The importance of feedback in the formation of realistic dwarf galaxies

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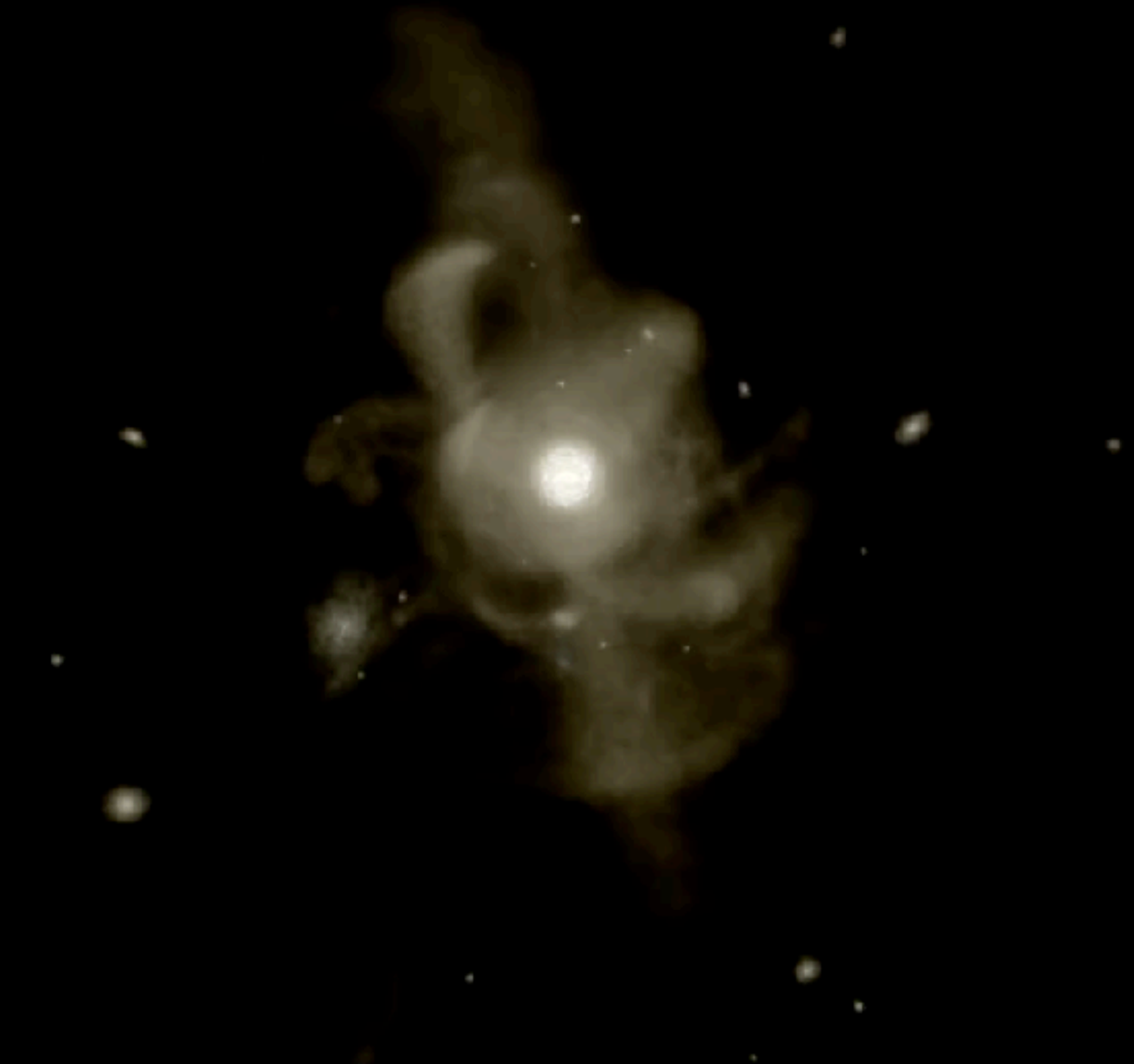
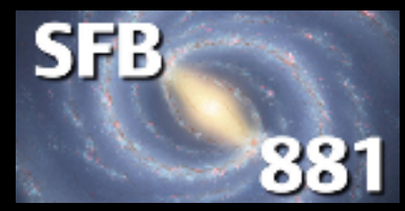
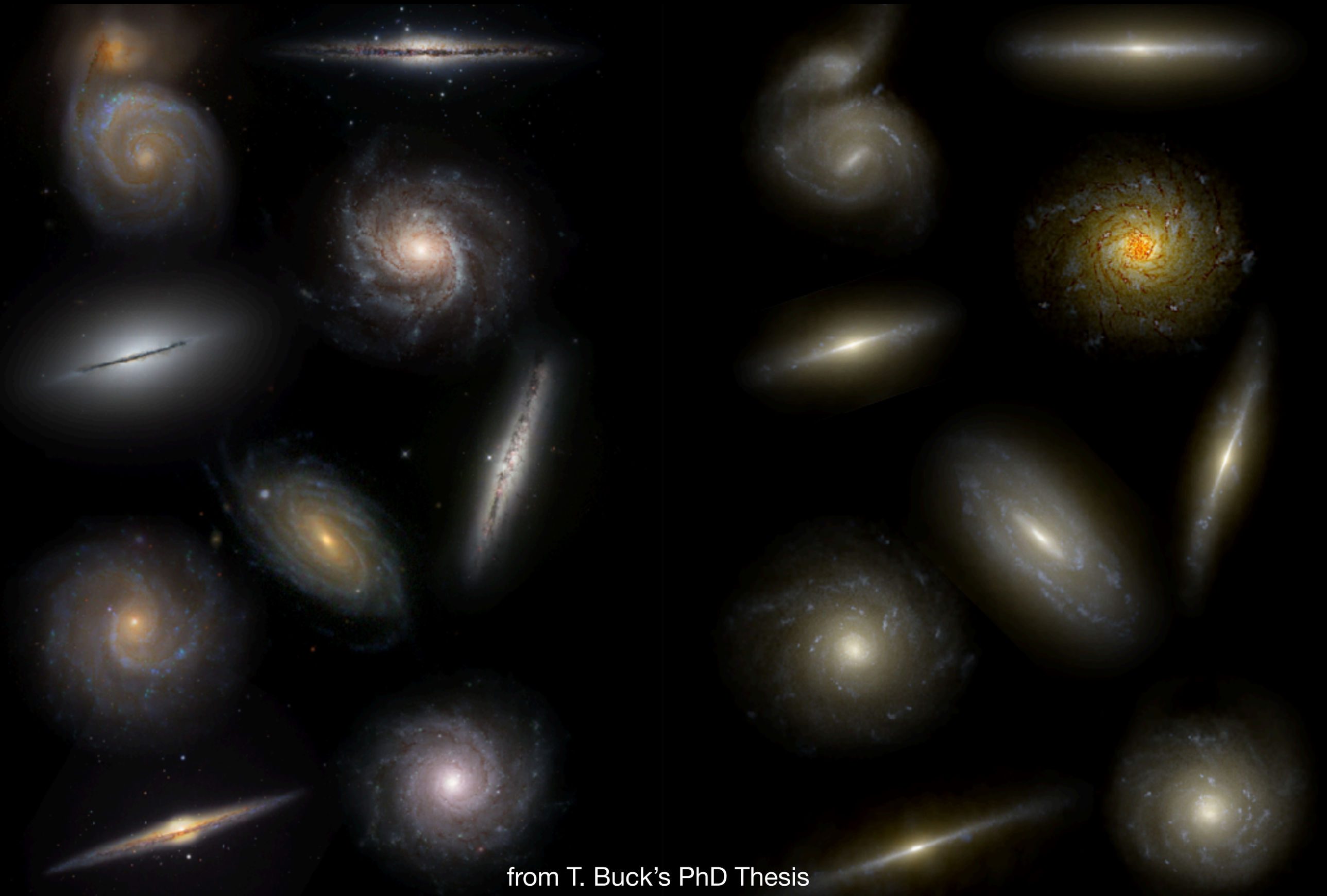




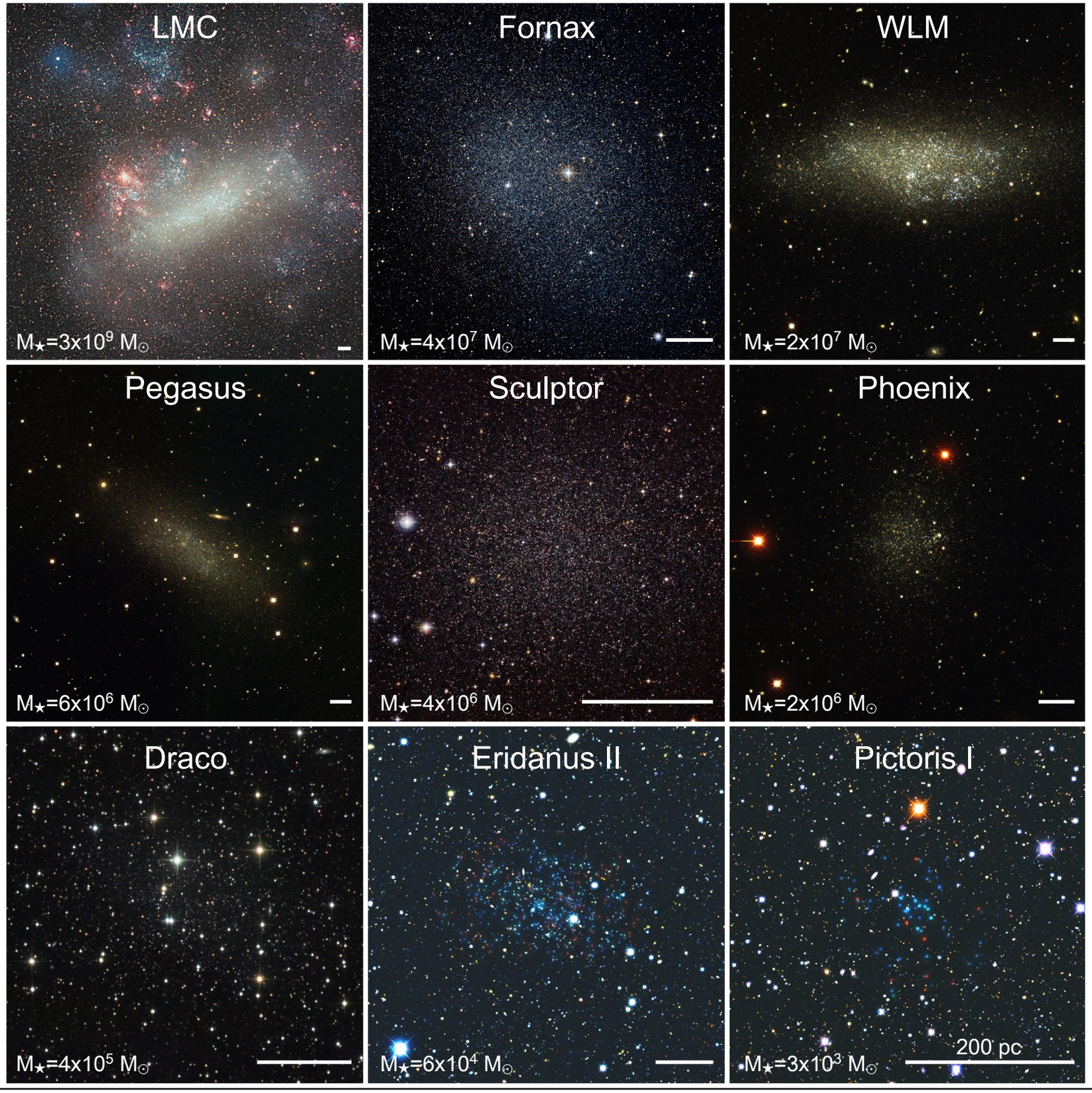
Is LCDM wrong?

