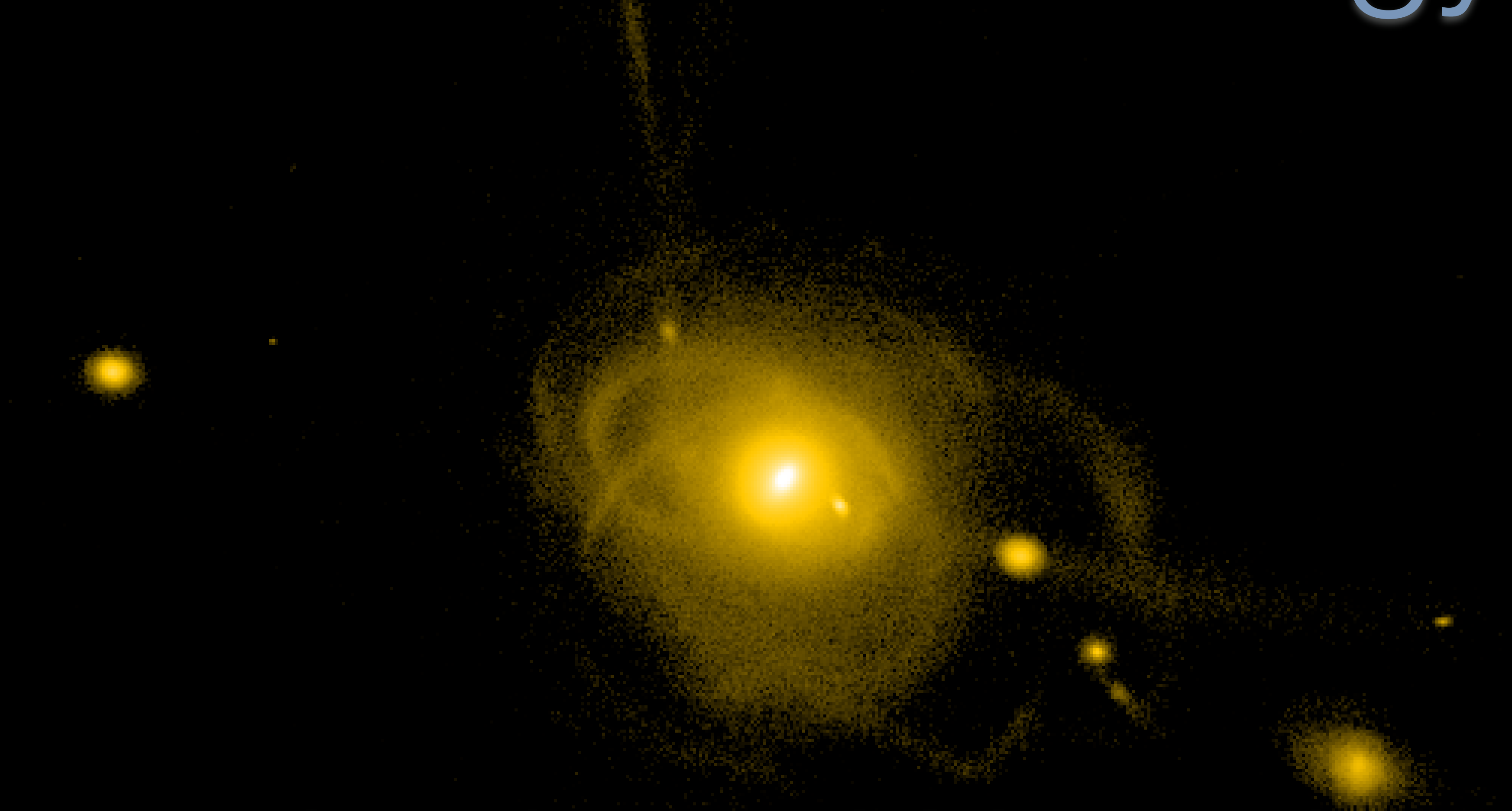
Reconciling Dwarf Galaxies with LCDM Cosmology



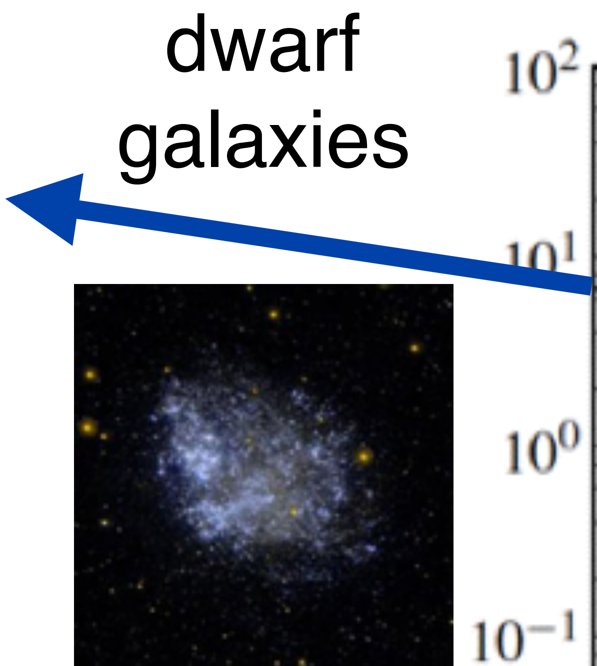
Andrew Wetzel

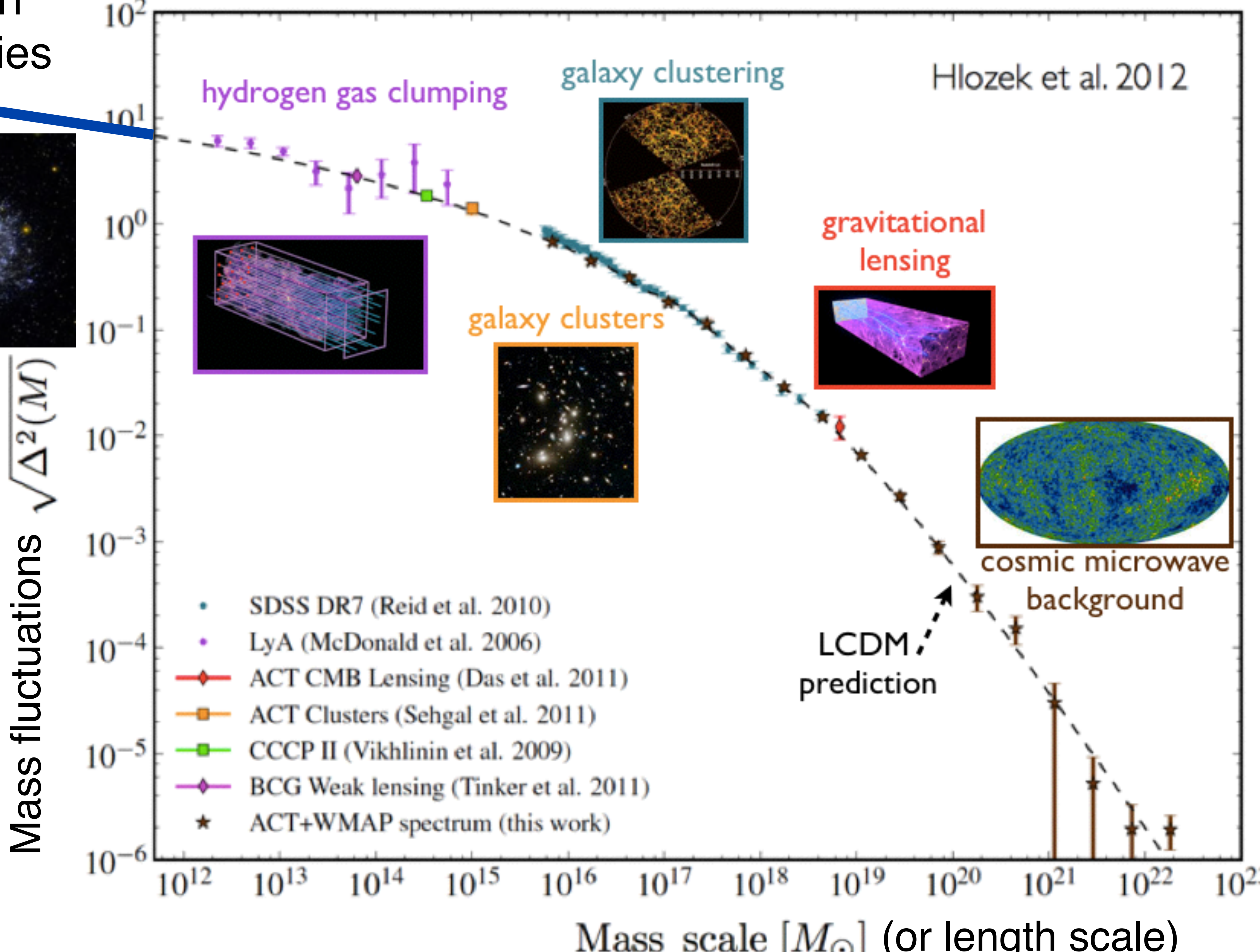
Moore Prize Fellow
Caltech

Carnegie Fellow in Theoretical Astrophysics
Carnegie Science

with the FIRE (Feedback In Realistic Environments) collaboration

cosmological structure formation

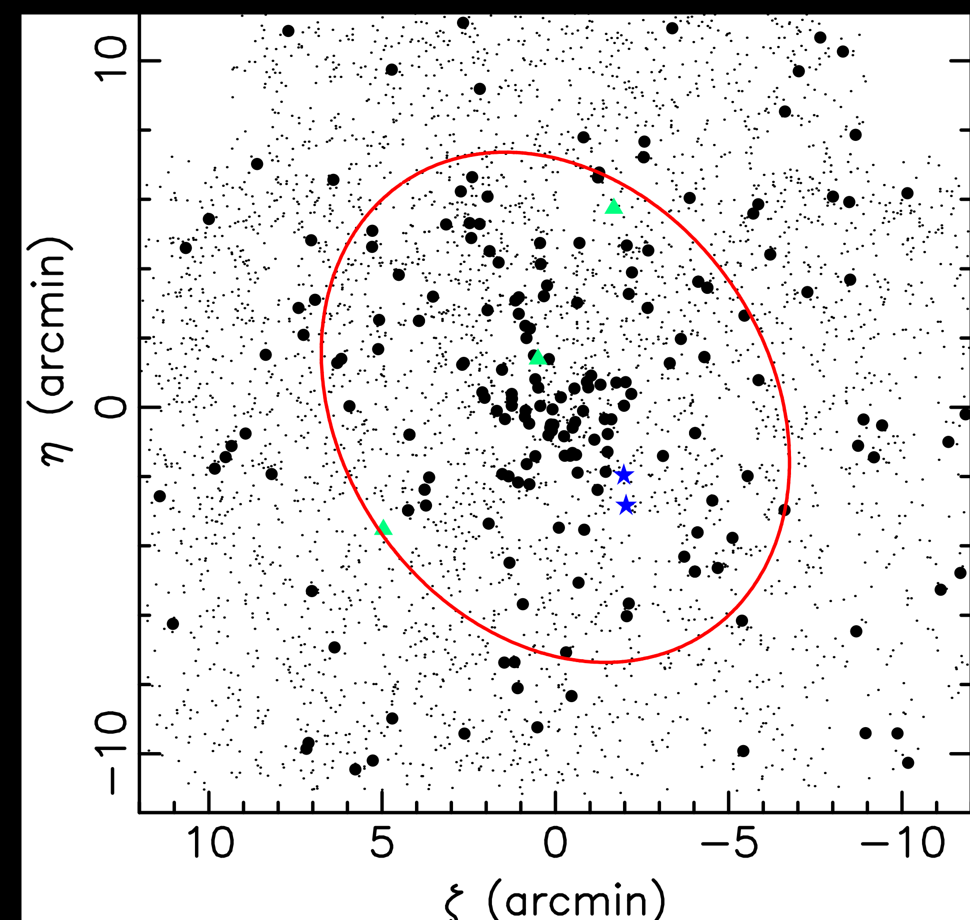




MW-like galaxy: 100 billion stars

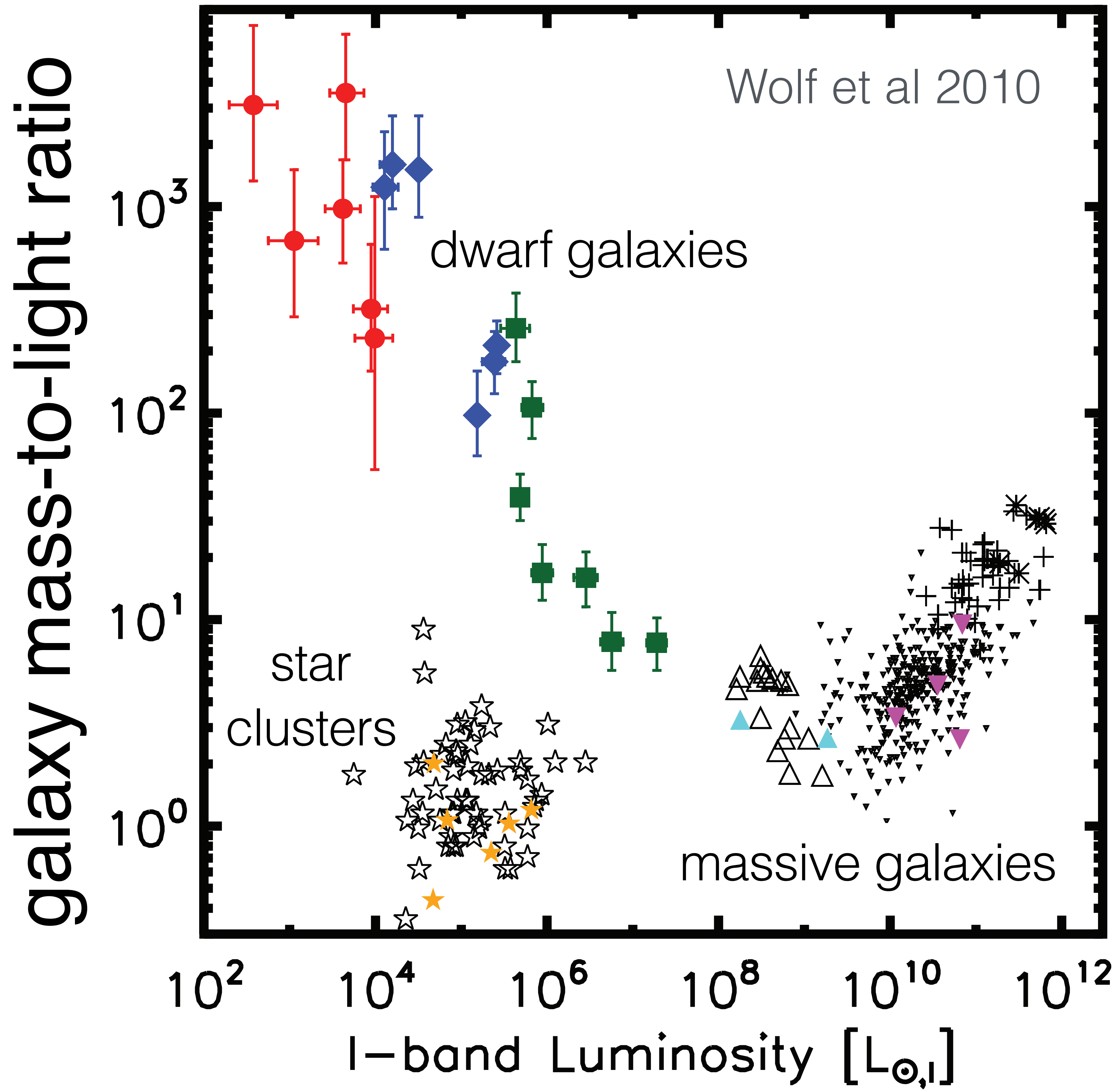
Magellanic Clouds: 1 billion stars

Fornax: 10 million stars



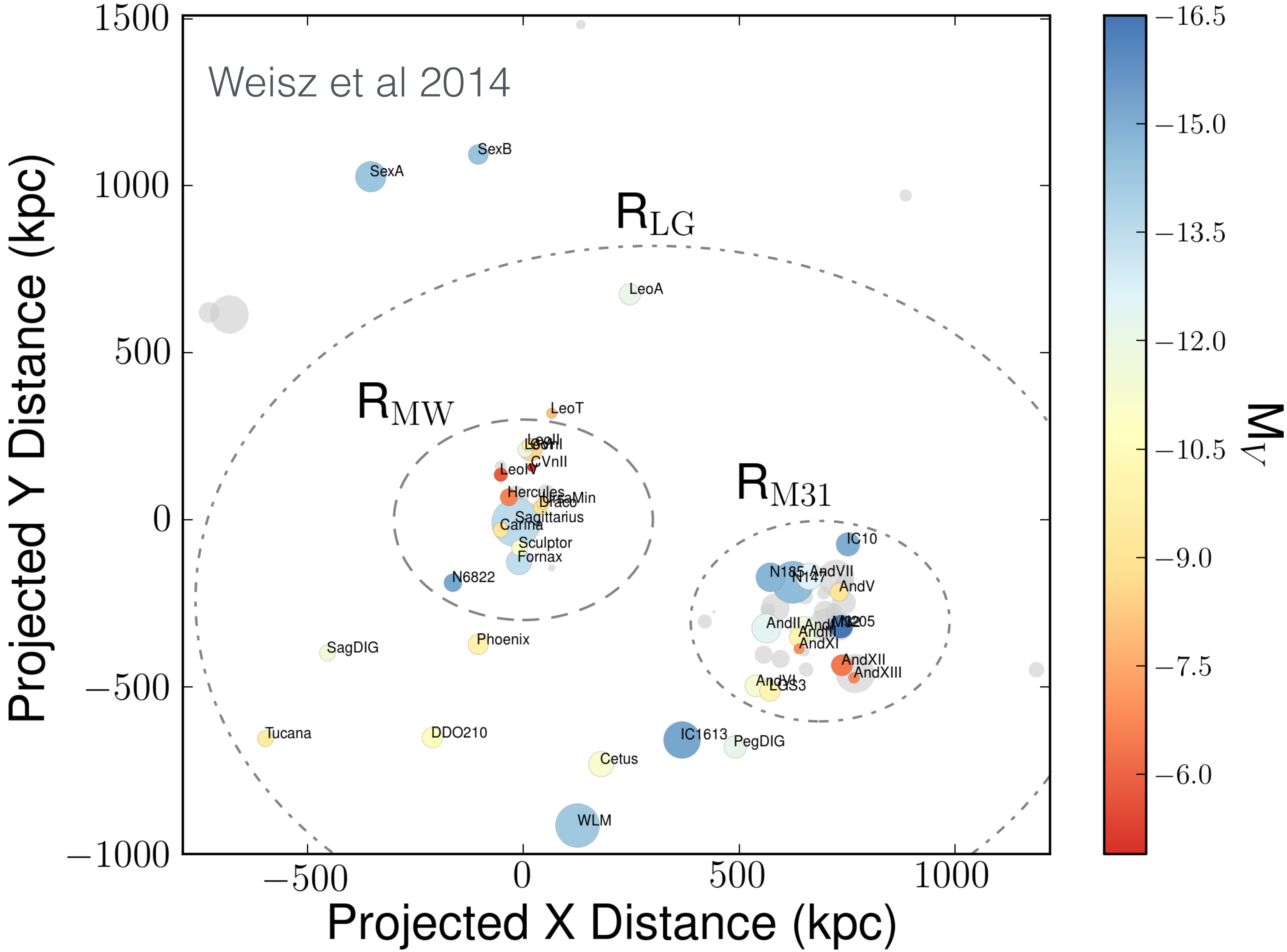
Triangulum II: 500 stars

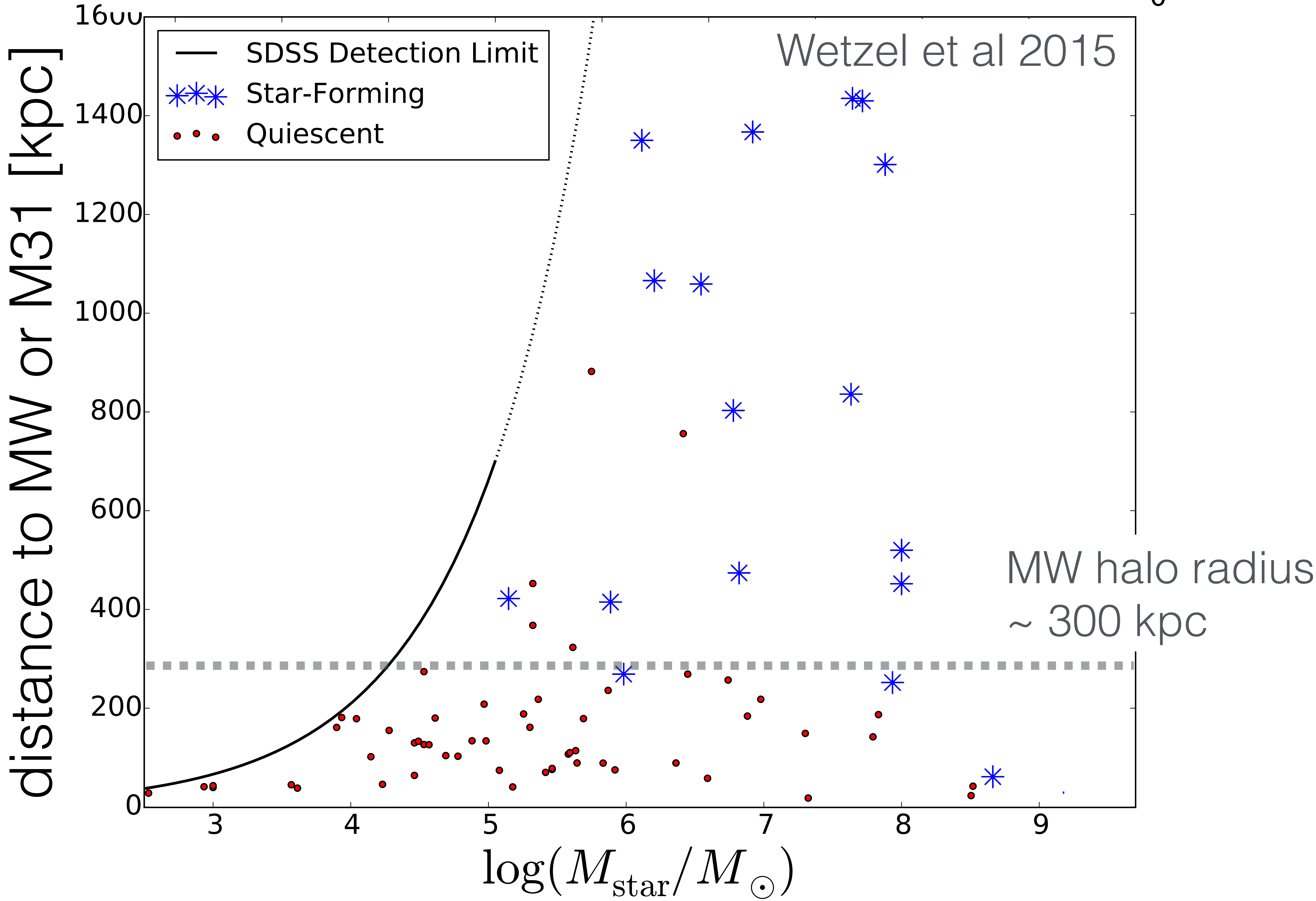
dwarf galaxies: the most dark-matter dominated systems



