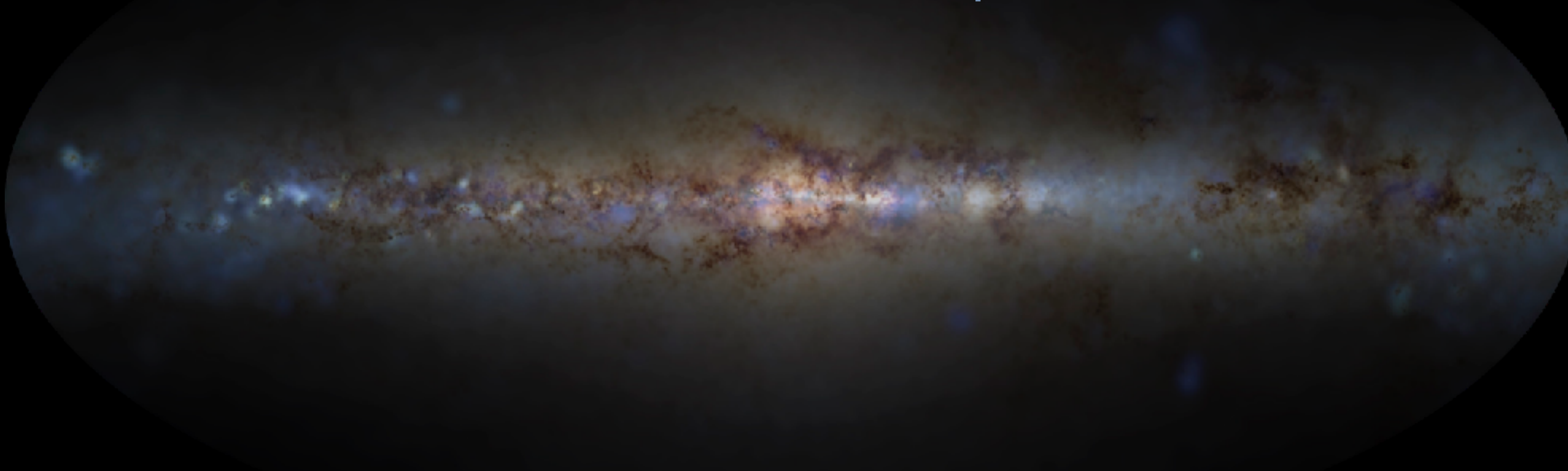
The Latte Simulations

Simulating Milky Way-like Galaxies with Realistic Satellite Populations



Andrew Wetzel

with the FIRE (Feedback In Realistic Environments) collaboration

Caltech

Carnegie Science

The Carnegie Observatories

UC DAVIS
UNIVERSITY OF CALIFORNIA

The Latte Simulations: the Milky Way on FIRE

- FIRE physics model
- formation of MW-like disk
- satellite dwarf galaxies

FIRE
Feedback In Realistic Environments

model for gas and star formation

high resolution to model structure of dense, multi-phase inter-stellar medium (ISM)

- resolution
  - $m_{gas,star}$ = 7070 M_{sun}
  - h_{gas} = 1 pc (min), 25 pc (med)
- gas cooling from atoms, molecules, and 9 metals to 10 K
- star formation in dense self-gravitating molecular clouds: n_{gas} > 1000 atom/cm^3

FIRE model for stellar feedback

Feedback In Realistic Environments

- Heating:
  - Supernovae: core-collapse (II) and Ia
  - Stellar Winds: massive O-stars & AGB stars
  - Photoionization (HII regions) + photoelectric heating
- Explicit Momentum Flux:
  - Radiation Pressure

$$\dot{P}_{\rm rad} \sim \frac{L}{c}\,(1+\tau_{\rm IR})$$

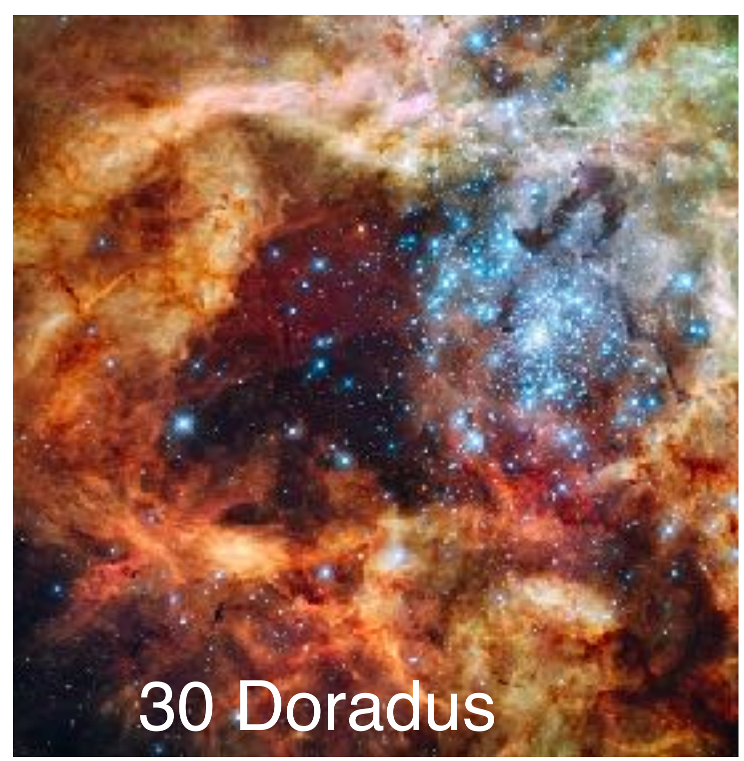
  - Supernovae

$$\dot{P}_{\rm SNe} \sim \dot{E}_{\rm SNe}\, v_{\rm ejecta}^{-1}$$

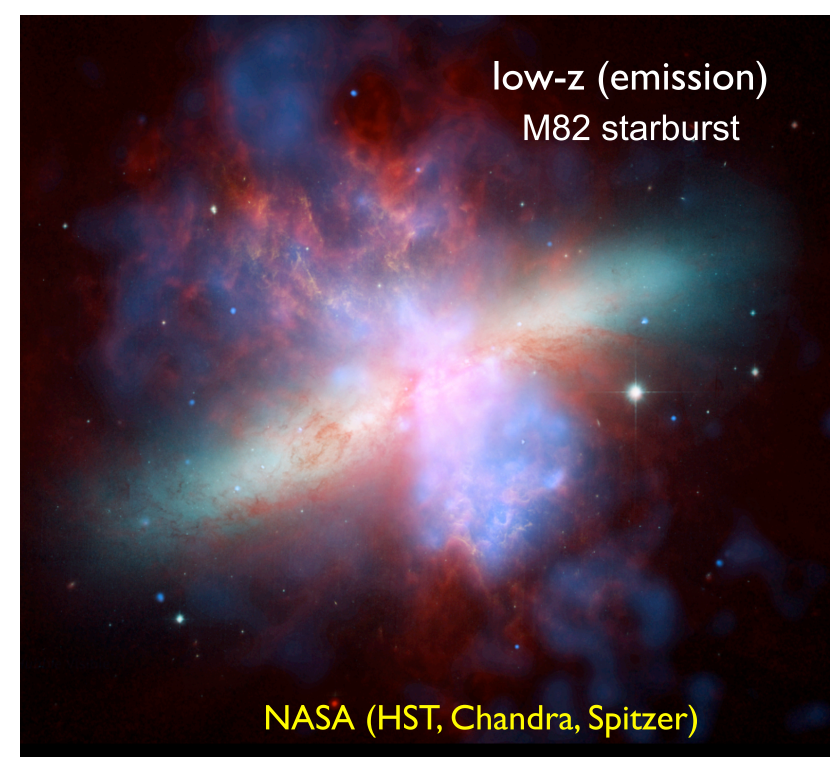
  - Stellar Winds

$$\dot{P}_{\rm W} \sim \dot{M}\, v_{\rm wind}$$

stellar scale



galaxy scale



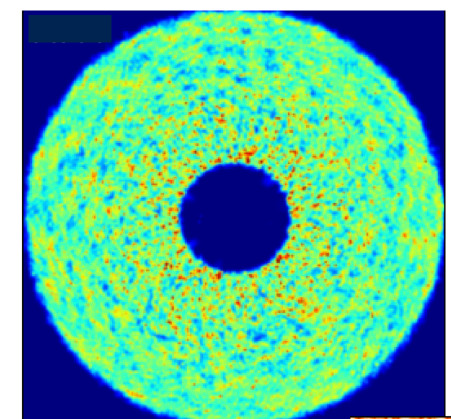
Mon. Not. R. Astron. Soc. **000**, 000–000 (0000) Printed 22 February 2017 (MN LaTeX style file v2.2)

FIRE-2 Simulations: Physics versus Numerics in Galaxy Formation

Philip F. Hopkins*[1], Andrew Wetzel[1,2,3]†, Dušan Kereš[4], Claude-André Faucher-Giguère[5], Eliot Quataert[6], Michael Boylan-Kolchin[7], Norman Murray[8], Christopher C. Hayward[9], Shea Garrison-Kimmel[1], Cameron Hummels[1], Robert Feldmann[6,10], Paul Torrey[11], Xiangcheng Ma[1], Daniel Anglés-Alcázar[5], Kung-Yi Su[1], Matthew Orr[1], Denise Schmitz[1], Ivanna Escala[1], Robyn Sanderson[1], Michael Y. Grudić[1], Zachary Hafen[5], Ji-Hoon Kim[12], Alex Fitts[7], James S. Bullock[13], Coral Wheeler[1], T. K. Chan[4], Oliver D. Elbert[13], Desika Narayanan[14]

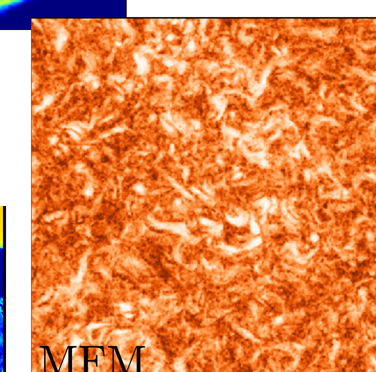
numerical improvements:

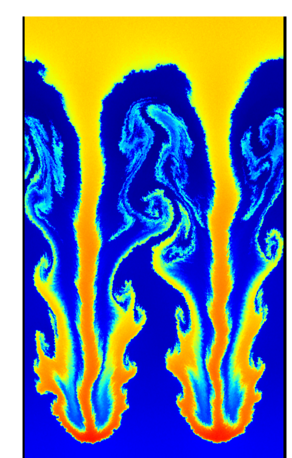
- new hydrodynamics method
  P-SPH —> Mesh-free Finite Mass
- feedback coupling is now geometrically aware - injection of mass, energy, momentum is isotropic



GIZMO:
disk after
100 orbits

sub-sonic
turbulence





Rayleigh-Taylor
instability
(with boost)

