cosmological baryonic simulations

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TAKE-AWAY MESSAGE

‘ΛCDM (ΛSIDM) predicts…’

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perspective on baryons + dark matter

- we cannot convince ourselves that an alternative DM model is viable/preferred unless we do so in the context of baryonic effects
- the last few decades have taught us that the effect of baryons on small scales is important - (nearly) all tensions that have arisen have plausible explanations via baryonic effects
- **assertion**: anyone working on DM models in galaxies should spend at least ~half of their time thinking about baryonic physics (that can cause similar effects)

caveats and scope for this talk

- cosmological baryonic simulations is an insanely broad topic
- I will not discuss too much implementations of SIDM in such simulations (see many other talks during this workshop)
- I will focus on the effects of **baryons** to help contextualize the effects of SIDM
- I will focus on low-mass (faint) galaxies, and subhalos around MW-mass galaxies, in cosmological zoom-in simulations
- I will be fairly opinionated and selective of what to discuss
    - So I encourage you to interrupt and disagree with me!

a note on terminology

- I refer to these as '**baryonic**' rather than '**hydrodynamic**' simulations
- While they do accurately model hydrodynamics, there is **so much more** to these simulations than hydrodynamics
- Almost all of the ongoing work/development/debate regarding such simulations focuses on star formation and feedback

cosmological baryonic simulations

why bother?

- **expensive**: millions of core-hours on supercomputer
    - ~100x more expensive than DM-only
- requires complex, multi-physics, parallel codes, large collaborations, often using someone else's 'established' code
- difficult to explore parameter space
- 'we do not understand anything about stellar feedback!'
- 'all the relevant physics is sub-grid (unresolved)!'
- 'different codes give completely different predictions!'

advantages of cosmological baryonic simulations

- **self-consistently** model all/most key physical processes at play (cosmology, dark matter, hydrodynamics, star formation, stellar evolution, stellar feedback)
- as a result, can compare directly with observables in gas or stars (especially via synthetic observations)

what goes into a baryonic simulation?

one of my big worries about our field is that (cosmological) simulations have become sufficiently complex and multi-physics that everyone outside of the simulation community (and even some folks within it) treats them as ‘black boxes’, with only superficial understanding of what goes into them

what goes into a baryonic simulation?

- gravity
- dark matter model: CDM, SIDM, fuzzy, atomic, etc
- (magneto)hydrodynamics
  - details secondary to uncertainties in stars + feedback, especially for low-mass galaxies
- gas cooling: ISM model
  - two types of approaches
    - impose smooth ISM (Illustris, Auriga, EAGLE, APOSTLE)
    - allow cold/dense multi-phase ISM (FIRE, NIHAO, Gasoline/ChaNGa, EDGE, Vintergatan, SMUGGLE)

what goes into a baryonic simulation?

- star formation
- stellar evolution + feedback
  - input: get models from stellar community
  - implementation
    - which feedback process to include
    - method of coupling to gas
      - example: injection of thermal energy v momentum
- black holes + AGN

stellar feedback: it's not a single thing!

supernovae

- **core-collape (prompt)**
- white-dwarf (type Ia) (delayed)

stellar radiation

- radiation pressure
- photoionization heating (HII regions)
- photoelectric heating (via dust)

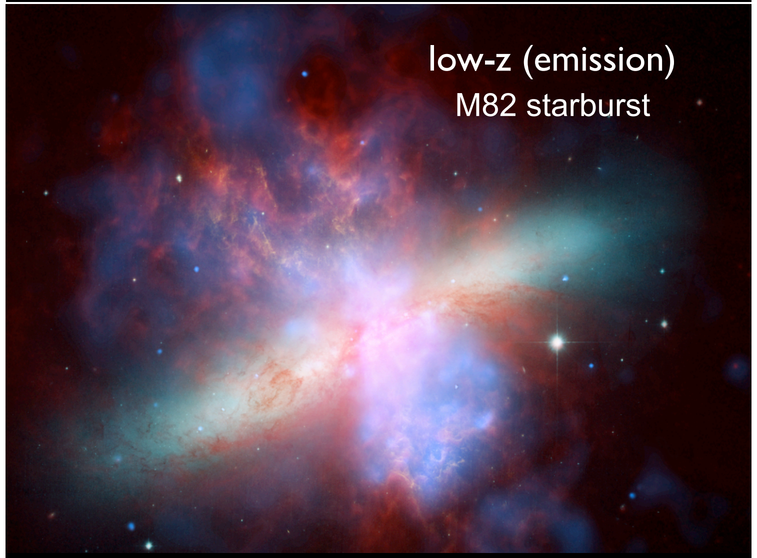
stellar winds

- massive O & B stars (prompt)
- AGB stars (delayed)

cosmic rays (recent development)

- supernovae, AGN

stellar scale



galaxy scale

possibly counterintuitive result

- including more feedback processes generally leads to less ‘violent’ feedback, with smoother (less bursty) star formation
- core-collapse (prompt) supernovae have maximal temporal/spatial coherence —> bursty feedback
- most other feedback processes occur over longer timescales and with less thermal heating of gas

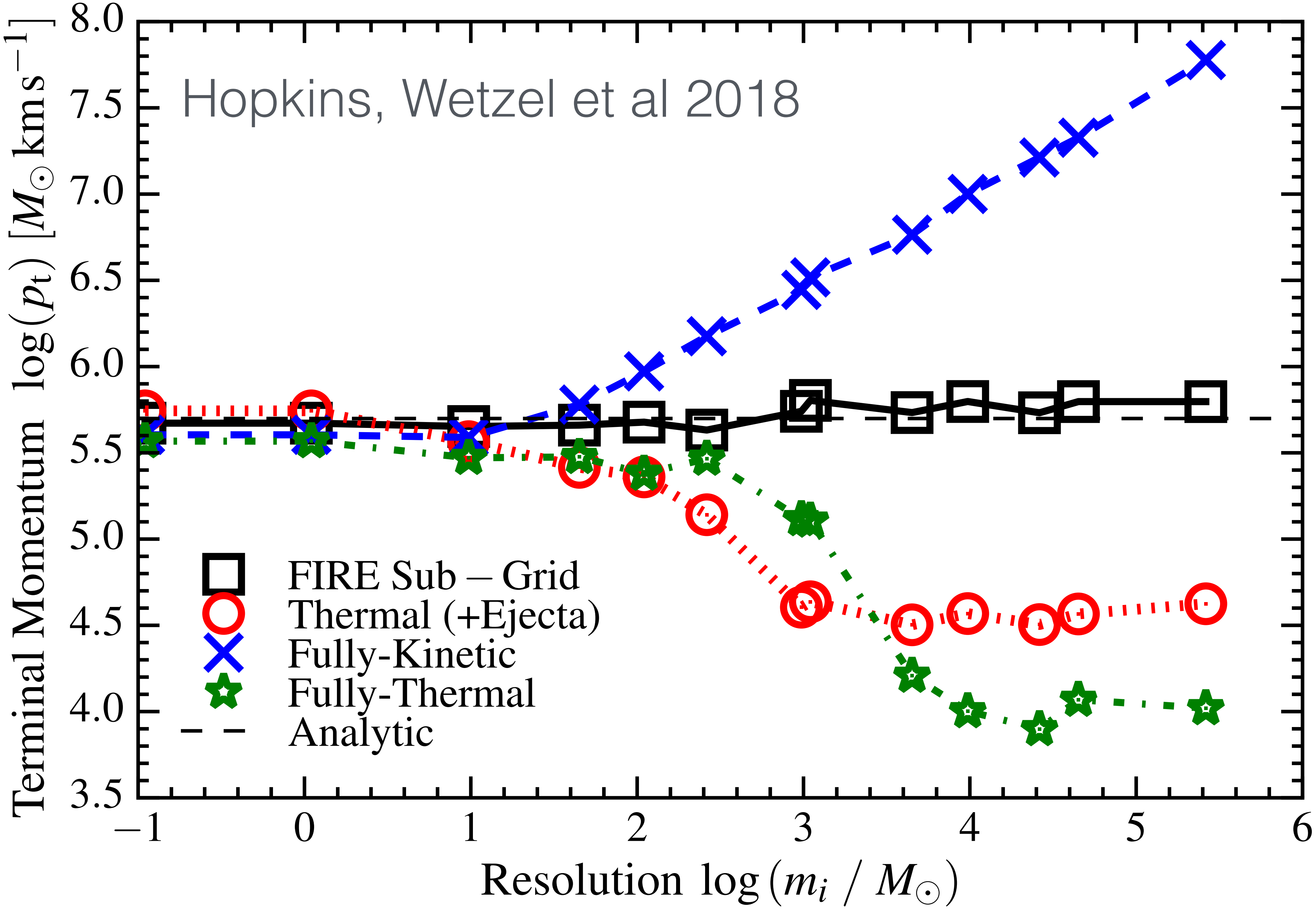
‘we do not understand anything about feedback’

- we understand **a lot** about how stars form, evolve, and interact with the gas around them
  - for example, supernovae
- however, factors of several in uncertainty persist in many cases
- **not** modeling the effects gas, stars, and feedback at all is (almost always) **overwhelmingly more unphysical/wrong**

‘your simulation relies on sub-grid physics’

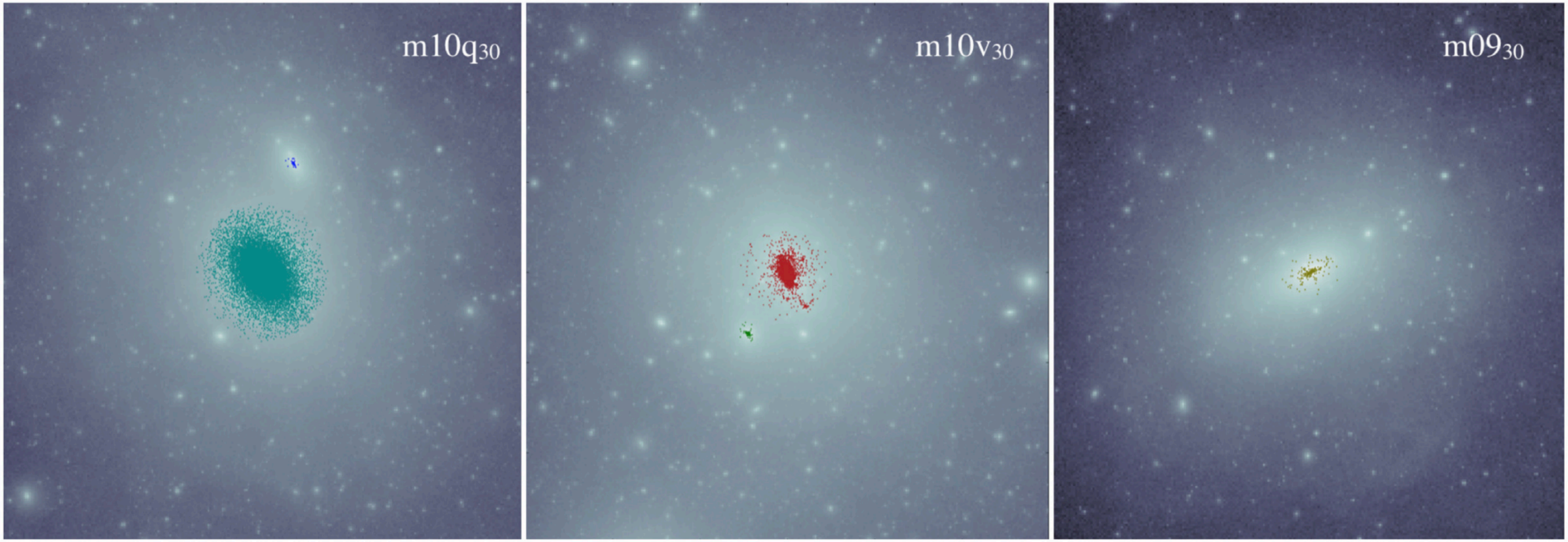
- ‘sub-grid’ is not a dirty word!
  - sub-grid = cannot (spatially) resolve a process
- models for star formation and stellar (+ AGN) feedback in a cosmological setting (within my lifetime) need to rely on ‘sub-grid’ components
- recent cosmological simulations of low-mass galaxies (start to) directly resolve key processes of stars and their feedback
- the key: be clear on what physical processes a given simulation resolves versus has to model via sub-grid

single supernova explosion in idealized ISM with different feedback models



at sufficient resolution, different feedback methods converge, because hydrodynamics resolves them (no longer ‘sub-grid’)

cosmological simulations of low-mass galaxies to $z = 0$ now reach 0.5 - 30 M_{sun} resolution



a few examples:

Wheeler et al 2019 (FIRE)

Gutcke et al 2021 (LYRA)

Lahen et al 2025 (GRIFFIN)

Andersson et al 2025 (EDGE)