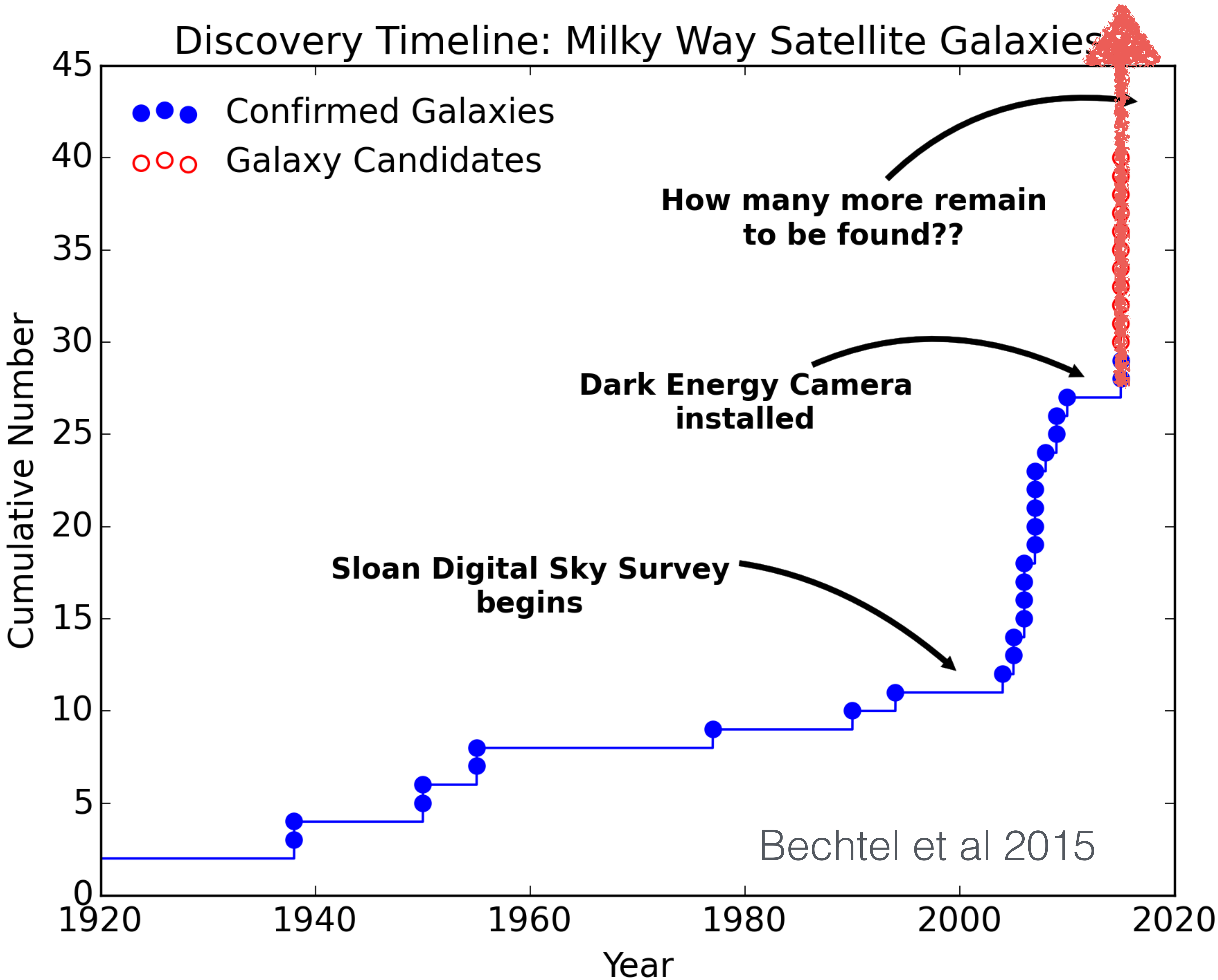
also Walker et al 2009, 2010

The Local Group





limited observational completeness of dwarf galaxies



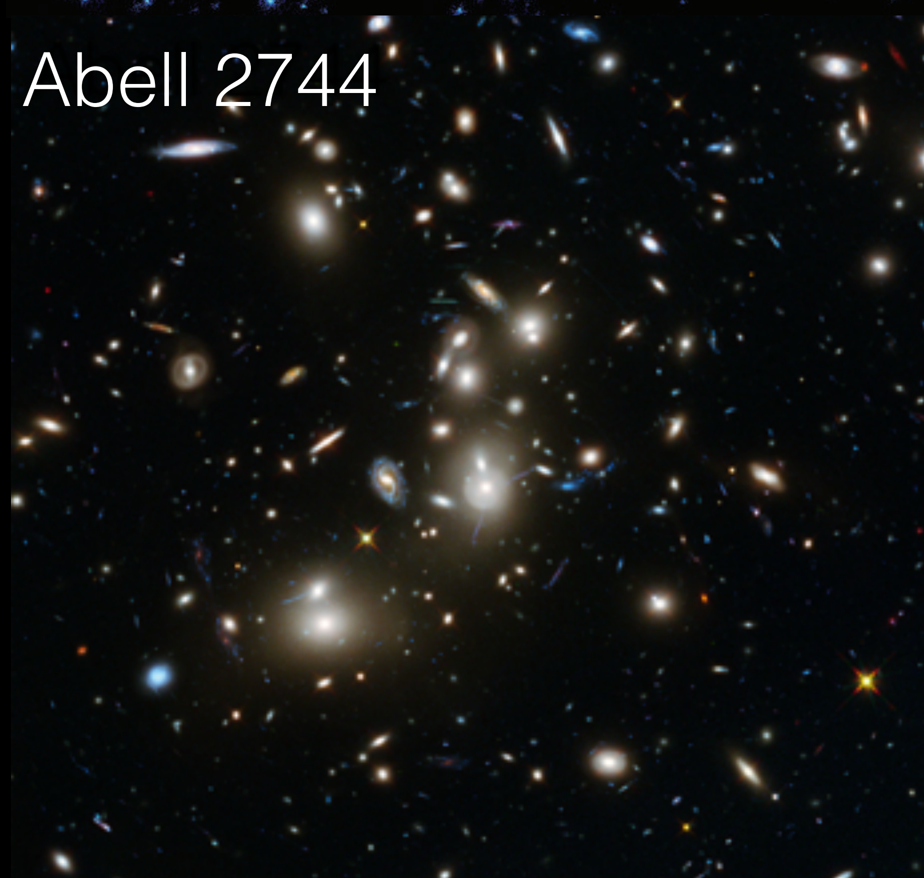
exciting era for dwarf galaxies and near-field cosmology!

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

(nearly) self-similar structure formation in CDM

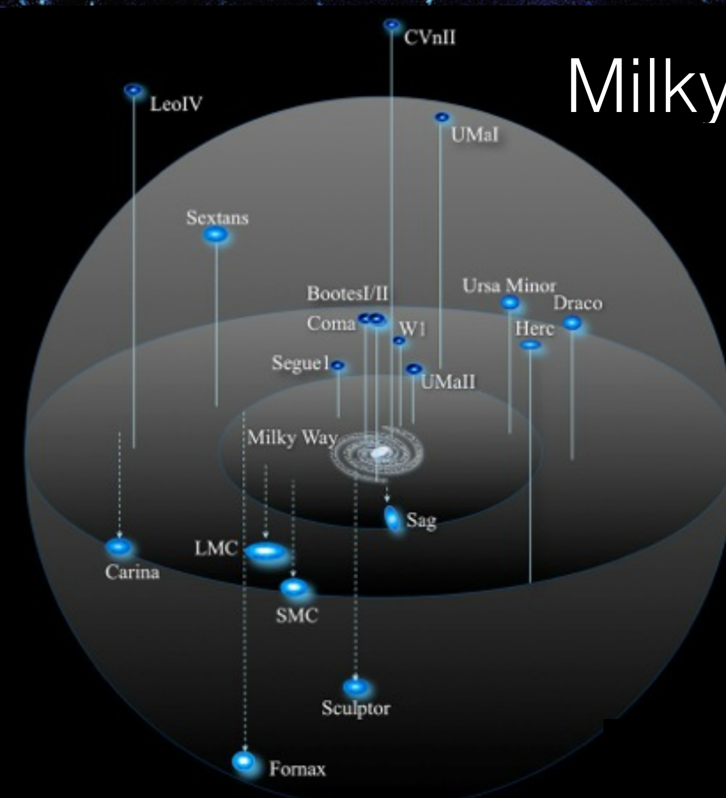
1000s of subhalos

Abell 2744

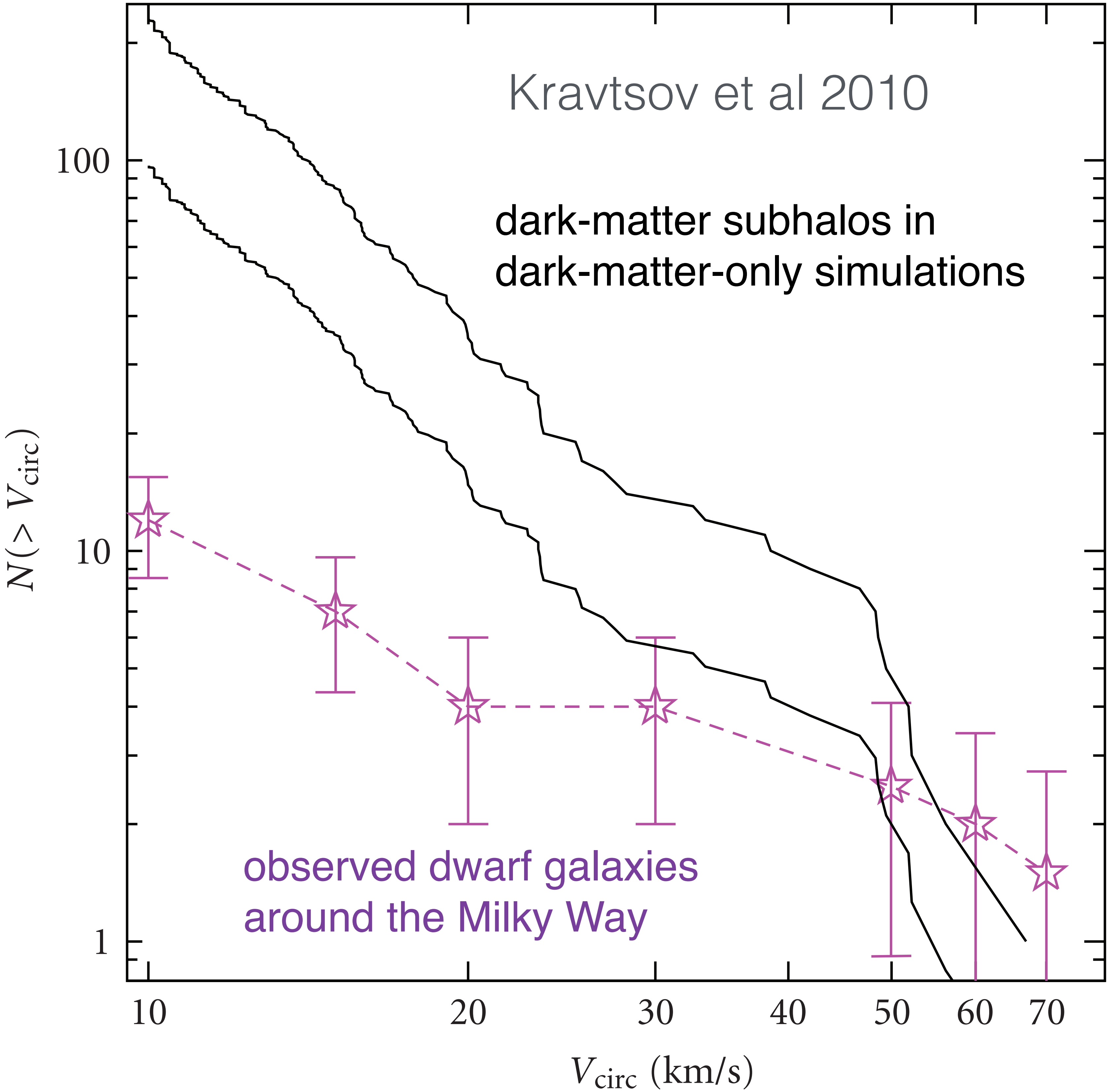


1000s of galaxies

Milky Way

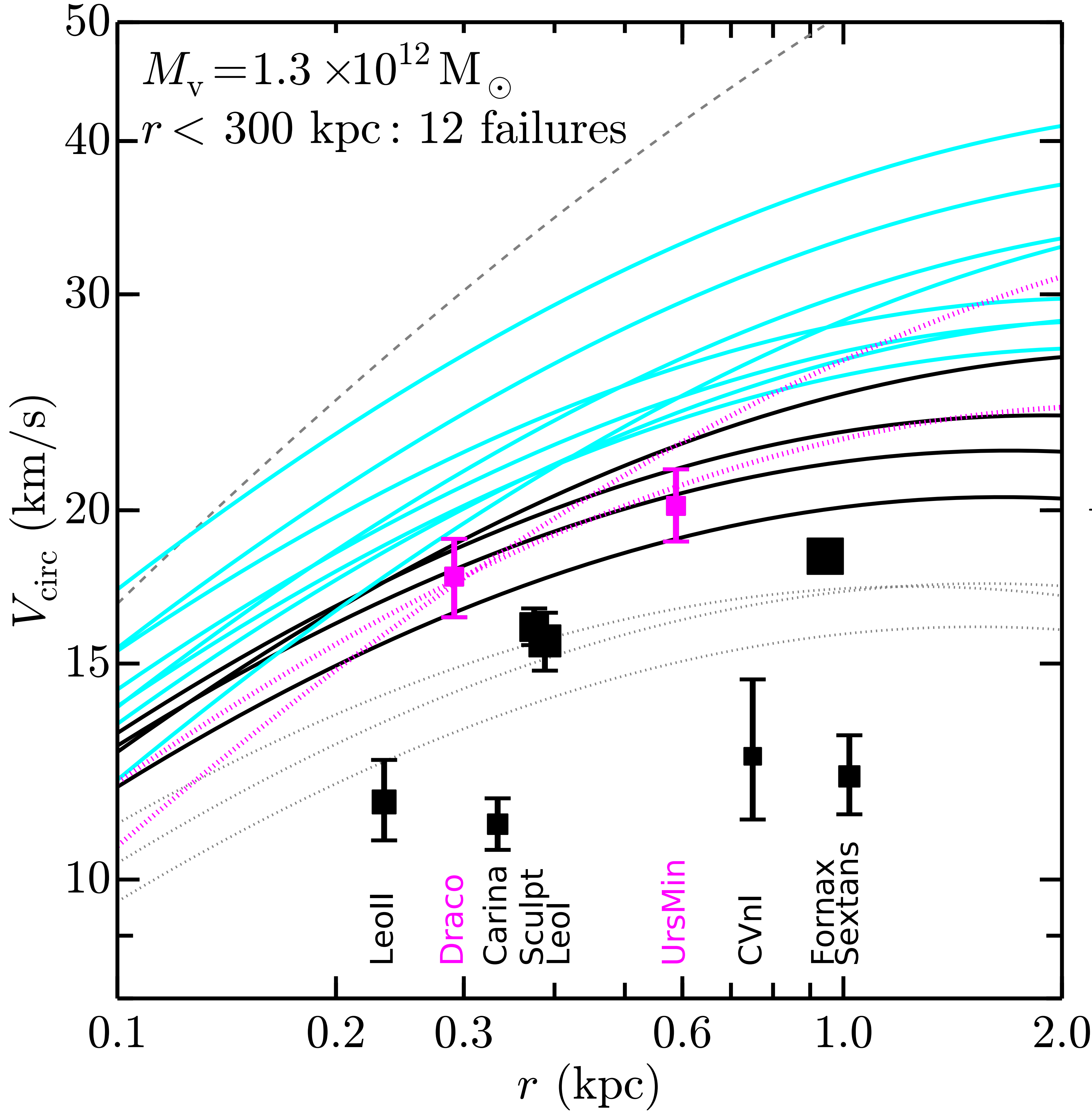


12 bright satellites $(L_V > 10^5 L_\odot)$



$$V_{\rm max} \approx \sqrt{\frac{GM_{\rm total}}{r}}$$

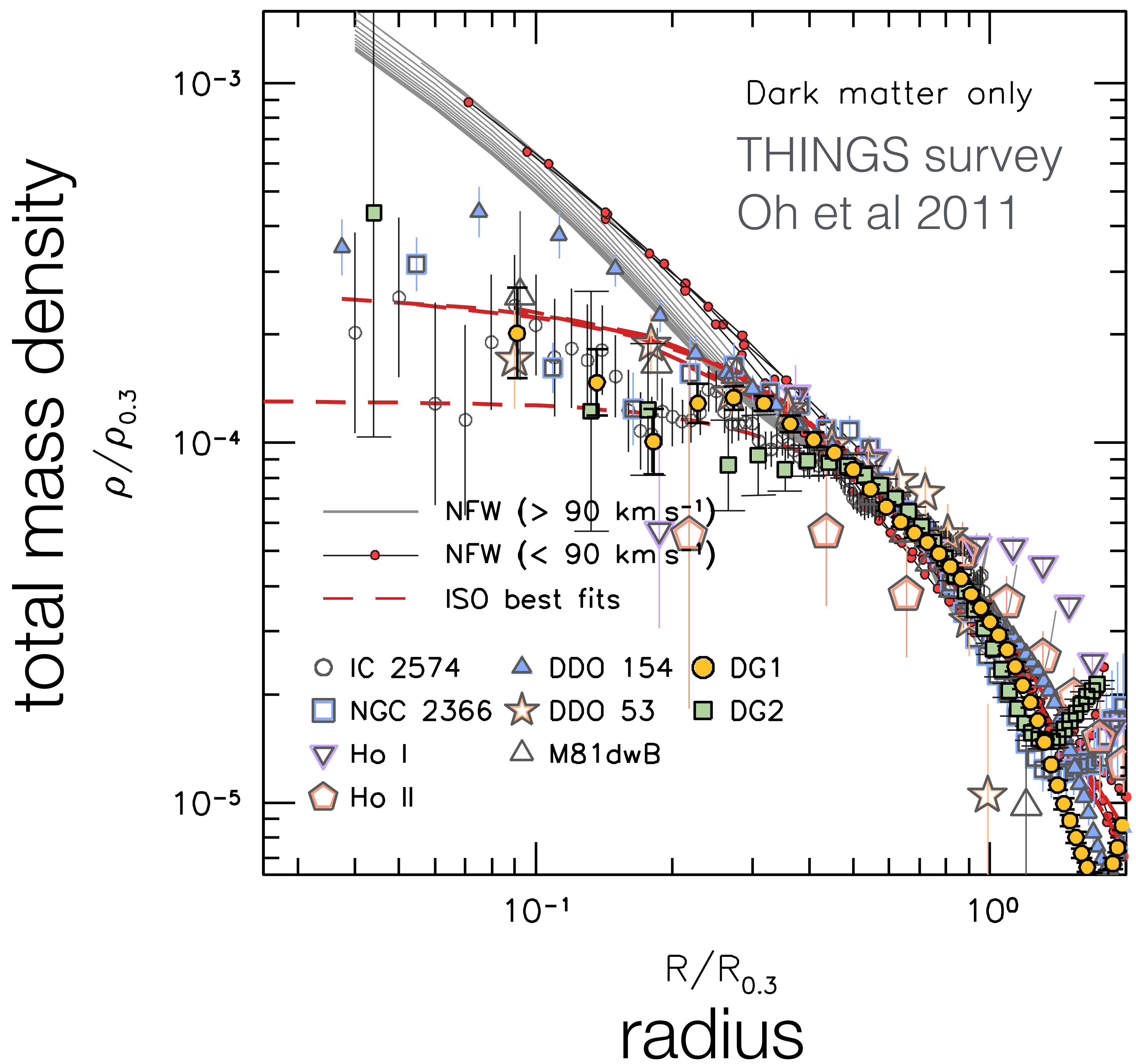
“missing satellites” problem: too few observed satellites compared with dark-matter subhalos in CDM



$$V_{circ}(r) = \sqrt{\frac{G M_{tot}(< r)}{r}}$$

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

"too big to fail" problem: dark-matter subhalos in CDM are too dense compared with observed satellite galaxies



"core-cusp" problem: inner density slope of observed galaxies is too shallow vs dark-matter (sub)halos in CDM

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

“missing satellites” problem

(probably) too few observed satellite galaxies compared with dark-matter subhalos in CDM

—> Can a CDM-based model produce a satellite stellar mass function as observed?

