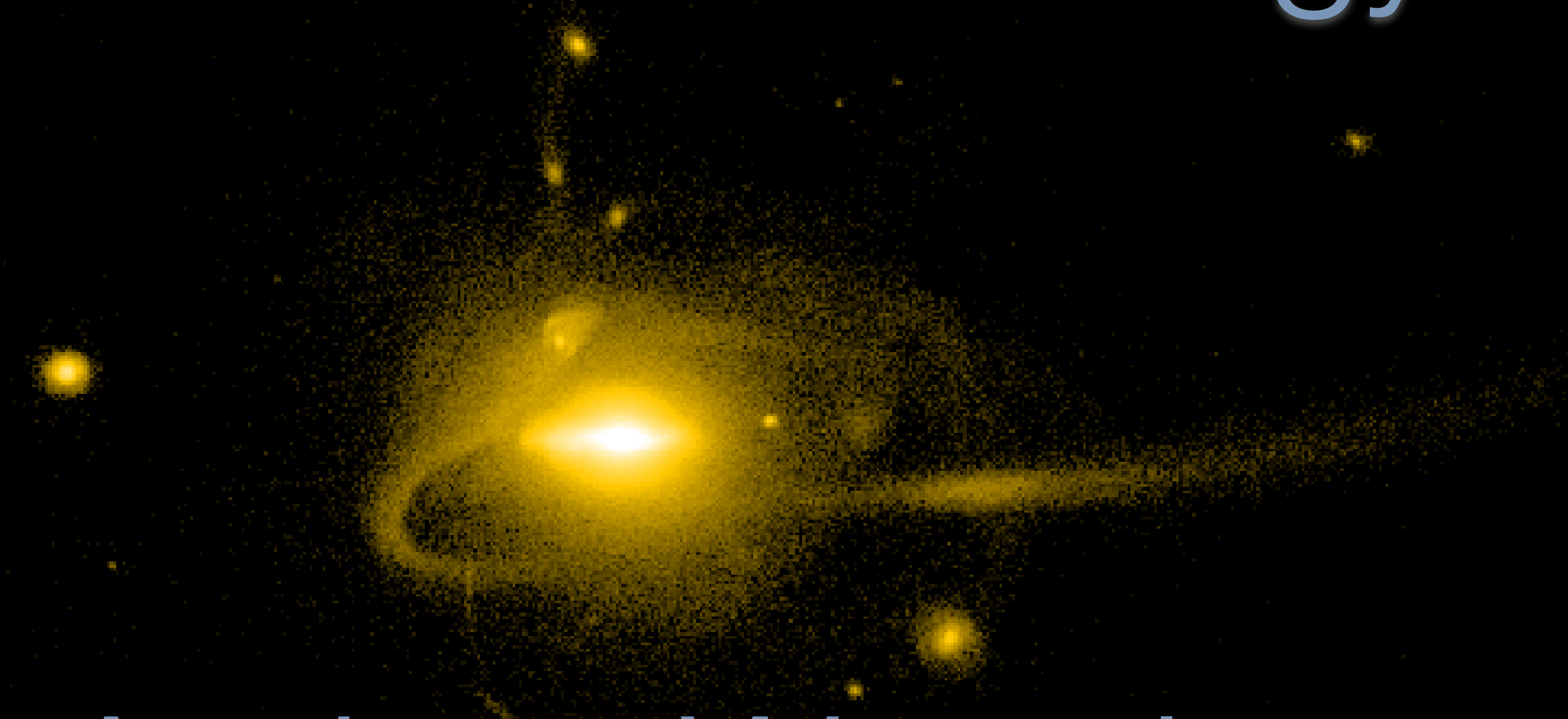
Reconciling Dwarf Galaxies with LCDM Cosmology



Andrew Wetzel

Caltech - Carnegie Fellow

with Phil Hopkins, Shea Garrison-Kimmel, Ji-hoon Kim, Dusan Keres, Claude-Andre Faucher-Giguere, Eliot Quataert

Caltech

Carnegie Science

The Carnegie Observatories

UC DAVIS
UNIVERSITY OF CALIFORNIA

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

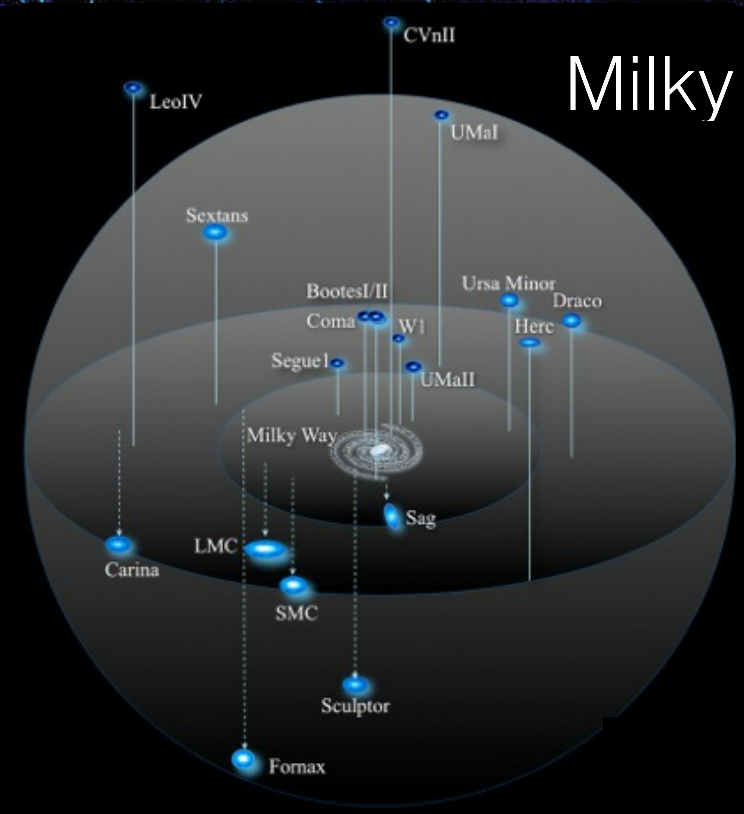
(nearly) self-similar structure formation in CDM

1000s of subhalos

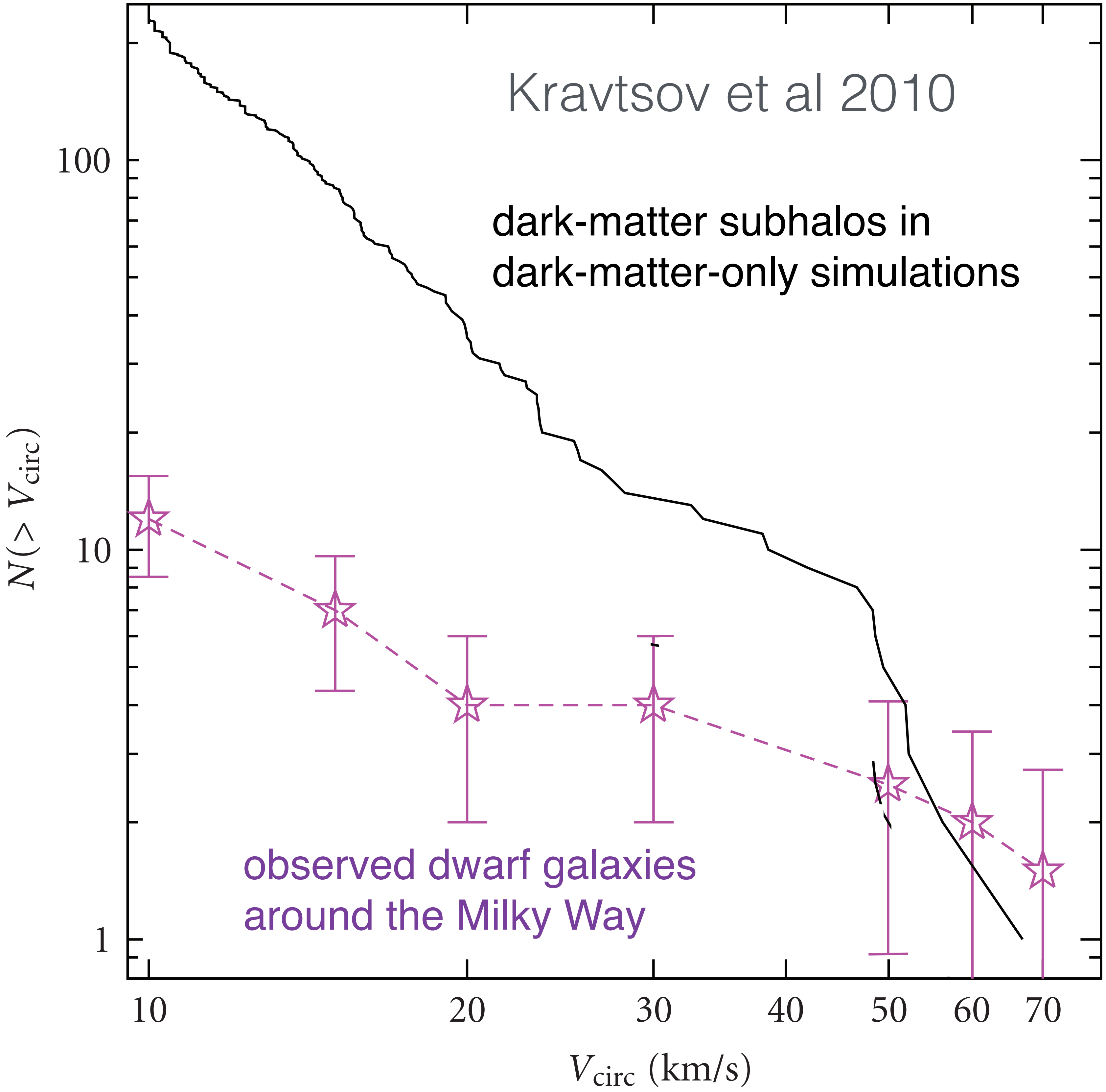
Abell 2744

1000s of galaxies

Milky Way

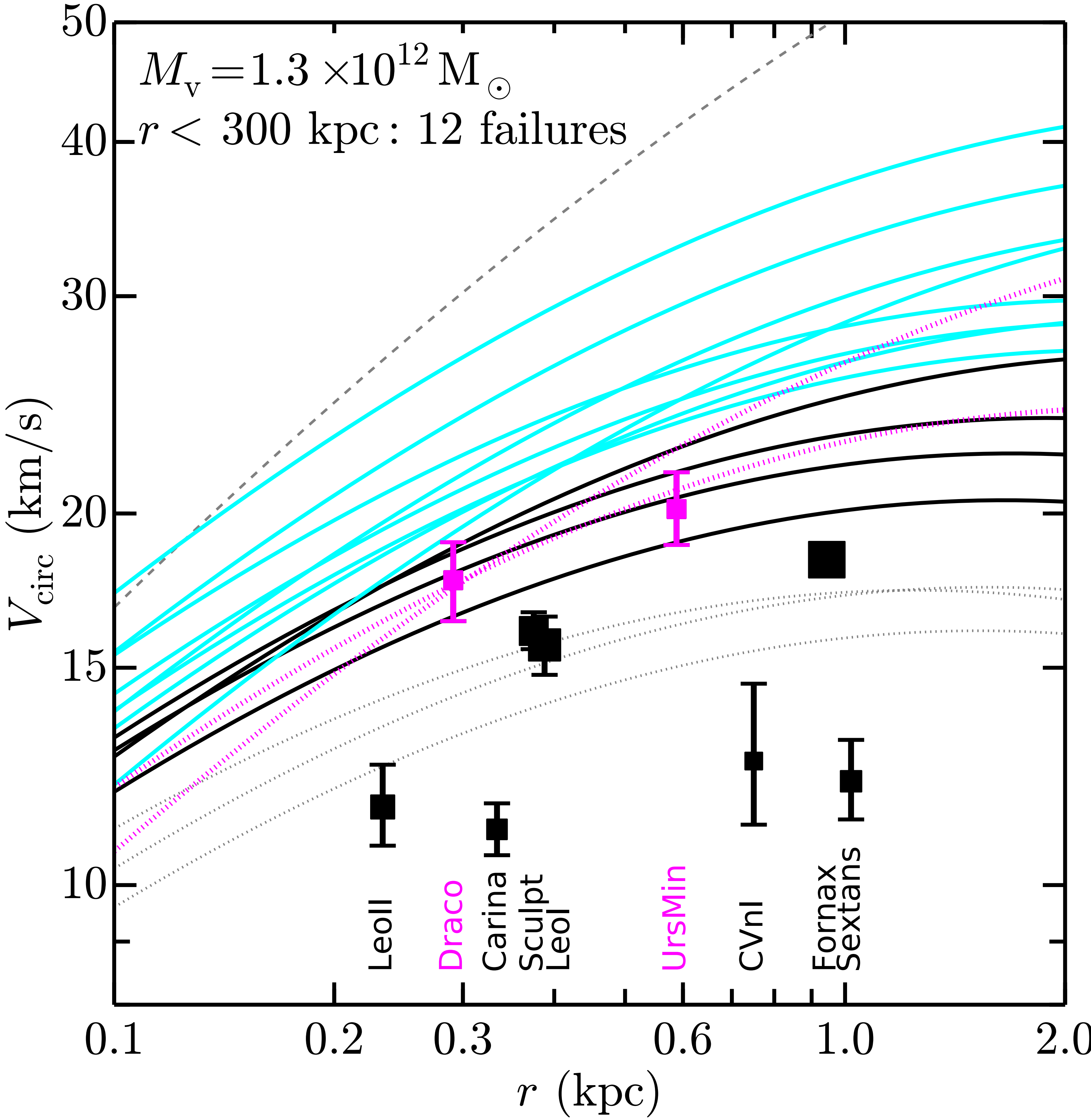


12 bright satellites $(L_V > 10^5 L_\odot)$



$$V_{\rm circ}(r) = \sqrt{\frac{GM_{\rm tot}(<r)}{r}}$$

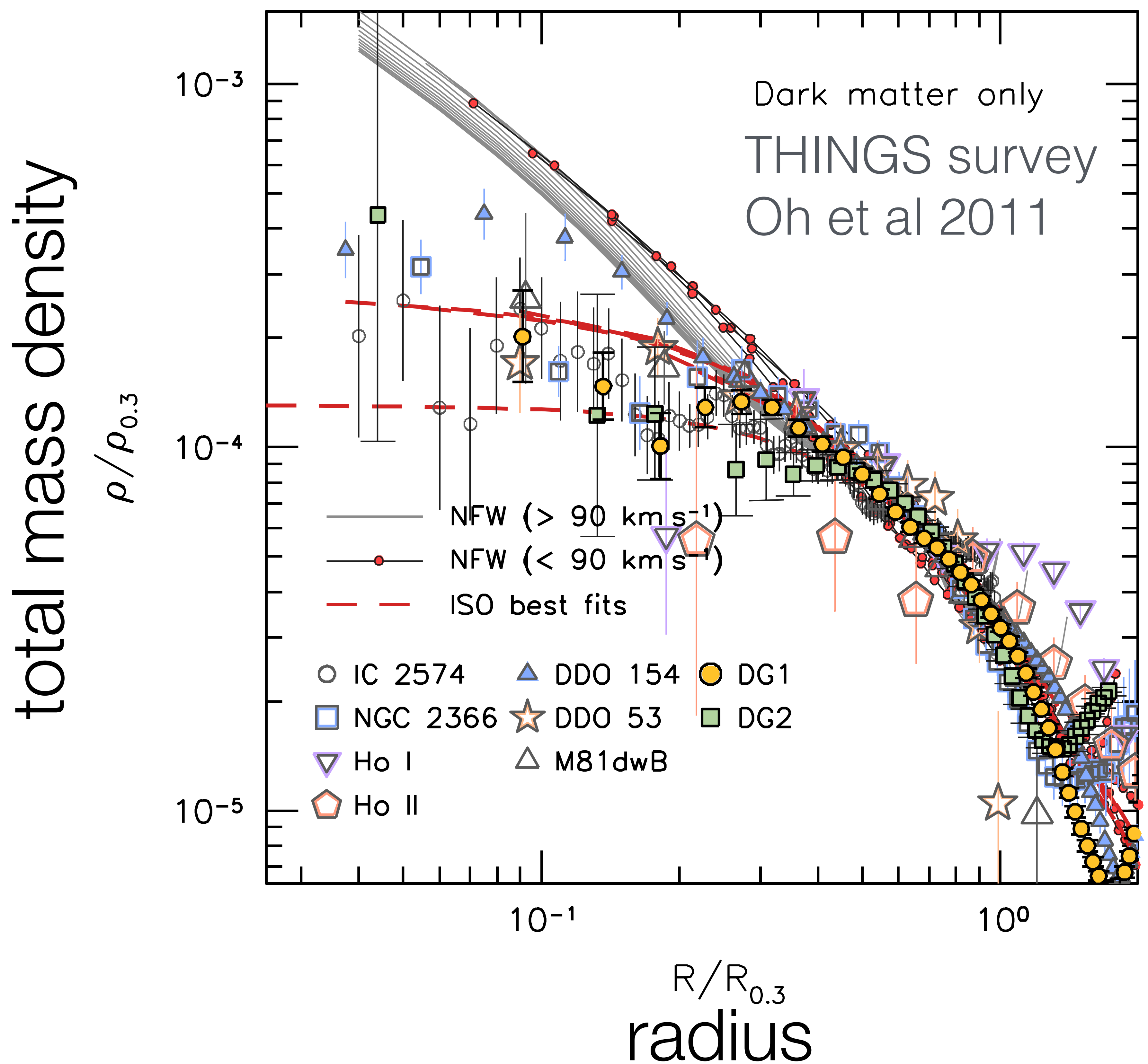
'missing satellites' problem: CDM predicts too many dark-matter subhalos compared with observed satellite galaxies



