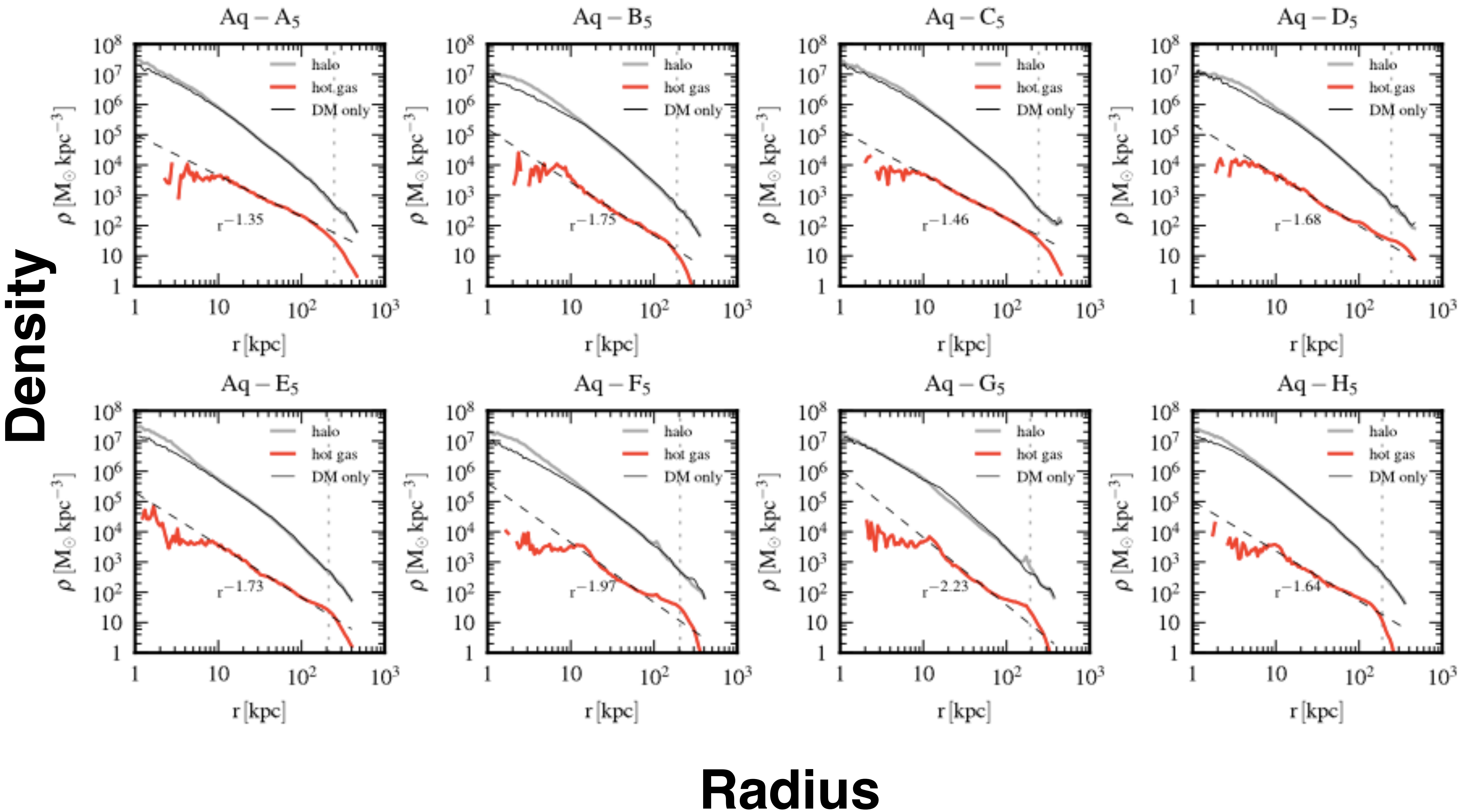
Milky Way mass zoom-ins



Marinacci, Pakmor, Springel, 2014, MNRAS, 437, 1750

AREPO

Contraction or no change

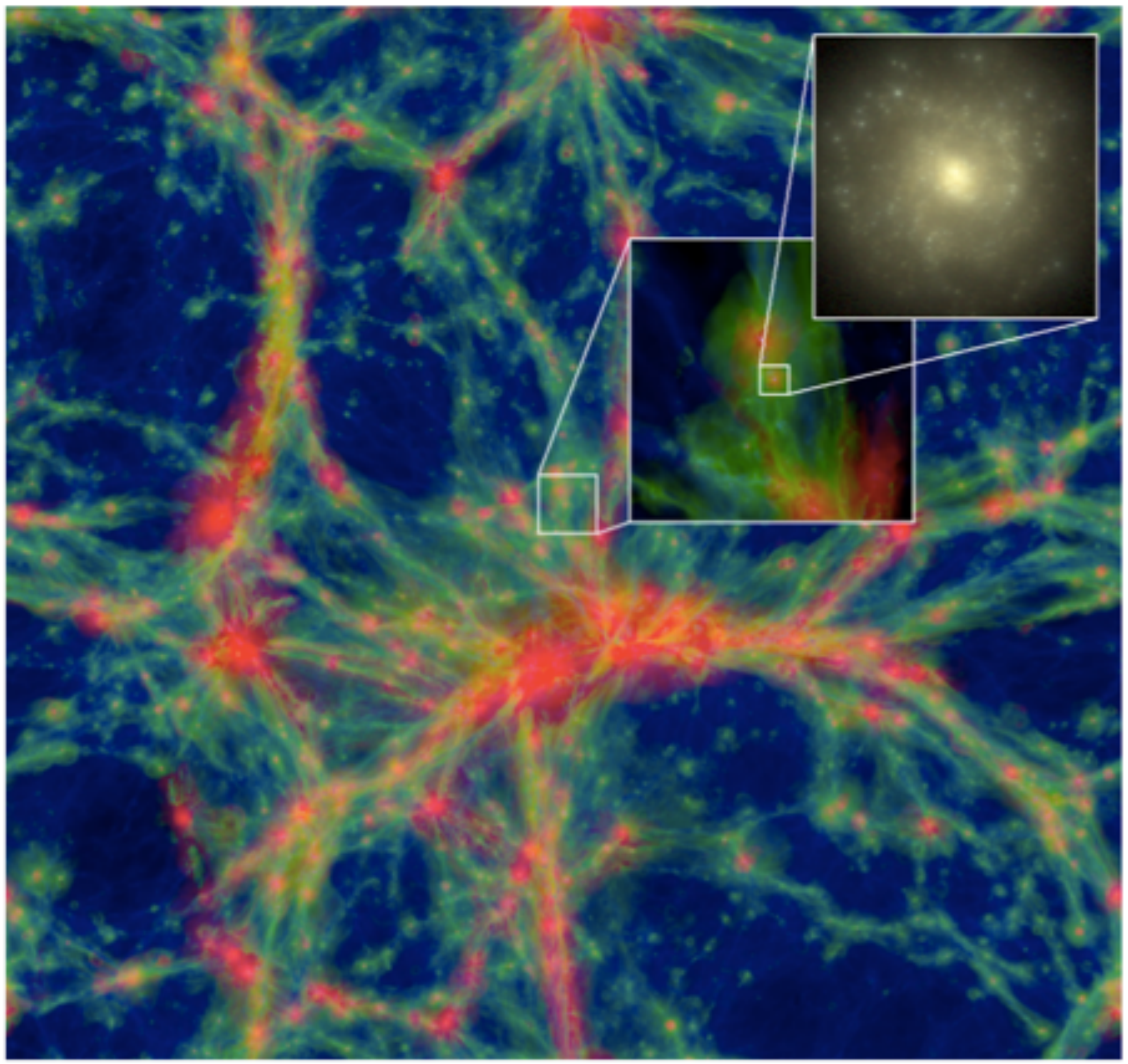