“too big to fail” problem

dark-matter subhalos in CDM are too dense compared with observed satellite galaxies

—> Can a CDM-based model produce a satellite dynamical mass (velocity dispersion) function as observed?

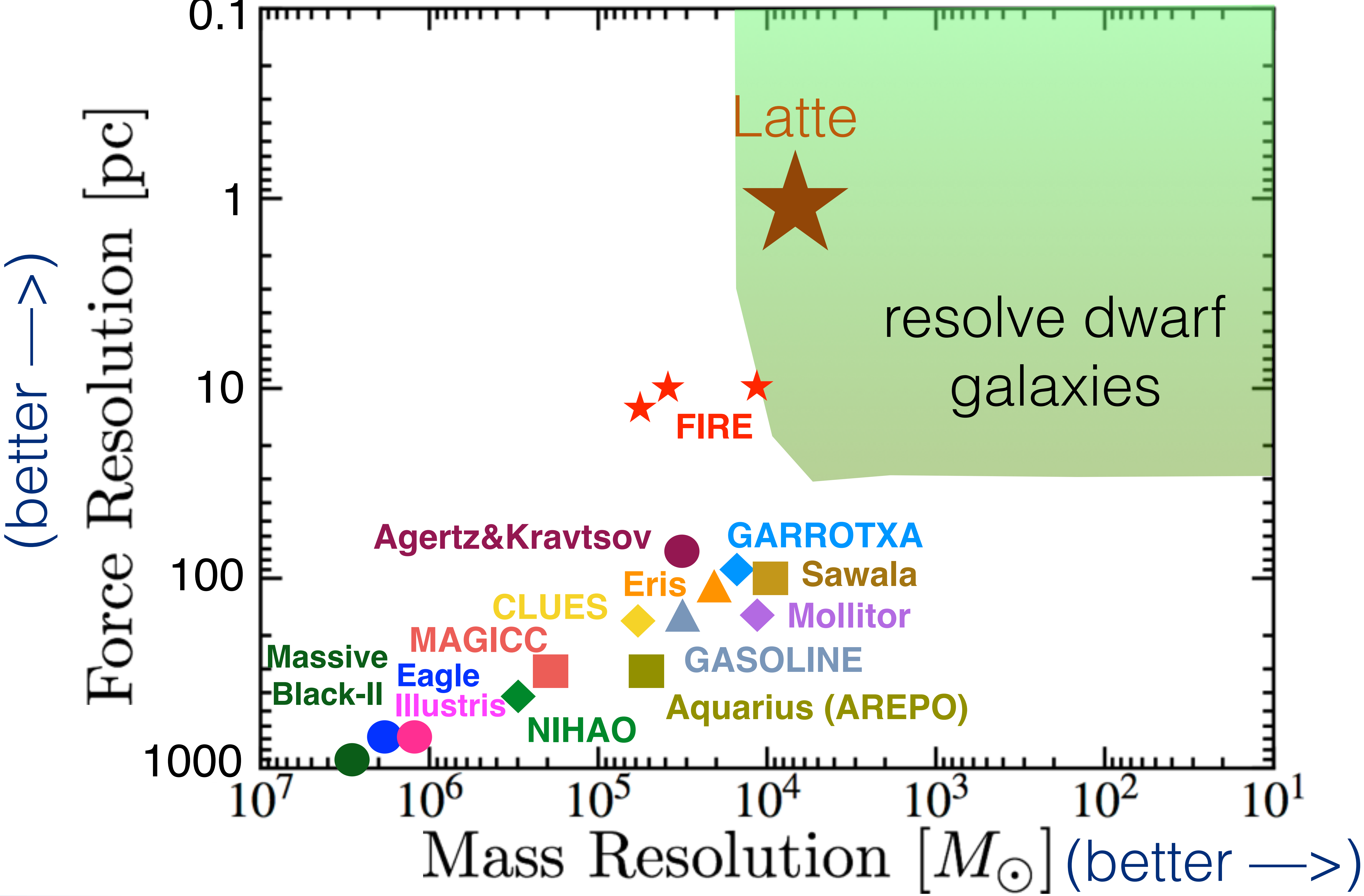
dwarf galaxies: the most significant challenges to the Cold Dark Matter (CDM) model

possible solutions

1. dark matter is not “standard” CDM
   examples:
   A. warm dark matter
   B. self-interacting dark matter

2. baryonic physics
   stellar feedback —> gas outflows —> dark matter cores

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



The Latte Project: the Milky Way on FIRE

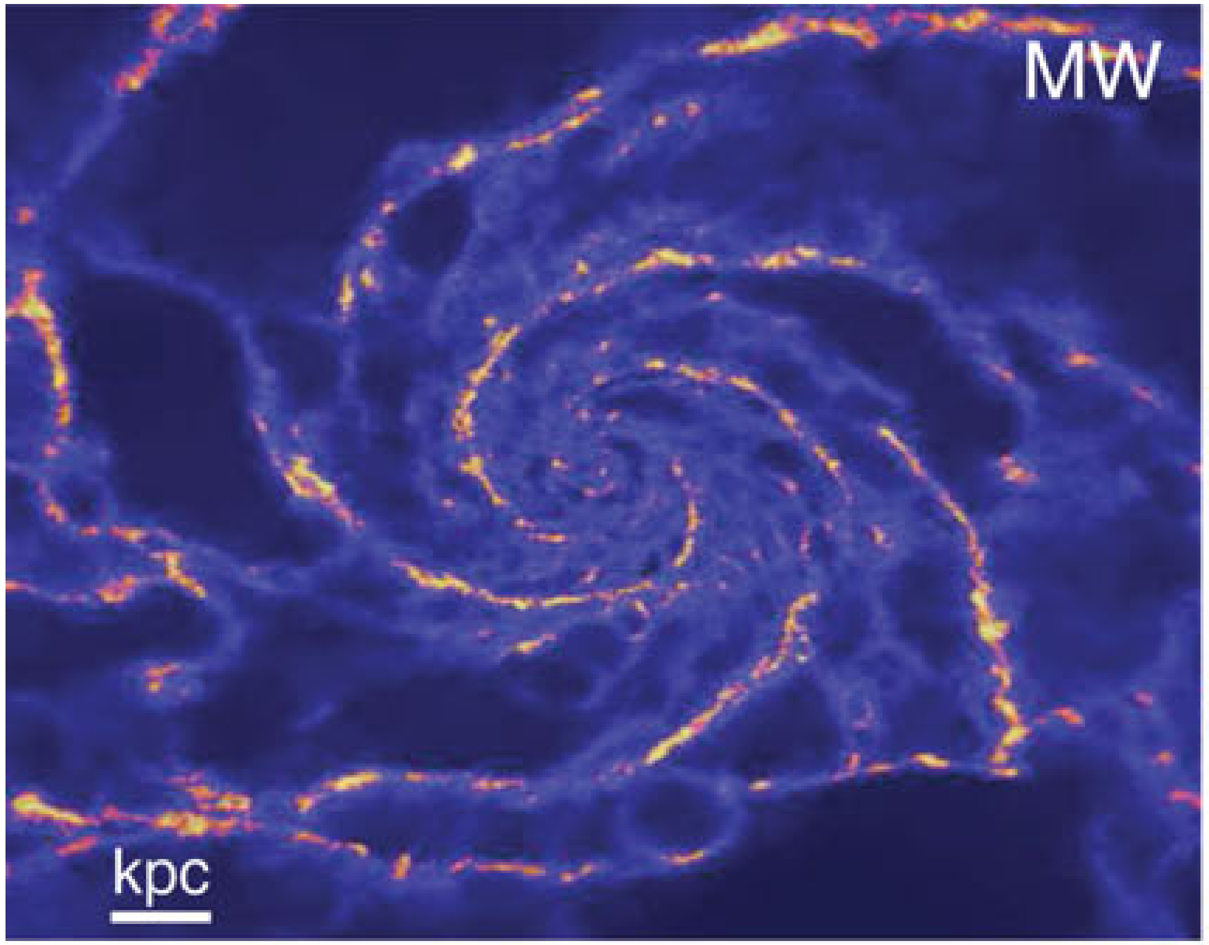
simulating a Milky Way-mass galaxy with a realistic population of satellite dwarf galaxies at parsec resolution

Wetzel et al 2016, ApJL submitted, arXiv:1602:05957

FIRE
Feedback In Realistic Environments

FIRE model for star formation

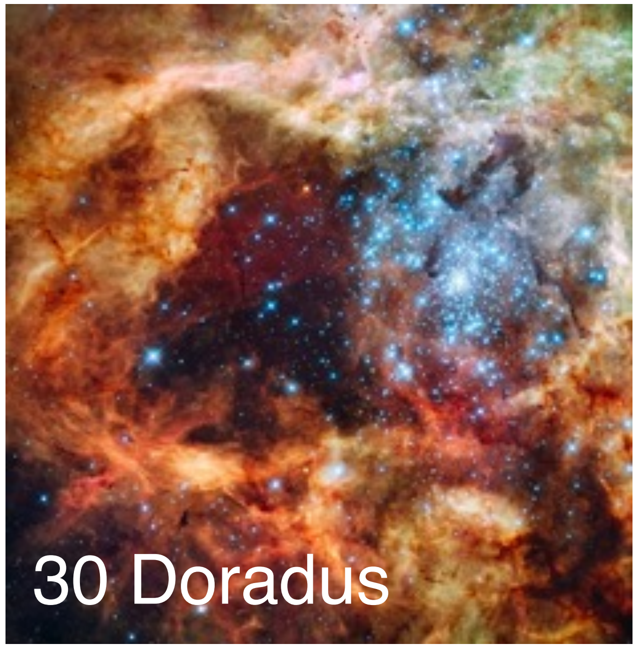
Feedback In Realistic Environments



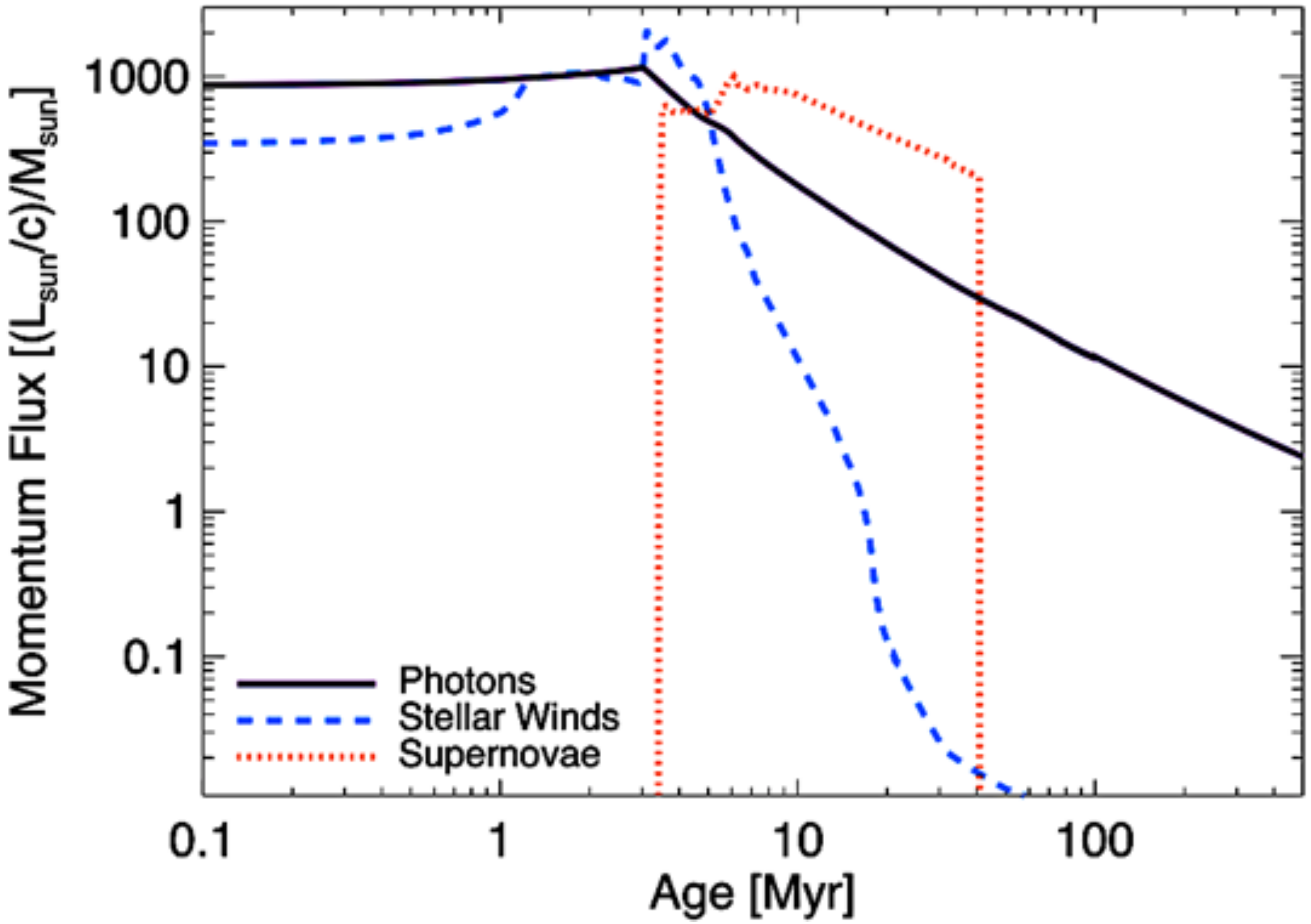
- Ultra-high resolution
  - $m_{gas} = 7000\ M_{sun}$
  - $h_{gas} = 1$ pc ($h_{dm} = 20$ pc)
  - captures multi-phase inter-stellar medium
- Cooling from atoms, molecules, and 9 metals down to 10 K
- Star formation only in self-gravitating clouds: $n_H > 100\ cm^{-3}$
- Star formation efficiency: 100% per free-fall time

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)



