Dark Matter halo response to gas inflows and outflows

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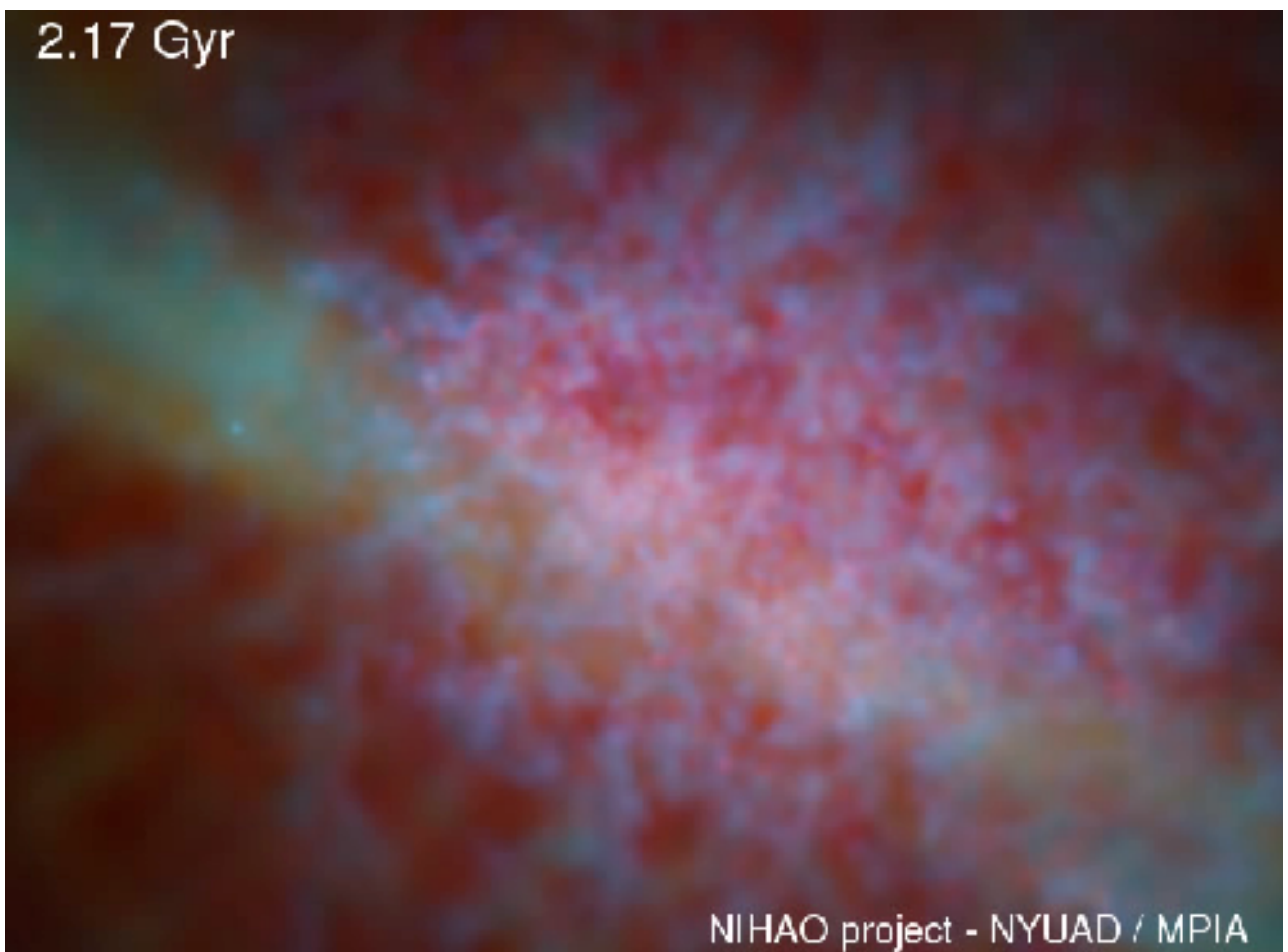

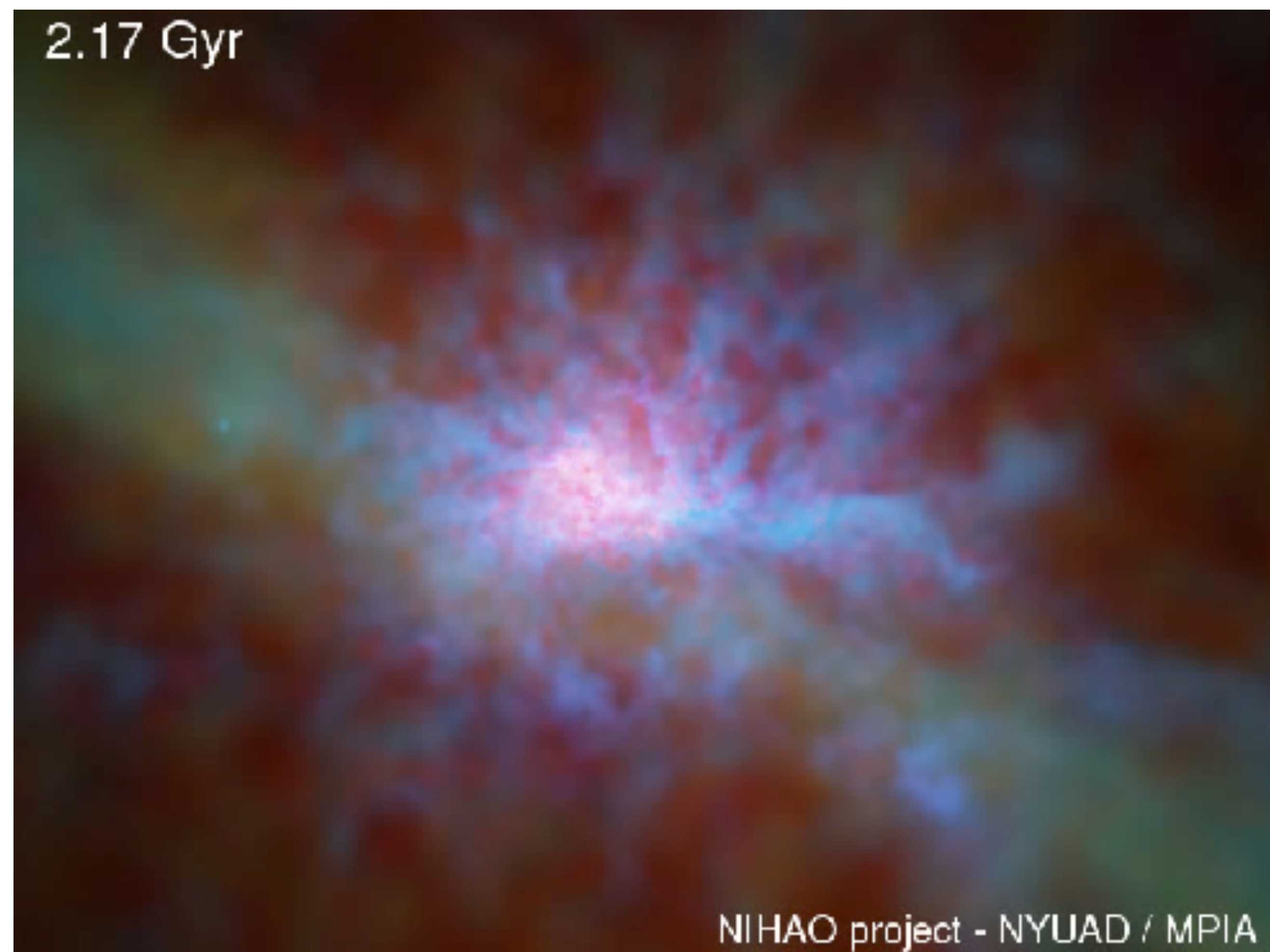

15th Potsdam Thinkshop - September 2018

The NIHAO team and collaborators

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- Liang Wang (I, VII)
- Greg S. Stinson (III)
- Aura Obreja (VI, XVI)
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- Iryna Butsky (II)
- Edouard Tollet (IV)
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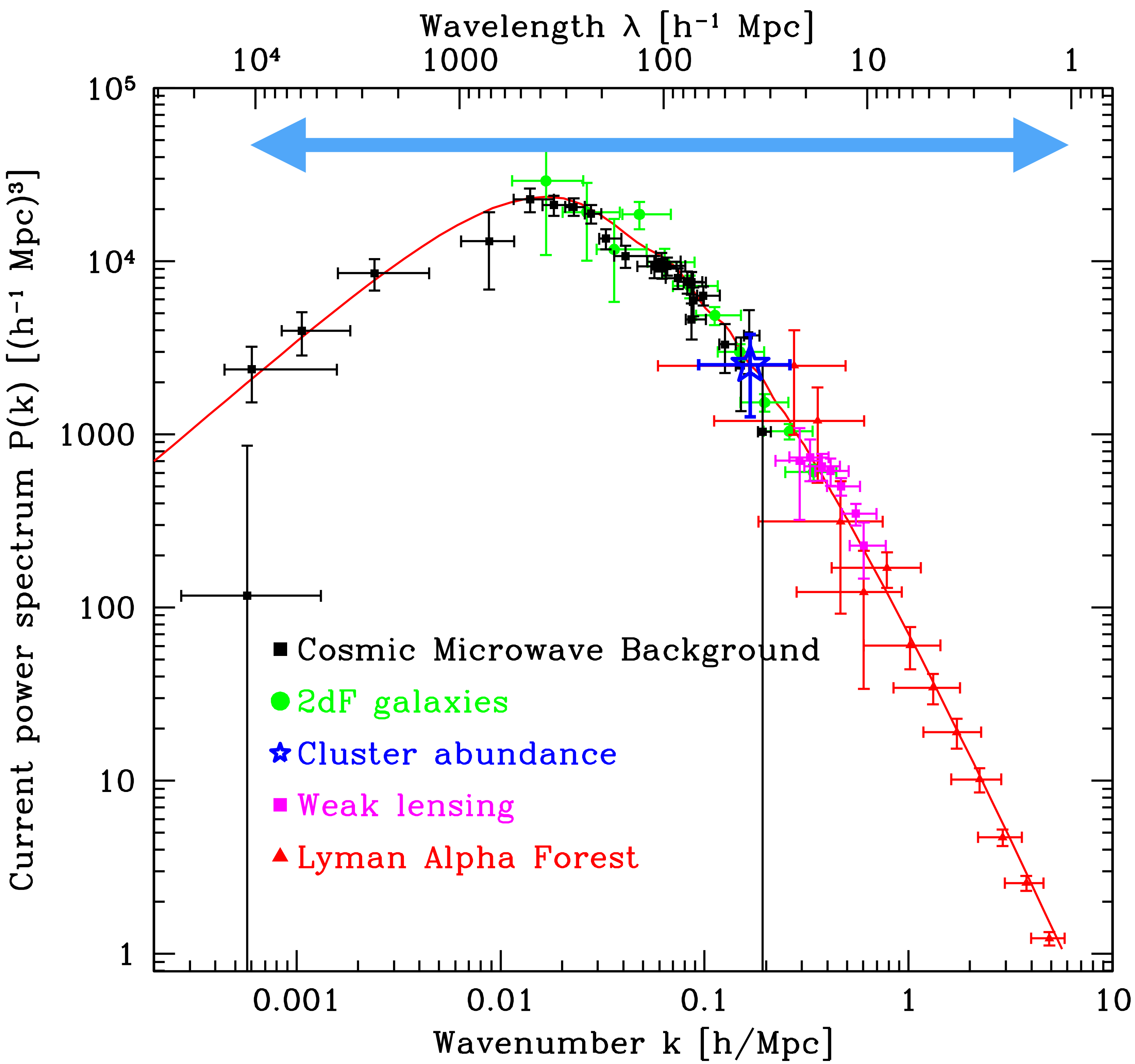
- Avishai Dekel
- Rosa Domínguez-Tenreiro
- Gian Luigi Granato
- Jacob Herpich
- Jeremy D. Bradford
- Tom R. Quinn
- Ben Moster
- Glenn van de Ven
- Ling Zhu