Boylan-Kolchin et al 2012
Garrison-Kimmel et al 2014

$$V_{\rm circ}(r) = \sqrt{\frac{GM_{\rm tot}(<r)}{r}}$$

'too big to fail' problem: CDM predicts dark-matter subhalos that are much denser than observed satellite galaxies



‘core-cusp’ problem: CDM predicts dark-matter halos with steeper inner density profiles than observed galaxies

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

‘missing satellites’ problem

CDM predicts **too many** dark matter subhalos compared with observed satellite galaxies

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

‘too big to fail’ problem

CDM predicts dark-matter subhalos that are **too dense** compared with observed satellite galaxies

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

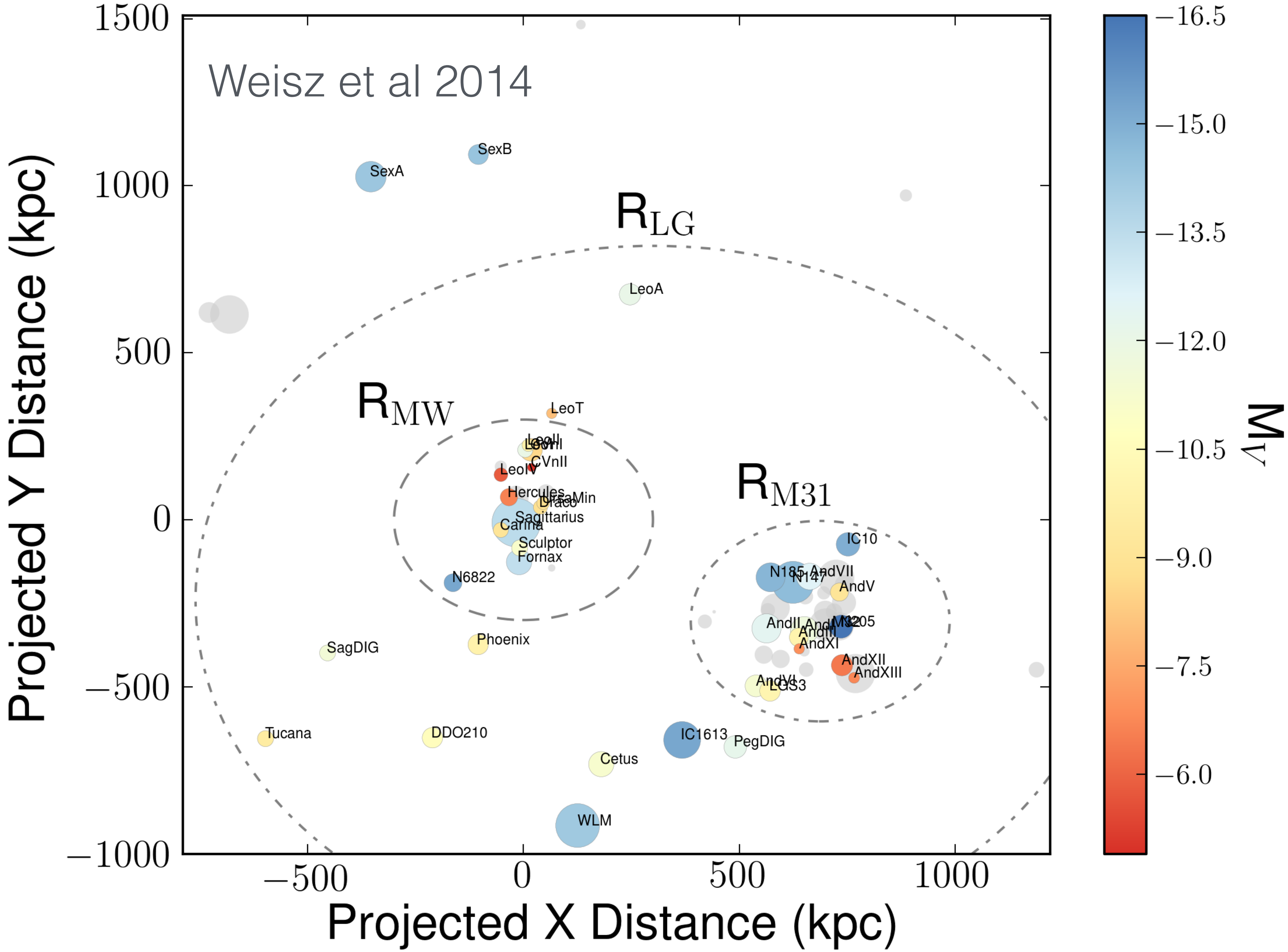
dwarf galaxies: significant challenges to the Cold Dark Matter (CDM) model

possible solutions

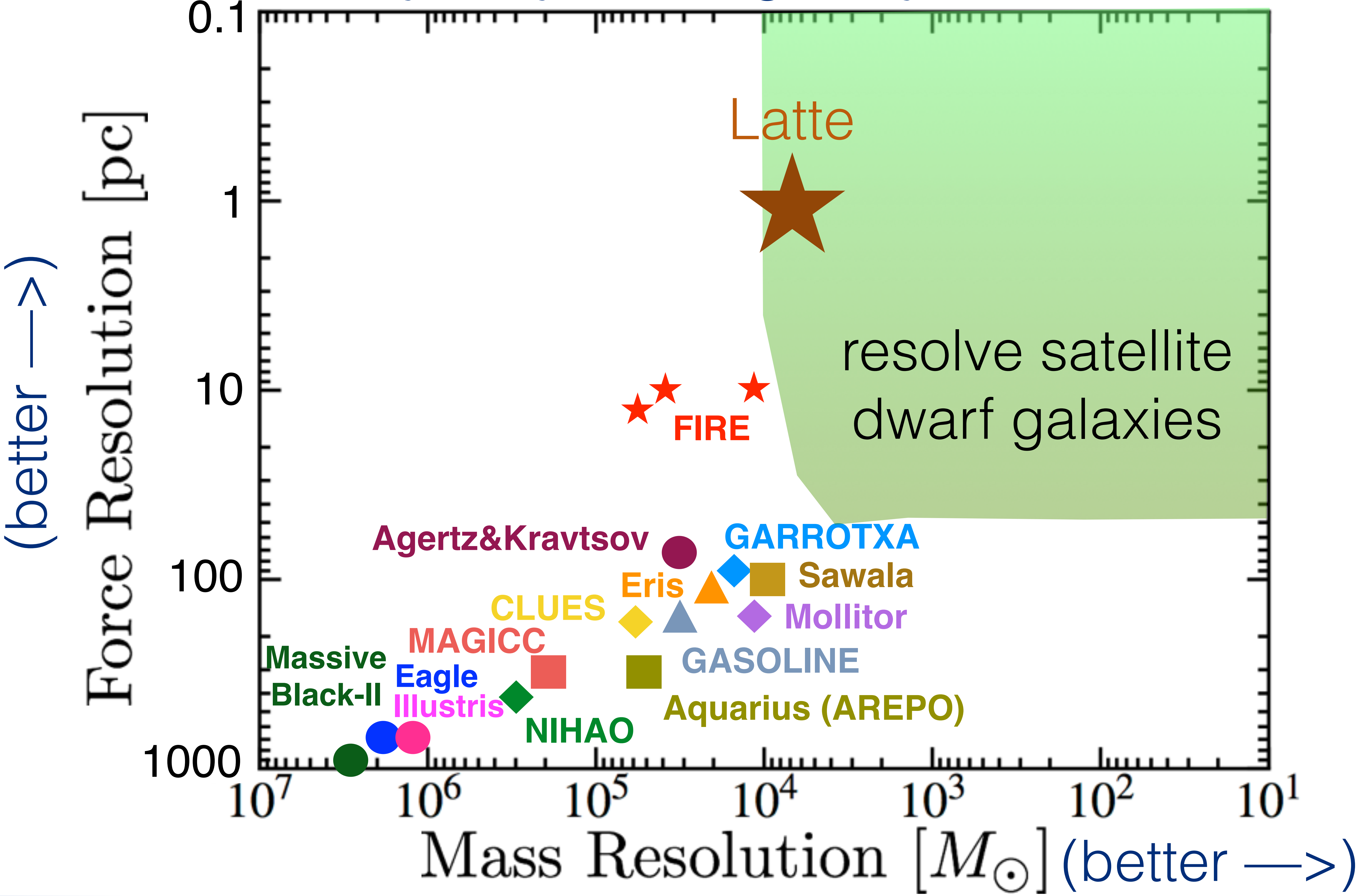
1. dark matter is not ‘standard’ CDM
   examples: warm dark matter, self-interacting dark matter

2. standard CDM + baryonic physics

The Local Group



cosmological hydrodynamic simulations of Milky Way-mass galaxy to z = 0



The Latte Project: the Milky Way on FIRE

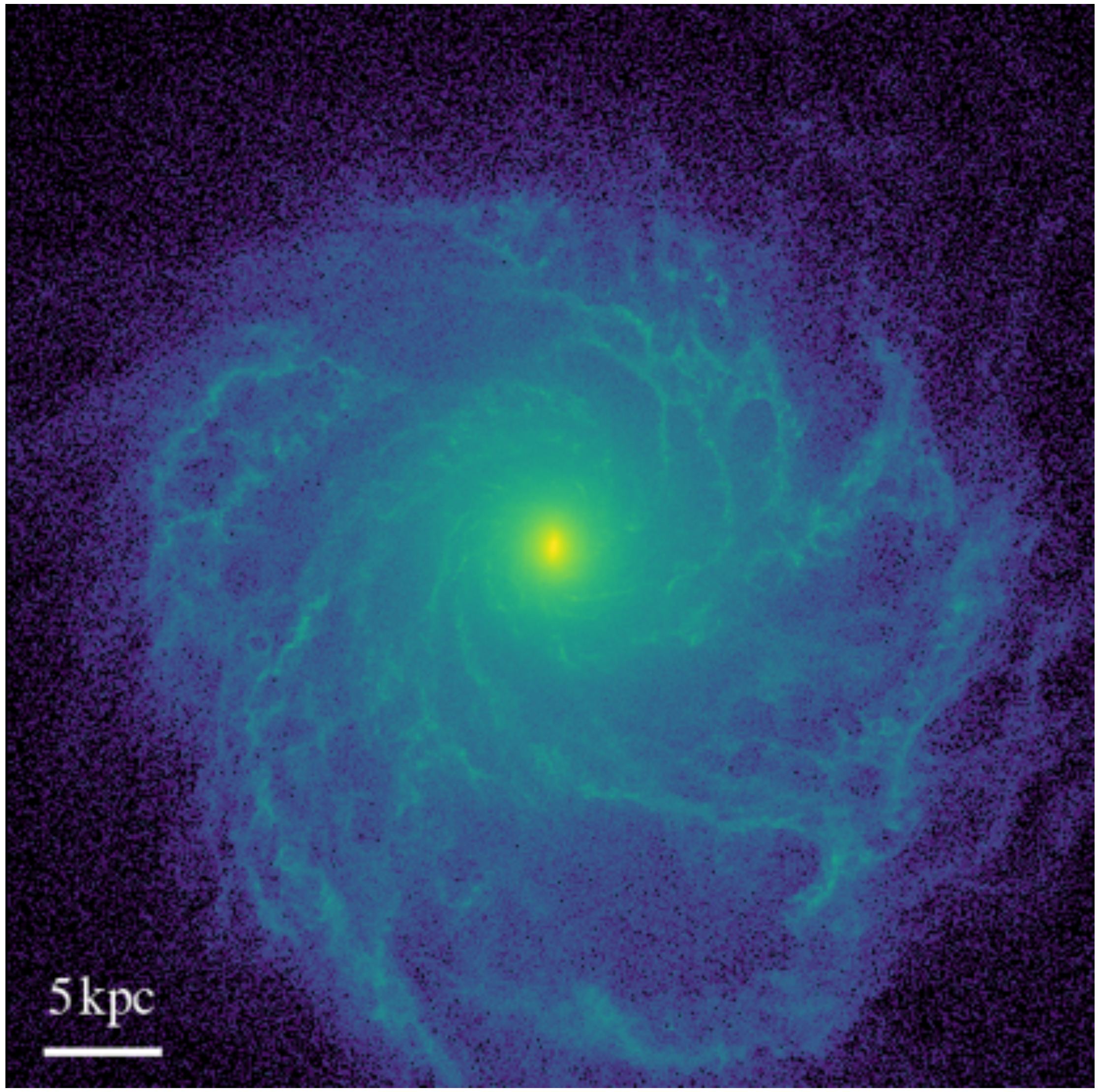
simulating a Milky Way-mass galaxy with a realistic population of satellite dwarf galaxies in LCDM

FIRE

Feedback In Realistic Environments

FIRE model for gas and star formation

Feedback In Realistic Environments



- High resolution to capture structure of multi-phase inter-stellar medium
  - $m_{gas} = 7070\ M_{sun}$
  - $h_{gas} = 1$ pc (min), 25 pc (typical)
  - $h_{dm} = 20$ pc
  - $t_{step,min} = 180$ yr
- Cooling from atoms, molecules, and 9 metals down to 10 K
- Star formation only in self-gravitating clouds

