

Fossils of the First Galaxies:

*ghost halos, and the
missing massive/bright satellites
problem*

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Preamble

- How small were the first galaxies? How many? ... and how do they look like? Where are the first galaxies today?
- We do not have definitive answers to these questions: formation is **regulated by a variety of feedback processes** (radiative, chemical and mechanical feedback)
- Typical pre-reionization galaxies are too faint to be observed at formation. My collaborators and I have been among the first to focus on identifying their fossil relics in the local universe to test our models, suggesting existence of the ultra-faints dwarfs (Ricotti & Gnedin 2005) before their discovery
- Guided by a set of cosmological simulations I propose three new observational tests of pre-reionization galaxy formation

Outline

Primordial dwarf galaxy formation/evolution:

1. **Pre-reionization evolution:** effects of ionizing radiation on primordial galaxy formation
2. **Post Reionization evolution:** fossils of the first galaxies and ultra-faint dwarfs in the Local Group: TEST#1 and #2
3. **Late time evolution:** gas condensation in isolated minihalos at redshift $z < 1$: TEST#3

Outline

Primordial dwarf galaxy formation/evolution:

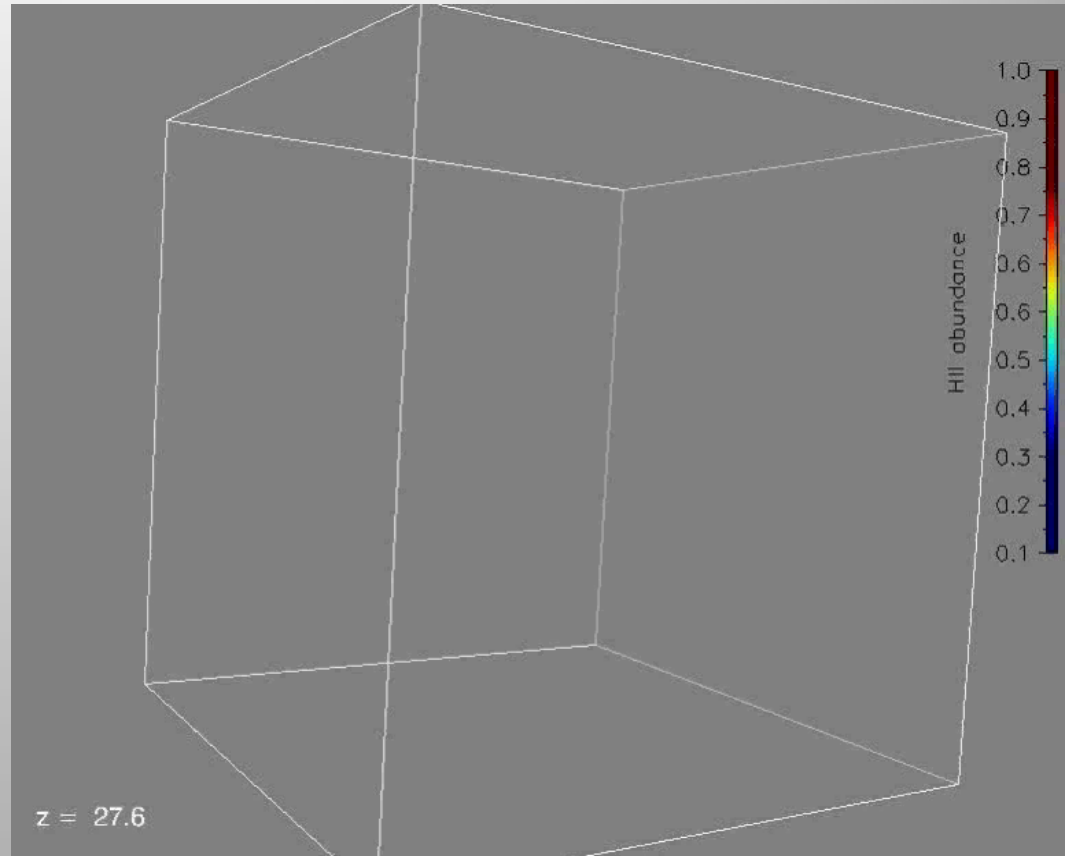
- 1. Pre-reionization evolution:** effects of ionizing radiation on primordial galaxy formation
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Simulations of the first galaxies

Feedback-regulated galaxy formation:

Global SF not sensitive to the sub-grid SFE!
> # of massive stars formed set to a constant value by feedback loops

- 1 Mpc box size
- $10^3 M_{\text{sun}}$ mass res.
- 10 pc spatial resolution
- **3D radiative transfer**
- Run ends at redshift of reionization



Ref: Ricotti, Gnedin & Shull 2002a, 2002b, 2008

What have we learned from the simulations?

1. Self-regulated star formation (insensitive to SFE in Schmidt law)
2. Stochastic SF at small masses
3. Photo-evaporation from internal sources very effective, makes SN feedback that happens later less important
4. Ionizing radiation is important for H₂ formation in relic HII regions and shells in front of ionization fronts (Ricotti et al 2001)
5. Ionizing radiation effects dominate over H₂ dissociating radiation feedback
6. Short repeated bursts of SF, first small dwarfs cannot reionize the IGM

Old results (2001-2002) but still in good qualitative agreement with recent simulations that include similar physics (see John Wise's and Oleg's talks). New simulations coming soon (Parry et al.)

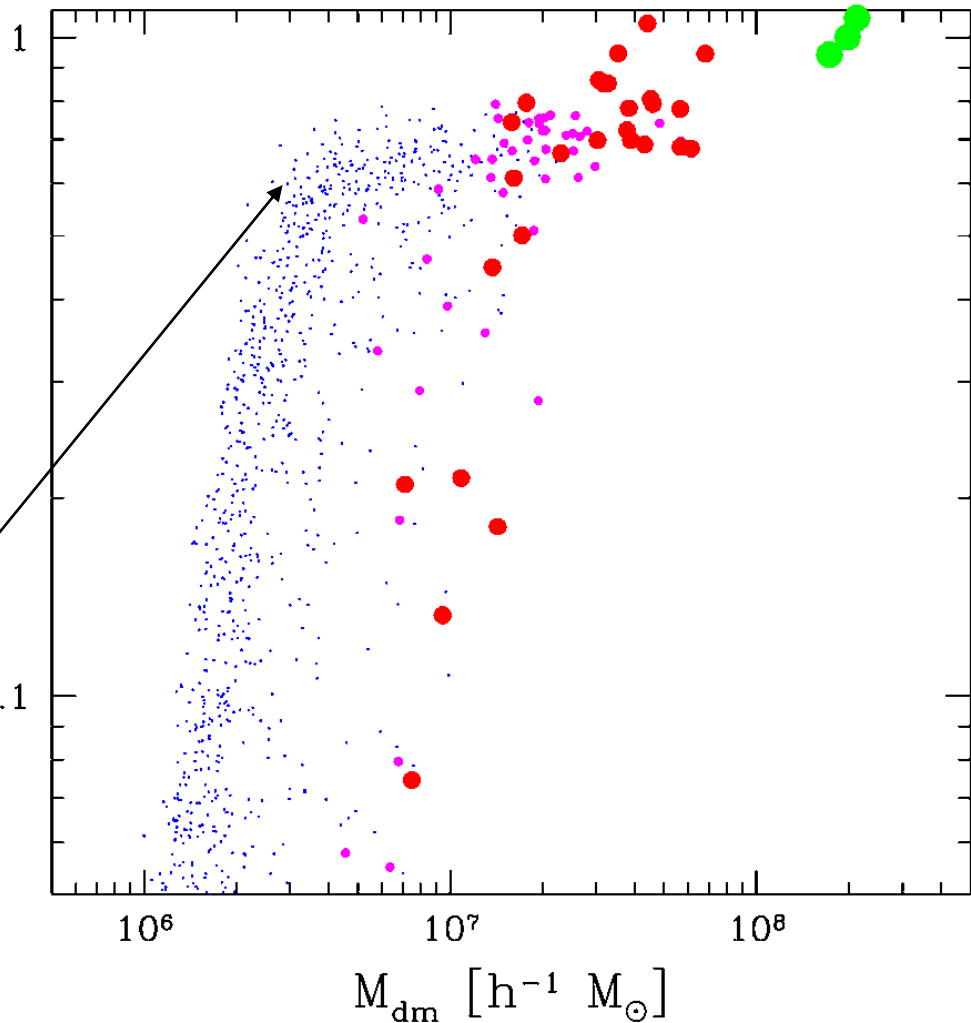
Radiation Feedback: Internal vs. external UV sources

@ redshift $z \sim 15$

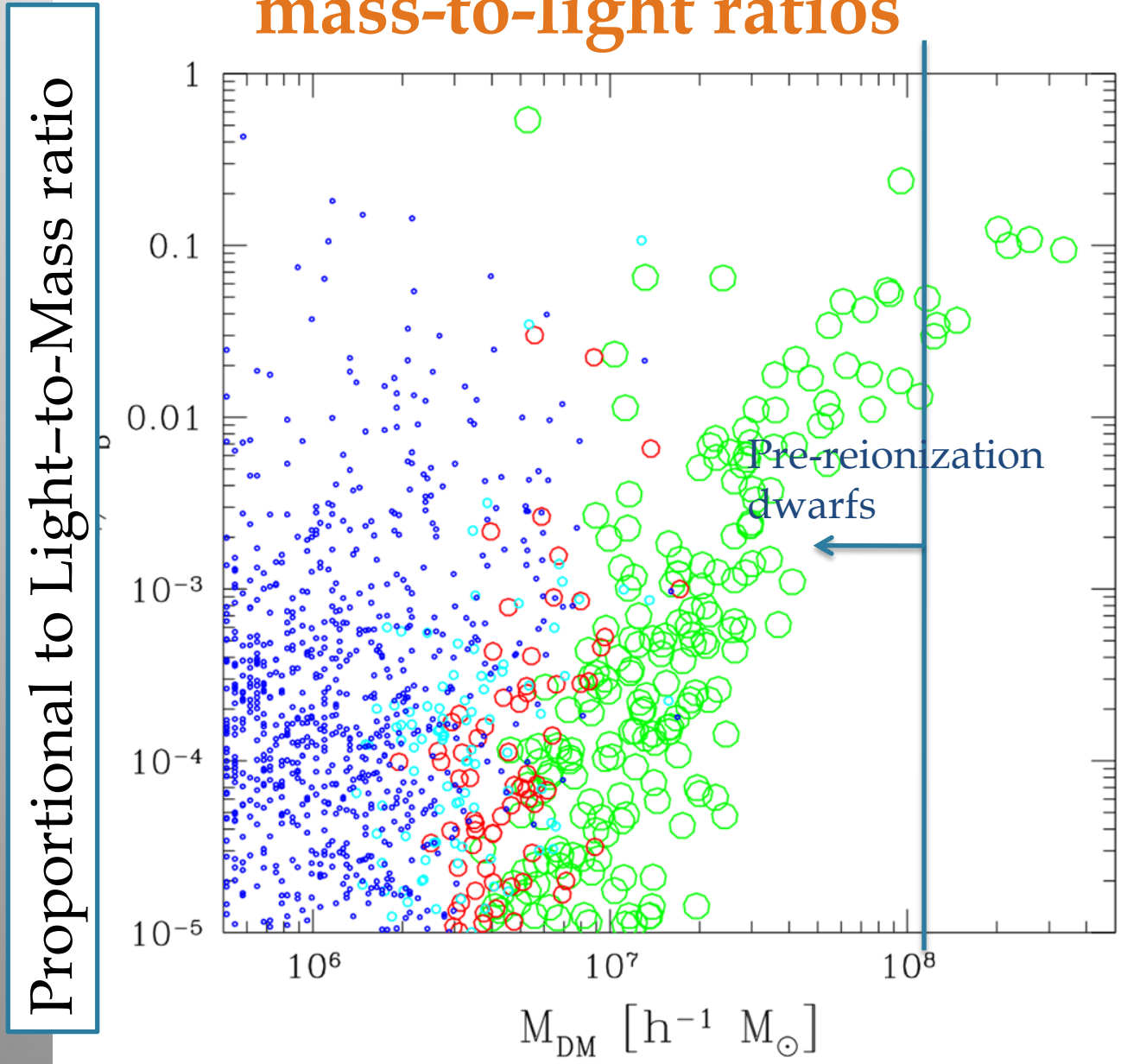
- no stars
- few stars
- more stars
- many stars

Dark galaxies

Fraction of cosmic baryons



First Galaxies: numerous, ultra-faint, stochastic mass-to-light ratios



Outline

Dwarf galaxy formation/evolution: 3-epochs

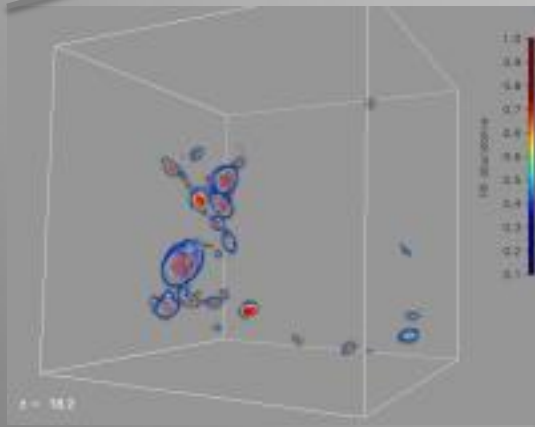
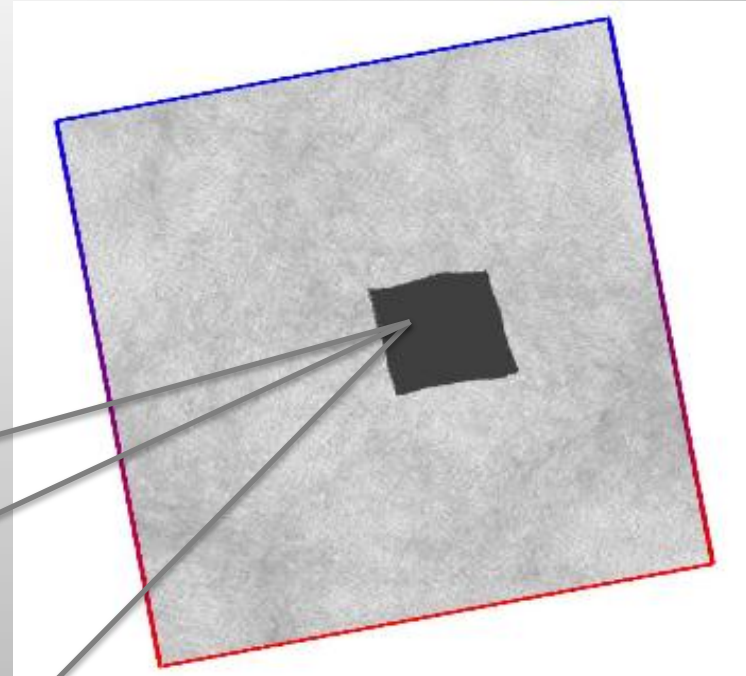
1. **Pre-reionization evolution:** effects of ionizing radiation on primordial galaxy formation
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How can we test these results?