- Explicit Momentum Flux:
  - Radiation Pressure

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

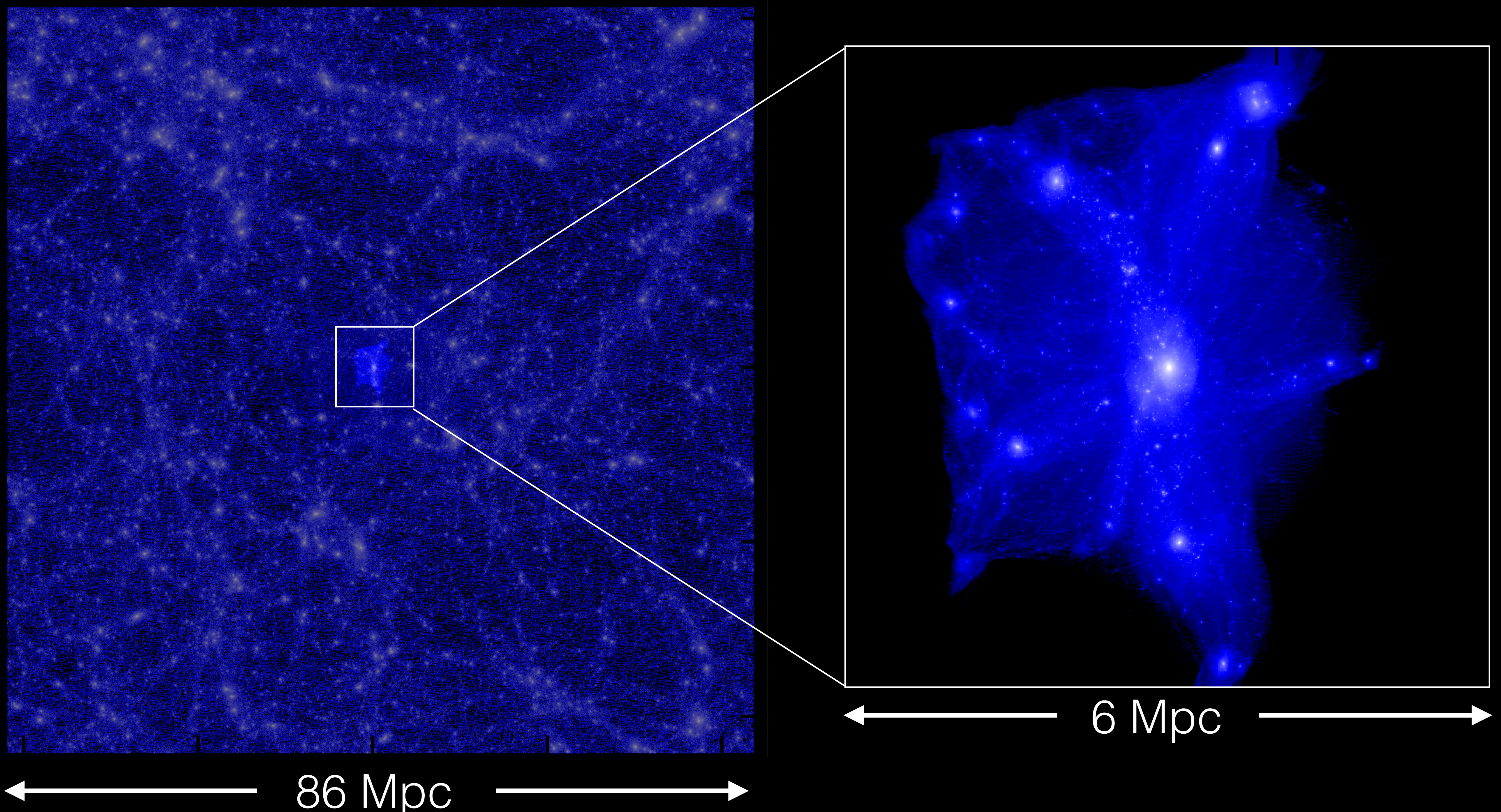
  - Supernovae

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

  - Stellar Winds

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

cosmological zoom-in simulation to achieve ultra-high resolution



top500.org

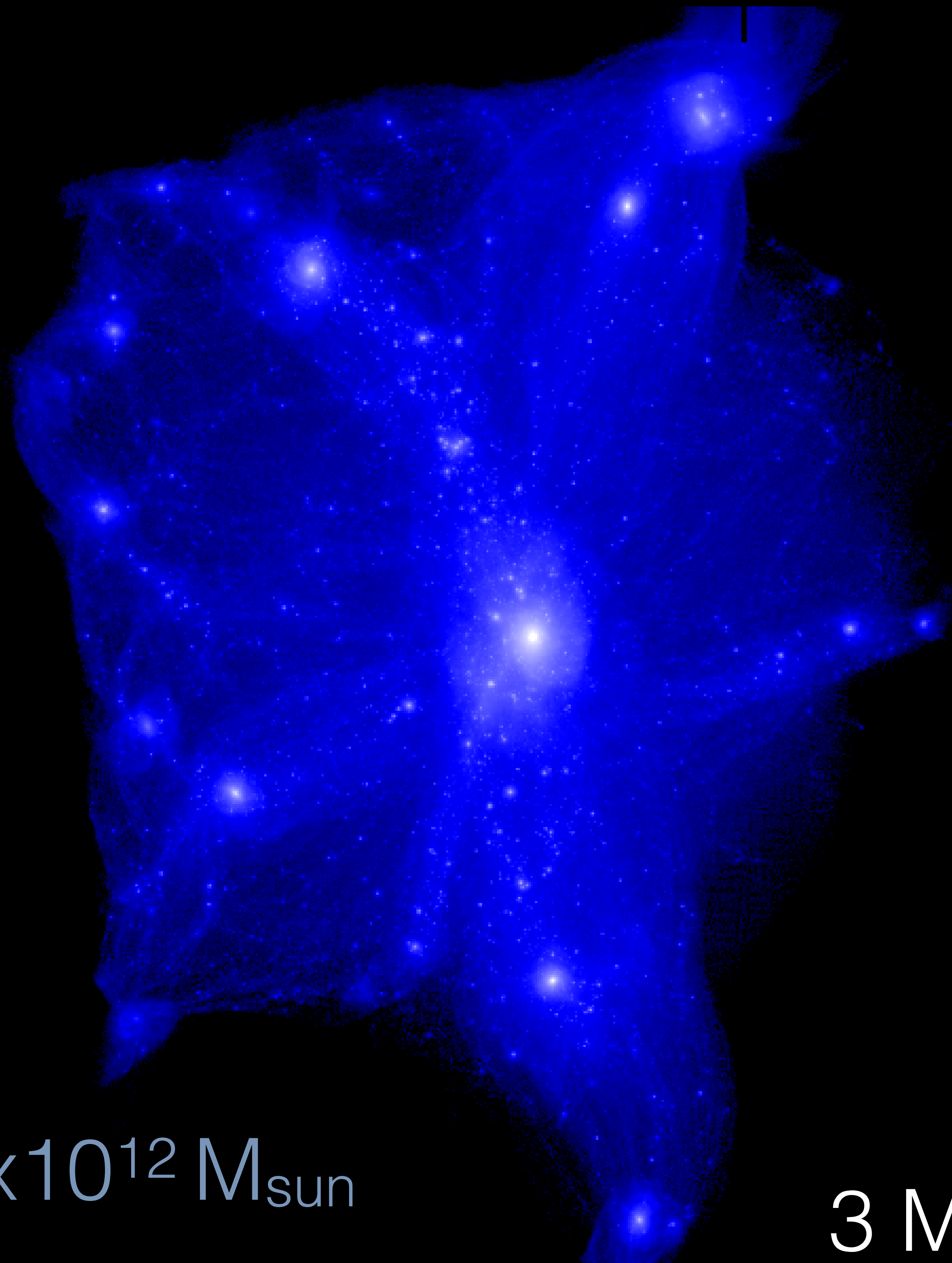
RANK	SITE	SYSTEM	CORES	RMAX (TFLOP/S)	RPEAK (TFLOP/S)	POWER (KW)
1	National Super Computer Center in Guangzhou China	**Tianhe-2 (MilkyWay-2)** - TH-IVB-FEP Cluster, Intel Xeon E5-2692 12C 2.200GHz, TH Express-2, Intel Xeon Phi 31S1P NUDT	3,120,000	33,862.7	54,902.4	17,808
2	DOE/SC/Oak Ridge National Laboratory United States	**Titan** - Cray XK7 , Opteron 6274 16C 2.200GHz, Cray Gemini interconnect, NVIDIA K20x Cray Inc.	560,640	17,590.0	27,112.5	8,209
3	DOE/NNSA/LLNL United States	**Sequoia** - BlueGene/Q, Power BQC 16C 1.60 GHz, Custom IBM	1,572,864	17,173.2	20,132.7	7,890
4	RIKEN Advanced Institute for Computational Science (AICS) Japan	K computer, SPARC64 VIIIfx 2.0GHz, Tofu interconnect Fujitsu	705,024	10,510.0	11,280.4	12,660
5	DOE/SC/Argonne National Laboratory United States	**Mira** - BlueGene/Q, Power BQC 16C 1.60GHz, Custom IBM	786,432	8,586.6	10,066.3	3,945
6	DOE/NNSA/LANL/SNL United States	**Trinity** - Cray XC40, Xeon E5-2698v3 16C 2.3GHz, Aries interconnect Cray Inc.	301,056	8,100.9	11,078.9	
7	Swiss National Supercomputing Centre (CSCS) Switzerland	**Piz Daint** - Cray XC30, Xeon E5-2670 8C 2.600GHz, Aries interconnect , NVIDIA K20x Cray Inc.	115,984	6,271.0	7,788.9	2,325
8	HLRS - Höchstleistungsrechenzentrum Stuttgart Germany	**Hazel Hen** - Cray XC40, Xeon E5-2680v3 12C 2.5GHz, Aries interconnect Cray Inc.	185,088	5,640.2	7,403.5	
9	King Abdullah University of Science and Technology Saudi Arabia	**Shaheen II** - Cray XC40, Xeon E5-2698v3 16C 2.3GHz, Aries interconnect Cray Inc.	196,608	5,537.0	7,235.2	2,834
10	Texas Advanced Computing Center/Univ. of Texas United States	**Stampede** - PowerEdge C8220, Xeon E5-2680 8C 2.700GHz, Infiniband FDR, Intel Xeon Phi SE10P Dell	462,462	5,168.1	8,520.1	4,510
11	Forschungszentrum Juelich (FZJ) Germany	**JUQUEEN** - BlueGene/Q, Power BQC 16C 1.600GHz, Custom Interconnect IBM	458,752	5,008.9	5,872.0	2,301