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

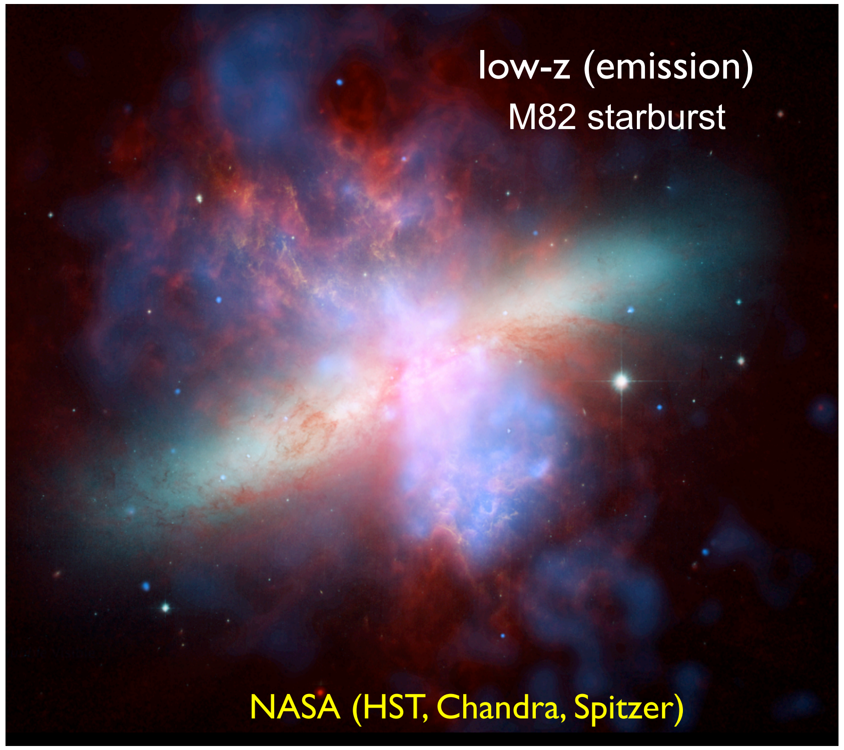
$$\dot{P}_{\rm SNe} \sim \dot{E}_{\rm SNe}\, v_{\rm ejecta}^{-1}$$

  - Stellar Winds

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

stellar scale

galaxy scale



Latte simulations

run on the Stampede supercomputer

supported by NSF XSEDE

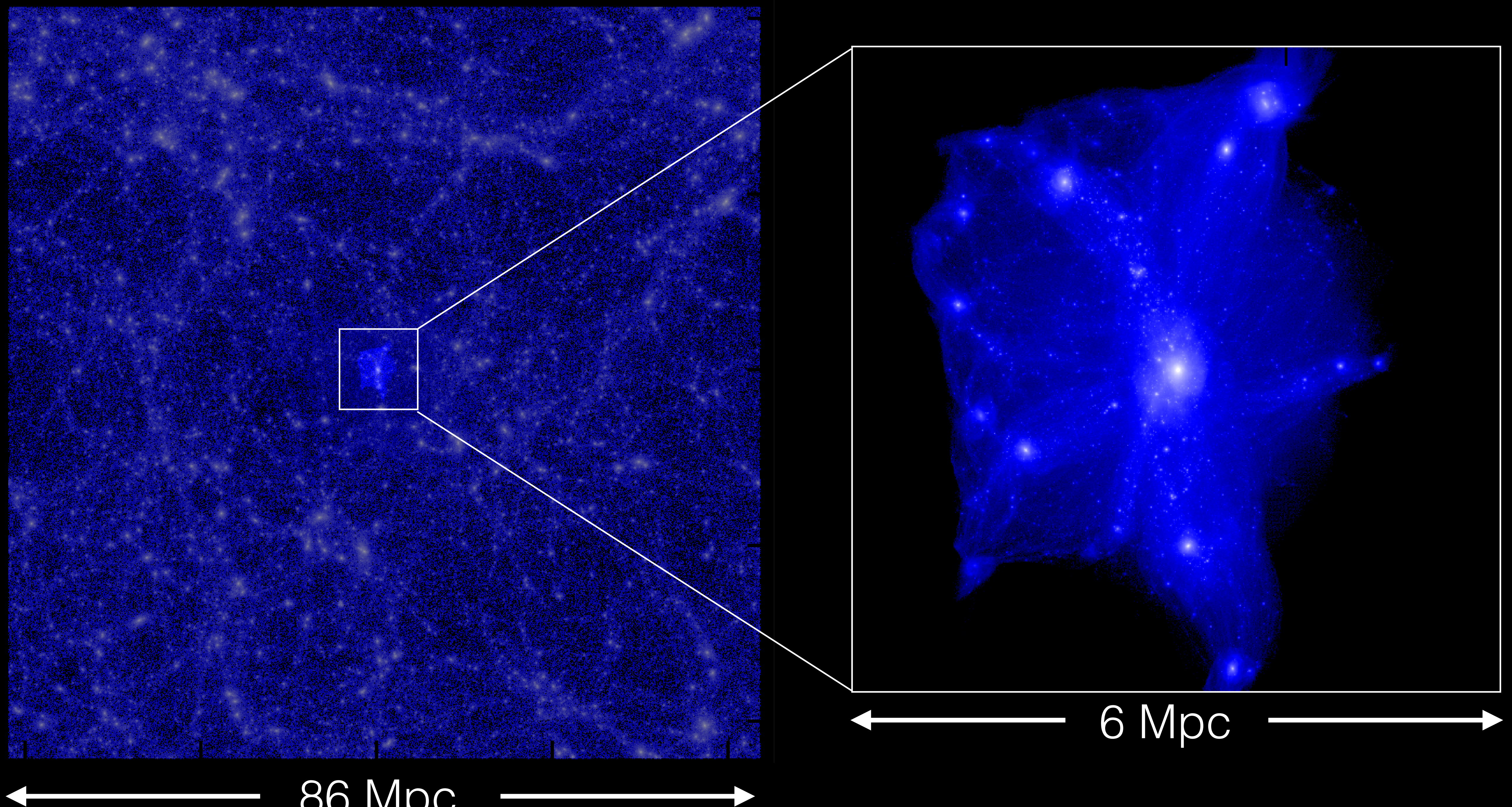
each MW-mass simulation is

massively parallel: 2048 cores

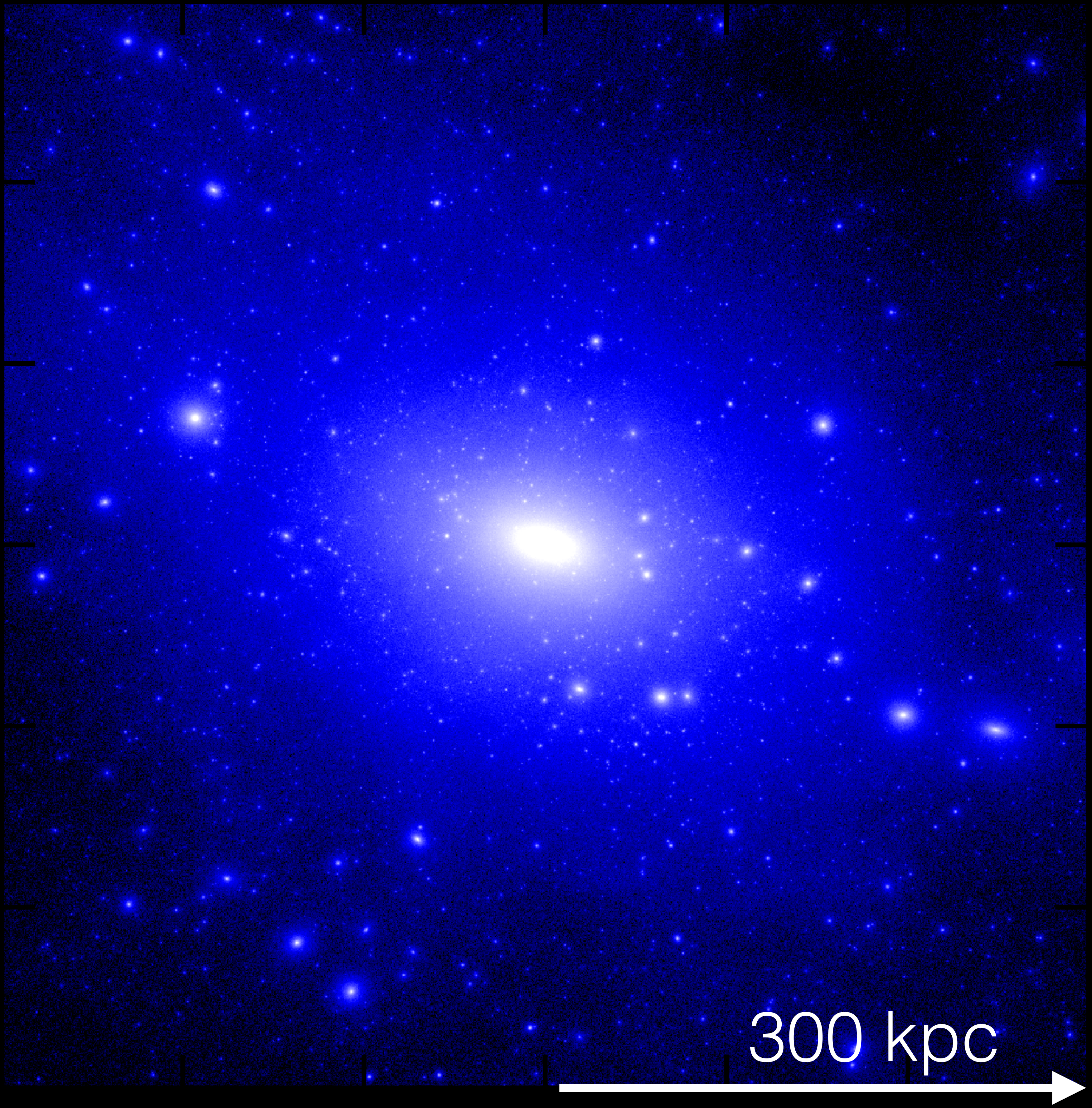
CPU time: 720k hours

wall time: 15 days

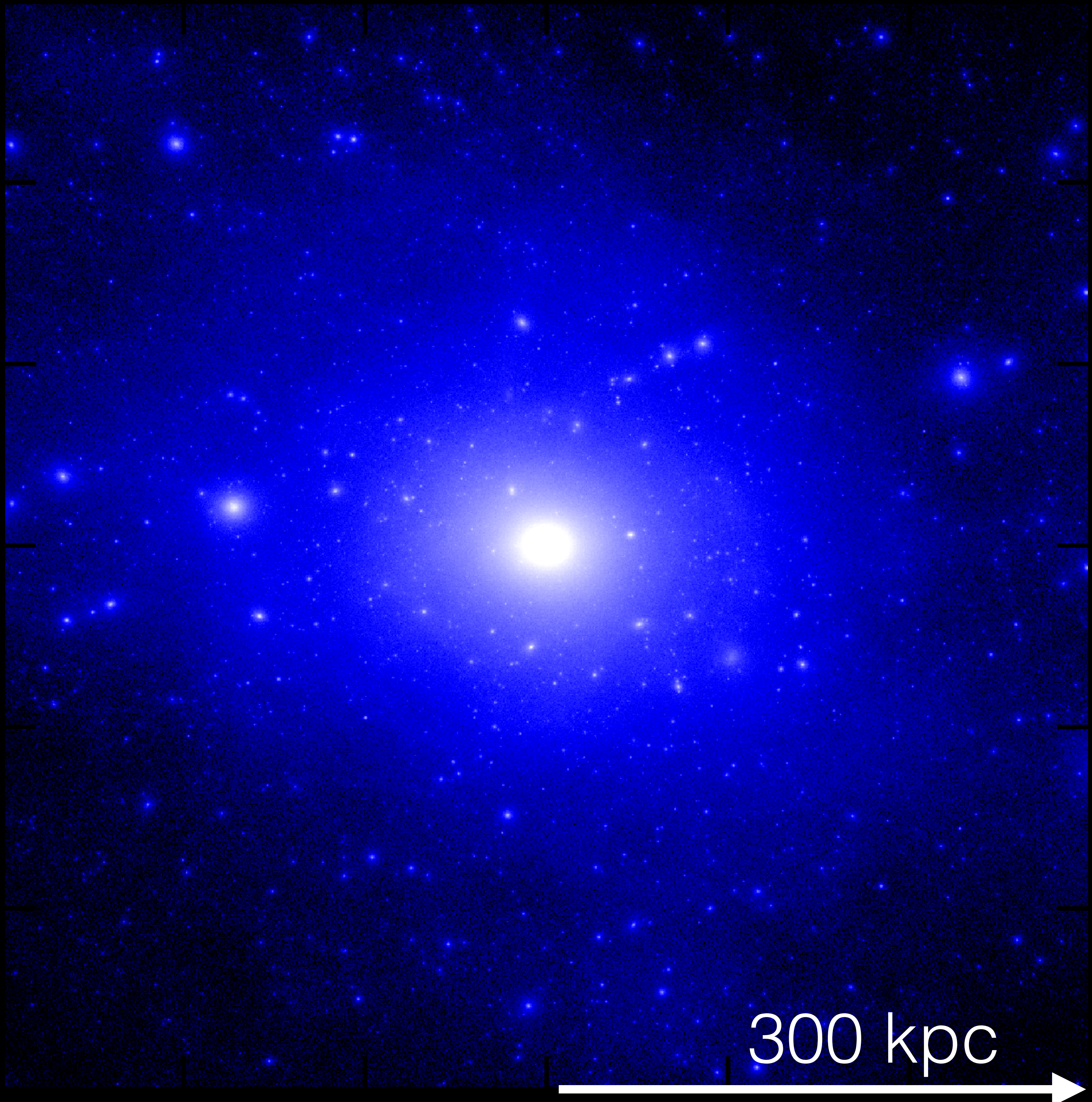
cosmological zoom-in simulation to achieve high resolution