Need to make connection with observations

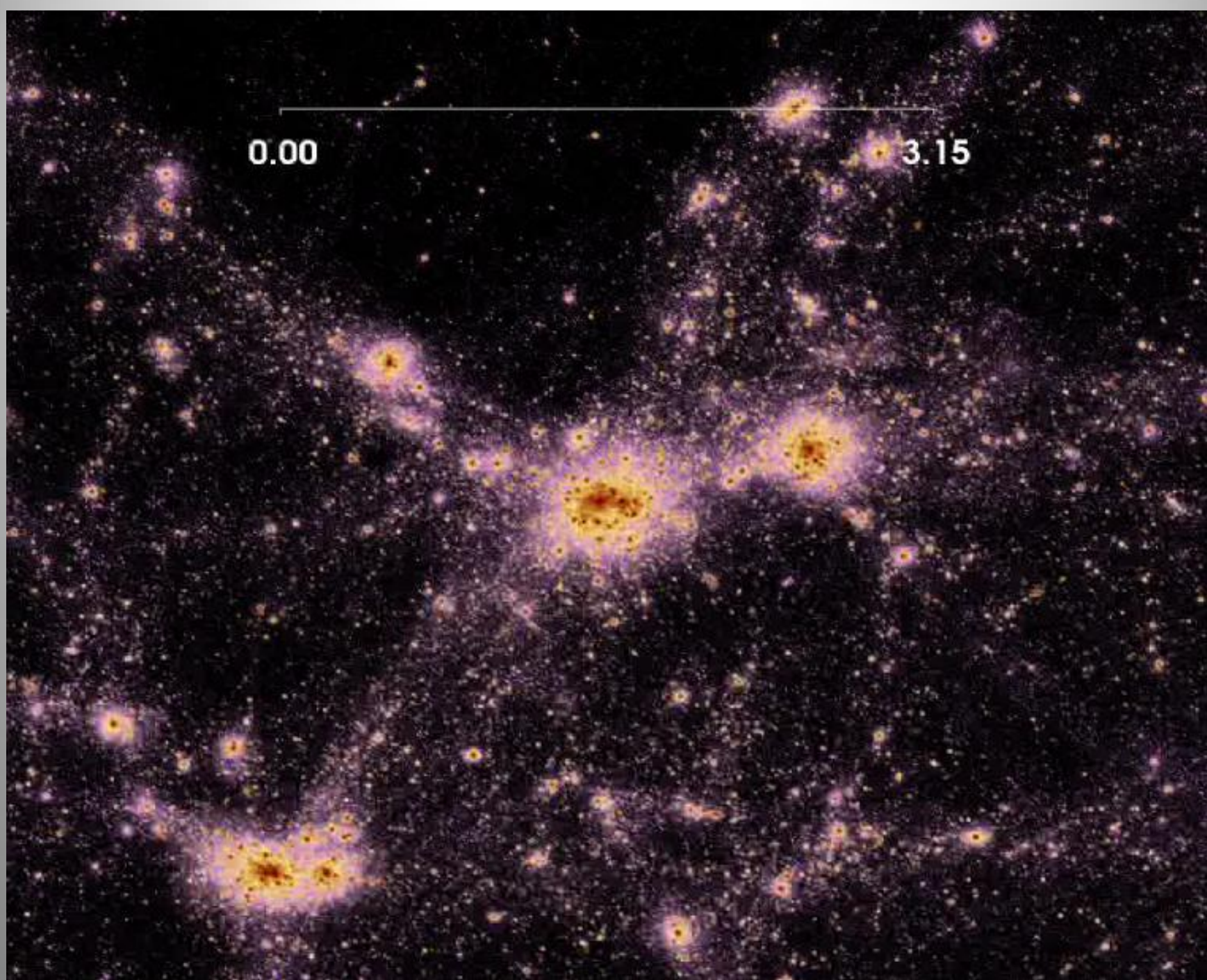
The final pre-reionization output is transformed in a 1 Mpc^3 box of particles.

We duplicate this box, adding perturbations to account for density variations with $l > 1 \text{ Mpc}$.



Each particle in the resulting N-body simulation represents a pre-reionization halo.

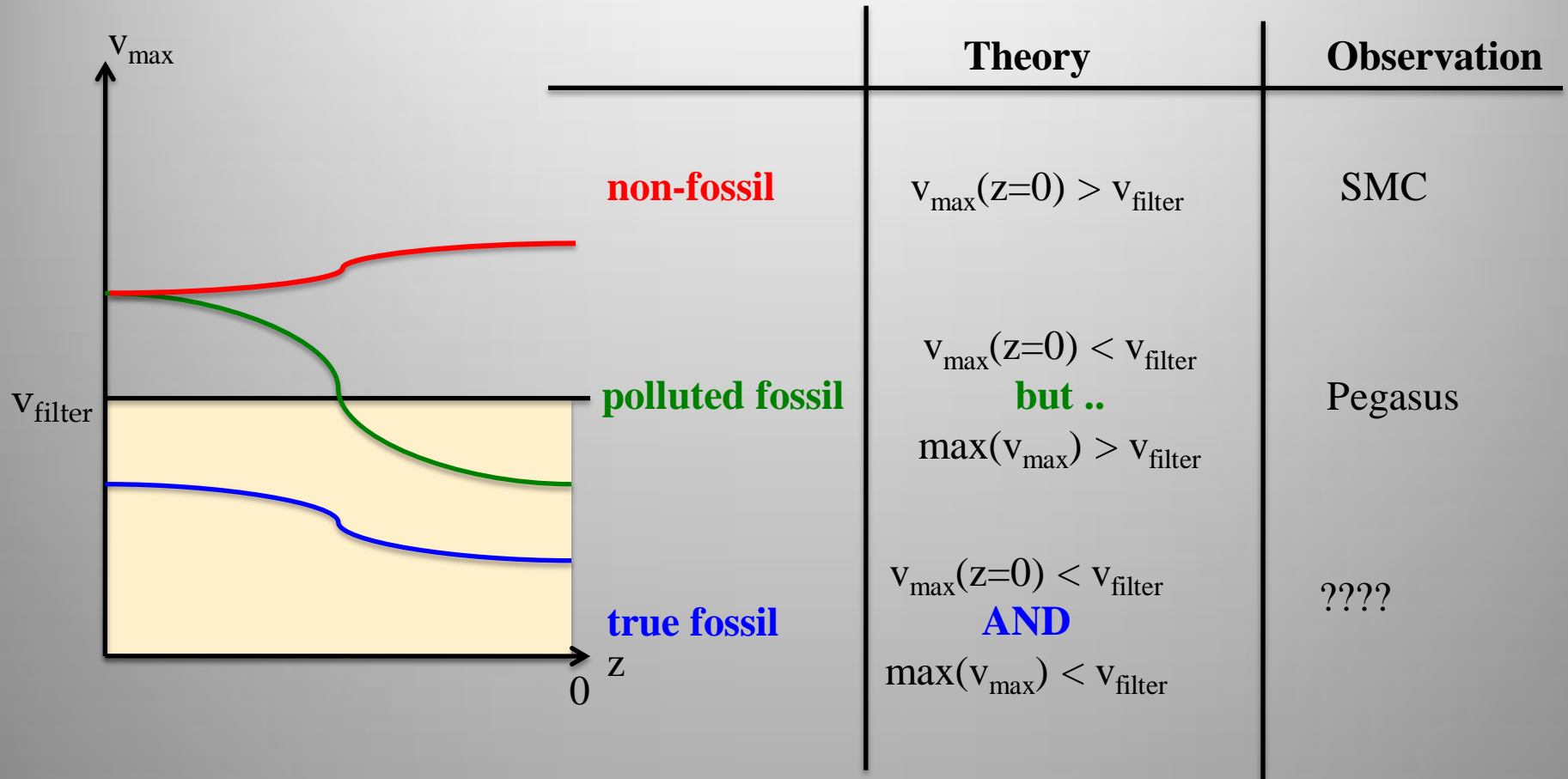
Unique IDs allow us to retrieve the stellar properties at $z = 0$ of halos $> 3 \times 10^7 M_{\odot}$.



0.00

3.15

What is a Fossil?

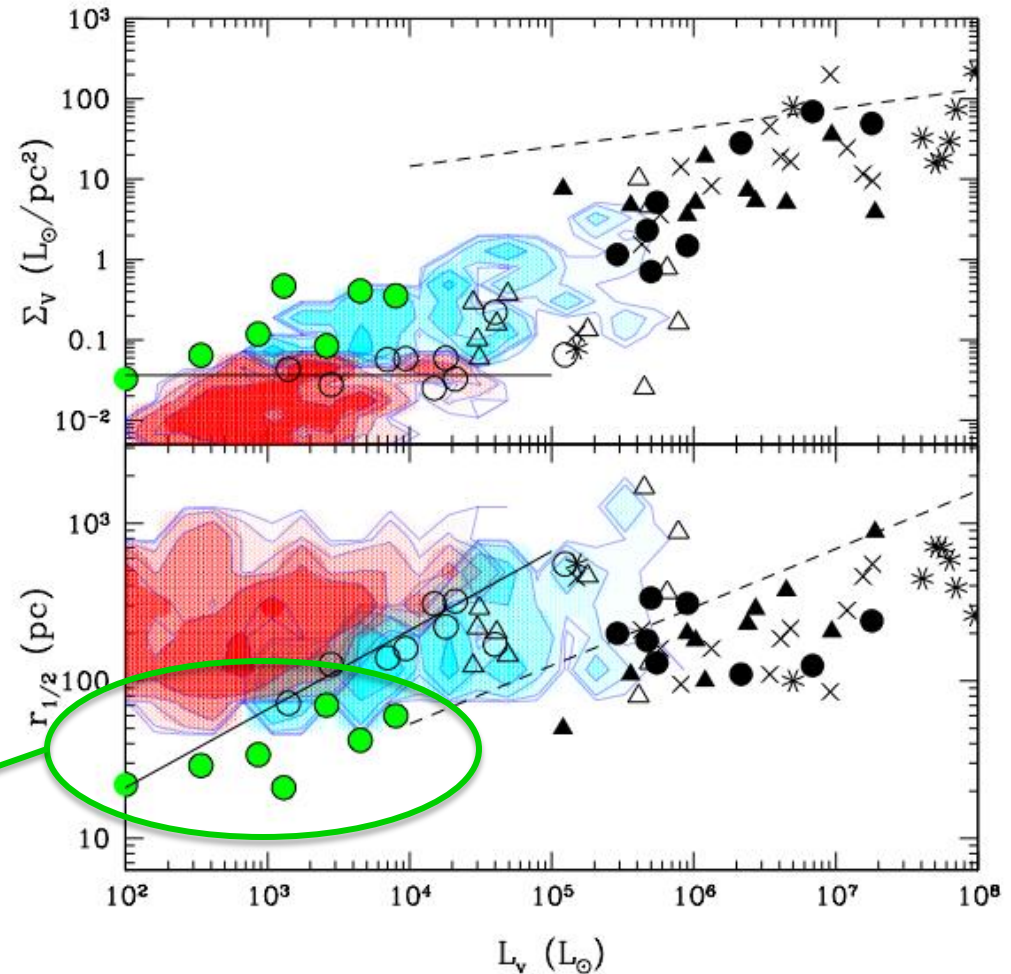


Fiducial value:
 $v_{\text{filter}} \sim 25 \text{ km/s}$

Eg., Gnedin 2000, Hoefft et al 2006, Okamoto et al 2008, Alvarez et al 2009, Guo et al 2010, Busha et al 2010.