massively parallel:
2048 cores

wall time:
22 days

CPU time:
1.1 million hours

Latte: cosmological zoom-in simulation

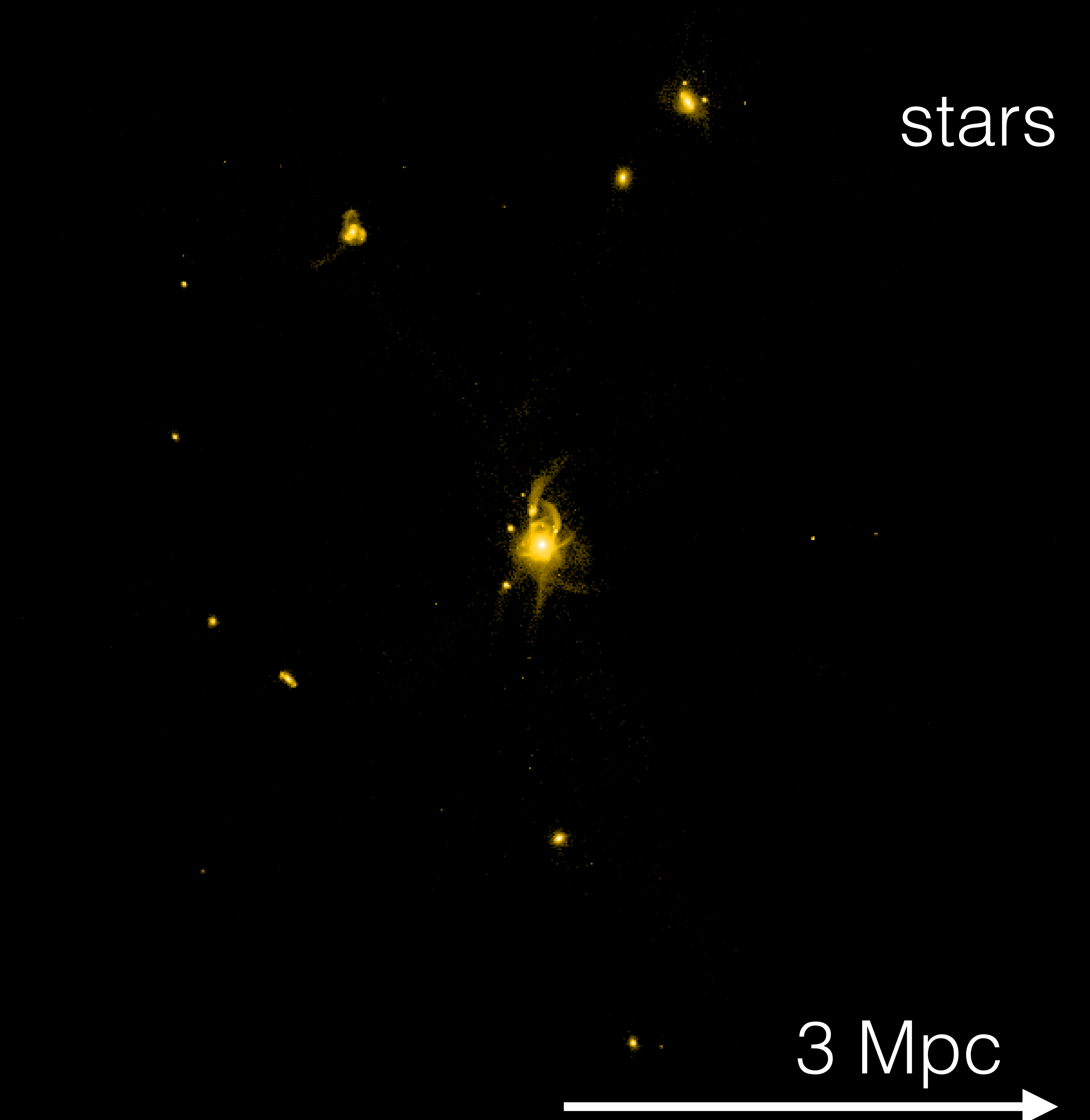


dark matter

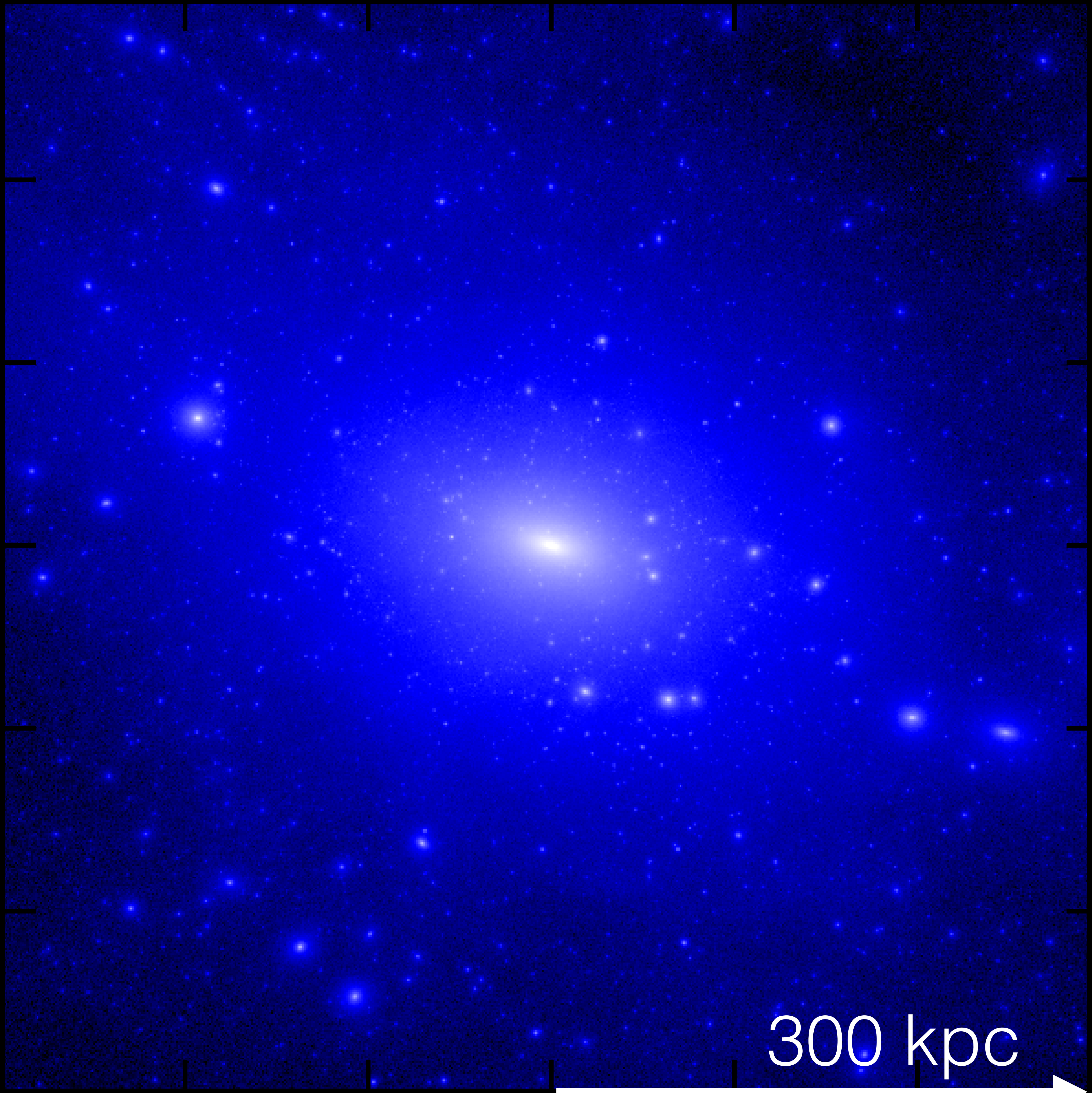
$M_{200m}=1.3x10^{12}\,M_{sun}$

3 Mpc

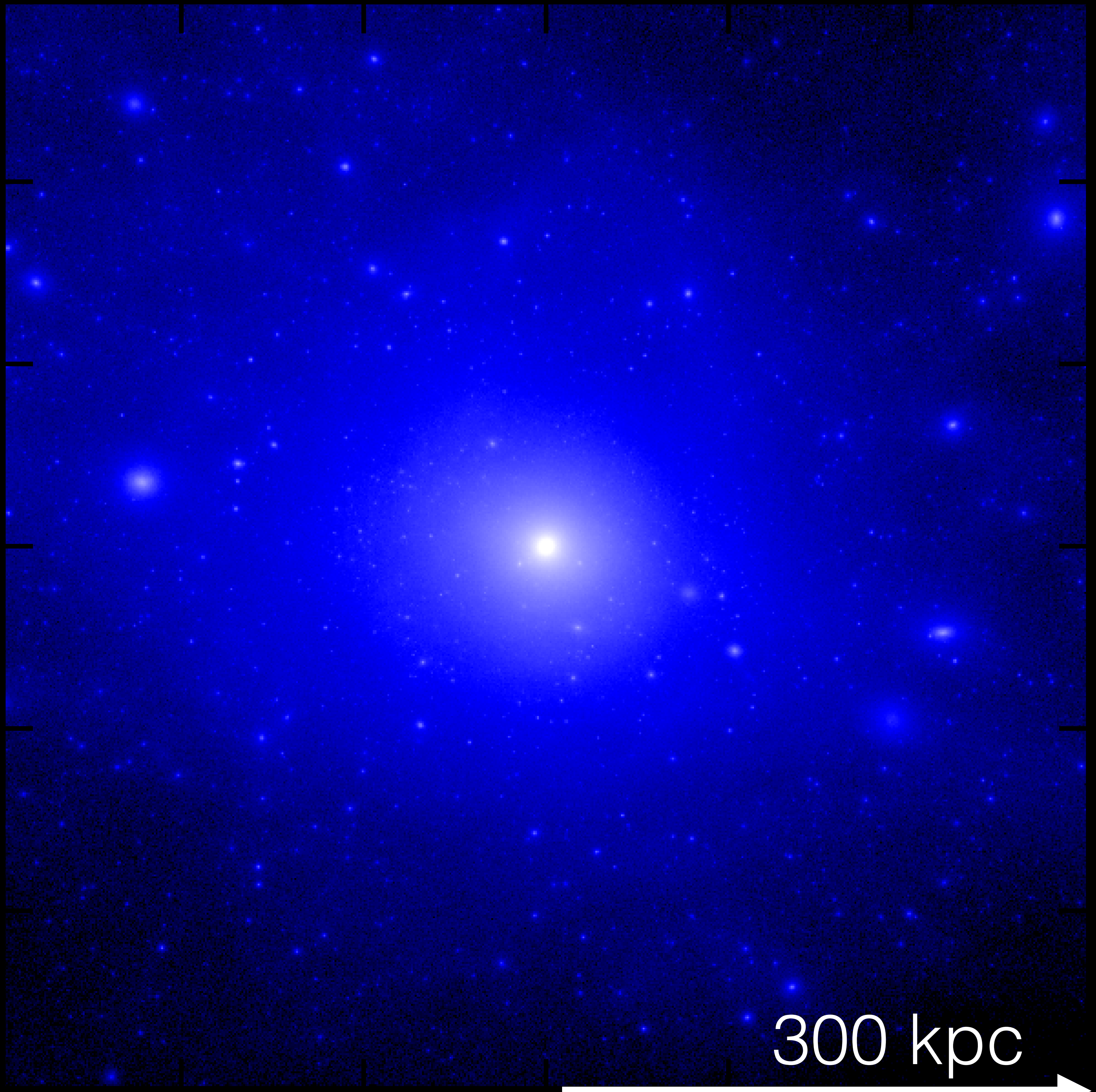
Latte: cosmological zoom-in simulation



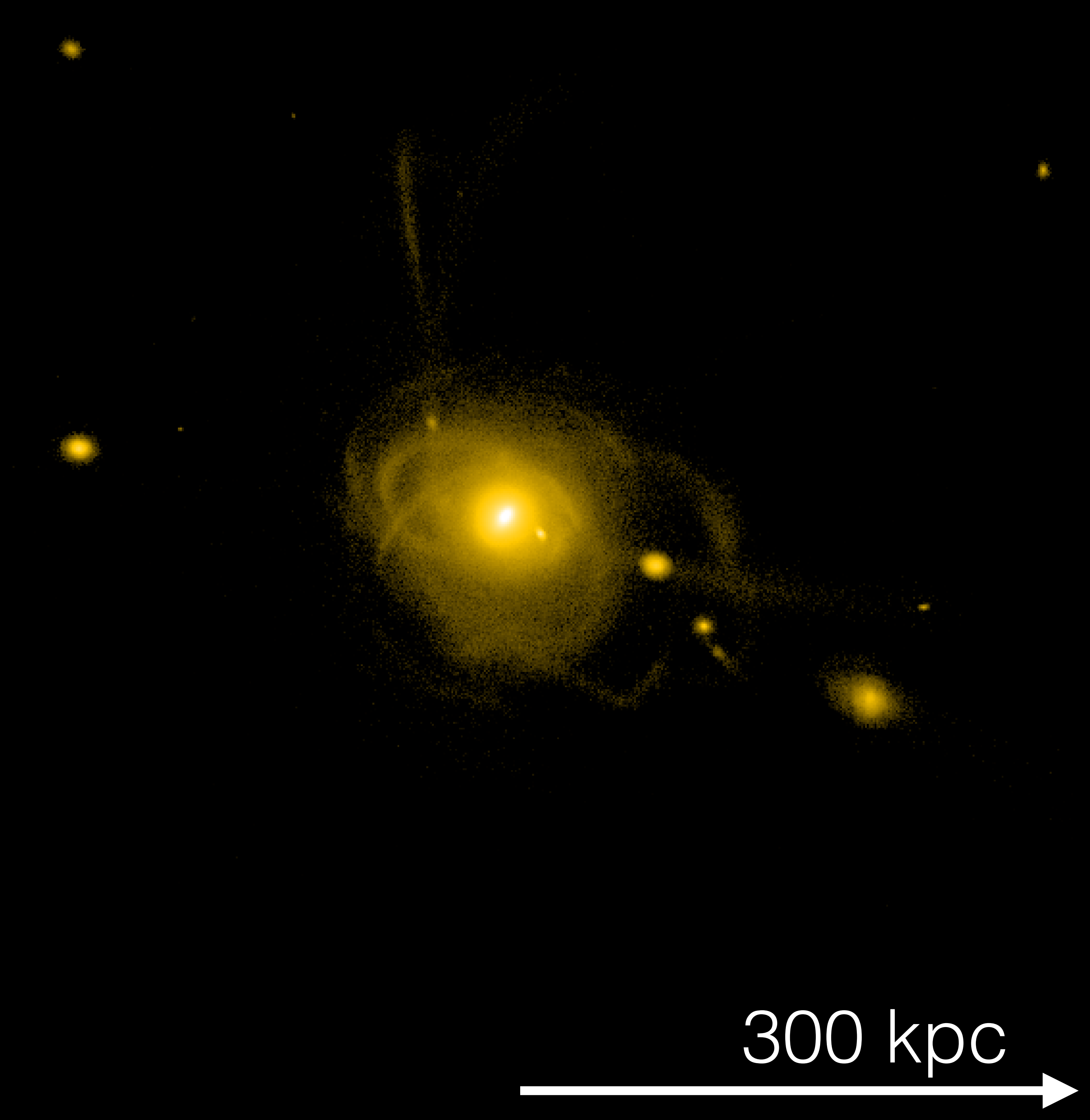
dark matter-only simulation

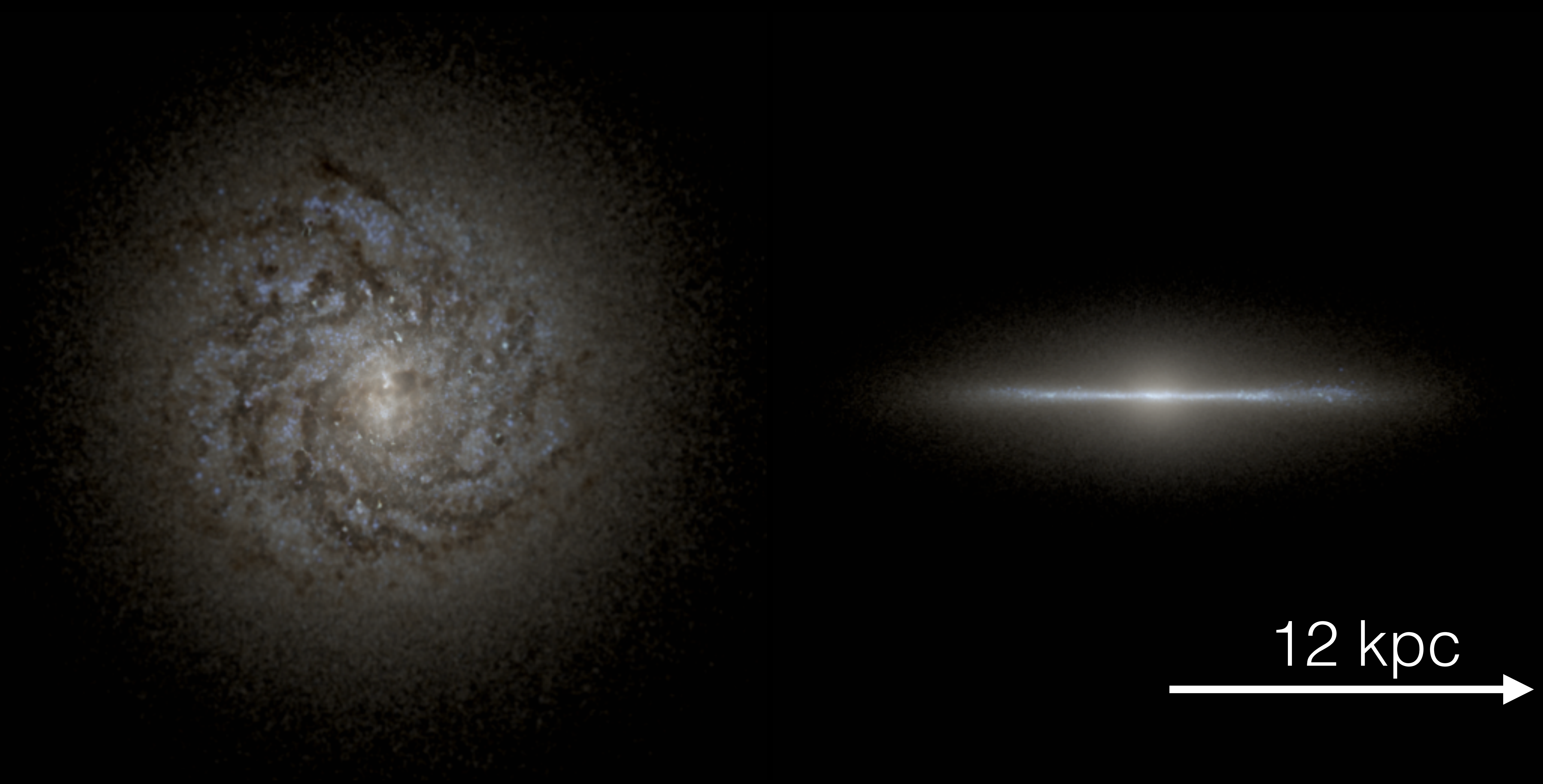


dark matter with effects of baryons



stars





$M_{star} = 9 \times 10^{10}\ M_{sun}$

$SFR = 3.4\ M_{sun}/yr$

The Latte Project: the Milky Way on FIRE

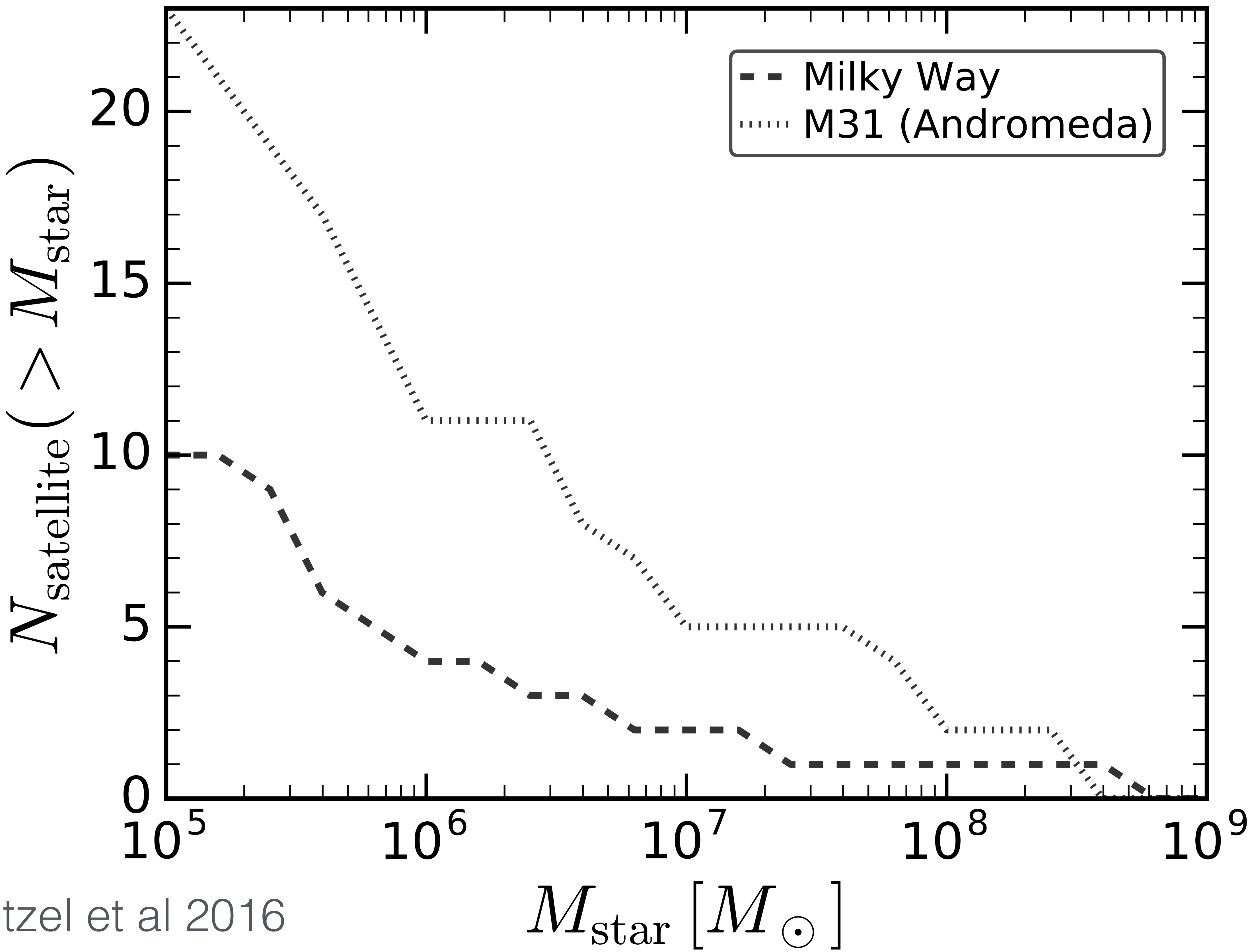
Population of satellite dwarf galaxies