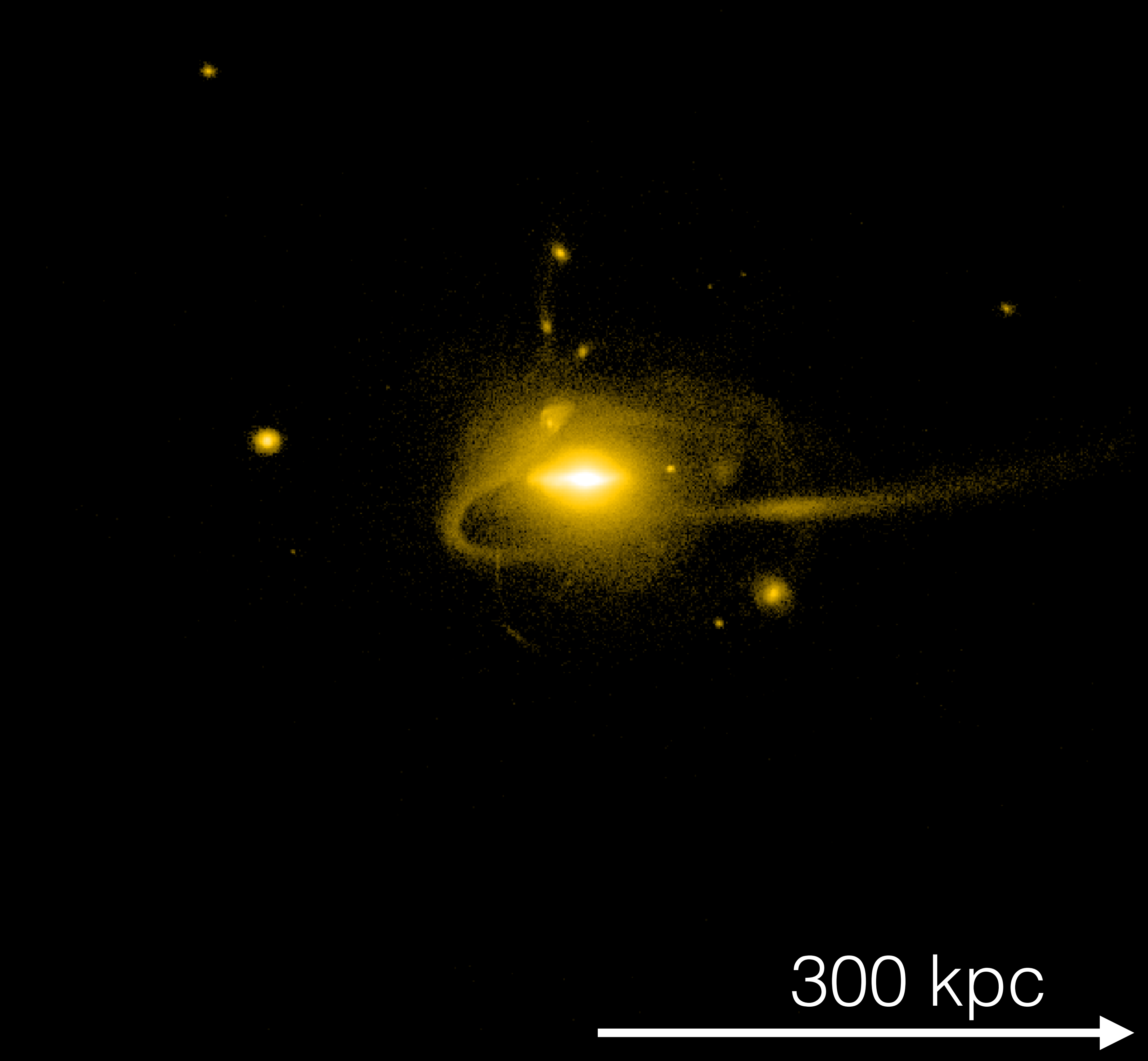
dark matter-only simulation



dark matter with effects of baryons

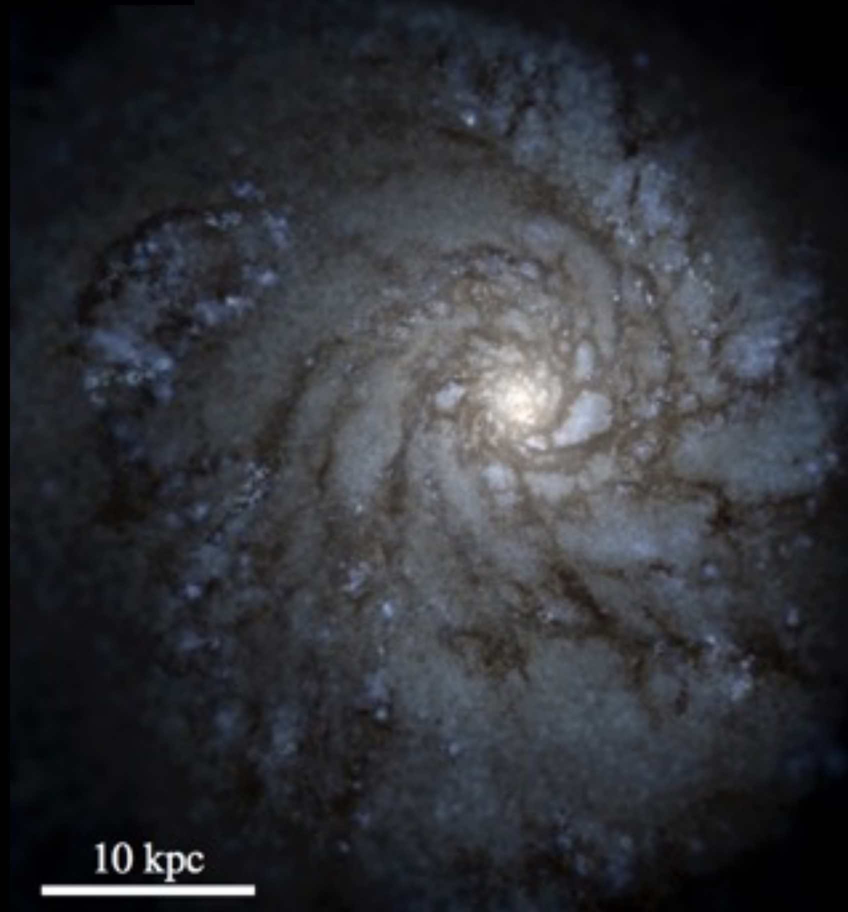


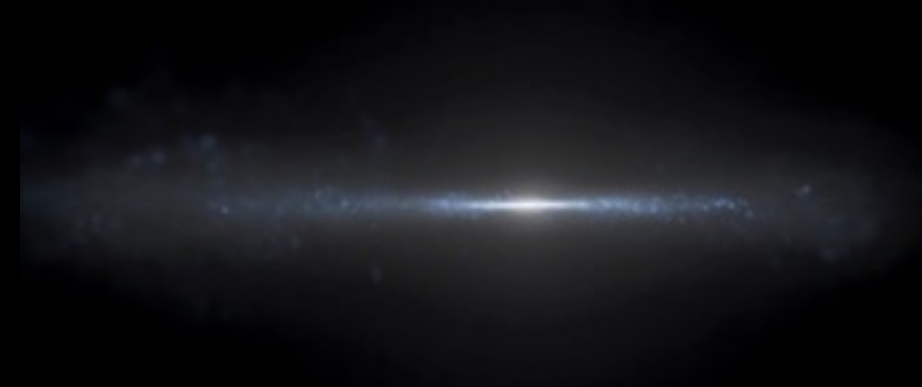
stars



host galaxies at z = 0

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



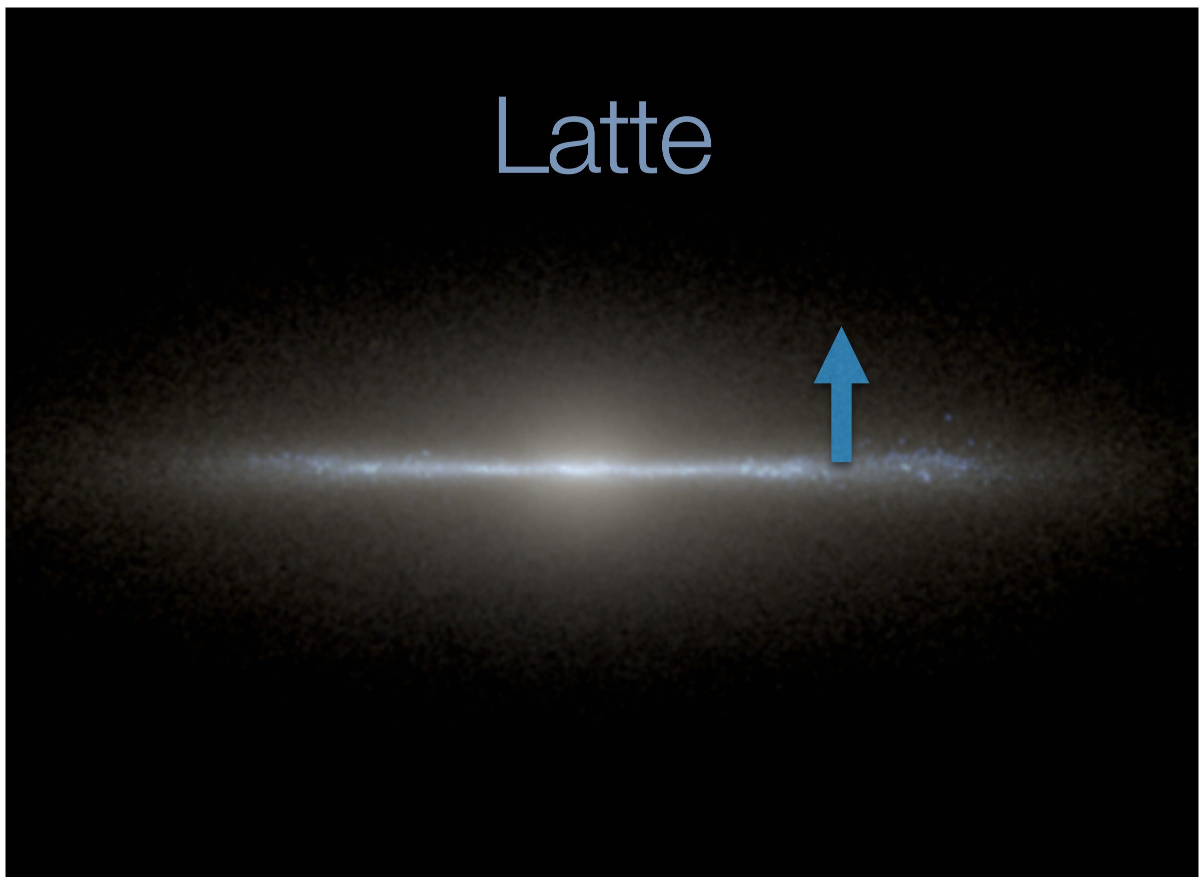


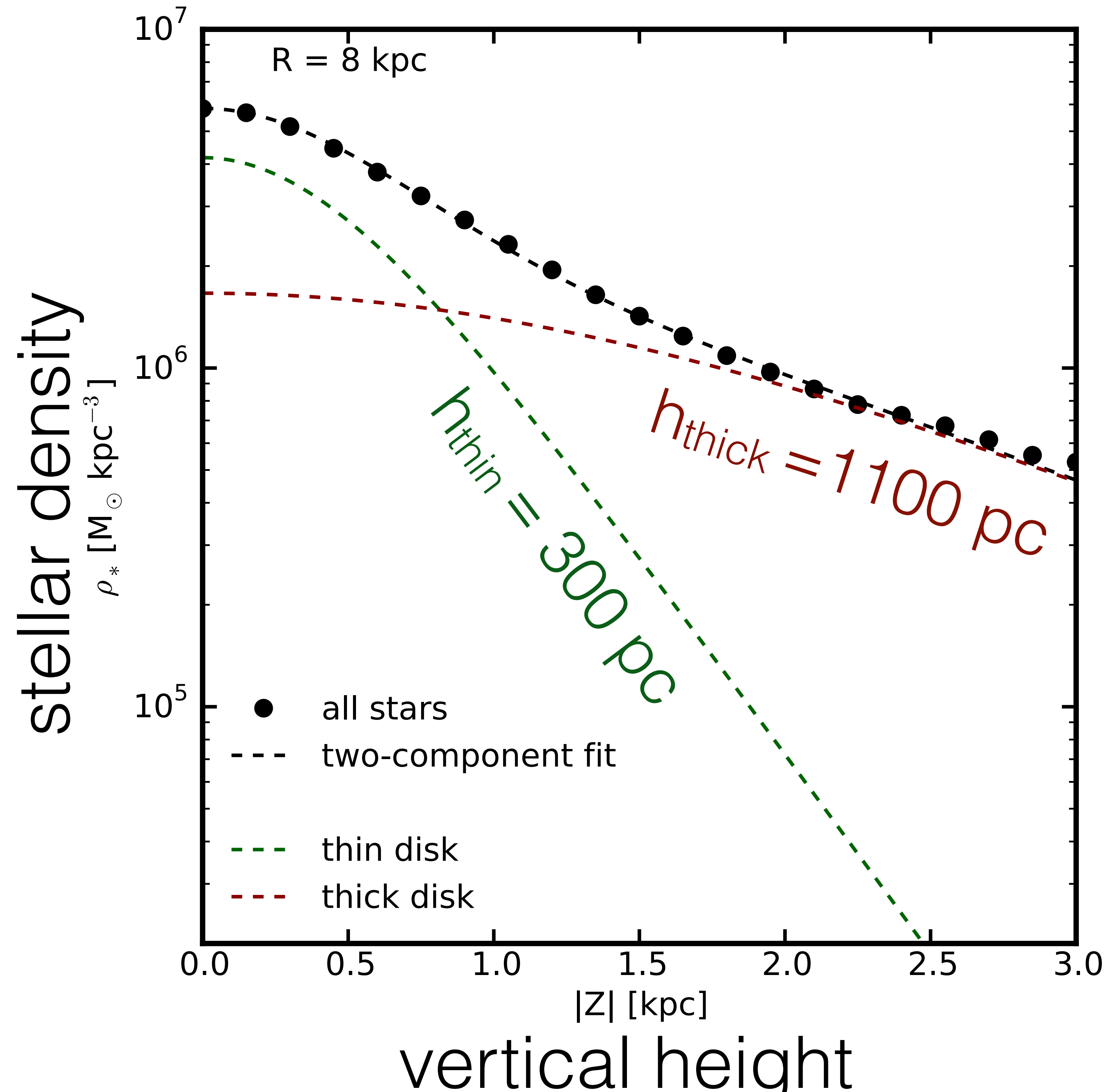
Latte

Flat White

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