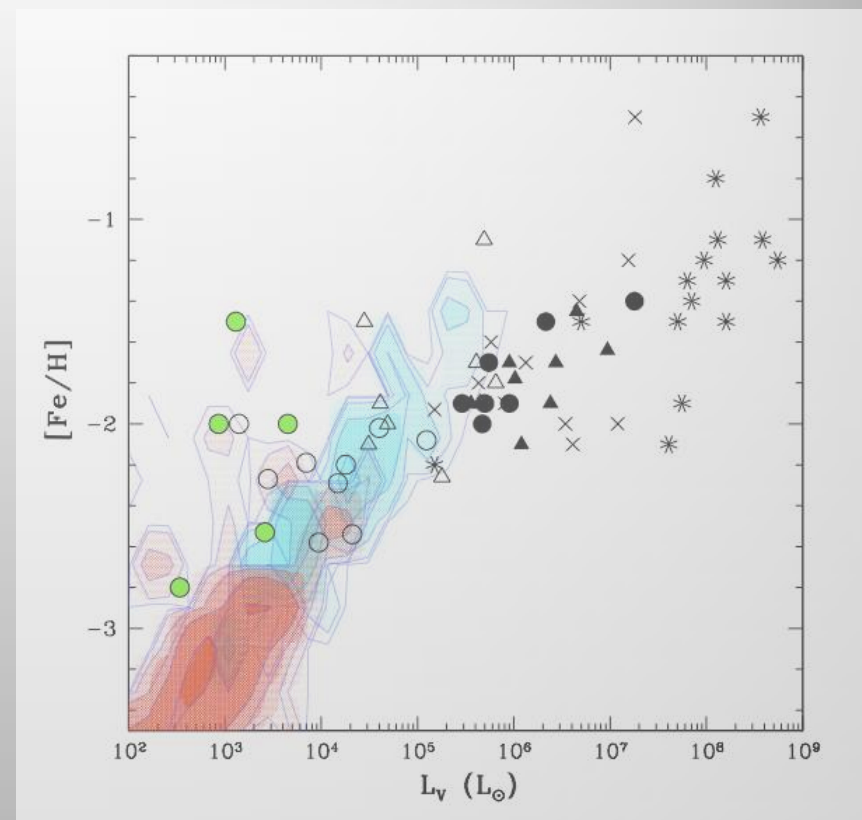
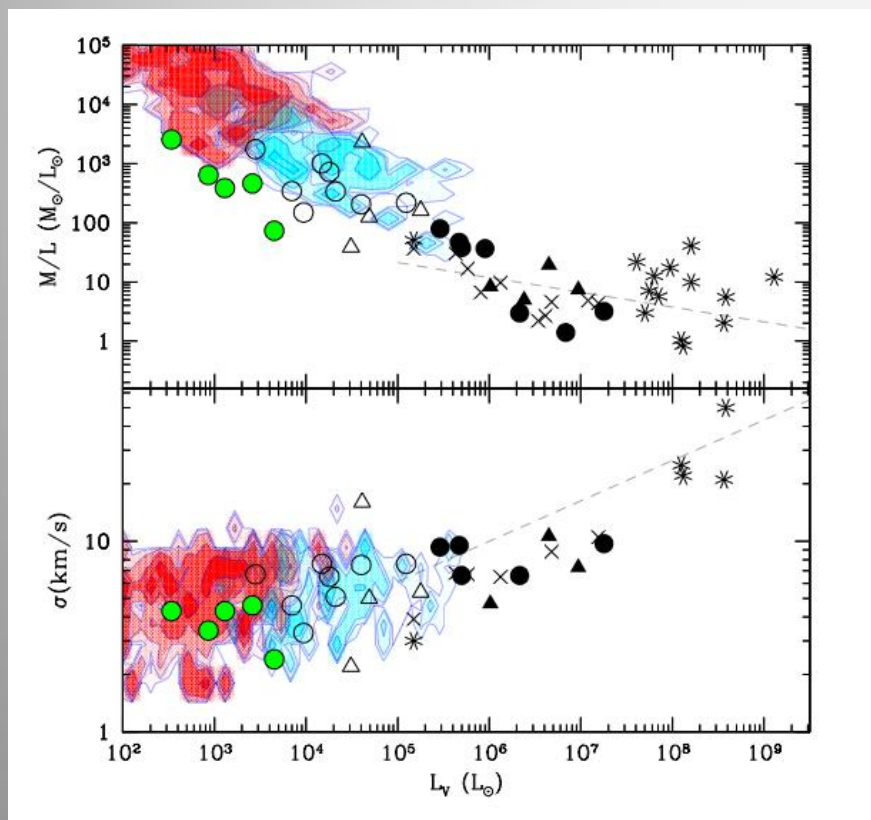
TEST#1: Ultra-Faint Dwarfs as Fossils of the First Galaxies >> Mega-faint dwarfs should exist

- ✱ dIrr
- ✕ dE
- classical MW dSph
- MW ultra-faints
- ▲ classical M31 dSph
- △ M31 ultra-faints
- light blue shaded region: fossils detectable by SDSS
- red shaded region: fossils *not* detectable by SDSS



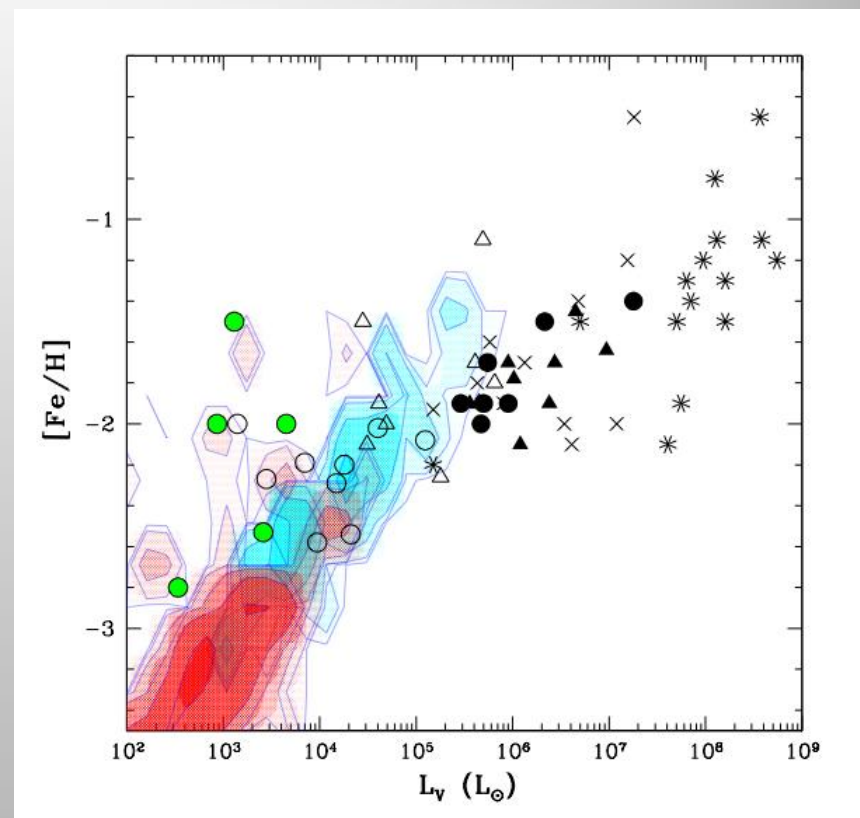
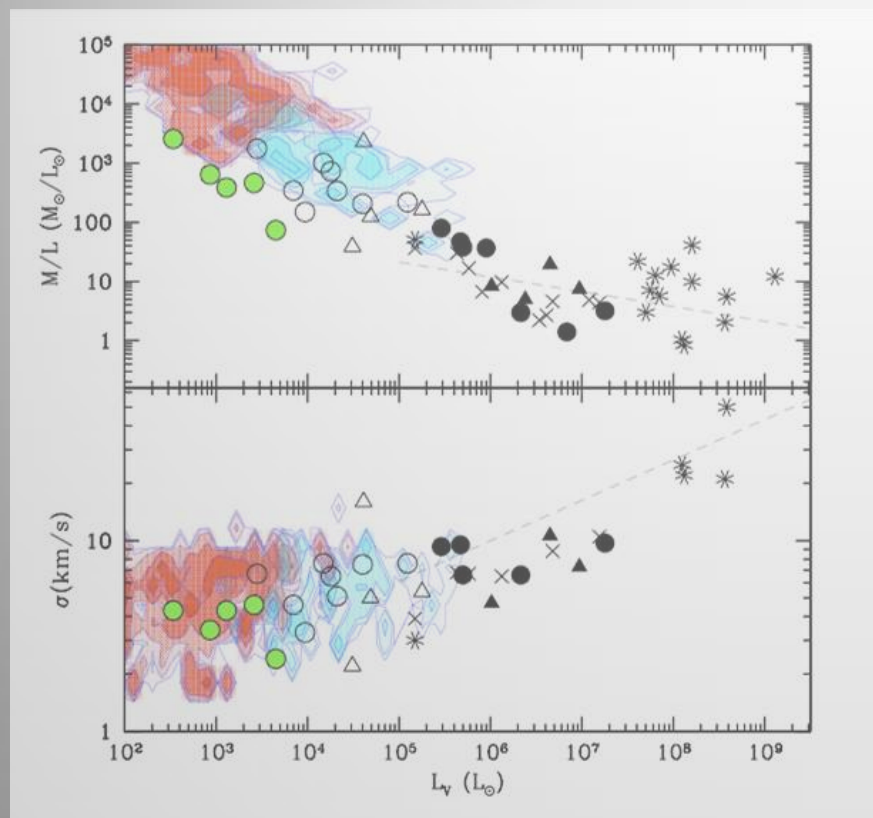
Σ_v and r_{hl} are not in agreement with predictions for unstripped fossils.

Ultra-Faint Dwarfs as Fossils of the First Galaxies



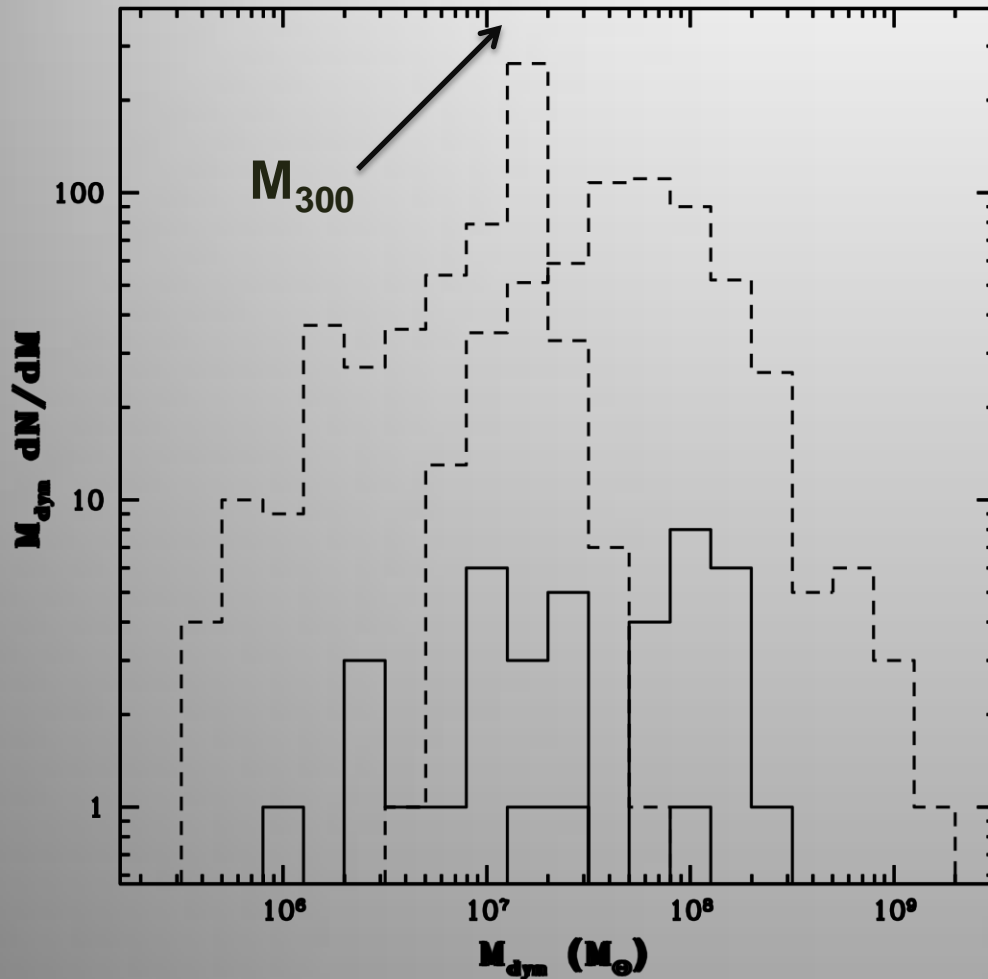
Bovill & Ricotti (2009, 2011)

Ultra-Faint Dwarfs as Fossils of the First Galaxies



Bovill & Ricotti (2009, 2011)

Mass Function of Fossils: common mass scale

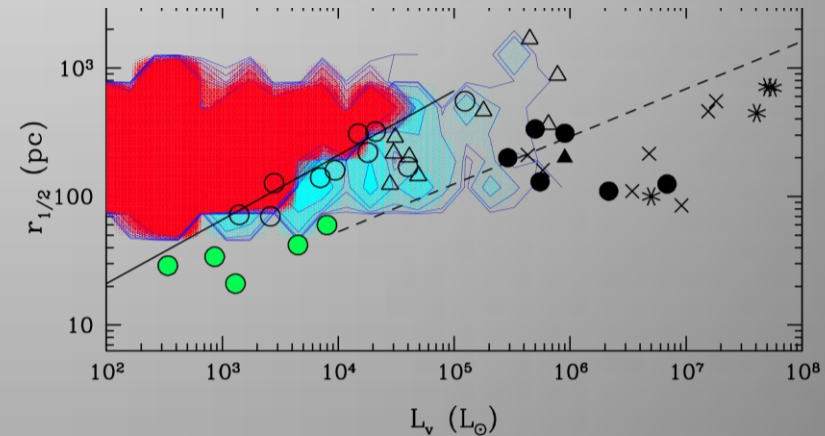


Bovill & Ricotti (2011a)