Cold **D**ark **M**atter works on large scales

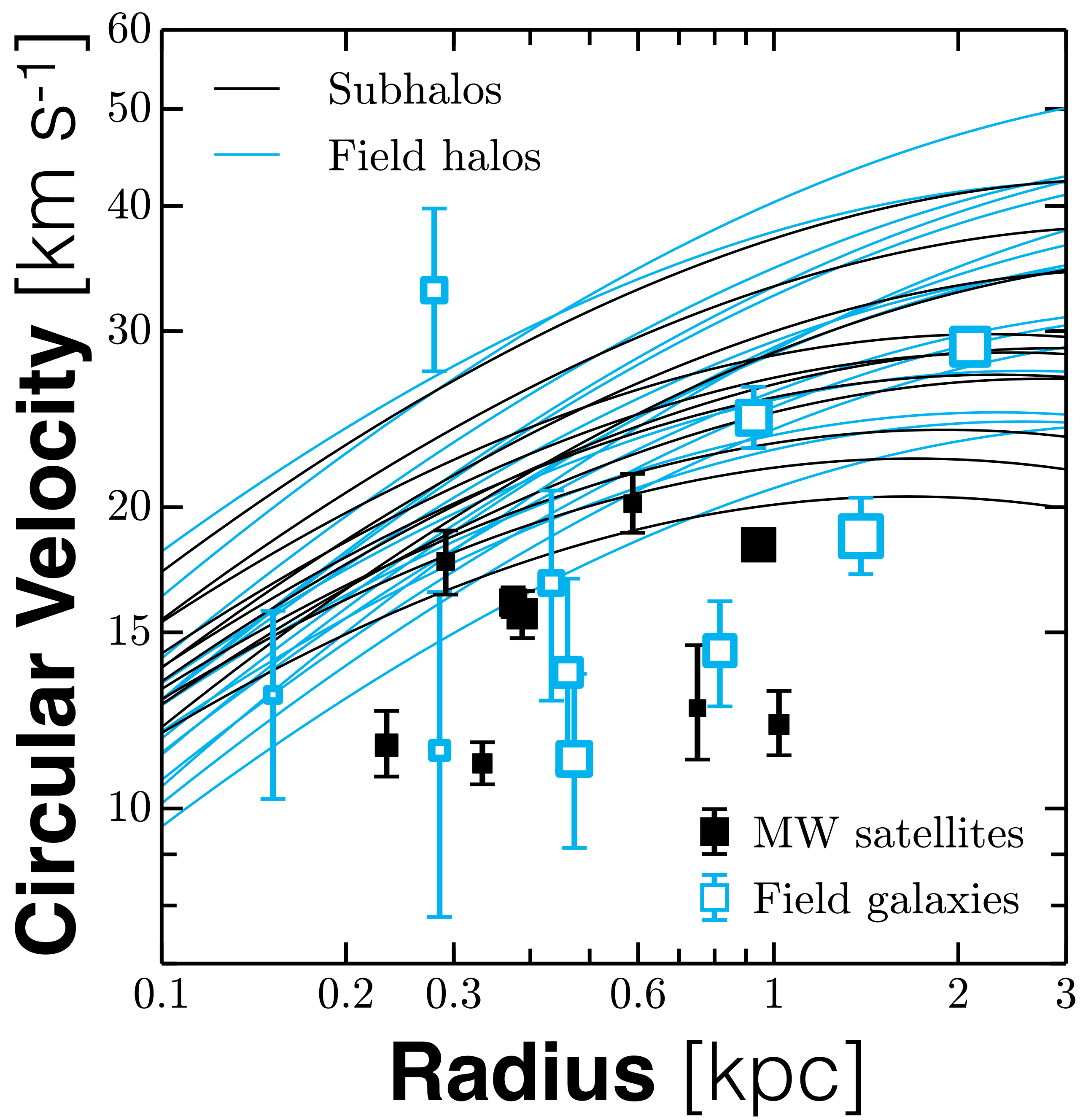


4

orders of magnitude in scale

Tegmark et al 2004

Cold **D**ark **M**atter fails on small scales

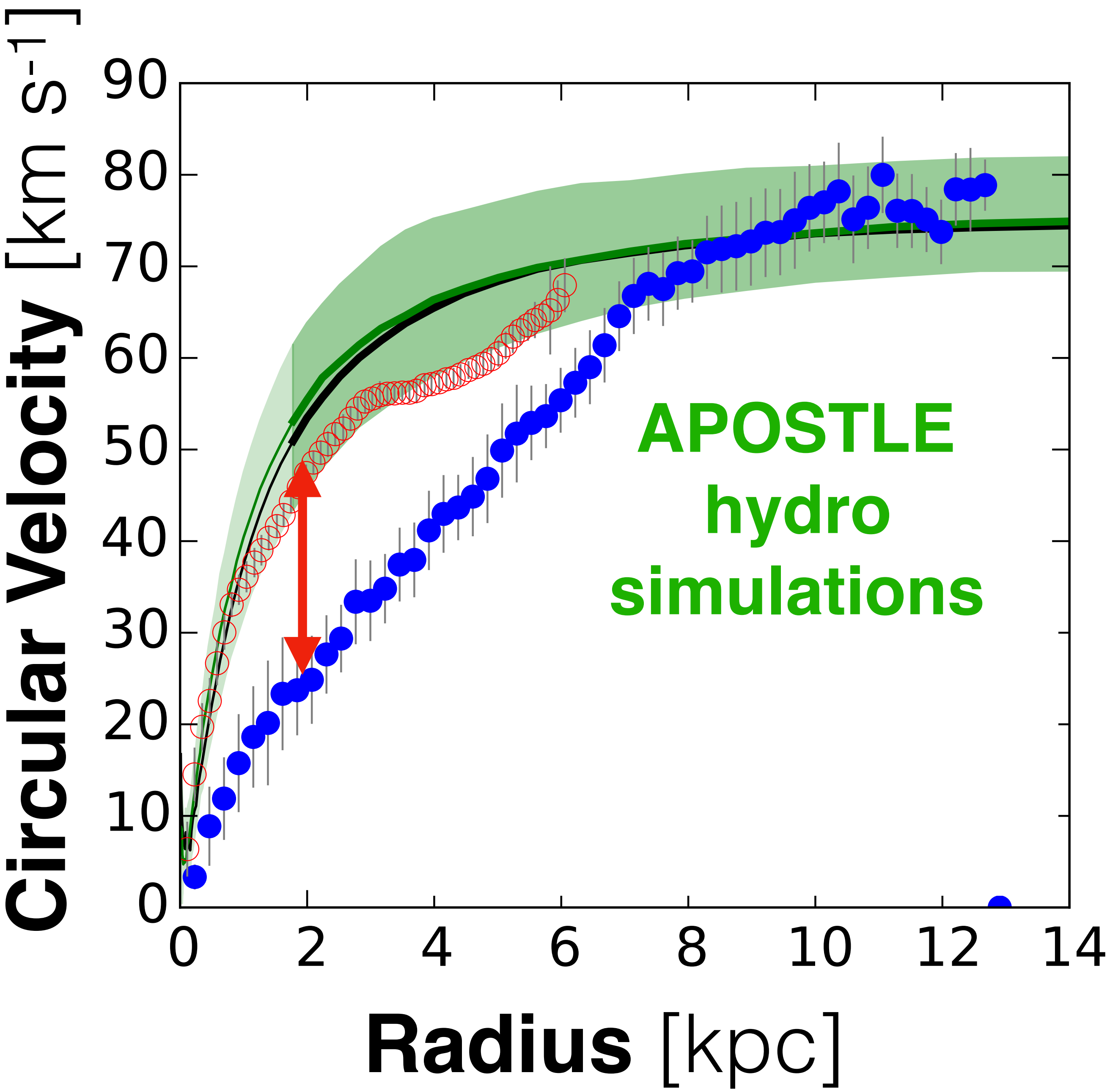


Garrison-Kimmel, Boylan-Kolchin, Bullock, Kirby 2014

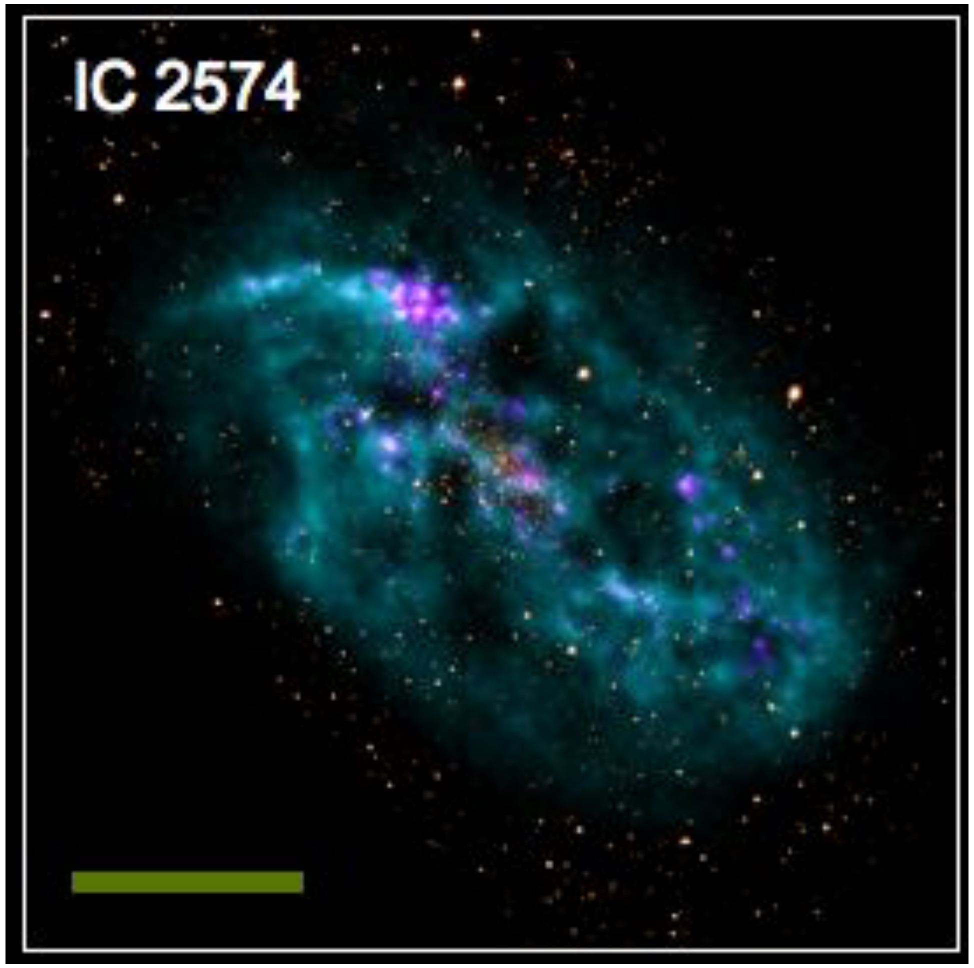
Cold **D**ark **M**atter fails on small scales