Marinacci, Pakmor, Springel, 2014, MNRAS, 437, 1750

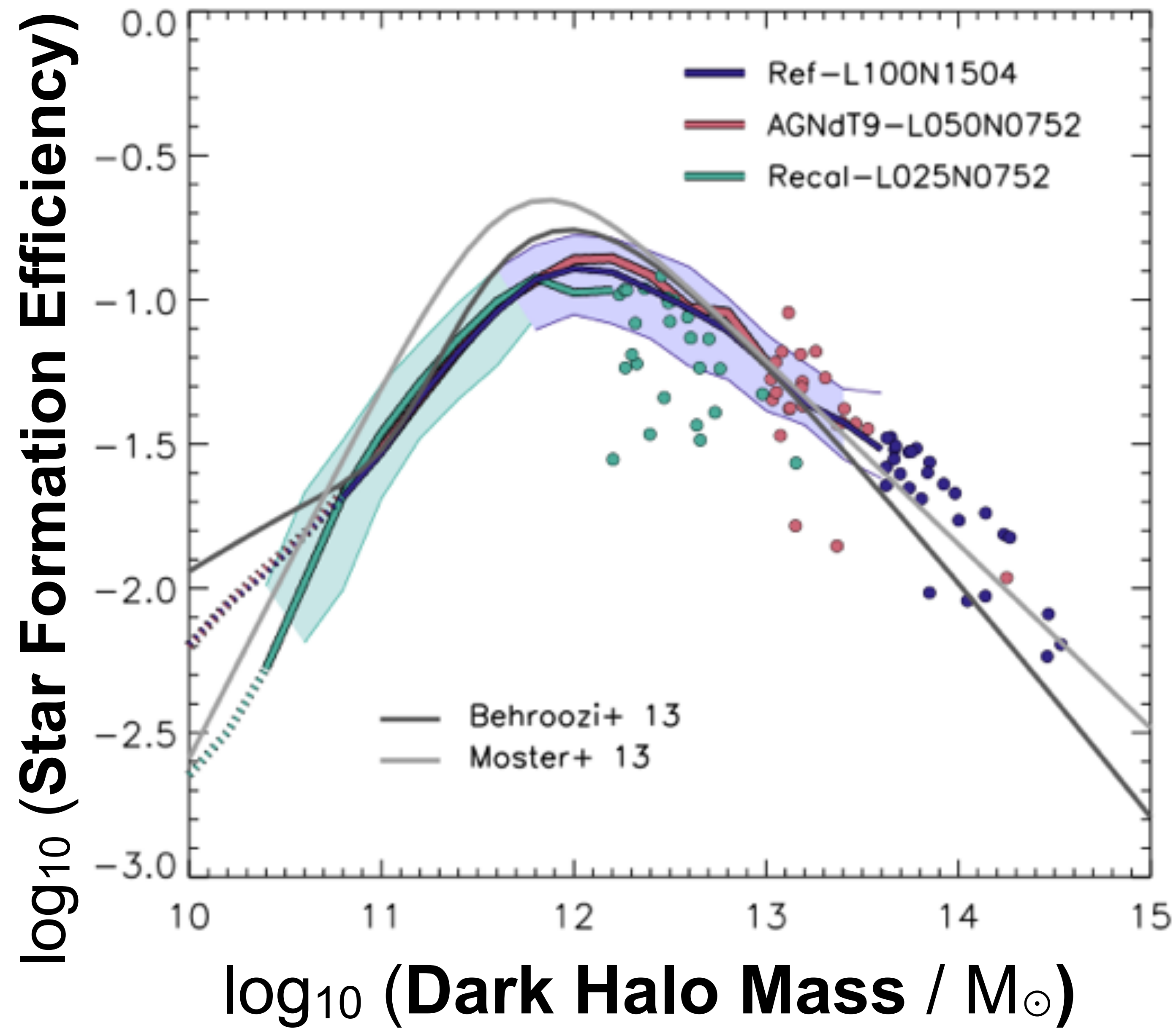
EAGLE

Schaye et al. 2015, MNRAS, 446, 521

Forms galaxies with the right amount of stars
(assuming a Milky Way IMF)