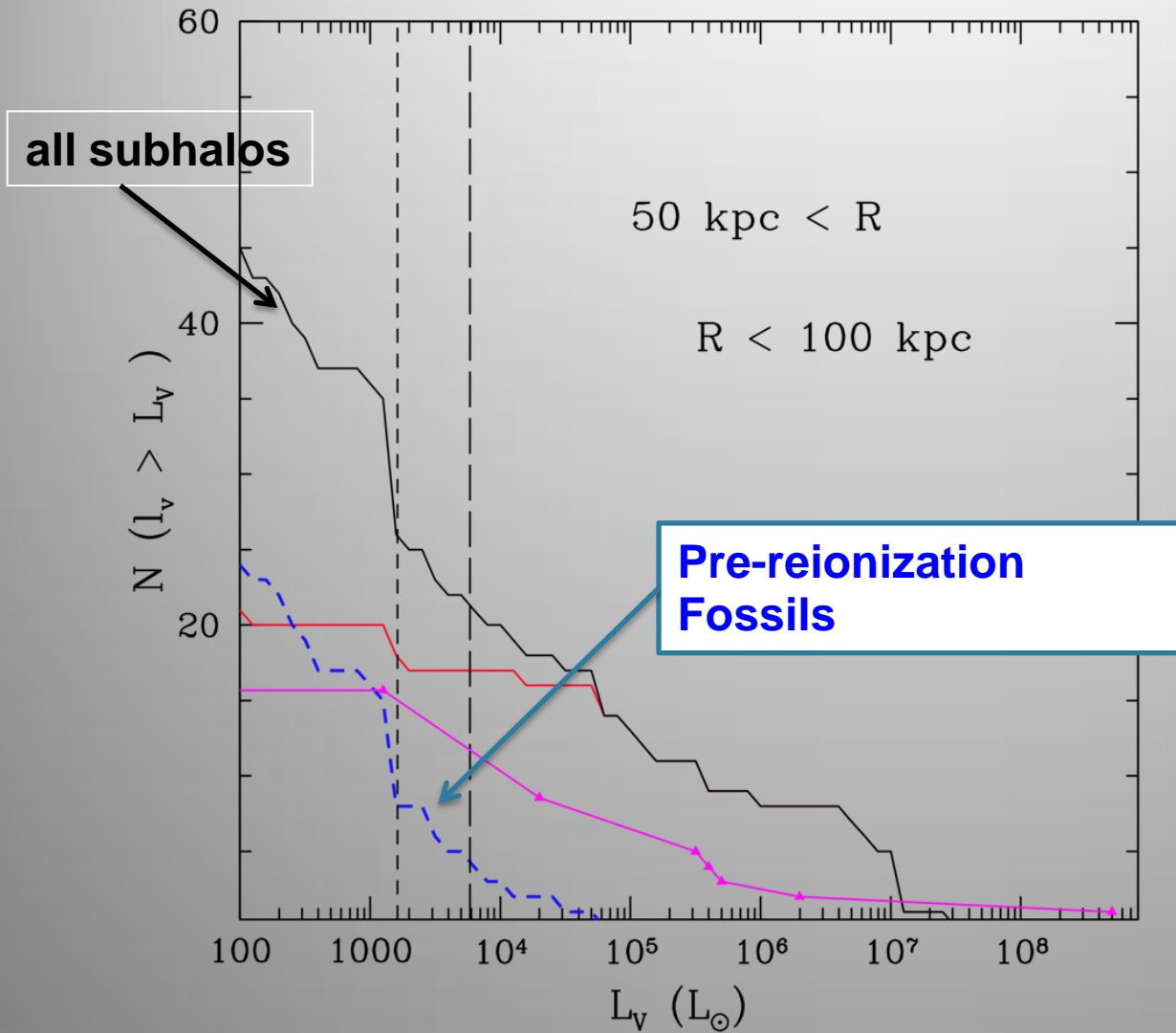
M_{dm} – from halo finder

$M_{\text{dyn}} = M_{1/2}$ from Wolf et al (2010)

Our $r_{\text{hl}} \sim 80\text{-}1000$ pc



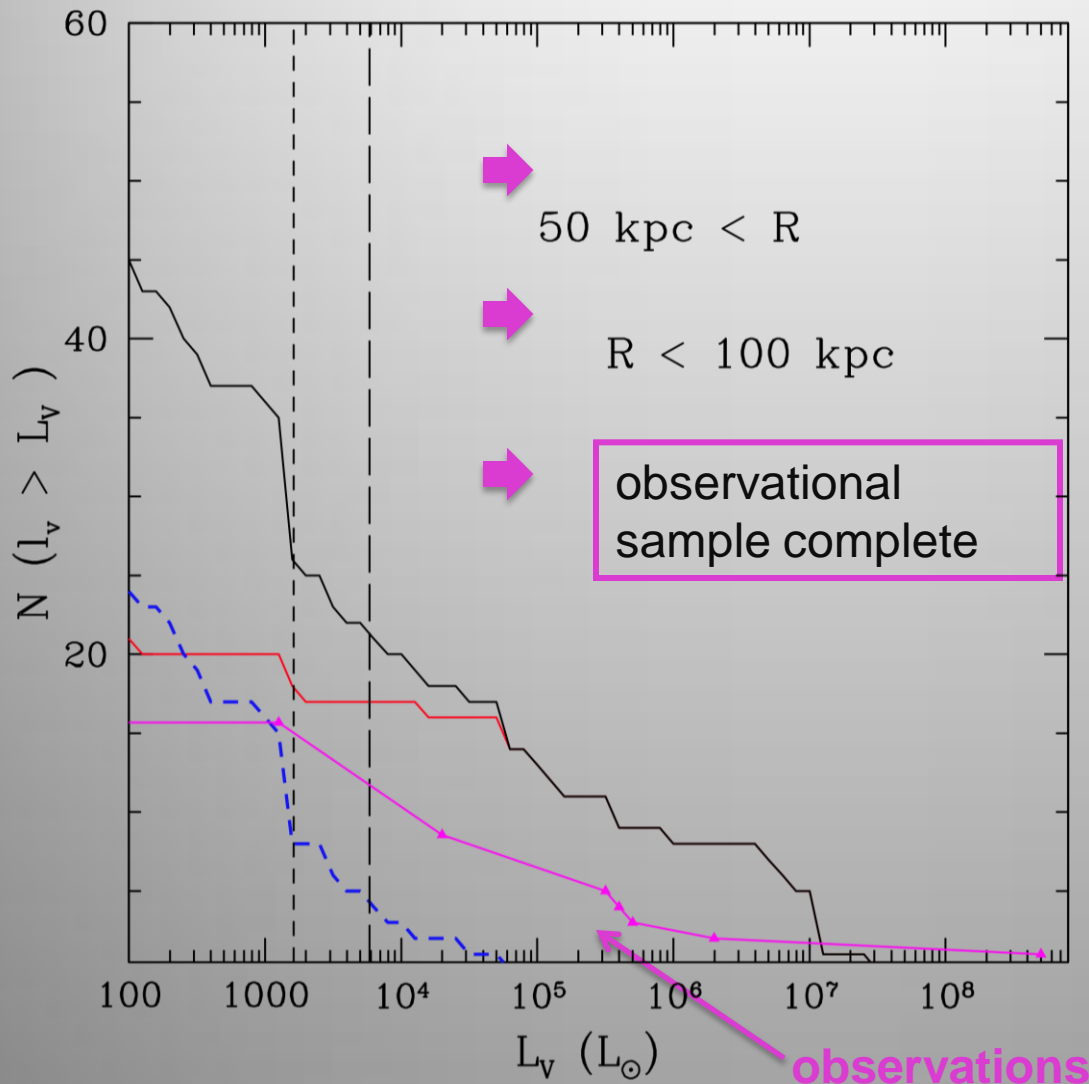
“Primordial” Cumulative Luminosity Function



Dominated by **fossils** for $L_v < \sim 10^4 L_\odot$, and by **non-fossils** for $L_v > \sim 10^4 L_\odot$.

There is a problem!

(too many fossil stars in massive dwarfs)



Includes all known dwarfs with $R > 50$ kpc.

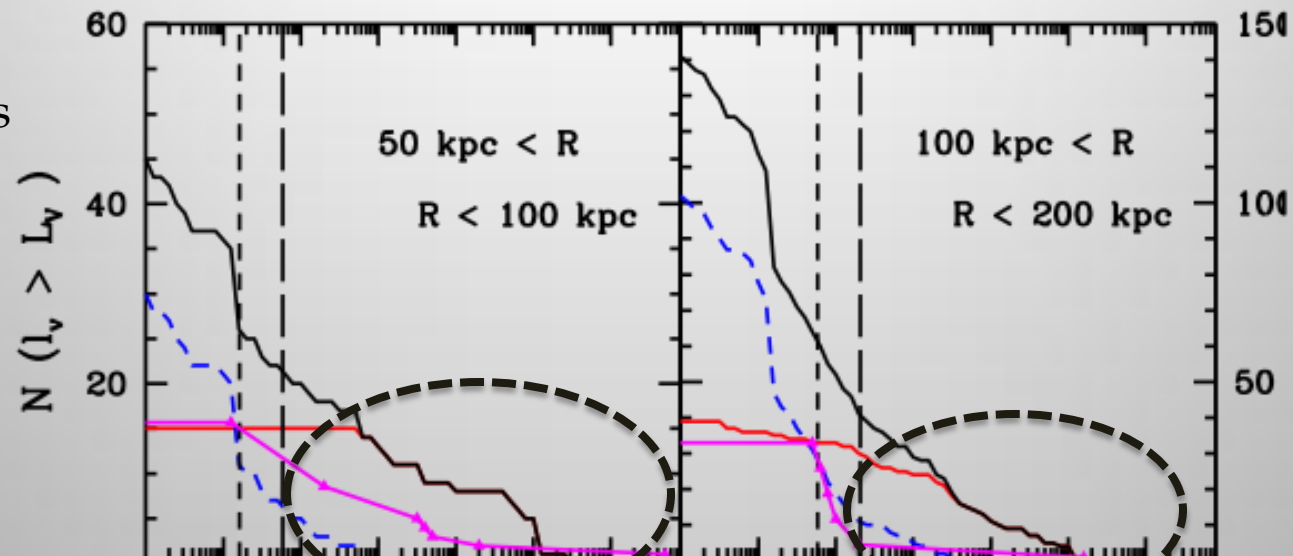
Ultra-faint sample is corrected only for SDSS sky coverage (Walsh et al, 2009)

Sample is complete to the right of the dashed lines.

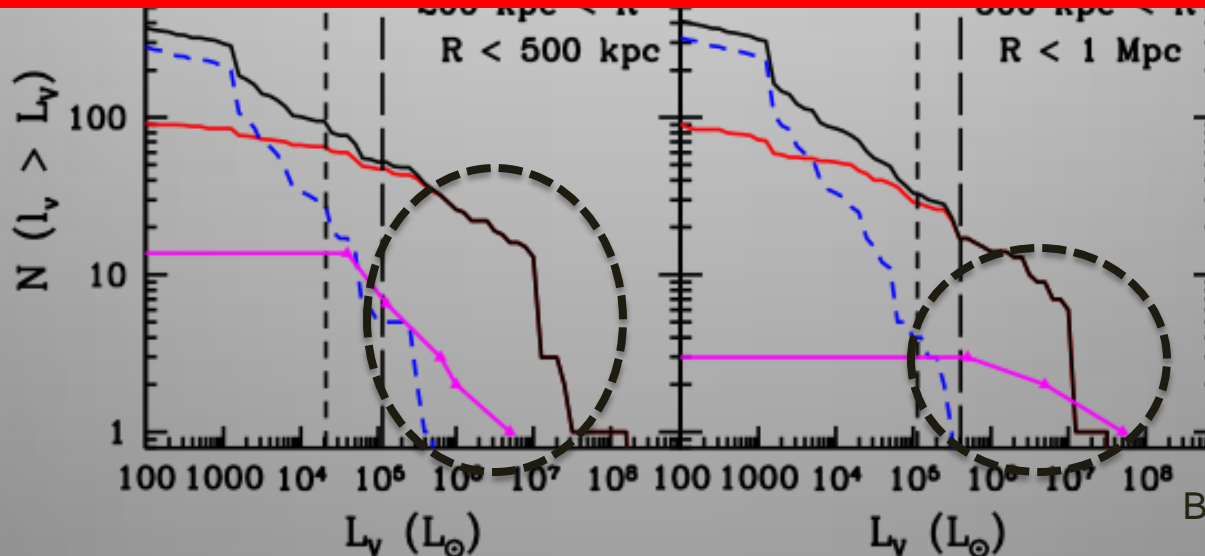
See also Michael Boylan-Kolchin's talk

The “Bright/massive” Satellites Problem

$V_{\text{filt}} = 25 \text{ km/s}$



Where are the bright/massive satellites!?