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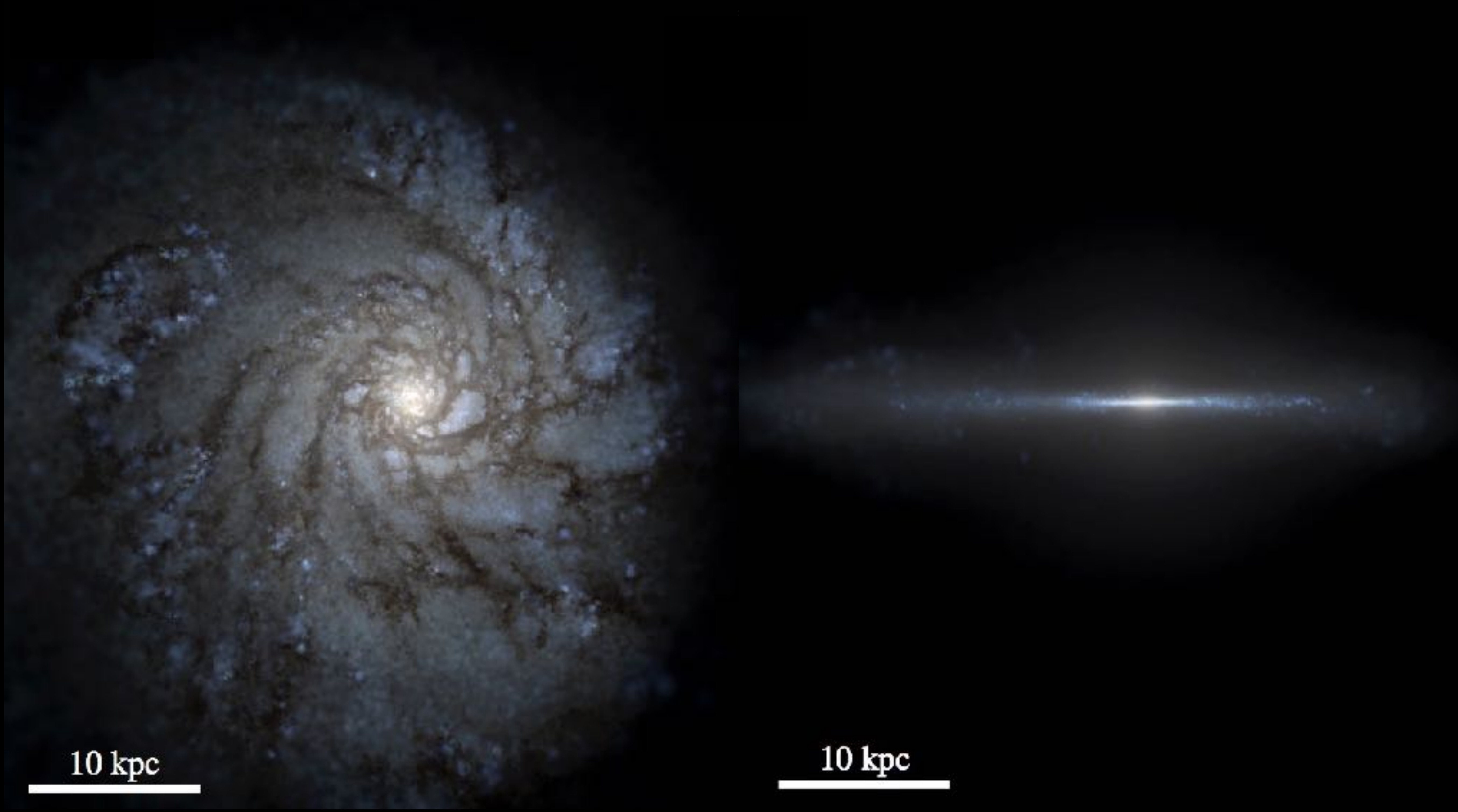
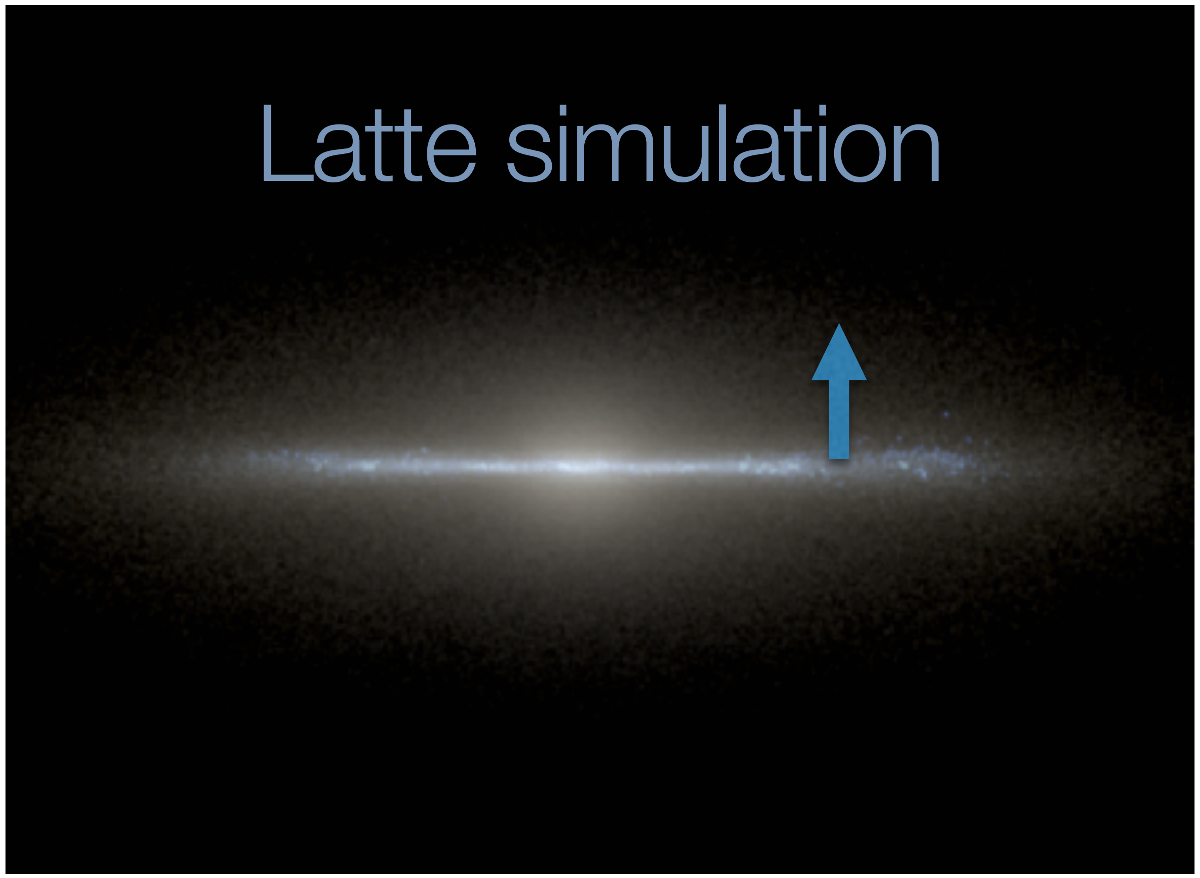
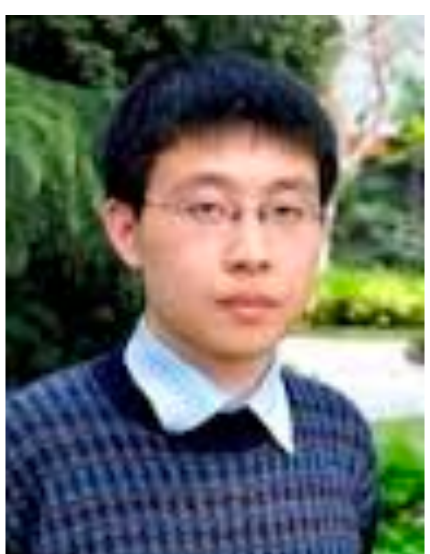
MW-like galaxy at z = 0