Ma, Hopkins, Wetzel et al, in prep



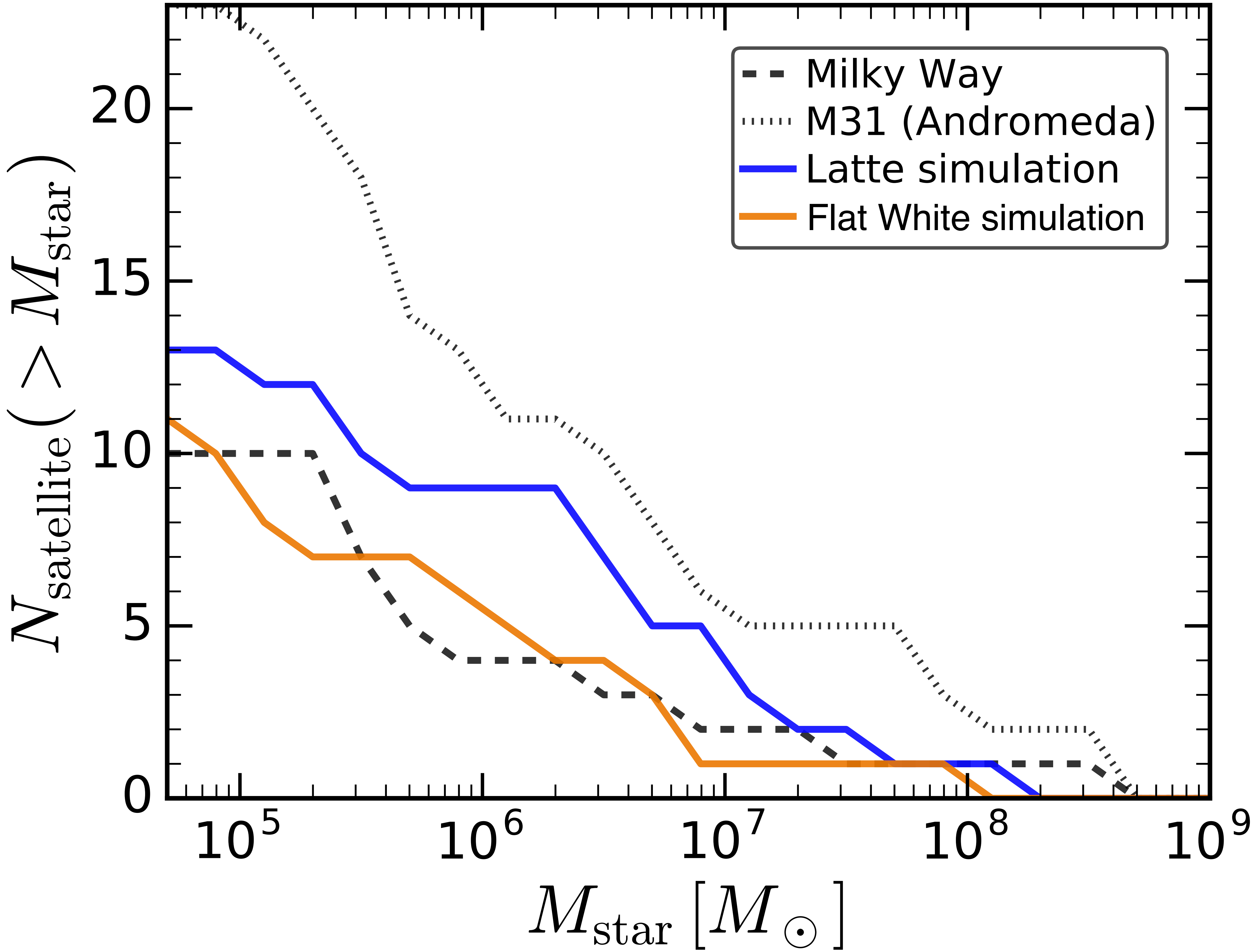


The Latte Project: the Milky Way on FIRE

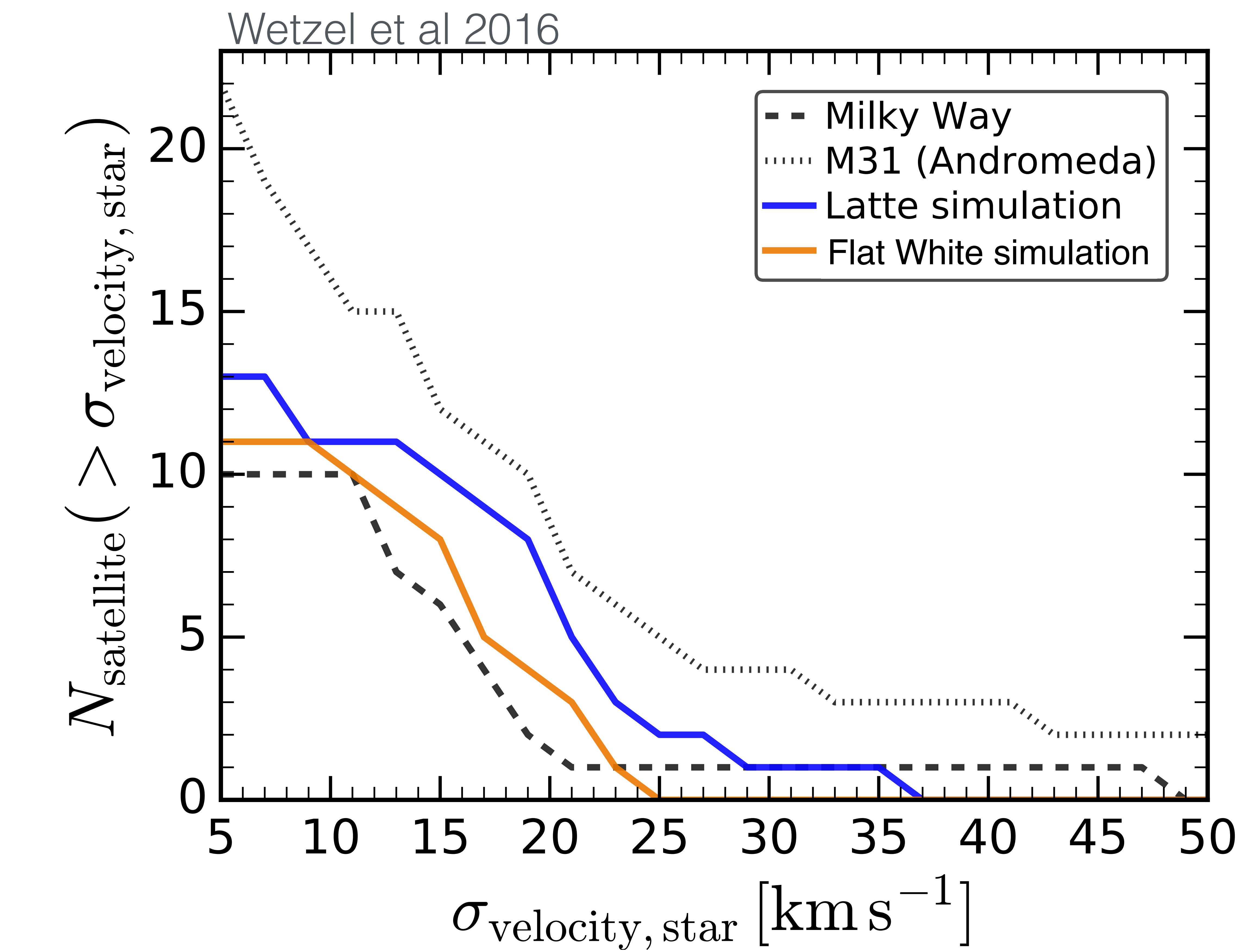
population of satellite dwarf galaxies

stellar masses of satellite galaxies

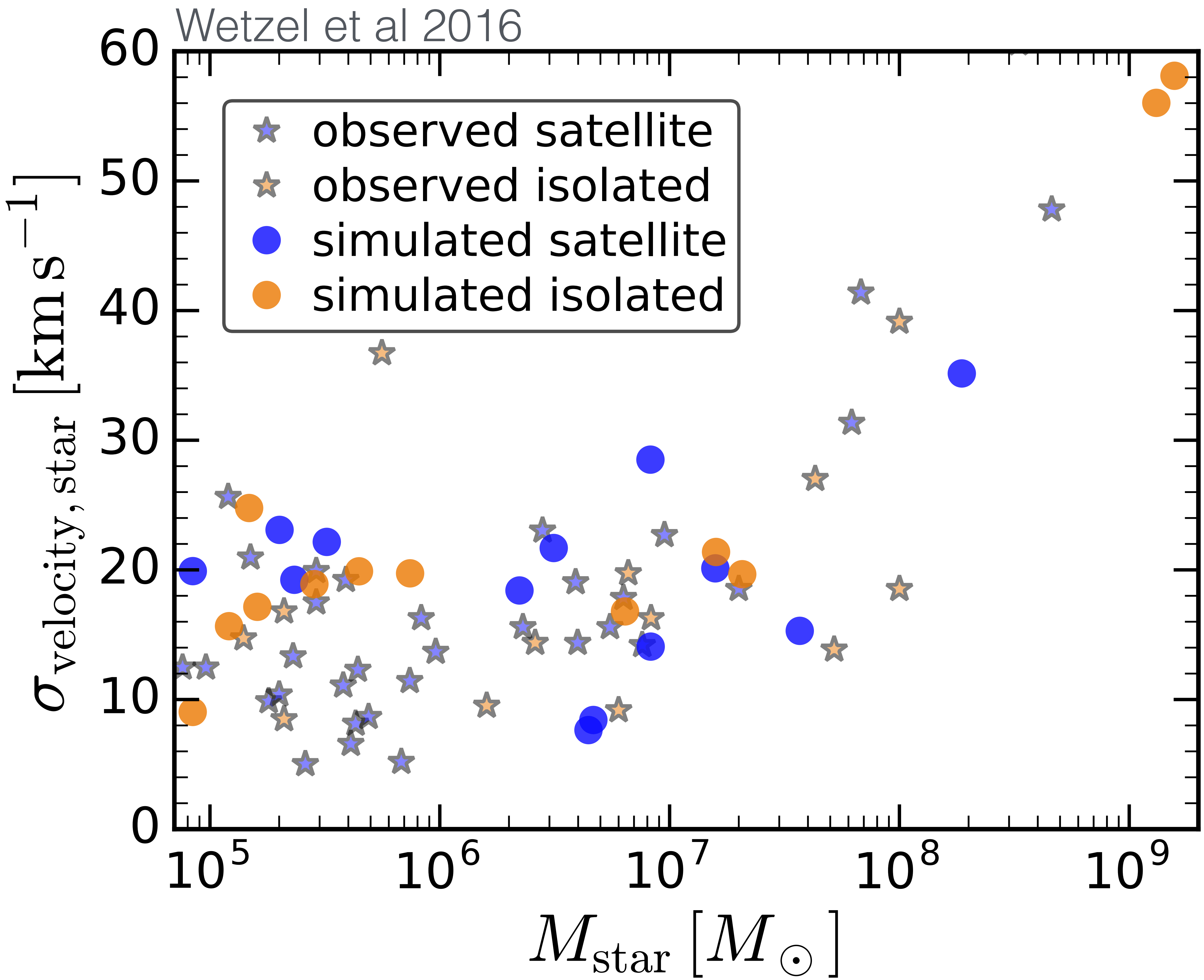
Wetzel et al 2016



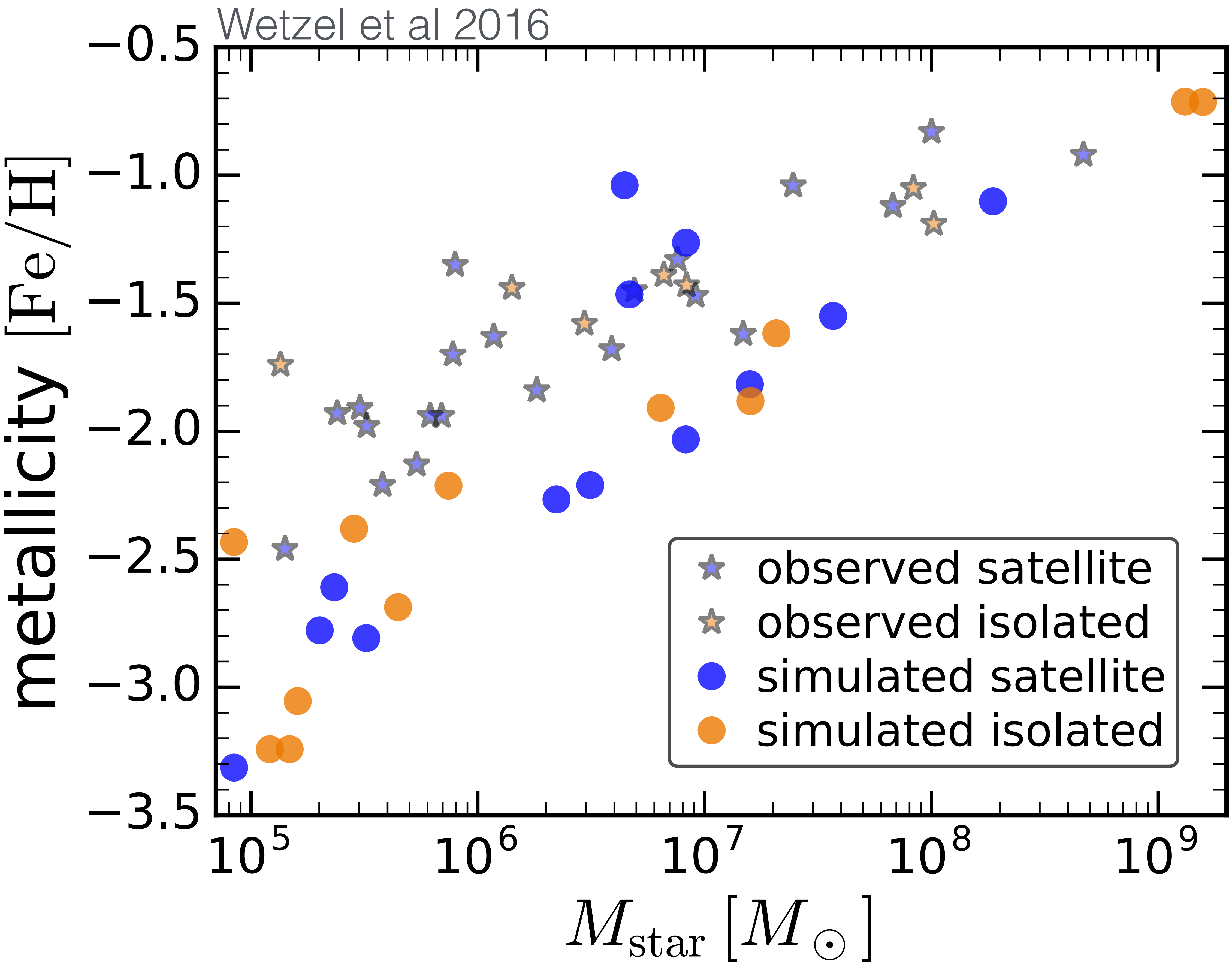
stellar velocity dispersions of satellites