Moore et al. 1994, Flores & Primack 1994, de Blok et al. 2001, 2008, …

Discrepancy: Factor ~2 in velocity ⇒ factor ~ 4 in mass



Oman et al. 2015

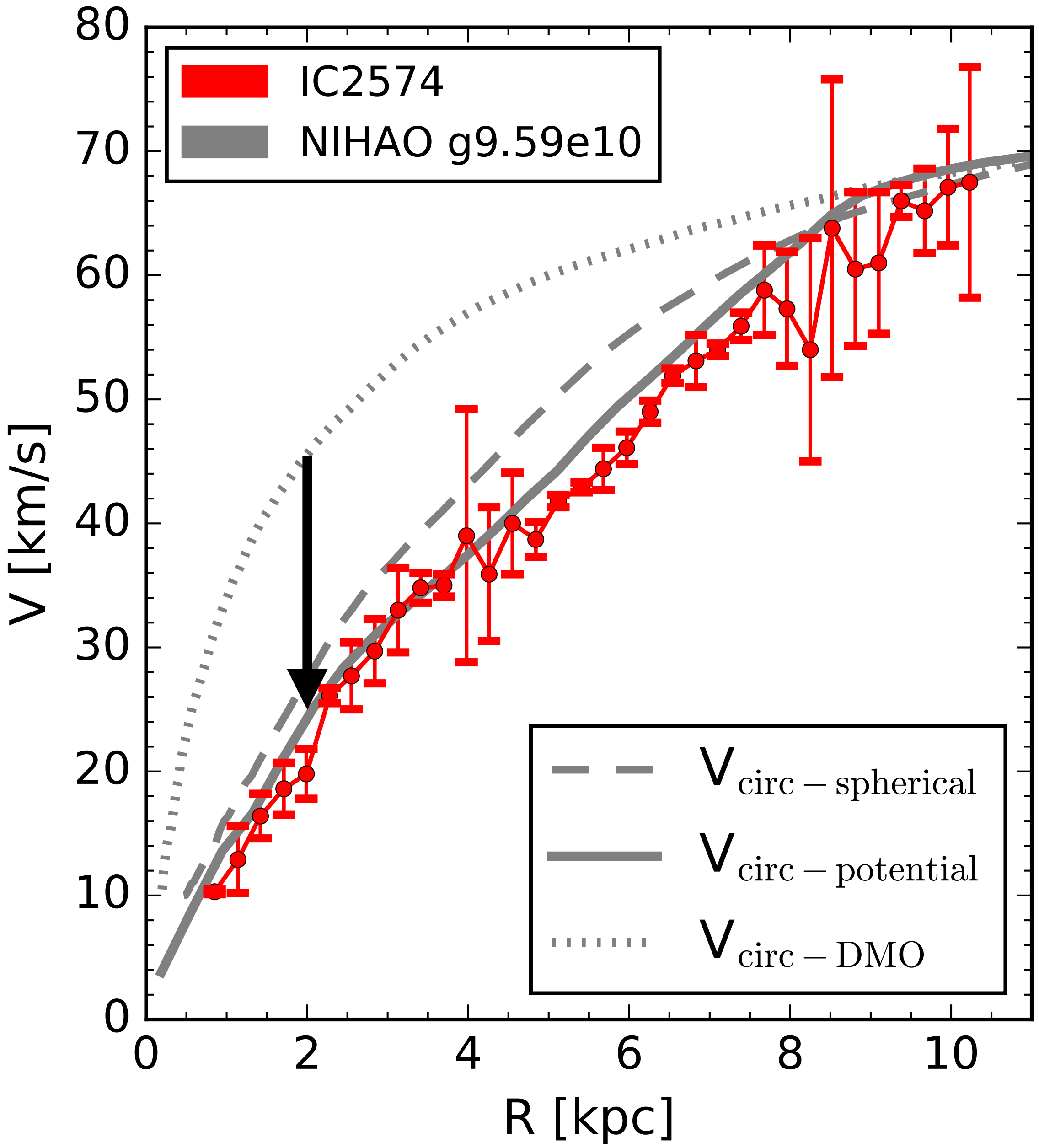


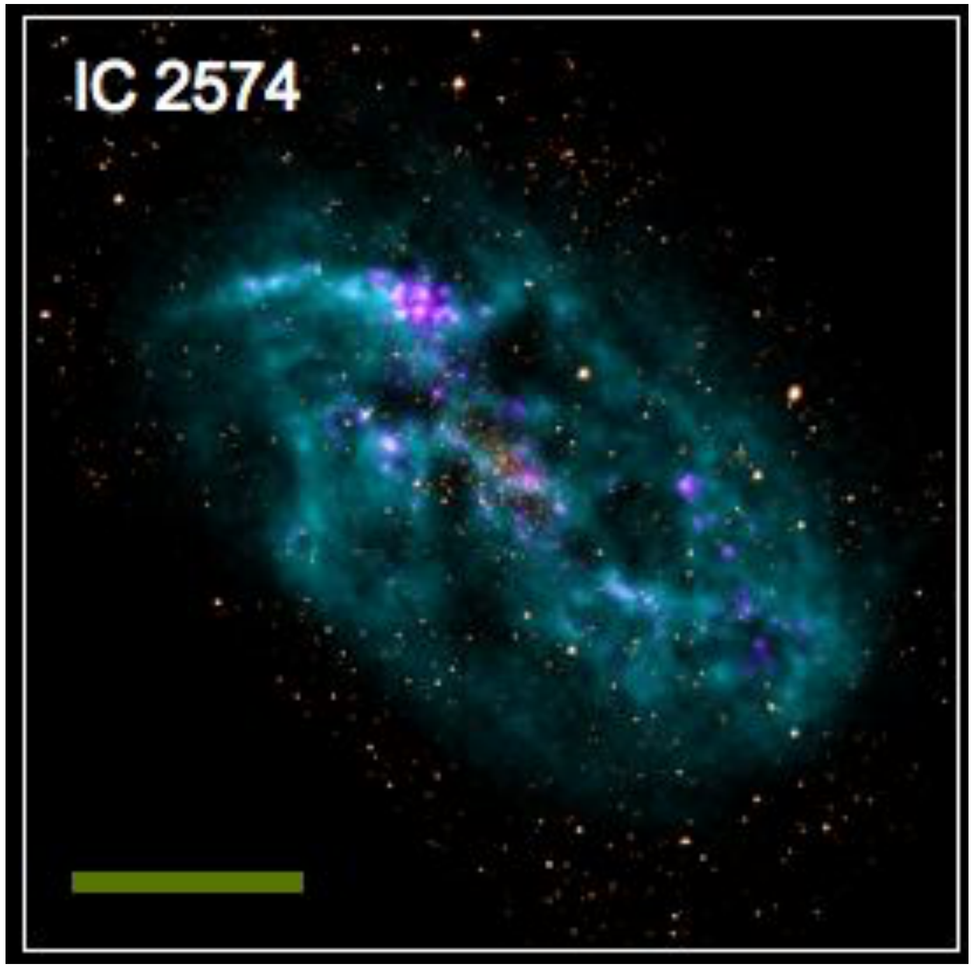
4.6 kpc

Cold **D**ark **M**atter works on small scales

SN driven gas outflows **can** expand the dark matter halo

e.g., Navarro, Eke, Frenk 1996; Read & Gilmore 2005; Mashchenko et al. 2006, 2008; Governato et al. 2010; Pontzen & Governato 2012; Teyssier et al. 2013; Di Cintio et al. 2014a,b; Chan et al. 2015; Trujillo-Gomez et al. 2015





NIHAO XIV - Santos-Santos et al. 2018 - see poster

What determines how **G**alaxy **F**ormation modifies the **D**ark **M**atter distribution in LCDM simulations?

M_{star} / M_{halo}

Star Formation Efficiency

n

Star Formation Threshold

Toy Model

Consider a shell of radius r_i and mass M_i

Adiabatic Inflow
(Blumenthal+1986)

$$\frac{r_{\rm a}}{r_{\rm i}} = (1 - f_{\rm in}), \quad \frac{M_{\rm a}}{M_{\rm i}} = \frac{1}{(1 - f_{\rm in})}.$$

Contraction

Impulsive Outflow

$$\frac{r_{\rm f}}{r_{\rm a}} = \frac{1 - f_{\rm out}}{1 - 2f_{\rm out}}, \quad \frac{M_{\rm f}}{M_{\rm a}} = 1 - f_{\rm out}.$$

Expansion

1 cycle $f_{\rm out} = \beta f_{\rm in}$

$$\frac{r_{\rm f}}{r_{\rm i}} = \frac{(1 - \beta f_{\rm in})(1 - f_{\rm in})}{1 - 2\beta f_{\rm in}}, \quad \frac{M_{\rm f}}{M_{\rm i}} = \frac{1 - \beta f_{\rm in}}{1 - f_{\rm in}}.$$

N cycles

$$\frac{r_{\rm f}}{r_{\rm i}} = \left[\frac{(1 - f_{\rm in})(1 - \beta f_{\rm in})}{(1 - 2\beta f_{\rm in})}\right]^N, \quad \frac{M_{\rm f}}{M_{\rm i}} = \left[\frac{1 - \beta f_{\rm in}}{1 - f_{\rm in}}\right]^N$$

NIHAO IX - Dutton et al. 2016b

Toy Model

N cycles $\beta=1$ $\quad r_f/r_i = (1 - 2f + f^2)^N / (1-2f)^N$

Net Expansion

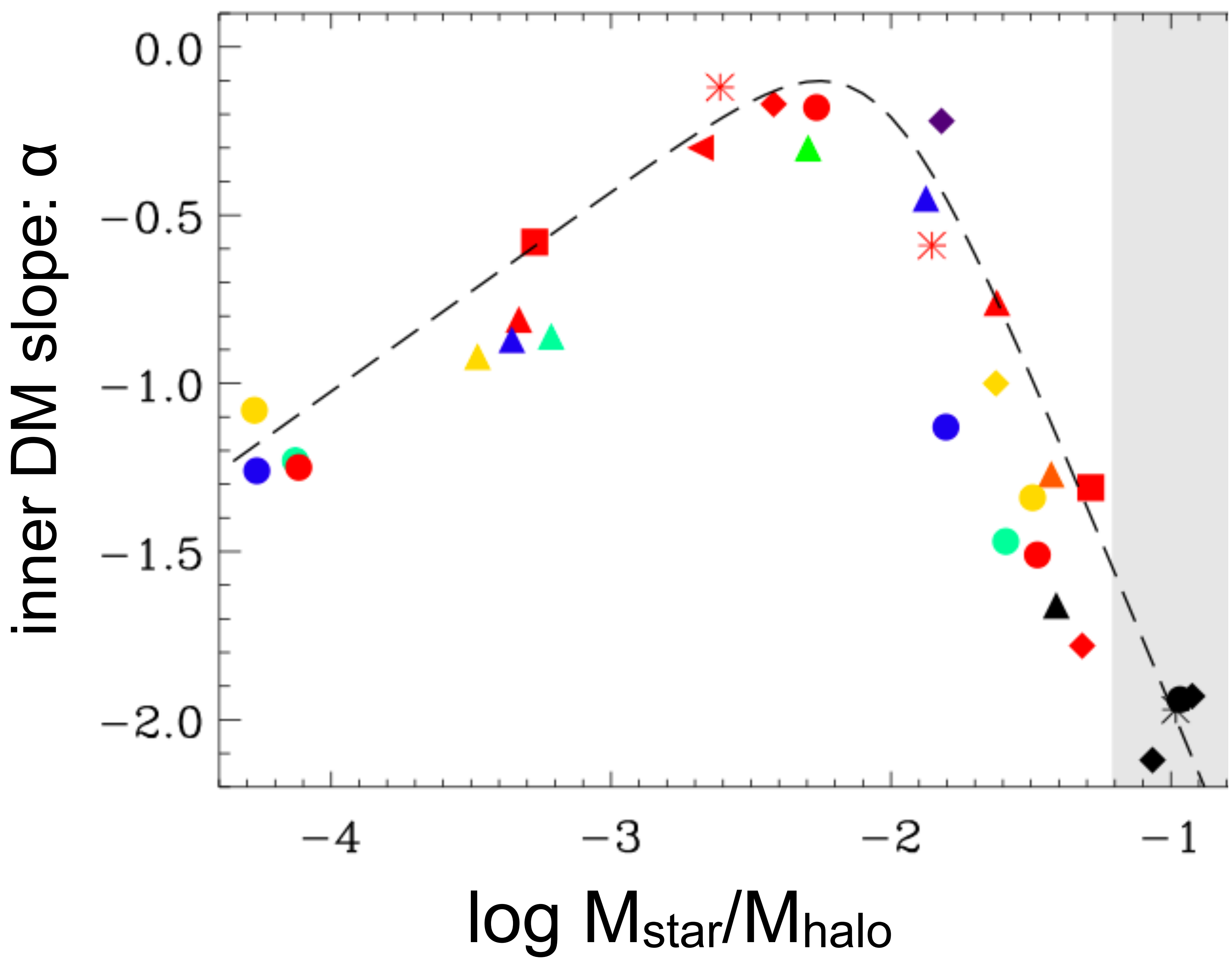
$$\boxed{r_f/r_i = 1 + N f^2 + O(f^3)}$$

- Need many cycles, with f≳0.1 to generate significant expansion
- If outflow events are small, then halo cannot expand much