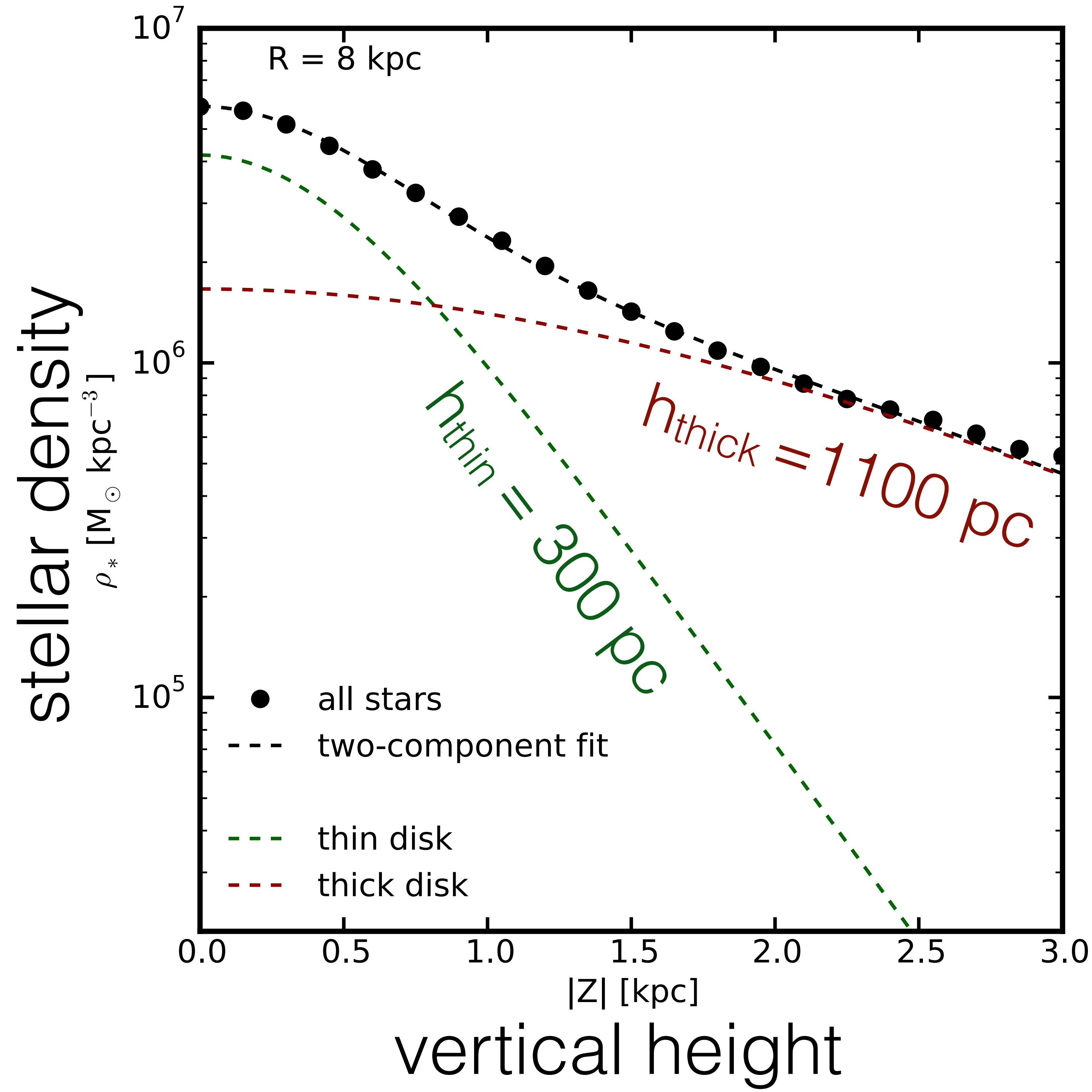
$M_{star} = 7x10^{10}\ M_{sun}$

successful formation of ‘thin’ and ‘thick’ stellar disk similar to Milky Way

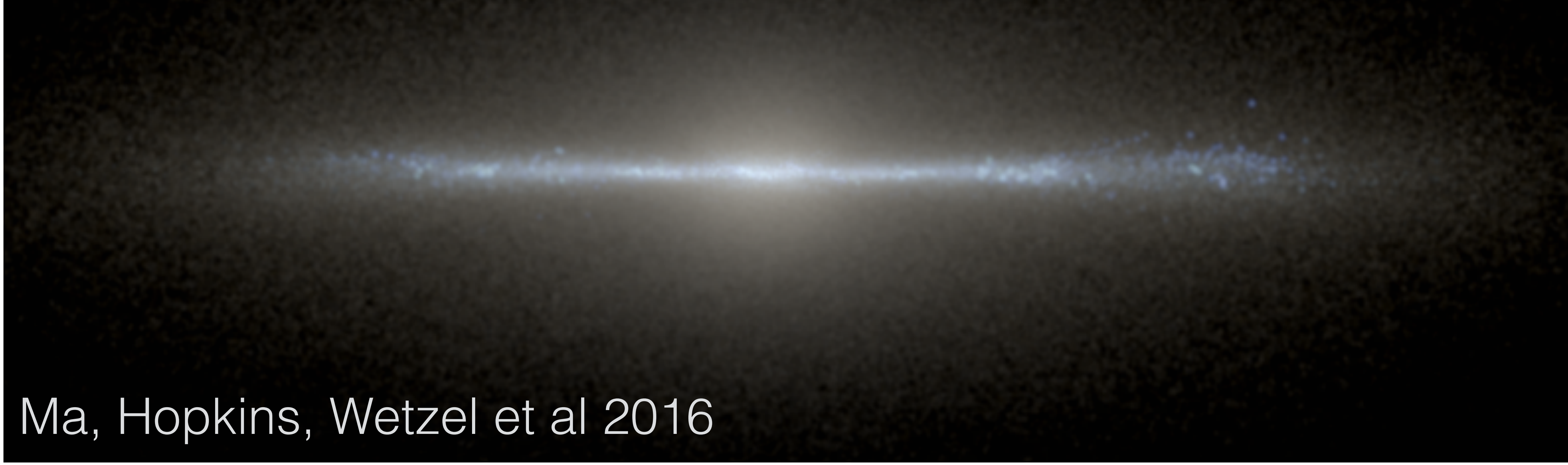


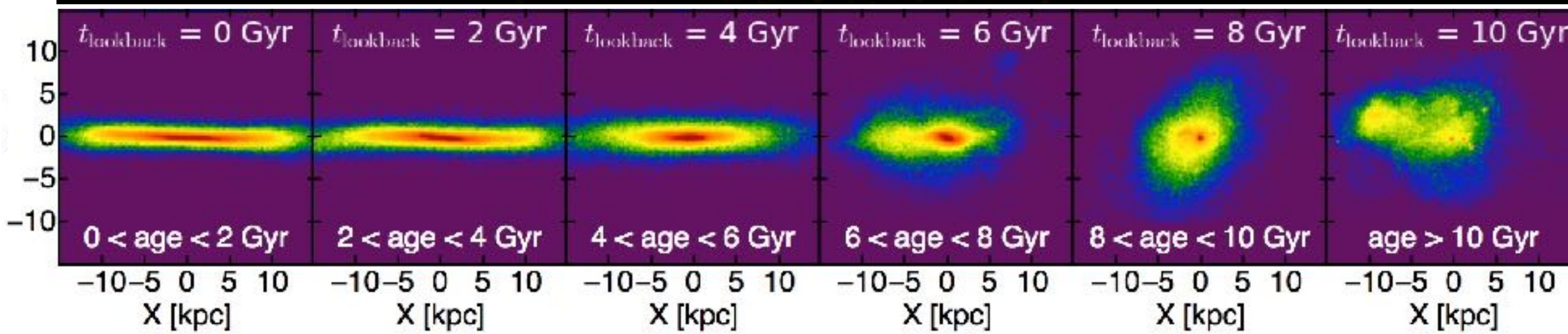


Xiangcheng Ma, Hopkins, Wetzel et al 2016



thick —> thin disk formation





radial evolution: inside —> out
vertical evolution: upside —> down

also Stinson et al 2013, Bird et al 2013, Agertz & Kravtsov 2016, Ceverino et al 2017

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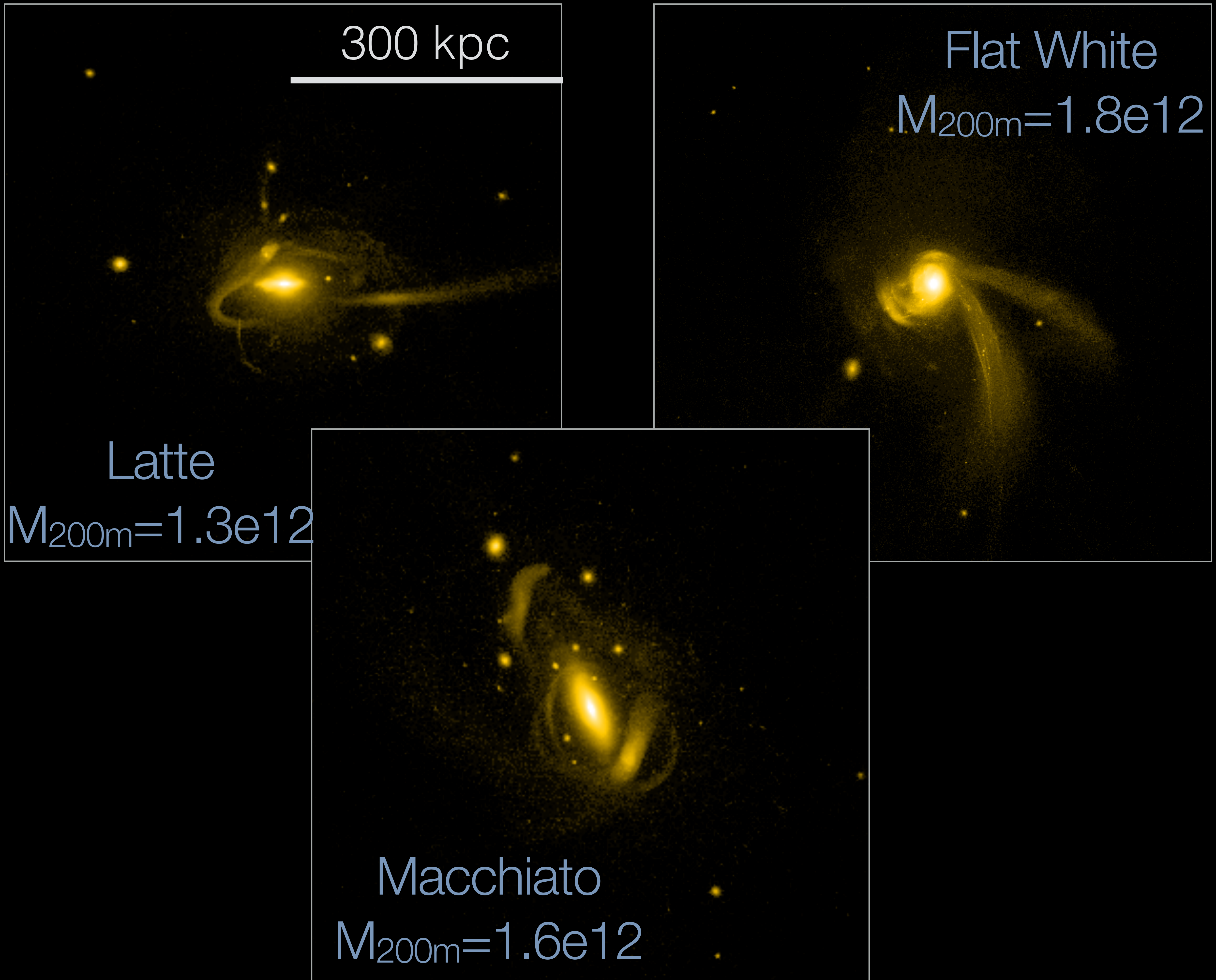
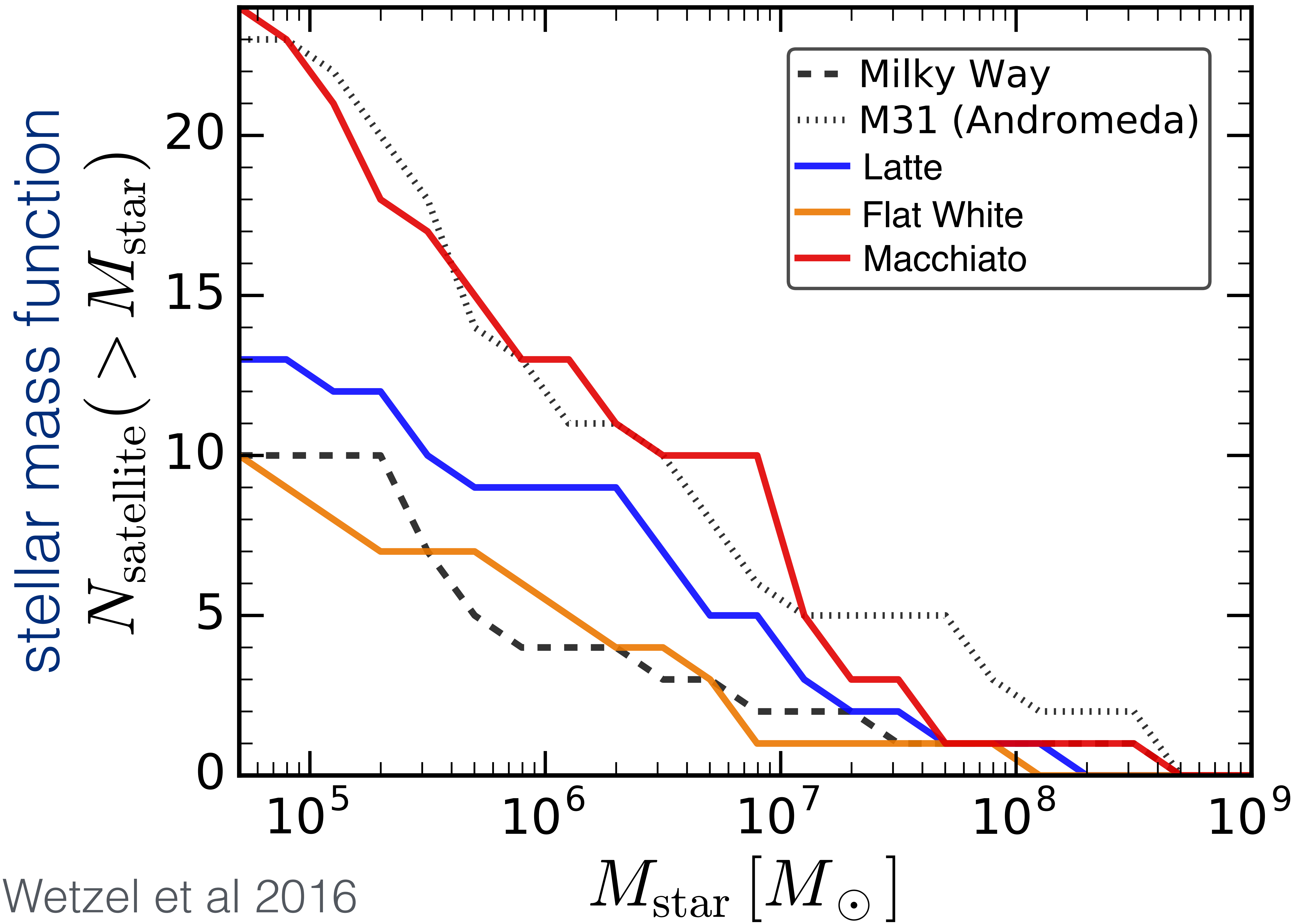
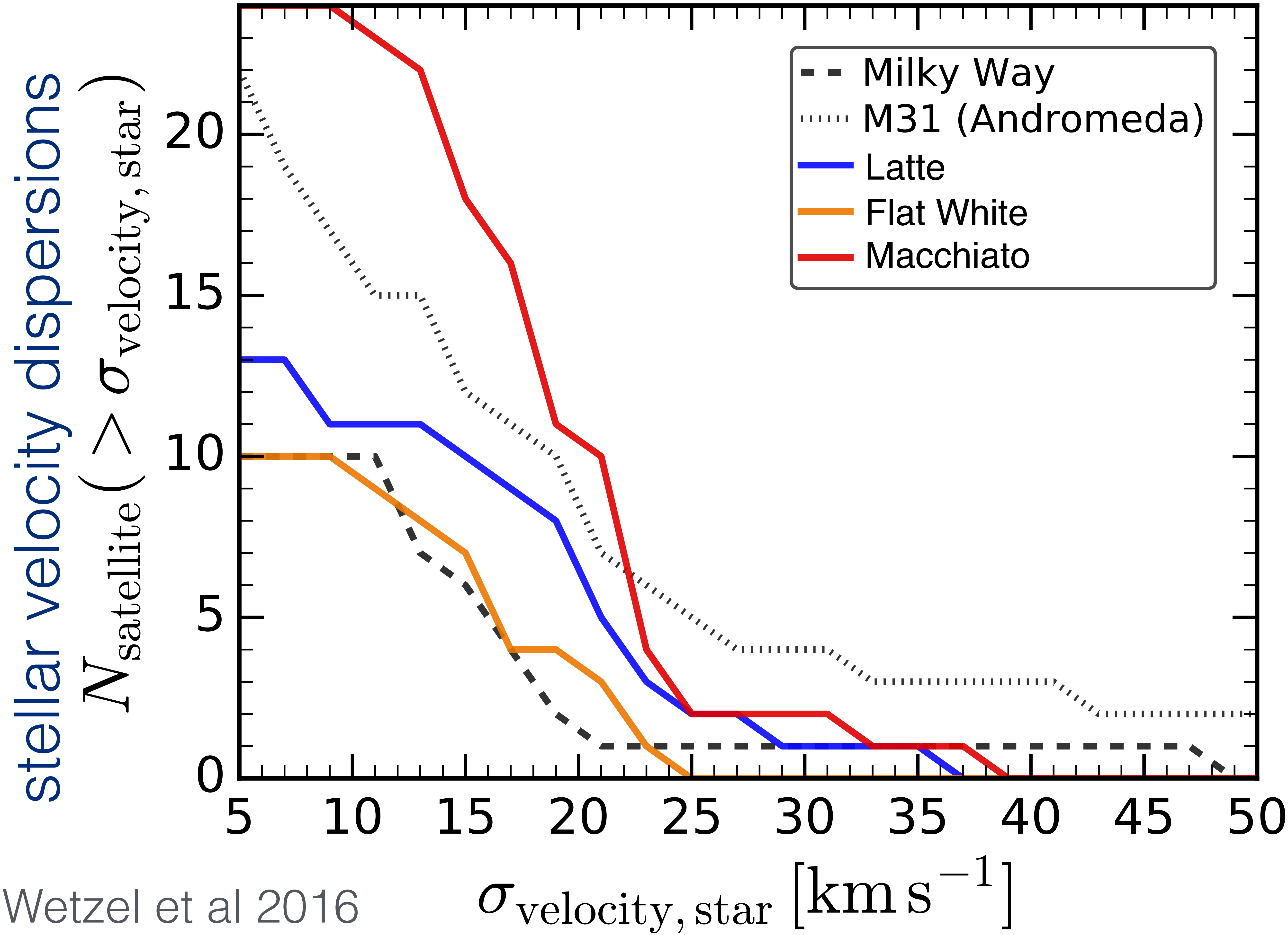

