Late gas accretion onto primordial mini-halos

a model for pre-reionization dwarfs and extragalactic compact High-Velocity Clouds

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I will discuss mainly 3 recent papers:

1. Ricotti, Gnedin & Shull 2008
2. Bovill & Ricotti 2008
3. Ricotti 2008

Outline:

- Part I : pre-reionization fossils
- Part II: late (cold) gas accretion onto mini-halos

I will describe an exciting but controversial hypothesis for the origin of (some) Local Group dwarf spheroidals: Fossil relics of the first galaxies

Near field Cosmology may provide the only observational test for theories of galaxy formation in early universe !

INTRO

The First Galaxies: important questions

- How small were the first galaxies?
- How many? … and how do they look like?
- Where are the first galaxies today?

- Still we do not have these answers: not only the properties of the galaxies but their **global formation rate** is **regulated by feedback** (radiative and chemical feedback)

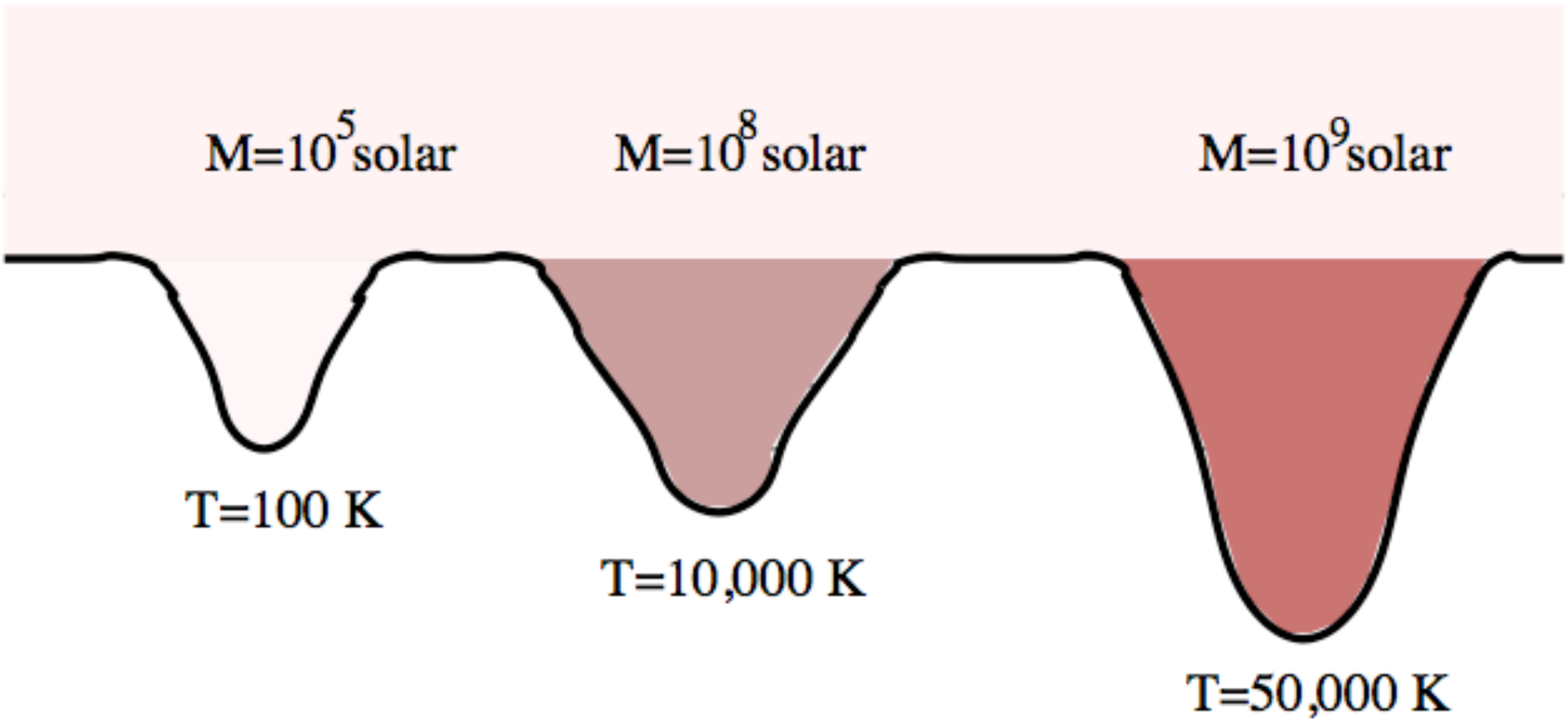
Reionization feedback:

- IGM temperature at reionization $T \approx 2\times10^4$ K
- Jeans mass $M_{jeans}(IGM) \approx 10^8\ M_{sun}$
- Suppression of gas accretion and star formation in halos with $v_{cir} < 20$ km/s (ref: Babul & Rees 1992, Efstathiou 1992)

$$\text{where } v_{cir} = \sqrt{\frac{GM}{r_h}}$$

Confirmed by simulations (ref: Gnedin 2000, Bullock et al. 2000)

After reionization star formation in mini-halos stops: passive stellar evolution



The smallest galaxies in the Universe can only form <u>before</u> reionization!

Definition: "pre-reionization" dwarfs

Galaxies that form in mini-halos with:

$T_{vir}< 20000$ K (M$_{dm}$ < 10^8 M$_{sun}$ or v_{cir}<20 km/s)

In order to initiate star formation one of the following is necessary:

1. Sufficient H_2 formation in metal free gas (catalyst: H^-)
2. Sufficient metal pre-enrichment

If none available: the mini-halo remains dark (forever?) and pre-reionization dwarfs do not form!

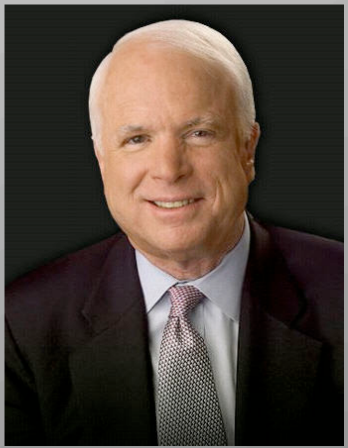
Why makes a difference?

Number of mini-halos ≈ $1/M^2$

Two Different views:

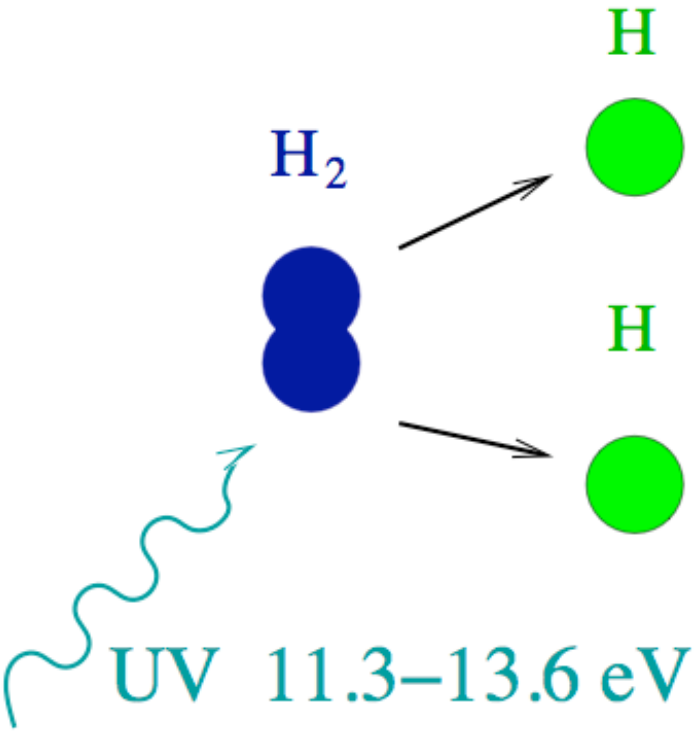
1. Our view: pre-reionization dwarfs formed in large number and some of their fossils can be found in the Local Group (a fraction of dwarf spheroidals)

1. Old view: none of Local group dwarf spheroidal are pre-reionization fossils. They are tidally stripped dIrr (more massive, formed mostly after reionization)



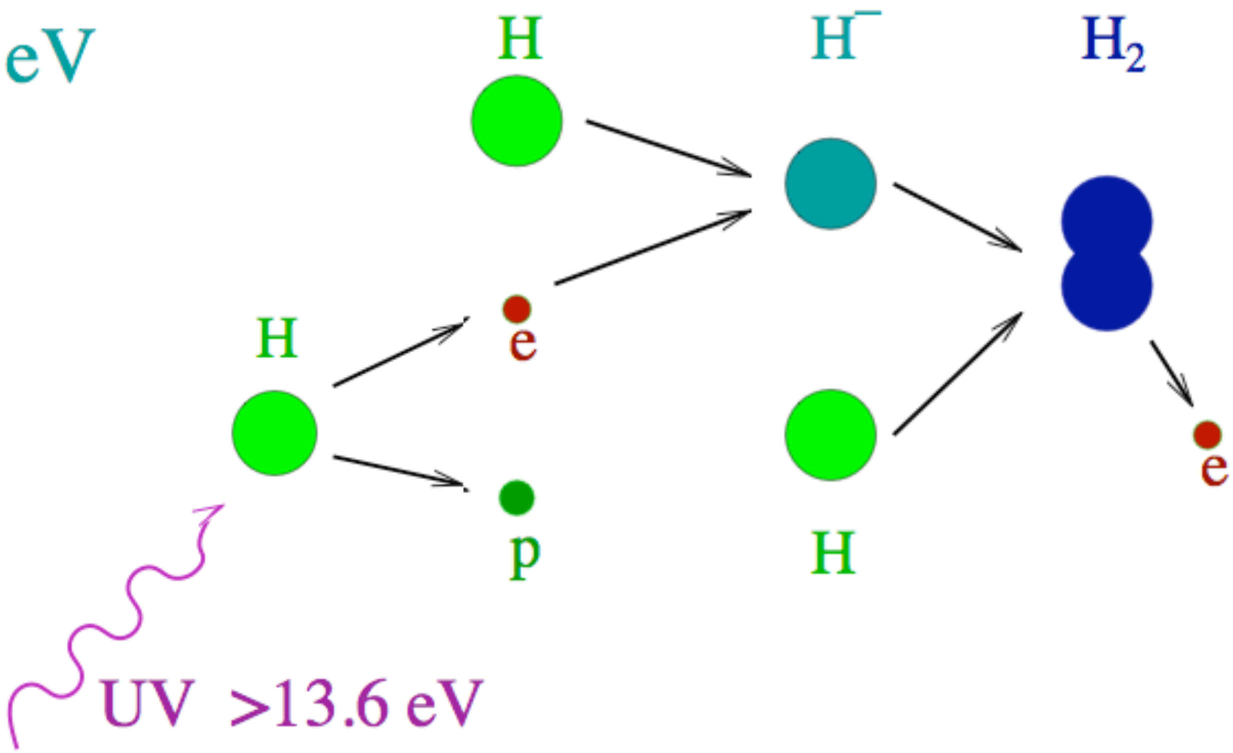
Why do we think so?