FIRE
Feedback In Realistic Environments

Andrew Wetzel

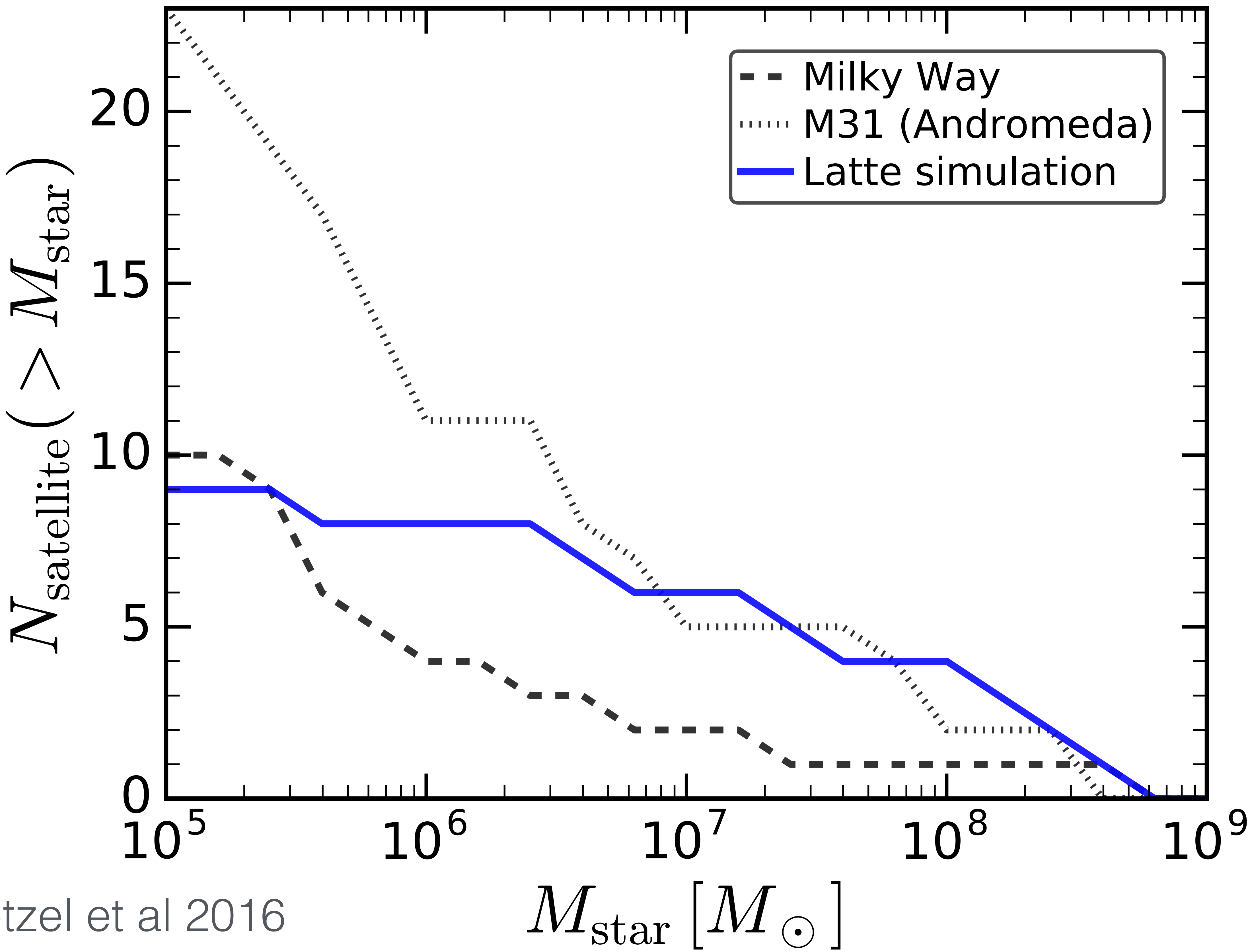
Caltech - Carnegie

stellar mass function of satellites



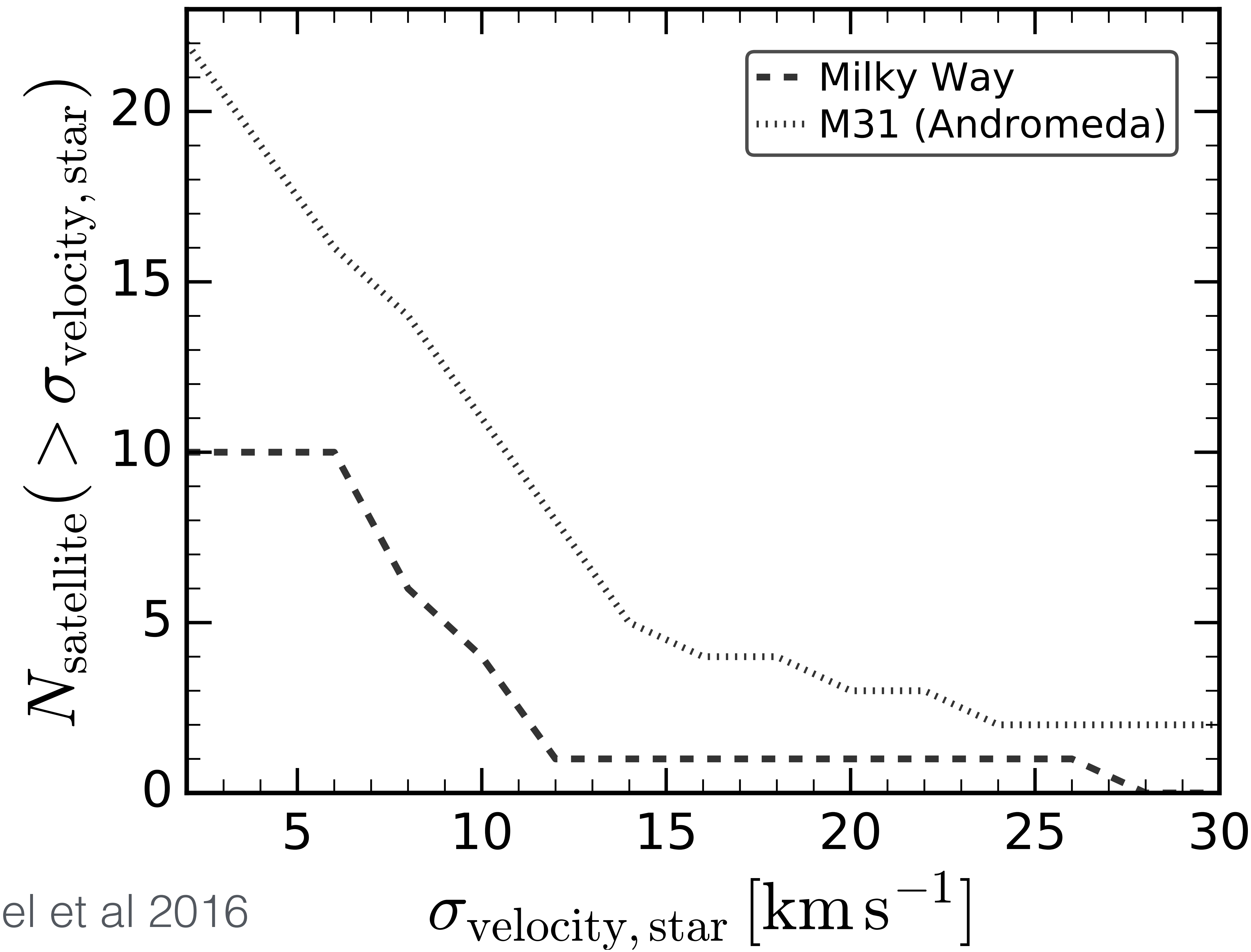
Wetzel et al 2016

stellar mass function of satellites



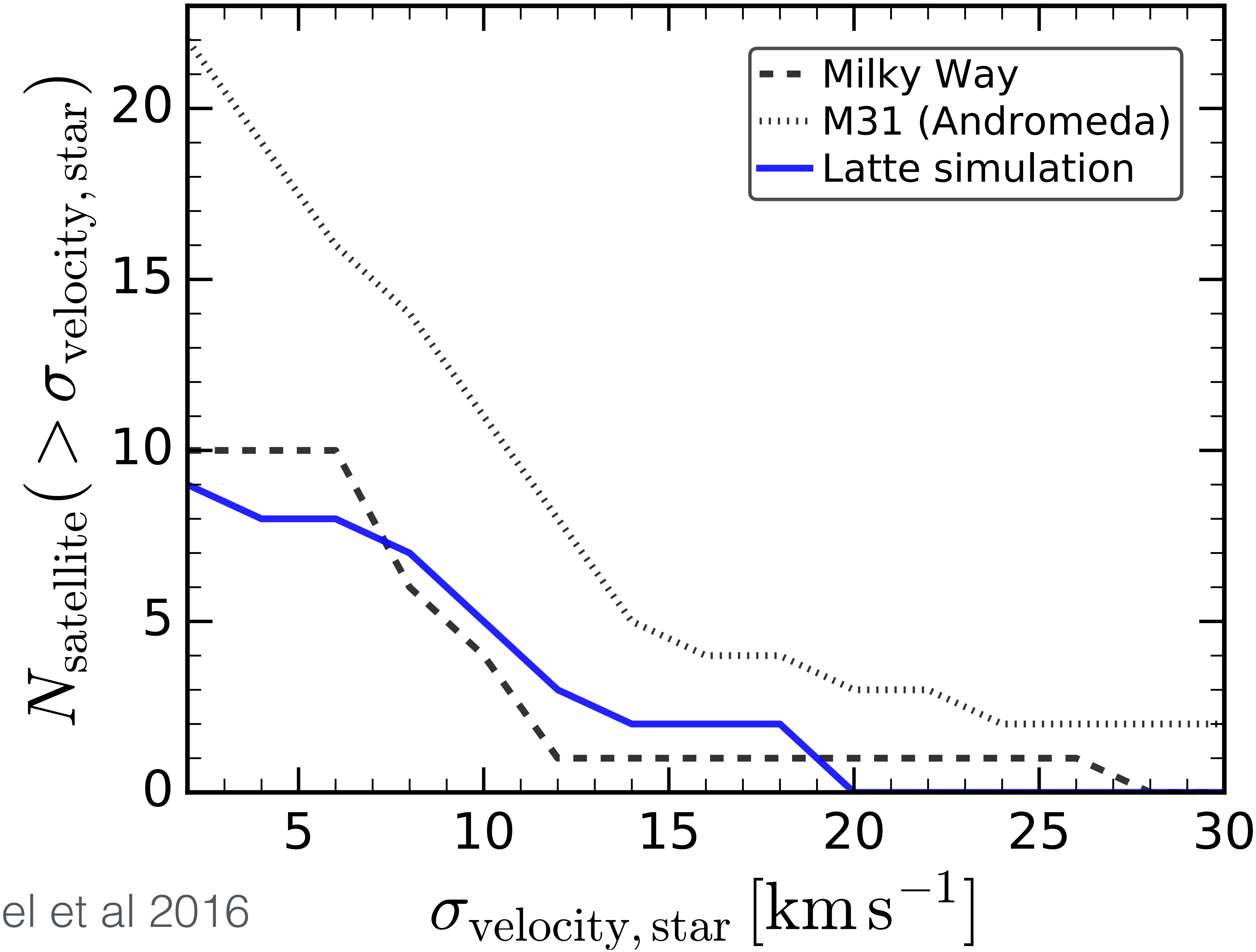
Wetzel et al 2016

stellar velocity dispersion function of satellites



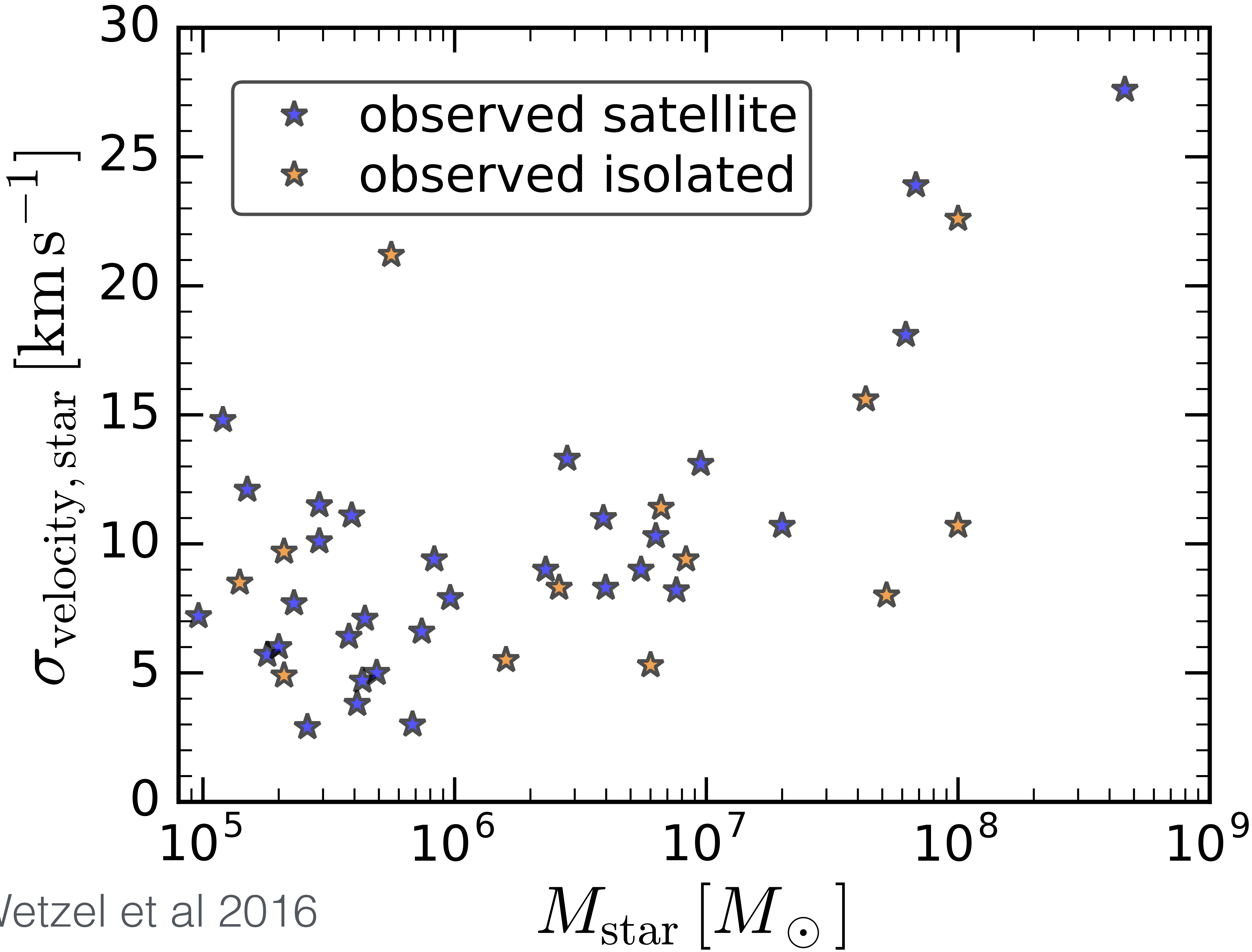
Wetzel et al 2016

stellar velocity dispersion function of satellites



Wetzel et al 2016

velocity dispersion - mass relation



Wetzel et al 2016

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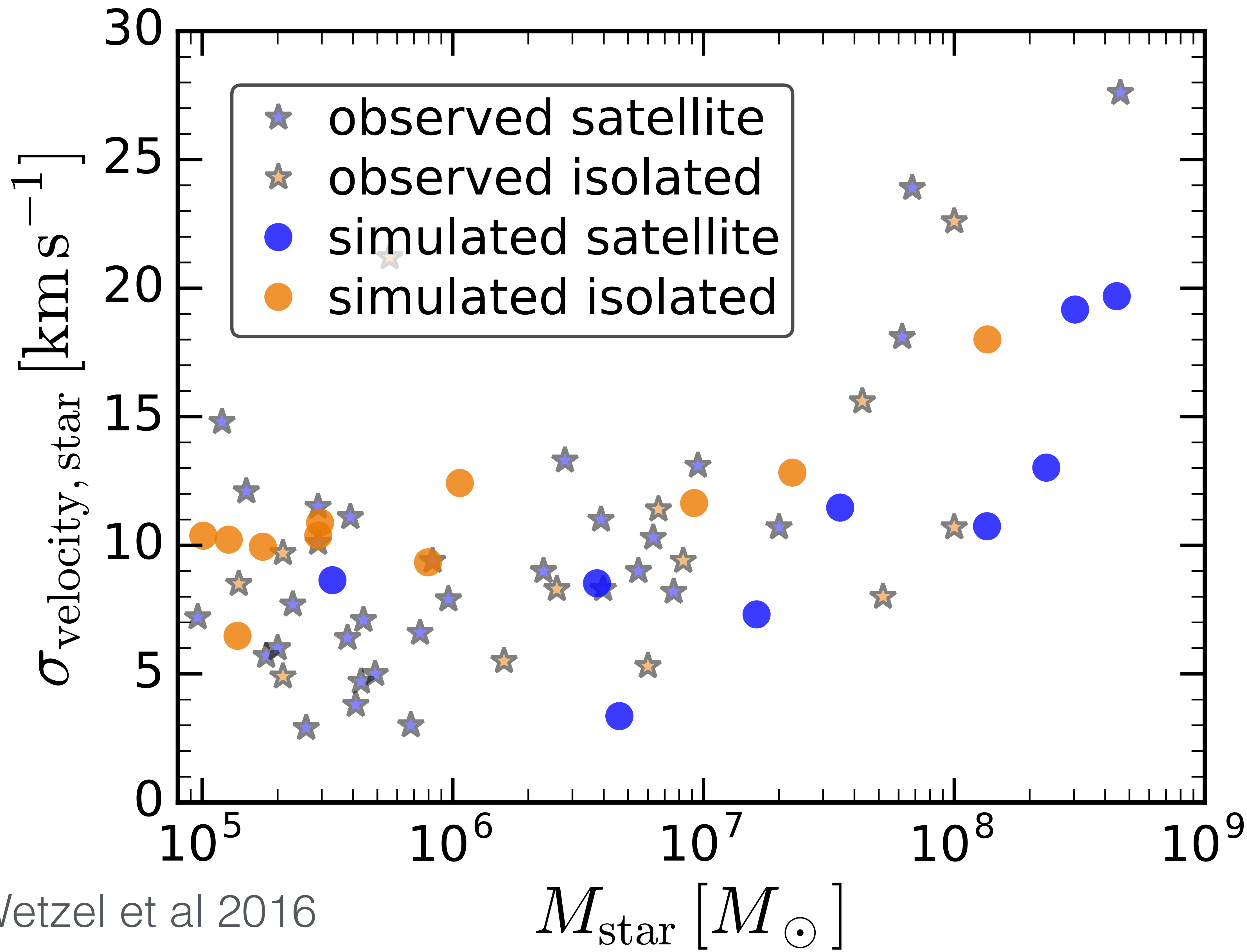
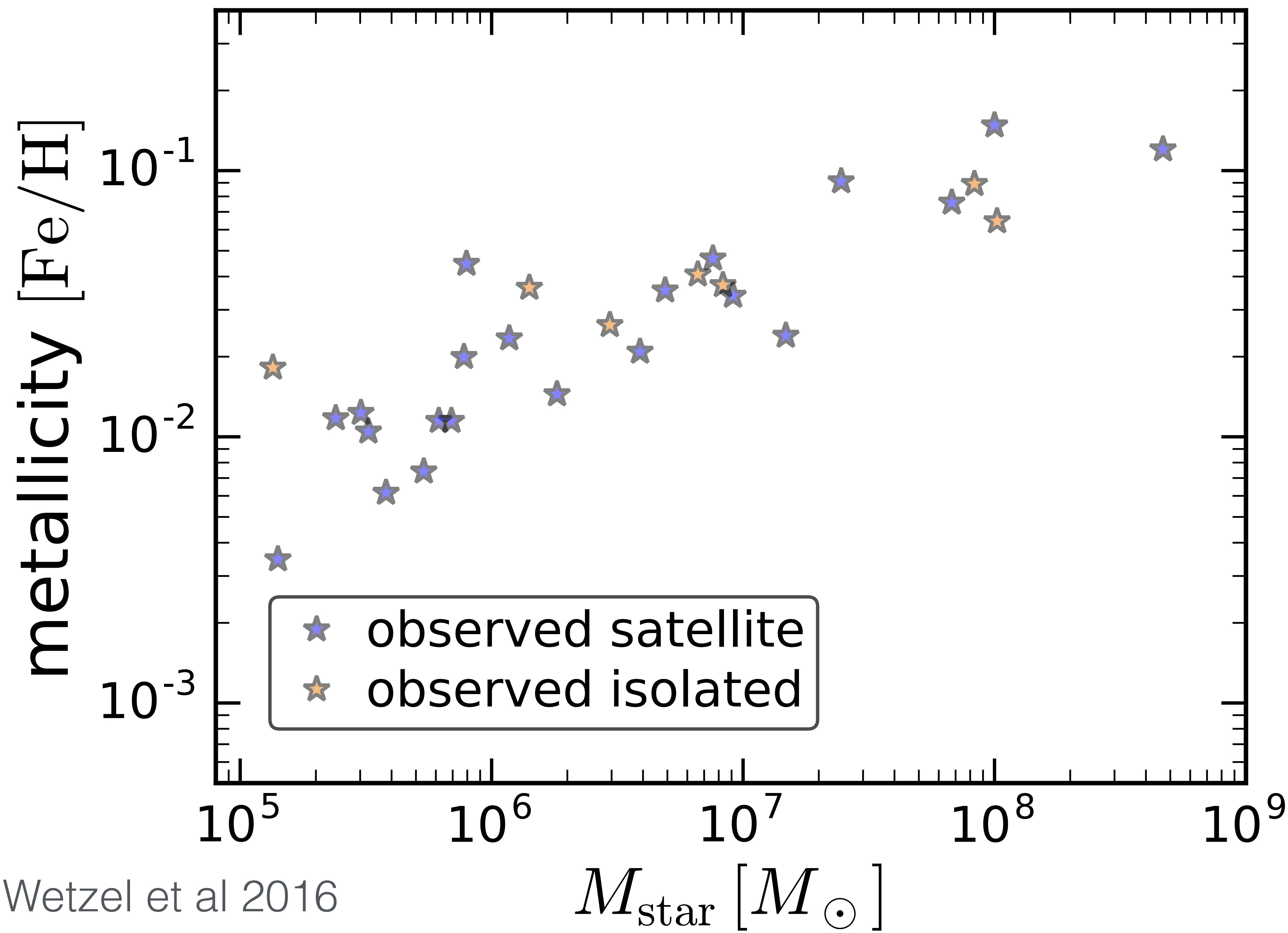