300 kpc
Flat White
M200m=1.8e12
Latte
M200m=1.3e12
Macchiato
M200m=1.6e12

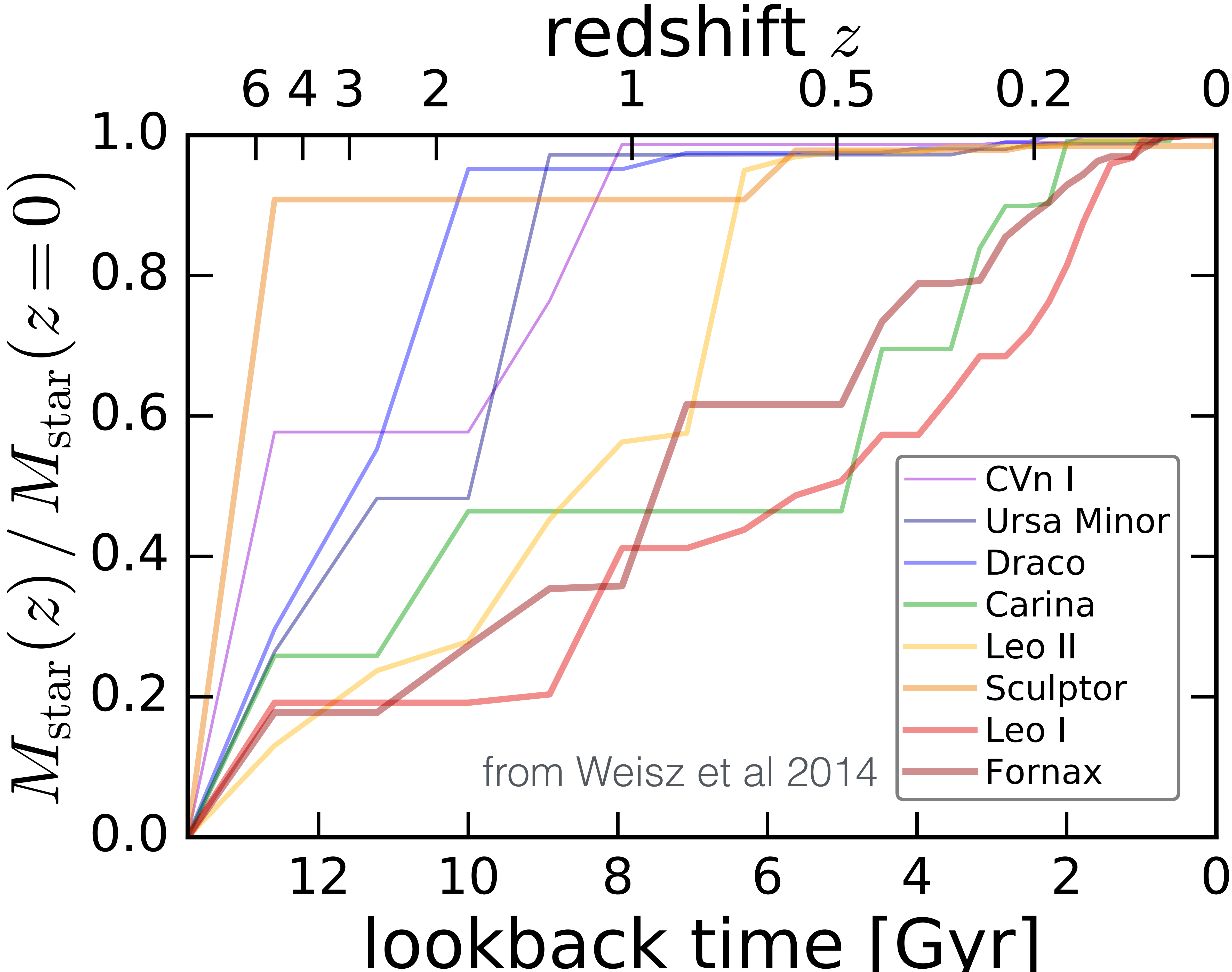


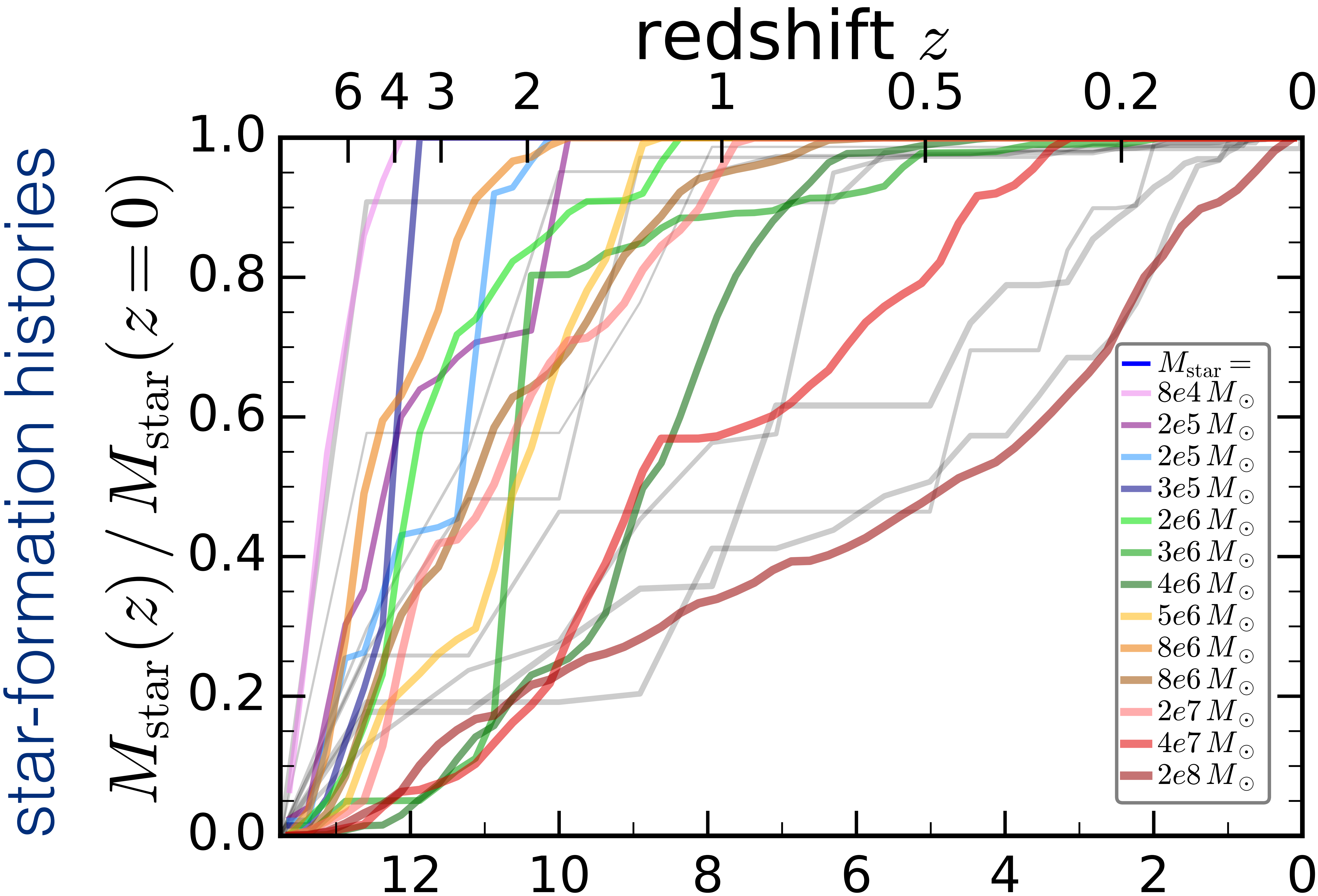
Wetzel et al 2016



Wetzel et al 2016

star-formation histories





Wetzel et al 2016

dwarf galaxies: significant challenges to the Cold Dark Matter (CDM) model

‘missing satellites’ problem

- Can a CDM-based model produce satellites with observed distribution of stellar masses?