(Physical processes at play)

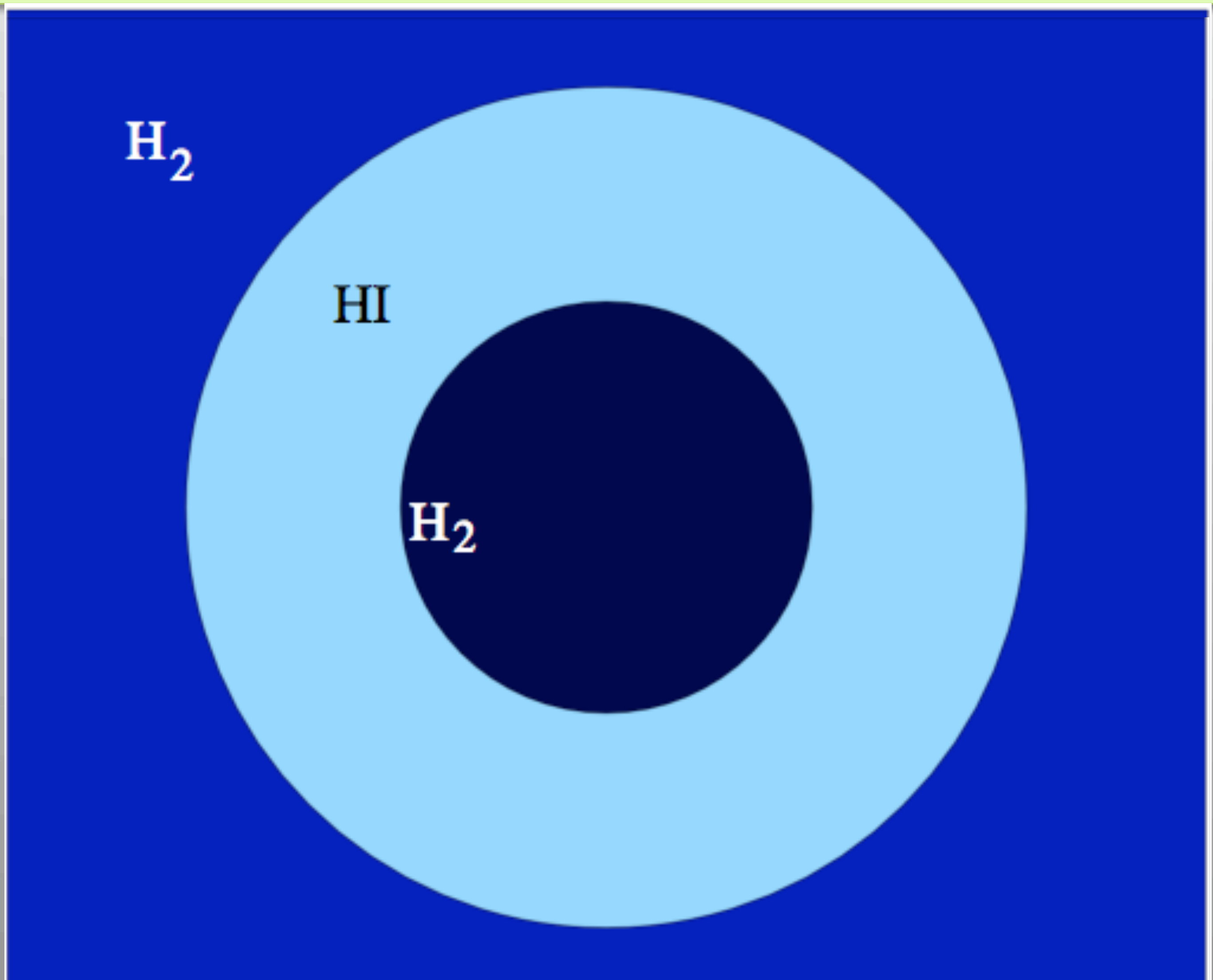


H2 photo-dissociation:
Negative feedback
Suppress galaxy formation

H2 formation:
Free electrons
at virialization



Positive Feedback regions



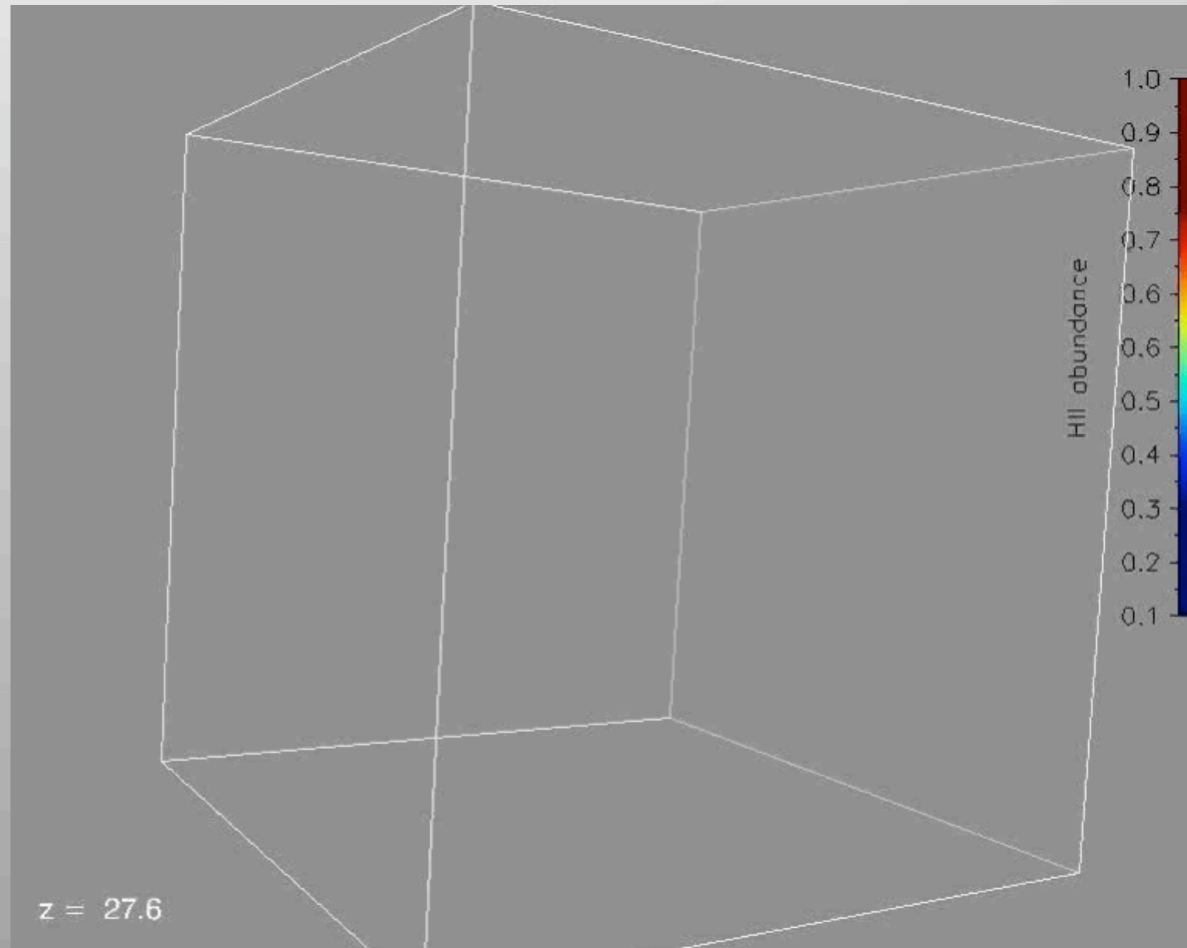
Net Positive or Negative Feedback?

- Radiation:
  - Ionizing UV and X-rays (effect mostly ignored):
    - promote H_2 formation and cooling (global-positive)
    - Heat the gas and produce galactic winds (negative)
  - Non ionizing UV: destroy H_2 (global-negative)
- Chemical (very uncertain):
  - Chemical enrichment (positive)
  - SN winds (negative?)