Simulations produce realistic discs



from T. Buck's PhD Thesis

But problems on dwarf galaxy scale

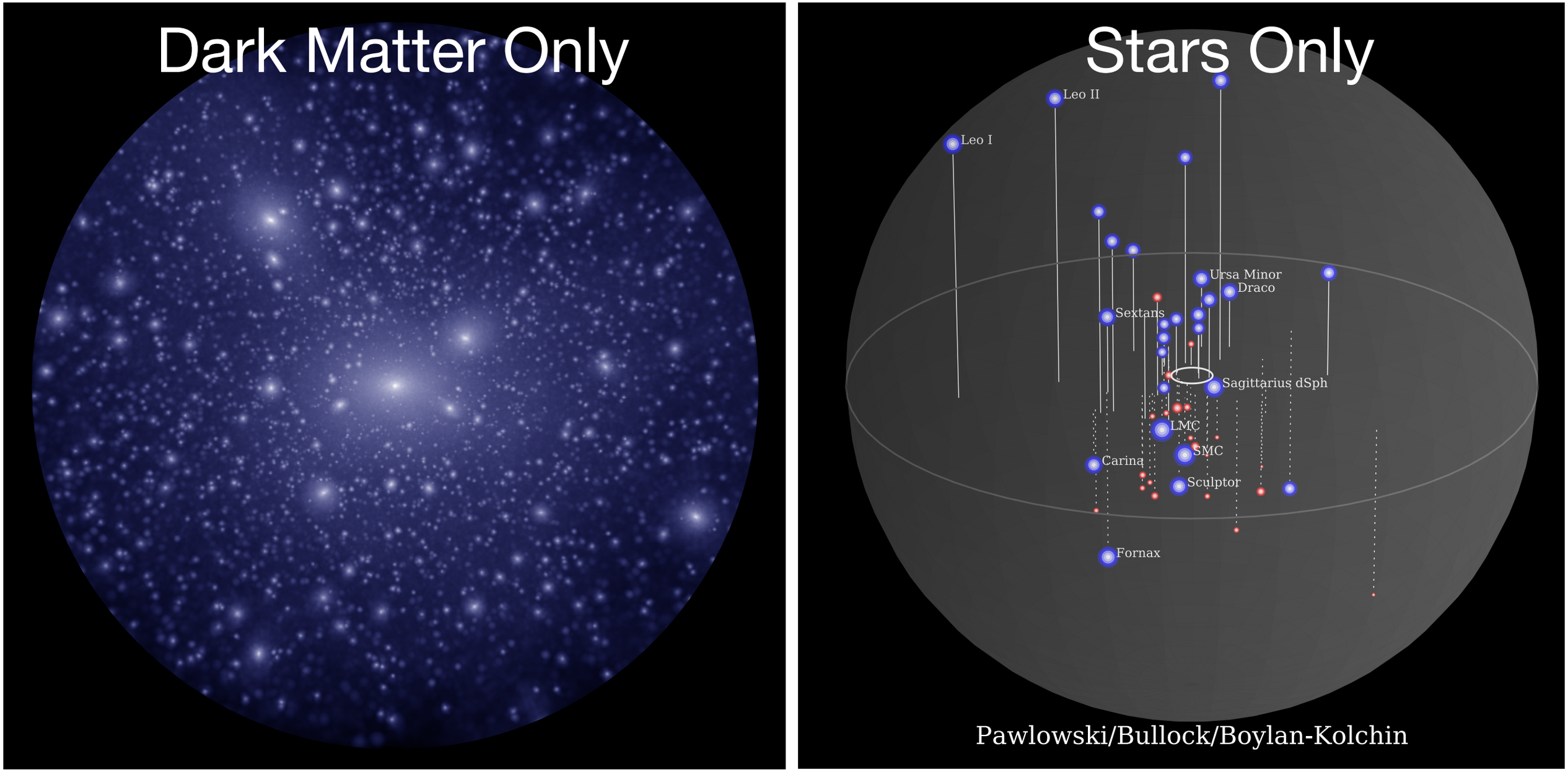


Bullock+2017

Small scale problems of LCDM

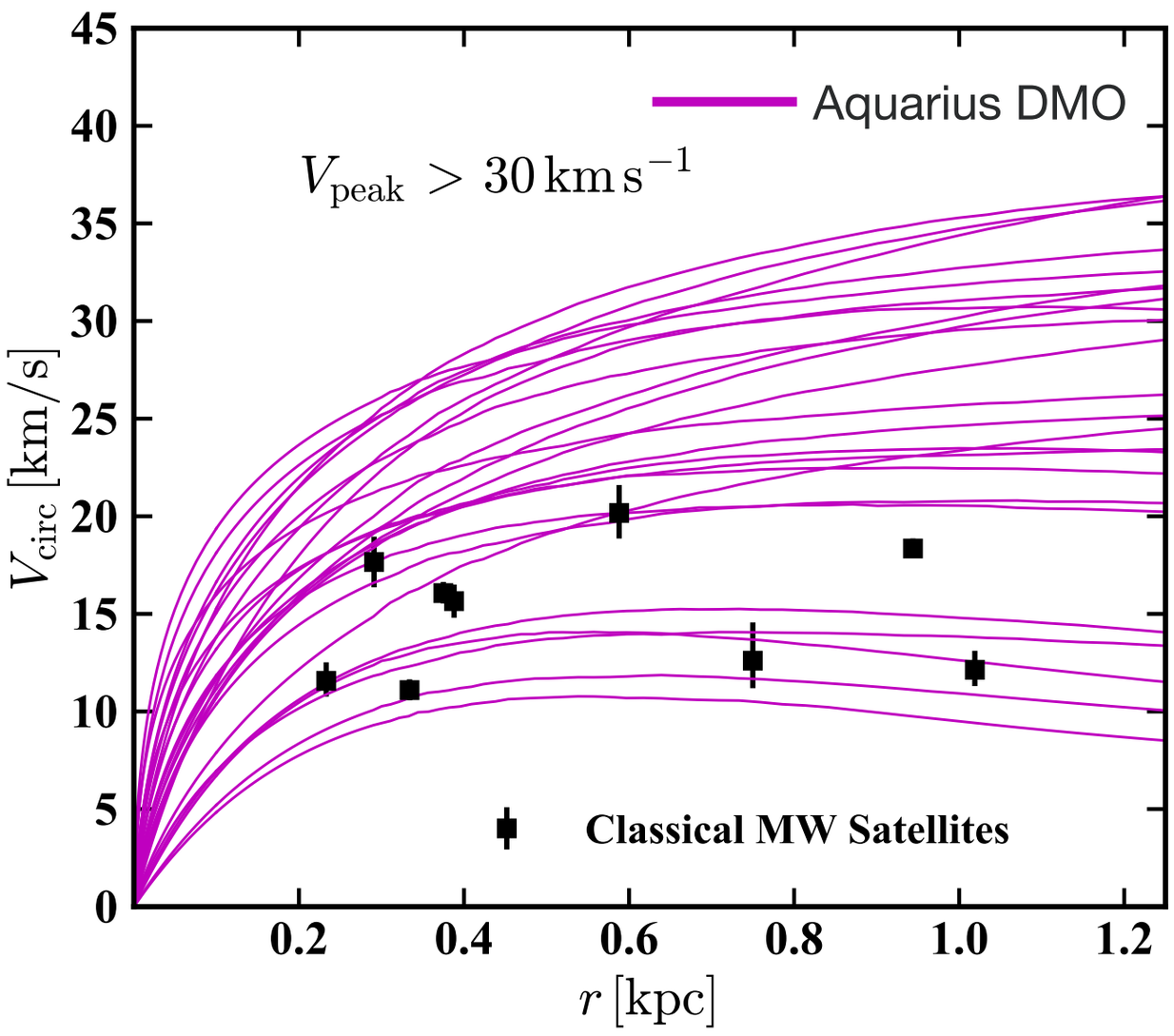
1. Missing satellites problem
2. Too-big-to-fail problem
3. cusp-core problem