velocity dispersion - mass relation

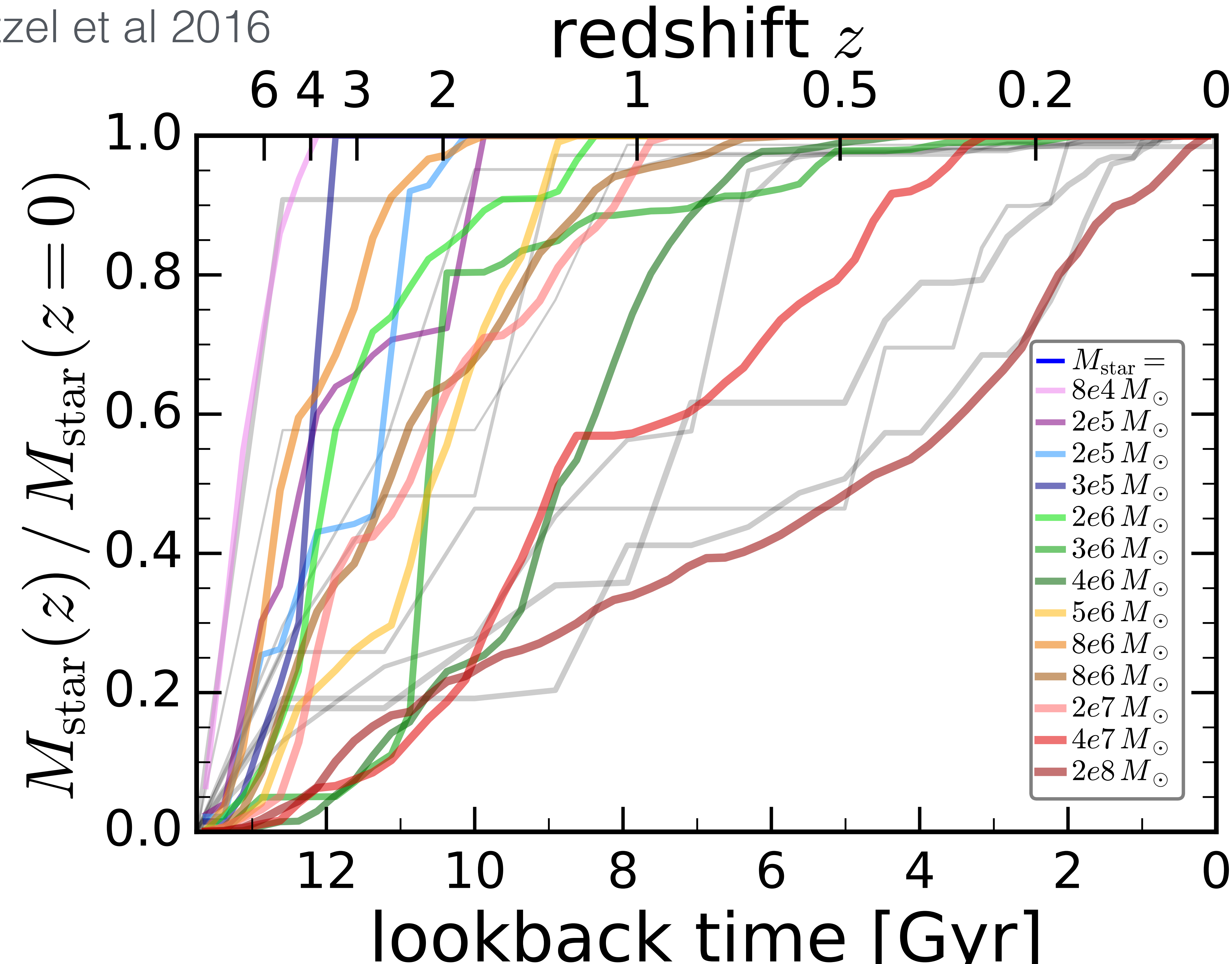


mass - metallicity relation



star-formation histories of satellite galaxies

Wetzel et al 2016



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

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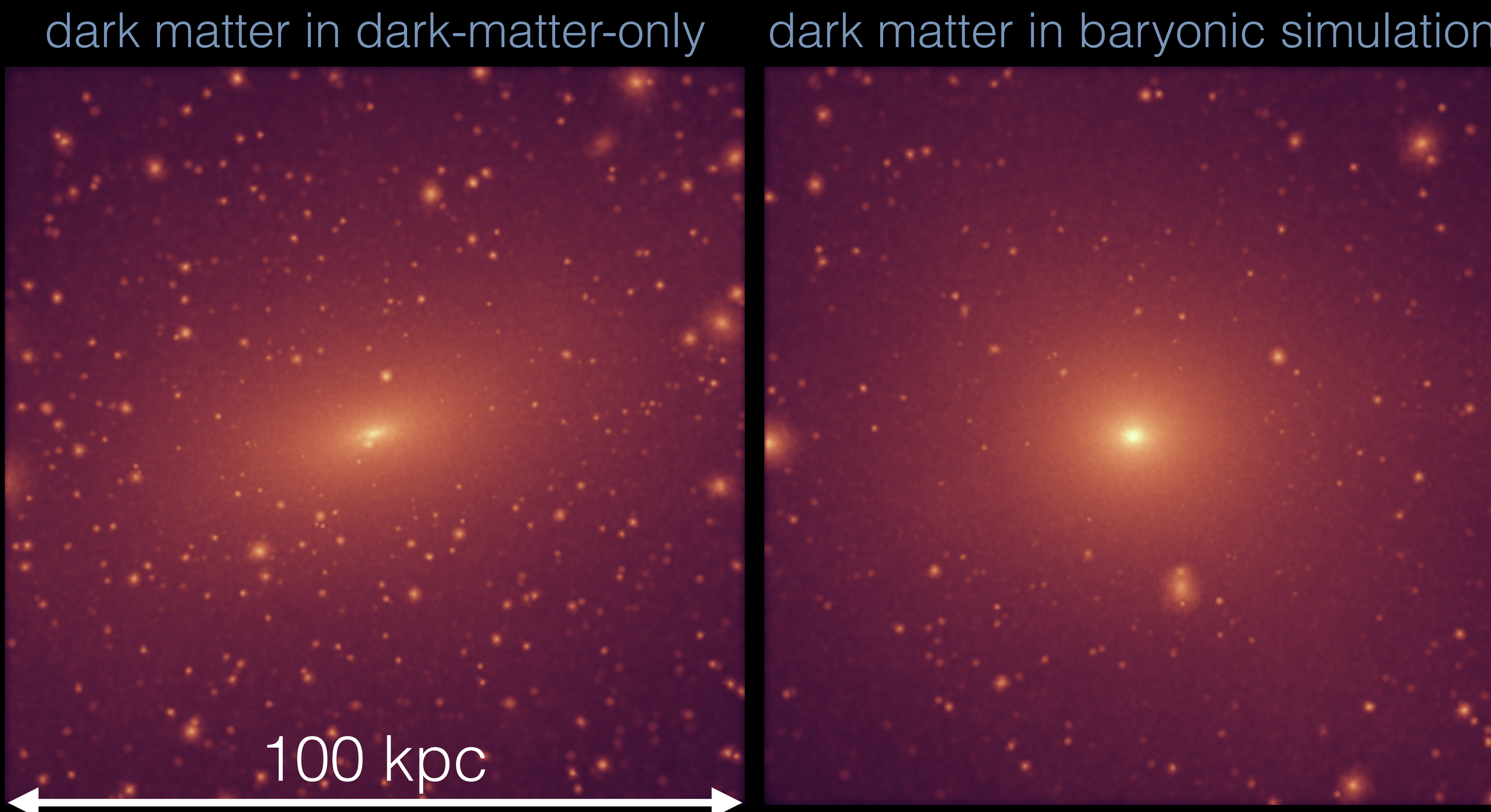
What causes the lack of (massive) satellite dwarf galaxies?

1. Stellar feedback drives significant gas outflows/inflows that dynamically heat dark matter, reducing the inner density (cores)

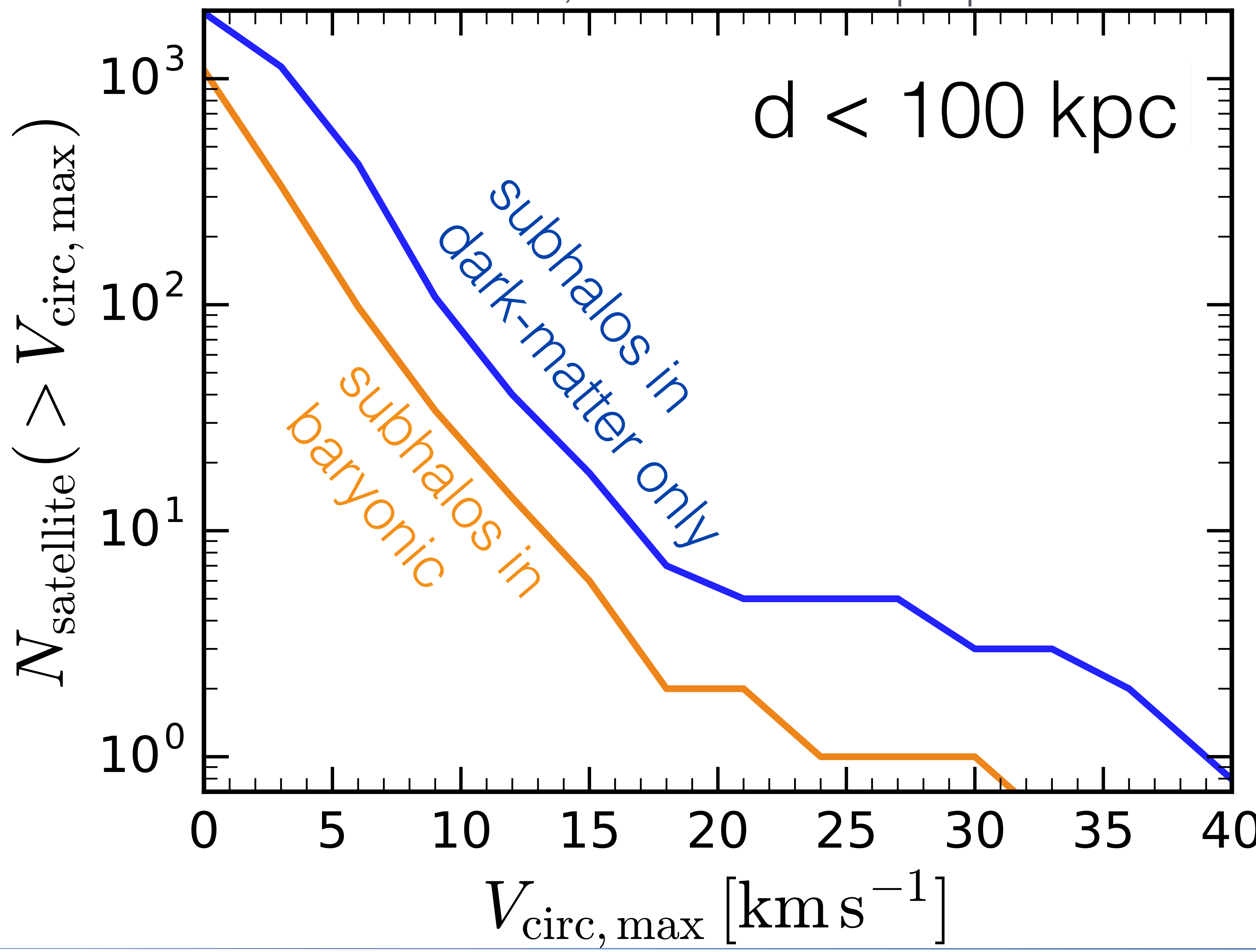
2. Stellar disk of Milky Way-mass host galaxy destroys satellites (via tidal shocking, etc)

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



dark-matter subhalo mass function

Garrison-Kimmel, Wetzel et al in prep



What causes the lack of (massive) satellite dwarf galaxies around the Milky Way-mass host?

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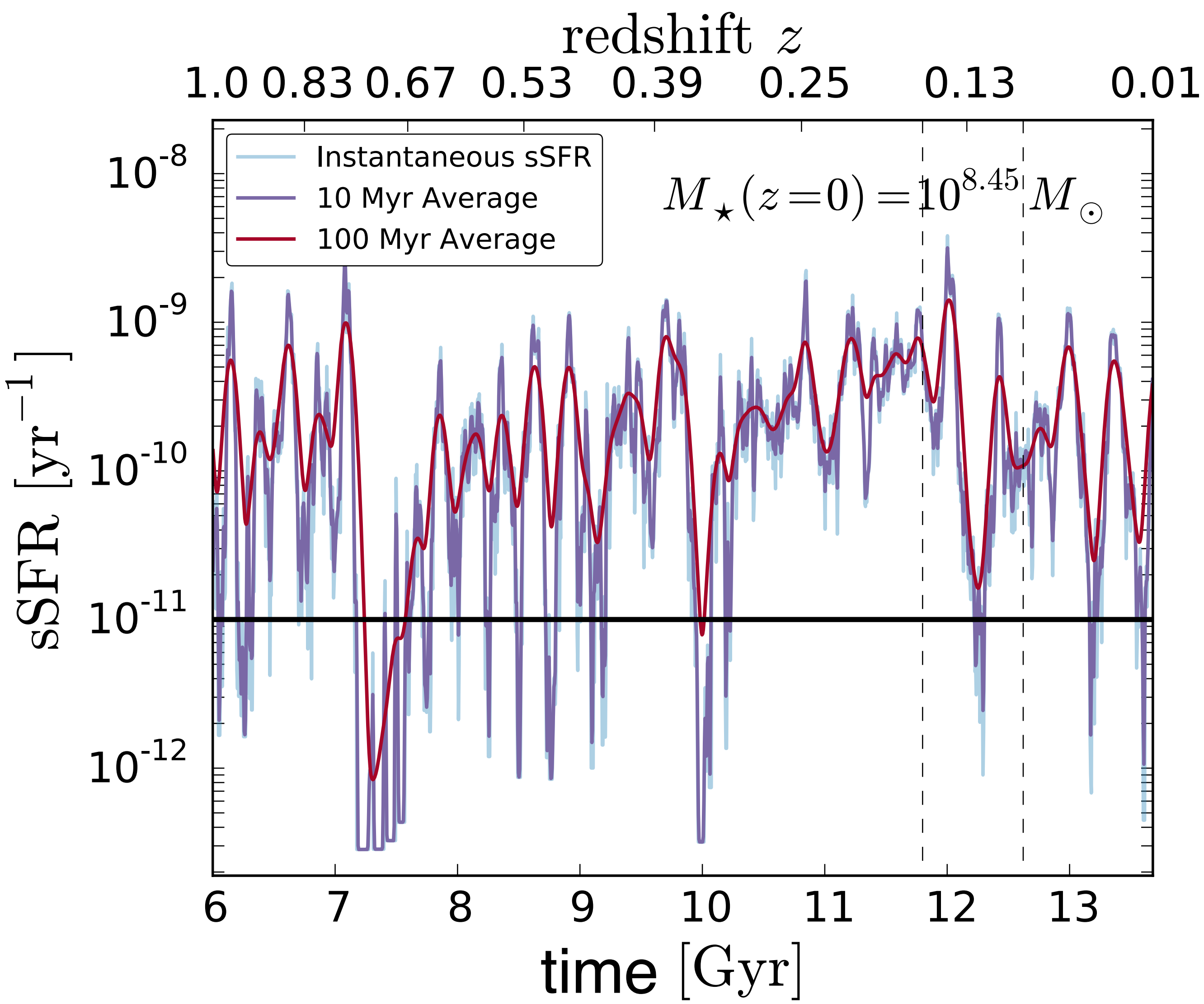
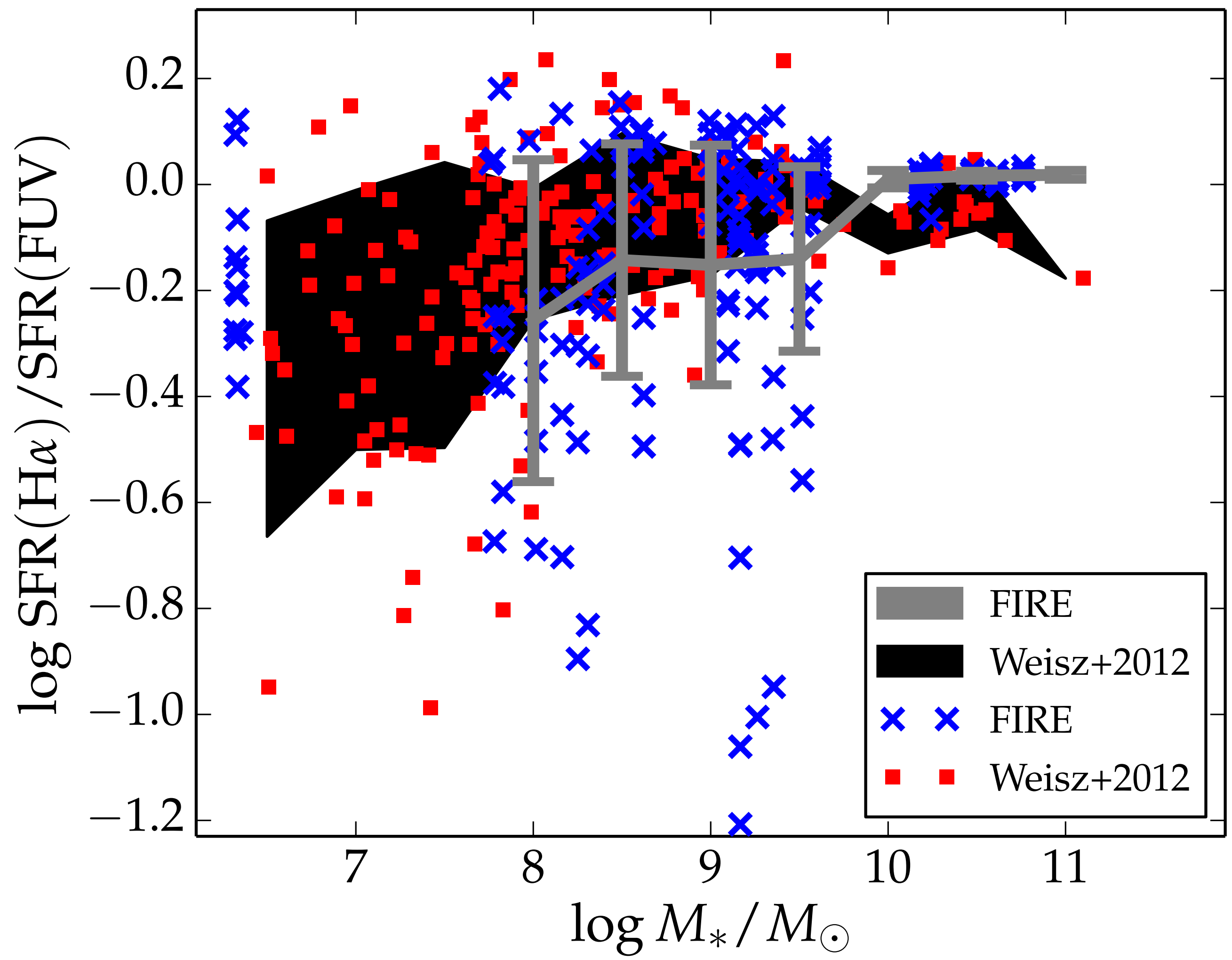
2. Stellar disk of Milky Way-mass host galaxy destroys satellites (via tidal shocking, etc)