Simulations of the first galaxies

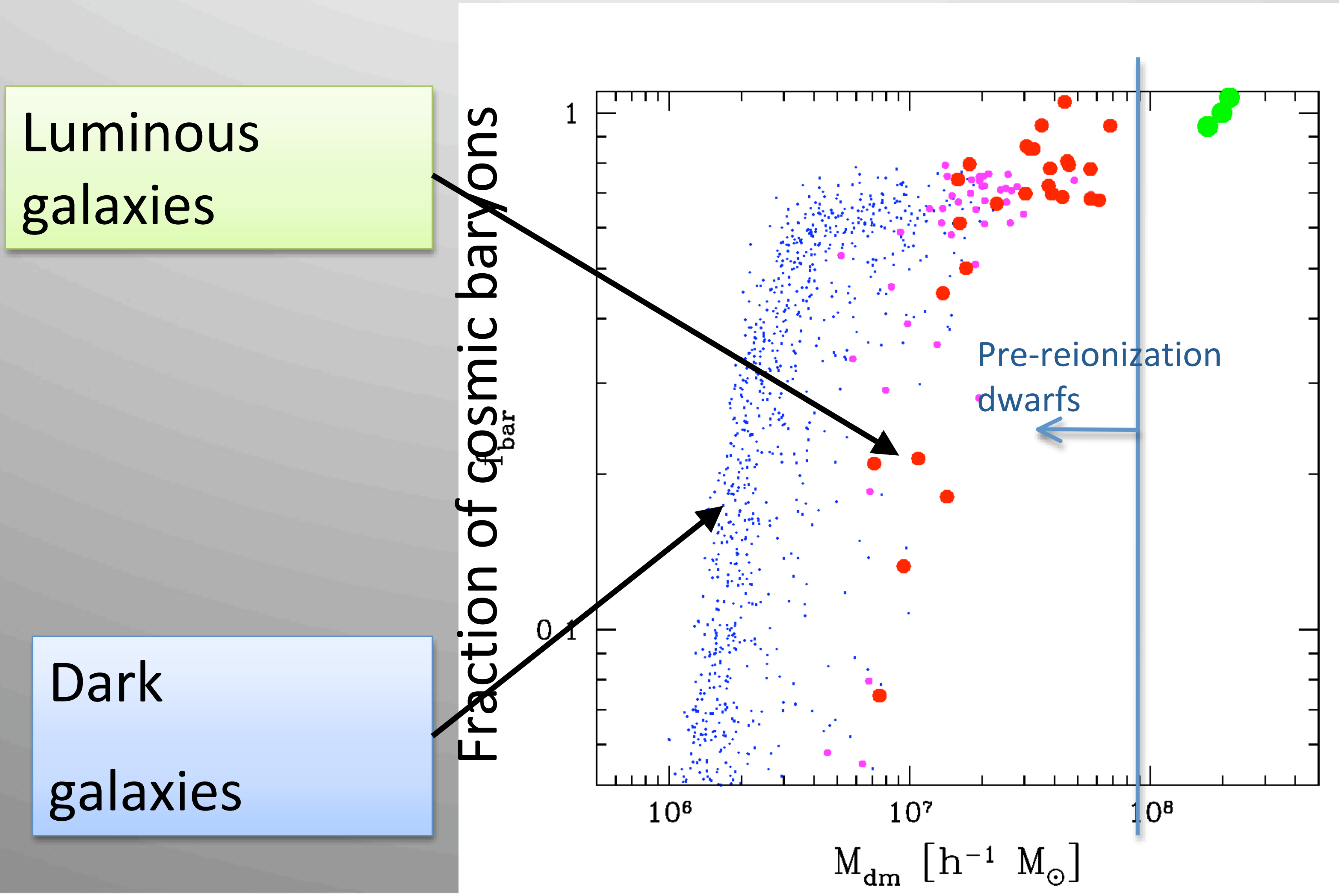
Feedback-regulated galaxy formation

- 1 Mpc box size
- 10^3 M_{sun} mass res.
- 3D radiative transfer
- Run ends at redshift of reionization