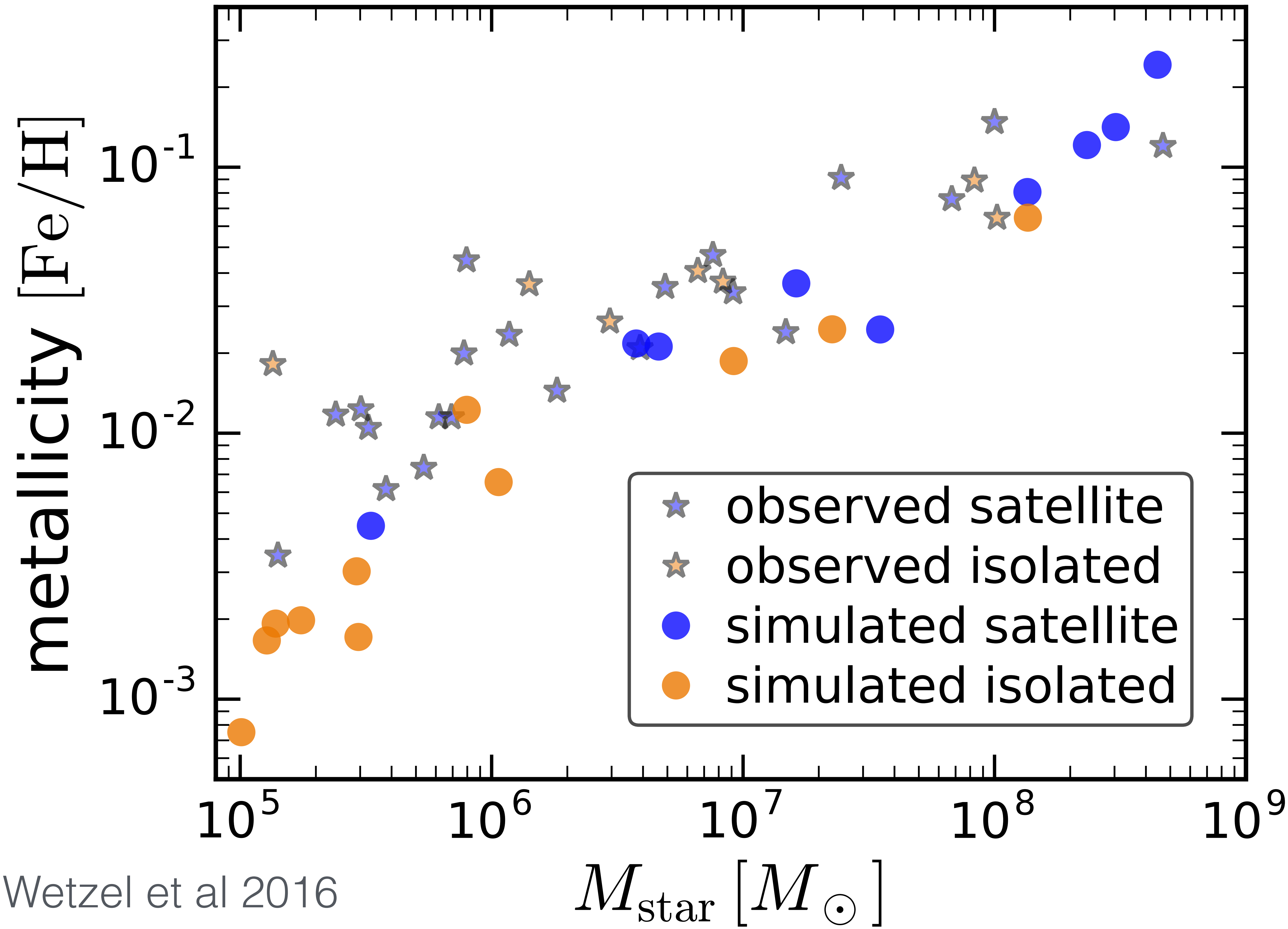
Wetzel et al 2016

mass - metallicity relation



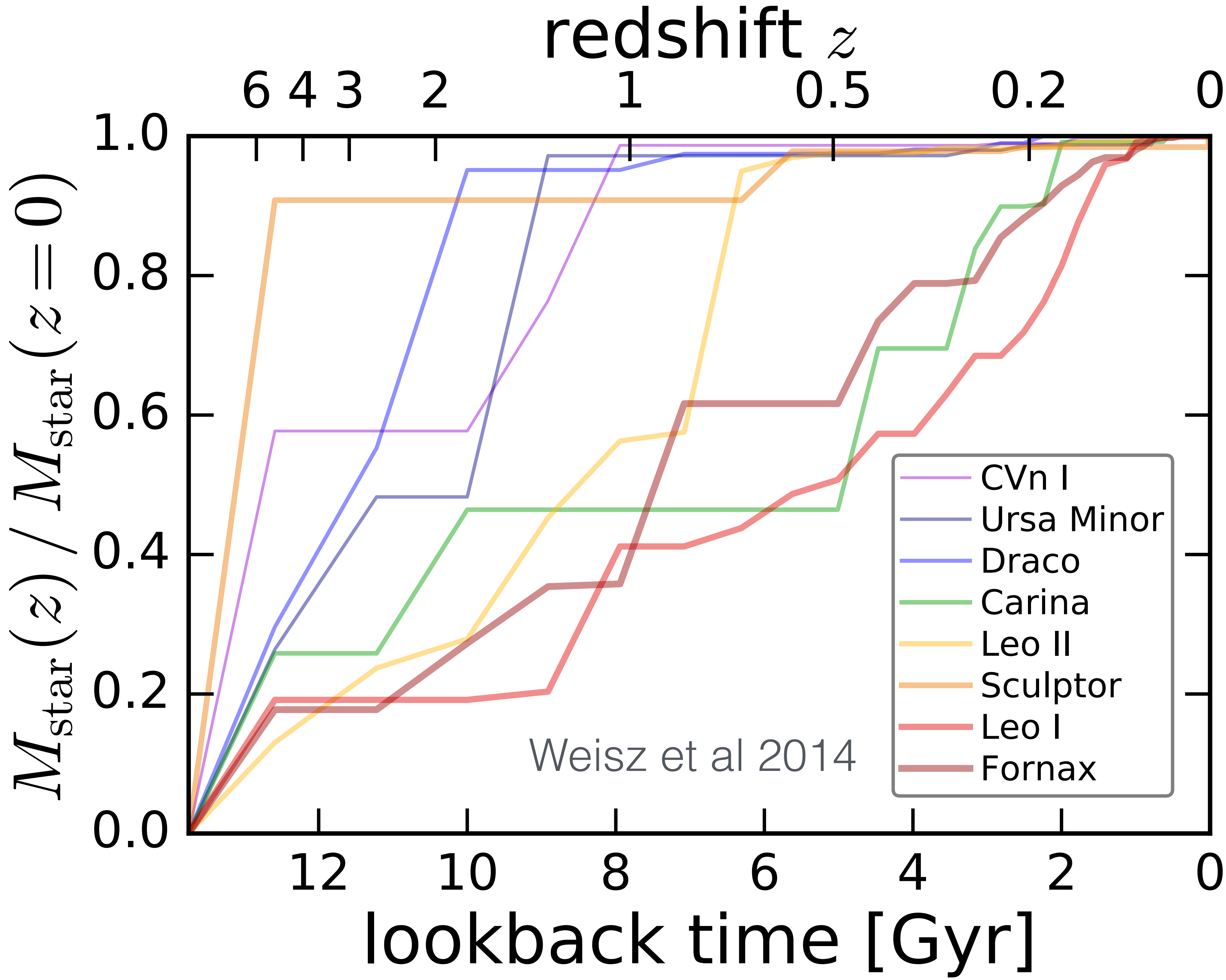
Wetzel et al 2016

mass - metallicity relation

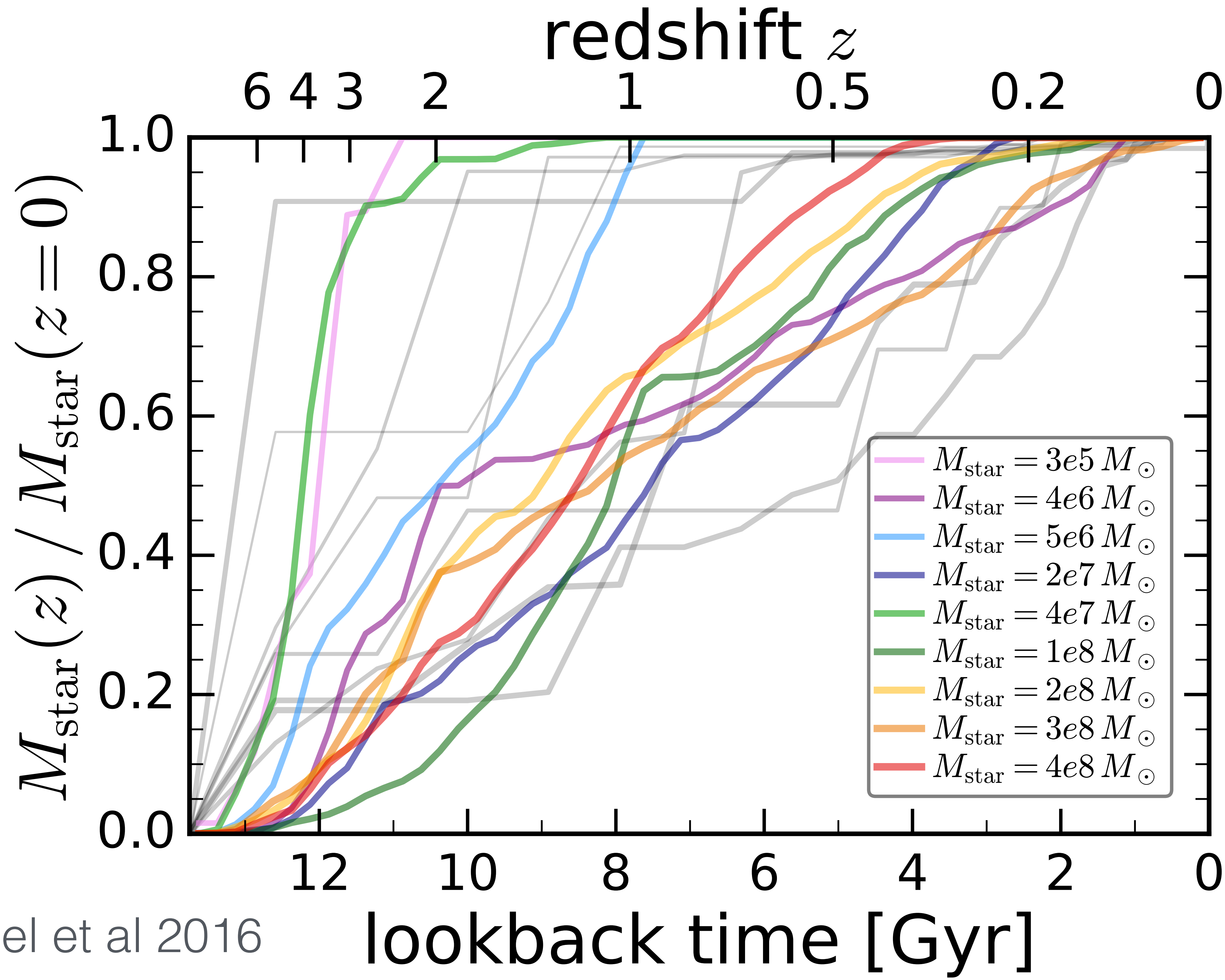


Wetzel et al 2016

diverse range of star-formation histories of satellite dwarf galaxies



diverse range of star-formation histories of satellite dwarf galaxies



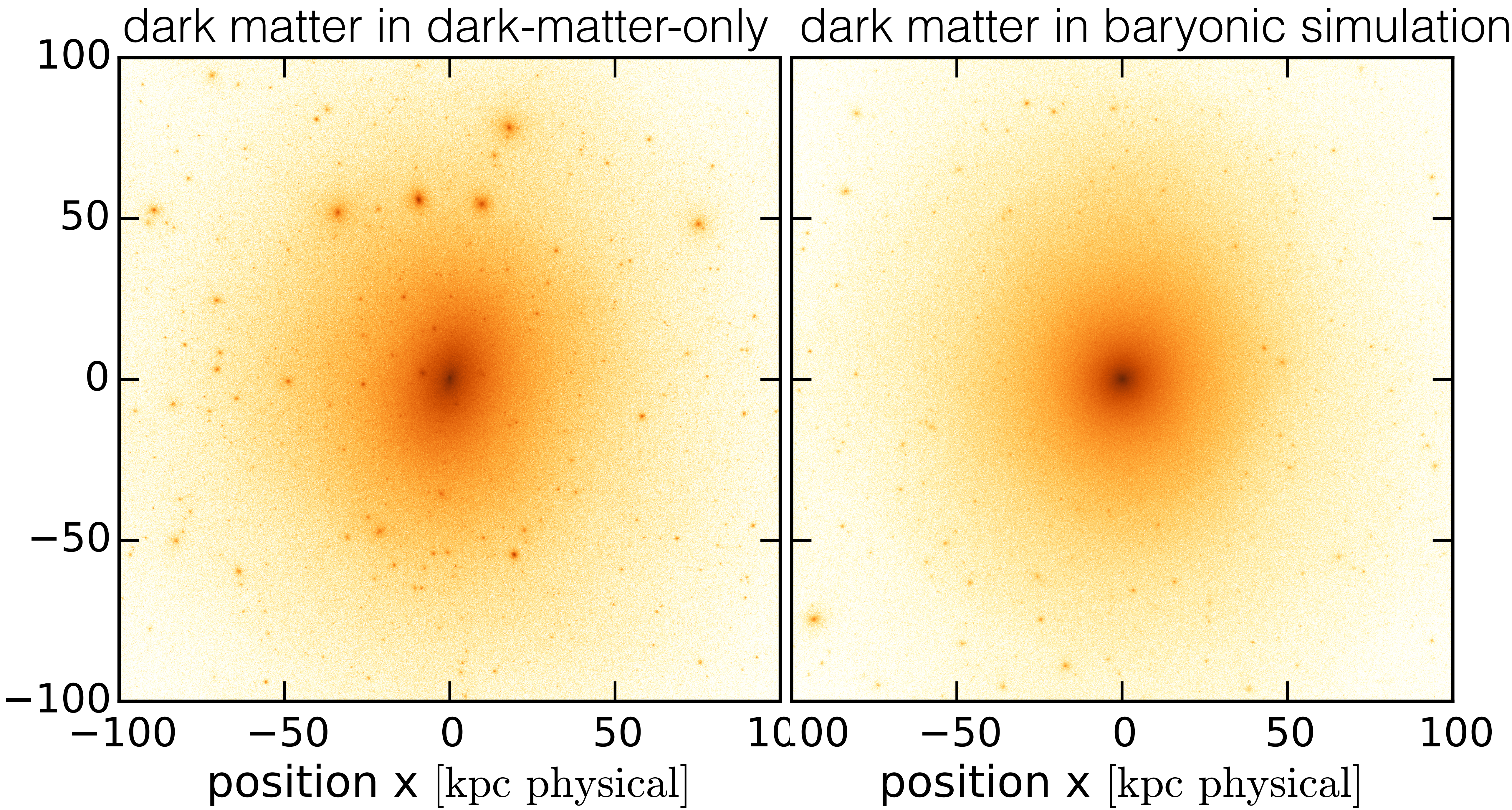
Wetzel et al 2016

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

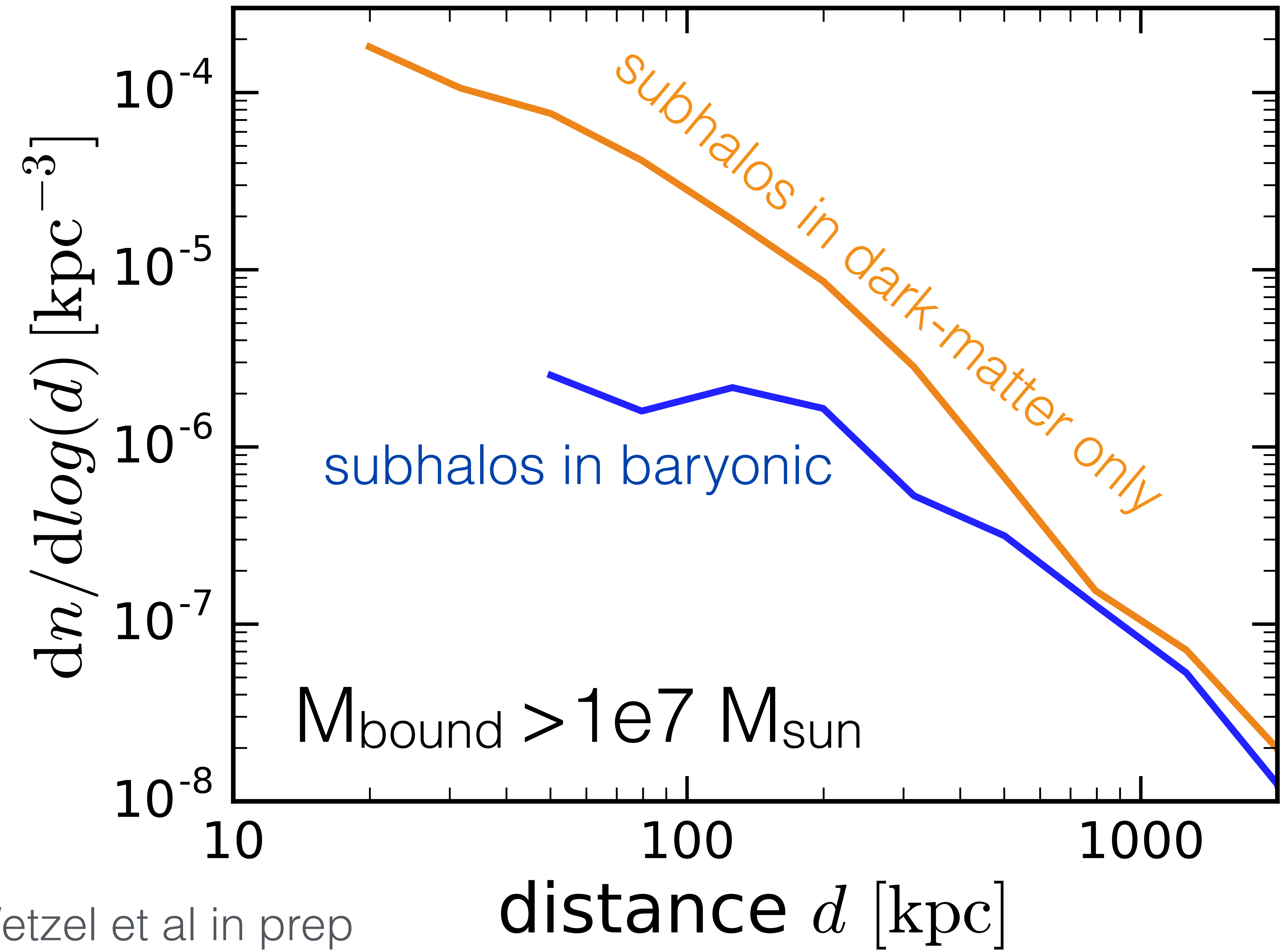
1. Stellar feedback forms dark-matter cores by driving significant gas outflows/inflows that transfer orbital energy to dark matter