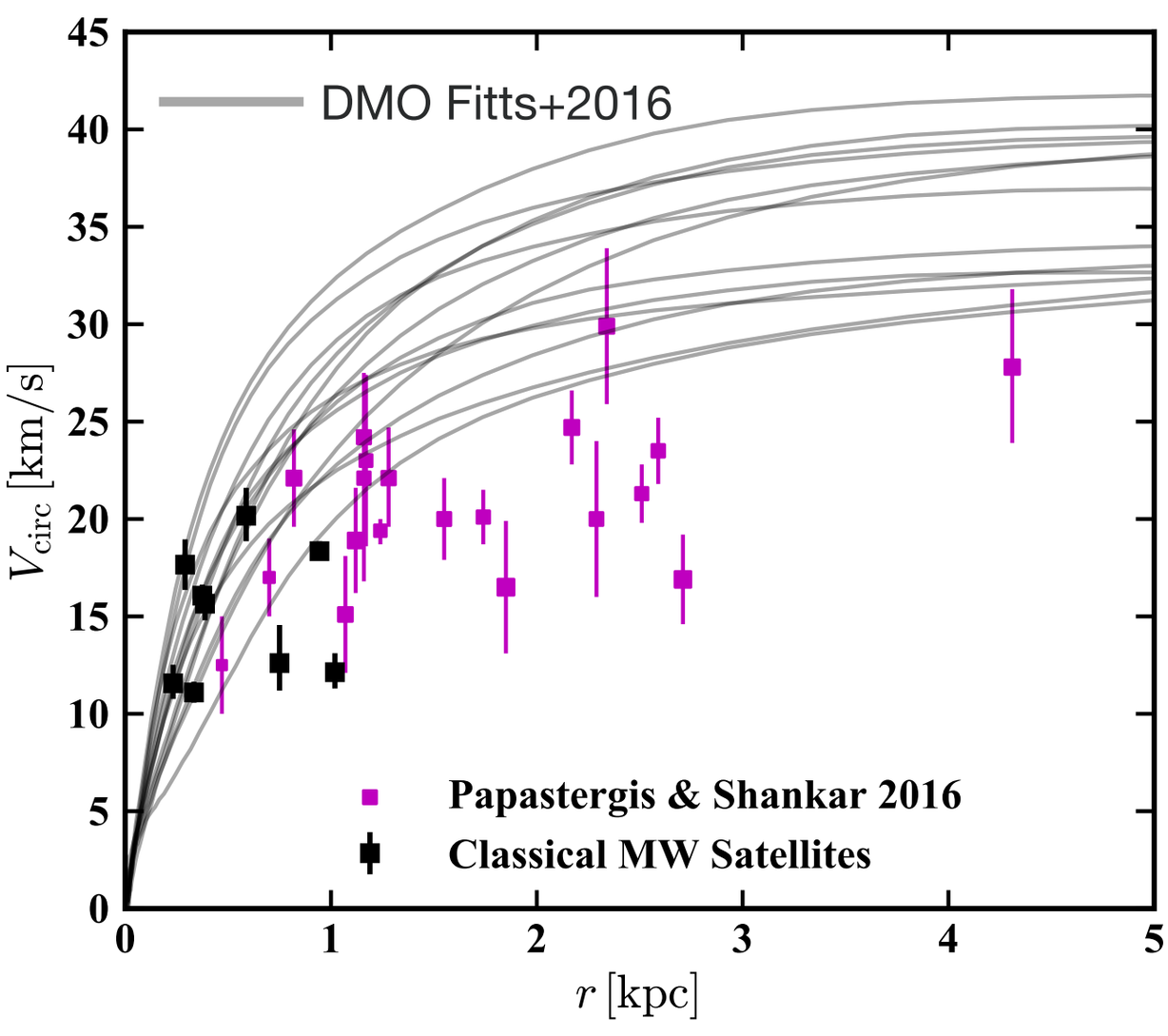
1. The missing satellites problem



Bullock+2017

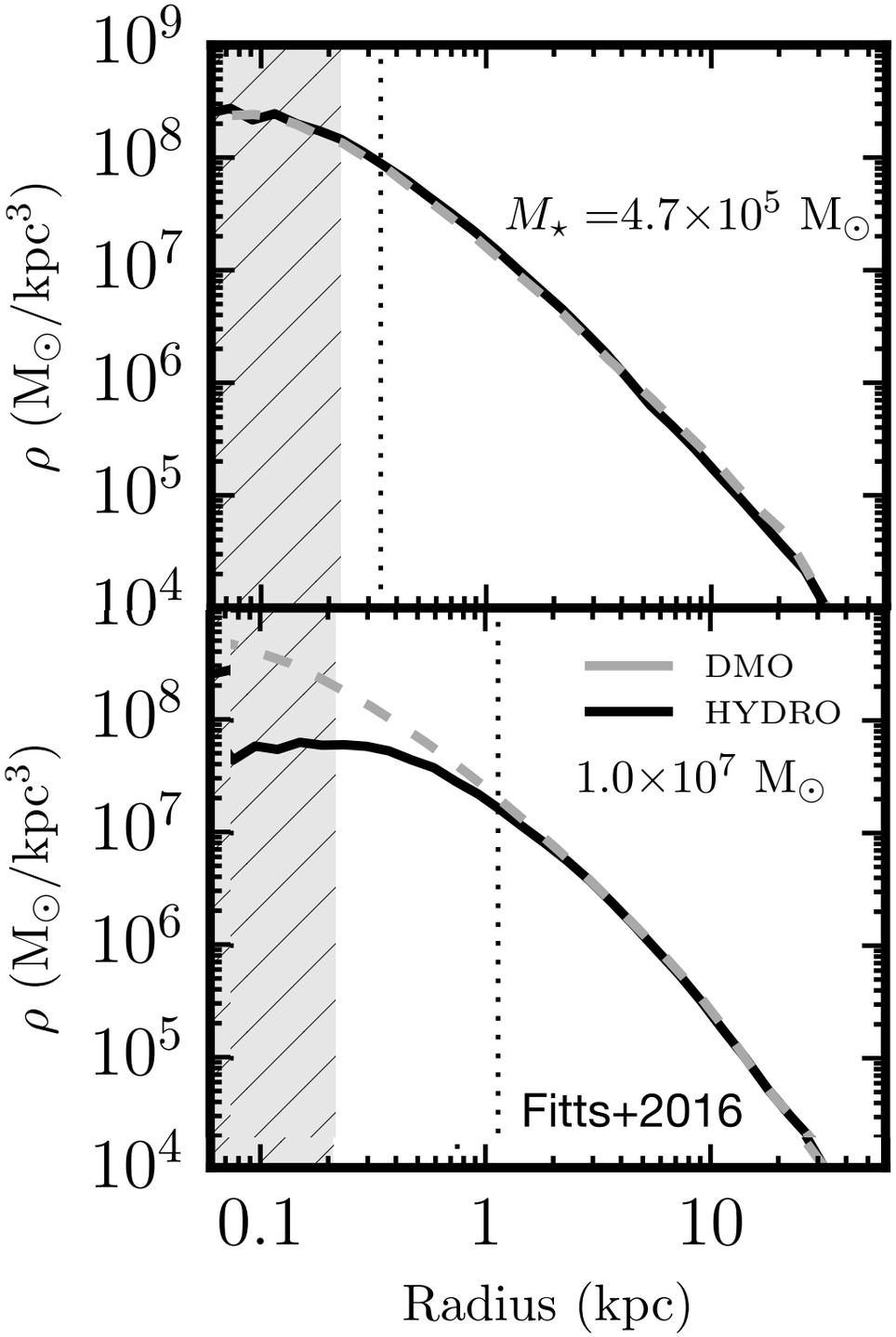
2. Too-big-to-fail problem

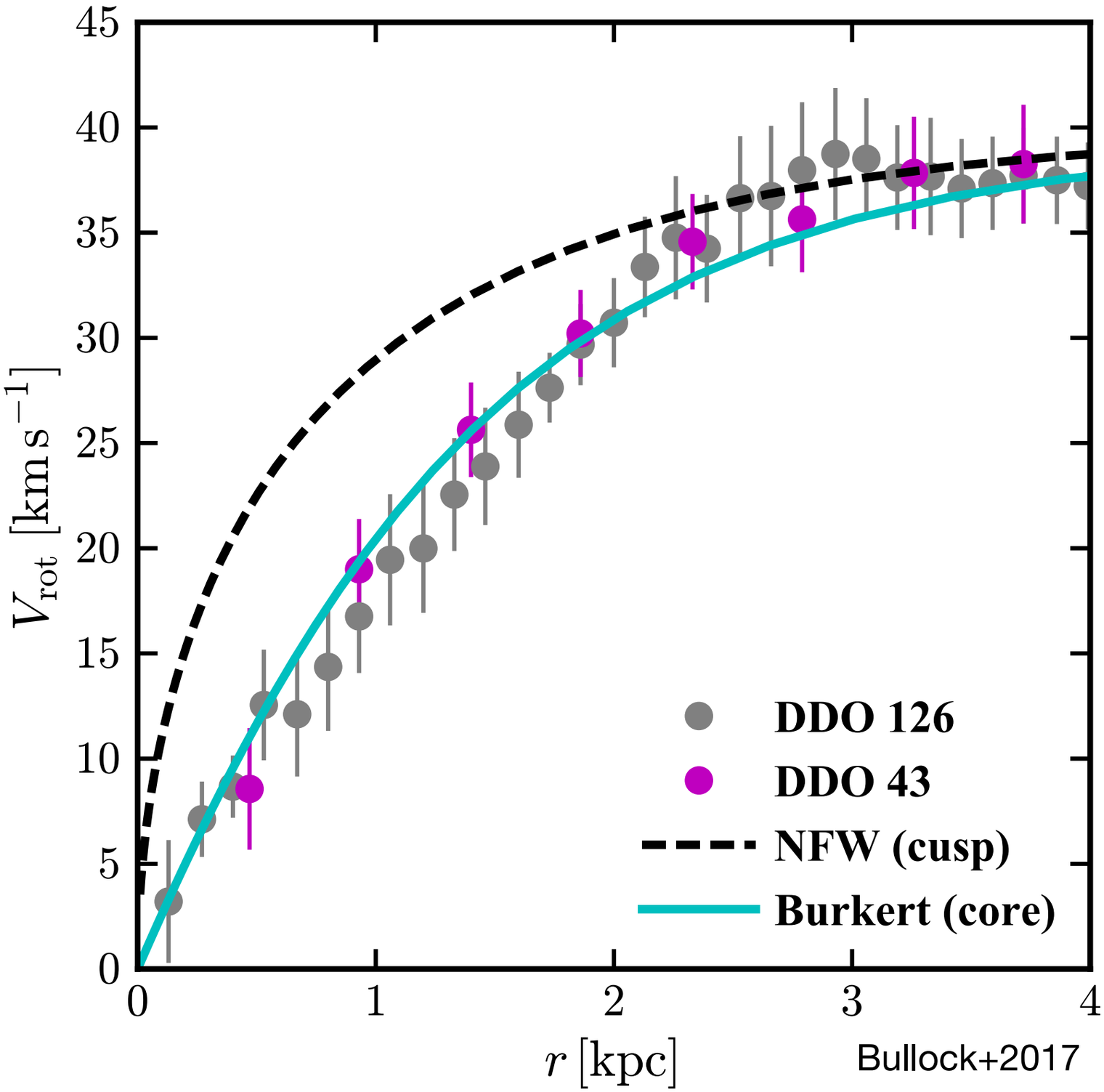




Bullock+2017

3. Cusp-Core problem





Is LCDM wrong?

NO!

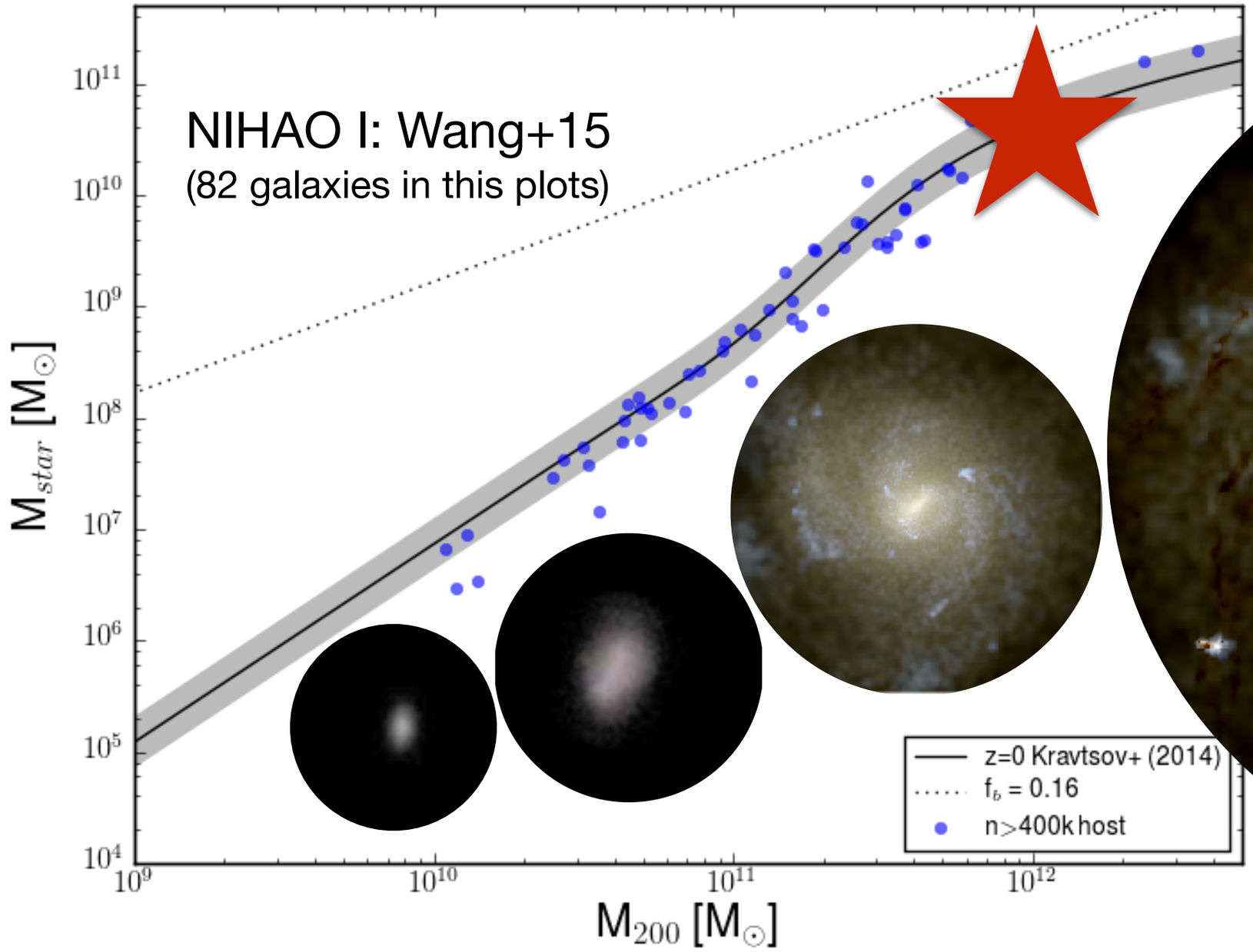
Hydrodynamics and feedback matter!

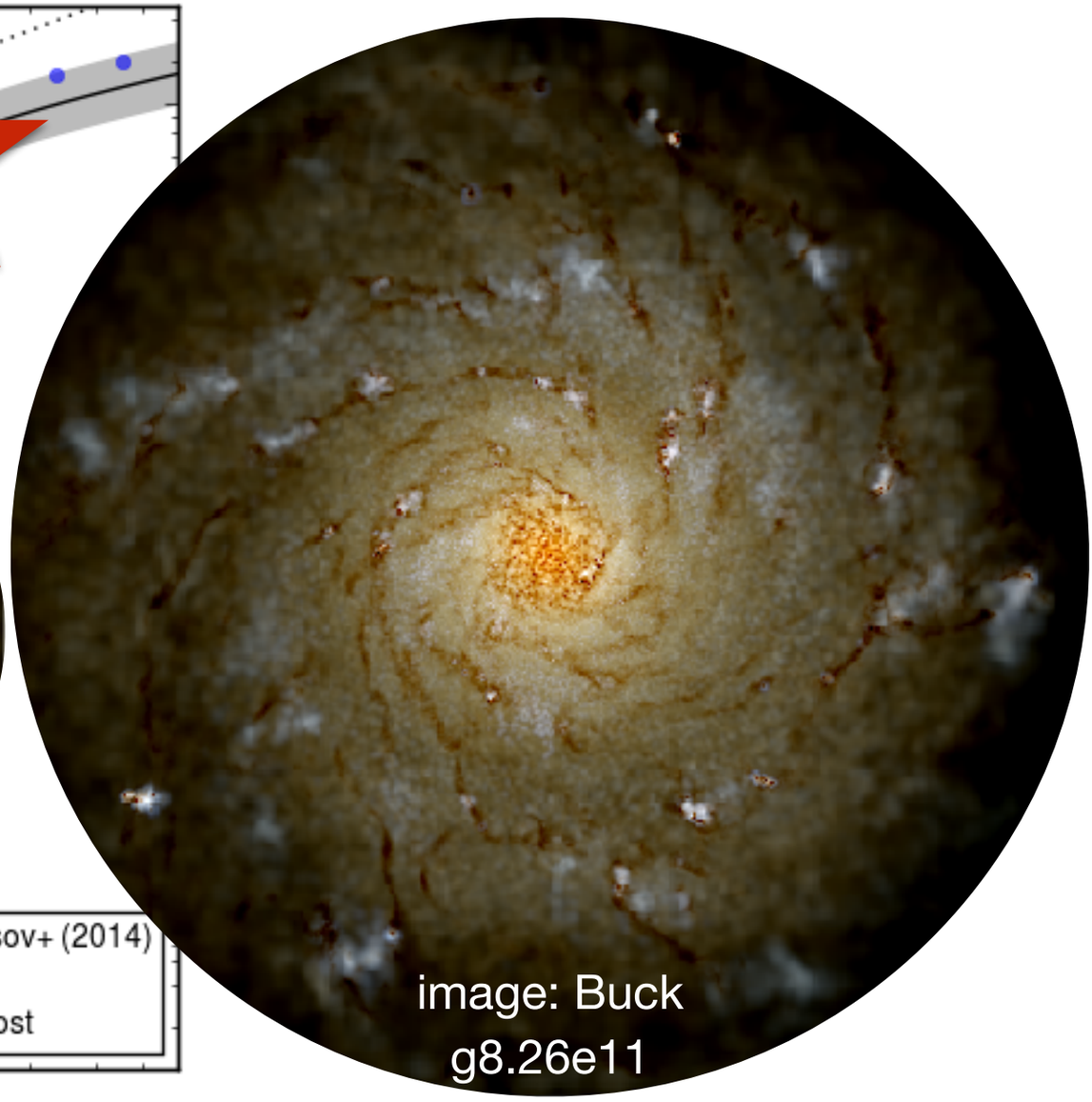
Numerical Investigation of a Hundred Astronomical Objects