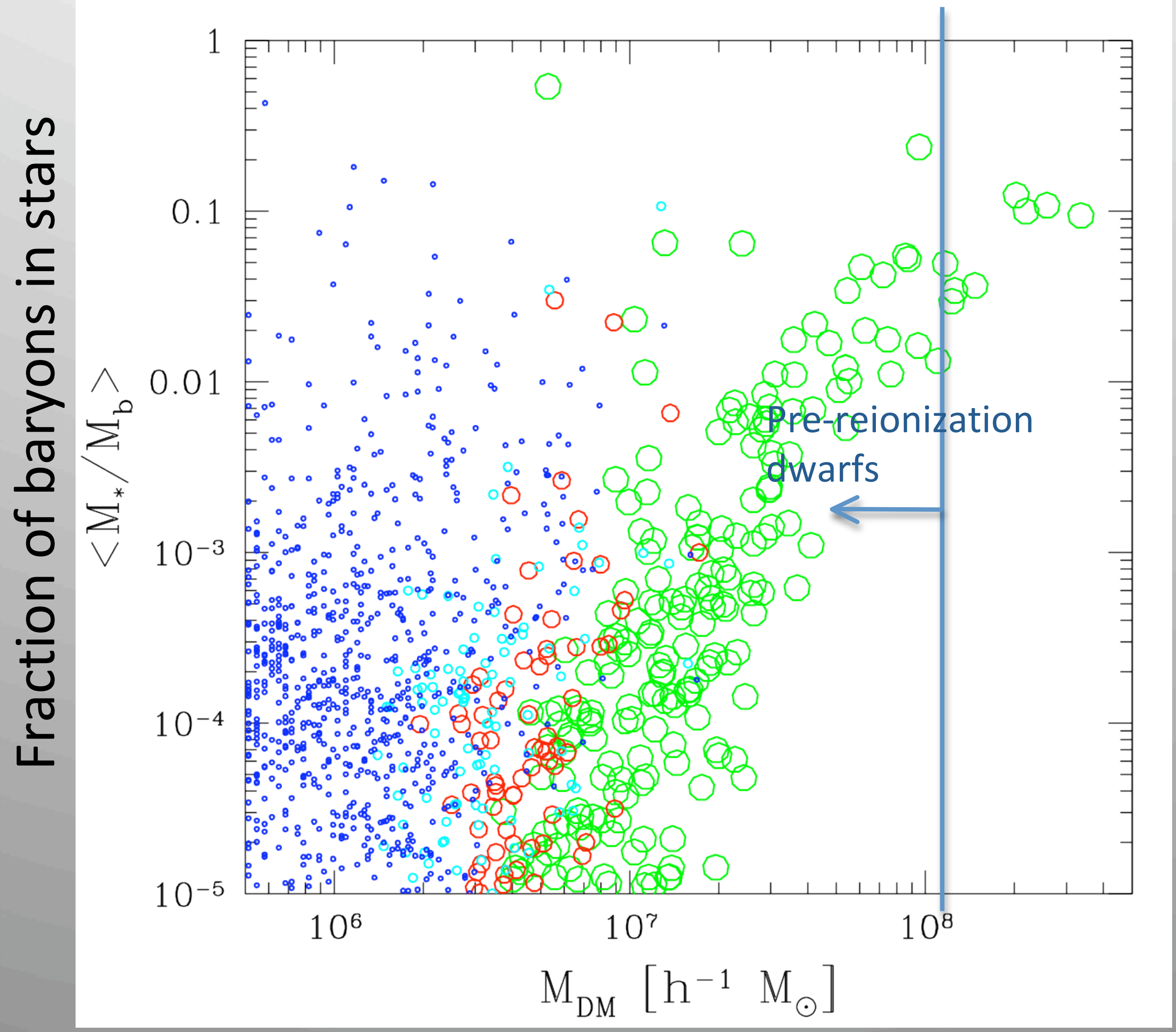


Ref: Ricotti, Gnedin & Shull 2002

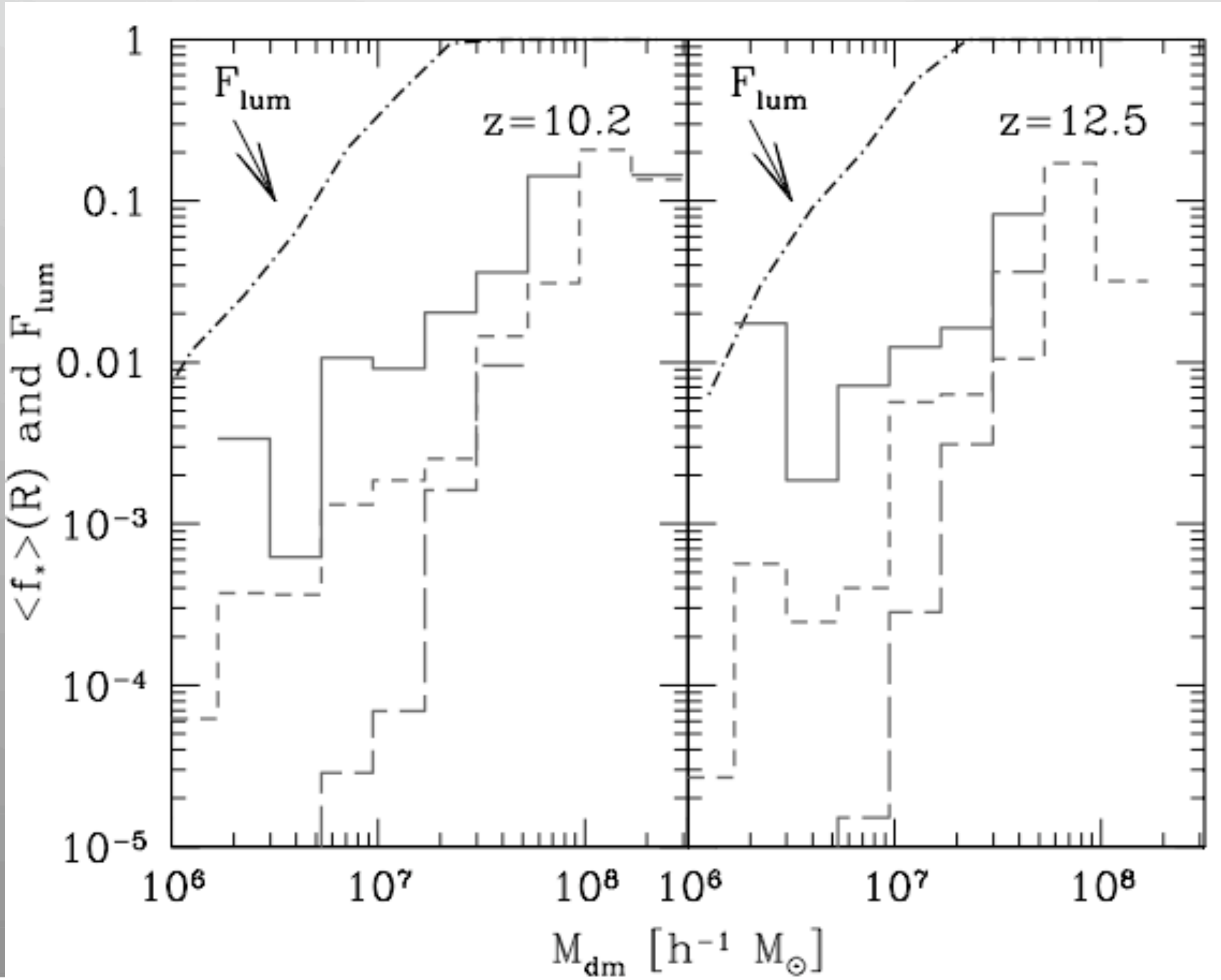
Feedback: photo-heating winds



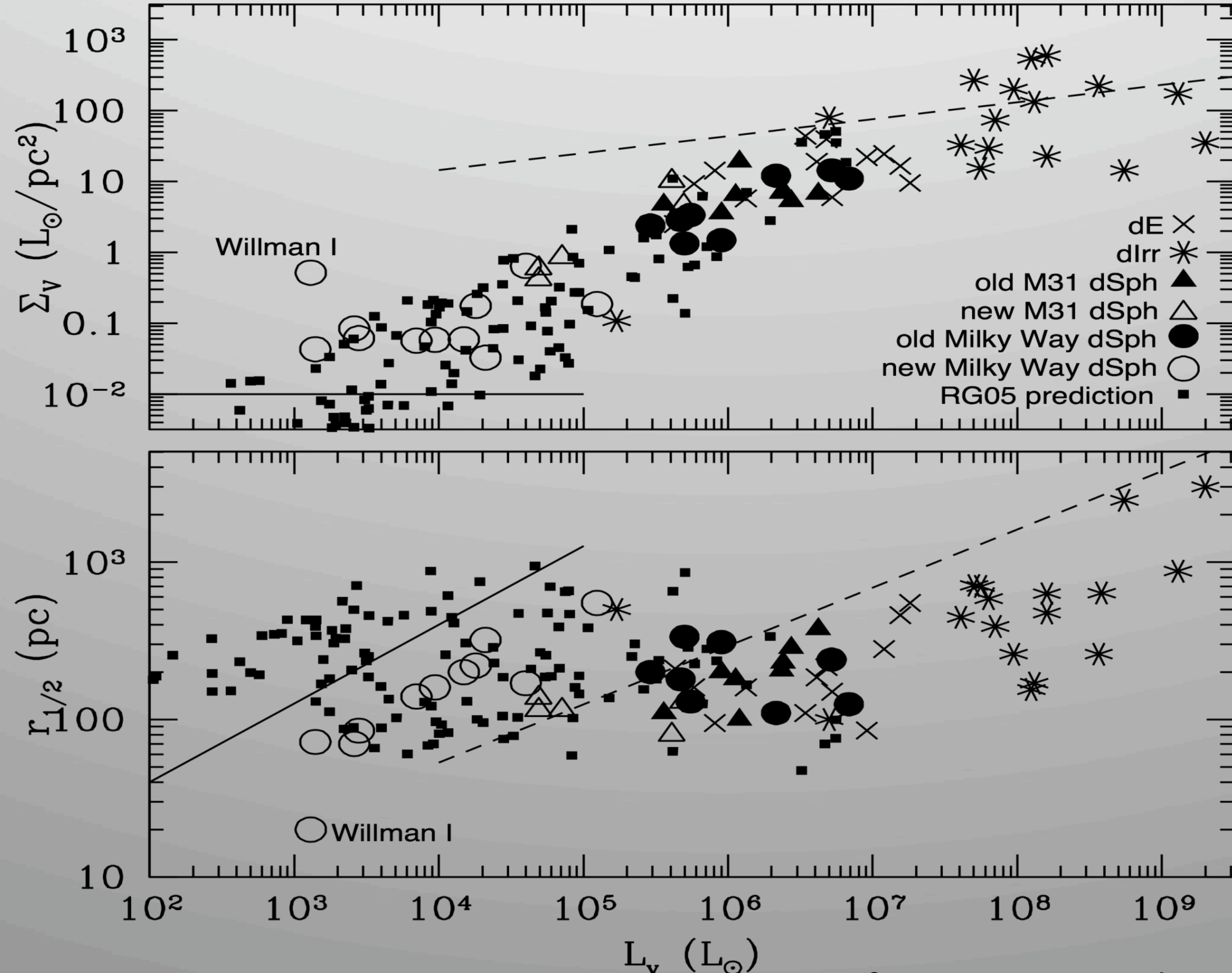
Pre-reionization dwarfs: numerous but faint!



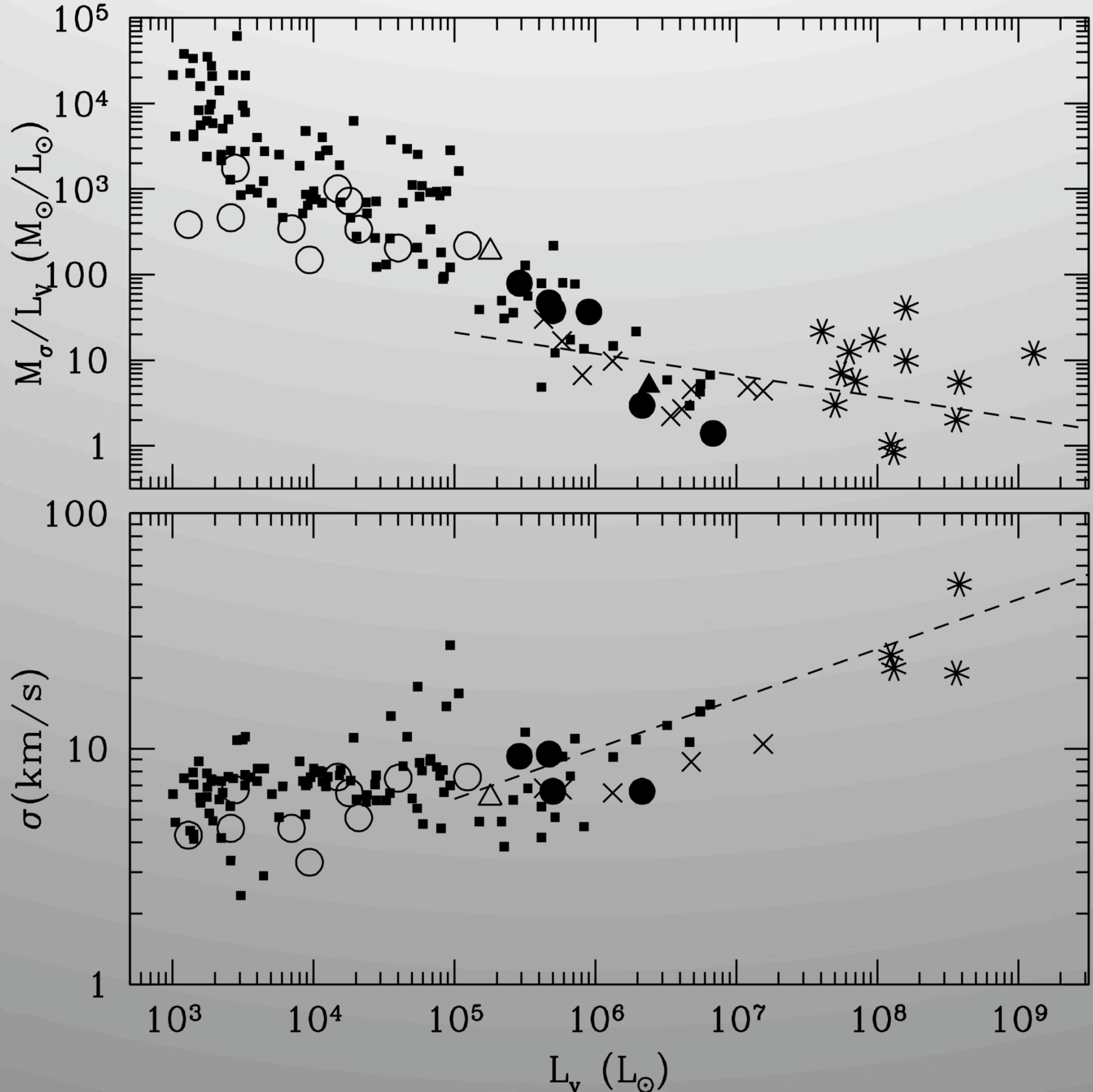
“Dark galaxies”



Pre-reionization fossils and ultra-faint dSphs: a model prediction!