MOST IMPORTANT EFFECTS OF BARYONIC PHYSICS ON LOW-MASS GALAXIES AND SUBHALOS

presence of central galaxy

additional gravitational tidal force on satellites/subhalos

meta-galactic ultraviolet background

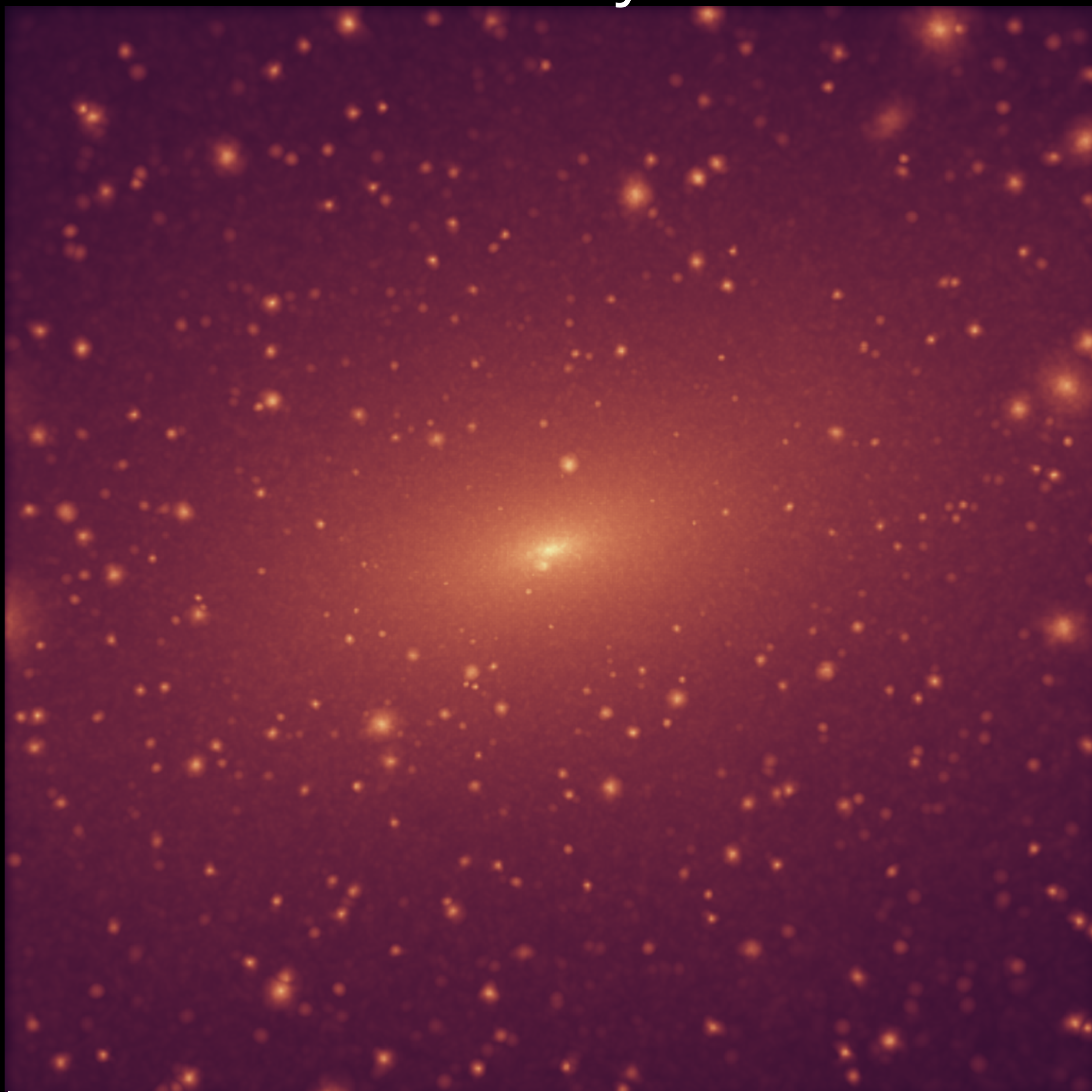
regulates gas content of low-mass halos

stellar feedback (supernovae)

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

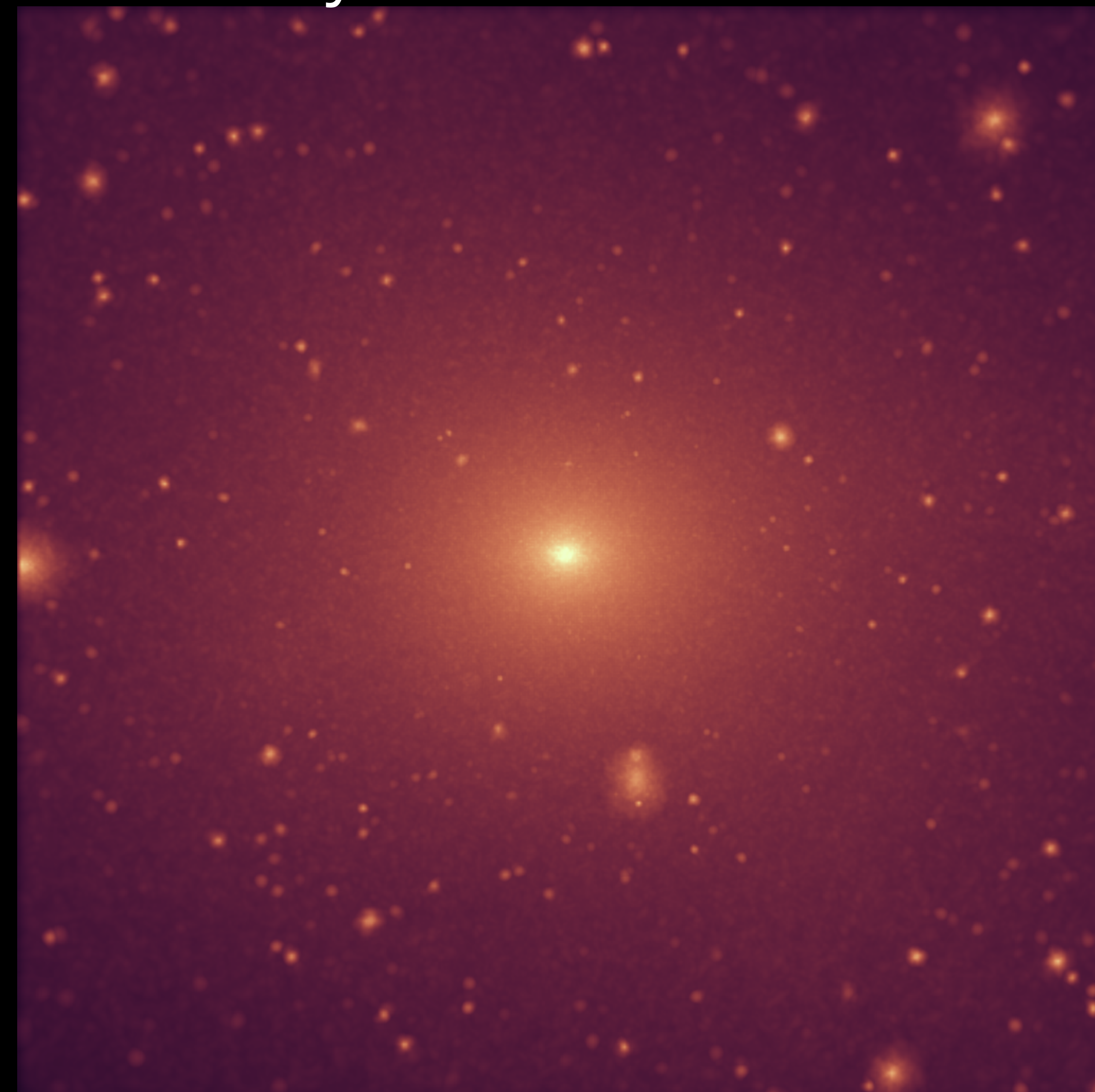
images of cold dark matter in

dark-matter-only simulation



100 kpc

baryonic simulation



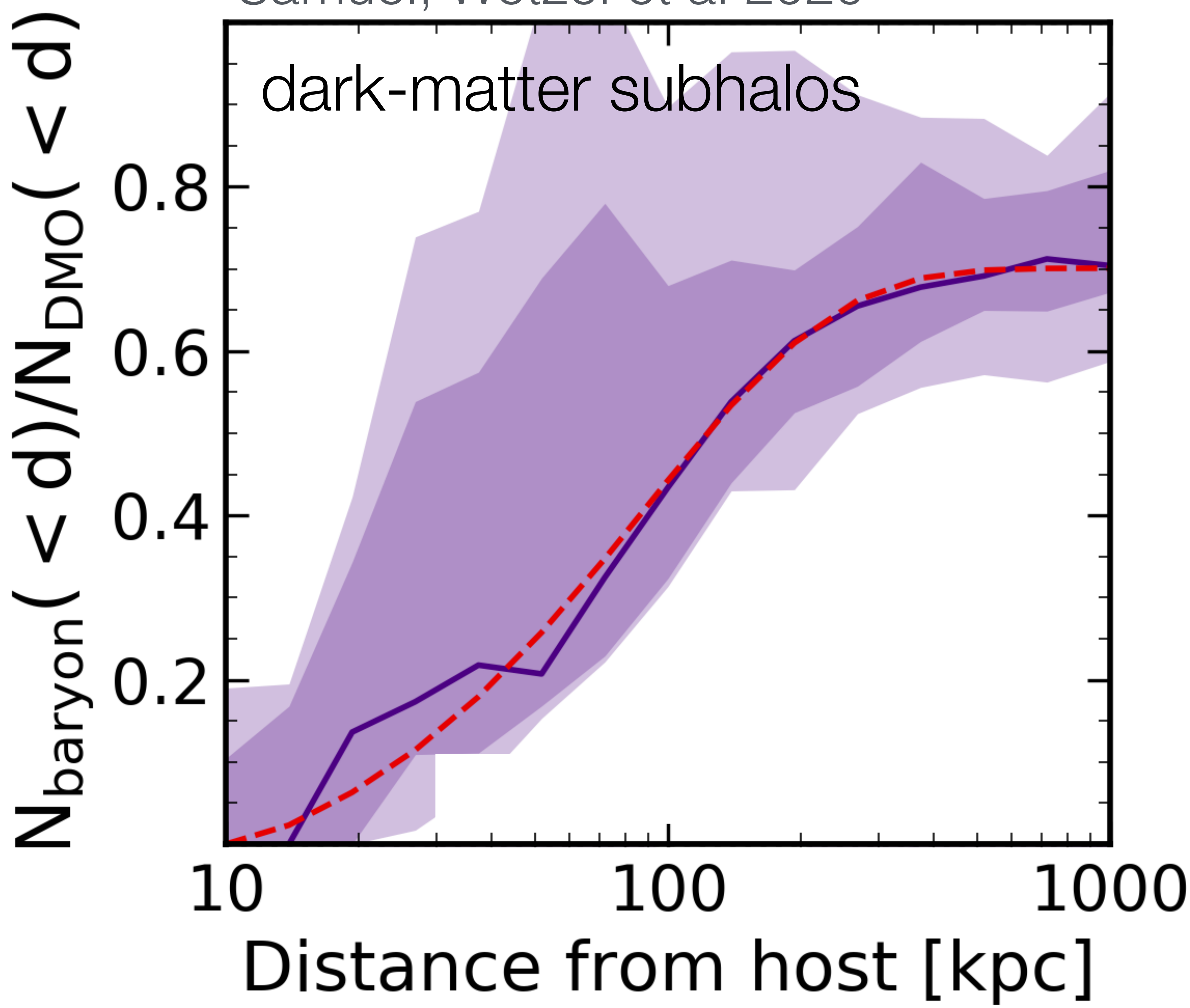
Garrison-Kimmel, Wetzel et al 2017

MW galaxy potential tidally strips subhalos

gravitational tidal stripping from the MW galaxy

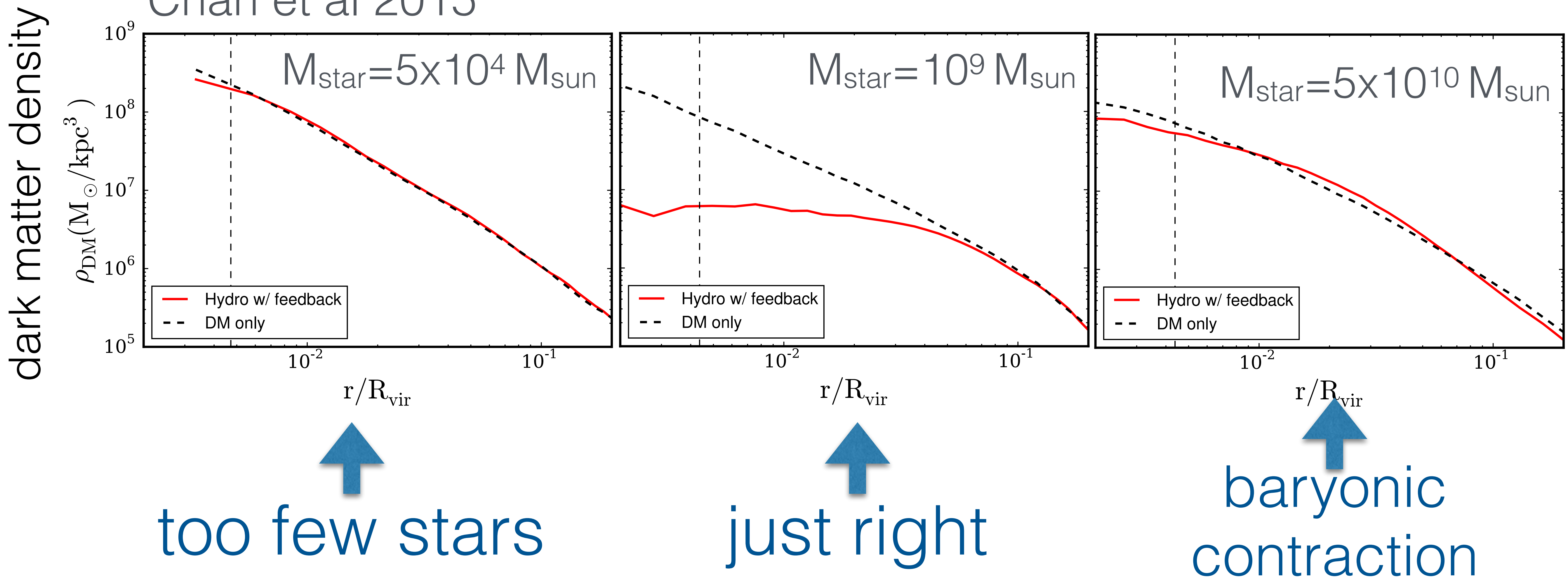
this is not a subtle effect! (but easy to model)