The NIHAO Simulation suite

125 zoom-in simulations from Milky-Way mass to dwarf galaxies scales

SPH - Gasoline2 (Wadsley+2017)





Simulation Physics

1

GASOLINE2.1
smooth particle hydrodynamics

„modern“ implementation of hydrodynamics, metal diffusion

Wadsley+2017, Keller+2014

2

gas cooling

via hydrogen, helium and various metal lines

gas heating

via Photoionisation from the UV background

Shen+2010, Haardt&Madau 2012

star formation regions

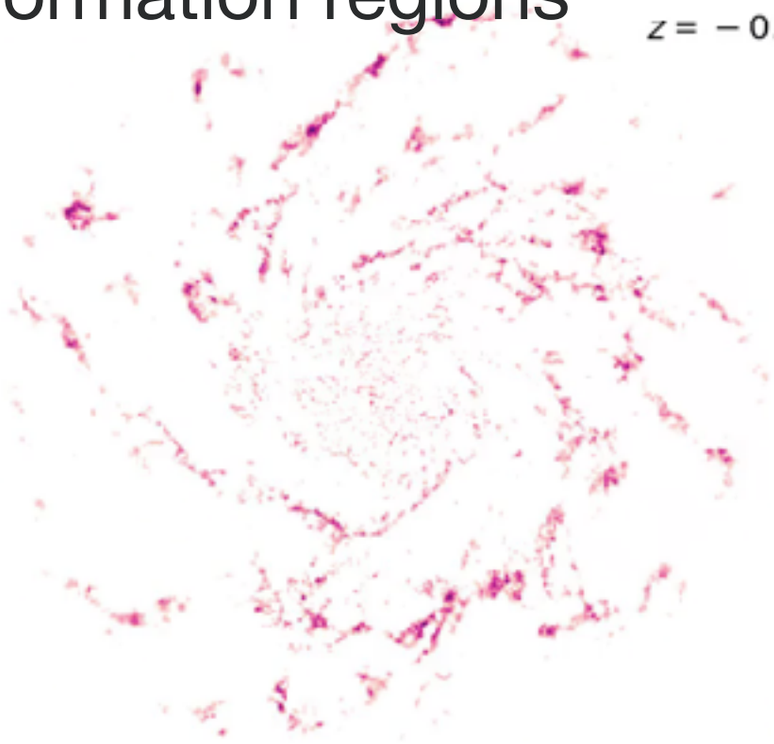


image size: 50x50 kpc

Animation by T. Buck (MPIA, NYUAD) based on NIHAO simulations

3

star formation from cold dense gas

n_{th}=10 parts/ccm

(Aaron Dutton’s talk on Friday)

Stinson+2006

4

early stellar feedback and SN feedback

- SNII energy + metals (delayed cooling)
- SNIa metals

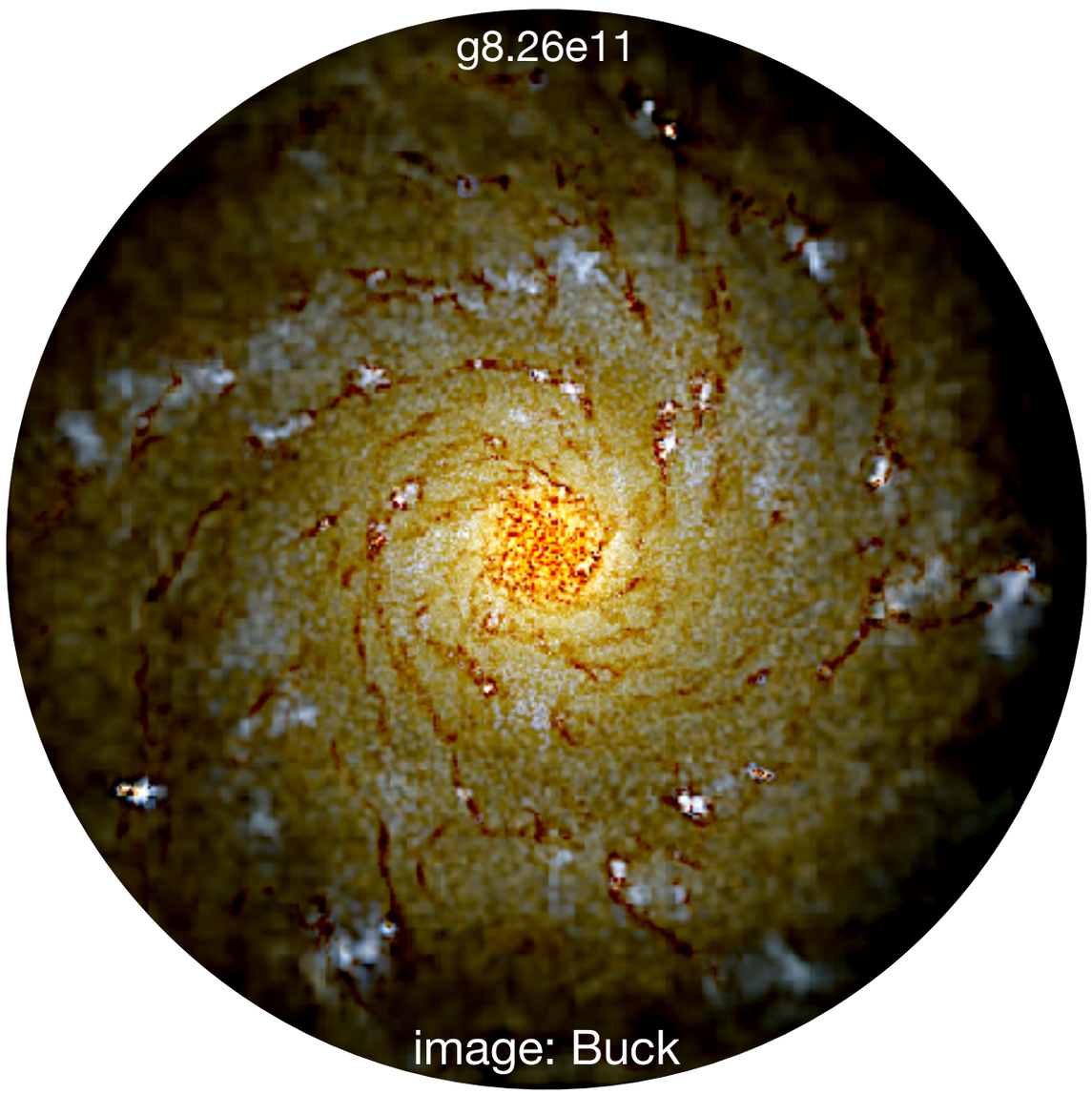
Stinson+2013

The Simulations

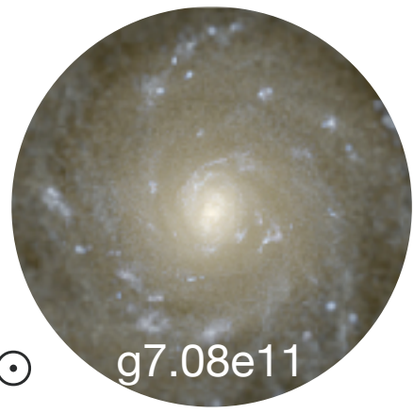
1. High-resolution zoom-in Milky Way sims
2. High-resolution zoom-in dwarf galaxy sims

1. High-res. MW simulations

halo masses: 5 x 10^{11} to 2.8 x 10^{12} $M_\odot$



- ~ 3 x 10^7 particles
- ~ 8 x 10^6 star particles
- ~ 10^7 gas particles



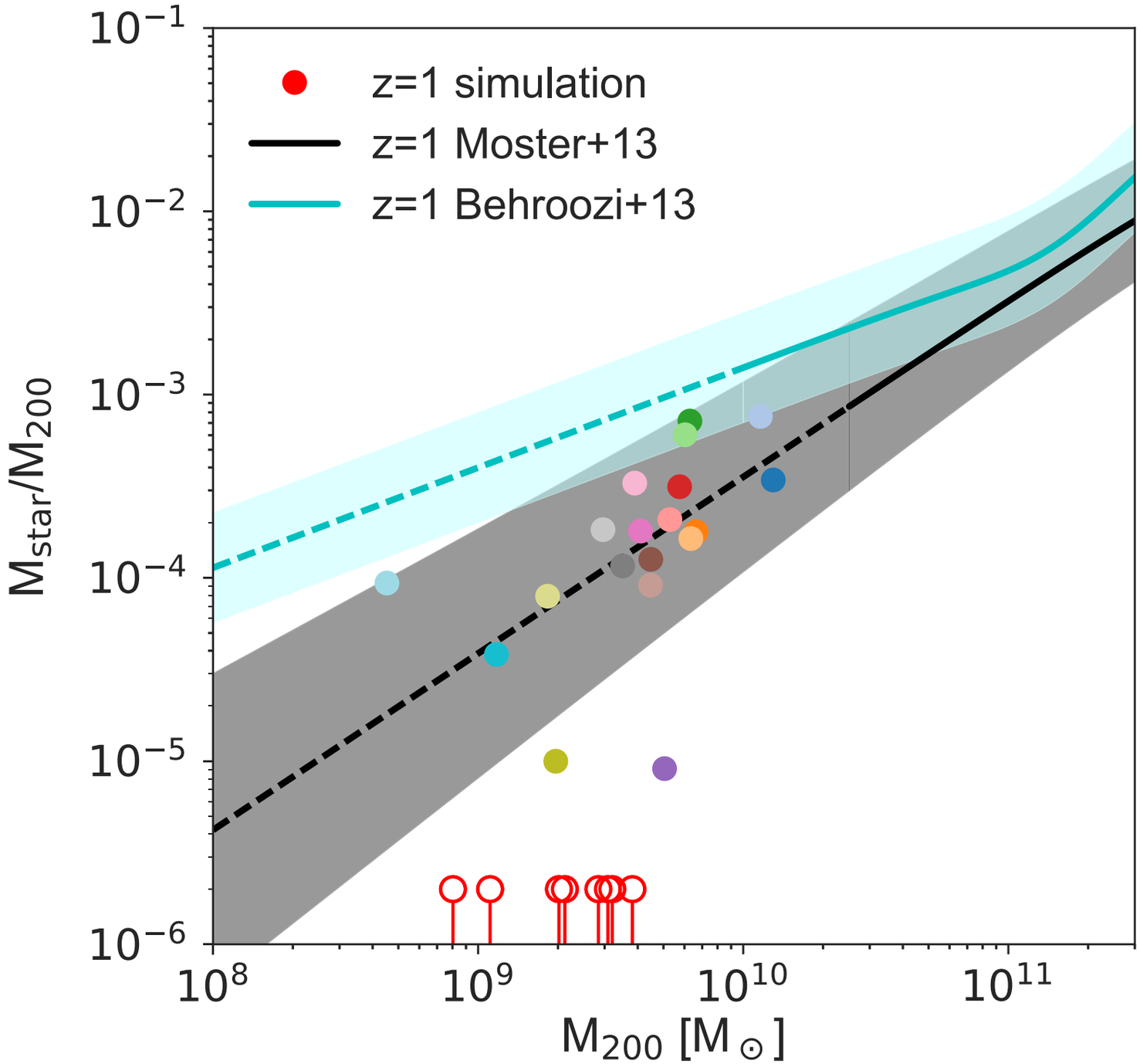
Gravitational softening and particle masses:

- dark matter: 400 pc, 1.5 x 10^5 $M_\odot$
- gas: 180 pc, 2.8 x 10^4 $M_\odot$
- stars: 180 pc, 9300 $M_\odot$

similar zoom-in projects: Aumer+2013, Latte-project (Wetzel+2016), Apostle (Sawala+2016), Auriga (Grand+2017)