‘too big to fail’ and ‘core-cusp’ problem

- Can a CDM-based model produce satellites with observed distribution of stellar velocity dispersions?

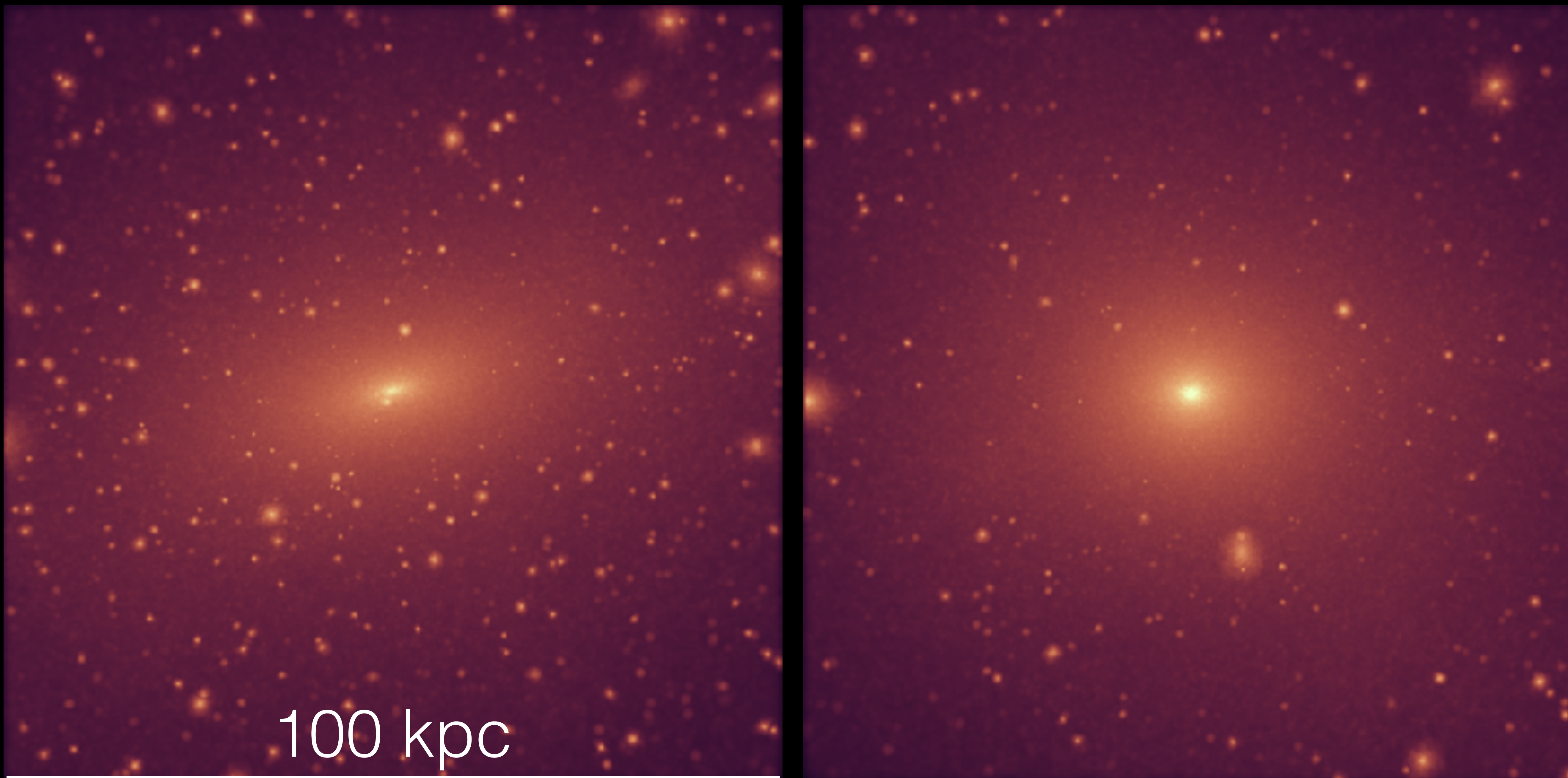
also, Brooks & Zolotov et al 2014, Sawala et al 2016, Fattahi et al 2016, Alyson’s talk, Carlos’ talk

What causes the lack of (massive) satellite dwarf galaxies?

presence of central galaxy

destroys satellites via gravitational tidal forces dark matter in dark-matter-only

dark matter in baryonic simulation



Garrison-Kimmel, Wetzel et al 2017

inclusion of baryons —> stellar disk destroys dark-matter subhalos

What causes the lack of (massive) satellite dwarf galaxies?

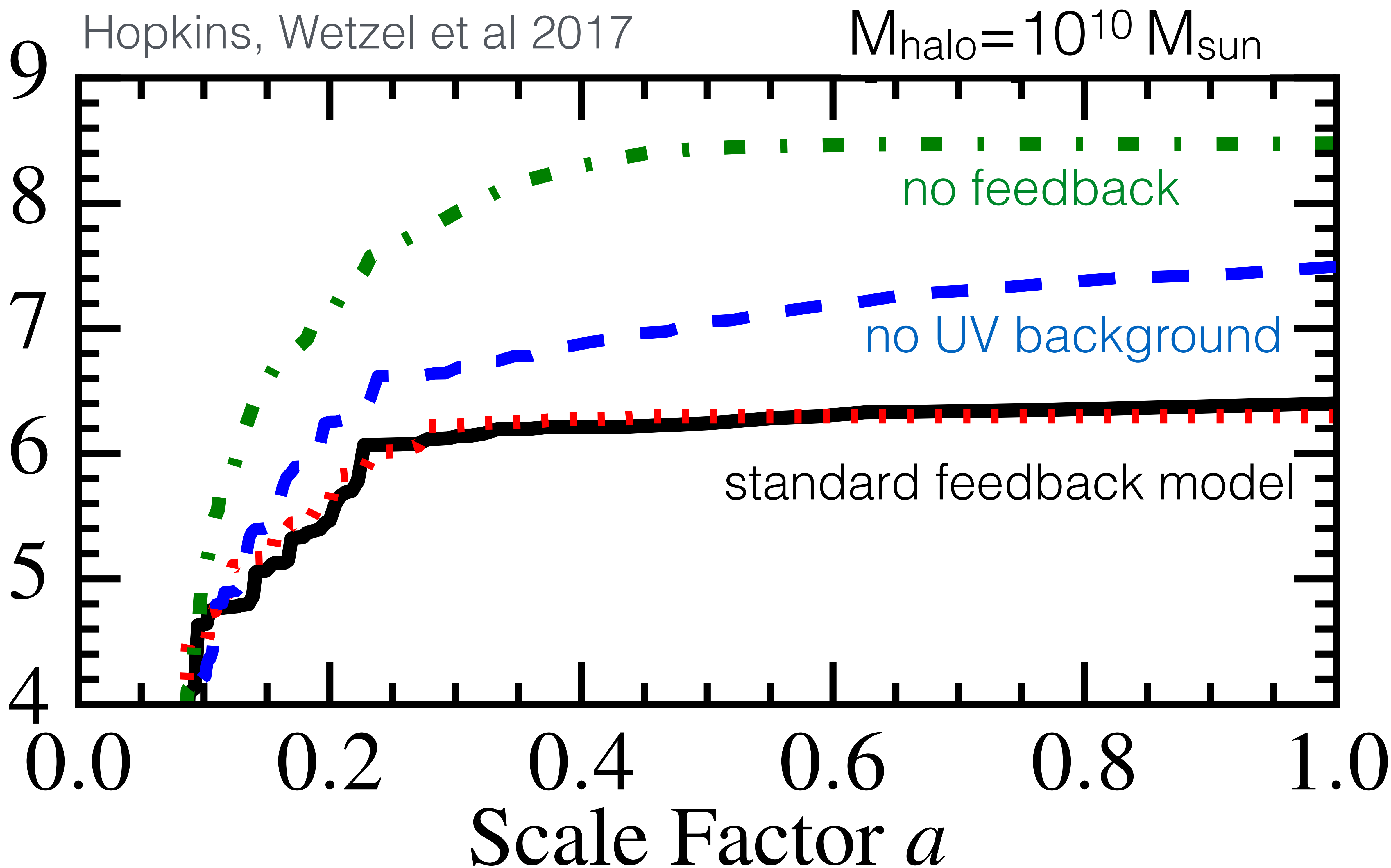
presence of central galaxy

destroys satellites via gravitational tidal forces

UV background

regulates gas cooling + star formation, even in more massive ‘classical’ dwarfs at low redshift

impact of UV background on star formation in dwarf galaxies



What causes the lack of (massive) satellite dwarf galaxies?