NIHAO IX - Dutton et al. 2016b

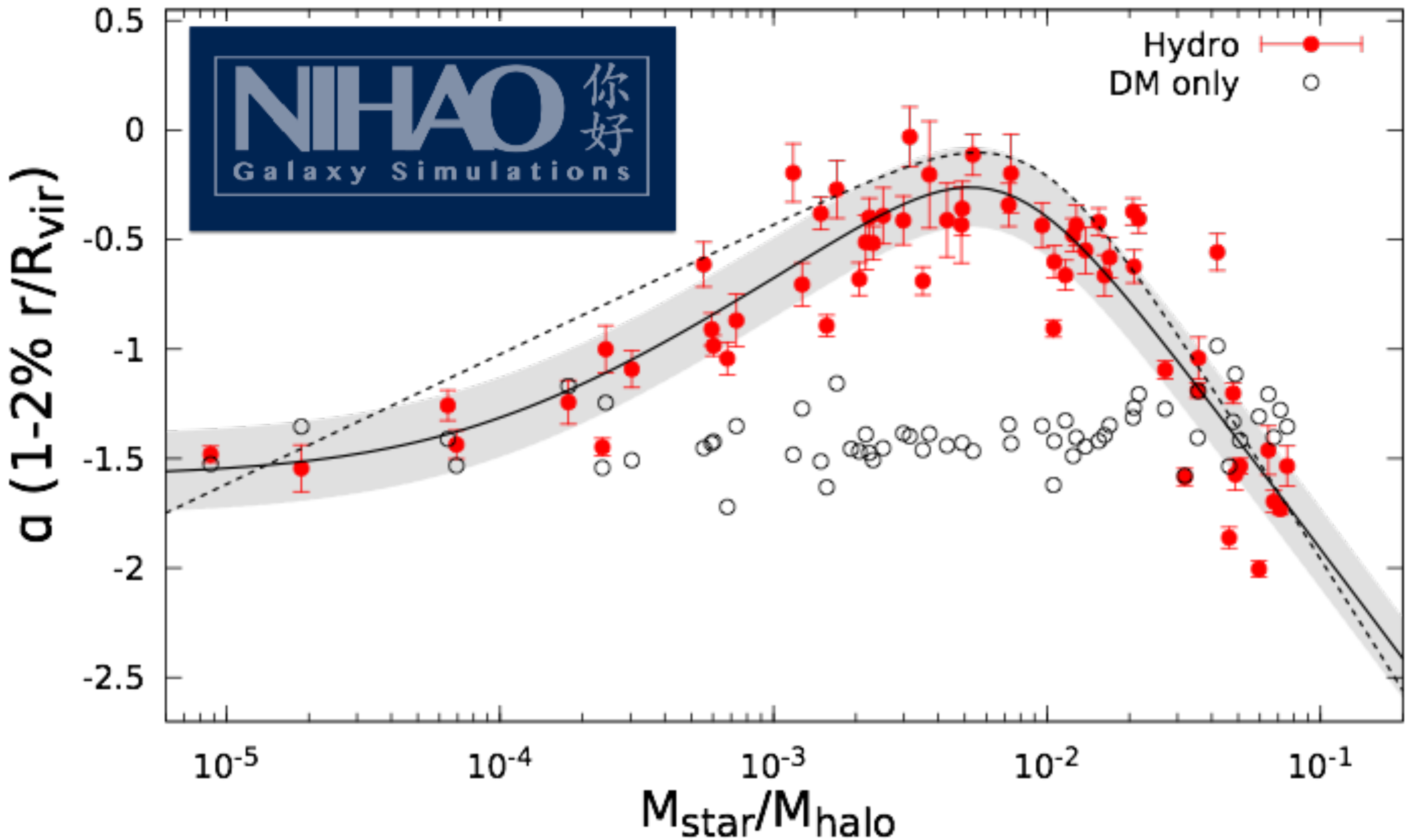
Halo Response depends on Star Formation Efficiency

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



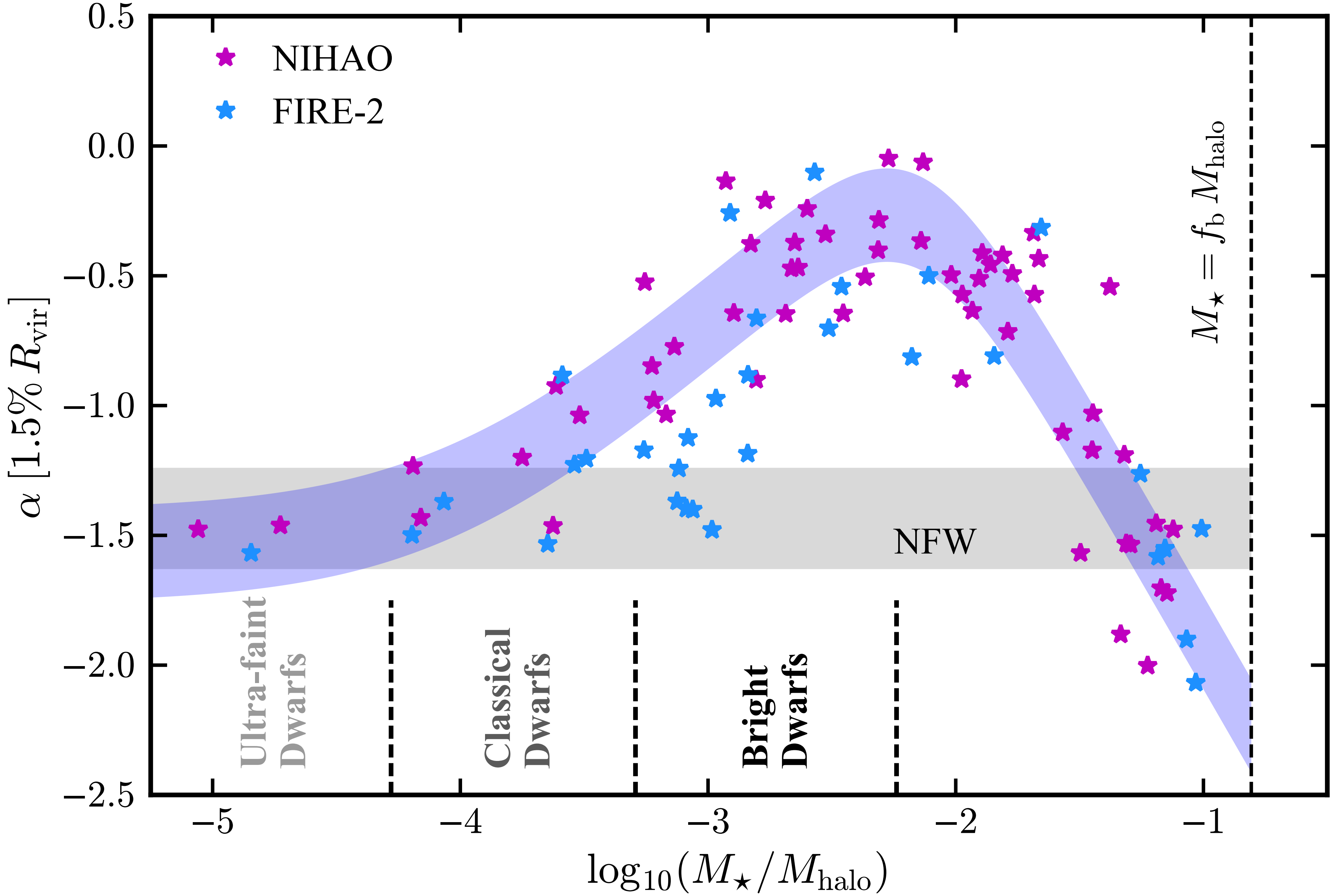
Halo Response depends on Star Formation Efficiency

Tollet et al. 2016, MNRAS, 456, 3542



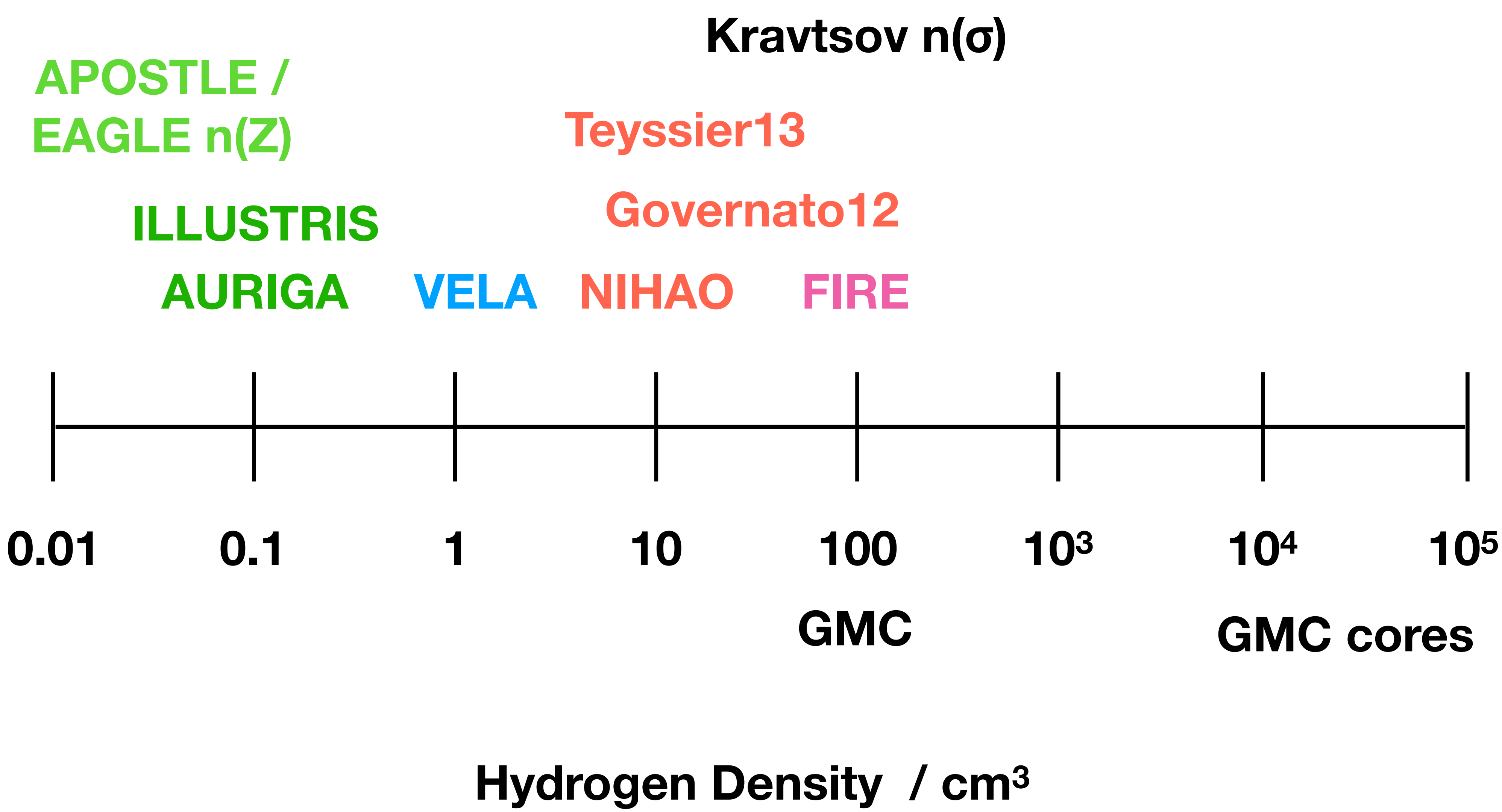
Halo Response depends on Star Formation Efficiency