2. High-res. dwarf galaxy sims

halo masses: 3 x 10^8 to 1 x 10^{10} $M_\odot$



Gravitational softening and particle masses:

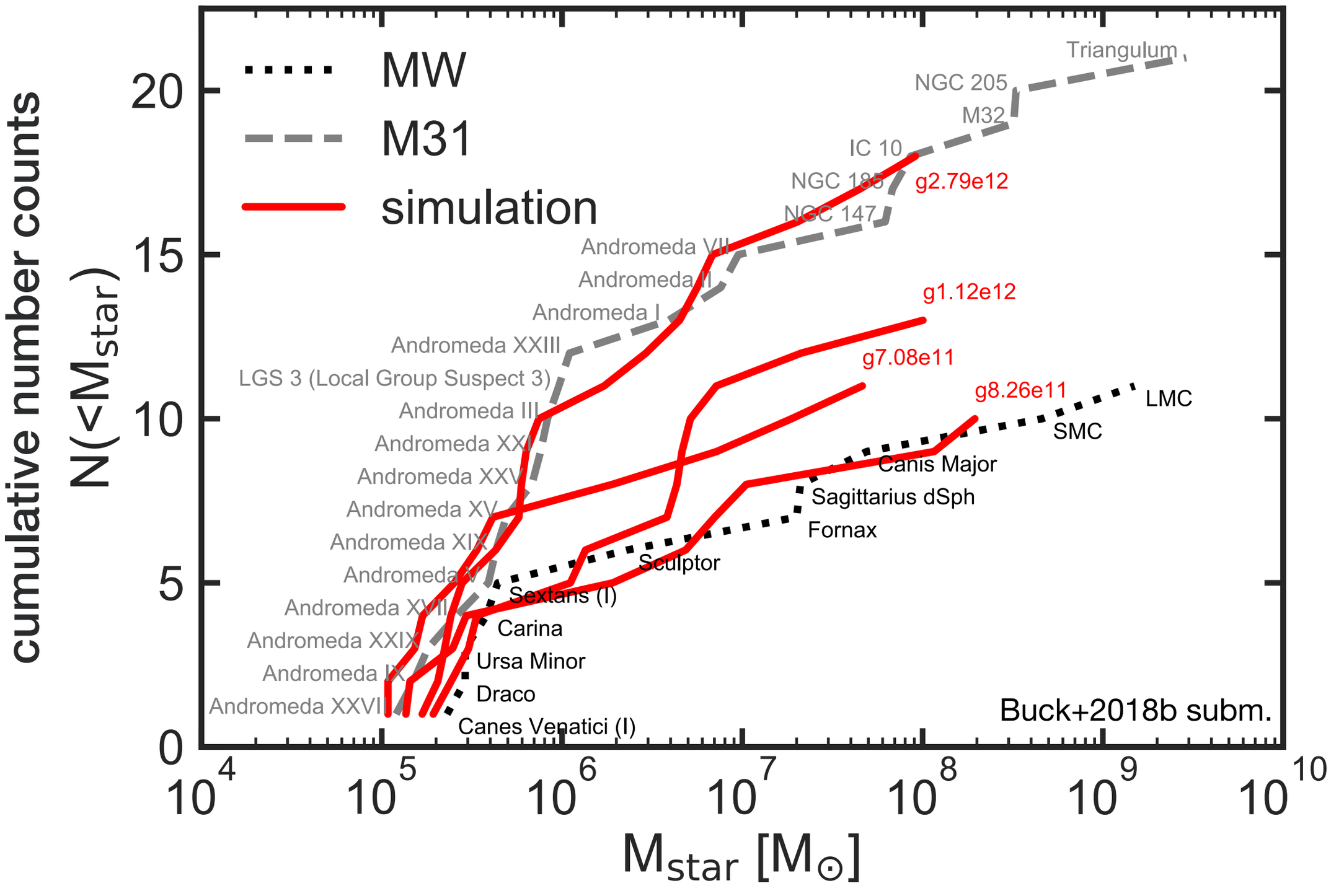
- dark matter: 30 pc, 2000 $M_\odot$
- gas: 14 pc, 400 $M_\odot$
- stars: 14 pc, 130 $M_\odot$

Macciò, Frings, Buck et al. 2017
Frings, Macciò, Buck et al. 2017

1. The Missing satellites problem:

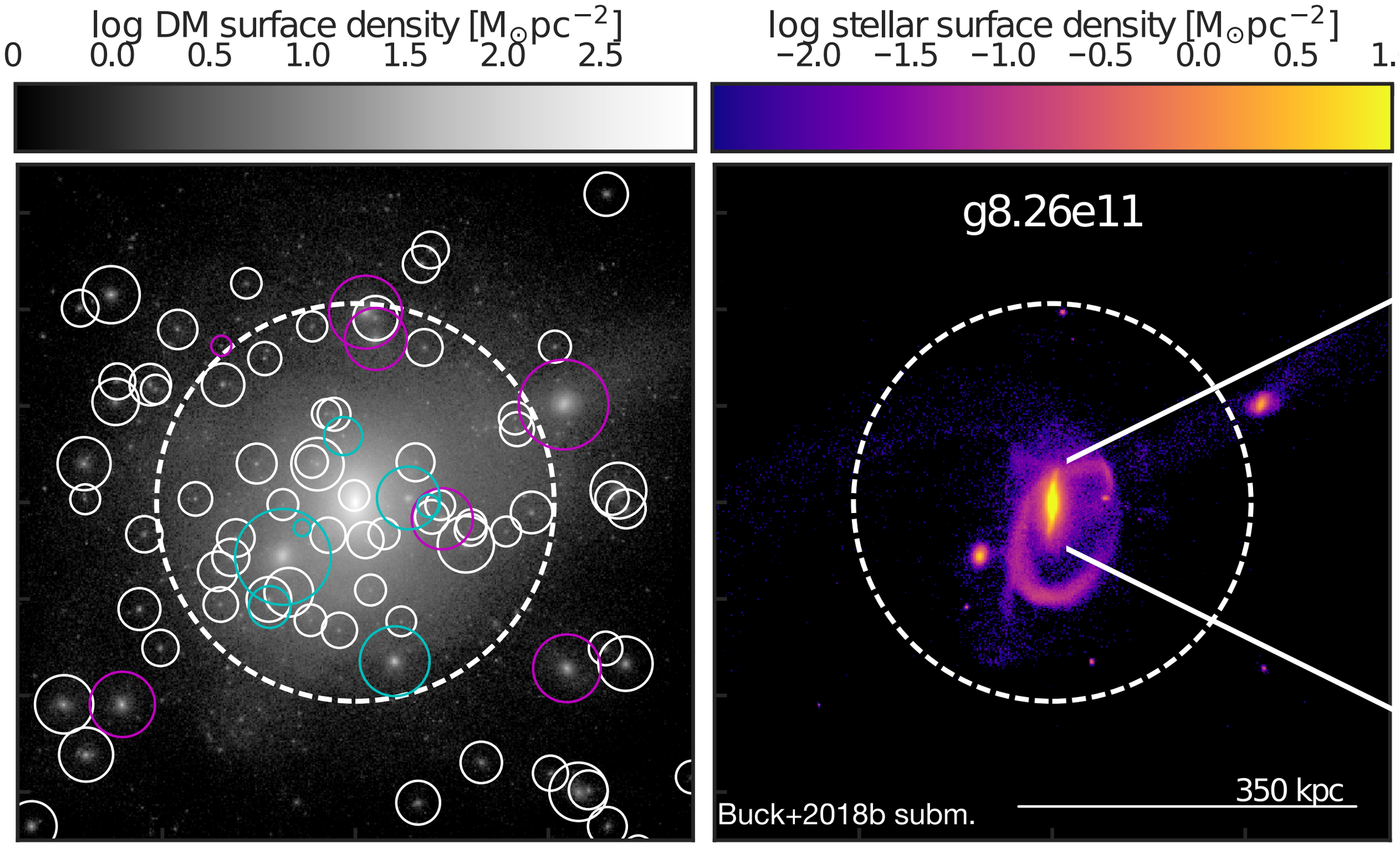
Can we reproduce the number counts of Local Group dwarf galaxies?

Satellite stellar mass function



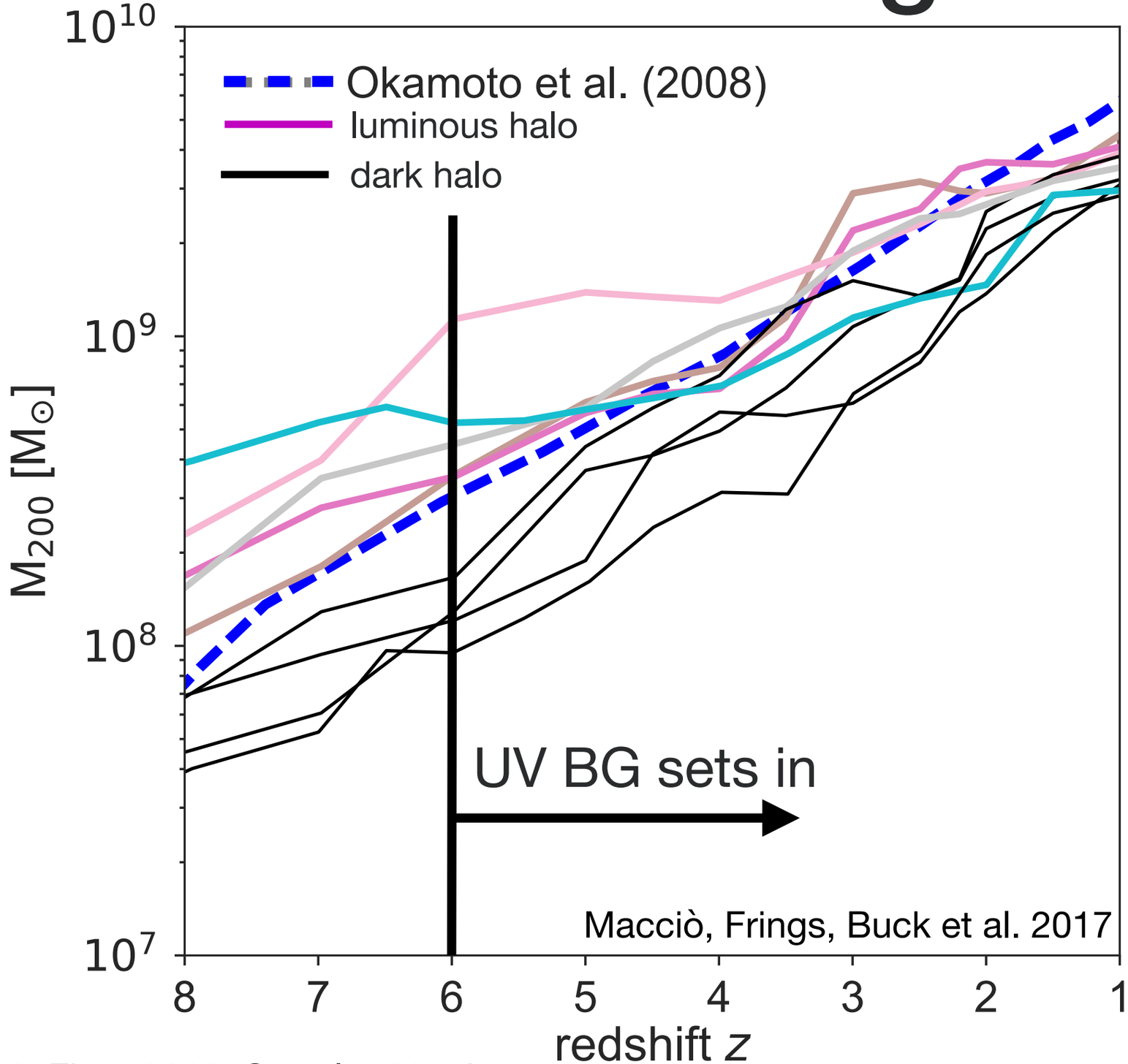
see also: Sawala+2015, Simpson+2017, Despali&Vegetti 2017 (baryonic modification of the mass function)