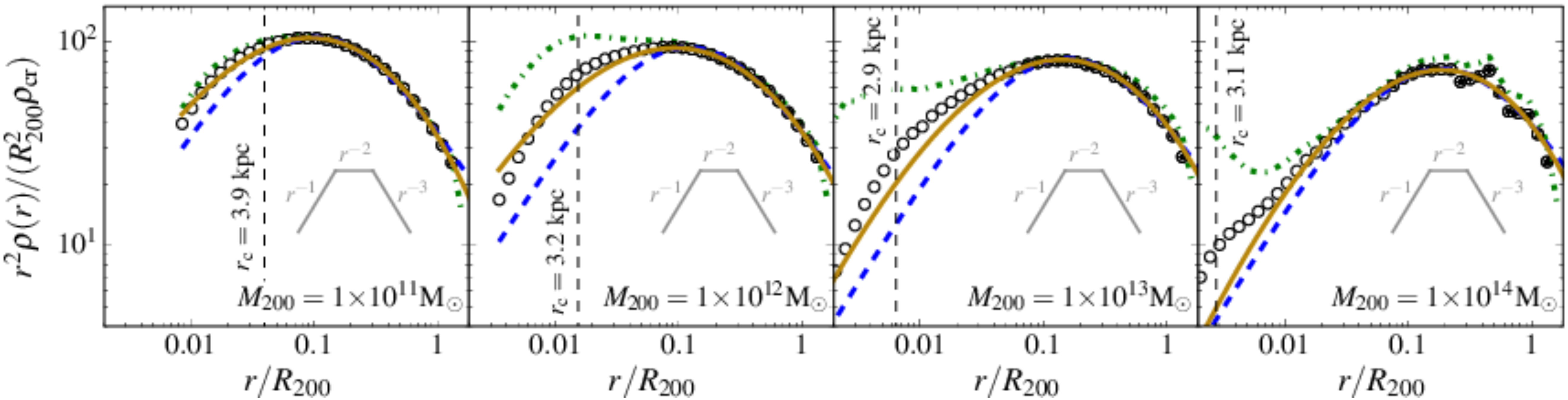


20 Mpc cutout



EAGLE

Slight Contraction or no change



Schaller et al. 2015, MNRAS, 451, 1247

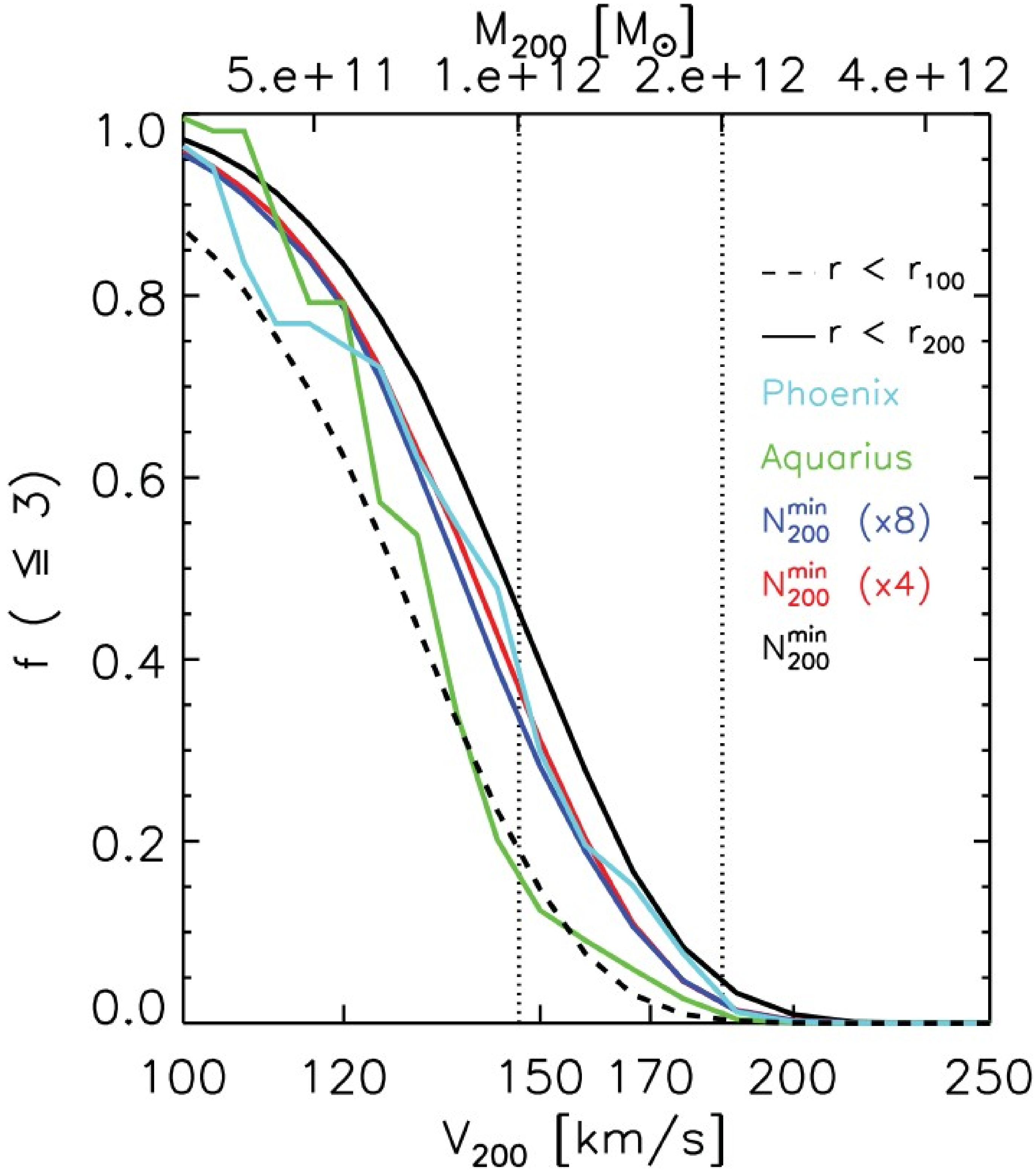
Challenge: Select a good MW host

Issue 1: What is the MW halo mass ?

a- Use abundance-matching

b- Use the number of (large) satellites

c- Use the internal structure (see later)



Wang et al., 2012, MNRAS, 424, 2715

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Issue 1: What is the MW halo mass ?

a- Use abundance-matching

b- Use the number of (large) satellites

c- Use the internal structure (see later)