Samuel, Wetzel et al 2020



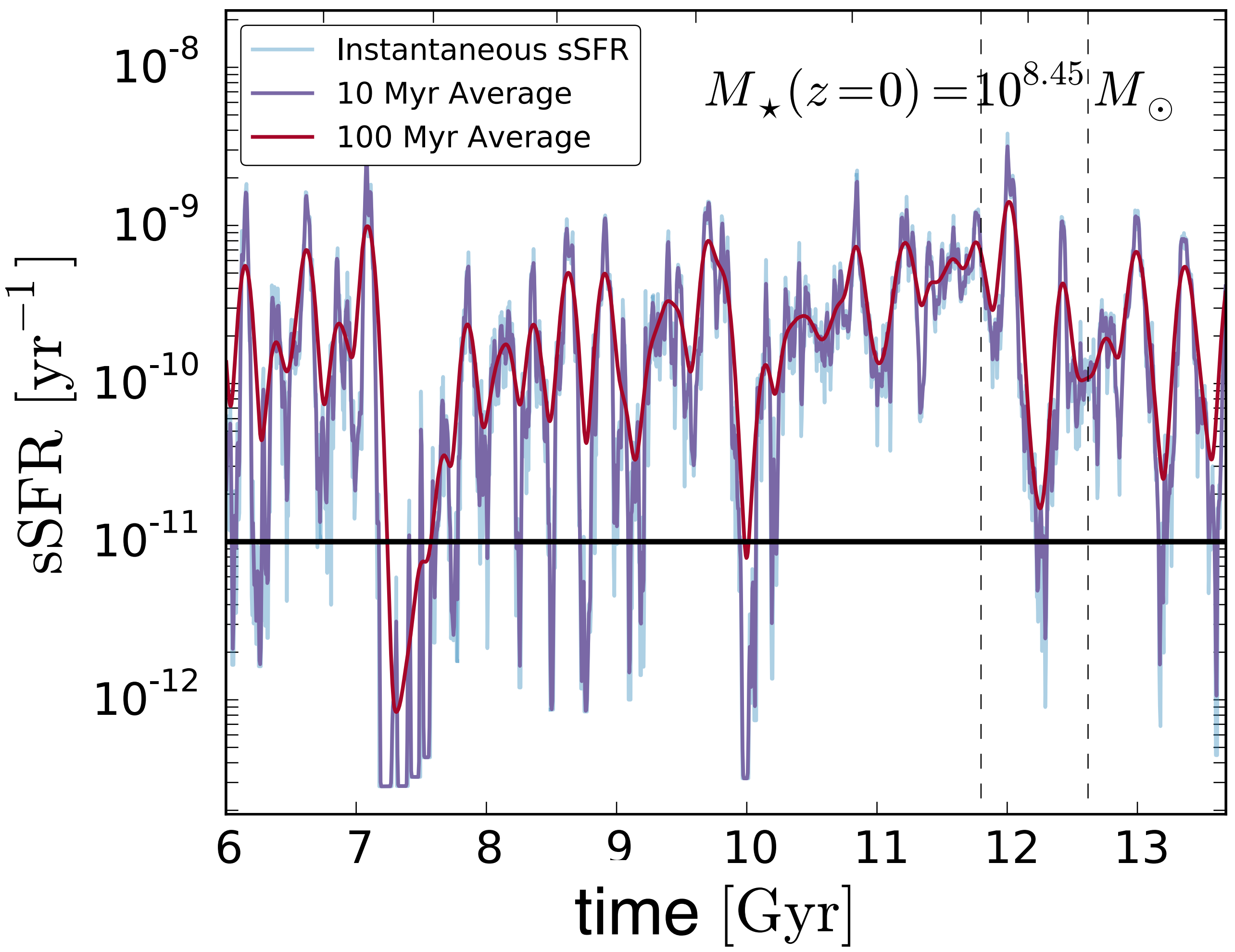
stellar feedback can generate dark-matter cores in low-mass galaxies

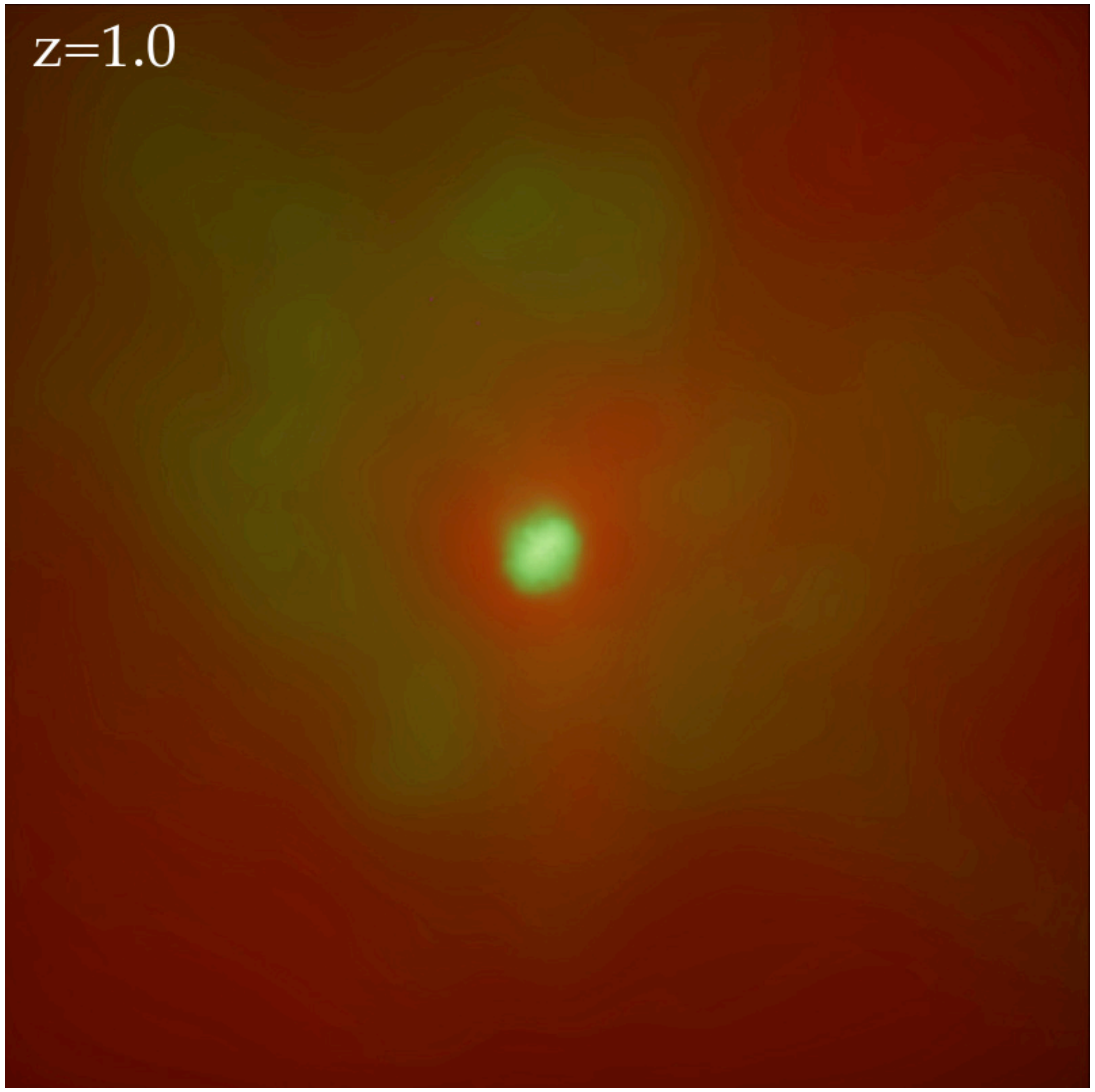
Chan et al 2015



also, Navarro et al 1996, Read & Gilmore 2005, Stinson et al 2007, Ceverino & Klypin 2009, Governato et al 2010, Pontzen & Governato 2012, Teyssier et al 2013, Madau et al 2014, Tollet et al 2015, Read et al 2015, and many others!

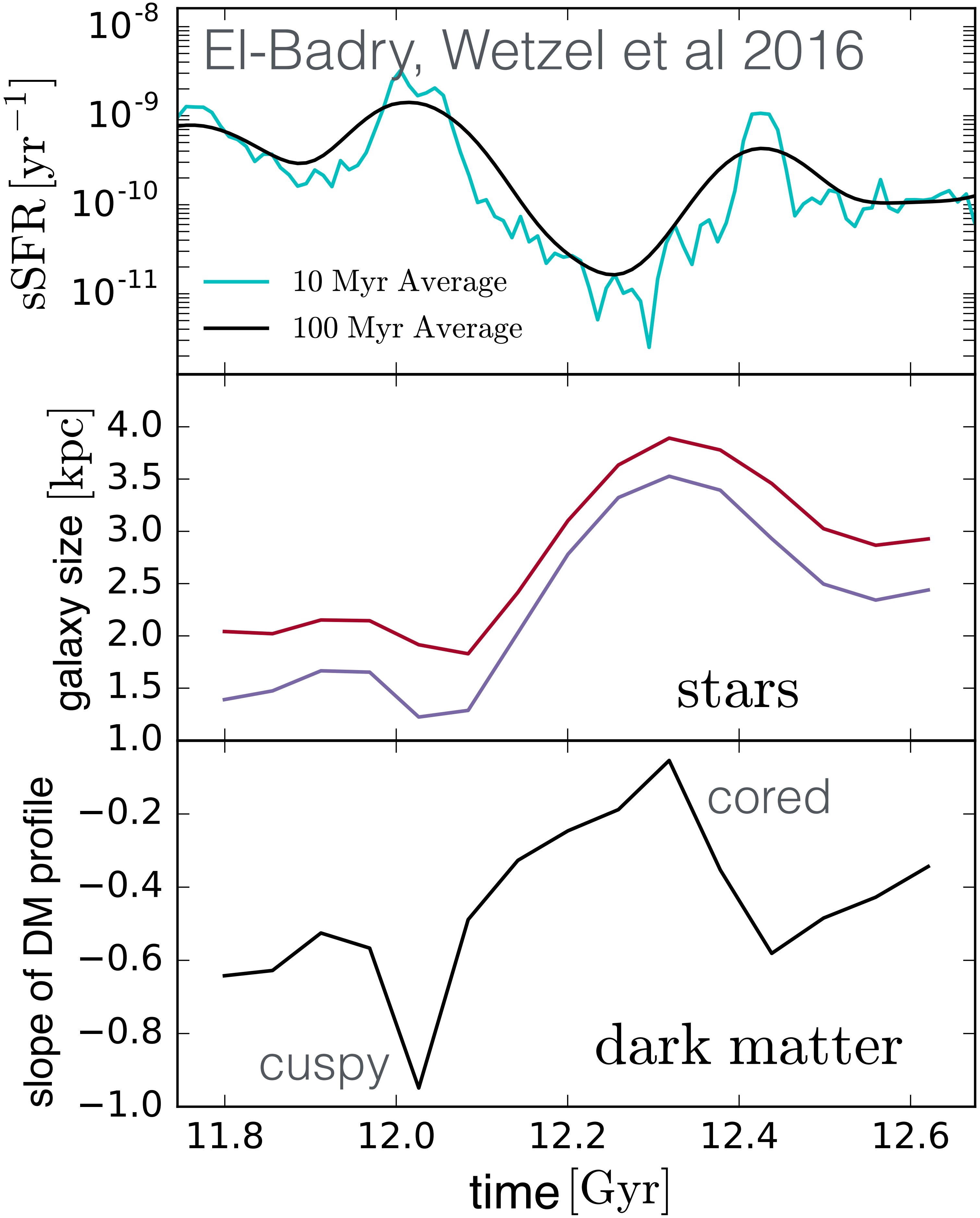
El-Badry, Wetzel et al 2016





low-mass galaxies have bursty star formation and form dark-matter cores in nearly all cosmological simulations that model dense multi-phase ISM at high resolution

also, Navarro et al 1996, Read & Gilmore 2005, Stinson et al 2007, Ceverino & Klypin 2009, Governato et al 2010, Pontzen & Governato 2012, Teyssier et al 2013, Madau et al 2014, Tollet et al 2015, Read et al 2015, and many others!



inevitable **diversity**

gas mass, stellar size, and dark-matter coring vary during each burst cycle

more burst cycles (more extended star formation) leads to more coring on average

summary of baryonic coring of DM

- almost all cosmological baryonic simulations that model dense multi-phase ISM at high resolution agree that baryons can cause diverse DM profiles, including DM cores
- but they disagree on the range of sizes of cores and the minimum halo mass to form a core

nature astronomy

REVIEW ARTICLE

https://doi.org/10.1038/s41550-022-01689-w

Check for updates

Baryonic solutions and challenges for cosmological models of dwarf galaxies

2022

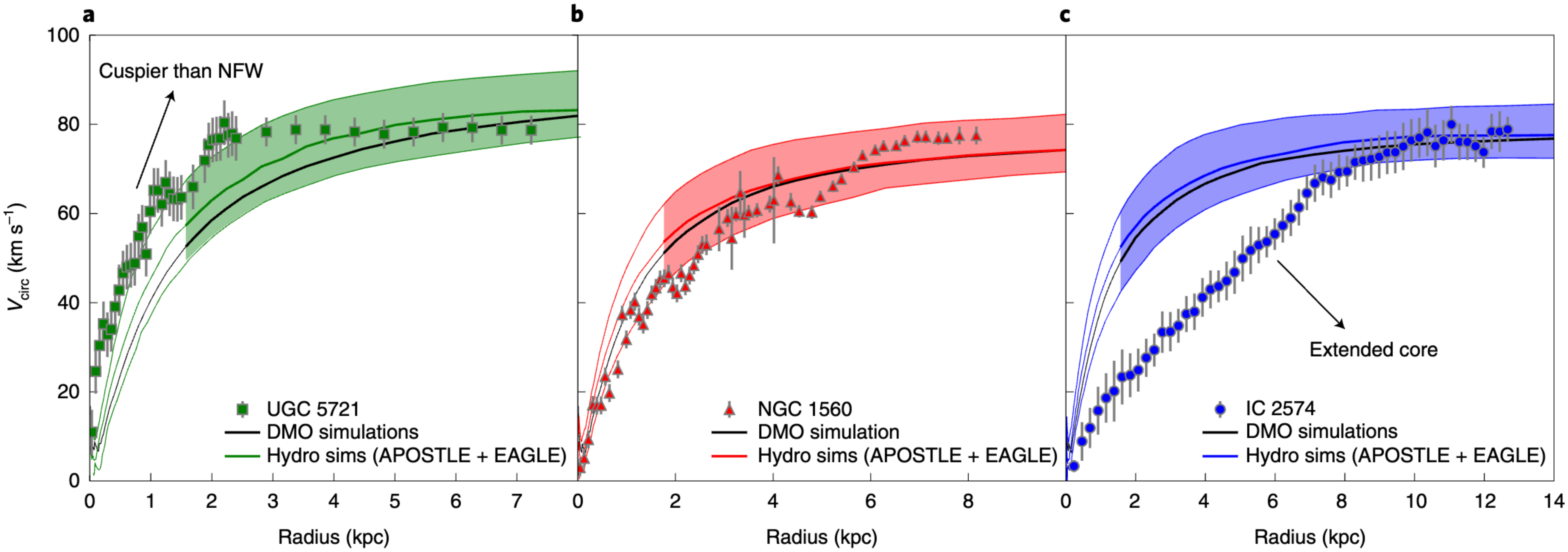
Laura V. Sales[1]✉, Andrew Wetzel[2] and Azadeh Fattahi[3]

ΛCDM tensions with dwarf galaxies

No tension	Uncertain	Weak tension	Strong tension
Missing satellites	$M_{\star}$–M_{halo} relation	Too big to fail	Diversity of rotation curves
	Core–cusp	Diversity of dwarf sizes	Satellite planes
		Quiescent fractions	