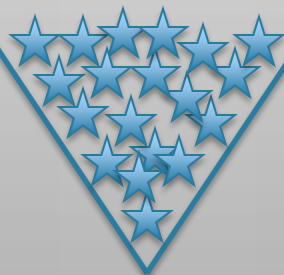
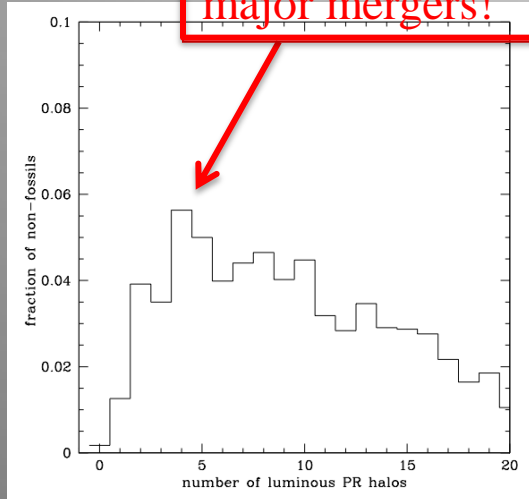


A partial solution to the problem: Ghost Halos

Fossil Halo around the Non-Fossil (massive) dwarfs

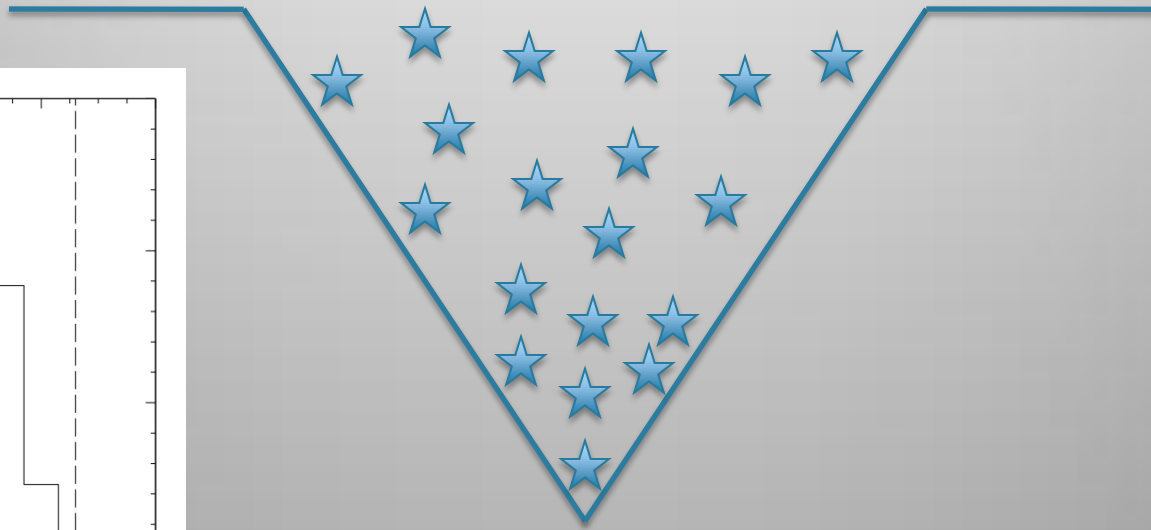
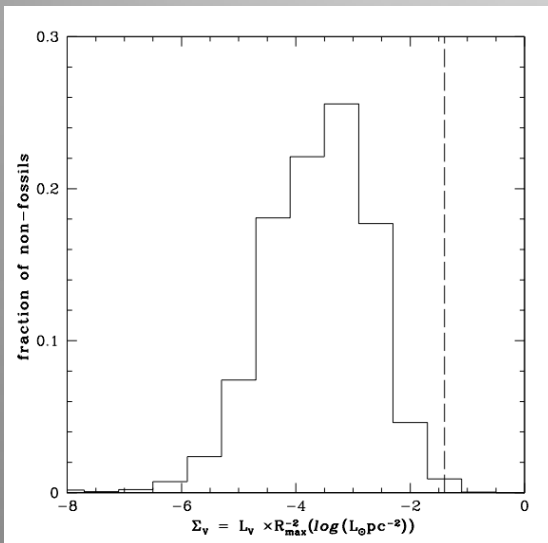
Stars initially form at the center of a dark matter halo.

Majority of the
non-fossils have
undergone > 4-5
major mergers!



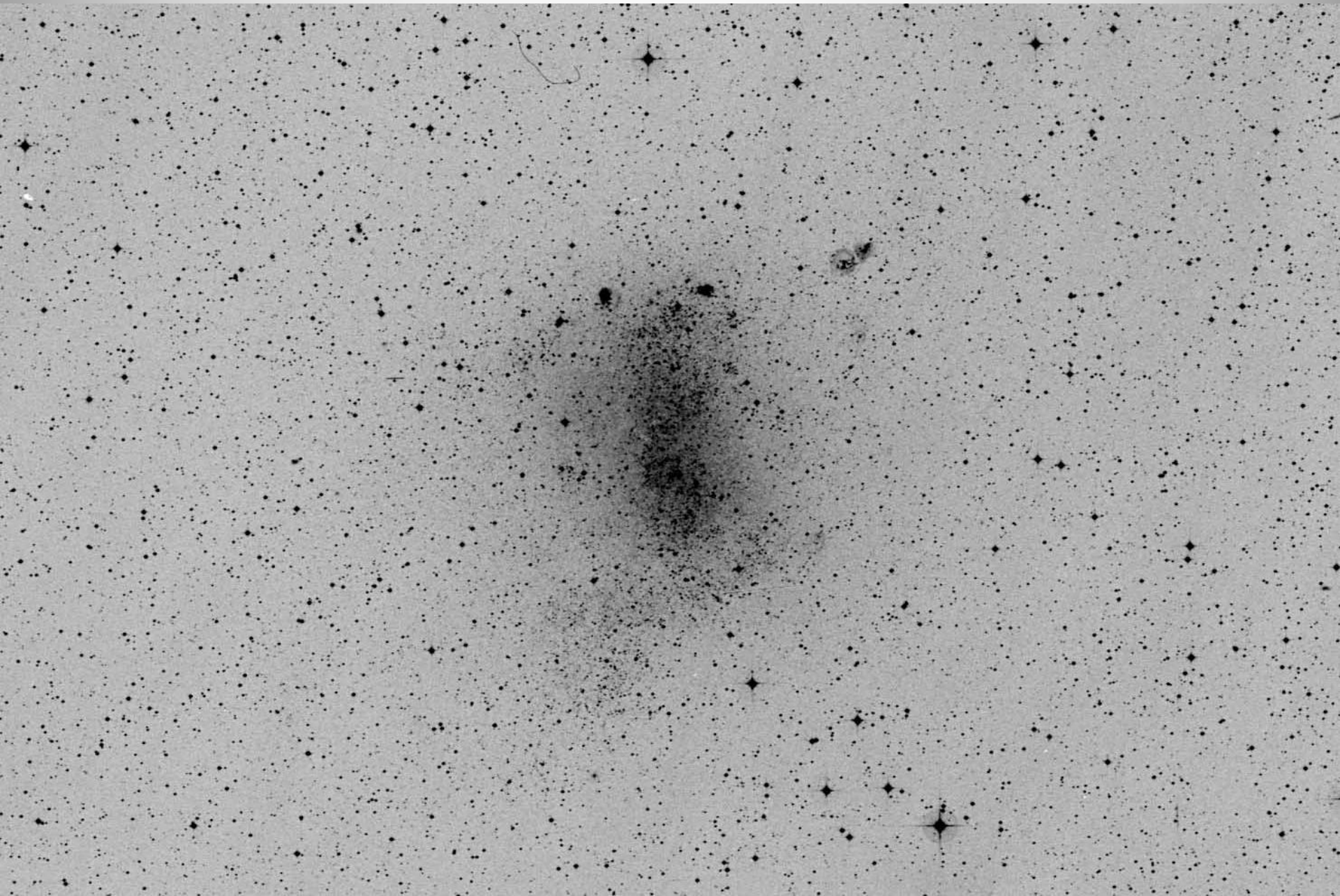
TEST#2: Ghost Halos

Kinetic energy from the repeated collisions heats the primordial stellar population.

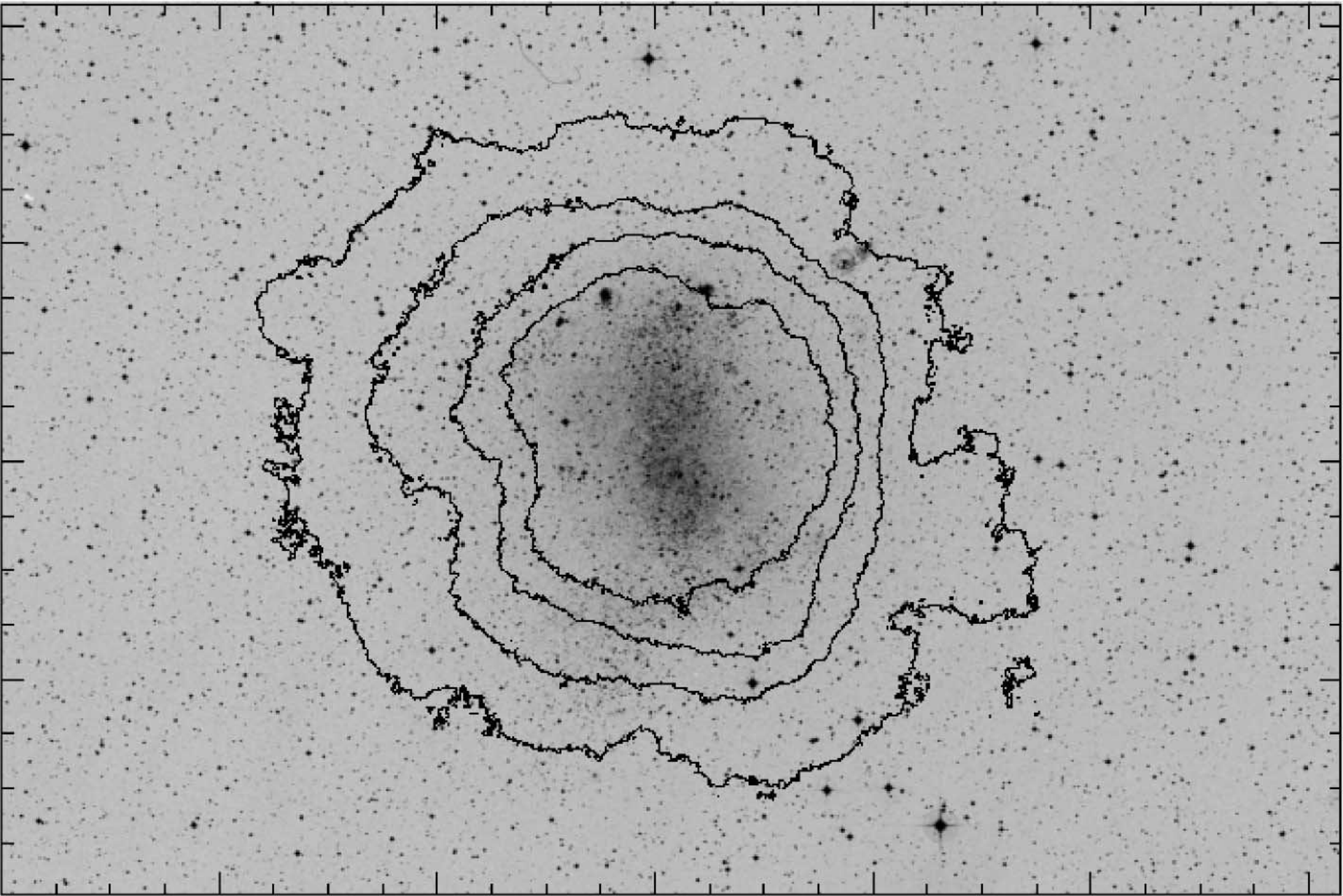


Stars at edge of dark matter halo are more easily stripped by future interactions, depleting the halo of its pre-reionization population.

NGC 6822



NGC 6822 (Ghost halo?)



But can the most massive MW satellites be so dark?

What about SF after reionization?

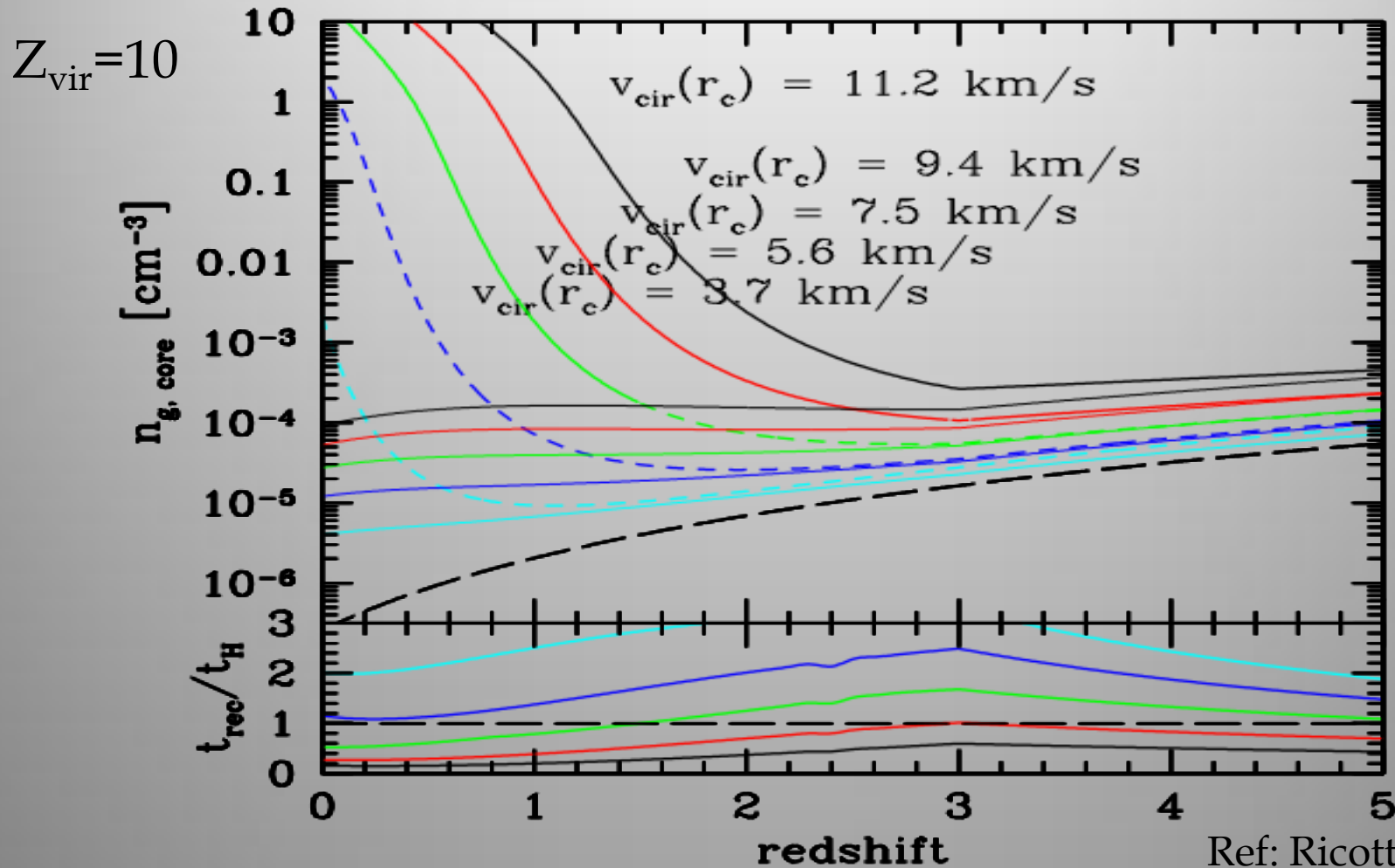
- One possible solution would be if massive dwarfs form stars less efficiently than the first small mass dwarfs (different feedback loops). But SF is needed for reionization!
- Another solution is if they loose most of their stars: perhaps globular cluster systems is the main mode of SF in these dwarfs (Ricotti 2002, Katz & Ricotti, in prep). GC systems can be stripped easily as the dwarf pass near the galactic center.