Di Cintio et al. 2014, Chan et al. 2015, Tollet et al. 2016



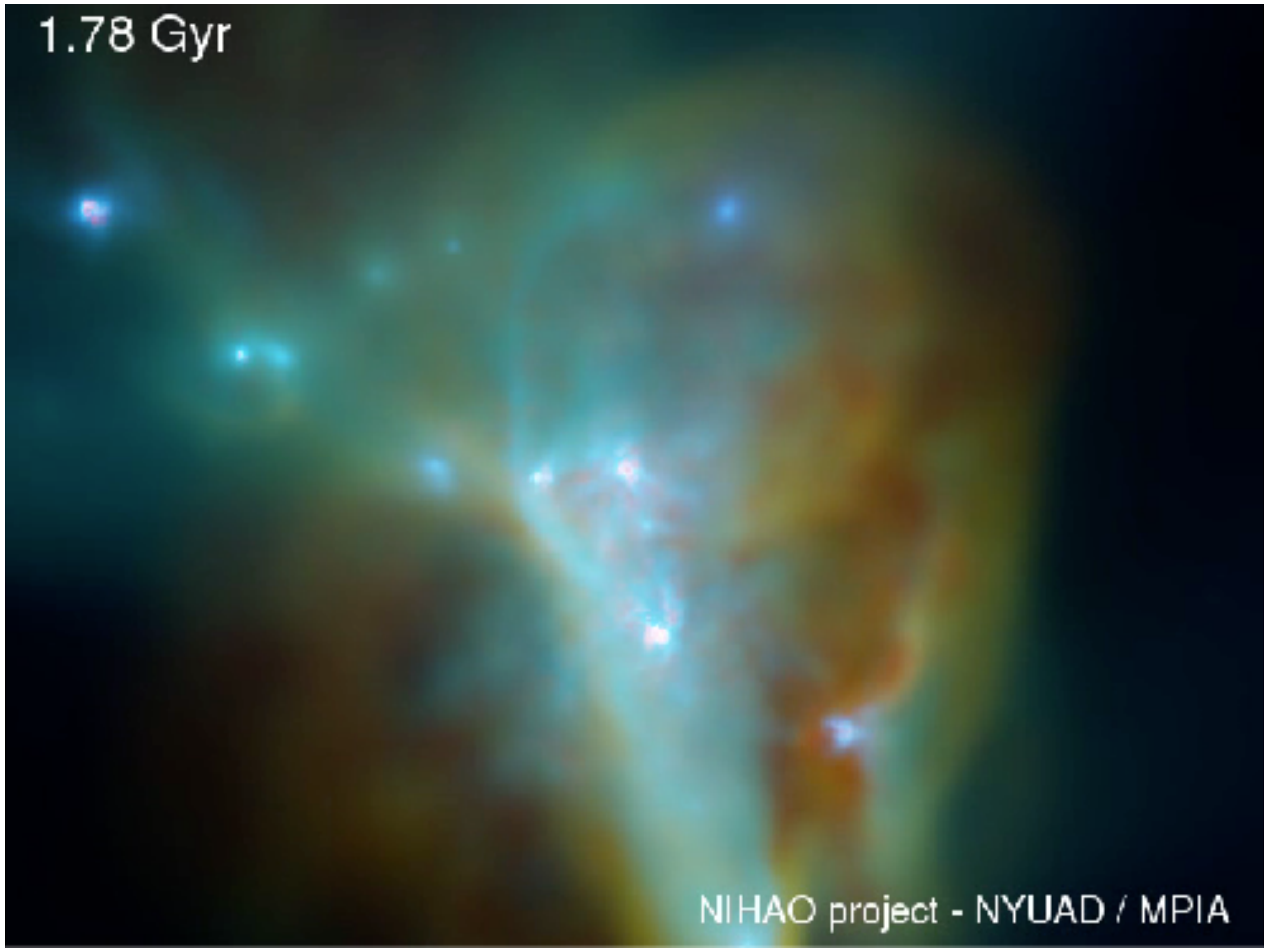
Bullock & Boylan-Kolchin 2017

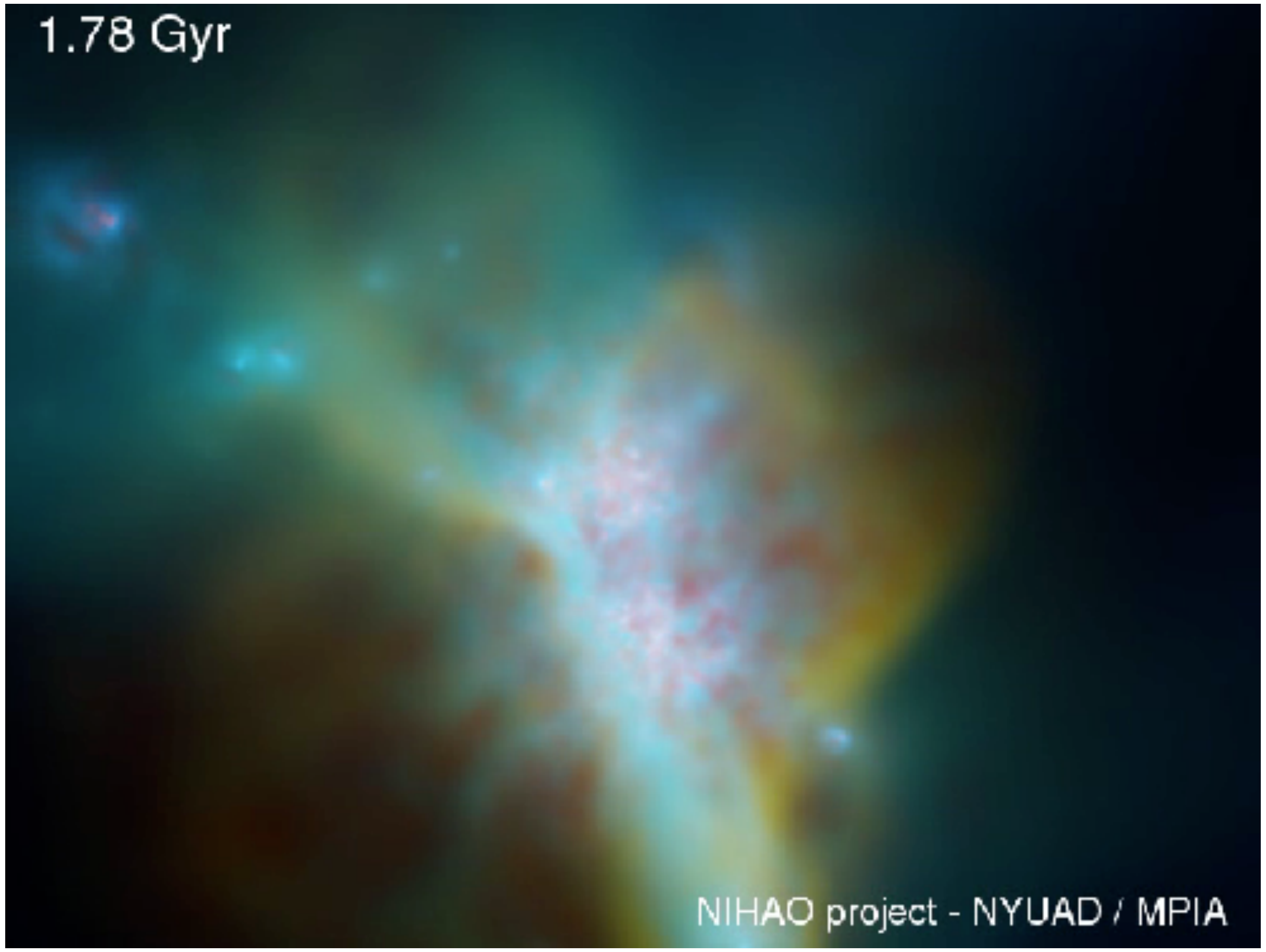
Star Formation Threshold is a common sub-grid parameter in galaxy formation simulations