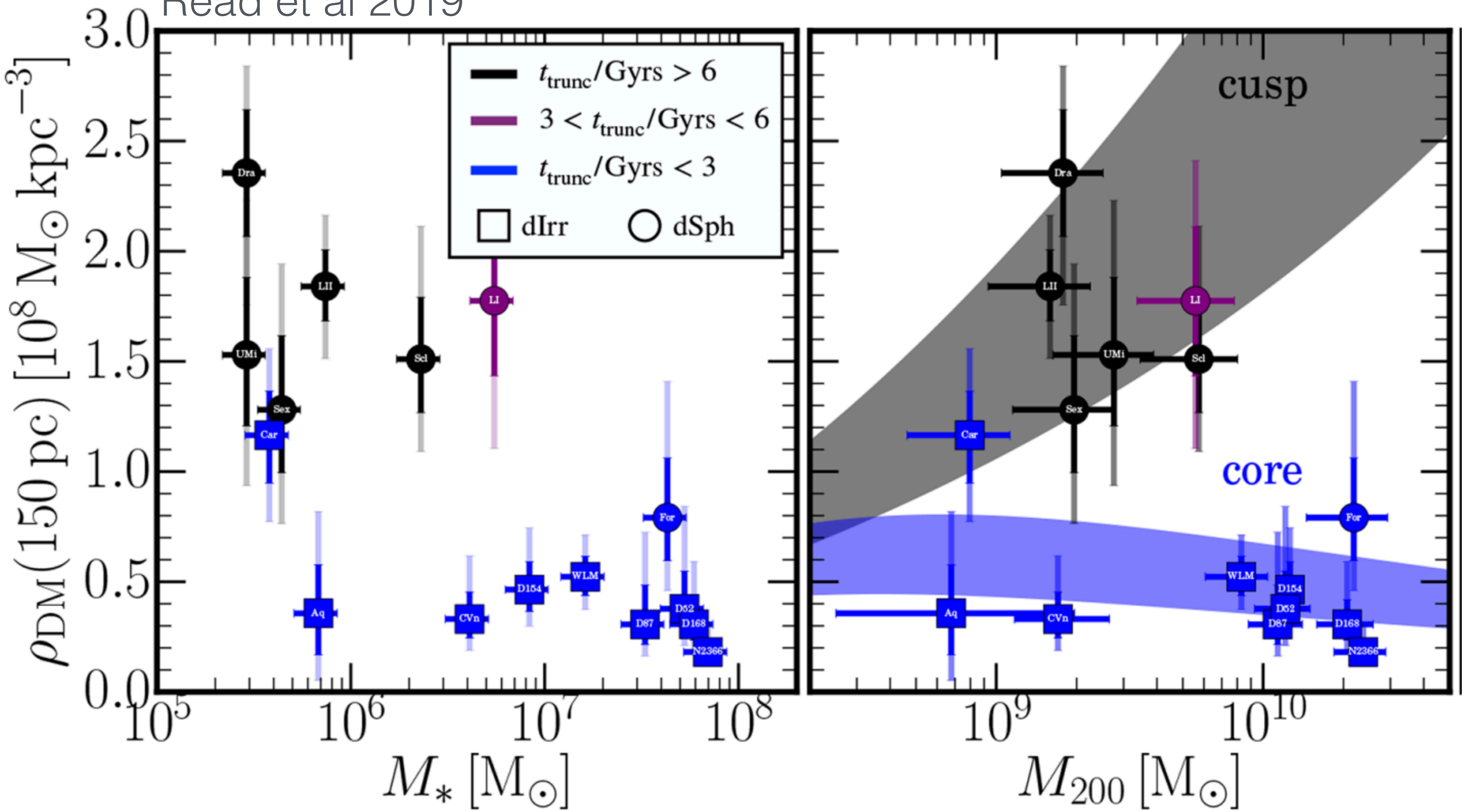
ongoing challenge: diversity of rotation curves

Oman et al 2015, Sales, Wetzel, Fattahi et al 2022



success of baryonic core formation
observed low-mass galaxies with more extended star-formation histories have stronger DM cores

Read et al 2019



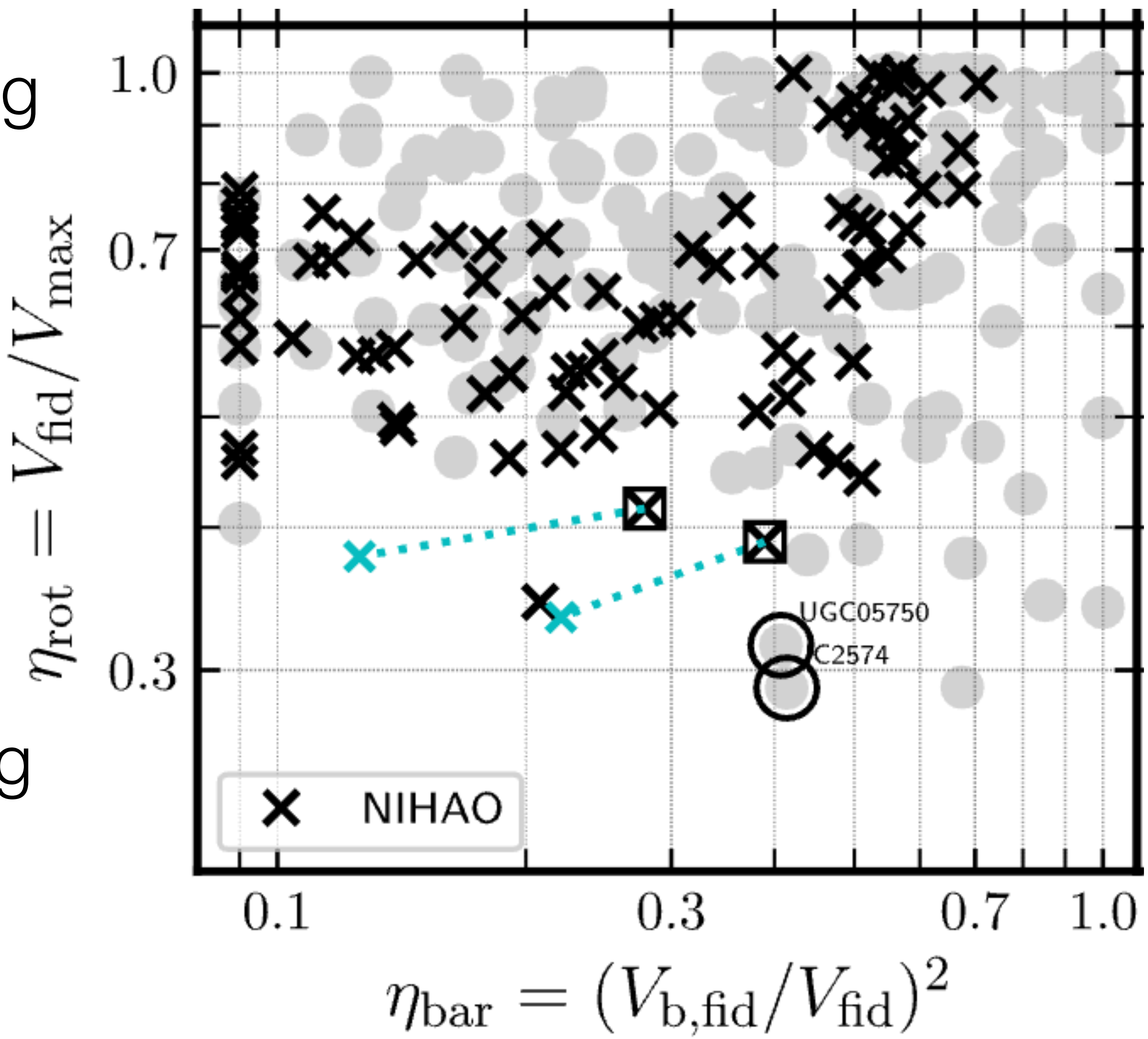
Andrew Wetzel

failure of baryonic core formation

shape of rotation curve correlates more tightly with baryonic mass than observed

rapidly rising (cuspy)

slowly rising (cored)



Santos-Santos et al 2020

baryon poor

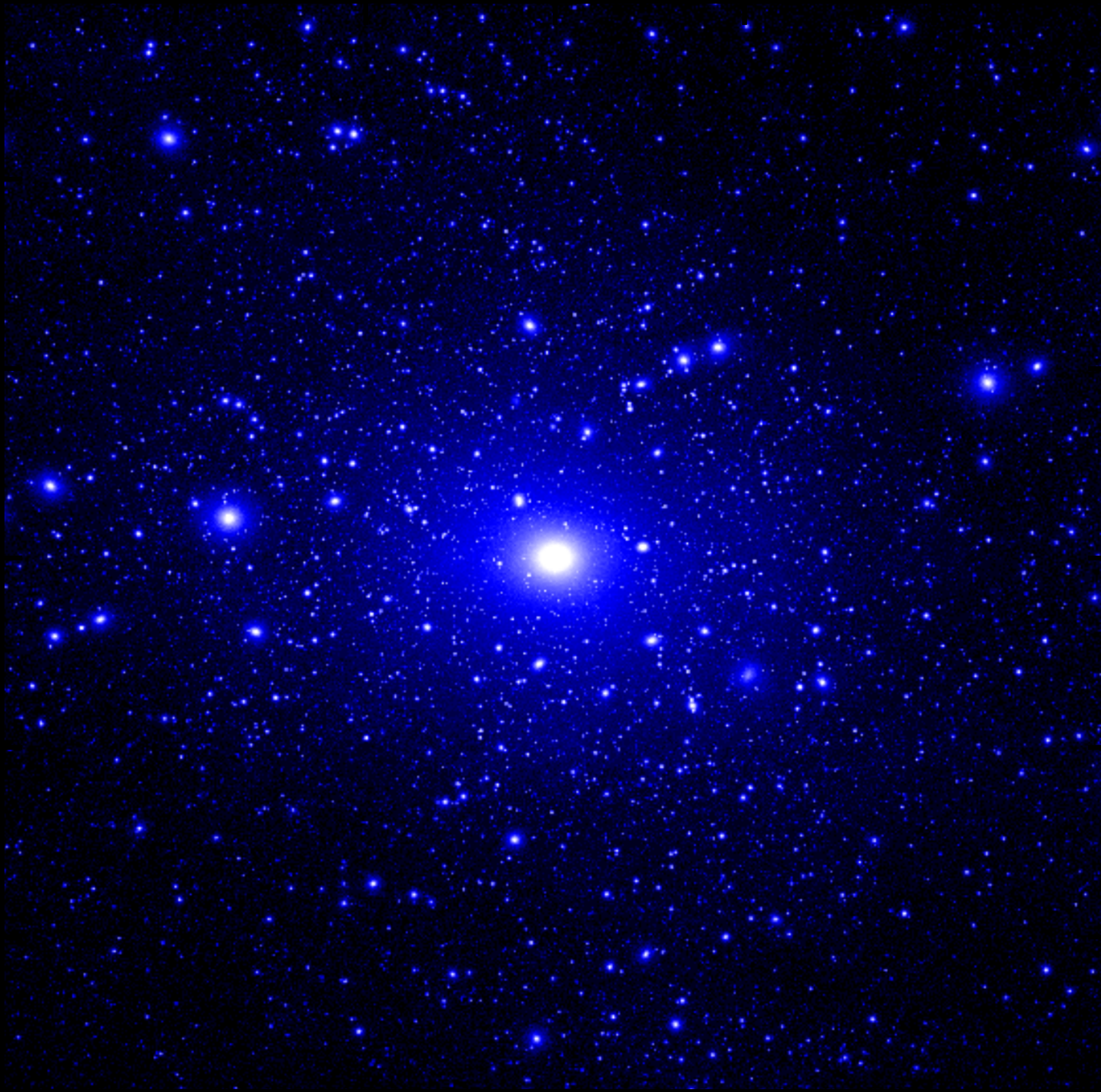
baryon dominant

caveat to observed diversity

- observational modeling of atomic hydrogen to get rotation curves (V_{circ} profiles) is nontrivial!
- need to model (possible) non-circular motions in gas
- we probably just should compare observed v predicted velocity maps (data cubes)

Strigari et al 2017, Genina et al 2015, Harvey et al 2018, Oman et al 2019, etc

predictions for low-mass subhalos around the Milky Way



Megan Barry
PhD student

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predicting low-mass subhalos around the Milky Way

Barry, Wetzel et al 2023

Megan Barry

- goal: quantify the subhalos most likely to cause perturbations on stellar streams
- instantaneous (bound) dark-matter mass: >1e6, >1e7, >1e8 M_{sun}
- distance from MW: 0 - 60 kpc

KEY QUESTIONS

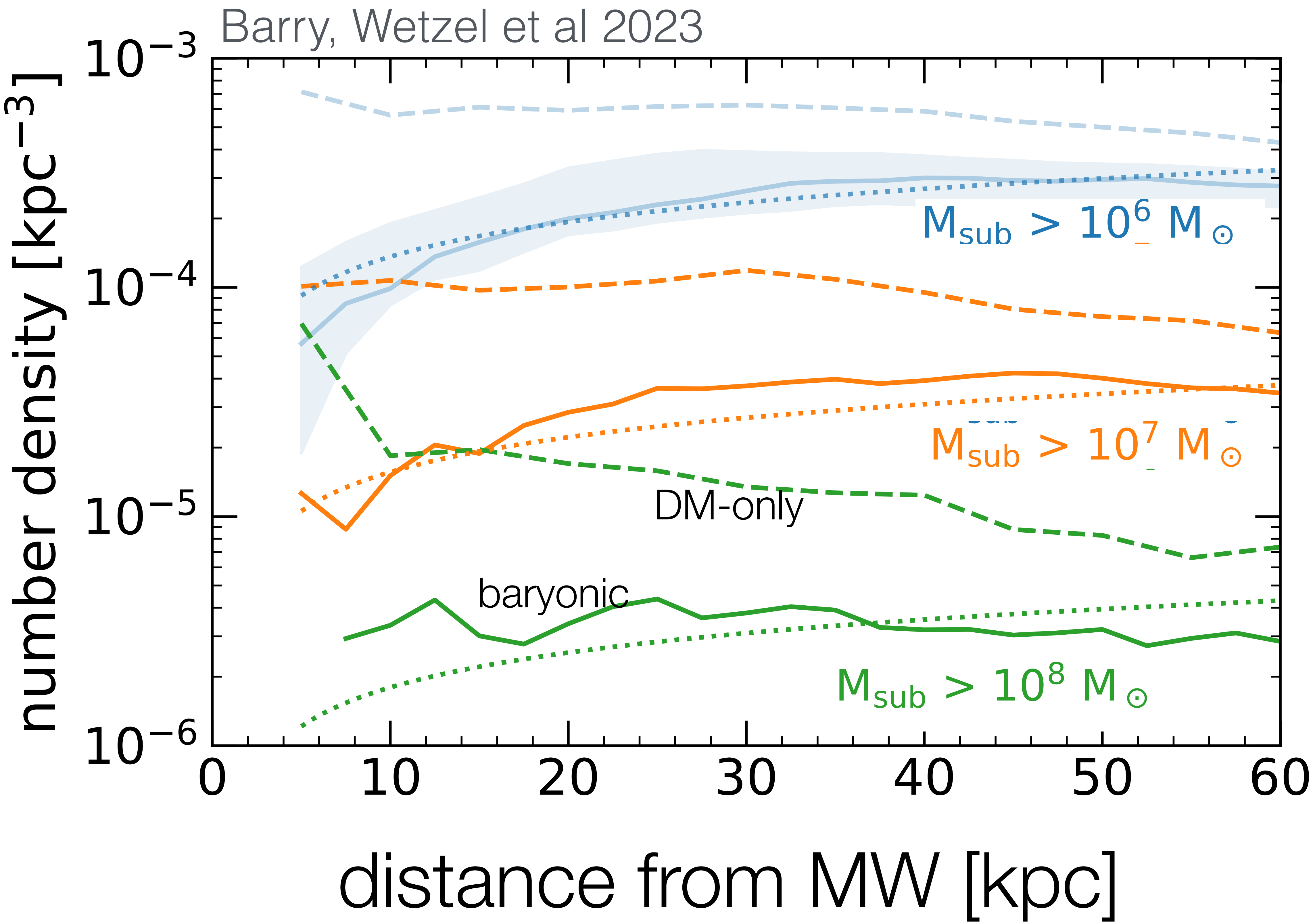
What is the population of low-mass (dark) subhalos near MW-mass galaxies?