Baryonic effects leave haloes dark



see also: Simpson+ 2017, Sawala+2016, Wetzel+2016,

The inefficiency of galaxy formation due to the UV background

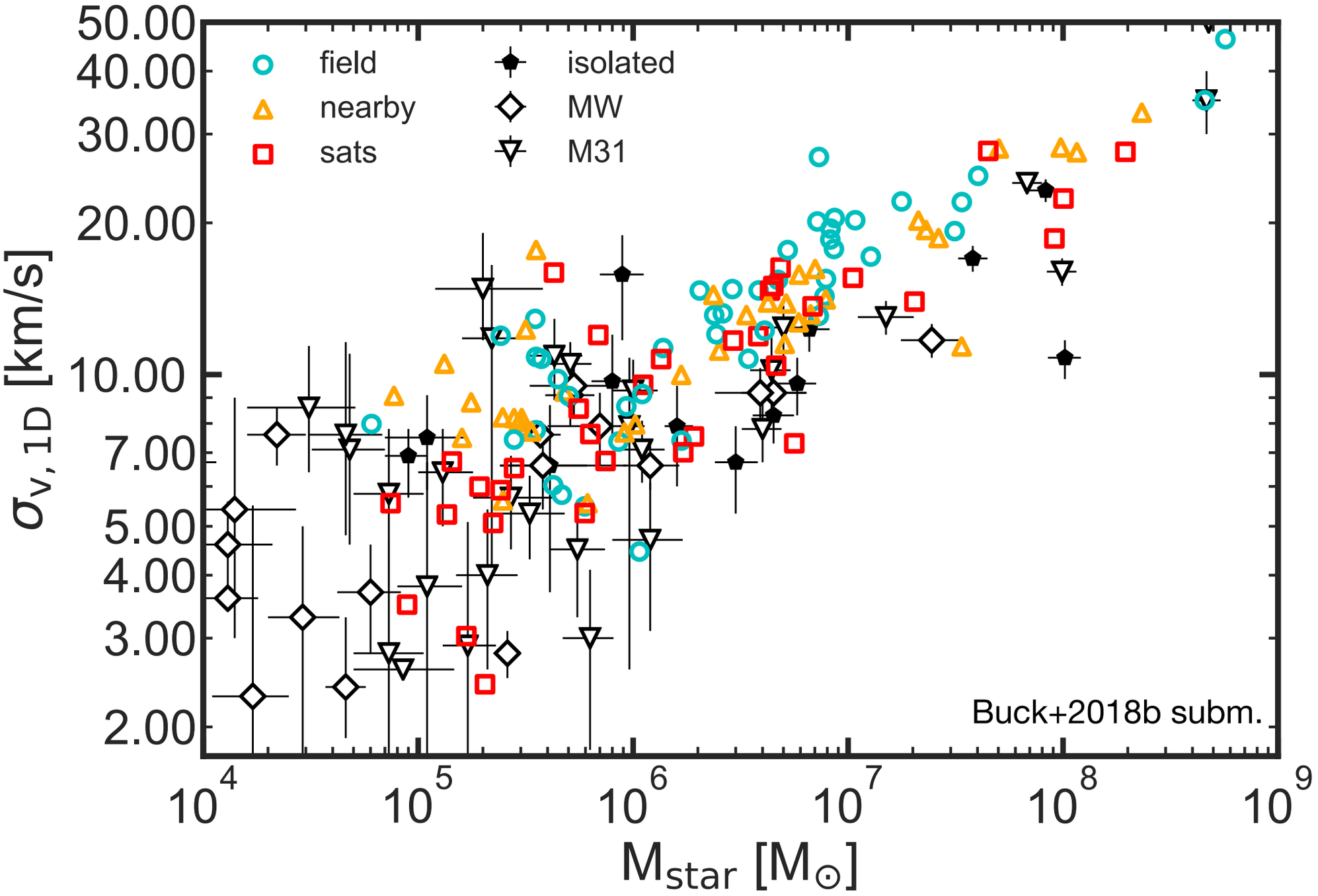


also: Simpson+ 2013, Fitts+2016, Sawala+2016b

2. The TBTF problem:

Can we reproduce the structure of Local Group dwarf galaxies?

Line-of-sight velocity dispersions of simulations and observations agree

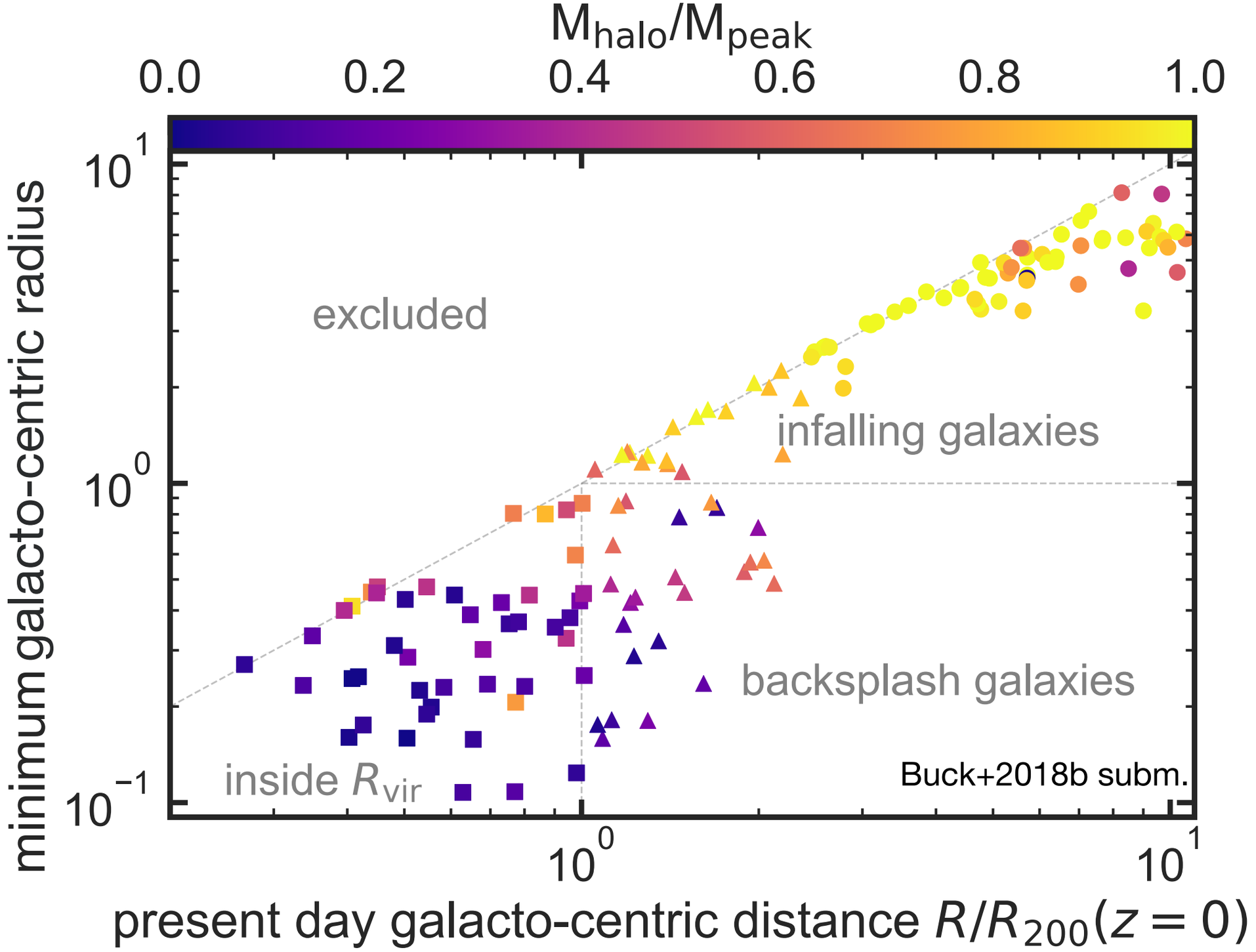


also: Macciò, Frings, Buck et al. 2017, Frings, Macciò, Buck et al. 2017

2. Resolving TBTF for satellites:

Tidal stripping!

Satellites and nearby dwarf galaxies are heavily tidally stripped

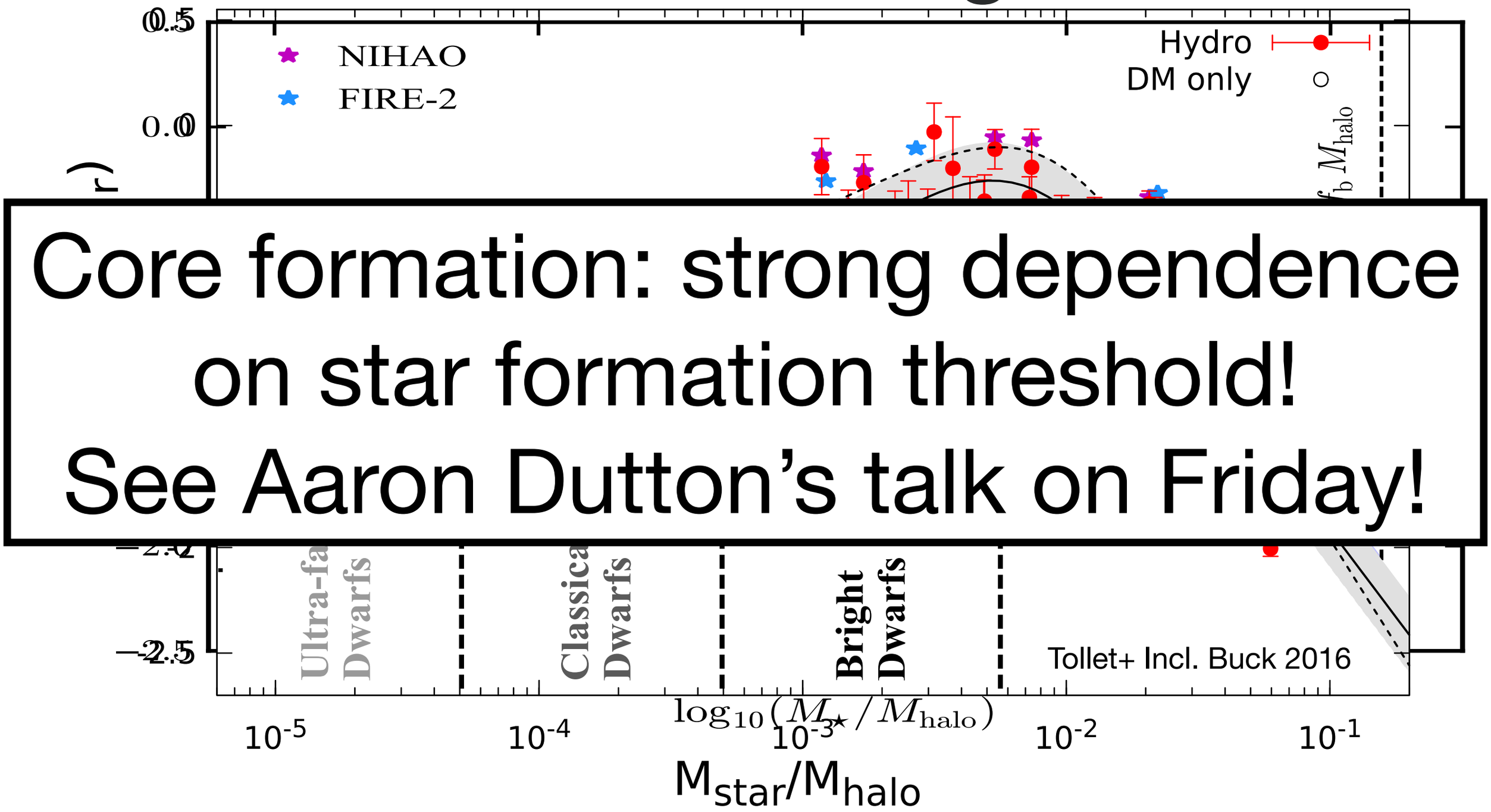


see also:
Knebe+ 2011;
Frings,Macciò,
Buck et al. 2017

2. **Resolving TBTF for field dwarfs:**

Core creation and halo expansion!