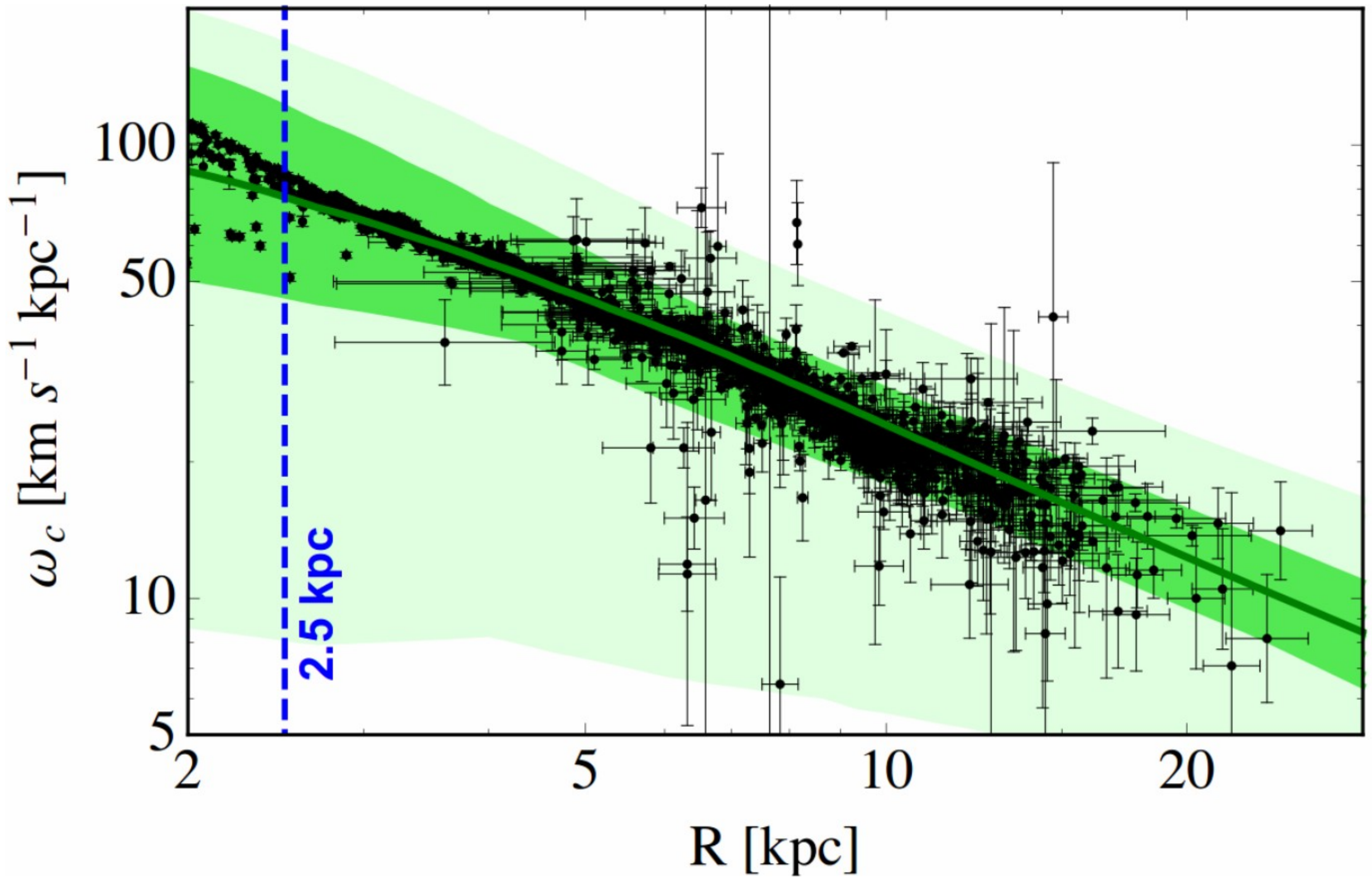
Issue 2: What is the MW internal structure ?

a- Use rotation curve data

b- Use local density estimate

c- Use morphology

d- Use SF history ?



Calore et al., 2015, JCAP, 12, 053

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Issue 2: What is the MW internal structure ?

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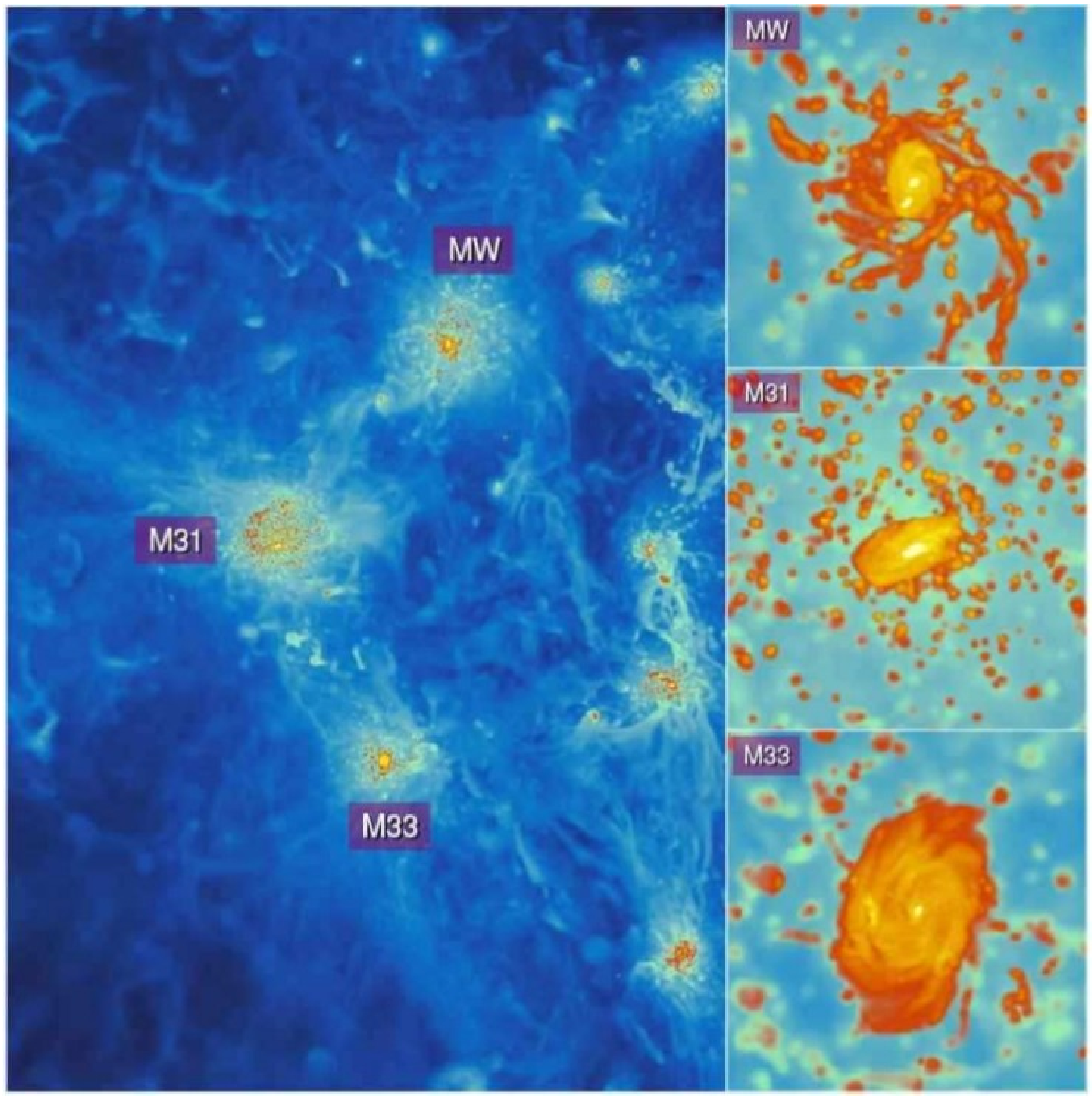
b- Use local density estimate