How did the population vary across cosmic time?

What is their velocity distribution?

Is the Milky Way special in any way?

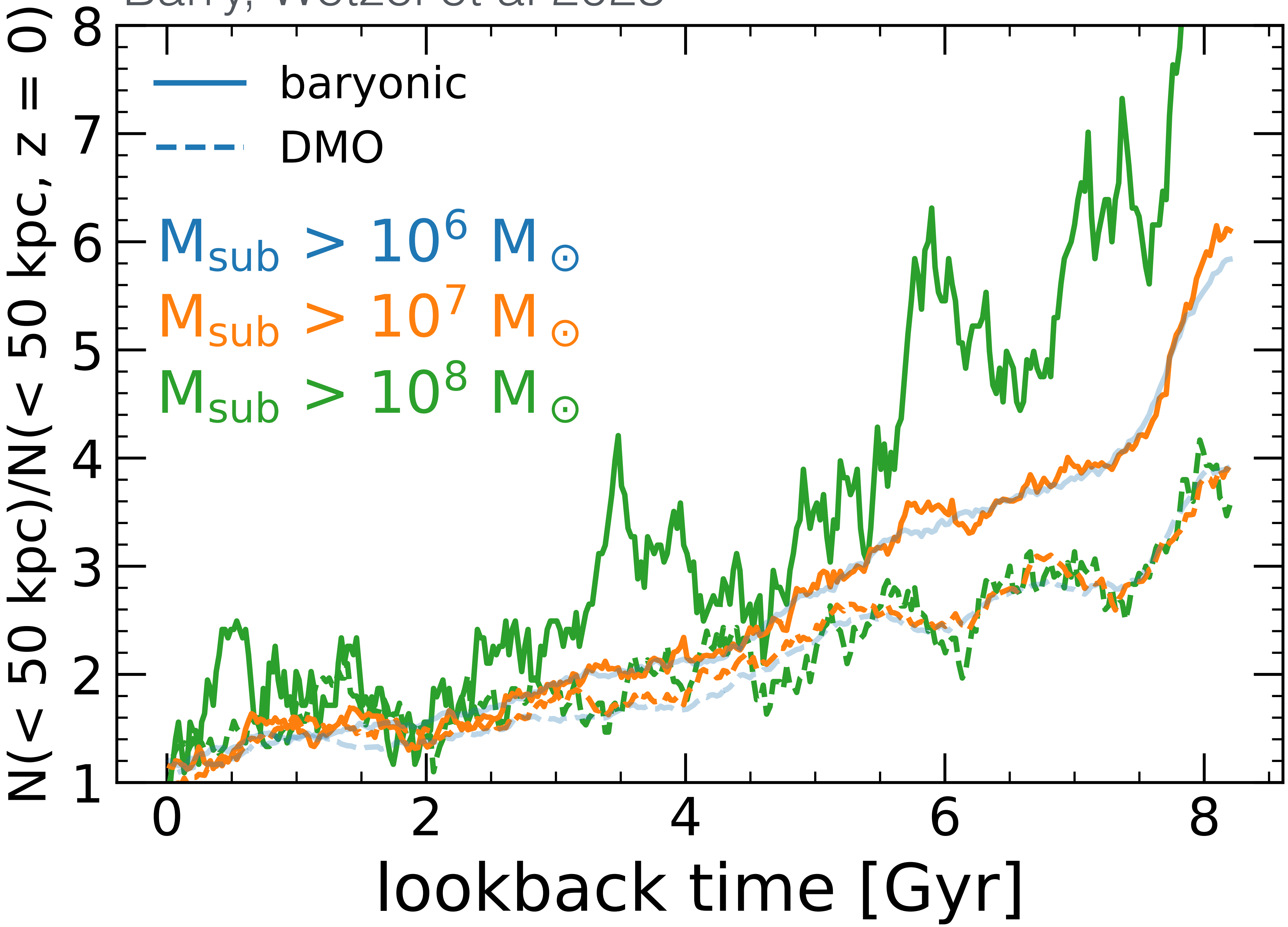
predictions for subhalos at z = 0



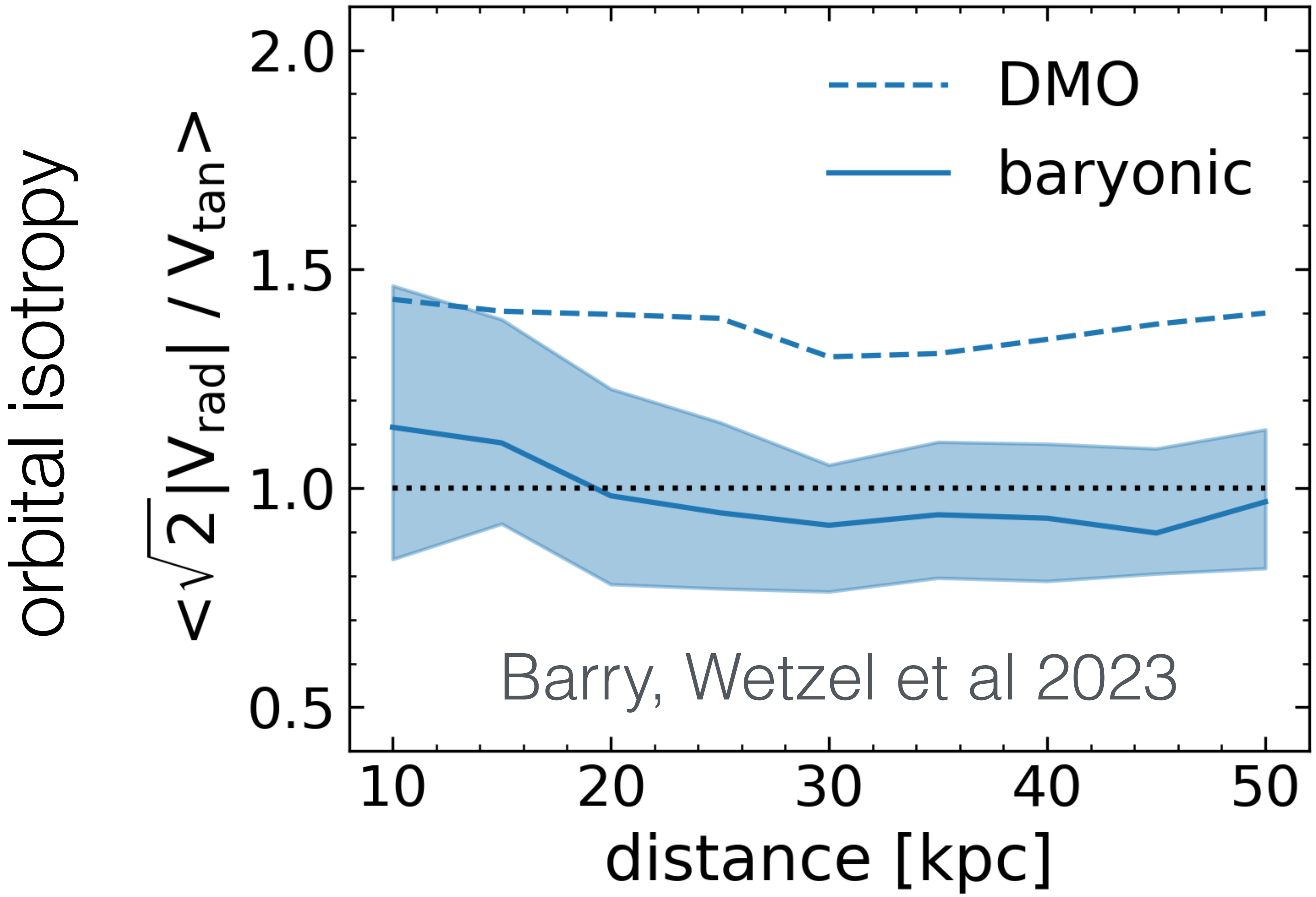
evolution of subhalo population

6-10x reduction since z ~ 1 (~8 Gyr)

Barry, Wetzel et al 2023



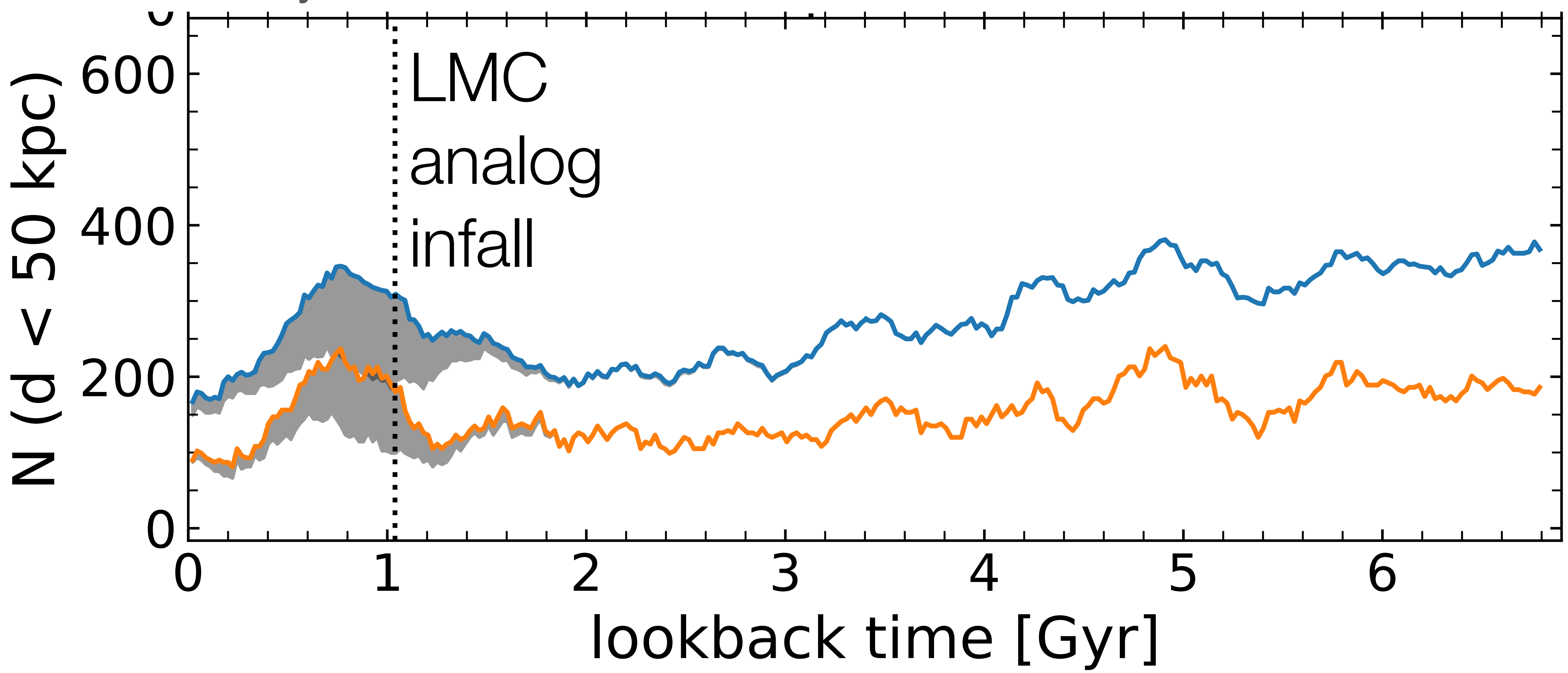
predictions for subhalo velocity distributions



- DM-only simulations predict radially biased orbits
- tidal stripping from MW galaxy more strongly affects subhalos with low angular momentum
- baryonic simulations predict ~isotropic orbits

Does the presence (recent infall) of the LMC affect the current subhalo population?

Barry, Wetzel et al 2023



yes! **~2 x** more subhalos with an LMC analog

KEY QUESTIONS

What is the population of low-mass (dark) subhalos near MW-mass galaxies?

number density is ~flat with distance to ~60 kpc,
~5x fewer subhalos than in DM-only

How did the population vary across cosmic time?

6-10x reduction since z ~ 1 (~8 Gyr ago)

What is their velocity distribution?