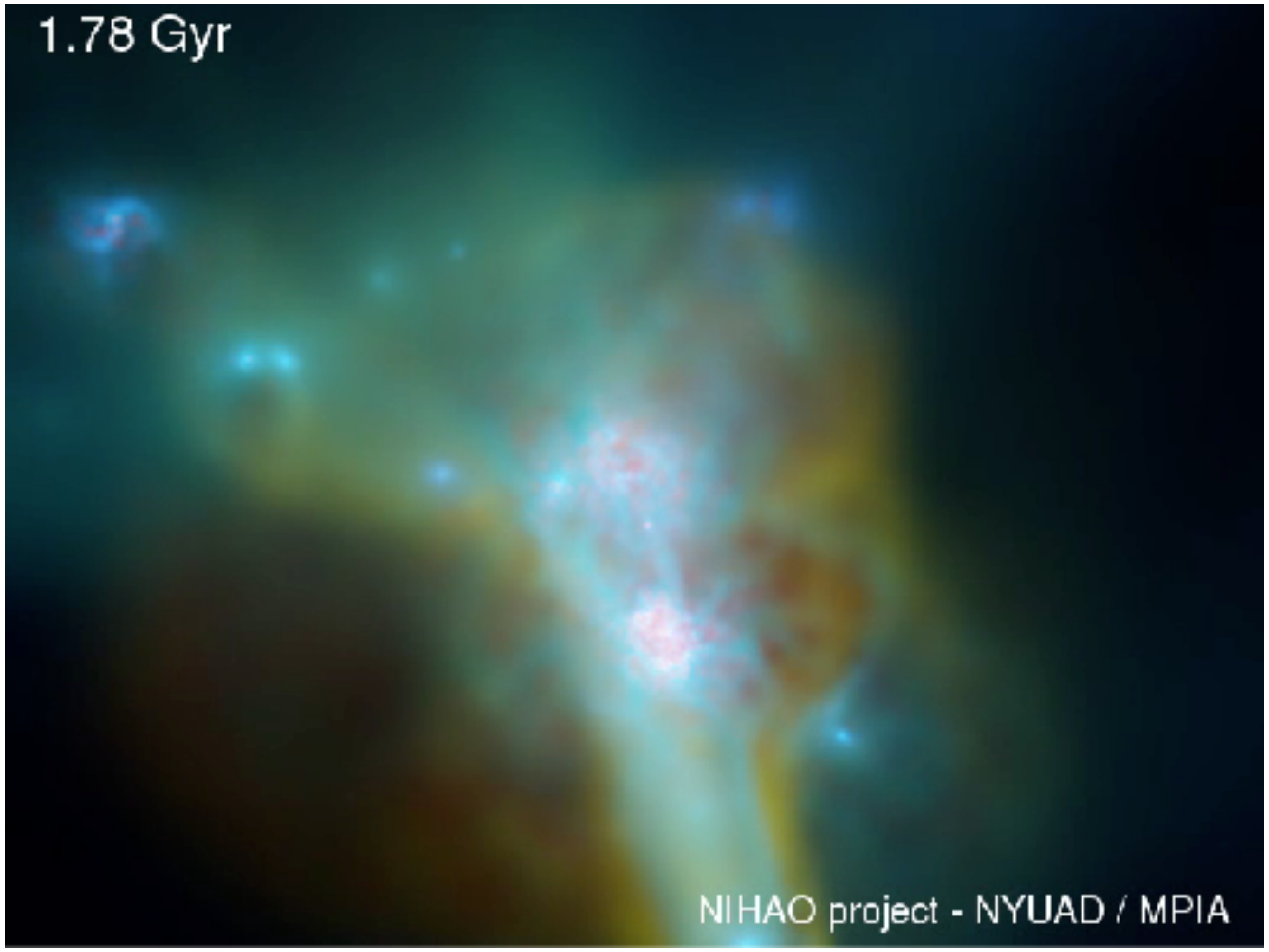


Re-simulate 20 NIHAO haloes with three SF thresholds

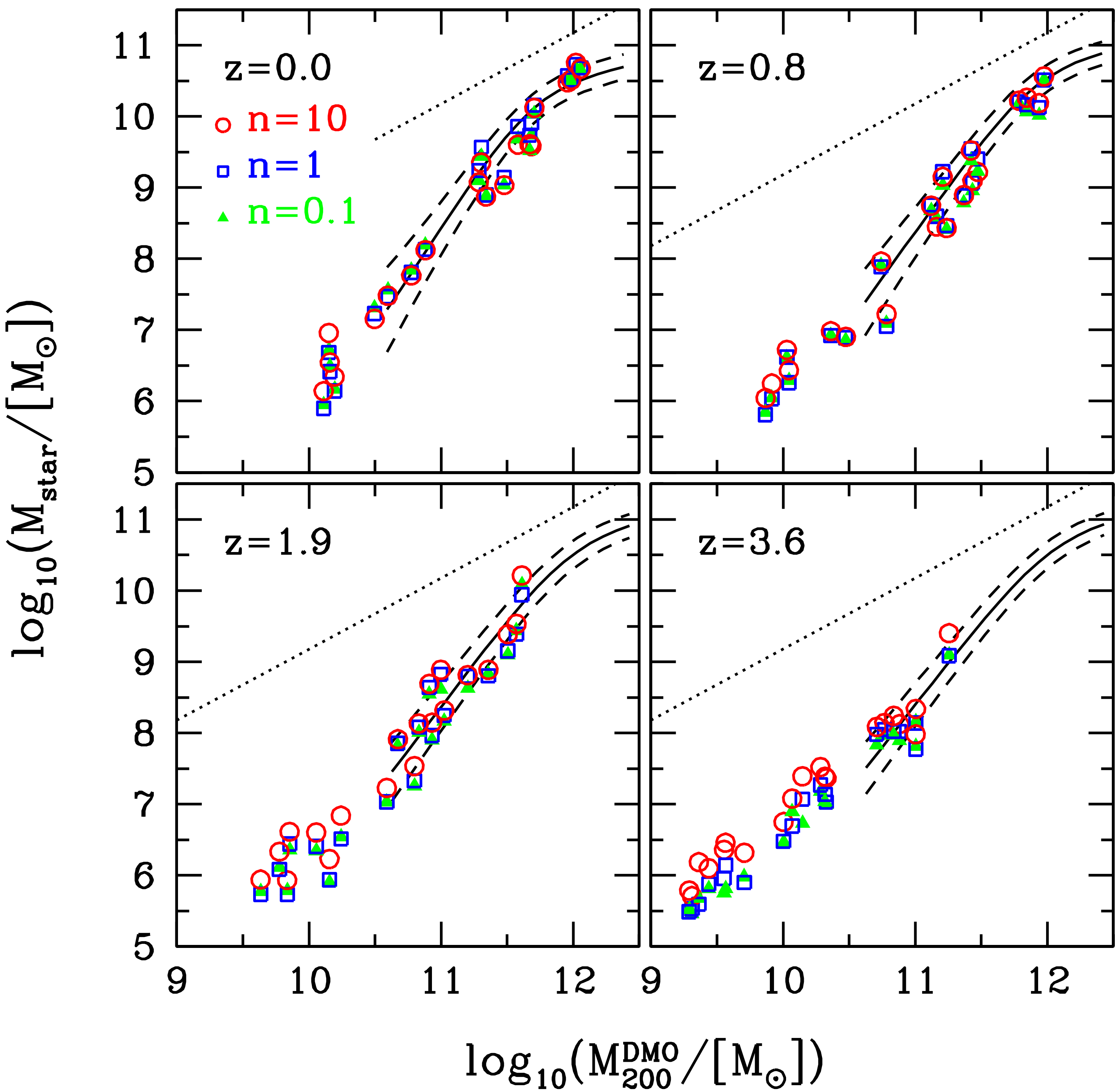
n=10,1,0.1 n_H cm^{-3}







Stellar Mass vs Halo Mass

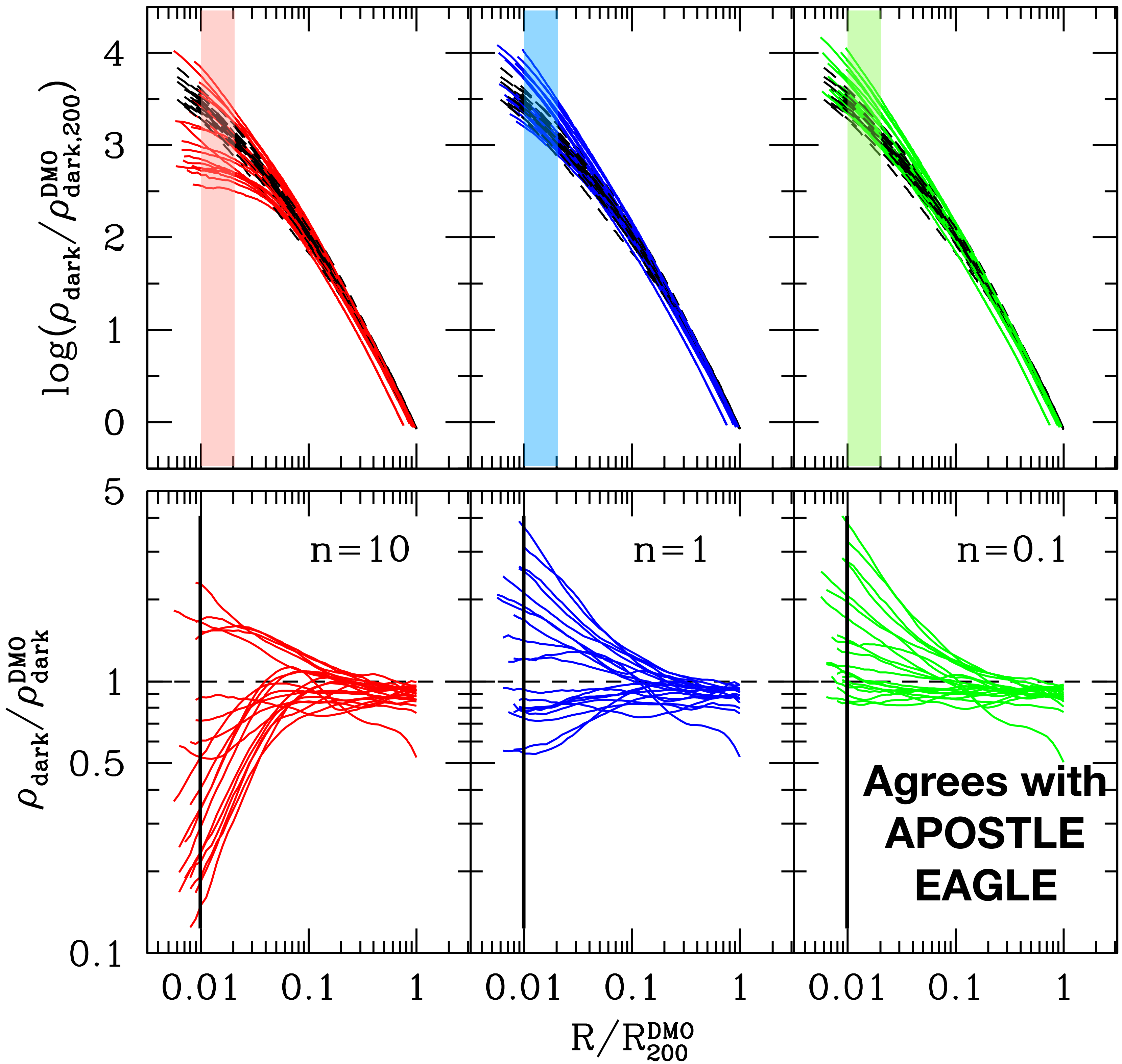


Abundance Matching
Moster et al. 2018

re-calibrated efficiency for n=0.1

NIHAO XIX - Dutton et al. 2018 in prep

Enclosed Dark Matter Density Profiles



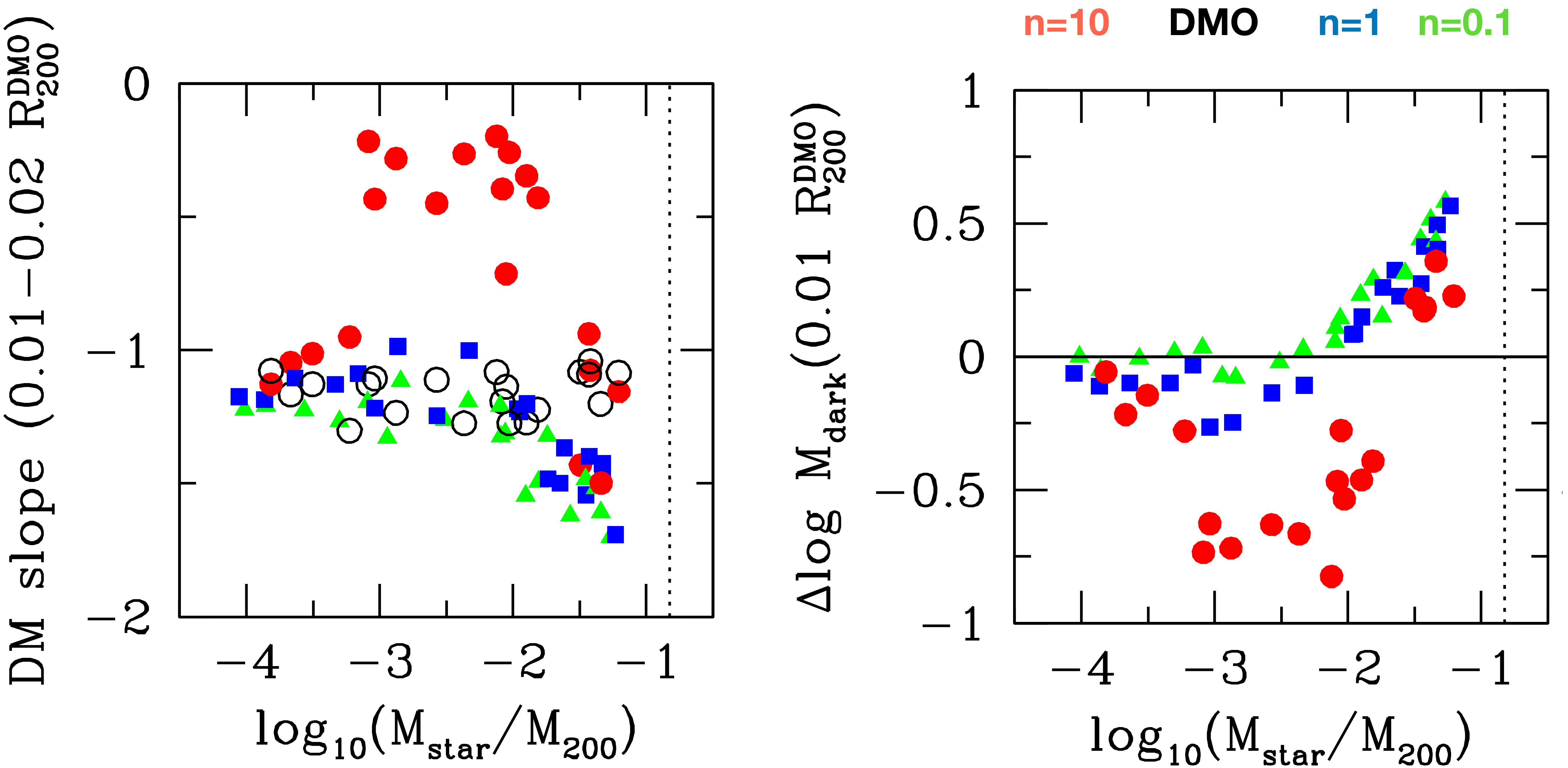
measure slope between 1 and 2% of R200

measure mass ratio at 1% of R200

Agrees with APOSTLE EAGLE

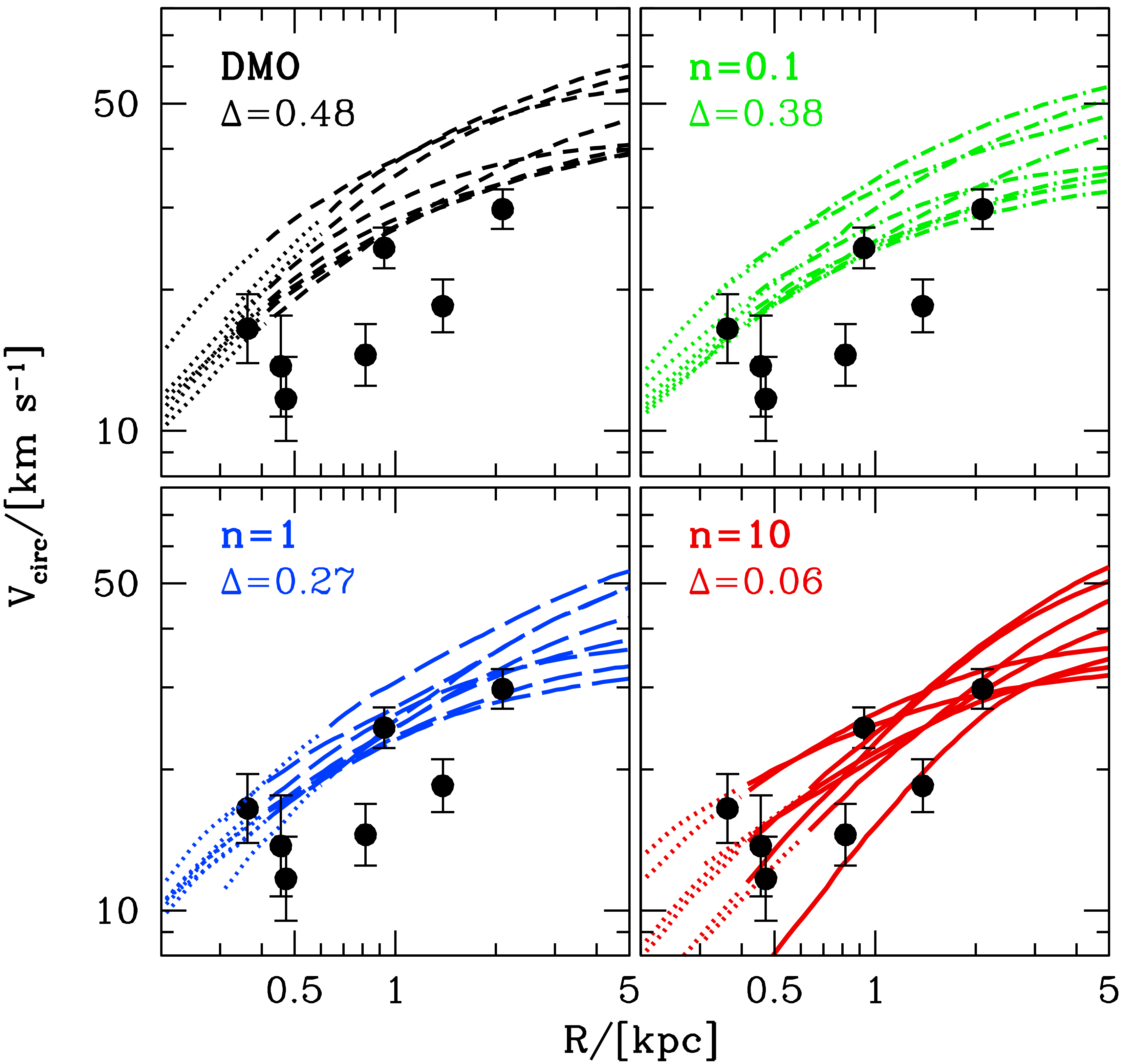
NIHAO XIX - Dutton et al. 2018 in prep

Halo Response depends on (M_{star}/M_{halo}, n)