c- Use morphology

d- Use SF history ?

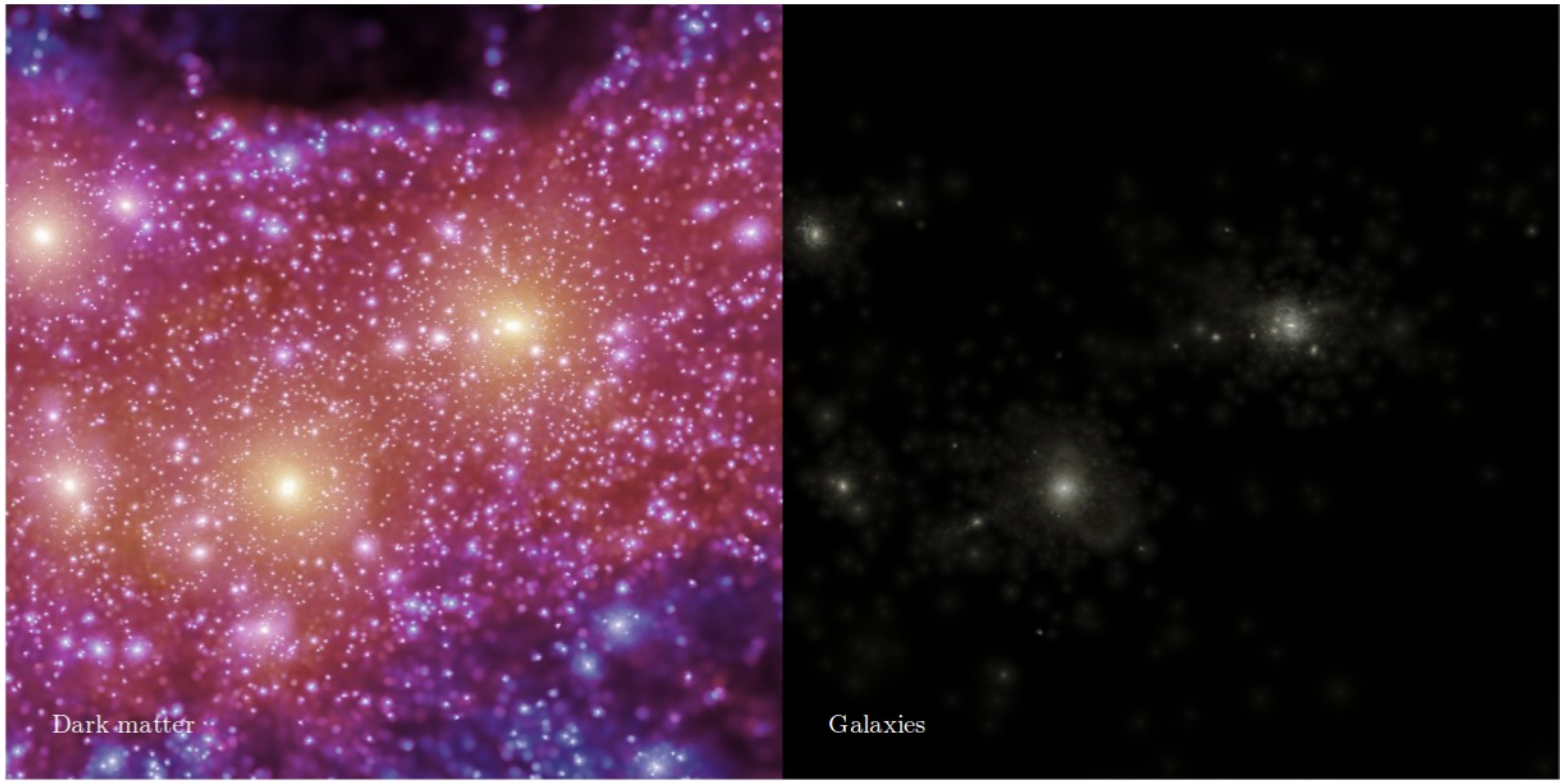
Issue 3: What is the environment of the MW ?