Outline

Dwarf galaxy formation/evolution: 3-epochs

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Gas condensation onto isolated mini-halos



Ref: Ricotti 2009

TEST#3: First galaxies and “dark galaxies” in local voids

- Minihalos virialized before reionization, that evolve to $z=0$ in the low-density IGM, may have a late phase of gas accretion and possibly star formation (e.g., Leo T)

Ref: Ricotti 2009



Summary

Where are the First Galaxies?

- ✓ **Some ultra-faint dwarfs may be “true pre-reionization fossils,”** if so we have detected only a small fraction of the satellites, LSST, PanSTARRS, and SkyMapper will see a lot more to higher distances from the Milky Way center.

- 1. TEST#1: Simulations suggest the existence of a population of “mega-faint” dwarfs with lower surface brightness than currently detectable with SDSS

- 2. TEST#2: There should be an extended “ghost halo” of stripped fossils around isolated dwarfs (NGC6822?)

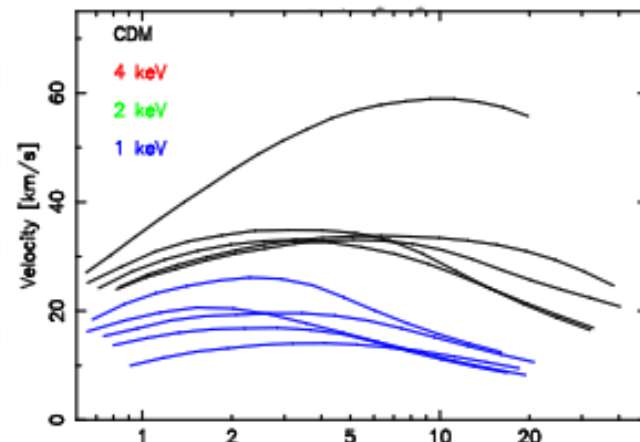
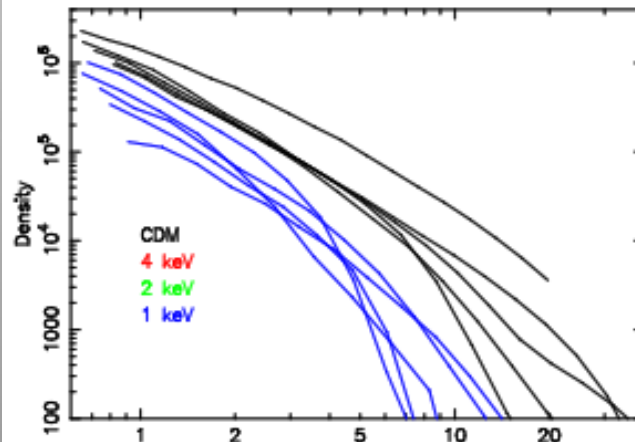
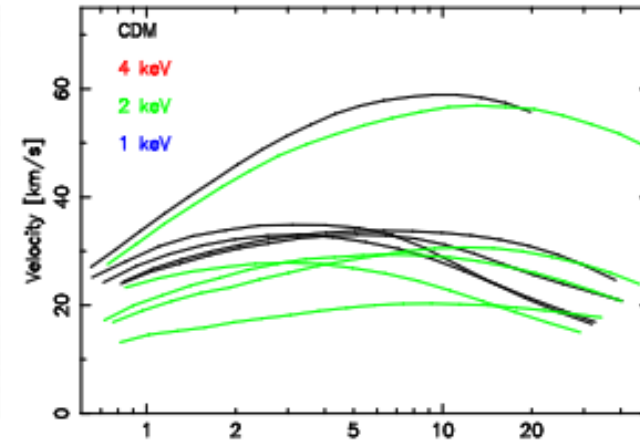
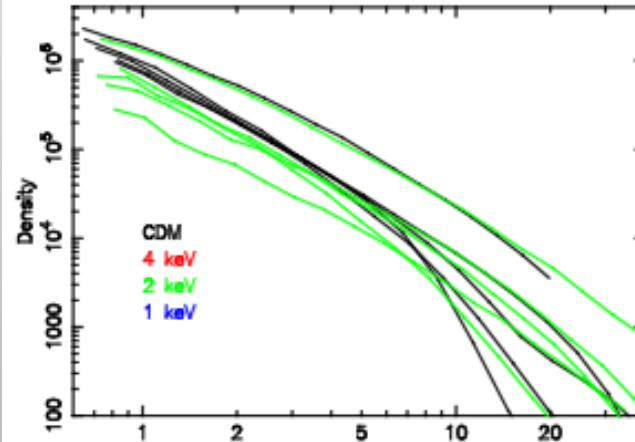
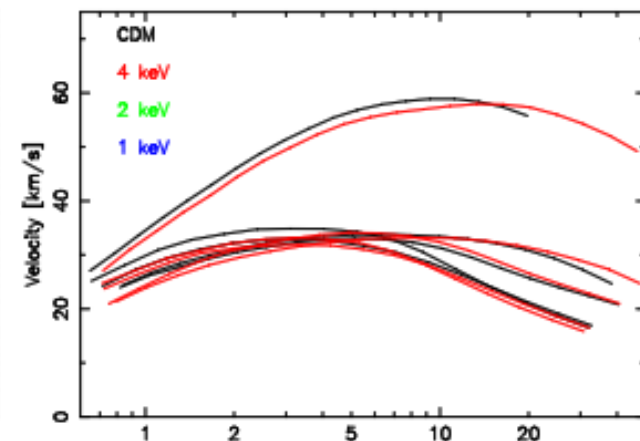
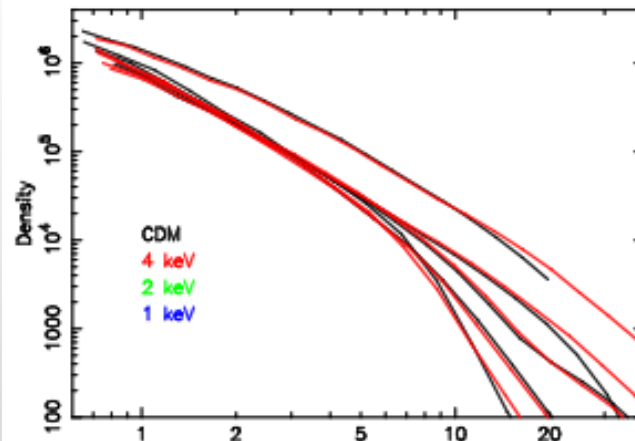
- 3. TEST#3: Late time gas condensation in minihalos may help finding fossils and “dark galaxies” in the local voids
 - 1) Pre-reionization fossils may have bimodal SFH
 - 2) Dark mini-halos may accrete gas for the first time at $z < 1$. Compact HVCs or undiscovered population?

BACKUP SLIDES

WDM

Simulations:

- Velocity and density profiles of the 5 most massive satellites



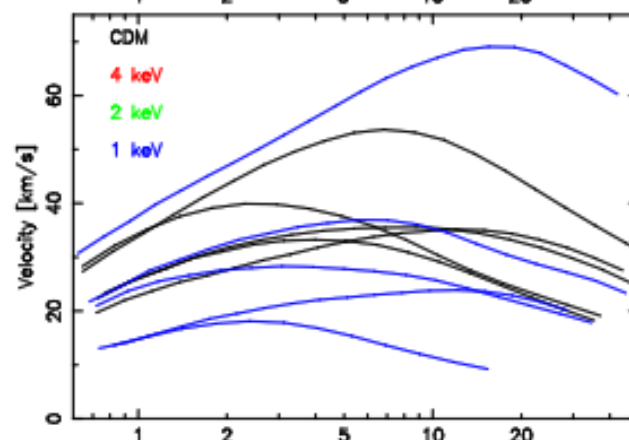
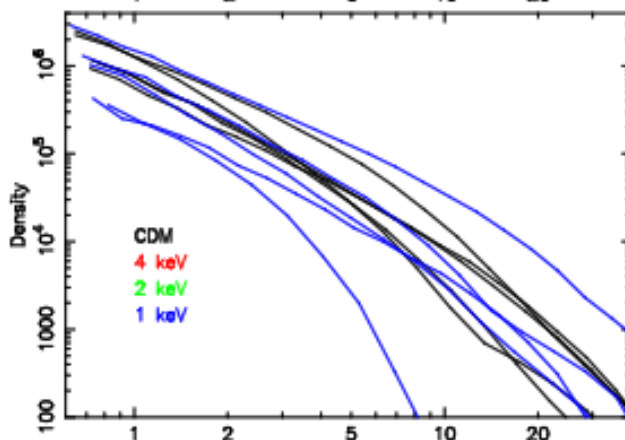
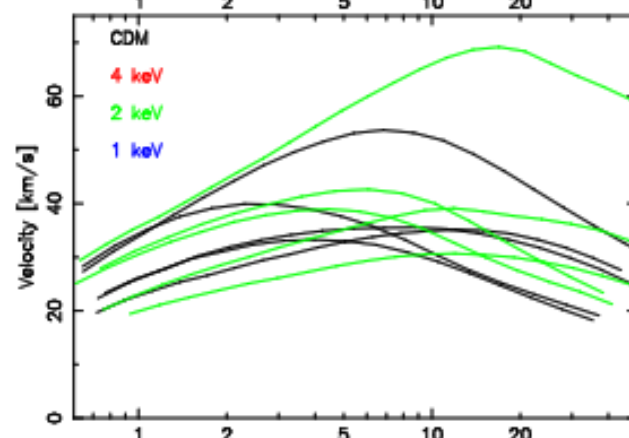
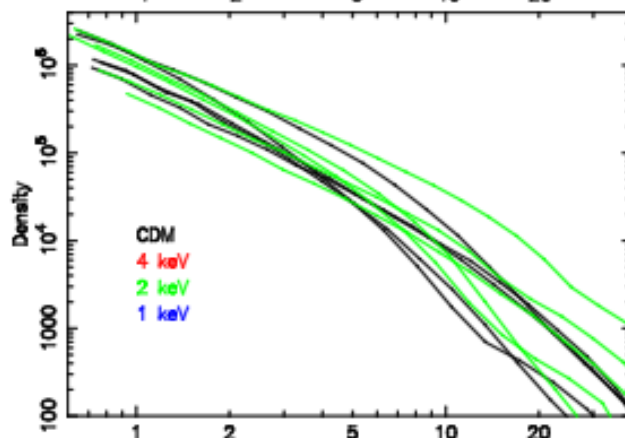
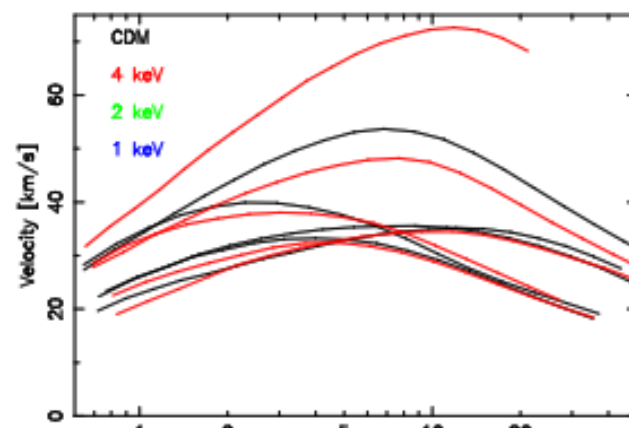
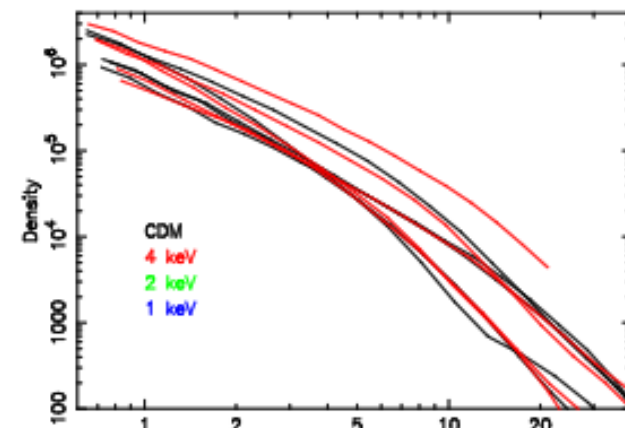
Radius [kpc]

Radius [kpc]