NIHAO XIX - Dutton et al. 2018 in prep

TBTF problem for field Dwarf Galaxies

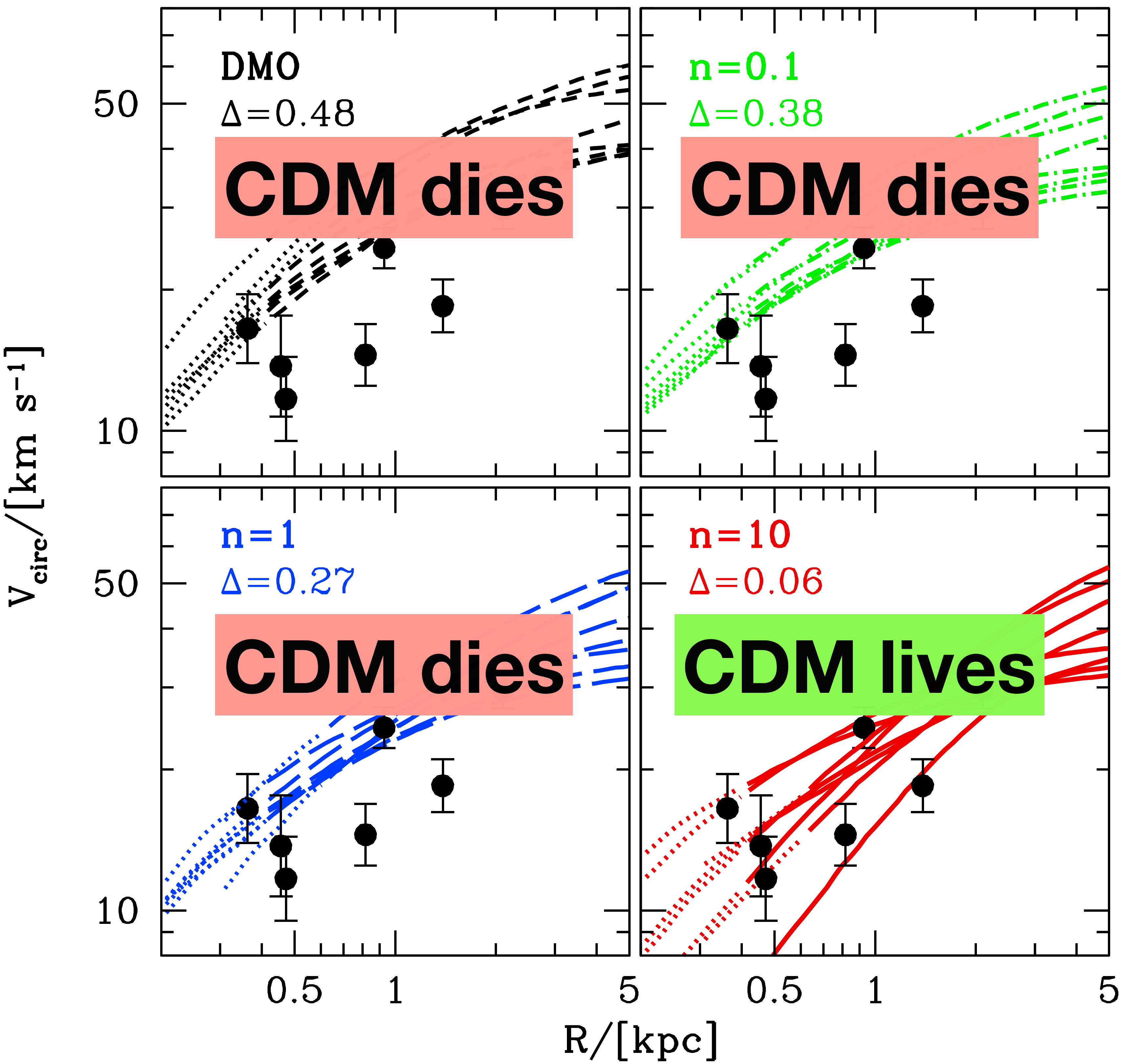


$10^6 < M_{star} < 10^8$

D > 500 kpc
from MW

NIHAO XIX - Dutton et al. 2018 in prep

TBTF problem for field Dwarf Galaxies



$10^6 < M_{star} < 10^8$

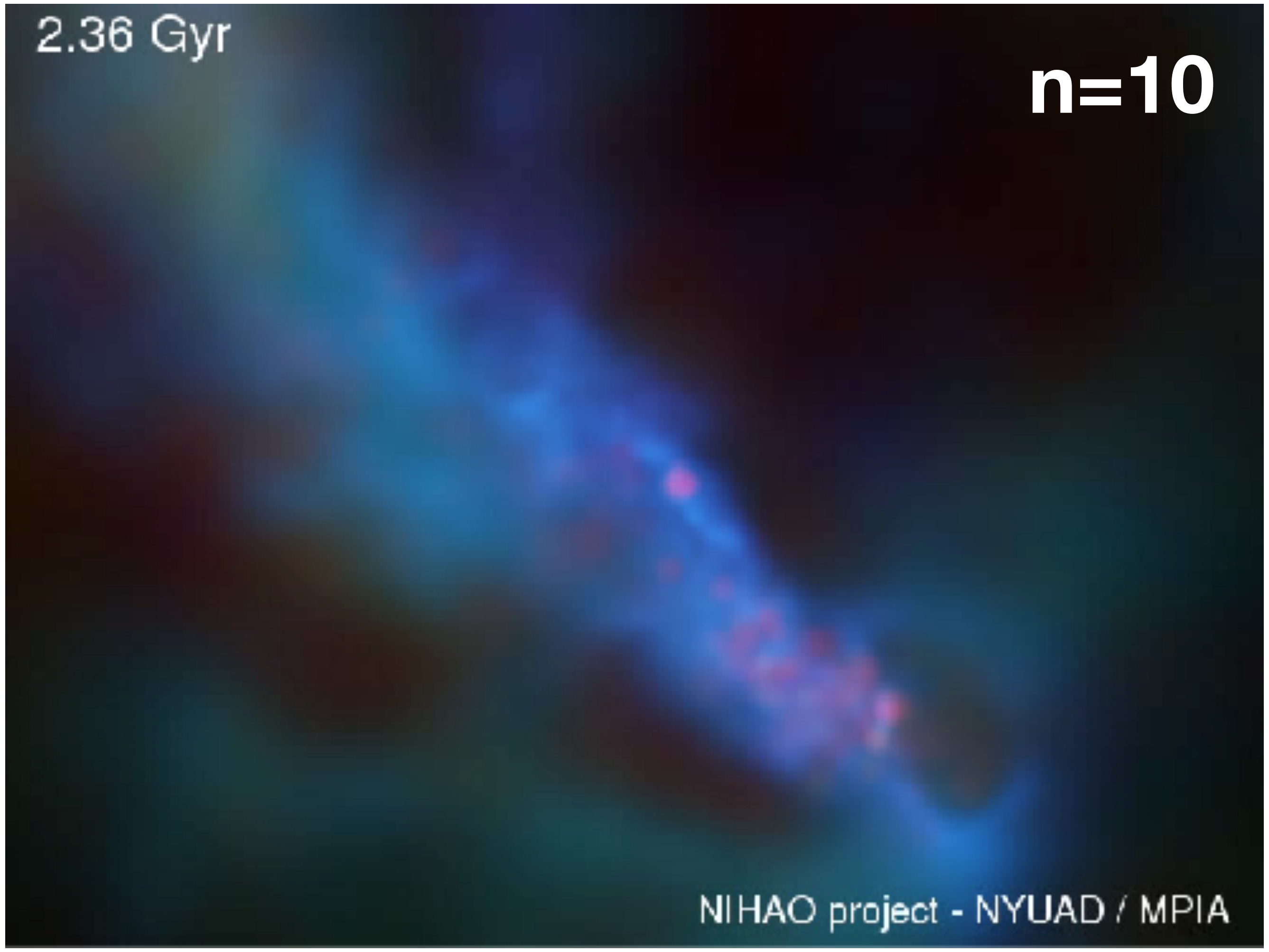
D > 500 kpc from MW

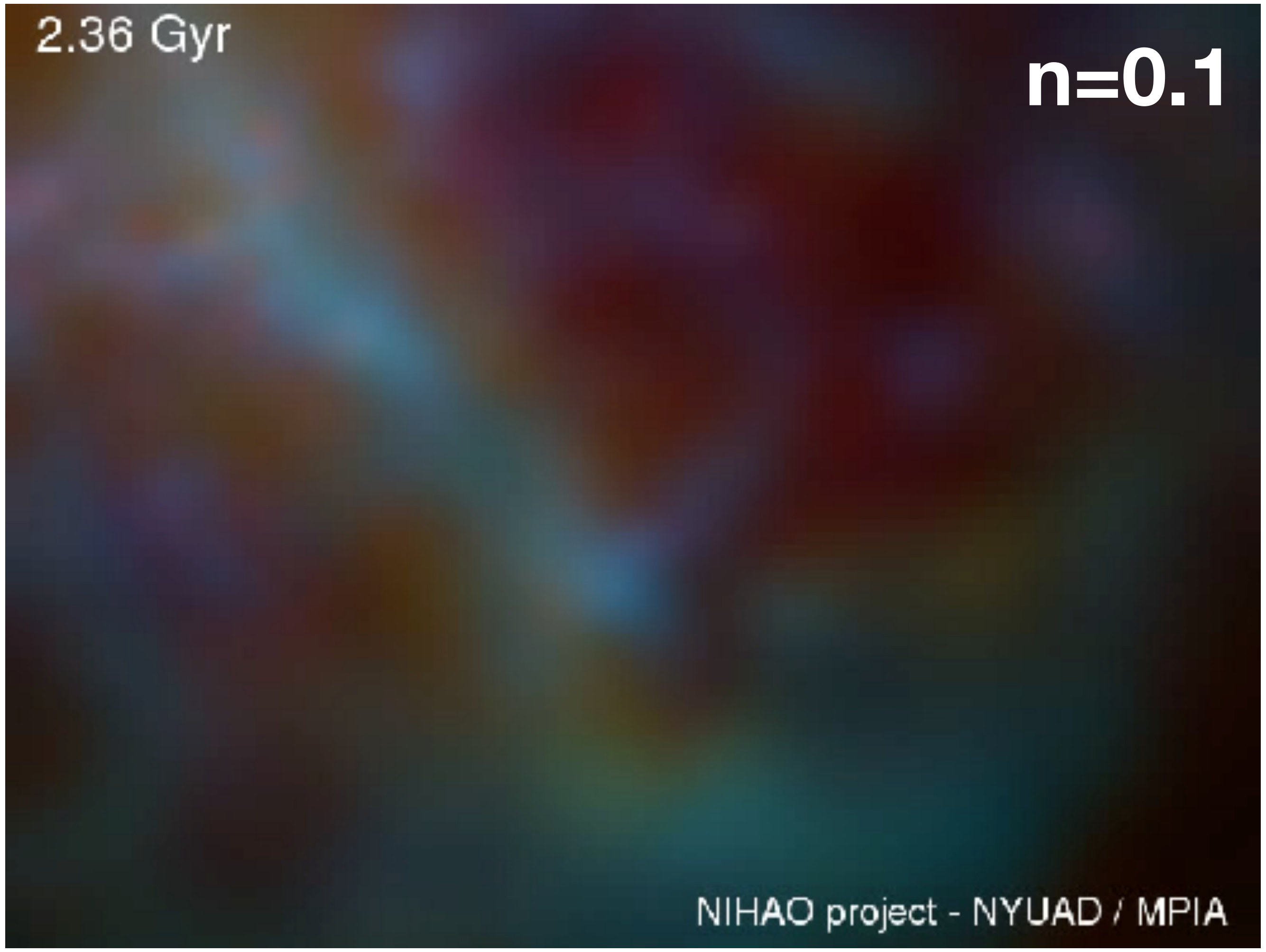
NIHAO XIX - Dutton et al. 2018 in prep

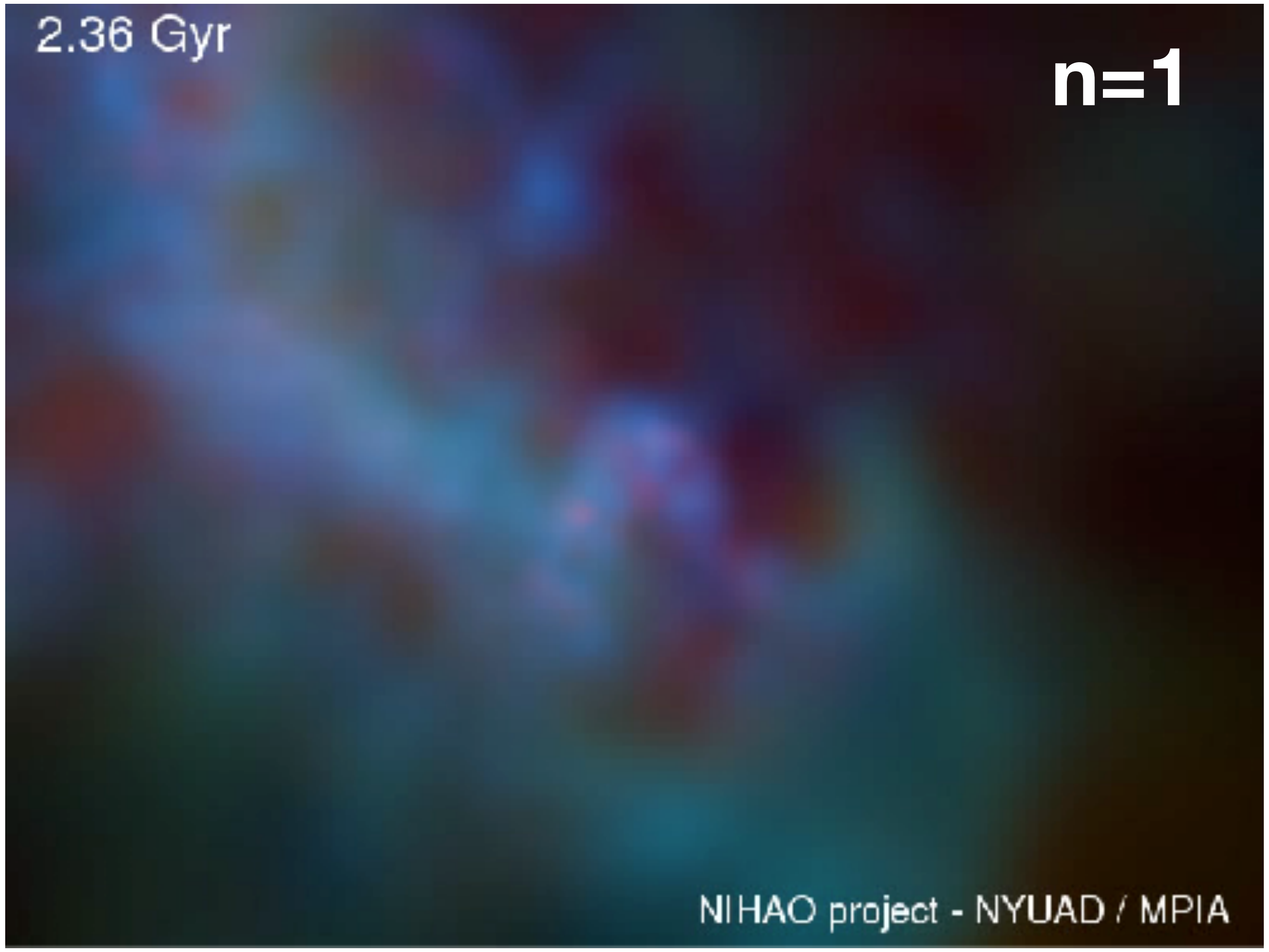
How do we test which SF threshold is most realistic?

Re-simulate 20 NIHAO haloes with three SF thresholds

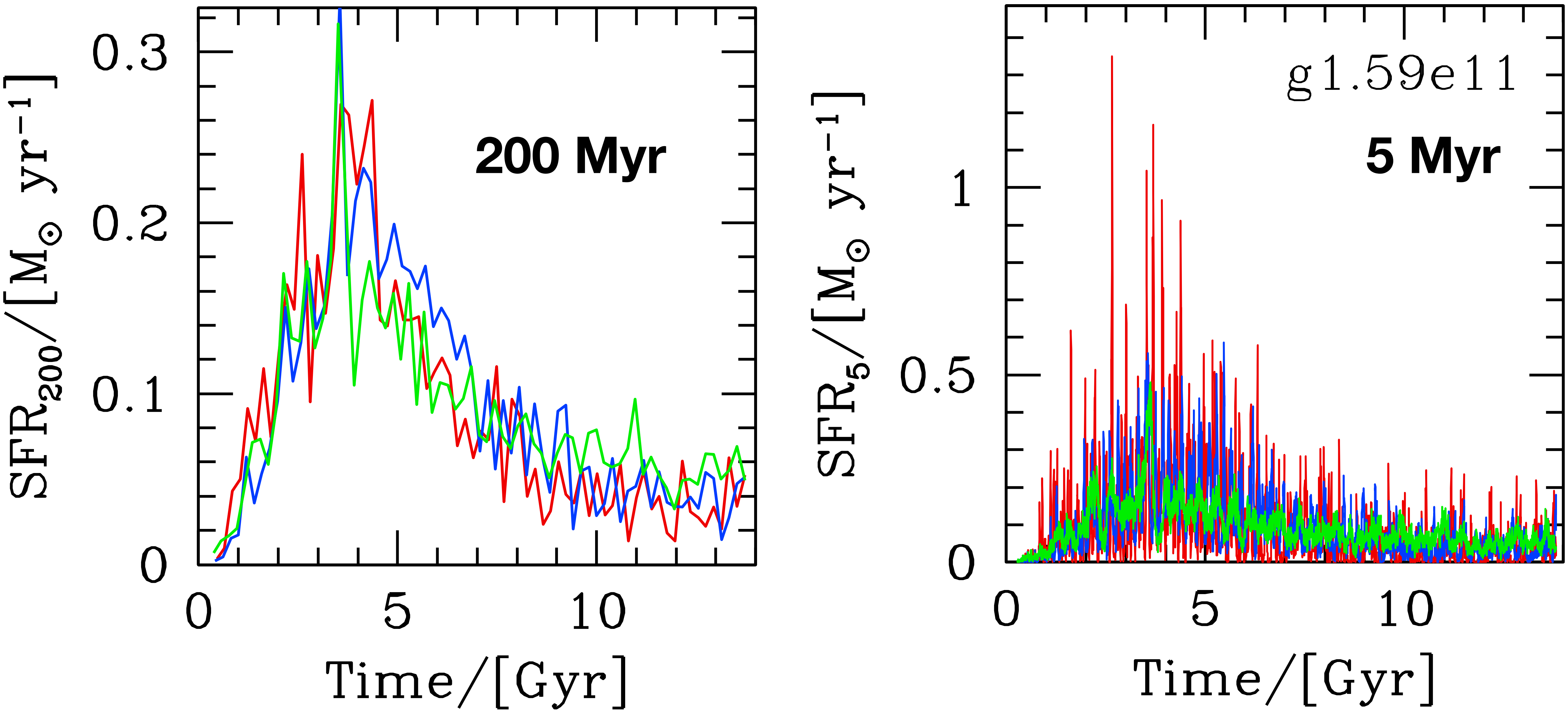
n=10,1,0.1 n_H cm^{-3}