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

inclusion of baryons destroys dark-matter subhalos

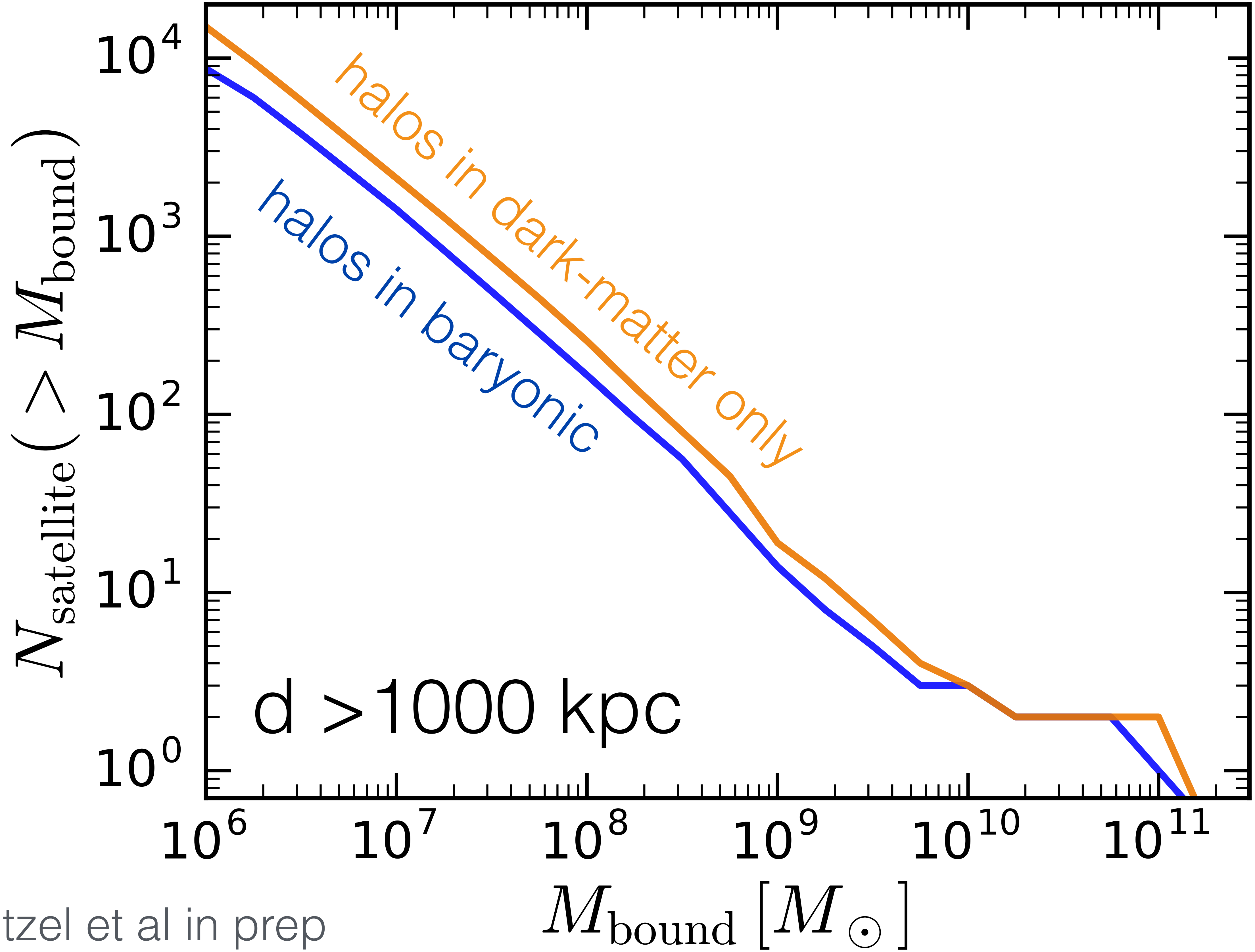


subhalo number density profile



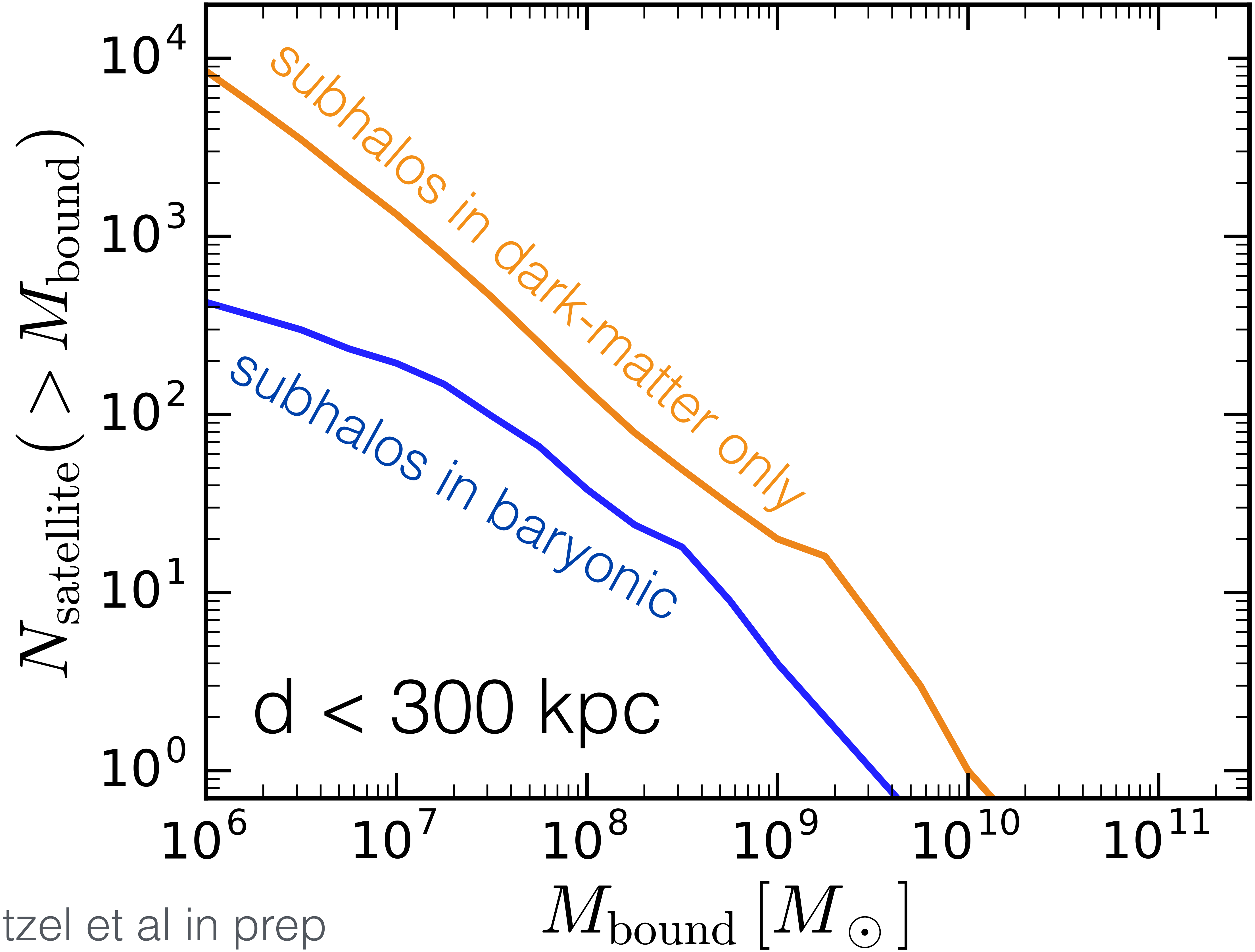
Wetzel et al in prep

dark-matter halo mass function



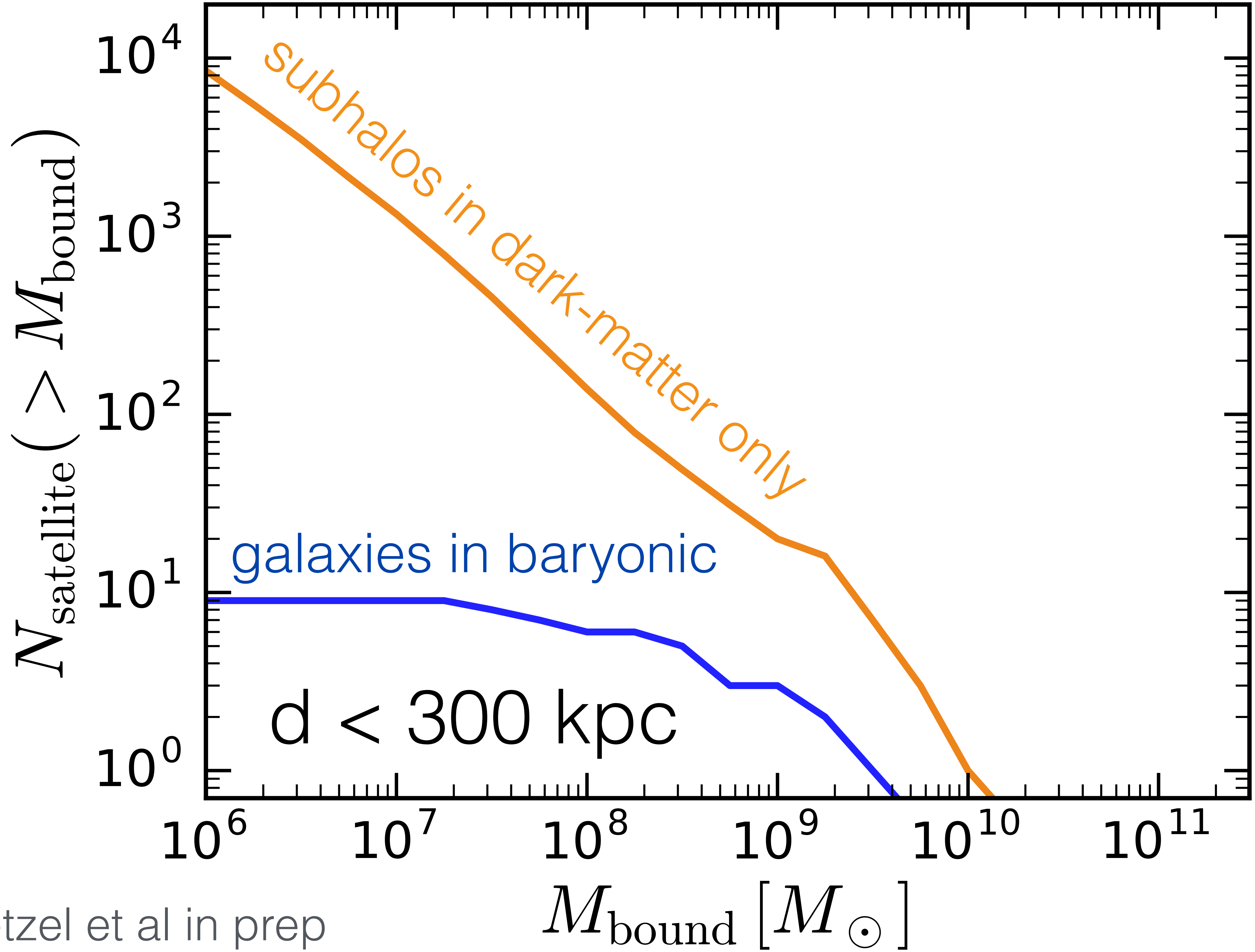
Wetzel et al in prep

dark-matter subhalo mass function



Wetzel et al in prep

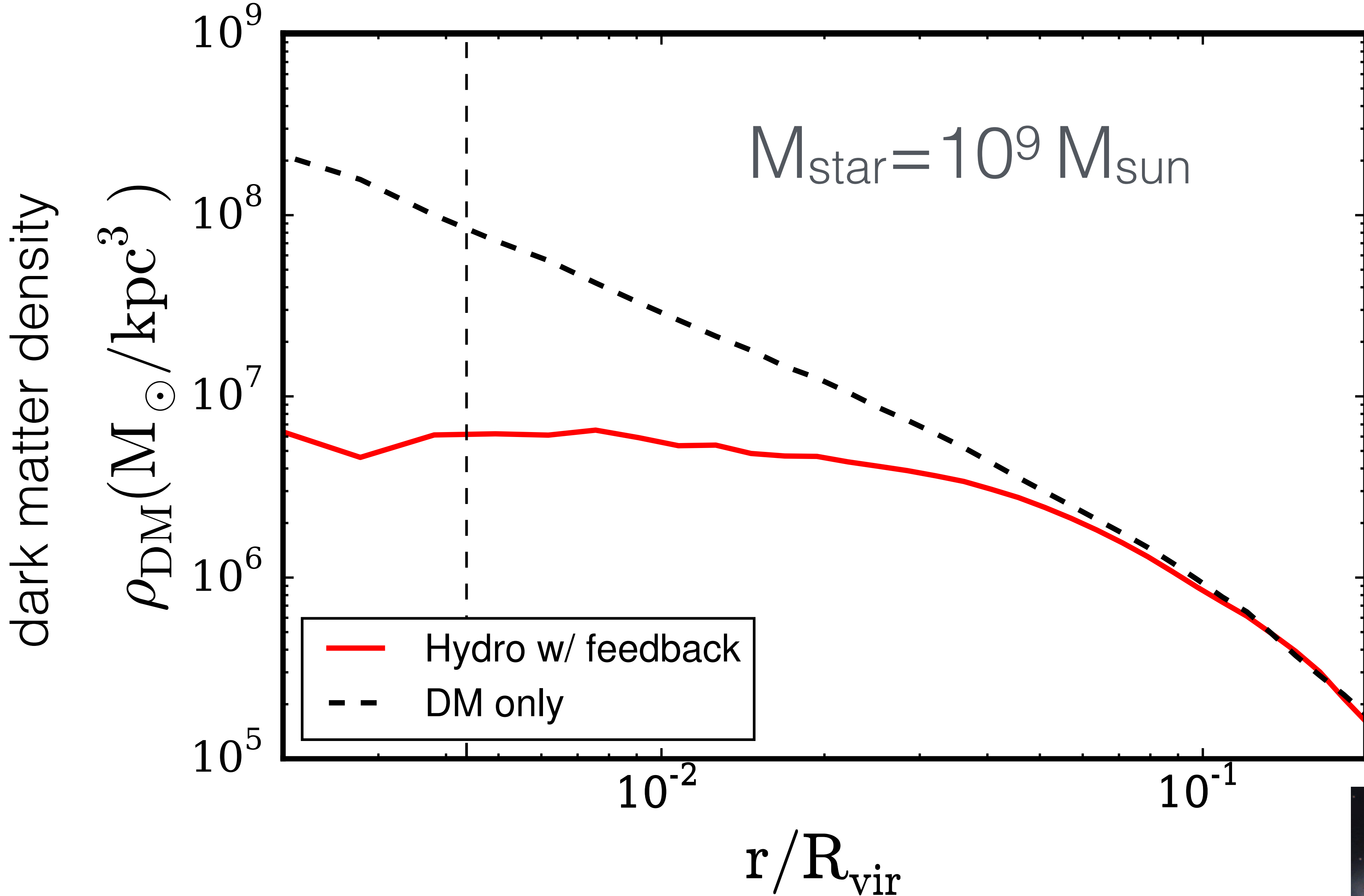
satellite mass function



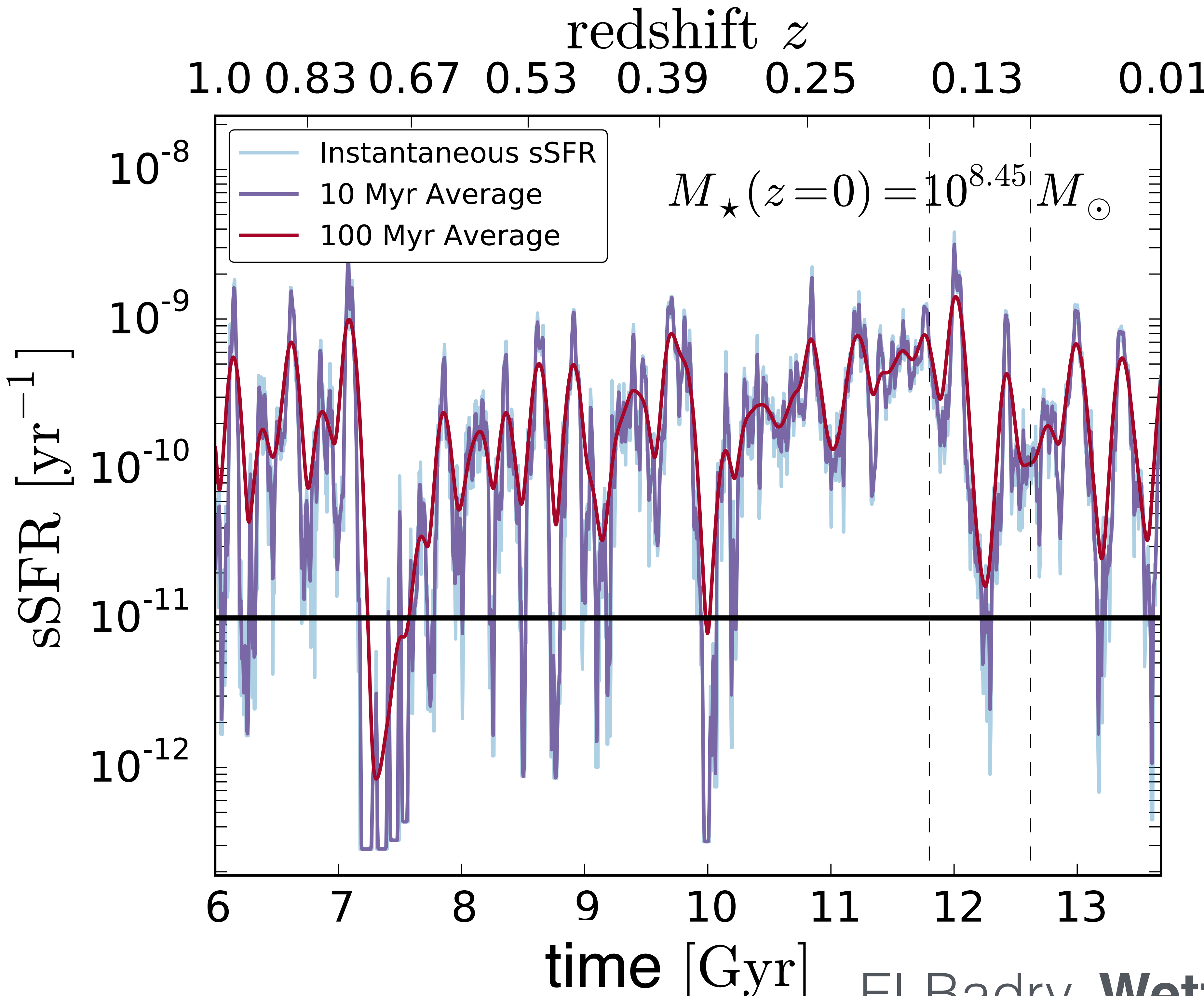
Wetzel et al in prep

stellar feedback can produce dark-matter cores in isolated dwarf galaxies

Chan et al 2015



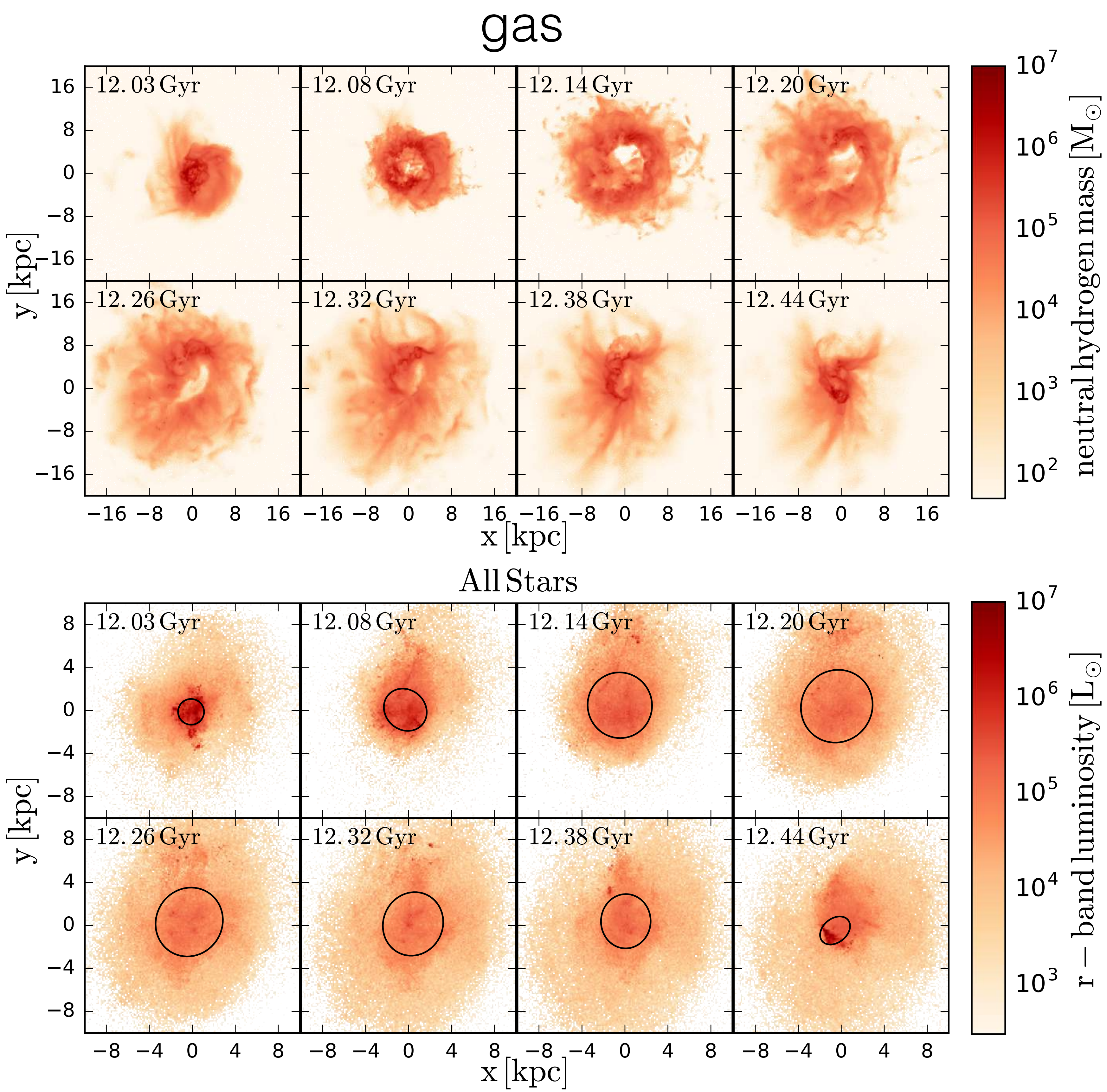
simulated dwarf galaxies have bursty star formation



El-Badry, **Wetzel** et al 2015

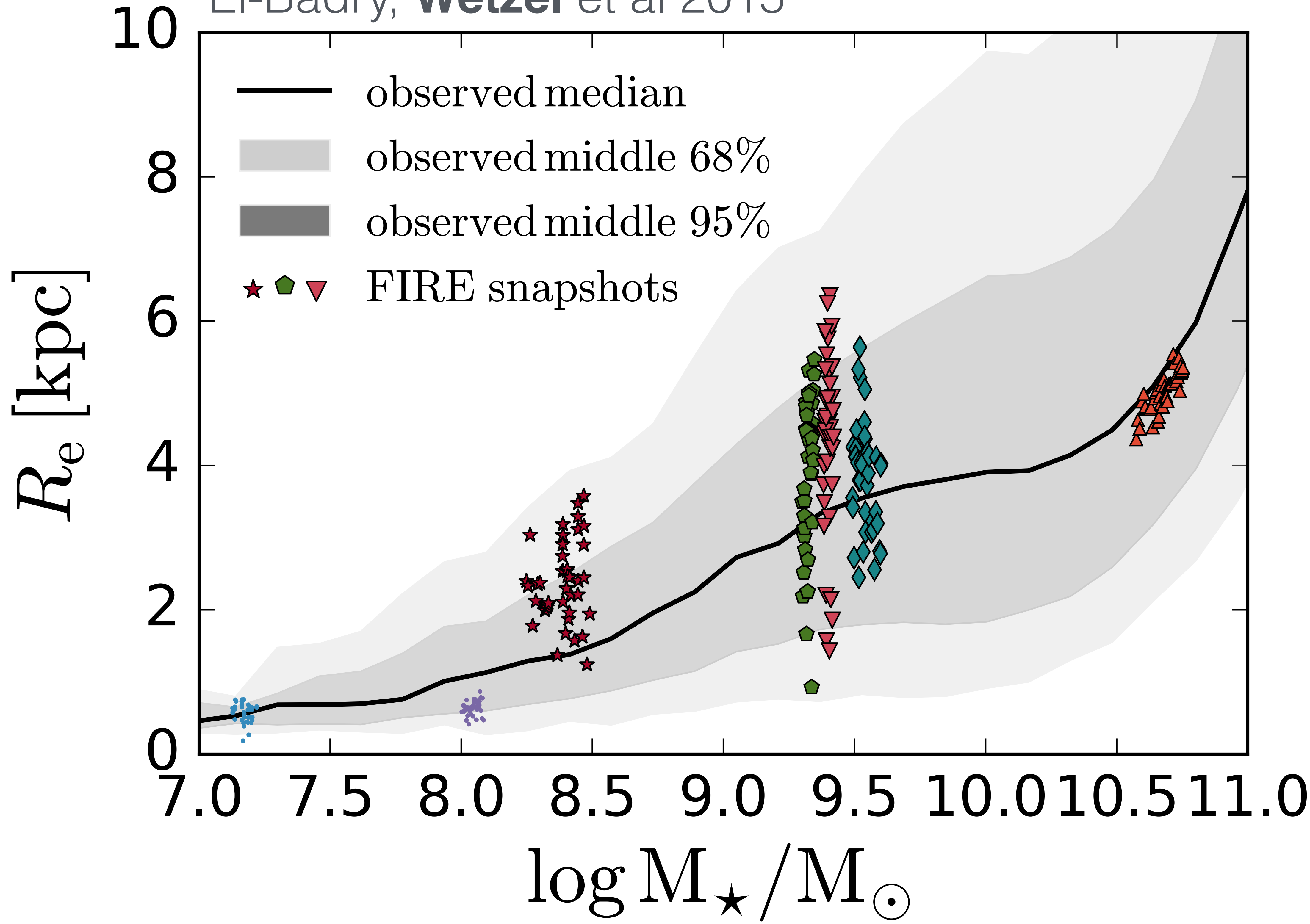
feedback-driven gas outflows in dwarf galaxies

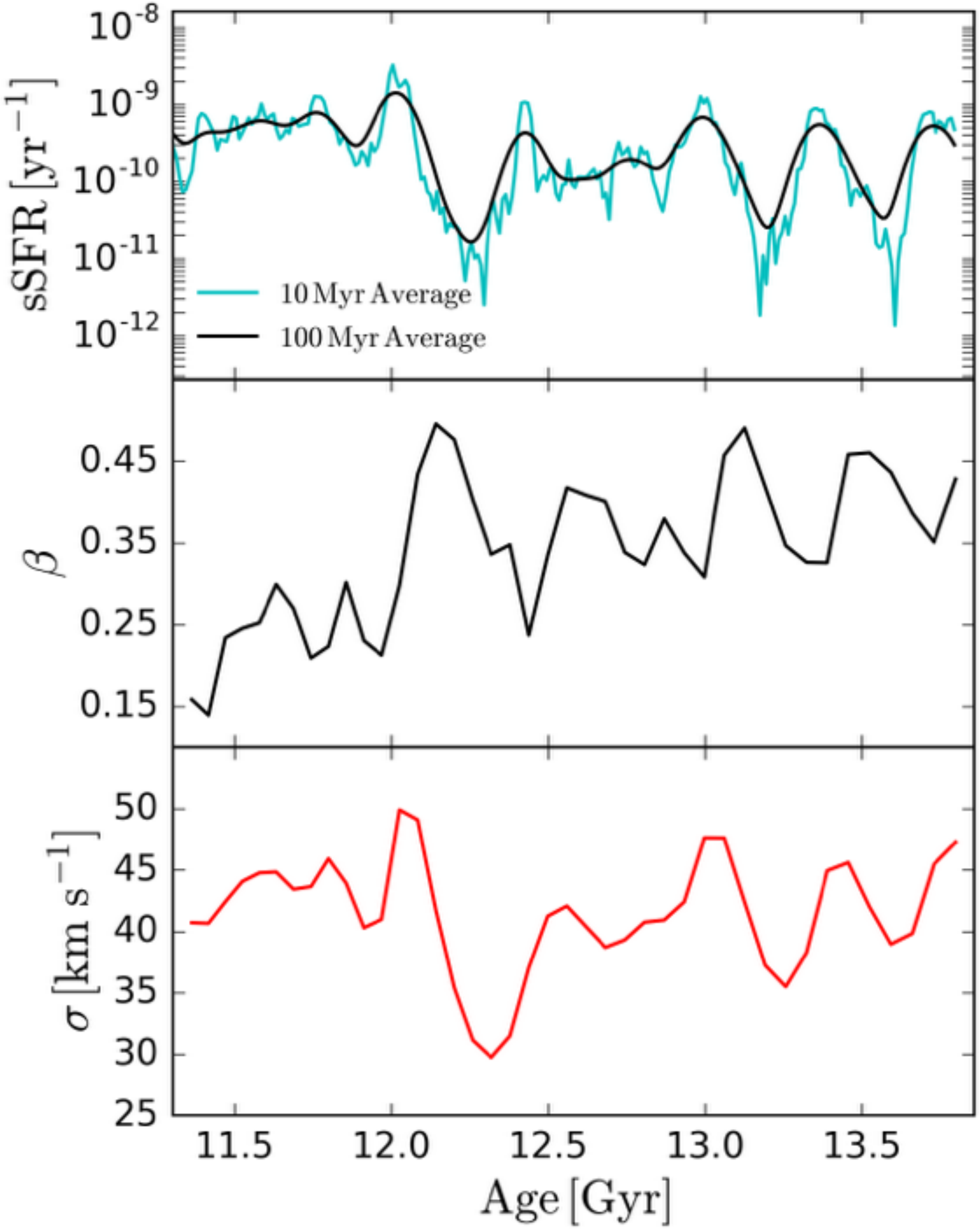
El-Badry, **Wetzel** et al 2015



fluctuations in galaxy radius at fixed M_{star}

El-Badry, **Wetzel** et al 2015





stellar feedback drives orbital anisotropy and dispersion

detailed stellar kinematics in nearby dwarf galaxies will provide **robust** tests of feedback models and the origin of dark-matter cores

A Modest Proposal

~~"LCDM predicts…"~~
~~(dark energy + cold dark matter)~~

"LCDMB predicts…"
(dark energy + cold dark matter + baryons)

The Latte Project: the Milky Way on FIRE

FIRE
Feedback In Realistic Environments