Gottloeber et al., 2010, 1005:2687

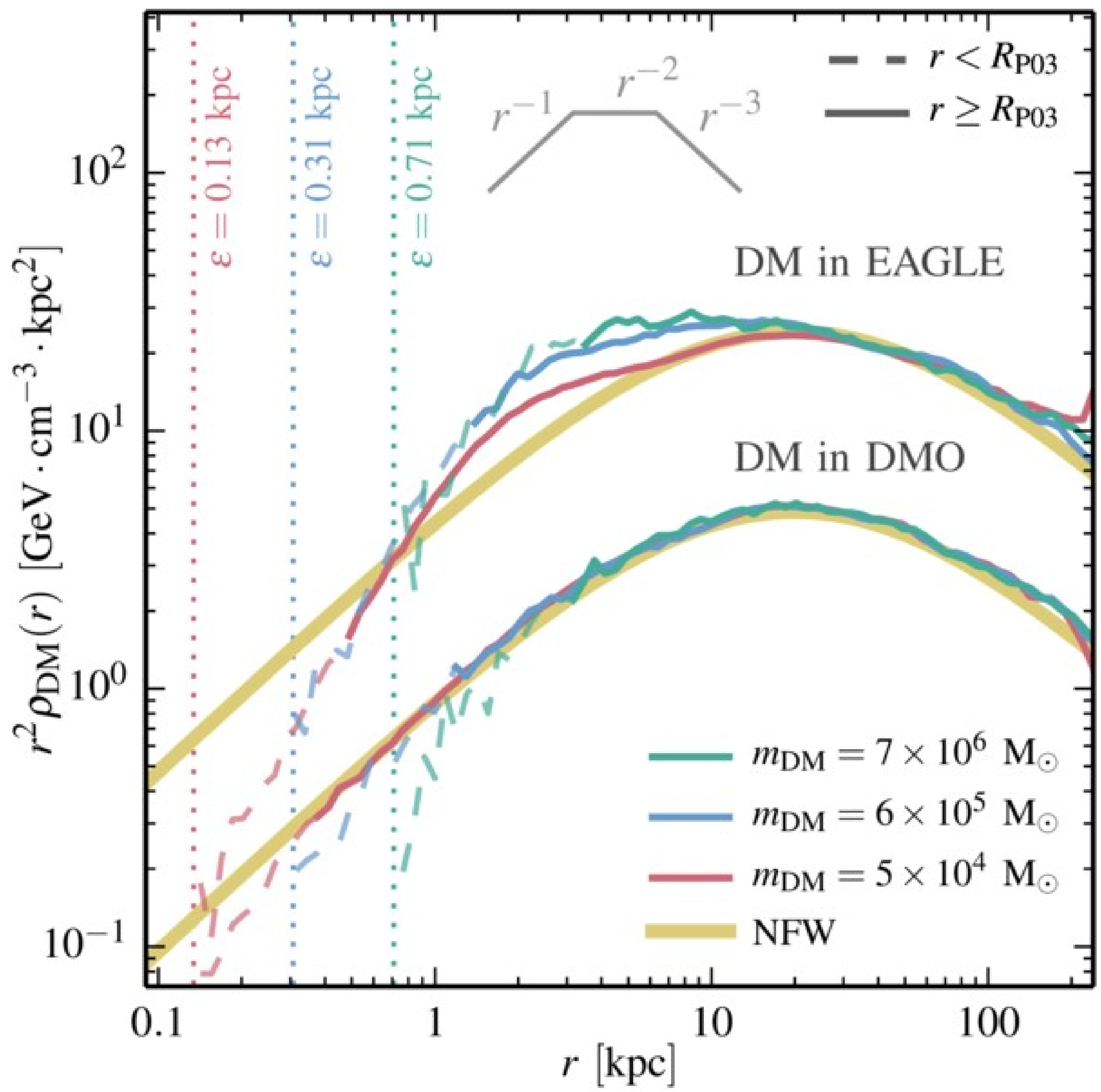
EAGLE MW-zooms

- Zoom regions containing a MW and M31 galaxy.
- Regions chosen to match dynamical properties of the Local Group.
- EAGLE code.
- Resolution of 10^4 for the gas/stars.



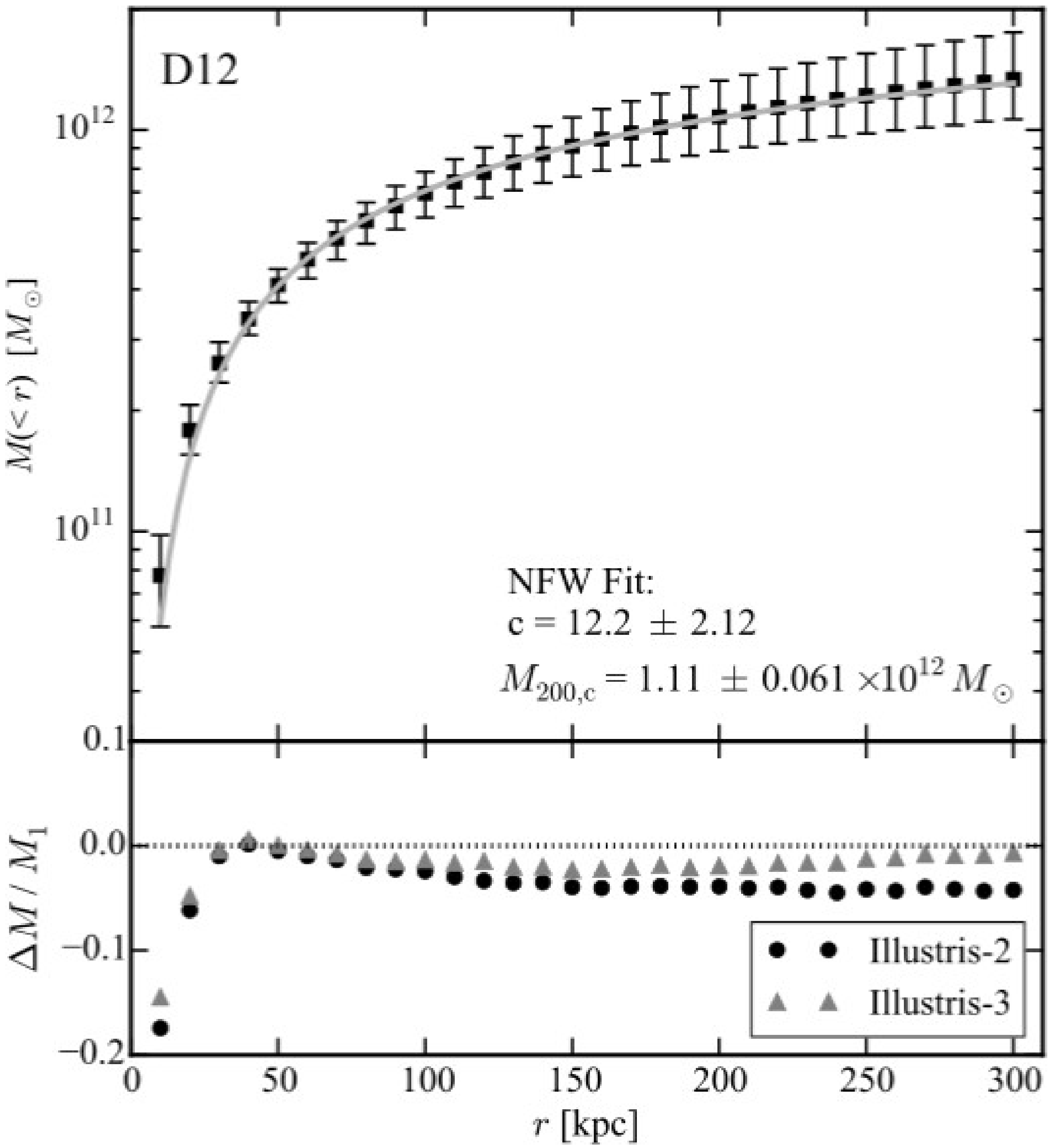
Sawala et al., 2016, MNRAS, 457, 1931
Fattahi et al., 2016, MNRAS, 457, 844