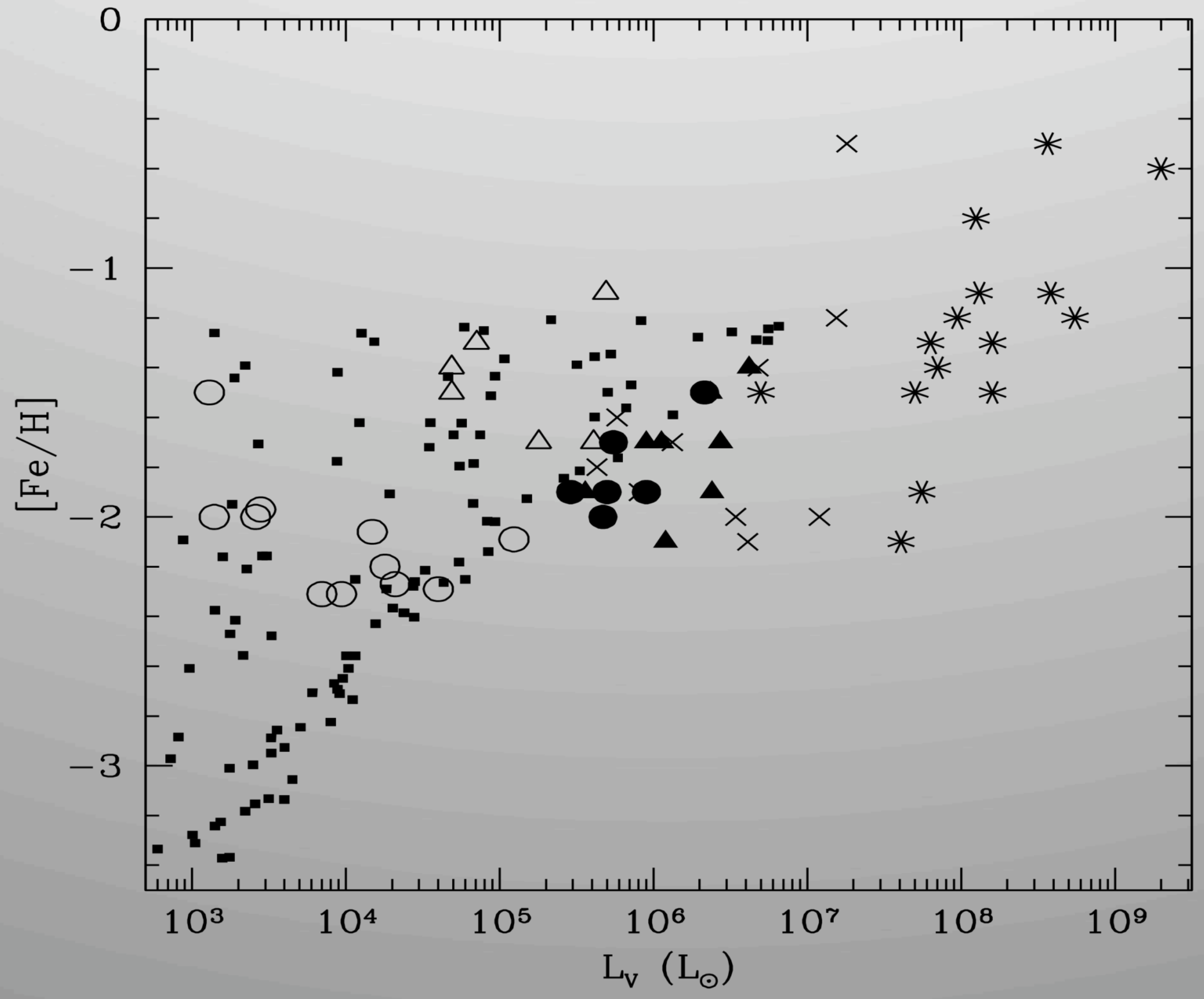


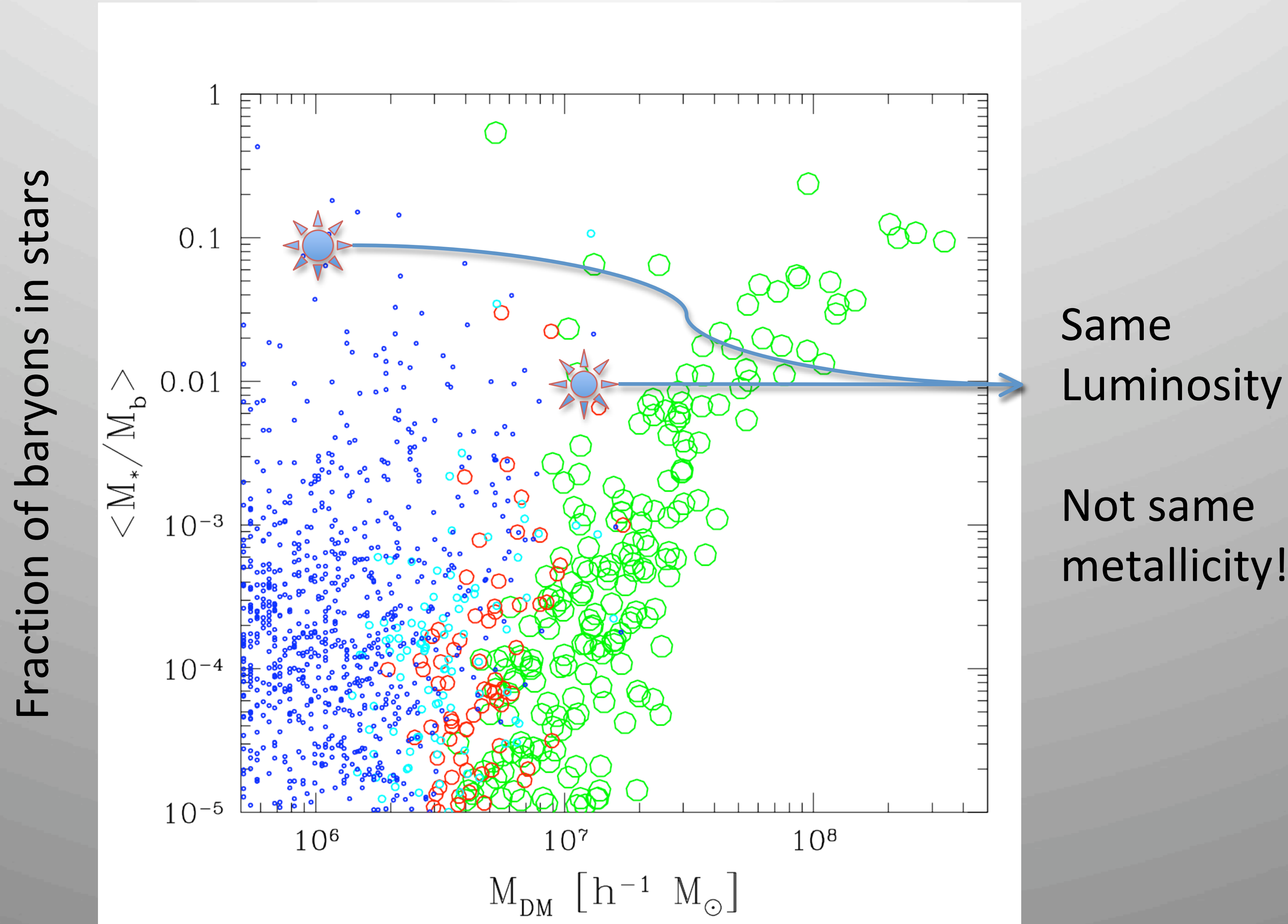
Ref: Ricotti & Gnedin 05, Bovill & Ricotti 08



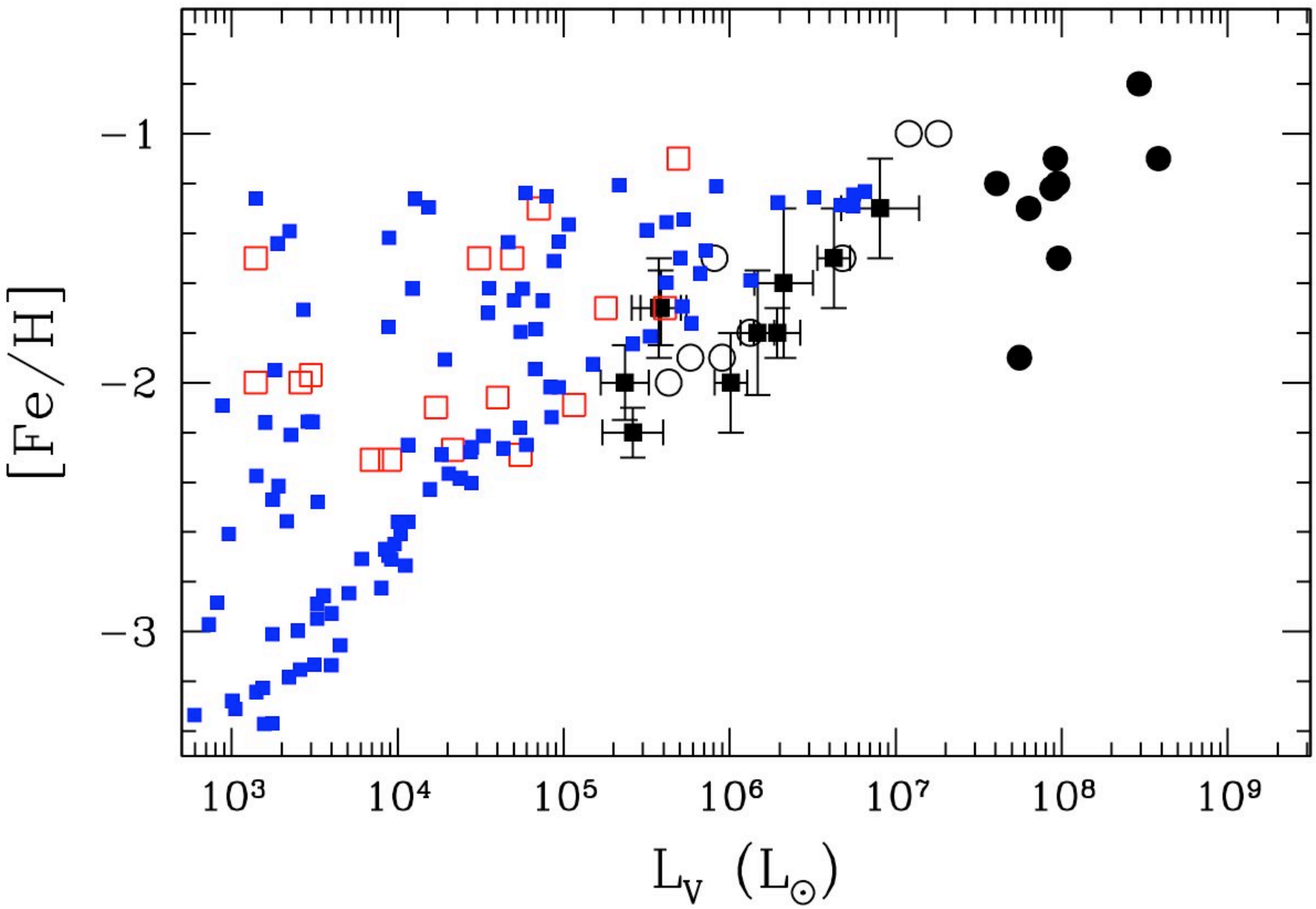
$M_\sigma/L_V\,(M_\odot/L_\odot)$
σ(km/s)
$L_V\,(L_\odot)$

Luminosity-metallicity relation




Fraction of baryons in stars
$\langle M_*/M_b \rangle$
1
0.1
0.01
10^{-3}
10^{-4}
10^{-5}
10^6
10^7
10^8
M_{DM} [h^{-1} $M_\odot$]
Same Luminosity
Not same metallicity!

Metallicity



Problem with stellar populations and abundance patterns

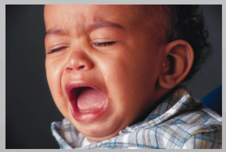
- Most dSphs have a dominant old stellar population (like Globular Clusters)
- However, the SFH in dSphs is often complex, with minor episodes of SF at later times (eg., see Grebel et al. 04 and Fenner et al.)
- Recent claim: some ultra-faint dwarfs show evidence for mixed stellar populations
- How bad is this for pre-reionization fossils ?