~isotropic (not radially biased as in DM-only simulations)

Is the Milky Way special in any way?

presence of LMC boosts subhalo population by ~2x

FIRE-2 public data release 2

Feedback In Realistic Environments

DR1: Wetzel et al 2023, ApJS

DR2: a few weeks away

FlatHUB flathub.flatironinstitute.org/fire

- 46 simulations, up to 600 snapshots across z = 0 - 99
- physics variations: core, MHD, cosmic rays, dark-matter only
- galaxy/halo catalogs and merger trees across all snapshots

TAKE-AWAY MESSAGE

‘ΛCDM (ΛSIDM) predicts…’

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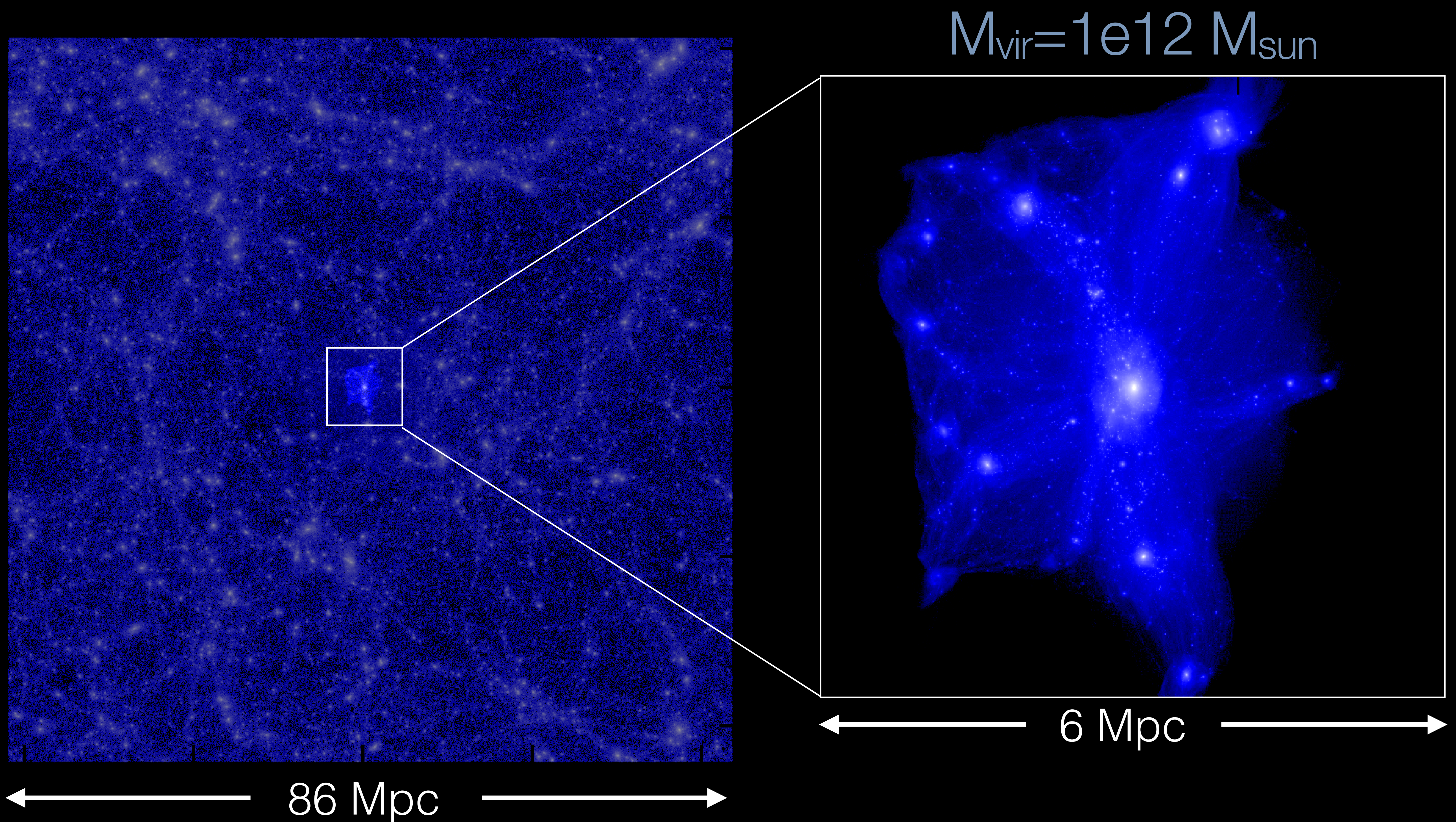
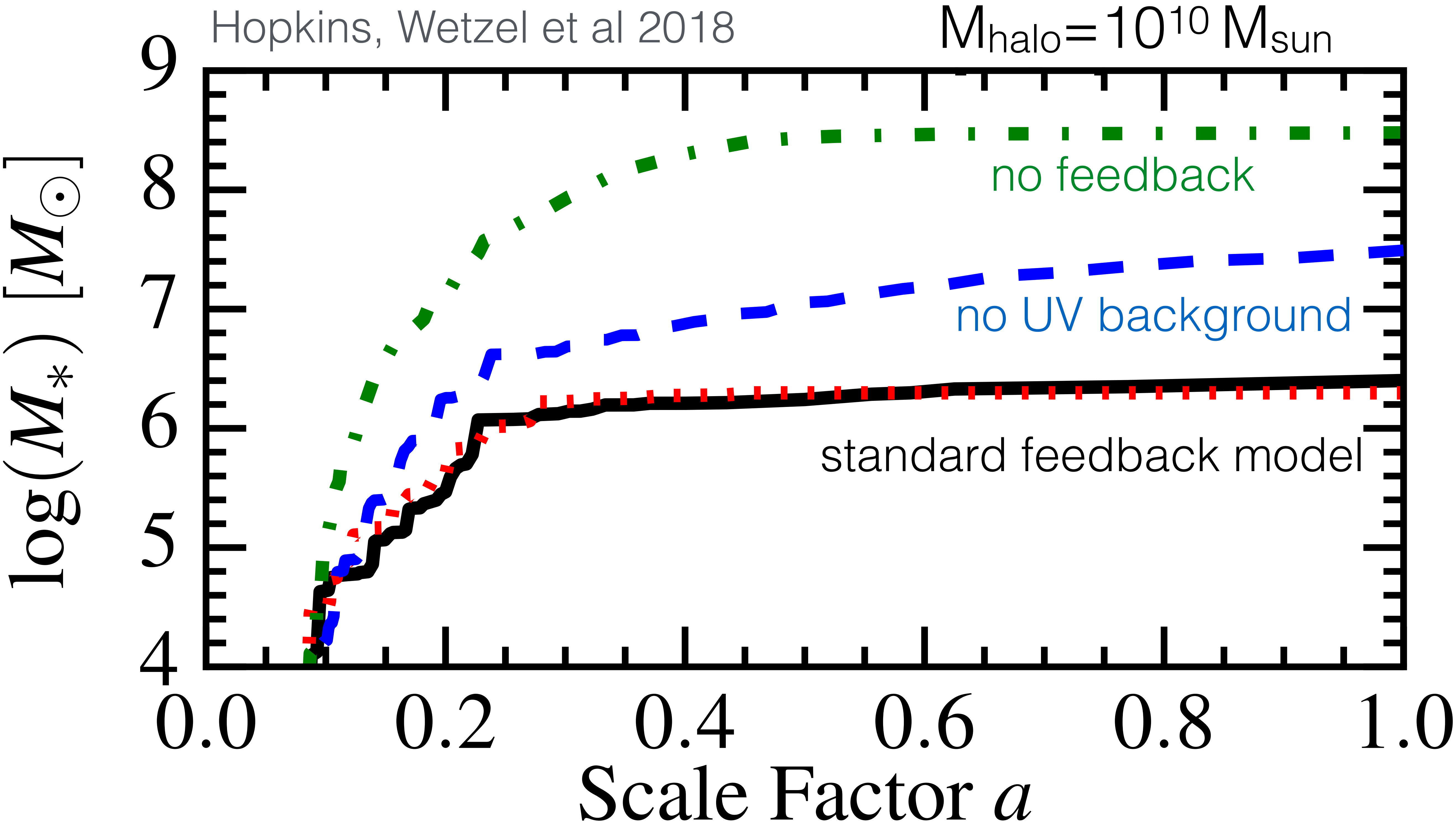
backup slides

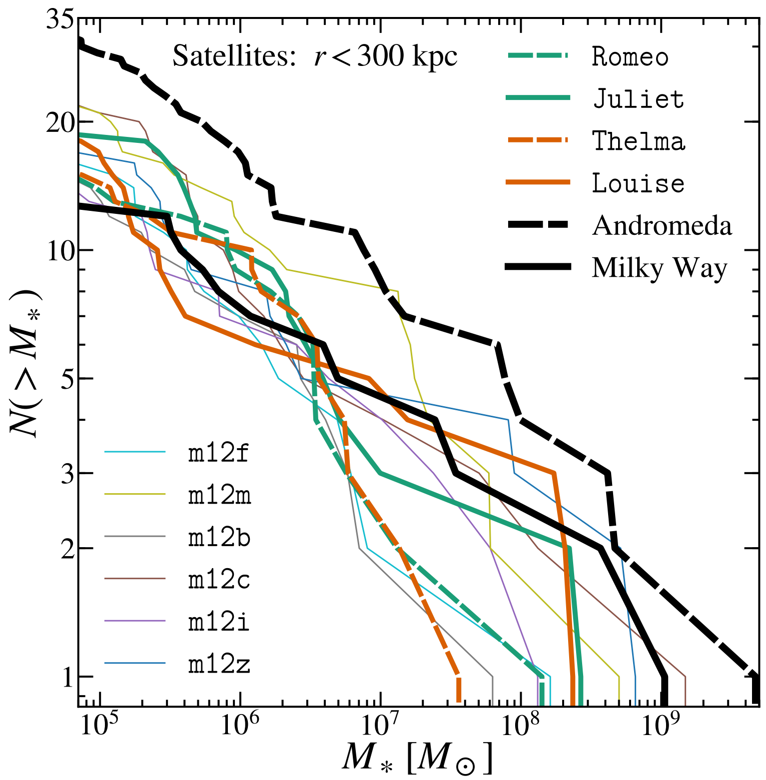
cosmological zoom-in simulation to achieve ultra-high resolution



impact of UV background on star formation in low-mass galaxies

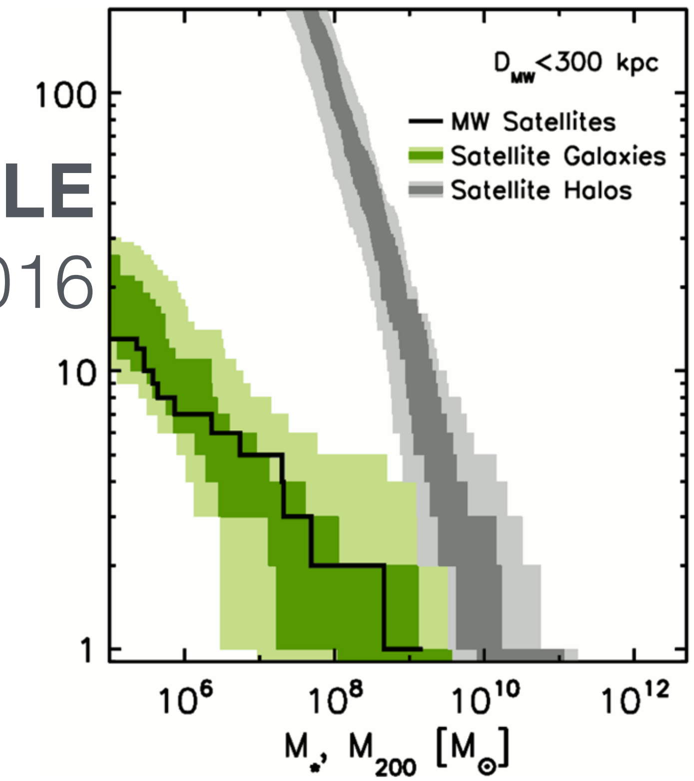


many different cosmological baryonic simulations now form realistic populations of satellite galaxies