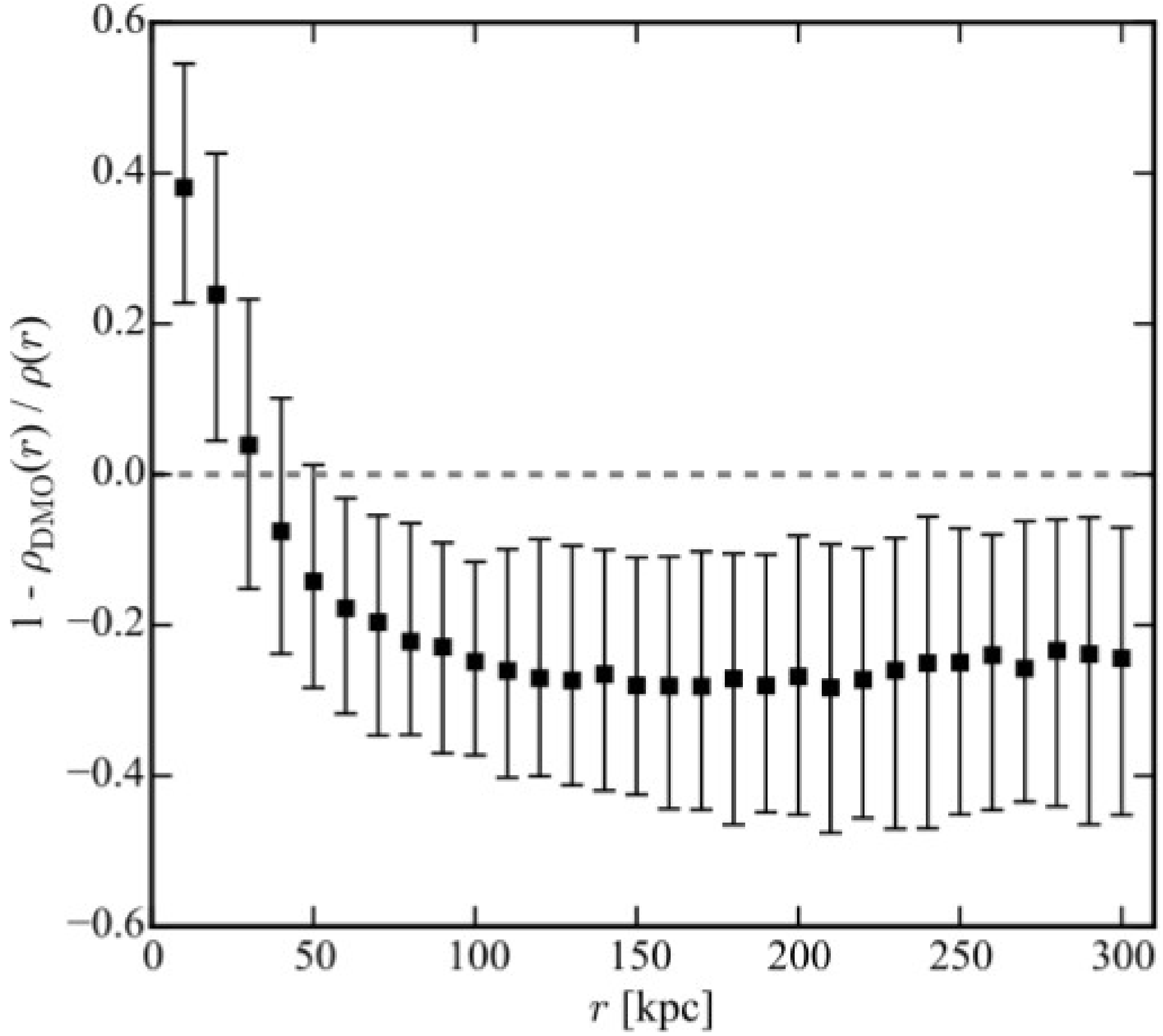
EAGLE MW-zooms



Schaller et al., 2016, MNRAS, 455, 4442

Illustris - GAIA halo selection

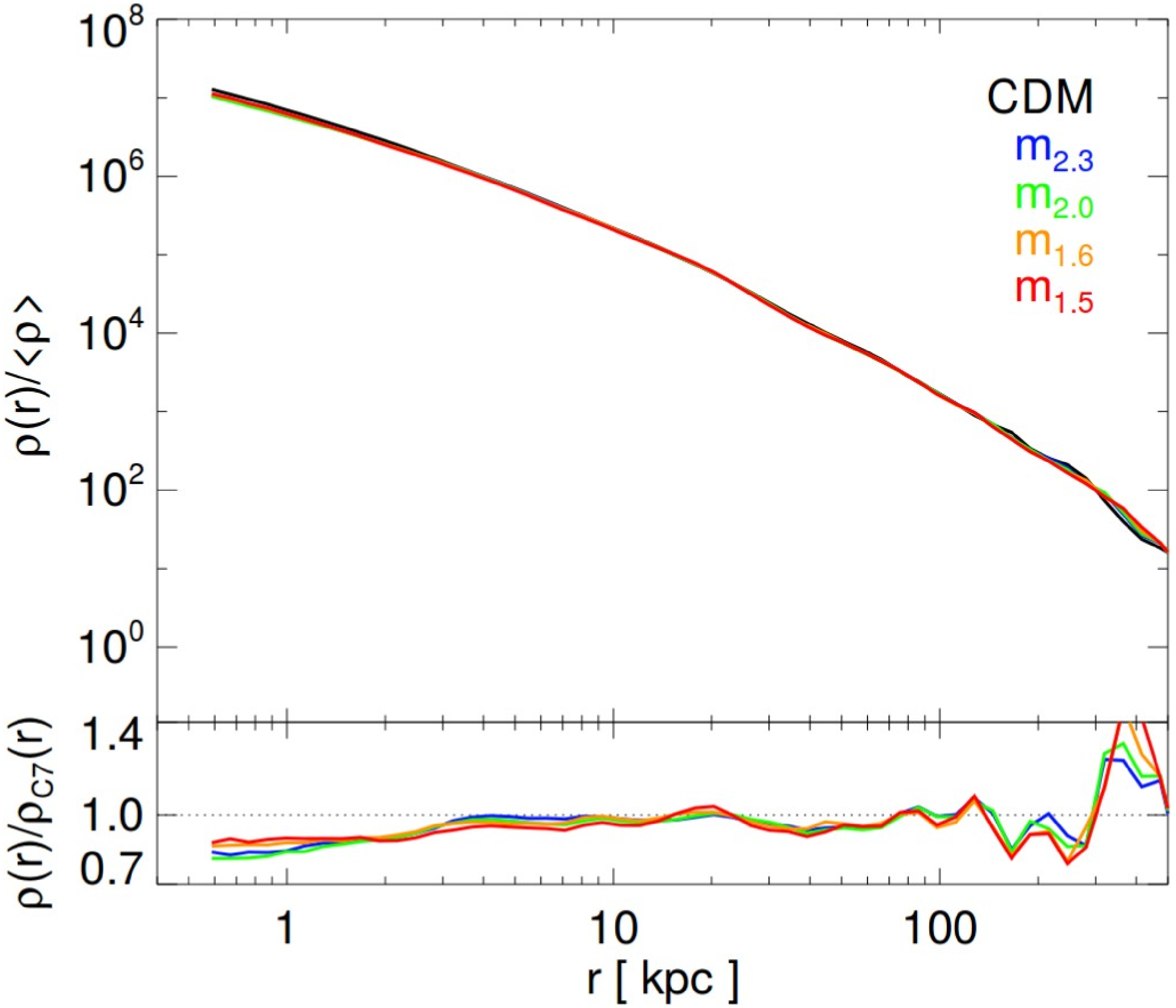




Taylor et al., 1510:06409

WDM

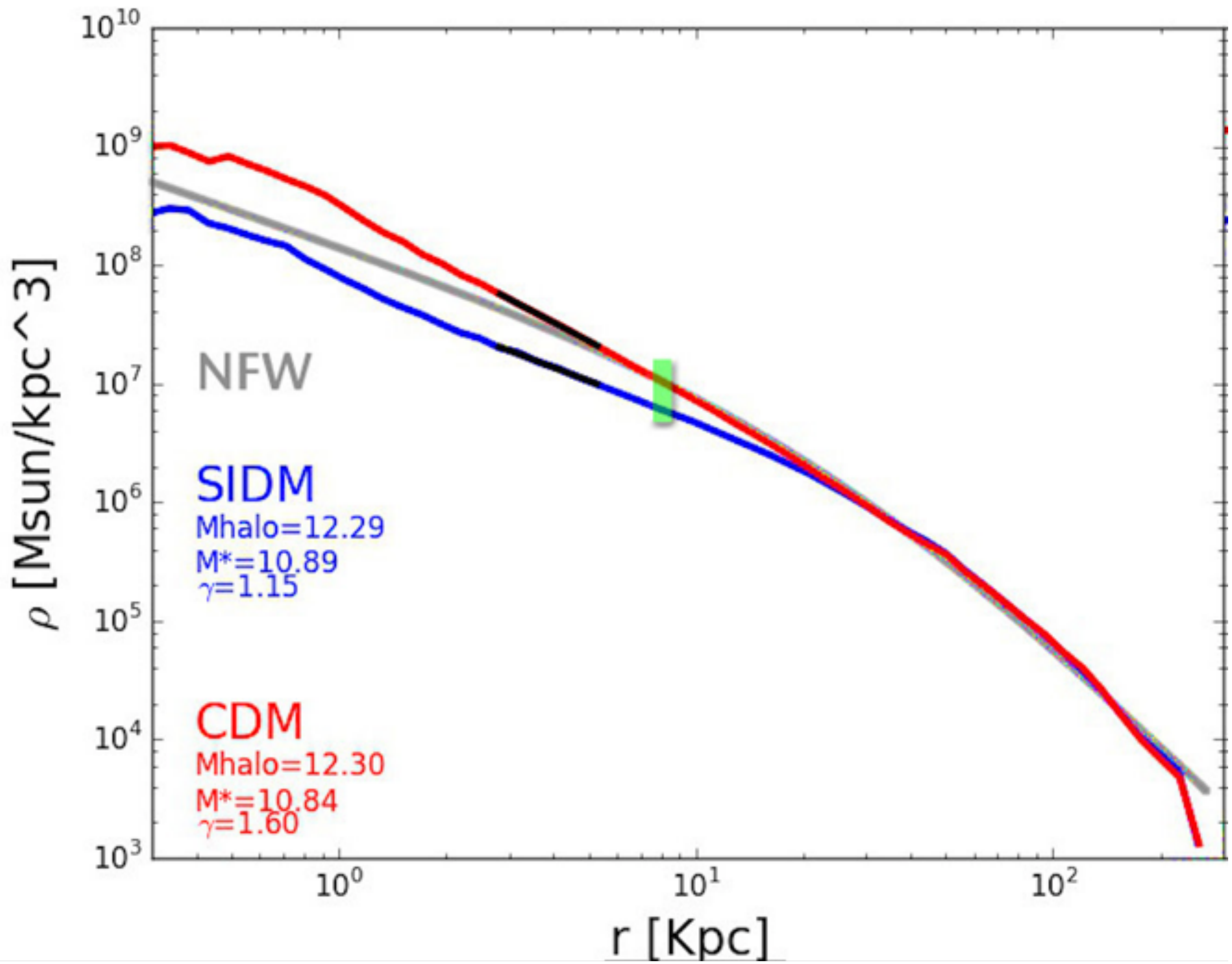
Very little effect



Lovell et al., 2014, MNRAS, 439, 300

SIDM

Halo expansion



Di Cintio, Governato, et al., in prep

Summary

- The Milky Way is at the mass scale where contraction from gas accretion and expansion from gas outflows roughly cancels out for resolved scales: $0.01 < r/r_{vir} < 1$.

- Selecting MW halos can be difficult and could explain differences. Select by stellar/halo mass ? SFR ? Satellite count ? Dynamics ? Environment ?

- Different hydro codes and sub-grid models give similar results (for weak halo response). Non-spherical symmetry not very much explored.

- What happens below 1% of the viral radius (~2 kpc)?