Core creation lowers central densities of dwarf galaxies

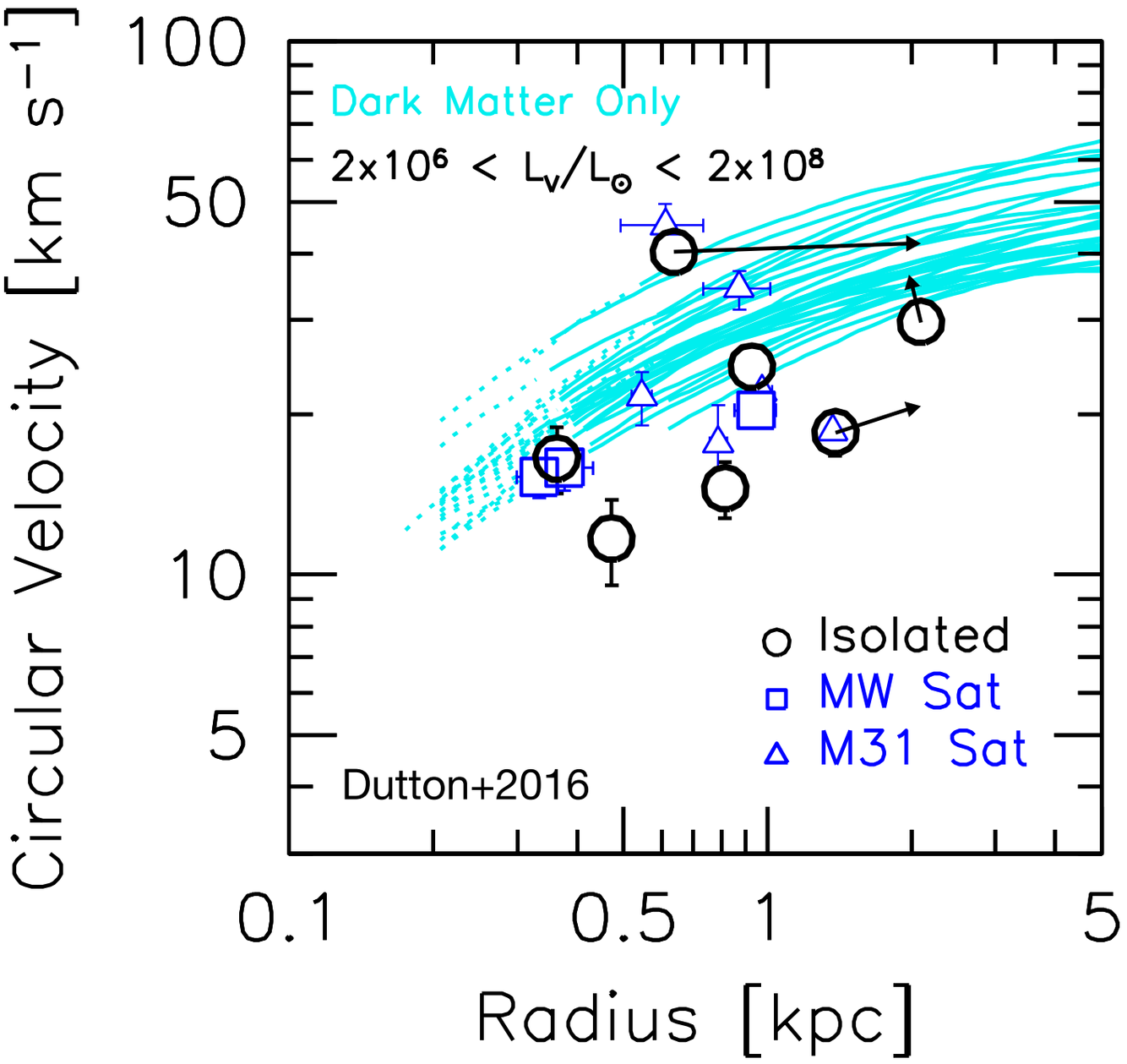


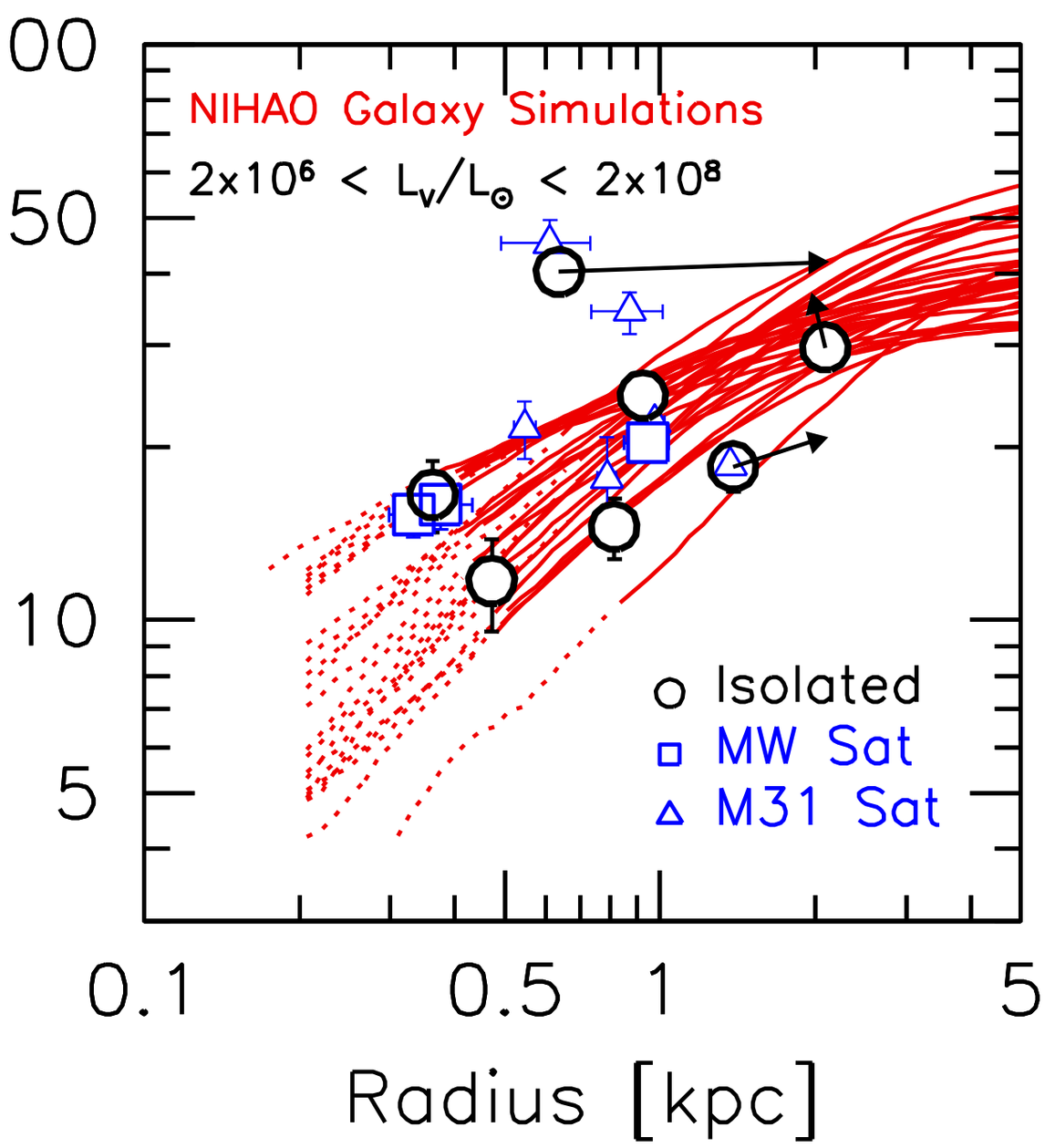
Core formation: strong dependence on star formation threshold!

See Aaron Dutton's talk on Friday!

also: Mashchenko+2008; Pontzen & Governato 2012; Governato et al. 2012; Madau+2014; Di Cintio et al. 2014; Onorbe+2015; Read+2016; Frings, Macciò, Buck et al. 2017

Core creation lowers central densities of dwarf galaxies





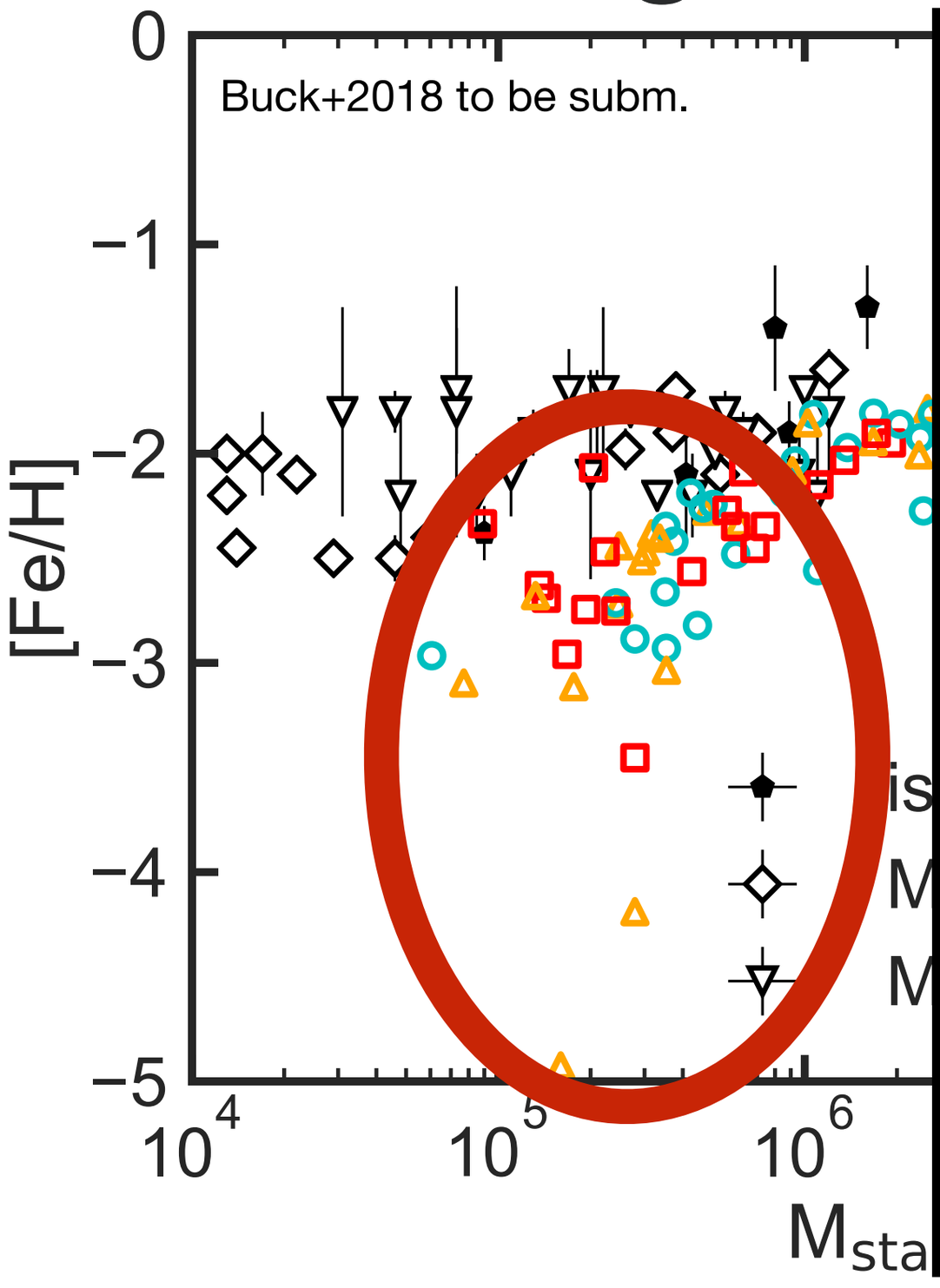
also: Mashchenko+2008; Pontzen & Governato 2012; Governato et al. 2012; Madau+2014; Di Cintio et al. 2014; Onorbe+2015; Read+2016; Frings, Macciò, Buck et al. 2017

Small scale problems of LCDM

1. Missing satellites problem - solved
2. Too-big-to-fail problem - solved
3. cusp-core problem - solved

Where does NIHAO fail?