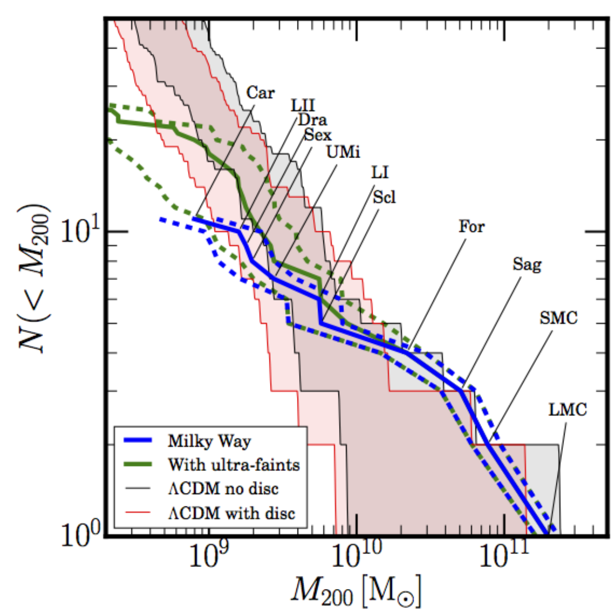


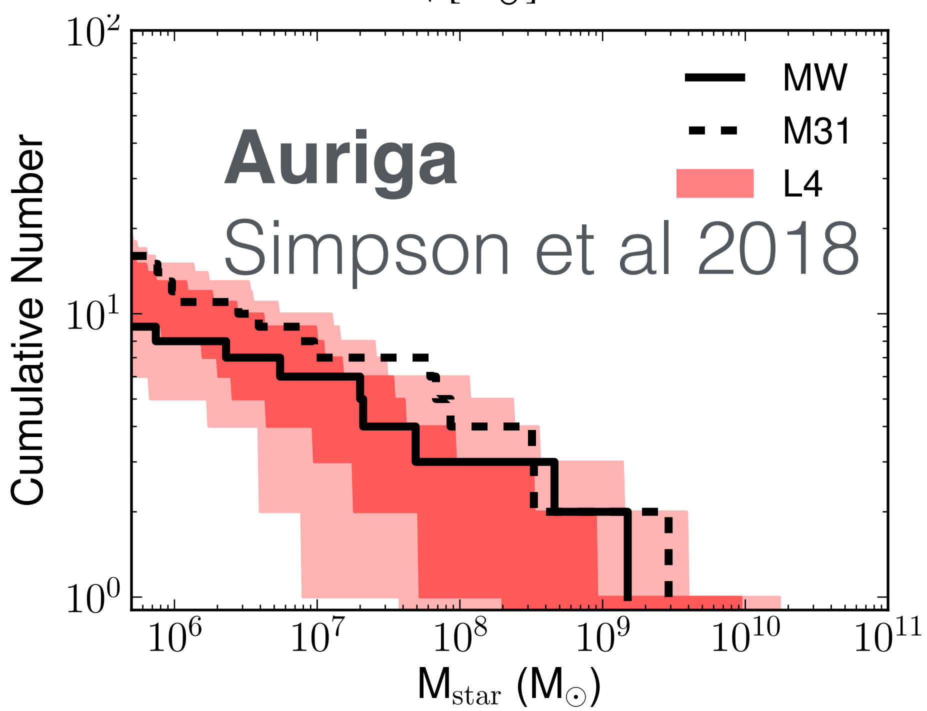
FIRE
Garrison-Kimmel et al 2019

APOSTLE
Sawala et al 2016

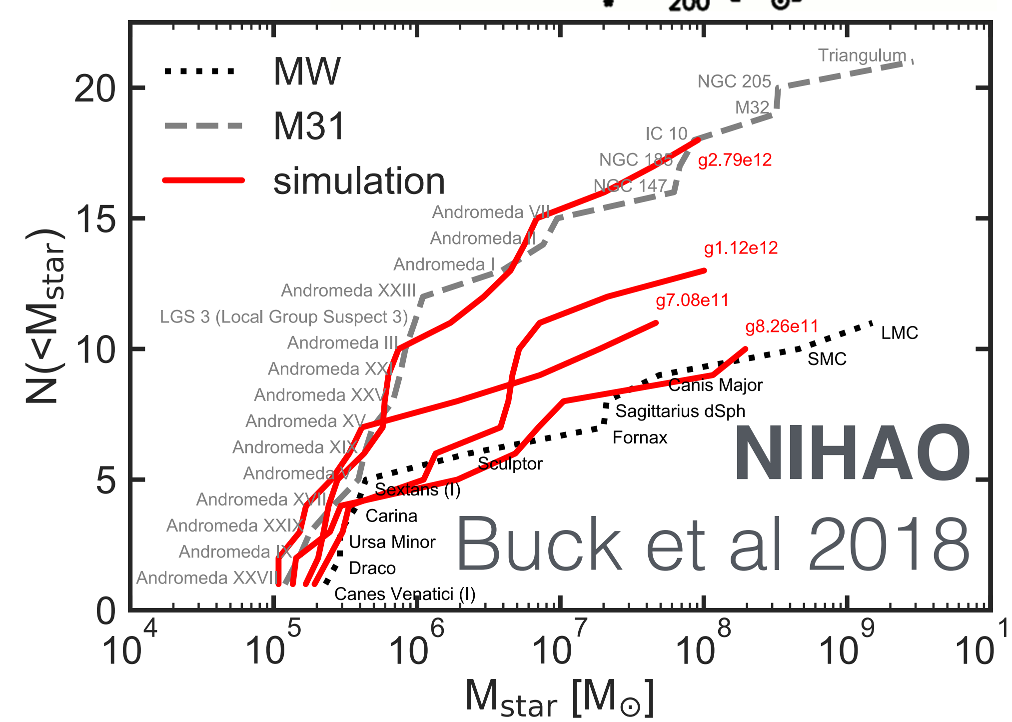


Read & Erkal 2018





Auriga
Simpson et al 2018



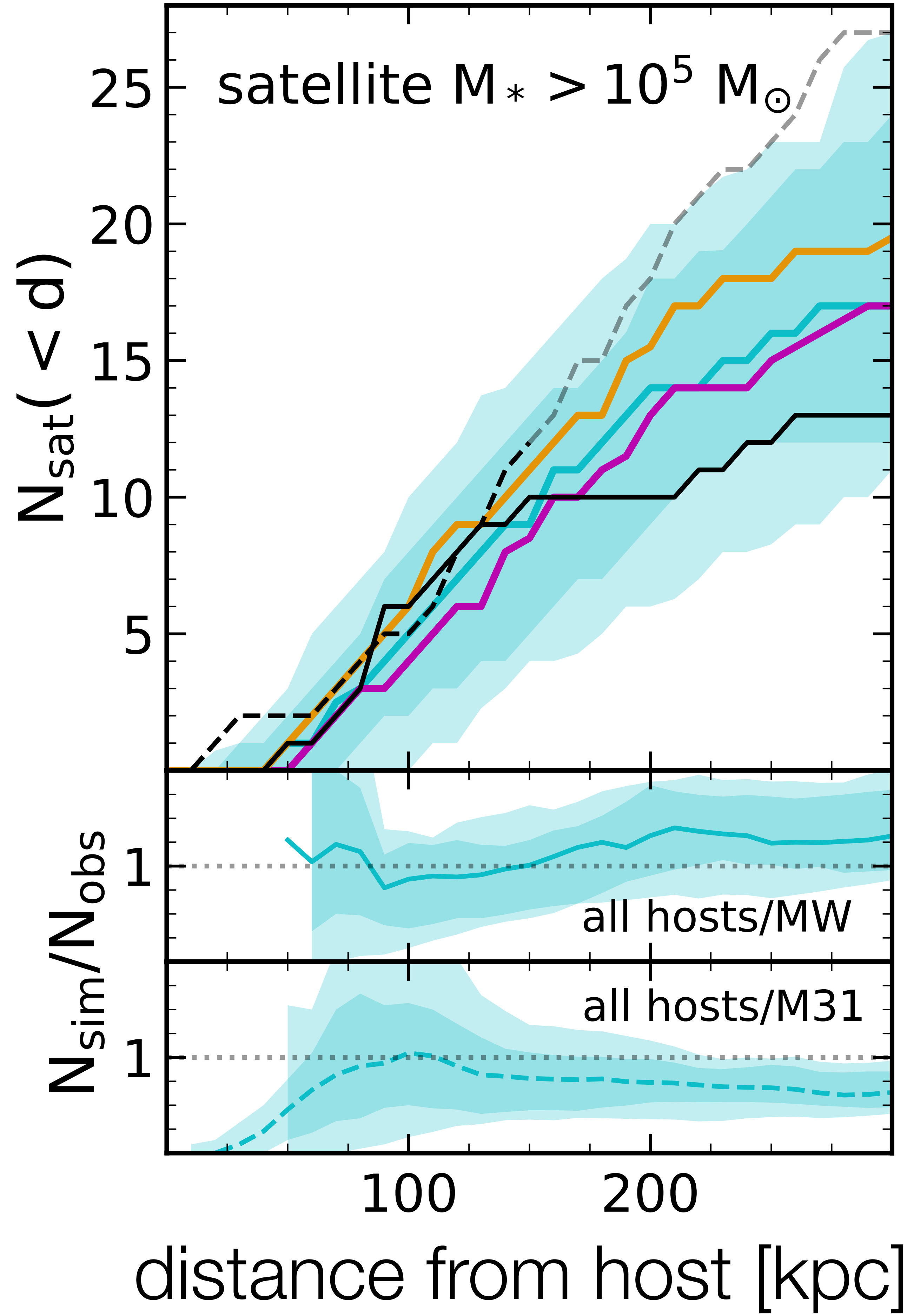
NIHAO
Buck et al 2018

underappreciated effect of rezioniation

- reionization at z ~ 8 not only removes ~all gas from low-mass halos (M_{halo} <~ 1e8 M_{sun})
- by lowering the total halo mass by ~20% and shallowing the gravitational potential at z ~ 8, this reduces **future** DM accretion into the halo

FIRE-2 simulations agree with MW + M31 in radial distance distribution of satellite galaxies

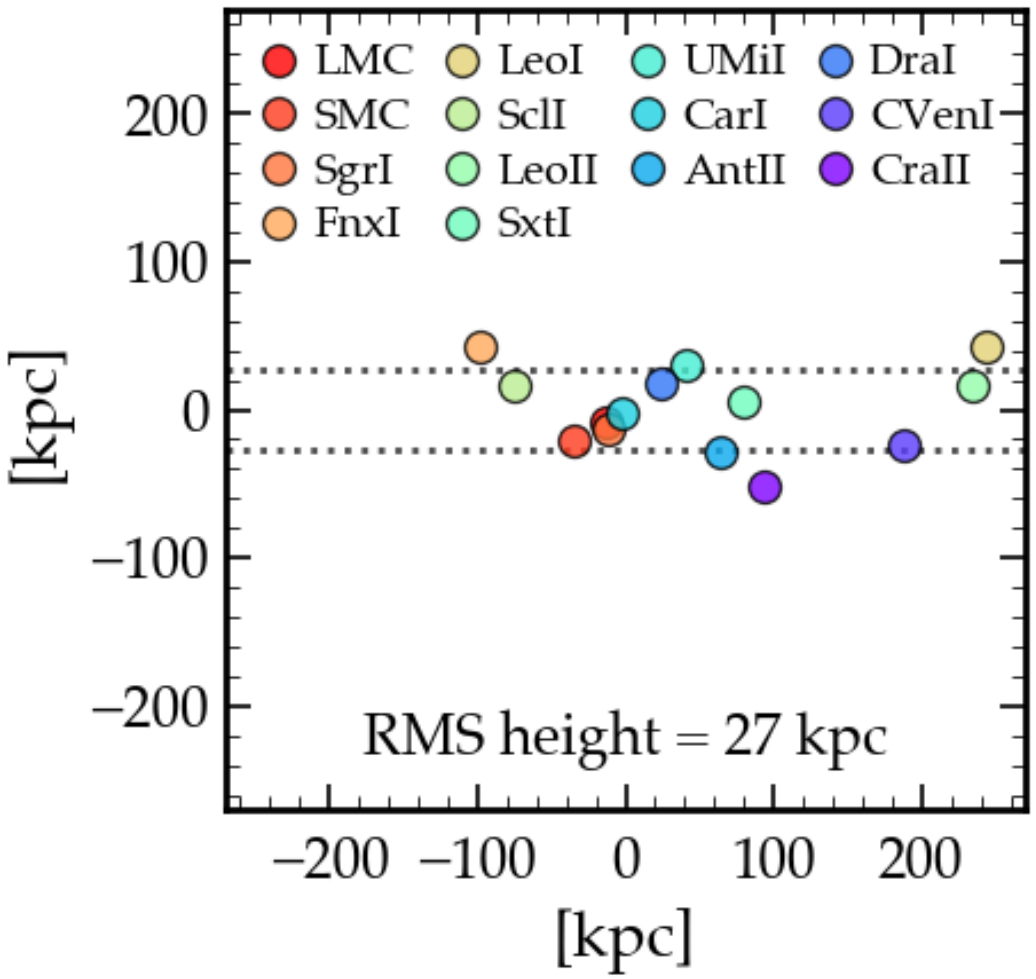
Samuel, Wetzel et al 2020

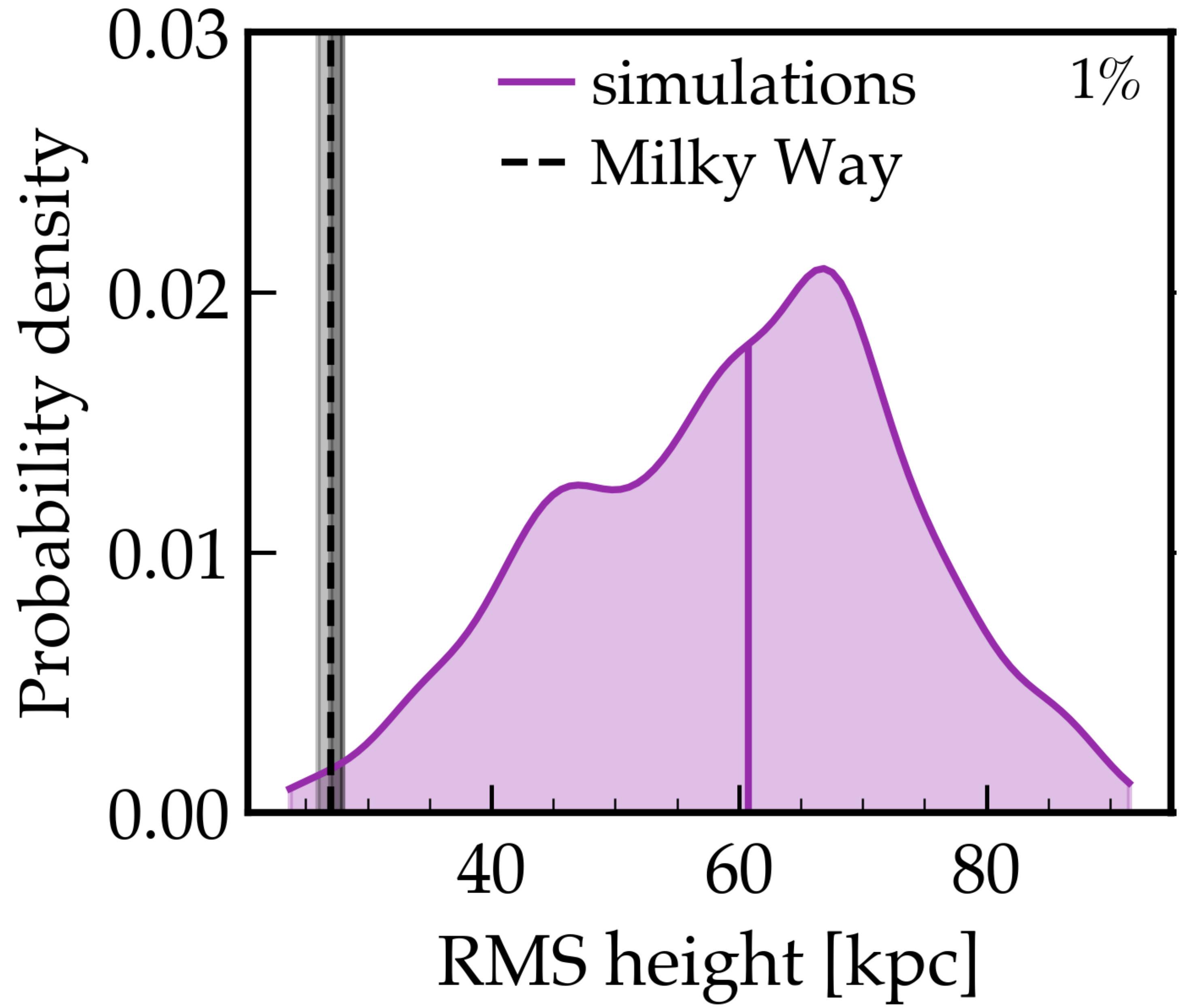


MW-like thin planes of satellites are **rare** (~1%) in LCDM cosmological simulations

(for example, Pawlowski 2021)