Part II

Can reionization suppress star formation in mini-halos forever?

The puzzle of Leo T

- Is one of the smallest dSphs: σ_{*}=6.9 km/s
- Looks as a pre-reionization fossil
- Distance 430 kpc from Galactic center
- Is gas rich! ☹
- Forming stars at z=0!



Leo T properties:
☐ r_{core}=100 pc
☐ M_{dm}/M_{gas}=10-30
☐ N_H=7x10^{20} cm^{-2}

Ref: Ryan-Weber et al 2008

Leo T definitively does not fit our model !

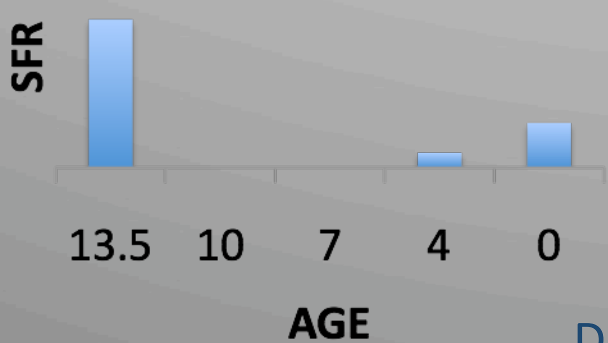
Revisiting gas accretion onto mini-halos

Ability to accrete gas increases with increasing:

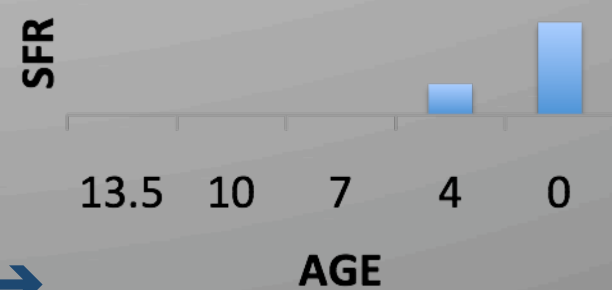
1. $\Gamma=[v_{cir}/c_{s(IGM)}]^2=T_{vir}/T_{IGM}$
   - ✓ IGM temperature decreases at redshift z<3
2. Concentration of dark halo, $c=r_h/r_s$
   - ✓ Concentration of first minihalos increases with decreasing redshift if halo evolves in isolation
3. Gas must be able to recombine (and cool) (note that $t_{cool}<t_{rec}$)

Message to take home

- The reionization feedback idea is valid but fails at z<2 if the halo is highly concentrated
- Minihalos virialized before reionization, that evolve to z=0 in the low-density IGM, have a late phase of gas accretion and possibly star formation



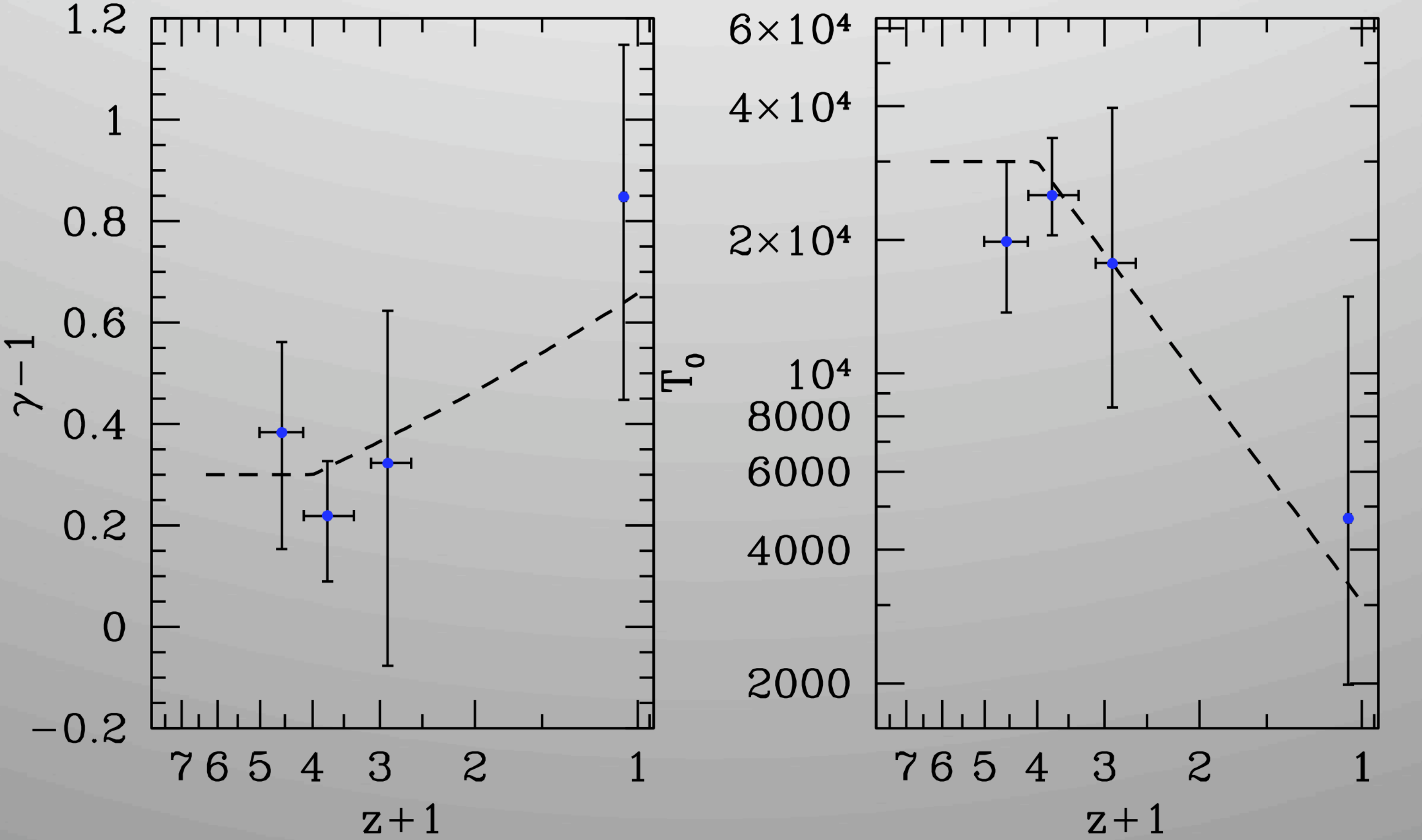
Do these objects exist? ➔



…. some details

Evidence 1:
Evolution of the IGM temperature

(from observations of the Lyman-alpha forest)



Ref: Ricotti, Gnedin & Shull 2000

Evidence 2:
Dark Halo Concentration

Concentration increase as the halo evolves, after virialization, in expanding universe (low density IGM).
From N-body simulations:

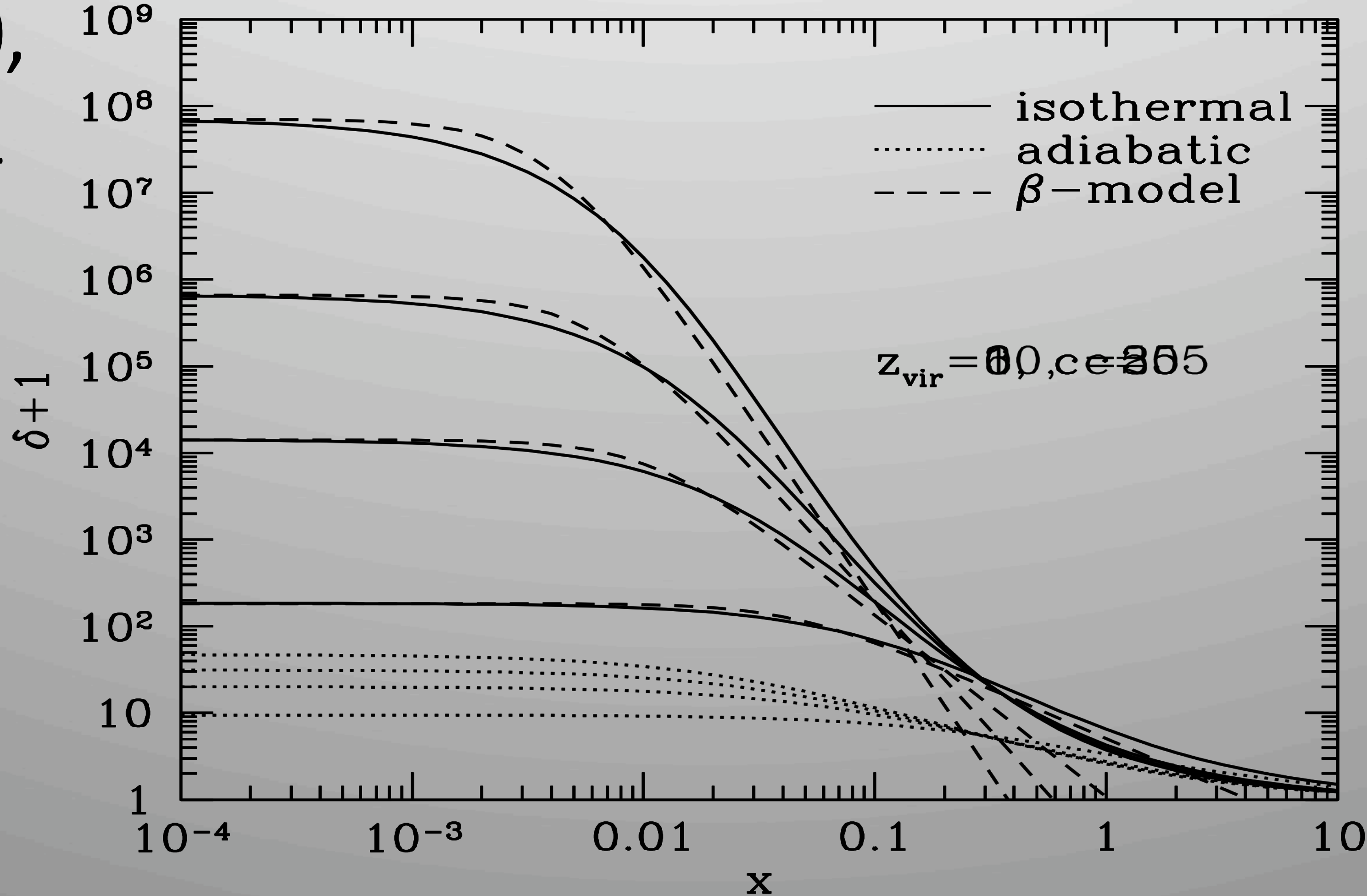
$$c(z) = c_{vir}\left(\frac{1+z_{vir}}{1+z}\right) \approx 5\left(\frac{1+z_{vir}}{1+z}\right)$$