WDM

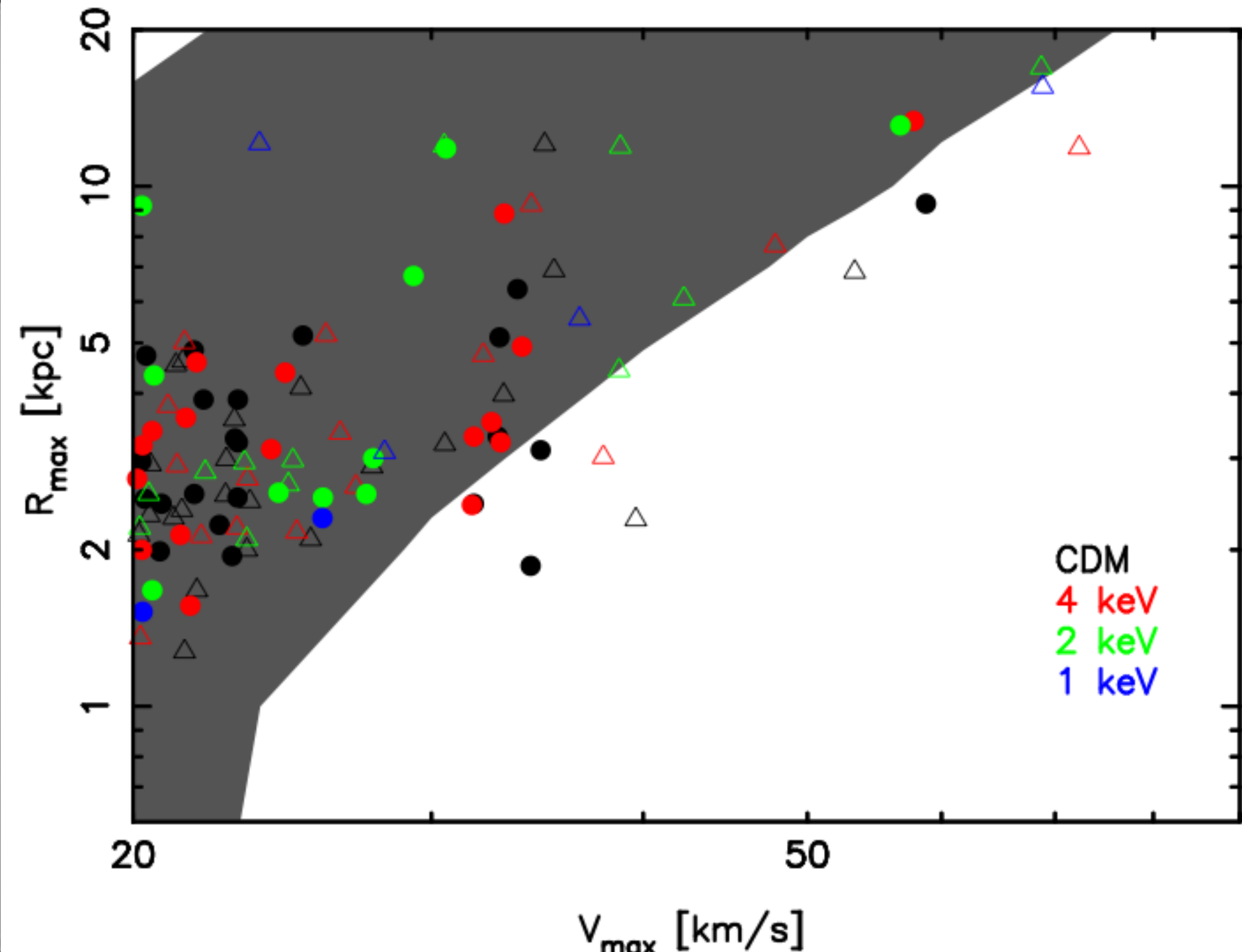
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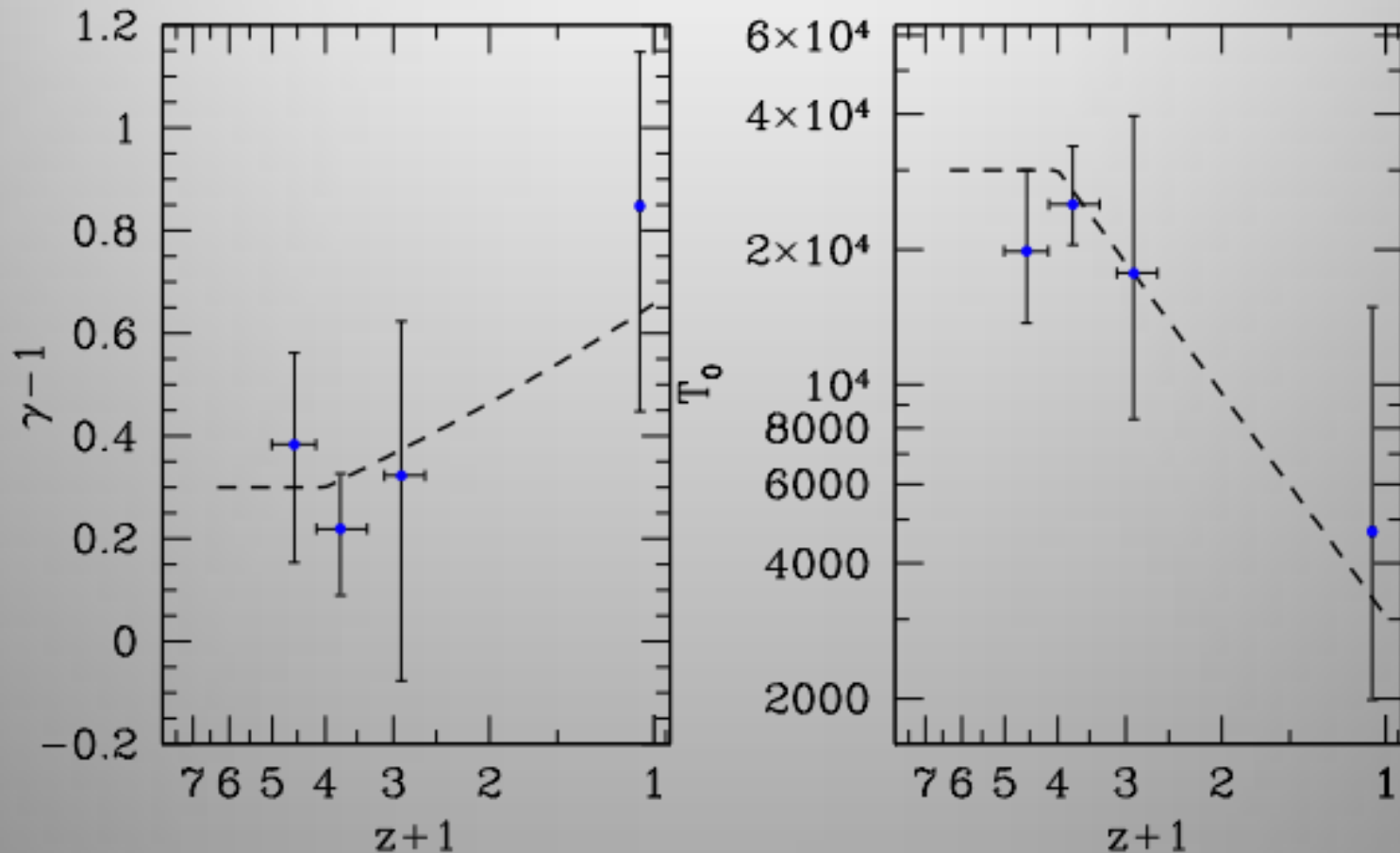
Radius [kpc]

Radius [kpc]



Evolution of the IGM temperature

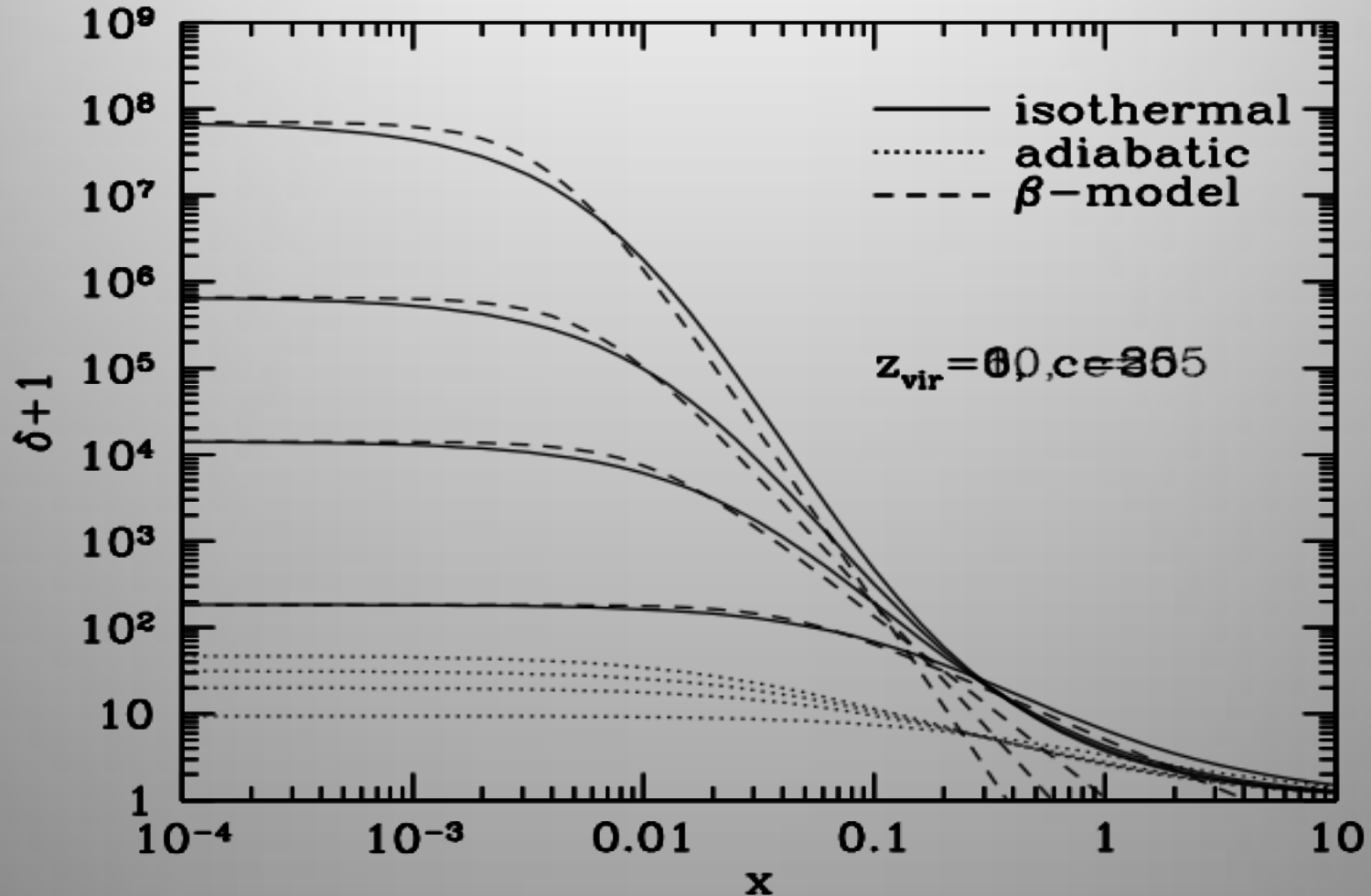
(from observations of the Lyman-alpha forest)



Ref: Ricotti, Gnedin & Shull 2000

Gas density profile in NFW potential

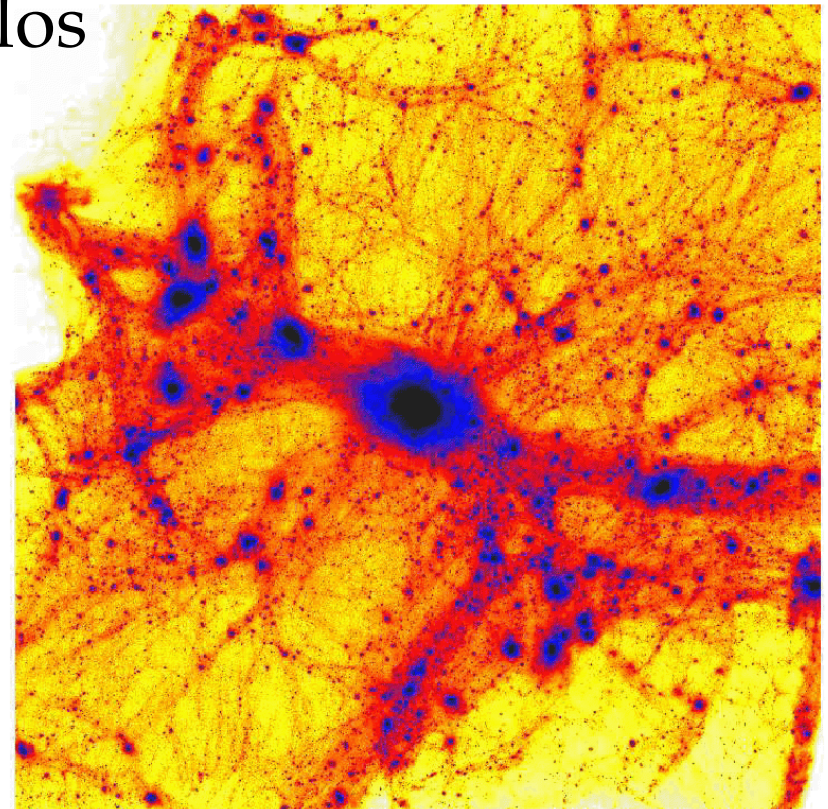
$$T_{\text{vir}} = T_{\text{IGM}}$$



Introduction: 3 basic points

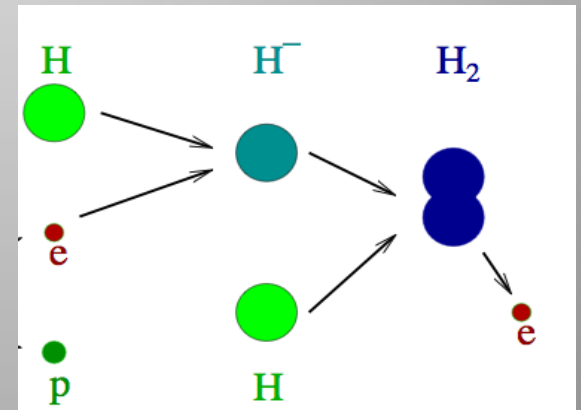
1. If the **dark matter is cold** starting at redshift 100 it clumps in halos with masses ranging from Jupiter mass to $10^8 M_{\text{sun}}$. Later these clumps merge to form larger halos