dwarf galaxies have bursty star formation

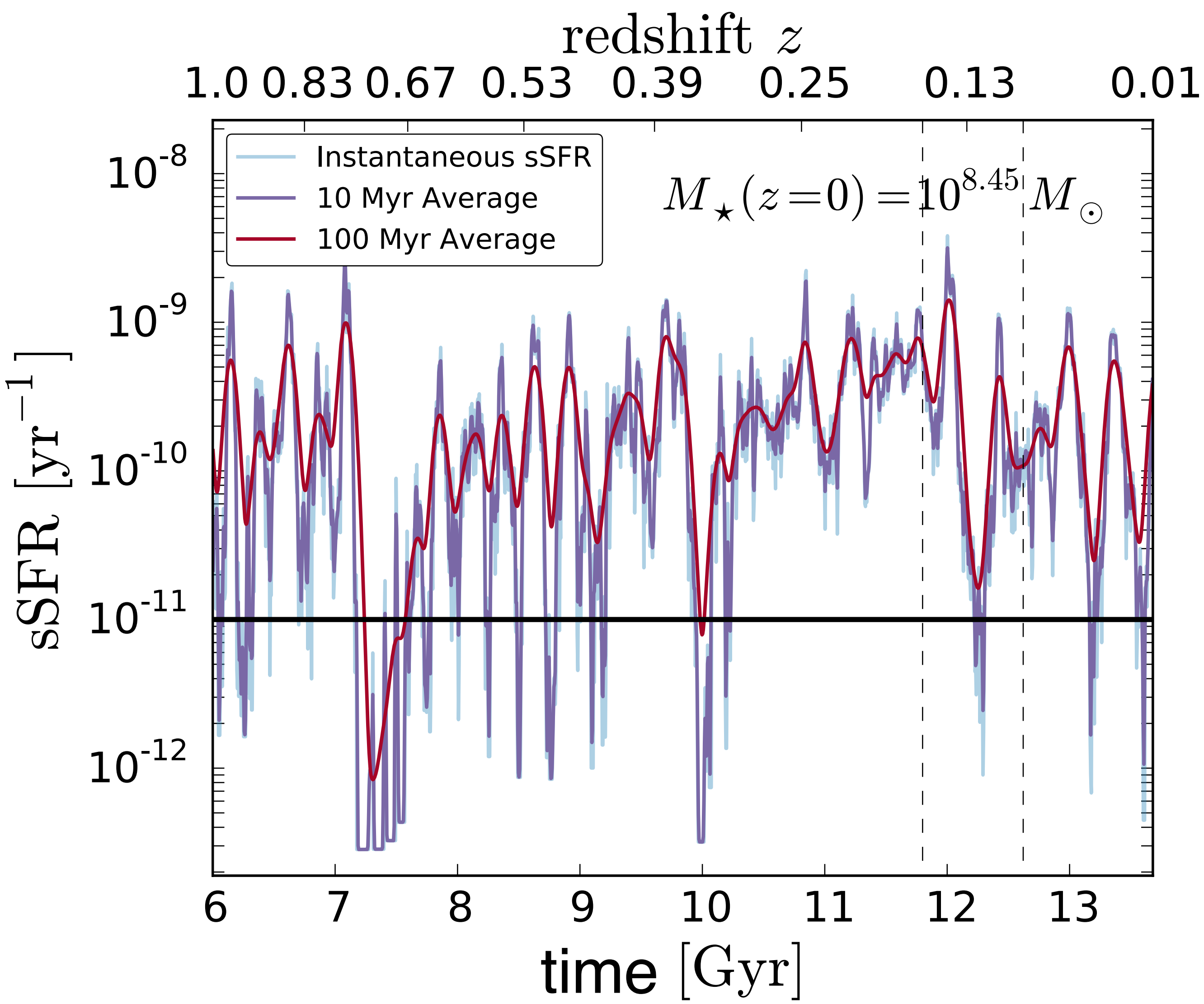


El-Badry, Wetzel et al 2015



Sparre et al 2015

dwarf galaxies have bursty star formation



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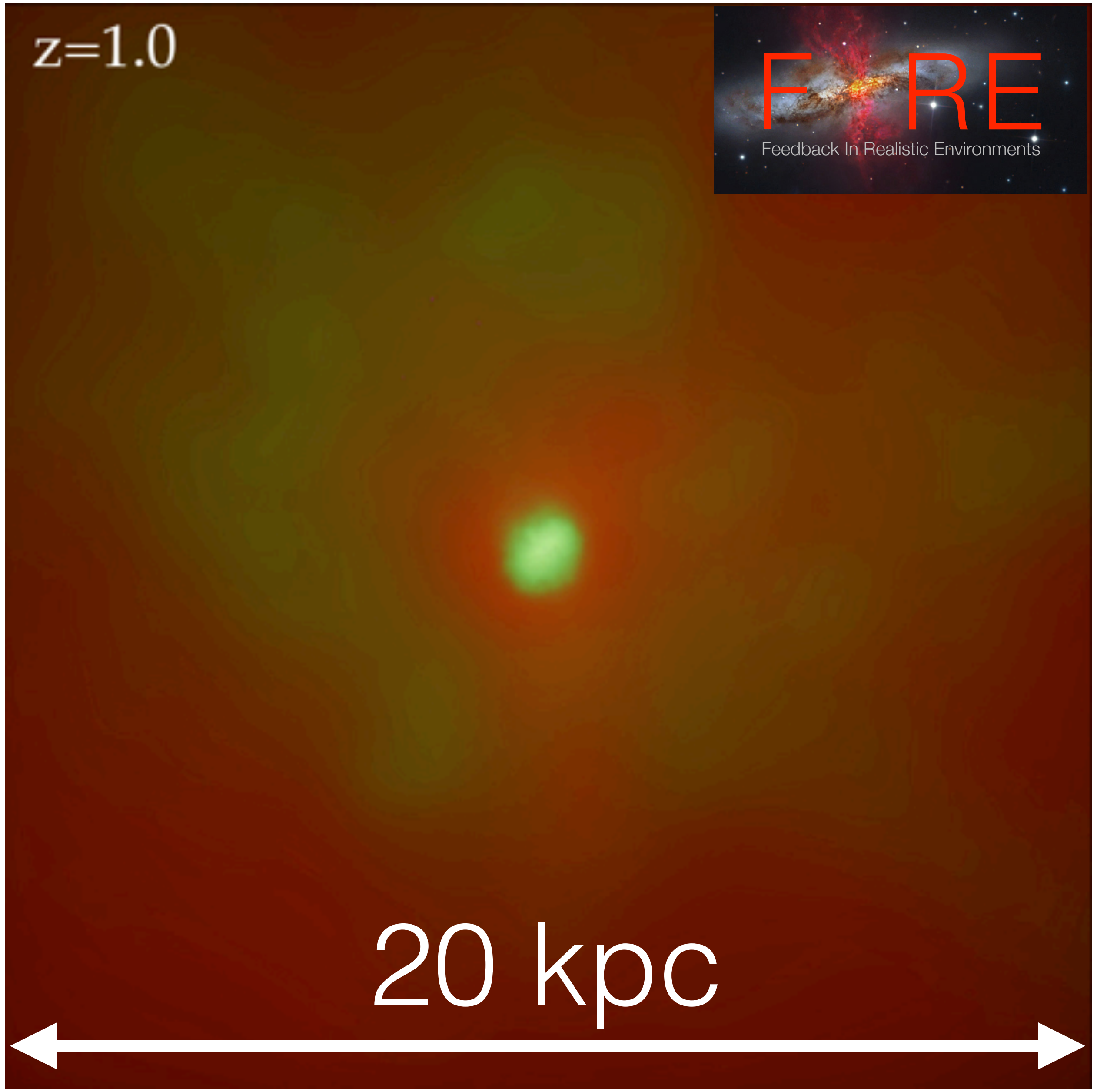
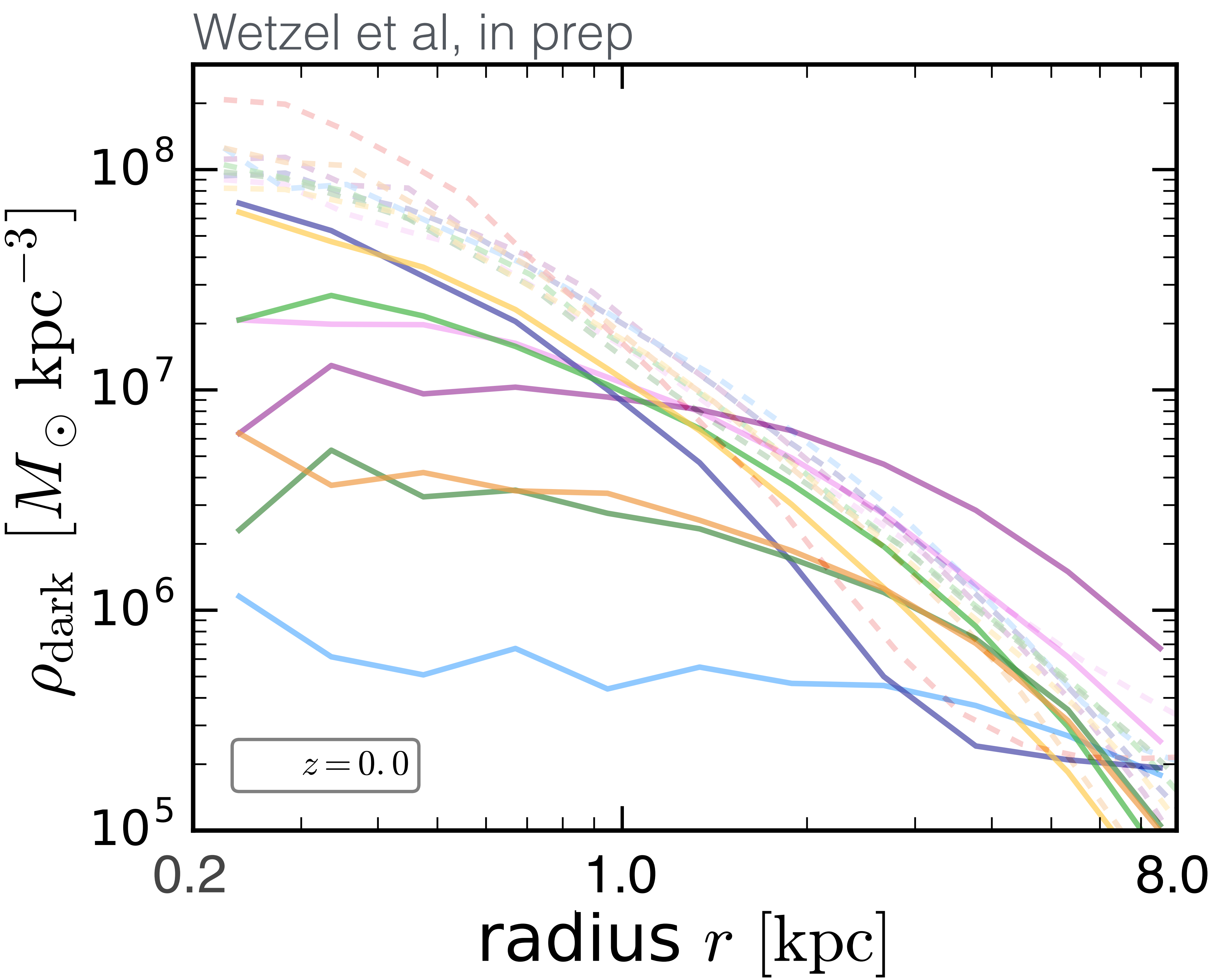


see also, e.g., Read & Gilmore 2005, Pontzen & Governato 2012, Di Cintio et al 2014, Chan et al 2015, etc