Refs: Bullock et al. 2001, Wechsler et al. 2002, Ricotti 2003, Ricotti, Pontzen & Viel 2007

Gas density profile in NFW potential

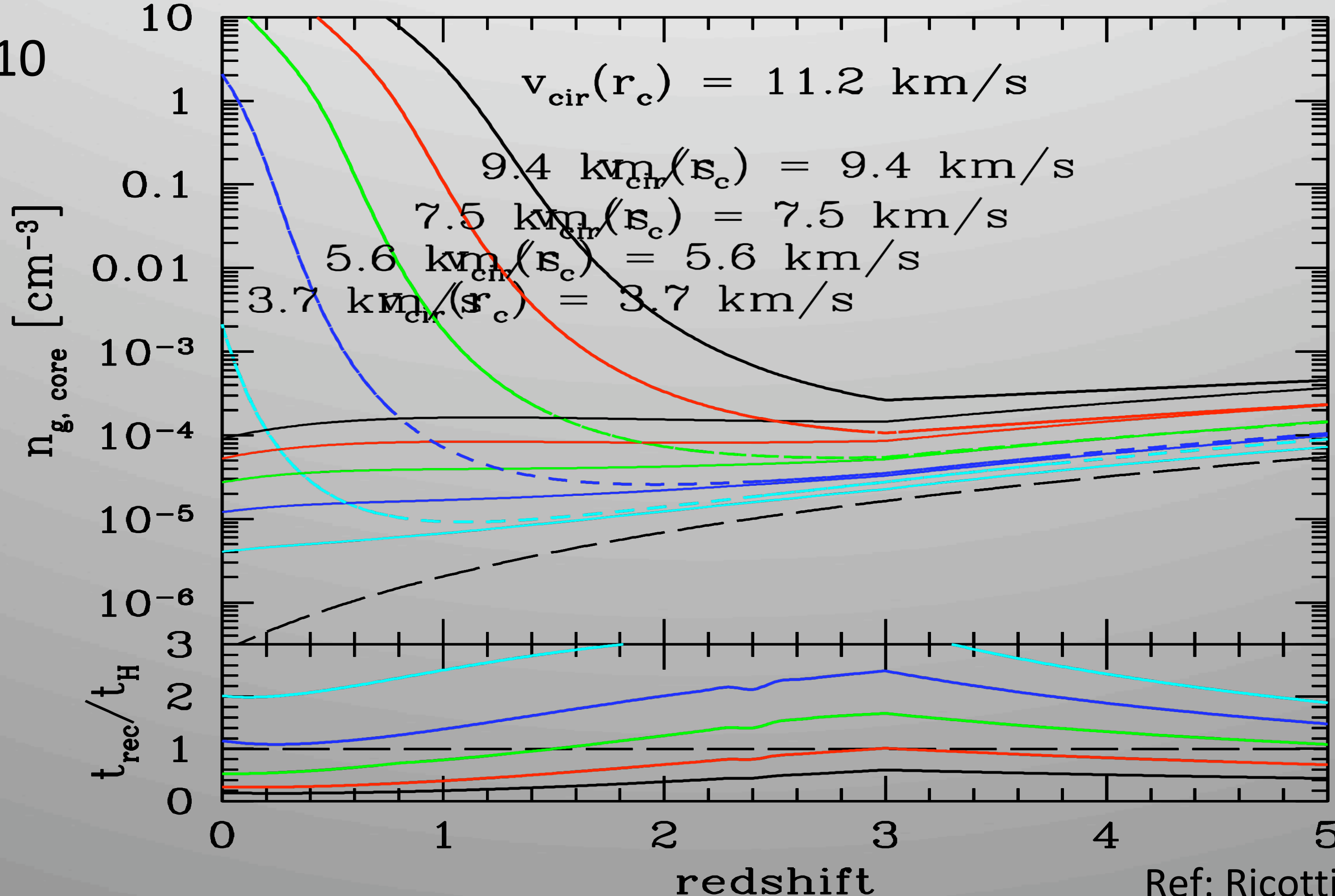
z=0,

Γ=1



Late gas accretion onto mini-halos

Z_{vir}=10



Ref: Ricotti 2008

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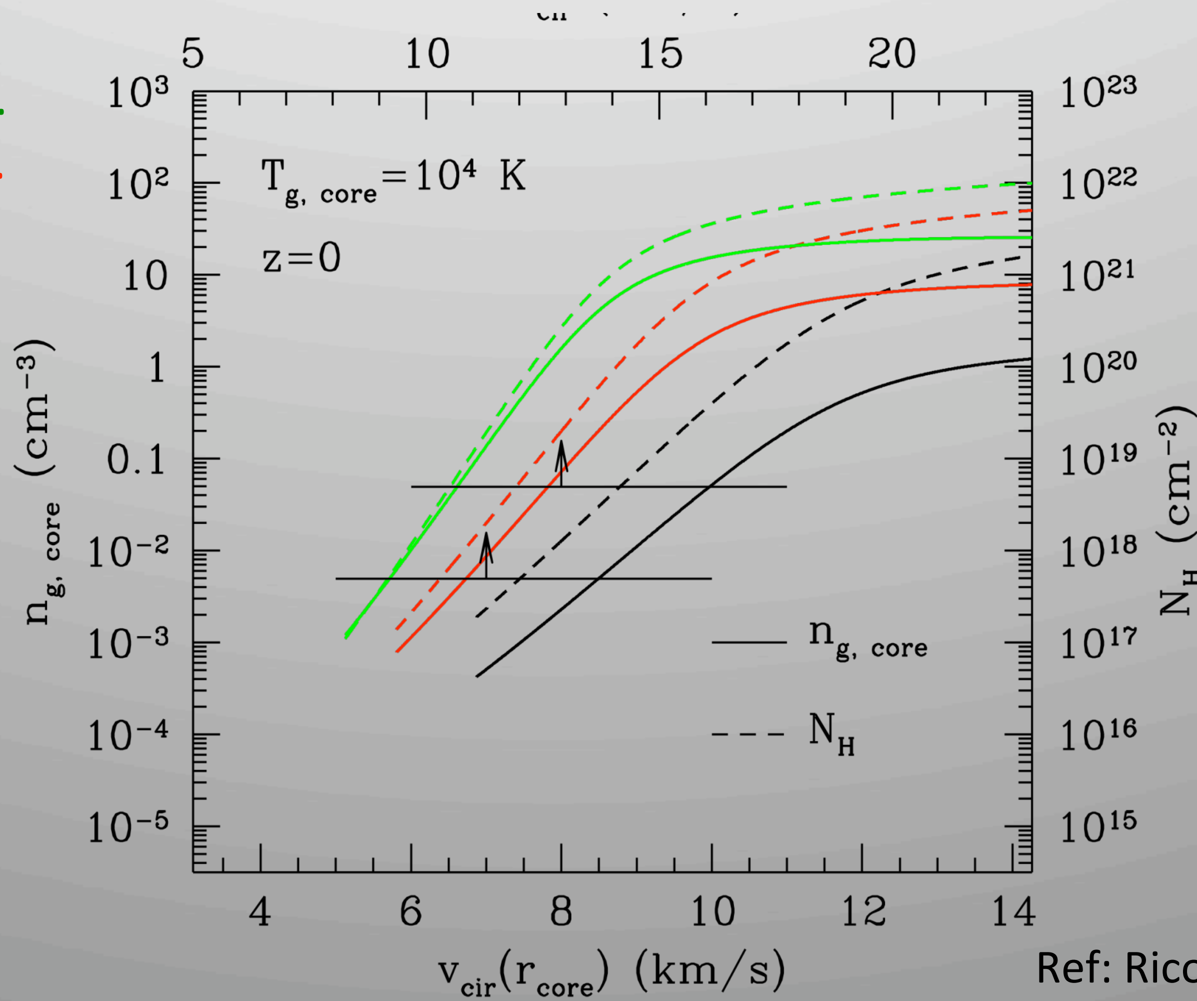
$$\frac{1+z_{vir}}{10} \approx \left(\frac{n}{3}\right)\left(\frac{\sigma_8}{0.74}\right)\left[0.95 - 0.19\log\left(\frac{M}{10^8 M_{sun}}\right)\right]$$

n = # of standard deviations from the mean density of initial density perturbation (ie, how rare the object is)

Mini-halos with gas and no stars (comp. HVC?)