Simulation of dark matter distribution around a Milky Way-mass halo
Ref: Polisensky & Ricotti 2011



Introduction: 3 basic points

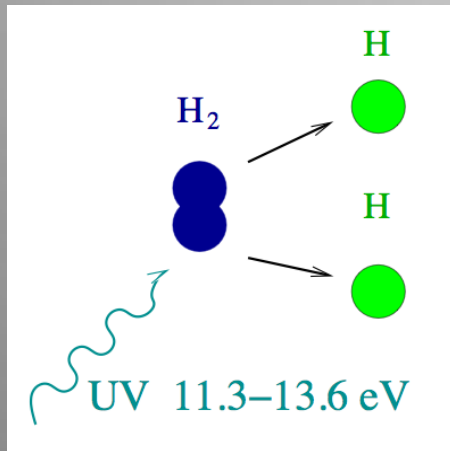
2. However not all halos can host a galaxy! The key is gas cooling. The first stars form at redshift $z \sim 30$ in dark halos of mass $10^5 - 10^6 M_{\text{sun}}$. Primordial gas cools via H_2 emission, but H_2 formation is very inefficient:



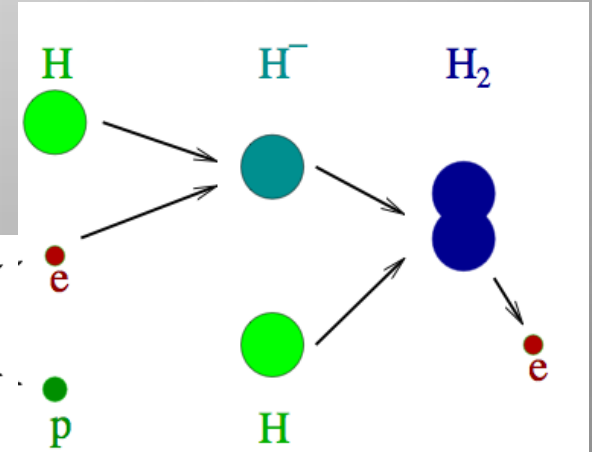
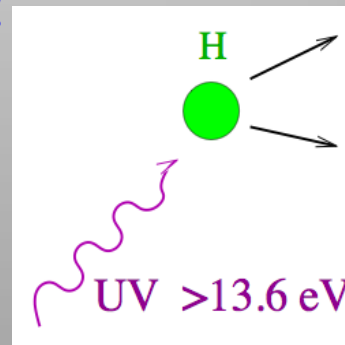
- Star formation is suppressed in small mass halos ($< 10^8 M_{\text{sun}}$) after reionization at $z \sim 7-10$ (IGM reheating suppresses gas accretion onto these halos)

Early evolution: H₂ chemistry

3. The first light can have a negative effect on star formation in the first small mass halos: halos larger than $10^8 M_{\text{sun}}$ are believed to host galaxies but the fate of galaxies in halos 10^6 - $10^8 M_{\text{sun}}$ is unclear.

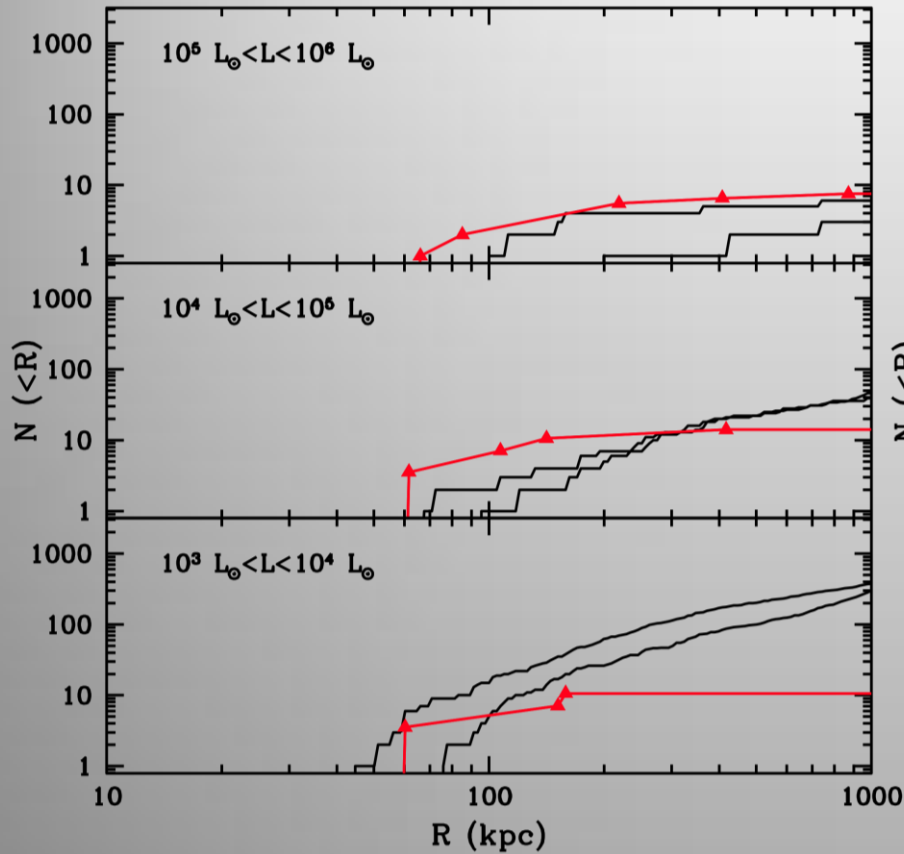


H₂ photo-dissociation: Negative feedback
Suppressed galaxy formation
EASY to simulate!

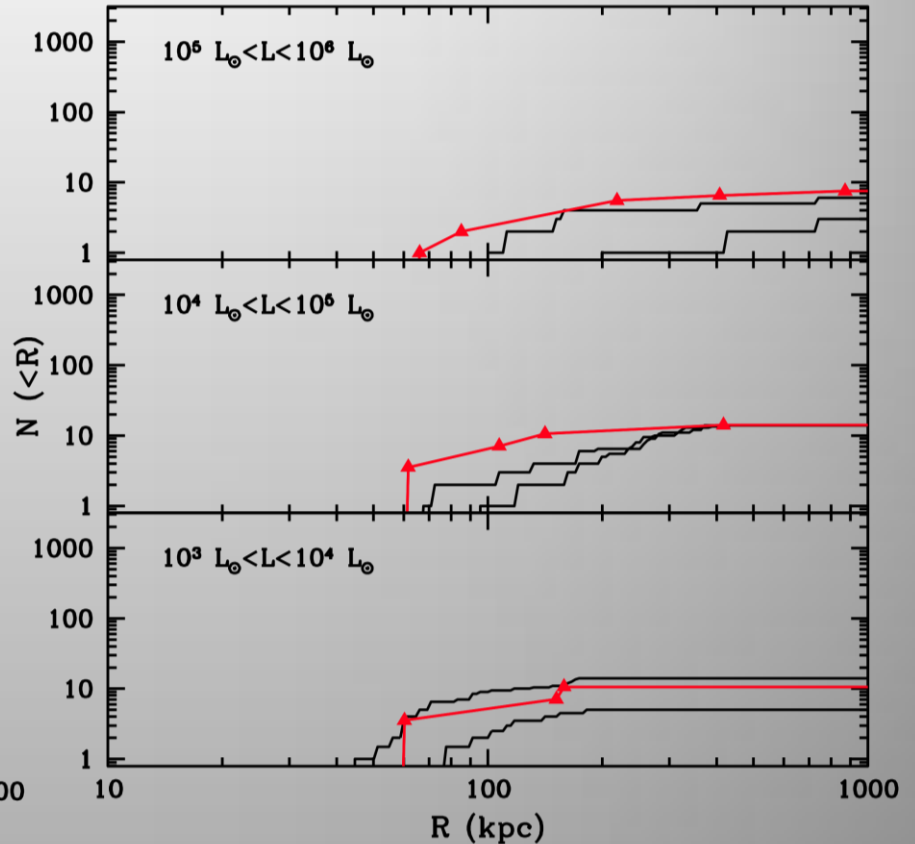


Ionizing UV radiation catalyzes H₂ formation.
HARD to simulate (3D-rad transfer)

Fossil Distributions – Milky Way

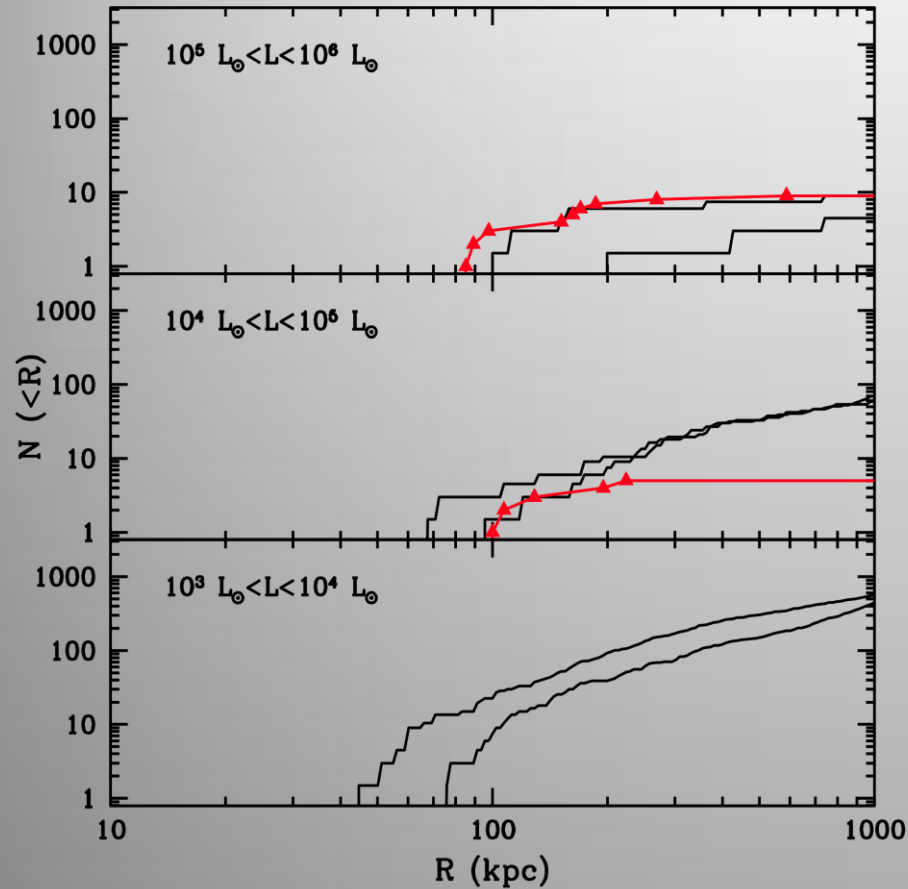


All the fossils ...

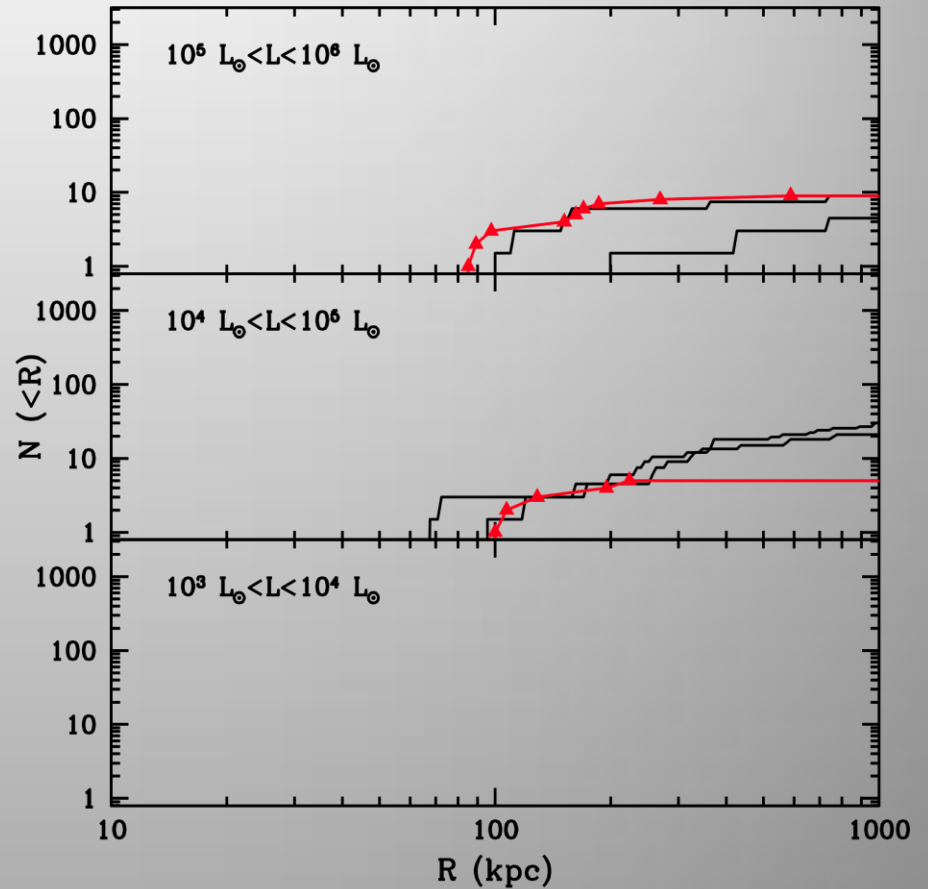


... the detectable fossils.

Fossil Distributions – M31



All the fossils ...



... the detectable fossils.

The “Bright” Satellite Problem