MW satellites

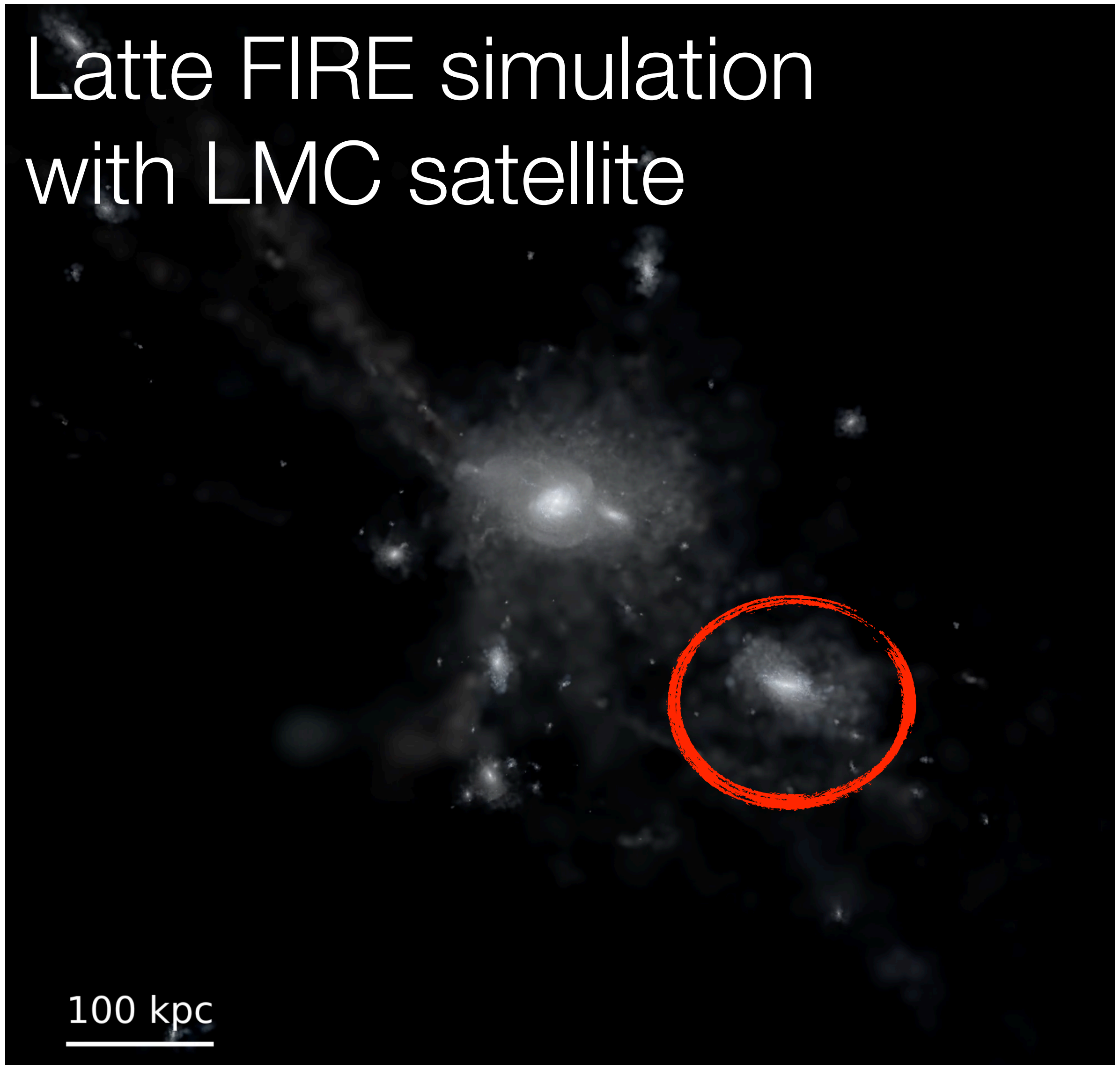


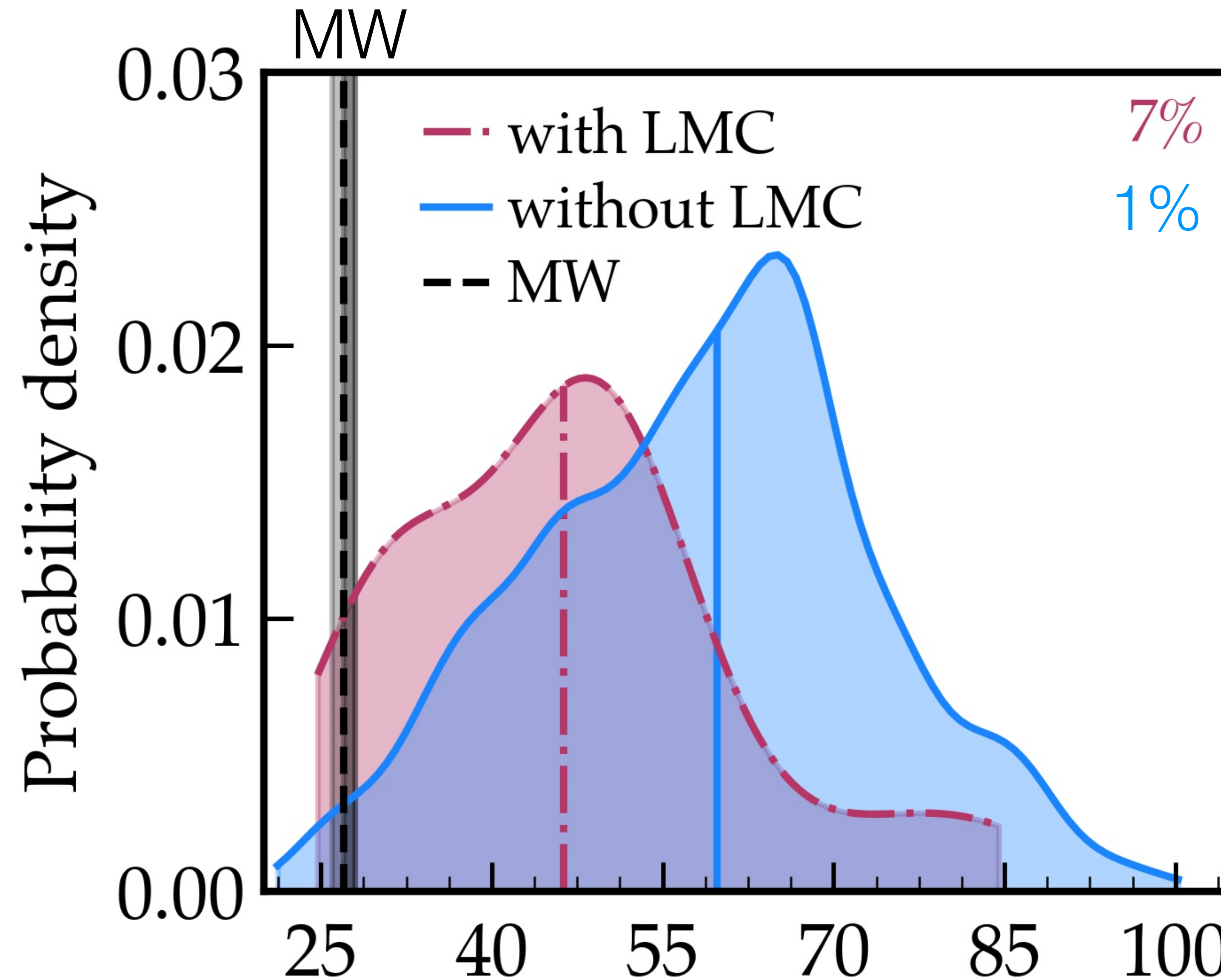


<— more planar

Samuel, Wetzel et al 2021

thin plane of satellites is 4-8 x more common in presence of an LMC-mass satellite



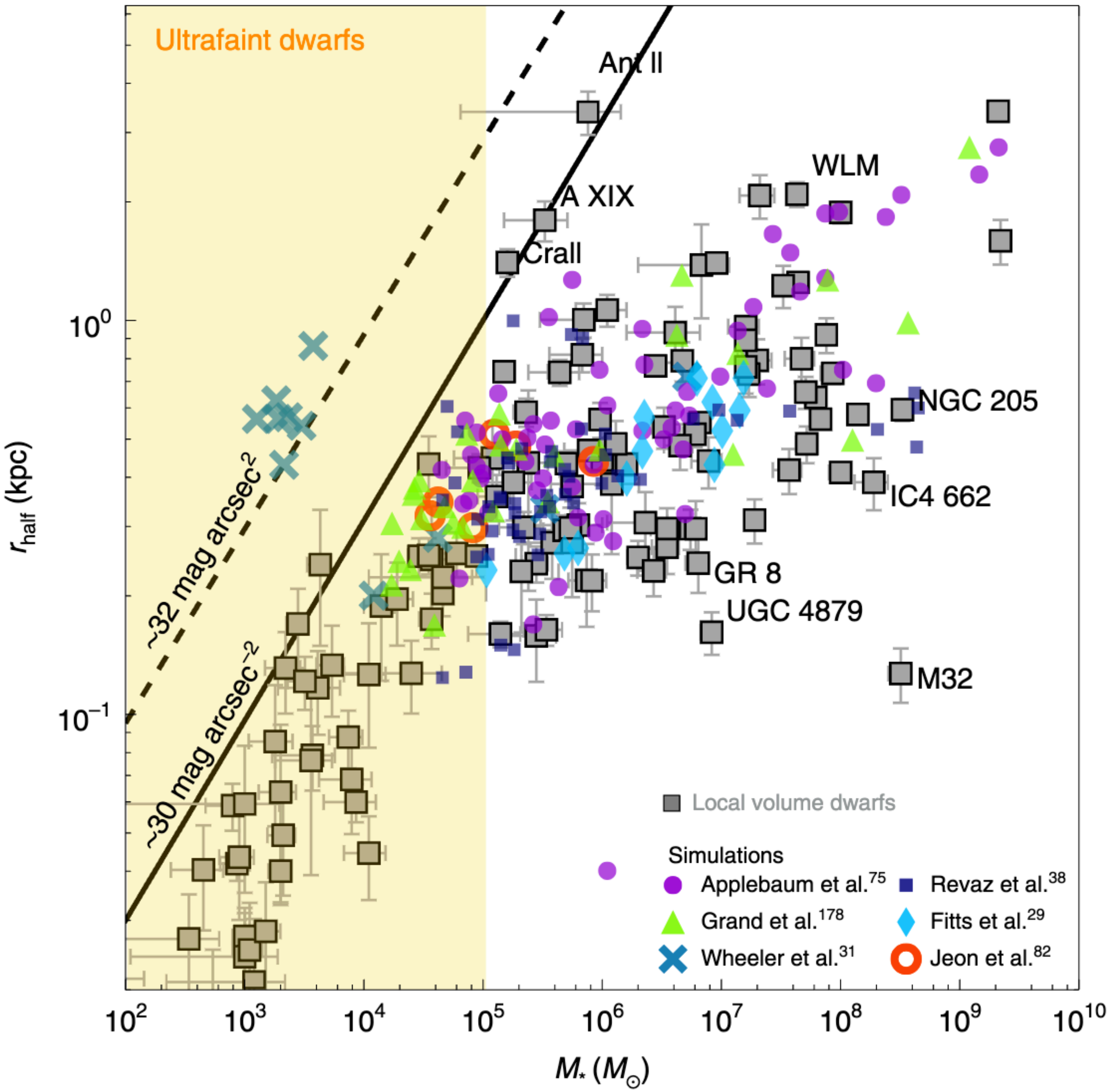


<— more planar

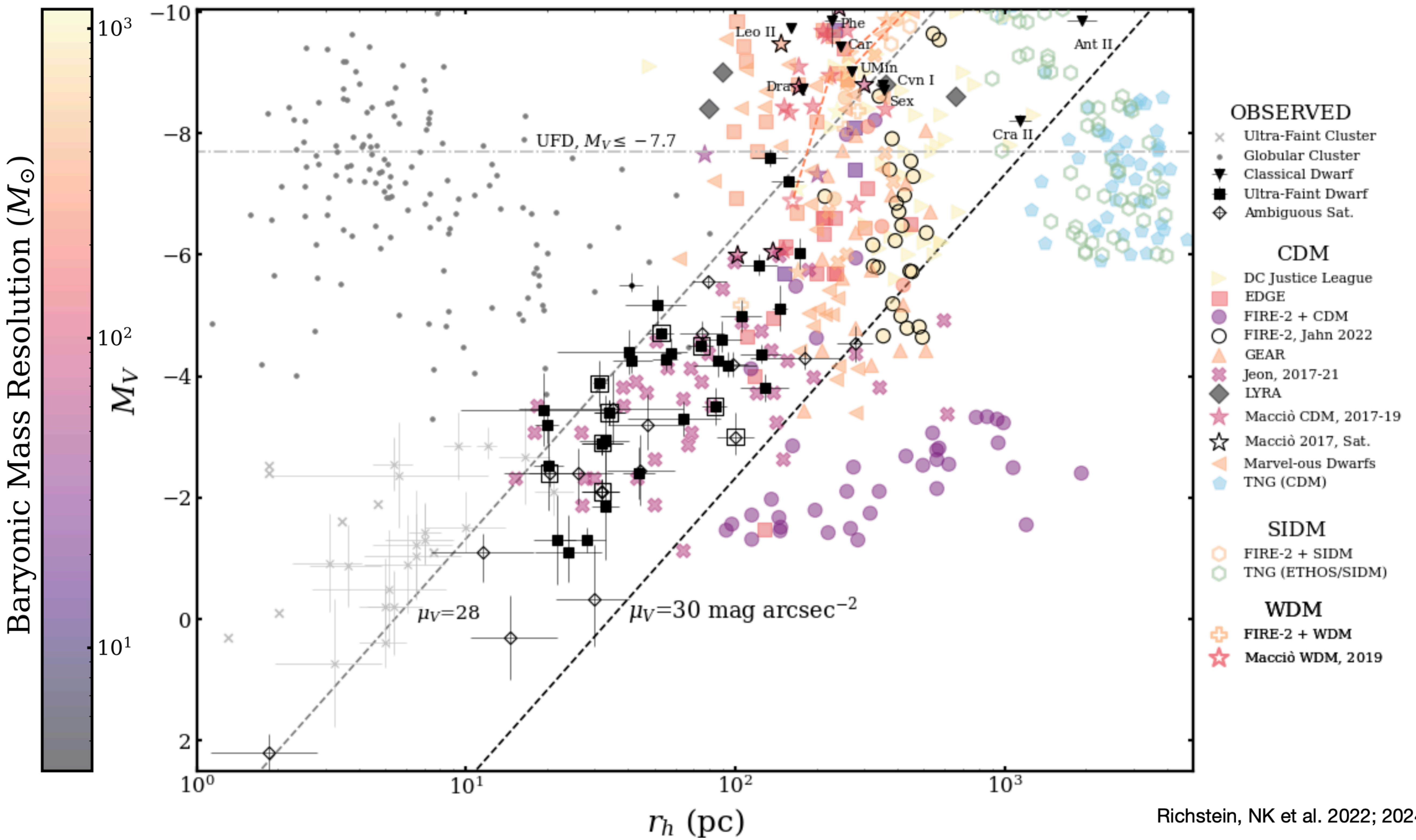
Samuel, Wetzel et al 2021

challenge: diversity of sizes of low-mass galaxies

Sales, Wetzel, Fattahi et al 2022



challenge: sizes of ultra-faint galaxies



Richstein, NK et al. 2022; 2024