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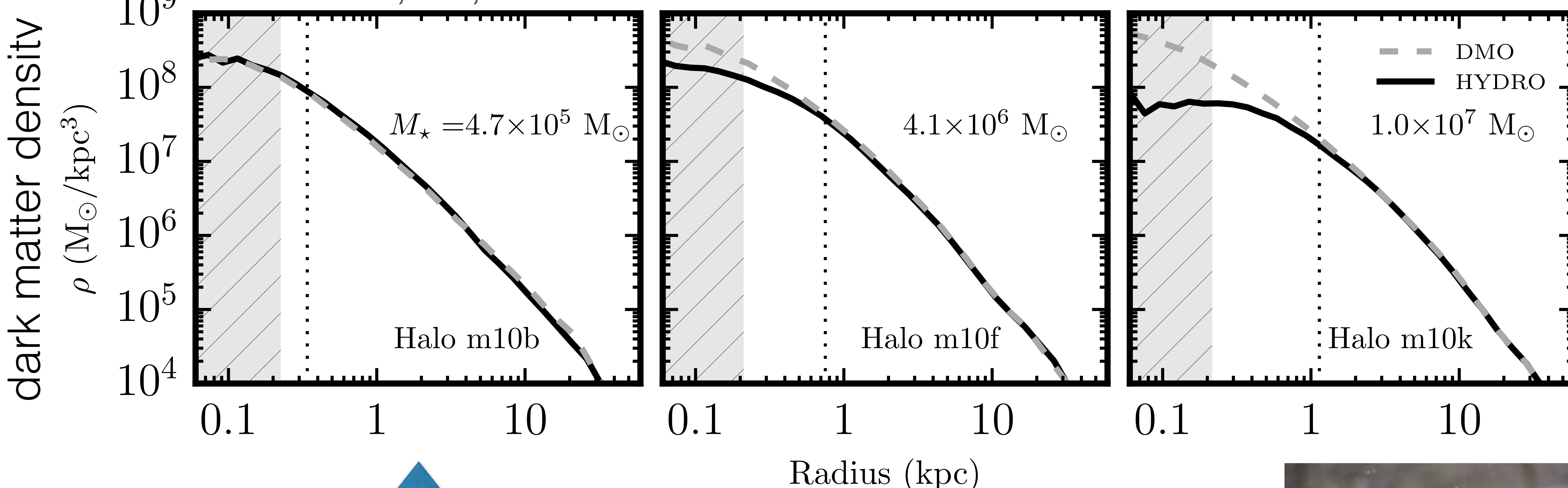
stellar feedback (supernovae)

bursty star formation —> gas outflows/inflows —> heat dark matter —> reduce inner density (forming cores)

stellar feedback generates dark-matter cores in dwarf galaxies at $M_{star} >\sim 10^6\ M_{sun}$

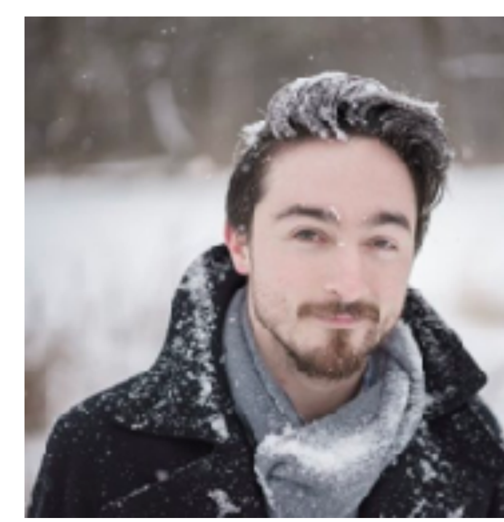
Alex Fitts, …, Wetzel et al 2016

$M_{halo} = 10^{10}\ M_{sun}$

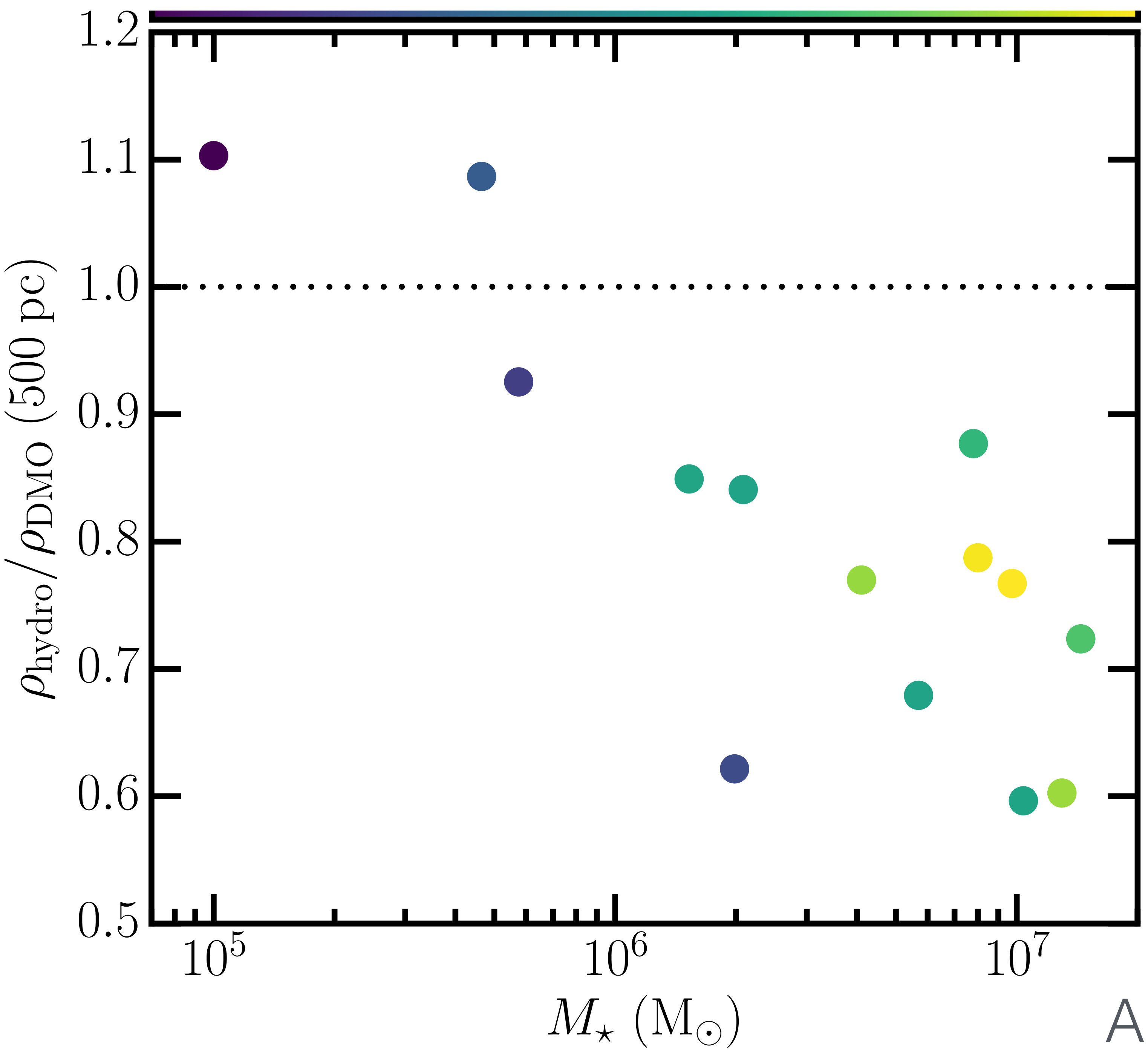


too few stars

also, Governato et al 2012, Teyssier et al 2013, Di Cintio et al 2014, Madau et al 2014, Tollet et al 2015, Read et al 2015



stellar feedback generates dark-matter cores in dwarf galaxies at $M_{star} > \sim 10^6\ M_{sun}$