stellar feedback drives gas outflows/inflows that produce dark-matter cores



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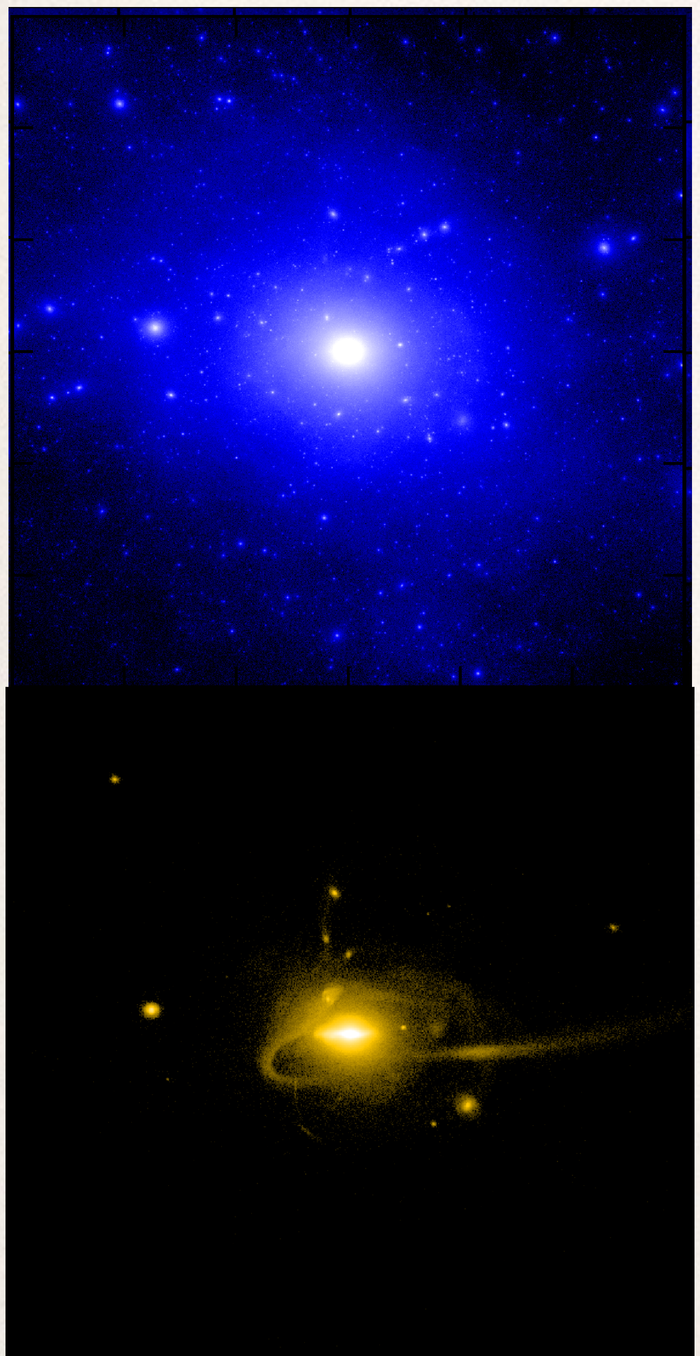
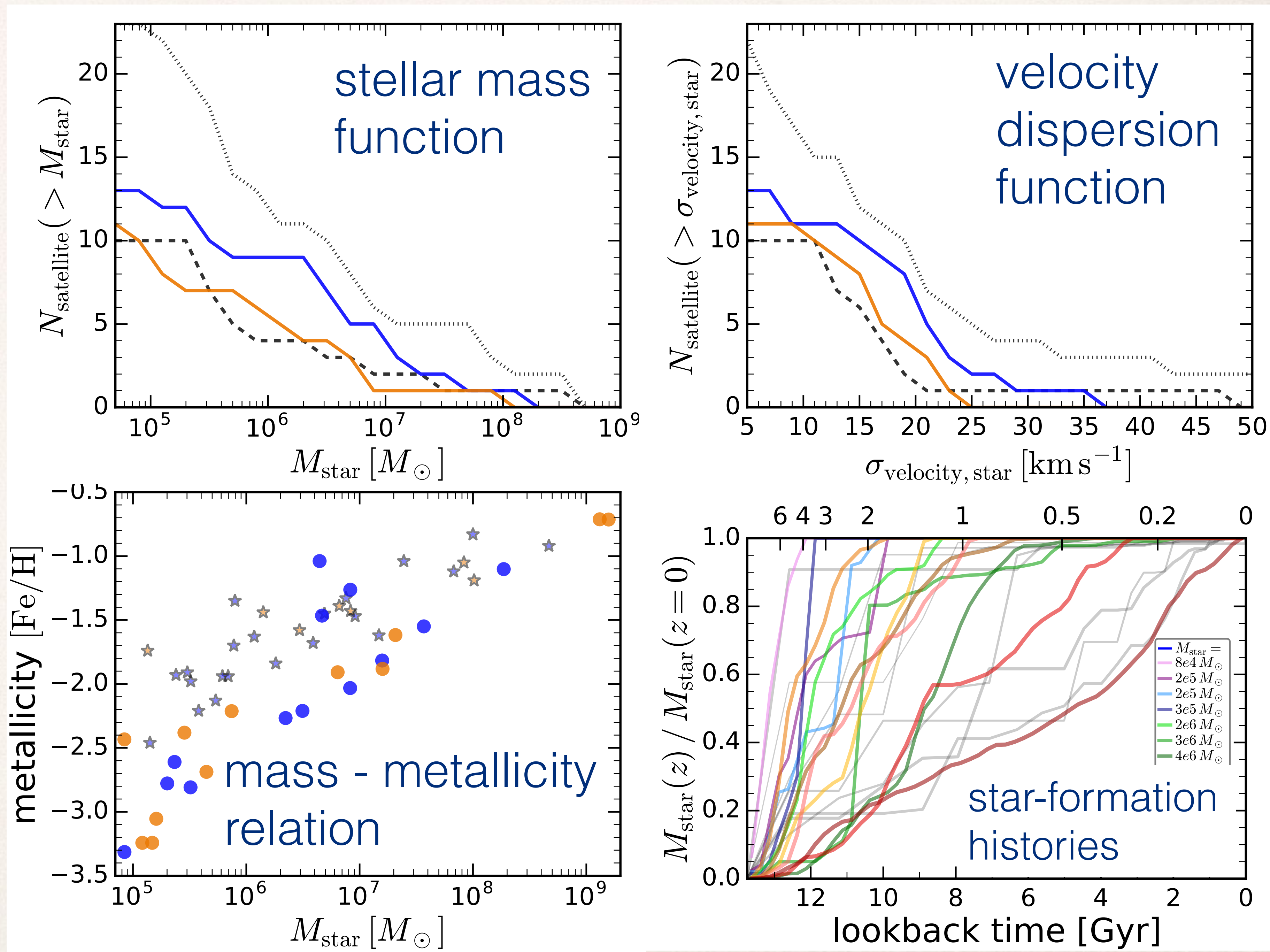
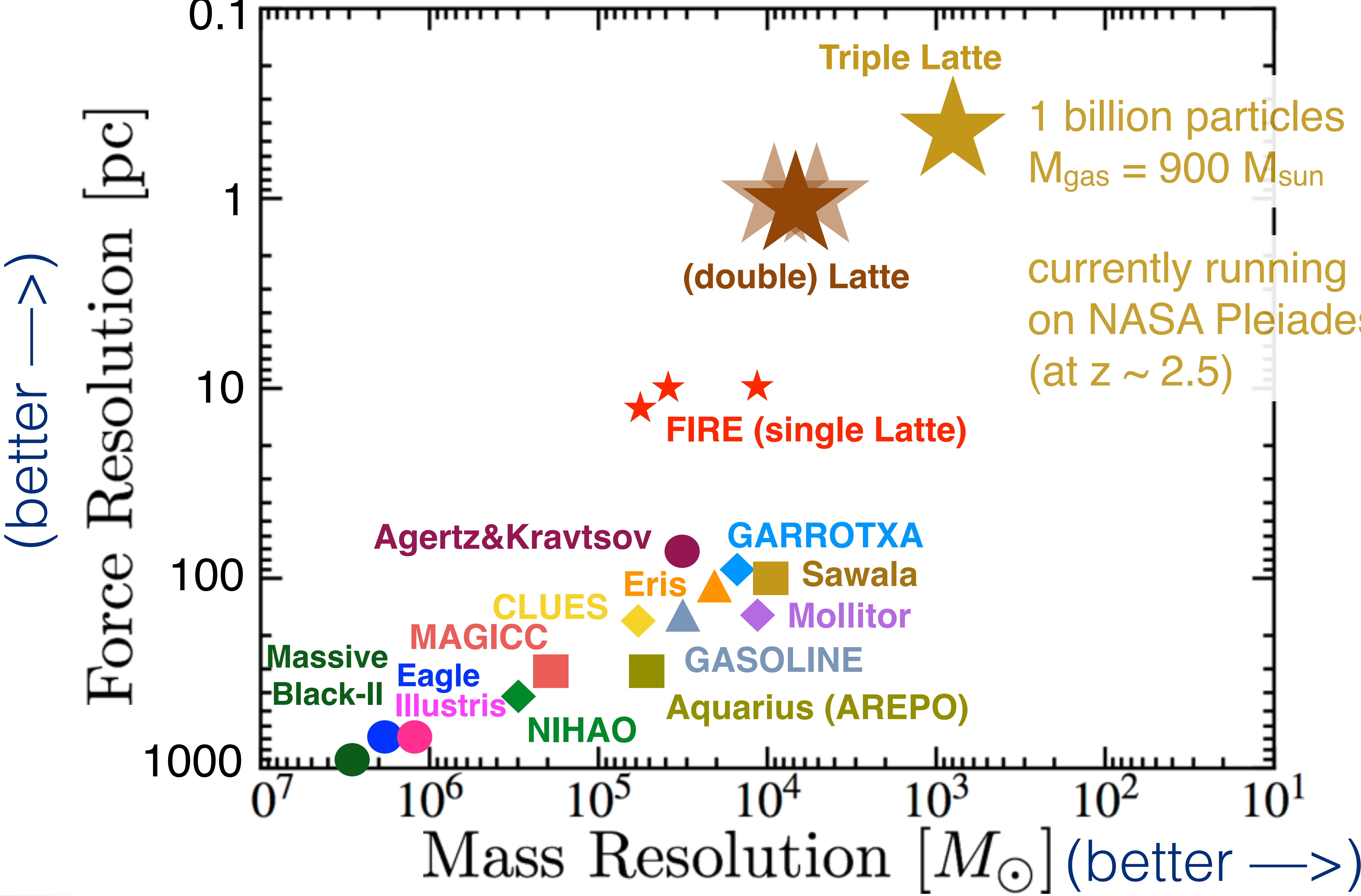
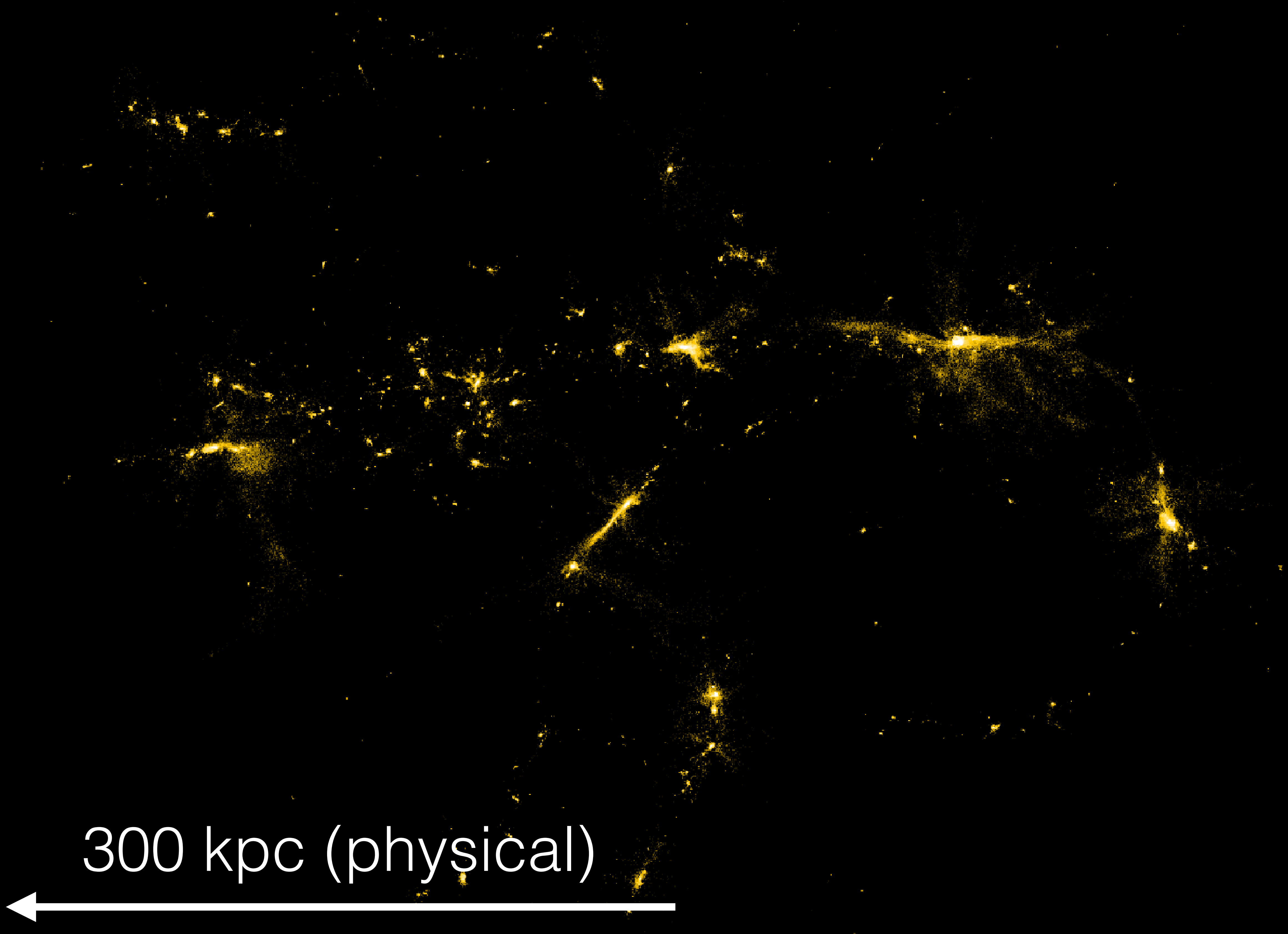




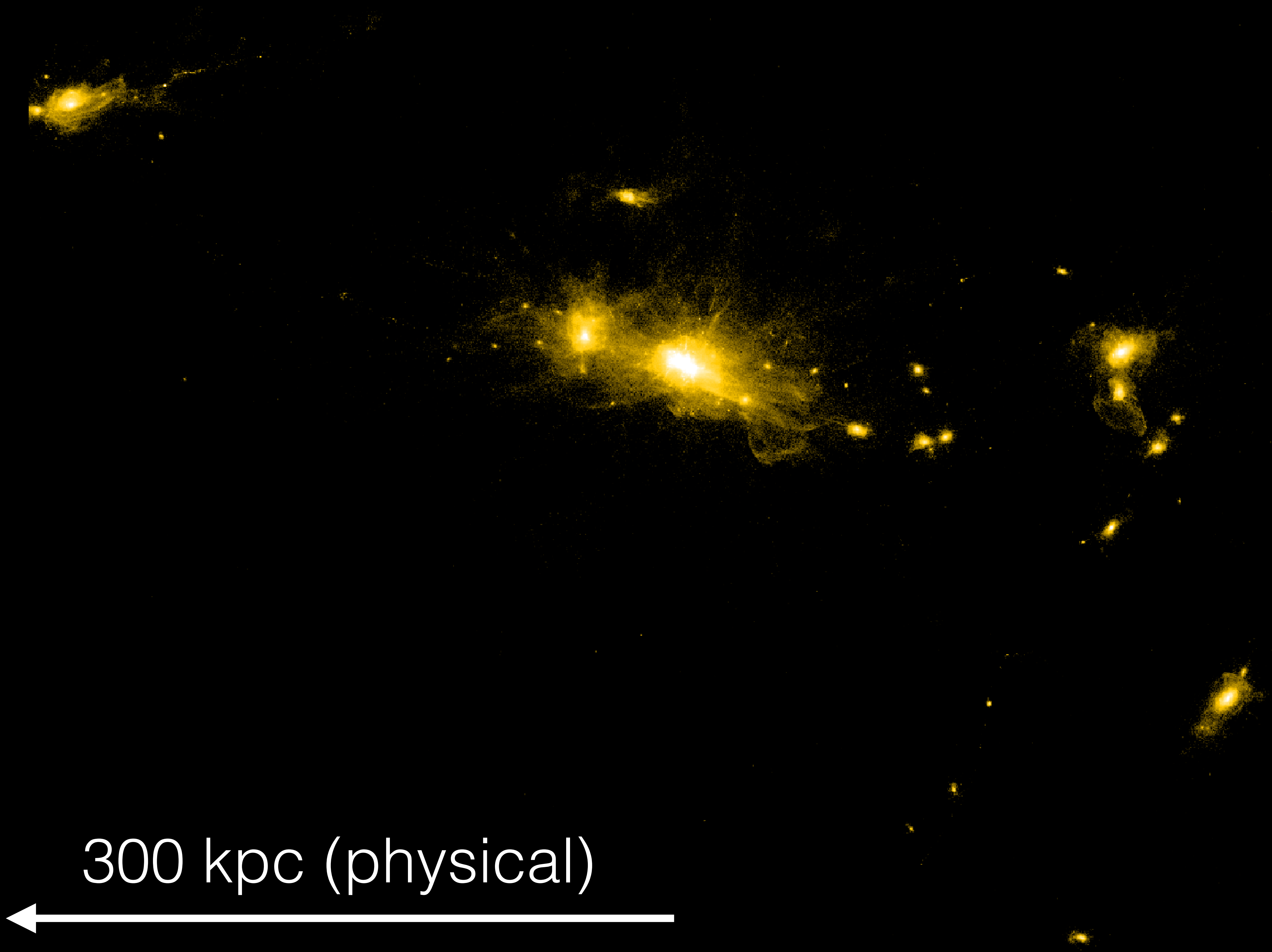
cosmological hydrodynamic simulations of Milky Way-mass galaxy to z = 0



MW-mass progenitor at z = 6



MW-mass progenitor at z = 2.5



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