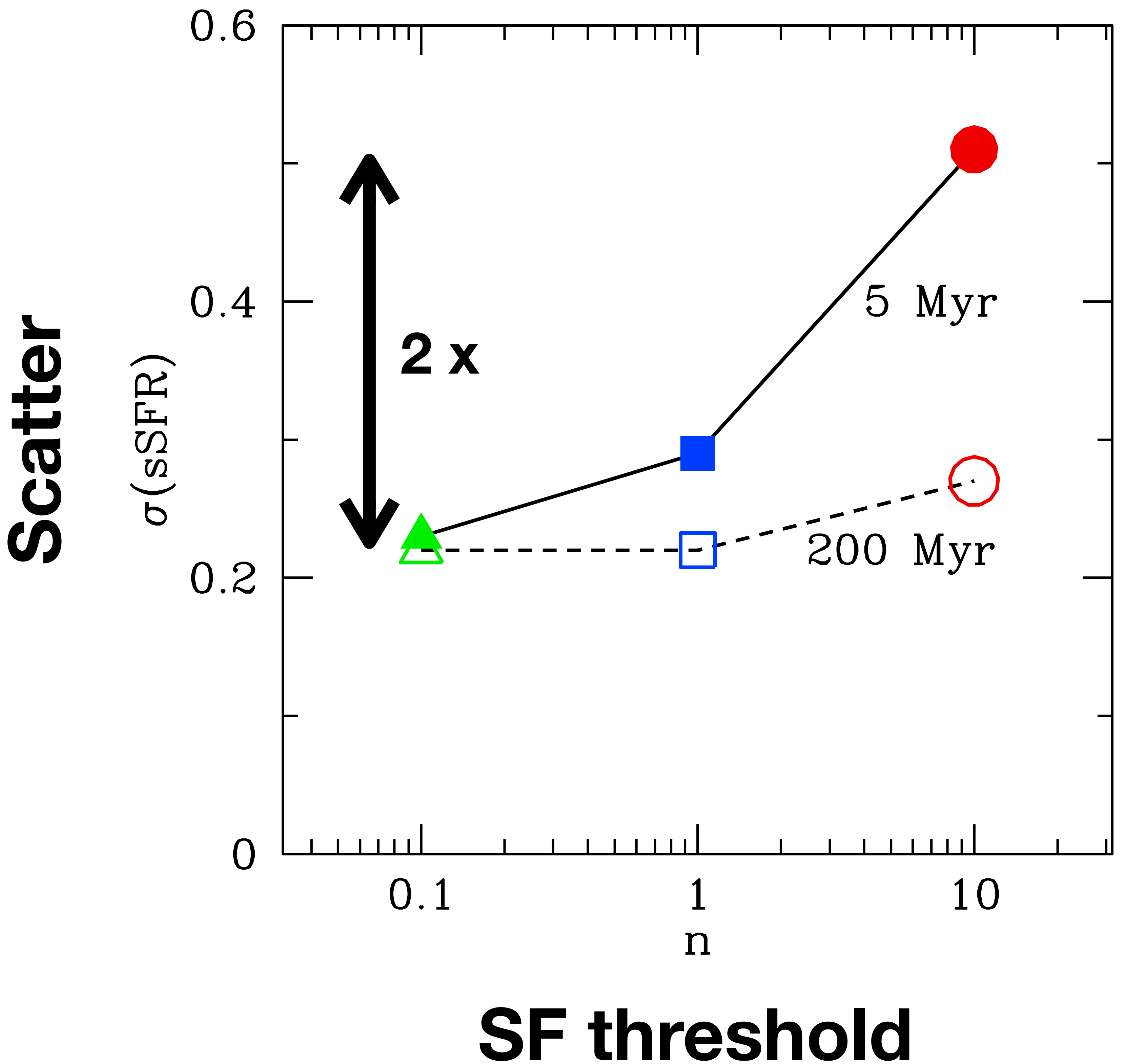




Higher SF threshold gives more bursty SFH



Scatter in SFR - M_{star} Relation



Redshift:
z<3

Stellar Mass
$M_{star}>10^7$

Summary

- **Low threshold** star formation (**n≤1**) EAGLE / APOSTLE / ILLUSTRIS produces **cuspy haloes** **(⇒CDM fails!)**
- **High threshold** star formation (**n≥10**) NIHAO/FIRE produces **expanded haloes** when $0.001 < M_{star}/M_{halo} < 0.01$ **(CDM ok)**
- Field galaxies in LG with $M_{star} \sim 10^7$ favor high threshold (Need more observations to improve statistics)
- High threshold yields **2x larger scatter** in sSFR measured over 5 Myr timescale. Testable with Halpha?