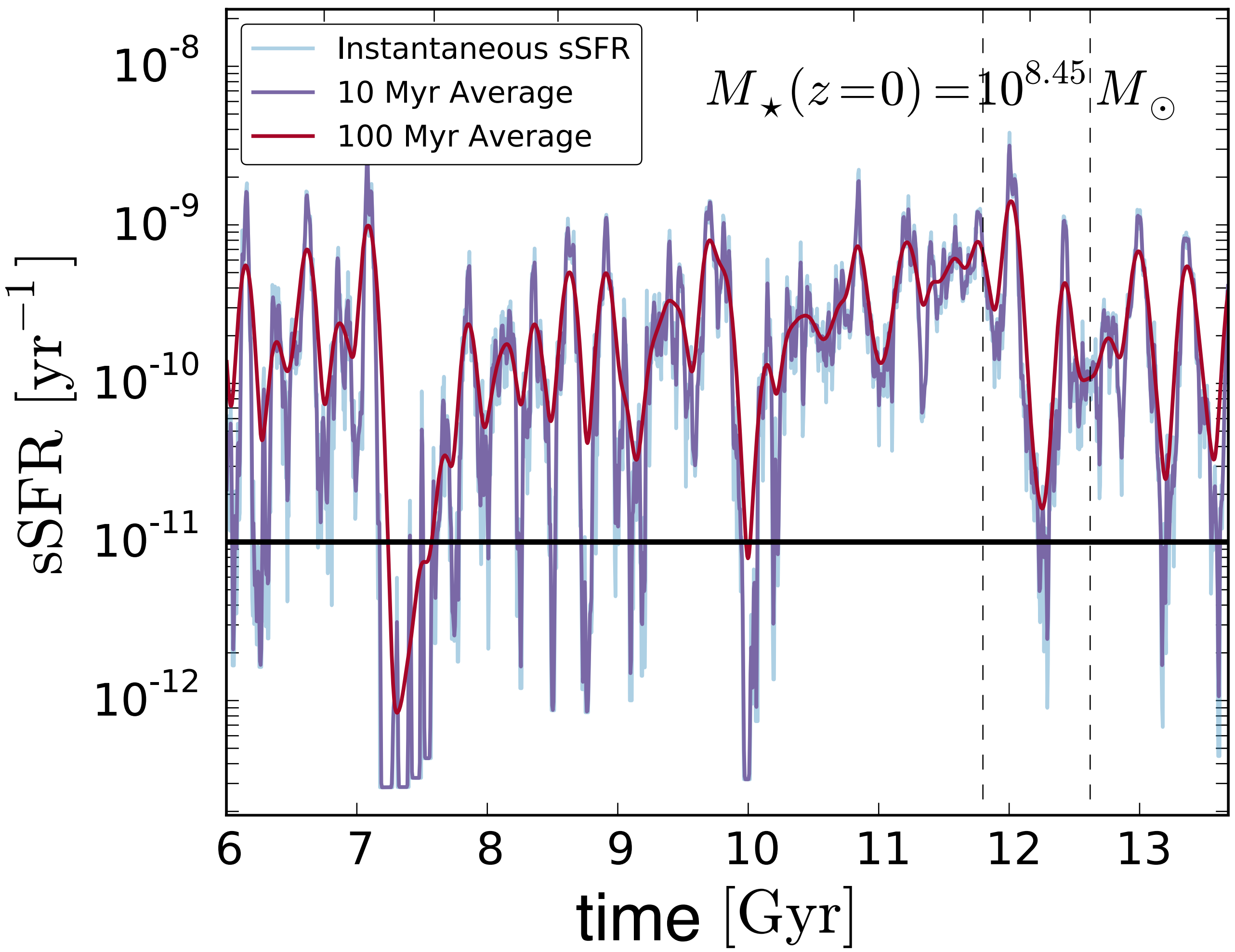


all of these galaxies have $M_{halo} = 10^{10}\ M_{sun}$

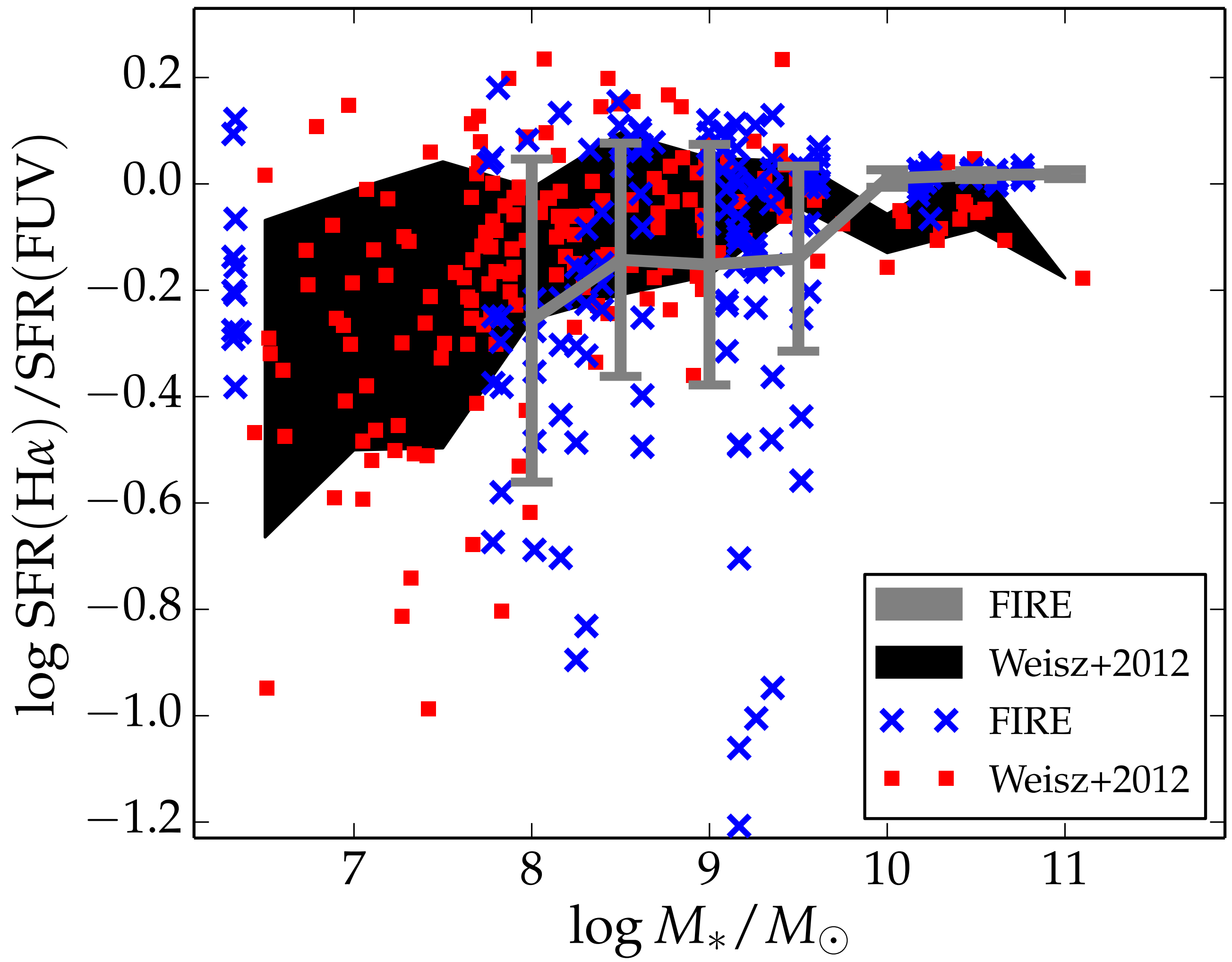
Alex Fitts, …, Wetzel et al 2016

dwarf galaxies have bursty star formation

El-Badry, Wetzel et al 2016

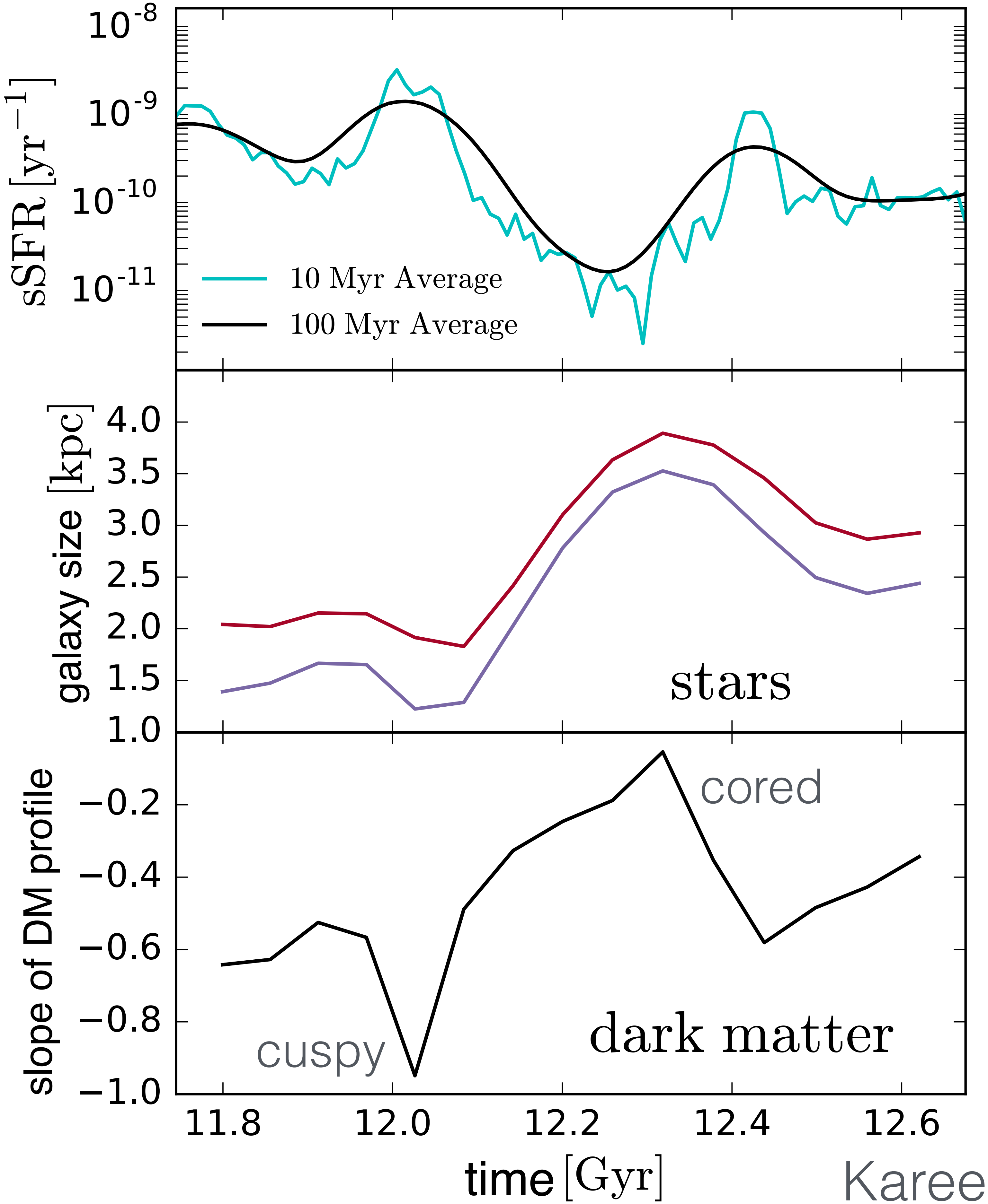


Sparre et al 2015



general prediction of simulations at high resolution

e.g., Stinson et al 2007, Ceverino & Klypin 2009, Governato et al 2010, Pontzen & Governato 2012, Teyssier et al 2013, Madau et al 2014



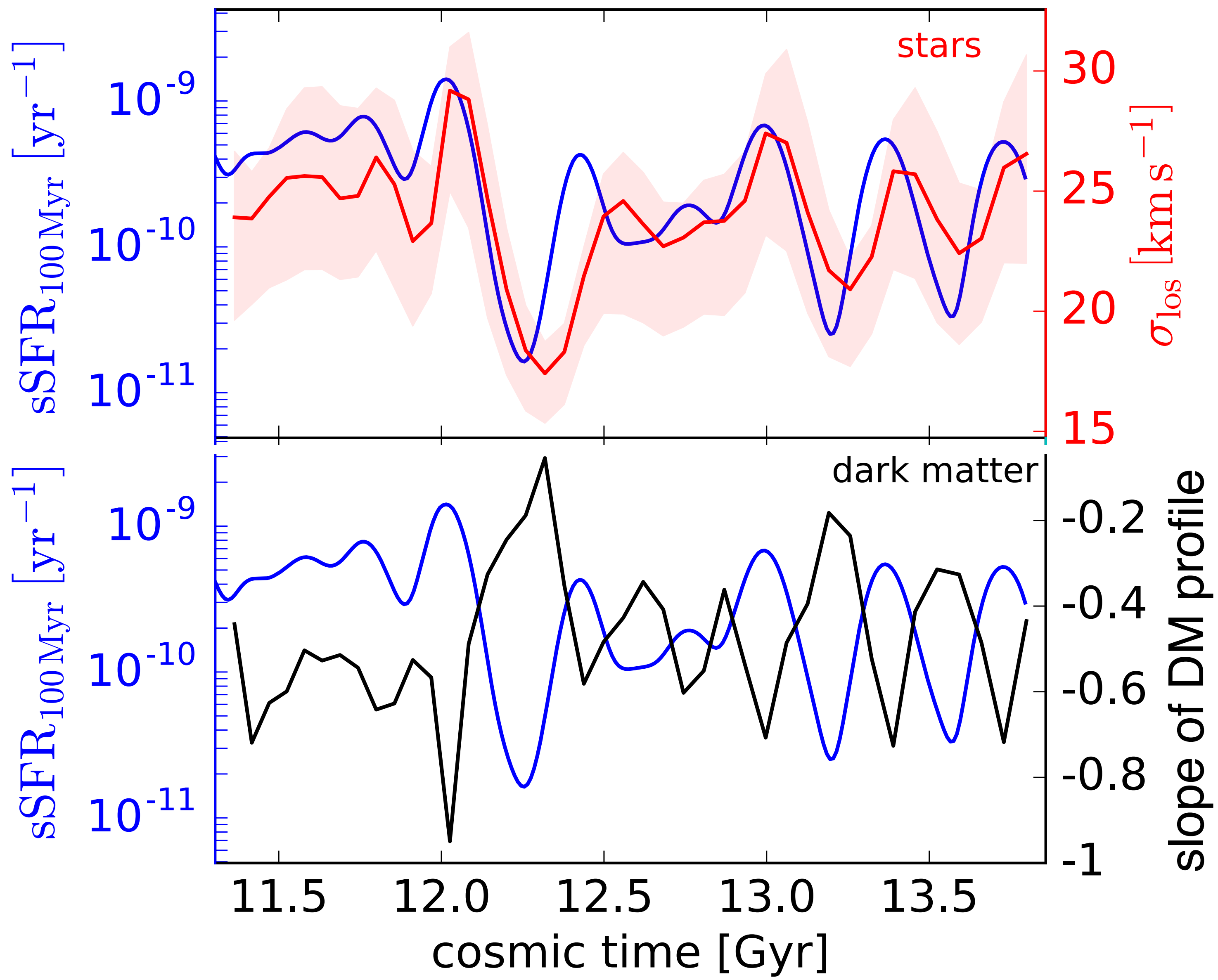
- galaxy size
- stellar kinematics
- dark-matter coring