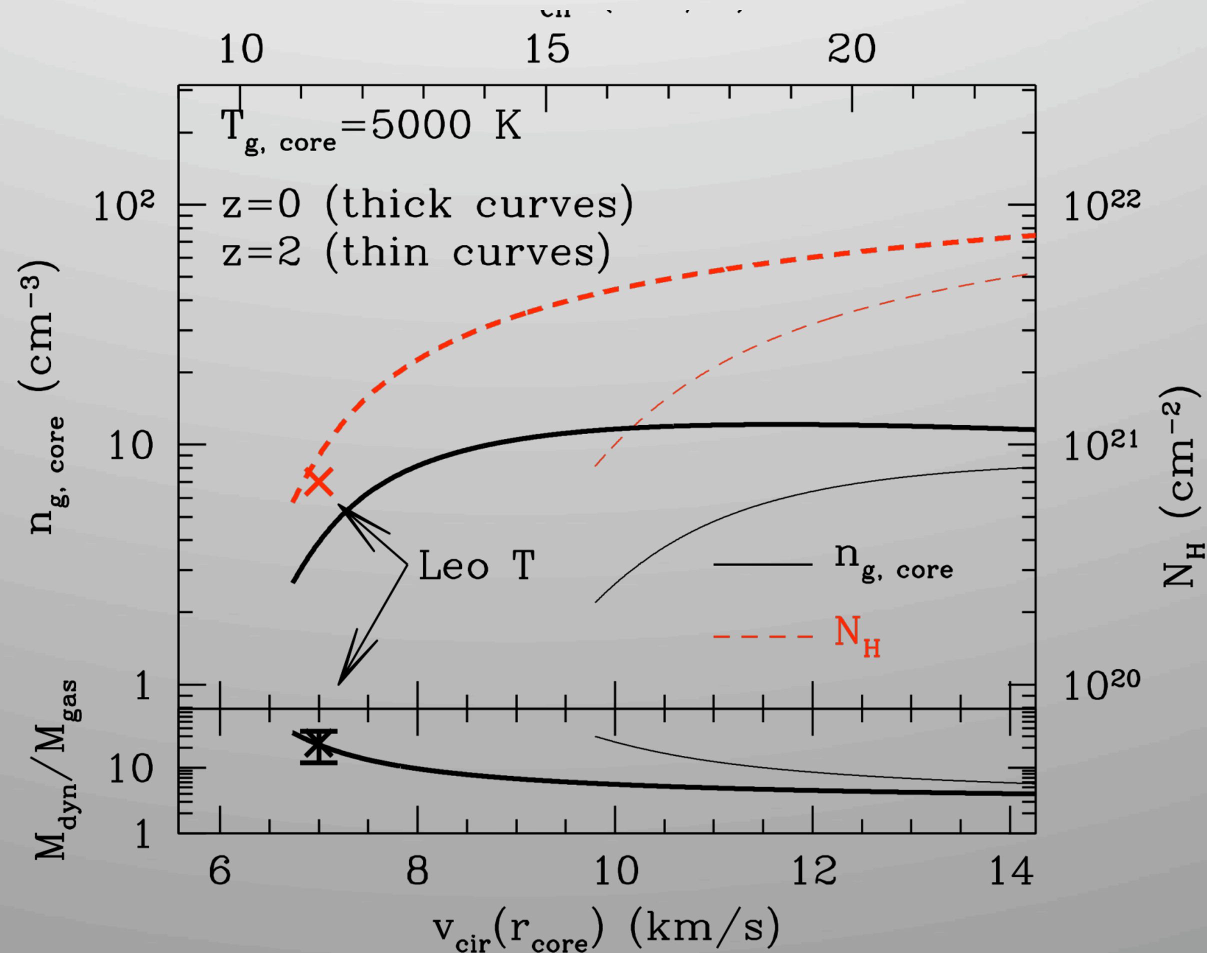
Green: 4-σ pert.
Red: 3-σ pert.
Black: 2-σ pert.



Ref: Ricotti 2008

Star forming mini-halos at z=0 and z=2

3-σ pert.



Ref: Ricotti 2008

More on properties of accreted gas

$$r_{core} \approx 140\text{pc}\left(\frac{\text{v}_{\text{cir}}}{17\text{km/s}}\right)\left(\frac{10}{1+z_{vir}}\right)^{\frac{3}{2}}$$

$$r_h \approx 18\text{kpc}\left(\frac{M_{dm}}{10^8 M_{sun}}\right)^{\frac{1}{3}} \quad \text{at z} = 0$$

$$\frac{M_{dm}}{M_{gas}} \approx 5 - 30$$

$$\text{v}_{\text{cir}}(r_{core}) \approx 0.66\text{v}_{\text{cir}} \approx 0.62\text{v}_{\text{cir}}^{\text{max}}$$

Leo T:
☑ r_{core}=100 pc
☑ M_{dm}/M_{gas}= 10-30
☑ N_H=7x10^{20} cm^{-2}

(V_{cir}=11 km/s)

Compact HVCs or unknown population?

If compact HVCs are at distances of about 1 Mpc model may work for some of them

- ☑ r_h= 15 kpc
- ☑ r_{core}=100 pc
- ☑ $N_H=10^{18} - 10^{19}$ cm^{-2}

Most are probably undetected because too faint and/or too small

Refs: Blitz et al. 1999, Braun & Burton 1999, Robinshaw et al. 2002, Sternberg et al. 2002, Putman et al. 2003, Maloney & Putman 2003,

The Astronomical Journal, 133:2569–2583, 2007 June

THE ARECIBO LEGACY FAST ALFA SURVEY. III. H I SOURCE CATALOG OF THE NORTHERN VIRGO CLUSTER REGION

Riccardo Giovanelli,[1,2] Martha P. Haynes,[1,2] Brian R. Kent,[1] Amélie Saintonge,[1] Sabrina Stierwalt,[1] Adeel Altaf,[3] Thomas Balonek,[2,4] Noah Brosch,[5] Shea Brown,[6] Barbara Catinella,[7] Amy Furniss,[8] Josh Goldstein,[3] G. Lyle Hoffman,[3] Rebecca A. Koopmann,[2,9] David A. Kornreich,[8] Bilal Mahmood,[9] Ann M. Martin,[1] Karen L. Masters,[10] Arik Mitschang,[8] Emmanuel Momjian,[7] Prasanth H. Nair,[11] Jessica L. Rosenberg,[10,12] and Brian Walsh[4]
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Can ALFALFA find these objects if they are nearby?

Very rough estimate (we need to asses ionization corrections):

- Angular size: 3-30 arcmin (for 1-10 kpc size at 1 Mpc)
- H Mass (total): 10^5-10^7 M_{sun} (but mostly ionized?)
- H Mass of the core (few 100 pc): 10^3-$10^5 M_{sun}$

- We do not know yet their number per square degree

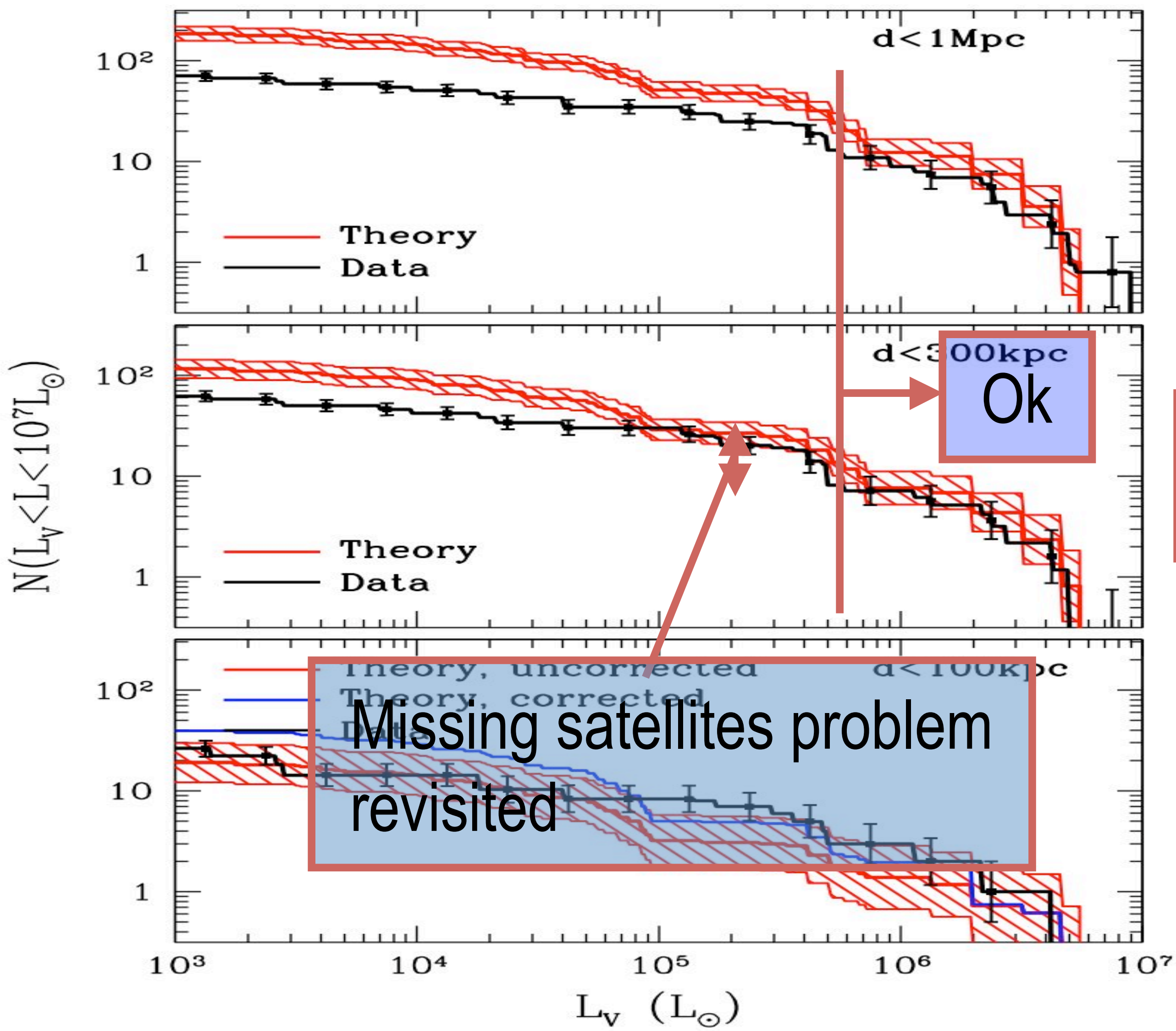
Summary

- ✓ Found pre-reionization fossils in the Local Group?
- ✓ Revisitation of reionization feedback on formation of dwarf galaxies
- o Mini-halos with v_{cir}< 20 km/s stop accreting gas after reionization but, if they evolve in isolation, have a recent (z<1-2) phase of accretion from IGM and star formation
    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?

Future work

- Work on testing the model versus known compact HVC population
- Zero metallicity star formation at z=0?
- Simulated maps of the distribution of gas rich mini-halos around the Milky Way in 21cm and H-alpha emission (including simulated maps with ALFALFA sensitivity and resolution)

Luminosity Functions



Let's include the new dwarfs

- If gas is isothermal:

$$\rho_{g,core} \propto e^{\beta} \text{ where } \beta = \Gamma \mathrm{c/f(c)} \approx \Gamma(4.4 + \mathrm{c}/4)$$