Mass-metallicity relation of dwarf galaxies:



Reasons:

- metal enriched gas gets blown out of the dwarfs before recycling
- too strong stellar feedback?
- too simplified stellar feedback?
  - enrichment solely from SNII and SNIa

Reproducing realistic dwarf galaxy populations

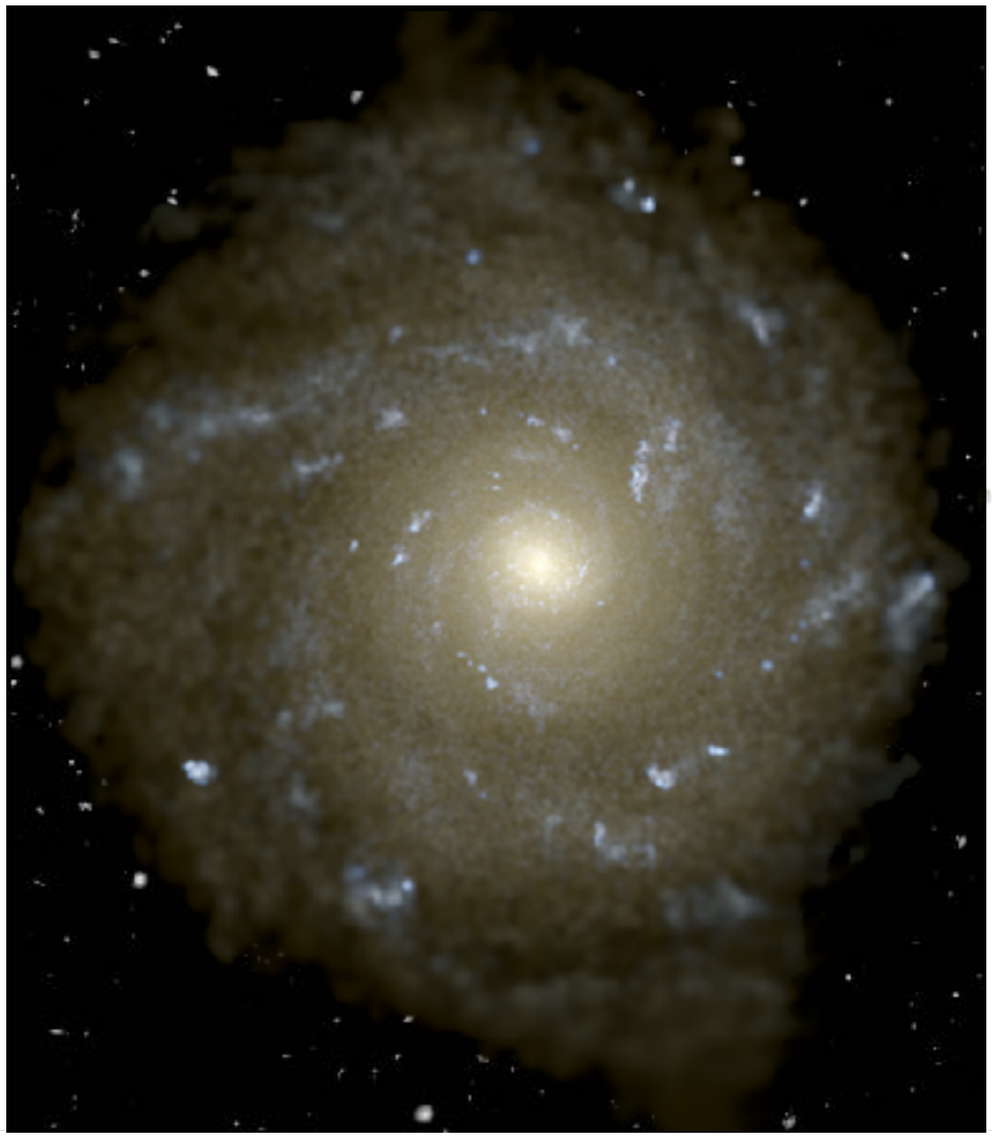
- In NIHAO the stellar mass function and structure of simulated dwarf galaxies agrees well with observations

- Solutions to small scale problems of LCDM: sophisticated feedback models

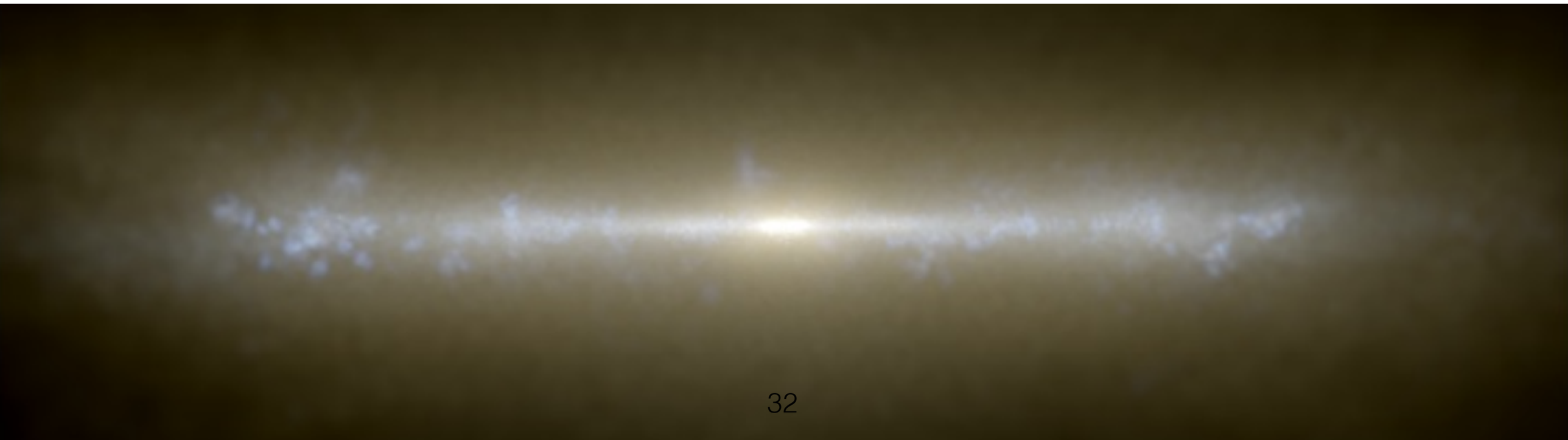
- Model shortcomings revealed by the chemical enrichment, improvements are work in progress

State of the art simulations resolve the small scale issues of LCDM.

Let’s get the details of stellar feedback right!



Extra Material



Stellar mass-metallicity relation

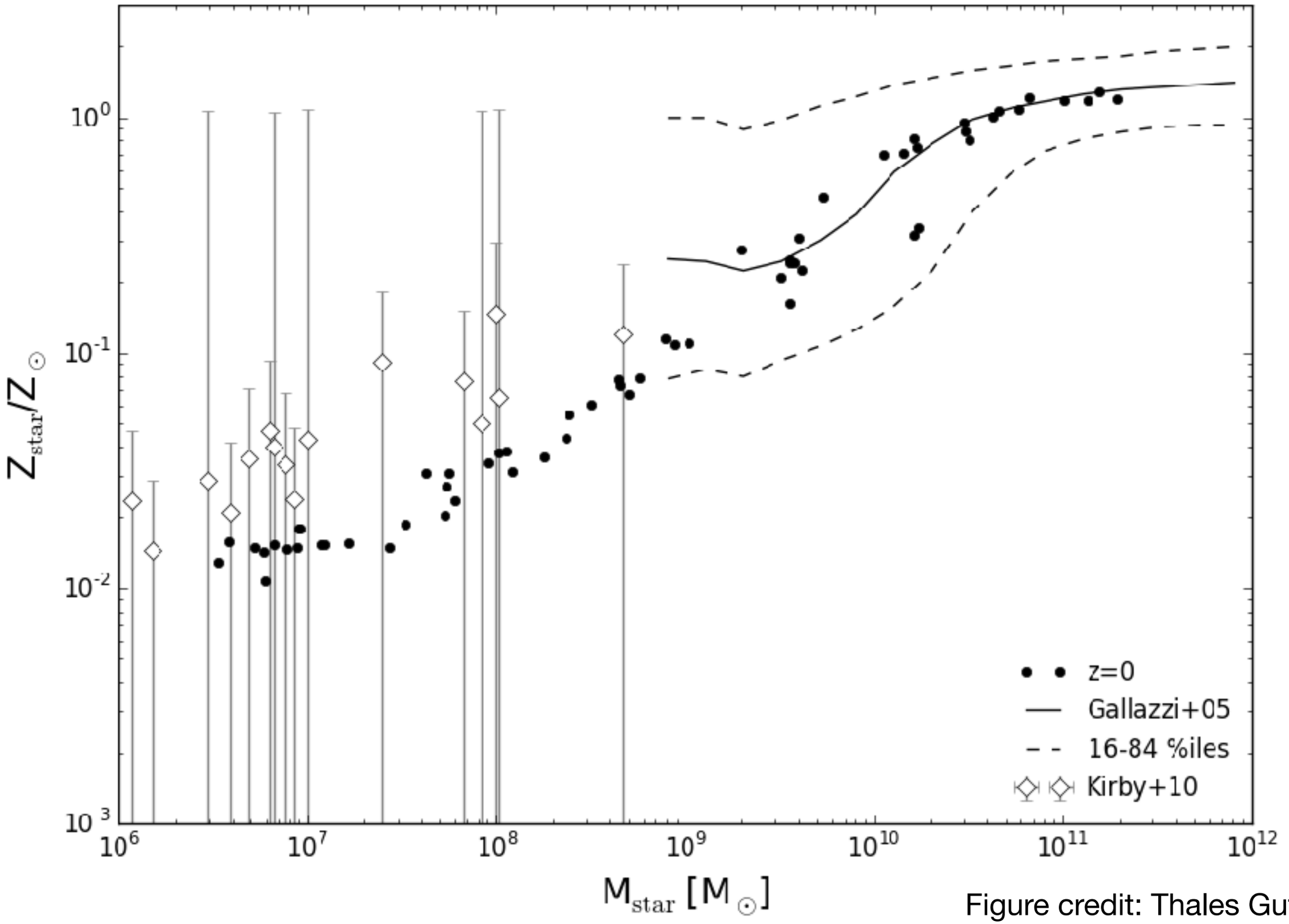


Figure credit: Thales Gutcke

Stellar mass-gas metallicity relation

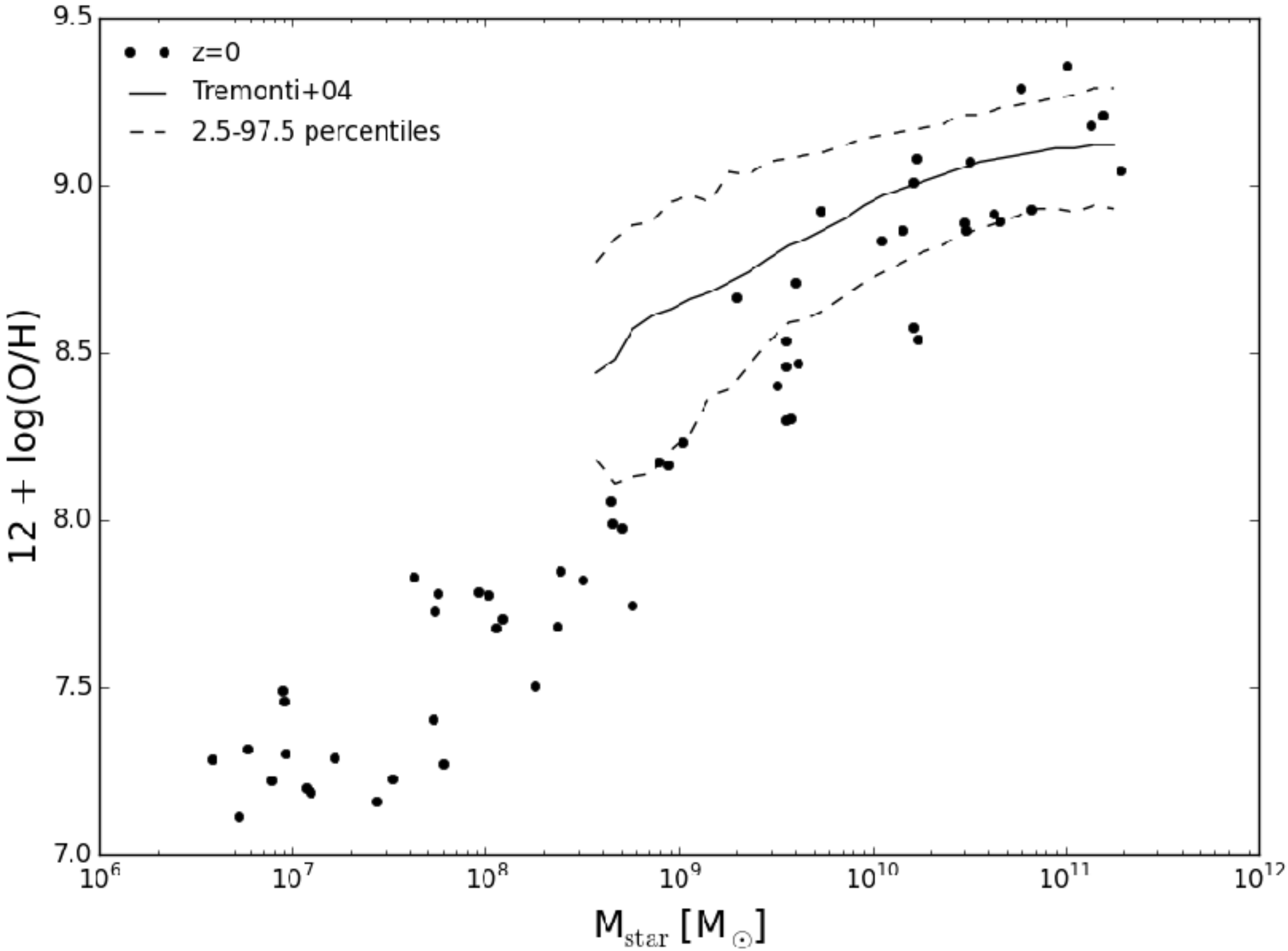


Figure credit: Thales Gutcke

Stellar mass-halo mass relation: the signature of stripping