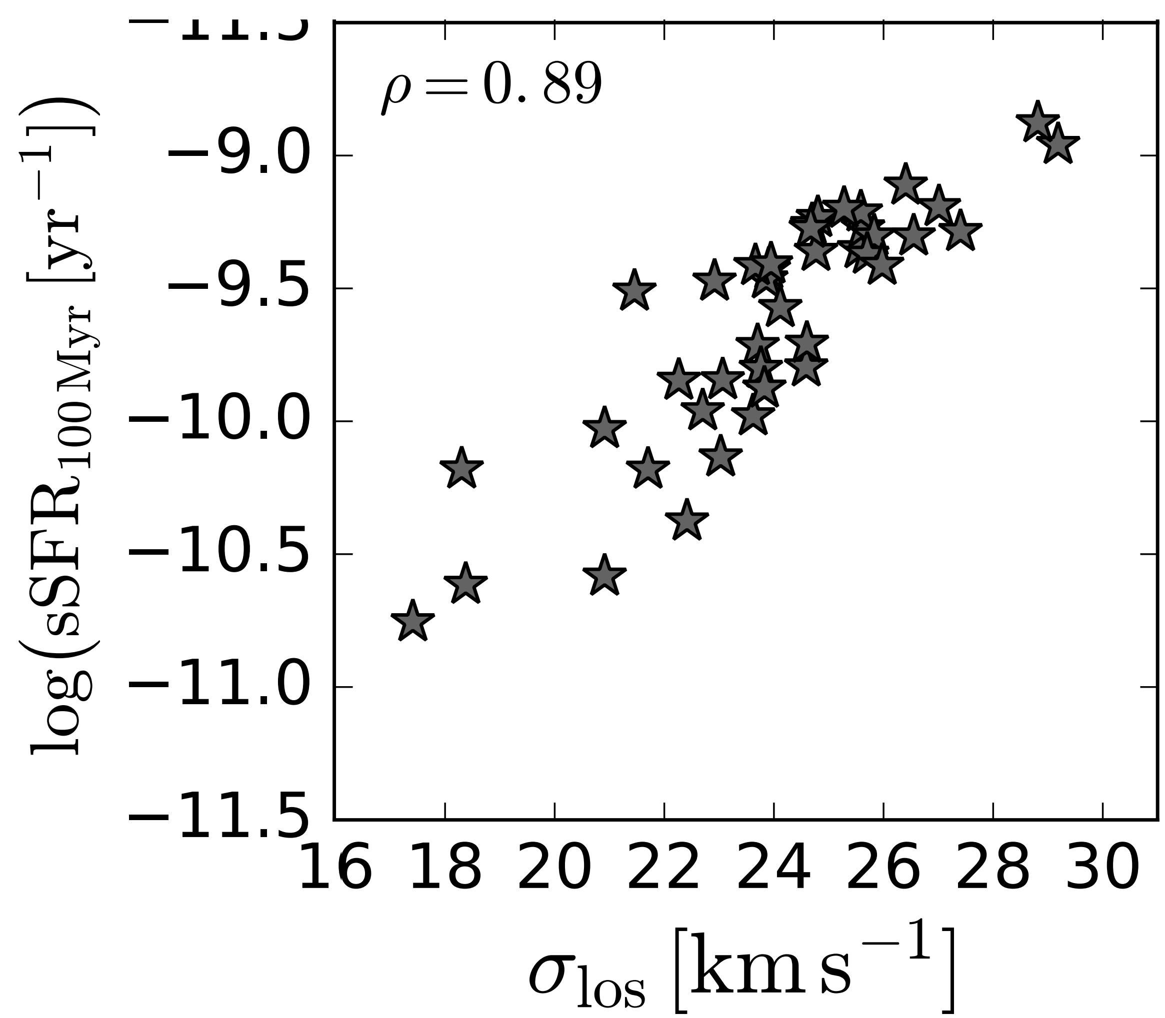
all correlate with star formation activity

Kareem El-Badry, Wetzel et al 2016

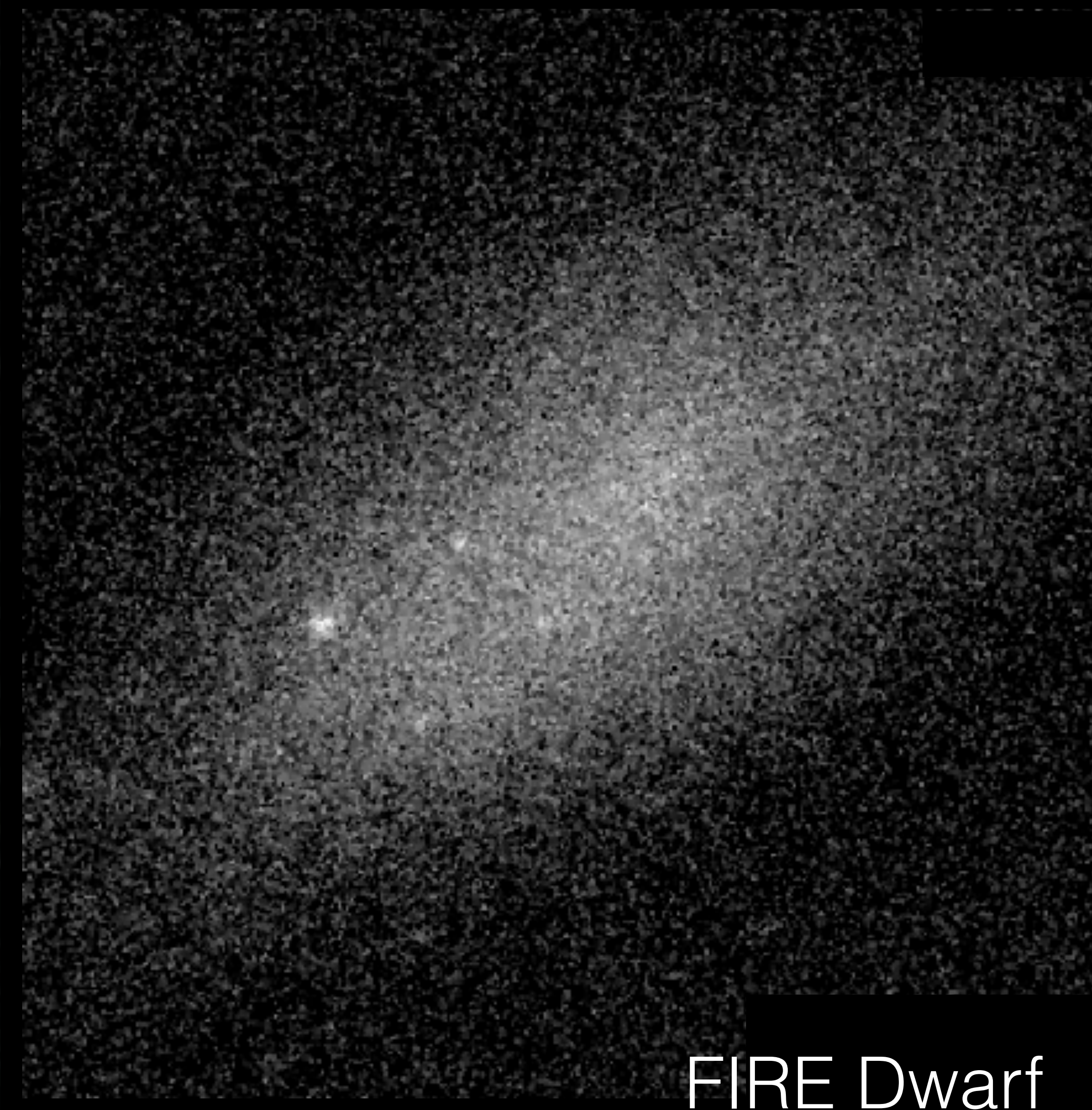
testable predictions of feedback-driven core formation

Kareem El-Badry, Wetzel et al 2017



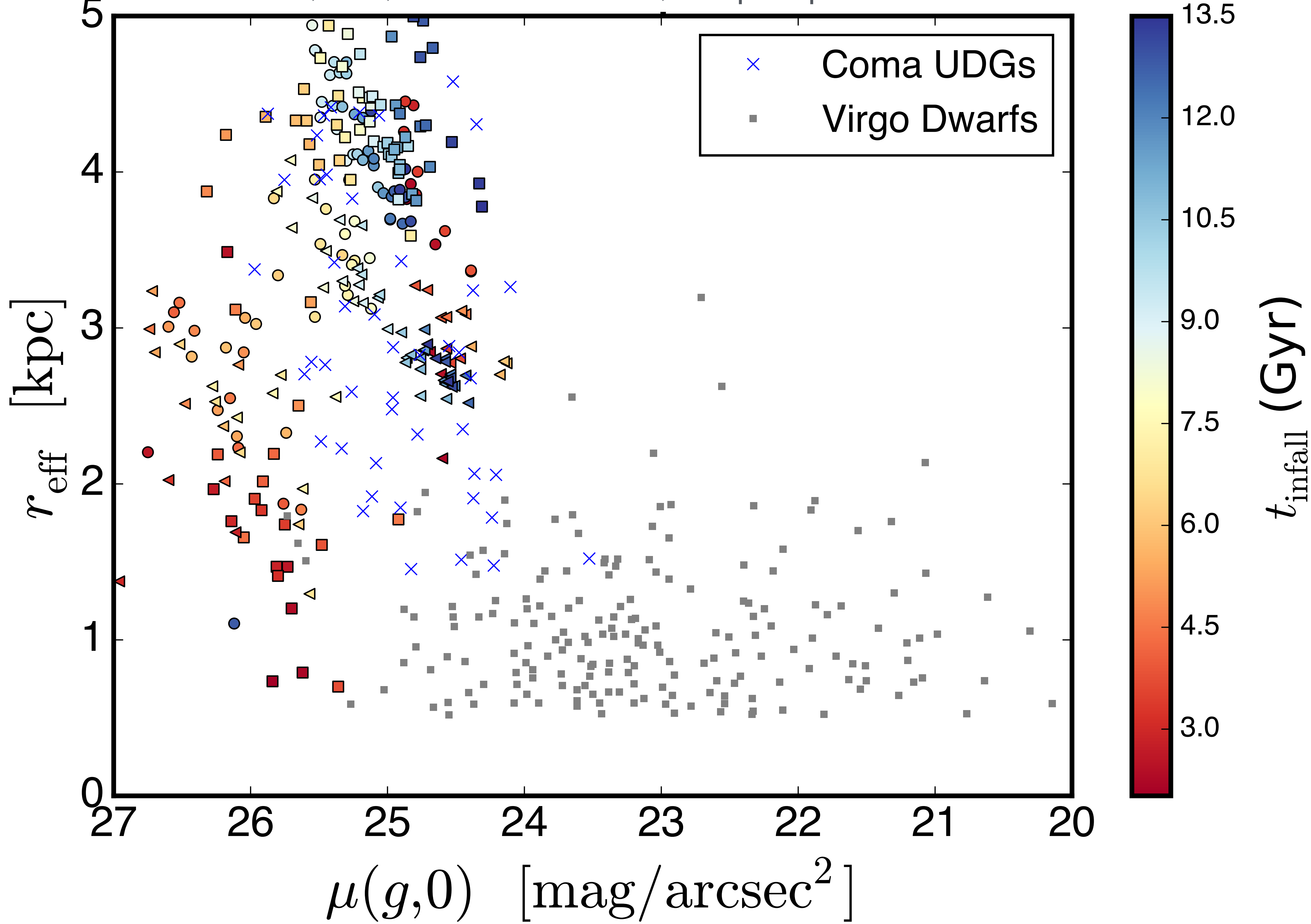


origin of ultra-diffuse galaxies



TK Chan, …, Wetzel et al, in prep
see also Di Cintio et al 2016

TK Chan, …, Wetzel et al, in prep



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