The First Galaxies and the quest for their Fossils

Massimo Ricotti

U. of Maryland

Credits




Credits




Mia Bovill (Phd student, UMD)

Nick Gnedin (Fermilab)

Mike Shull (Colorado)

Andrey Kravtsov (Chicago)

Primordial dwarfs

- CDM cosmology: from small to large galaxies
- Two distinct populations of galaxies:
  I. First population: V<20 km/s or $M < 10^8\ \mathrm{M}_{\mathrm{sun}}$
  II. Second population: V>20 km/s or $M > 10^8\ \mathrm{M}_{\mathrm{sun}}$

Primordial dwarfs

- CDM cosmology: from small to large galaxies
- Two distinct populations of galaxies:
  I. First population: V<20 km/s or $M < 10^8$ M_{sun}
  II. Second population: V>20 km/s or $M > 10^8$ M_{sun}
- Unique features to the First population:
  1. Gas can collapse in DM halos only if cooling by diffuse molecular hydrogen is important
  2. Photo-ionized gas escapes from the halo
  3. At z >10-15 the global star formation history is self-regulated
  4. Multiple short starbursts in primordial dwarfs

The simulations

Box size	1.4 Mpc
DM particles	17 millions
Star particles	1 million
Mass resolution (baryons)	900 solar masses
Resolution (physical at z=8.3)	24 pc
Number of galaxies	~ 100,000
Final redshift	8.3

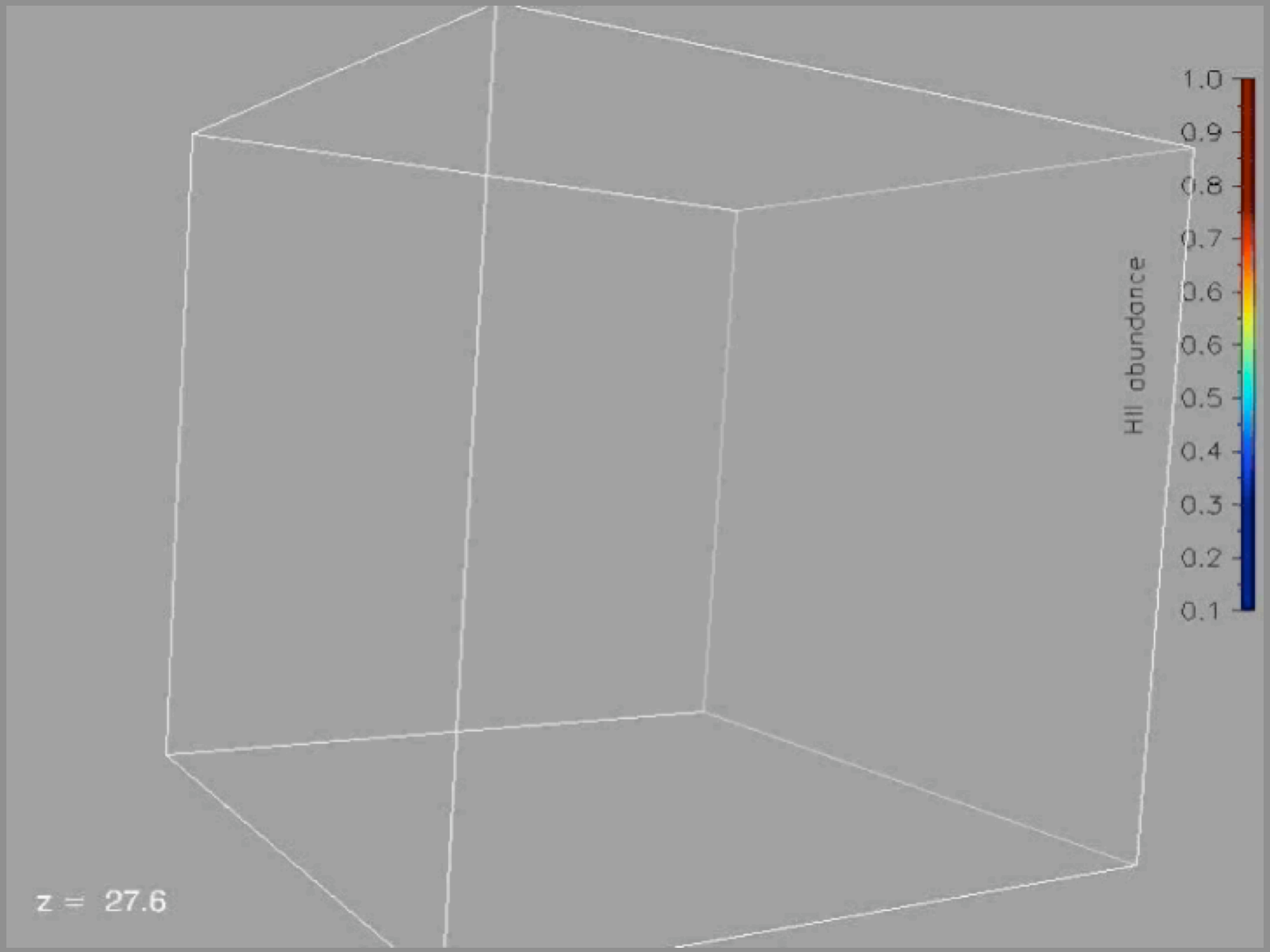
Physics included:

4 components: DM, gas, stars, photons

- 3D time-dependent radiative transfer of continuum radiation
- line radiative transfer of background
- atomic and molecular chemistry
- cooling and heating processes

Empirical laws:

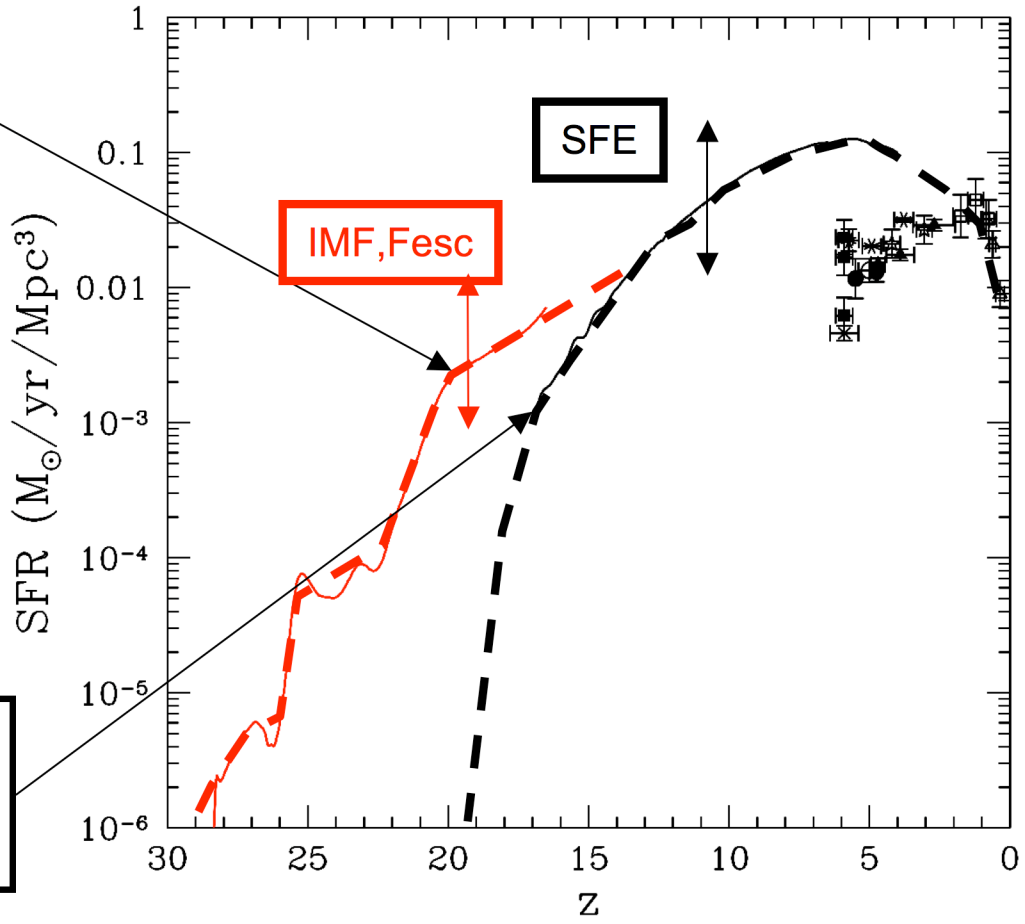
- star formation (IMF, SF efficiency, Fesc)


1.0
0.9
0.8
0.7
0.6
0.6
0.5
0.4
0.3
0.2
0.1
HII abundance
z = 27.6

Self regulated star formation rate

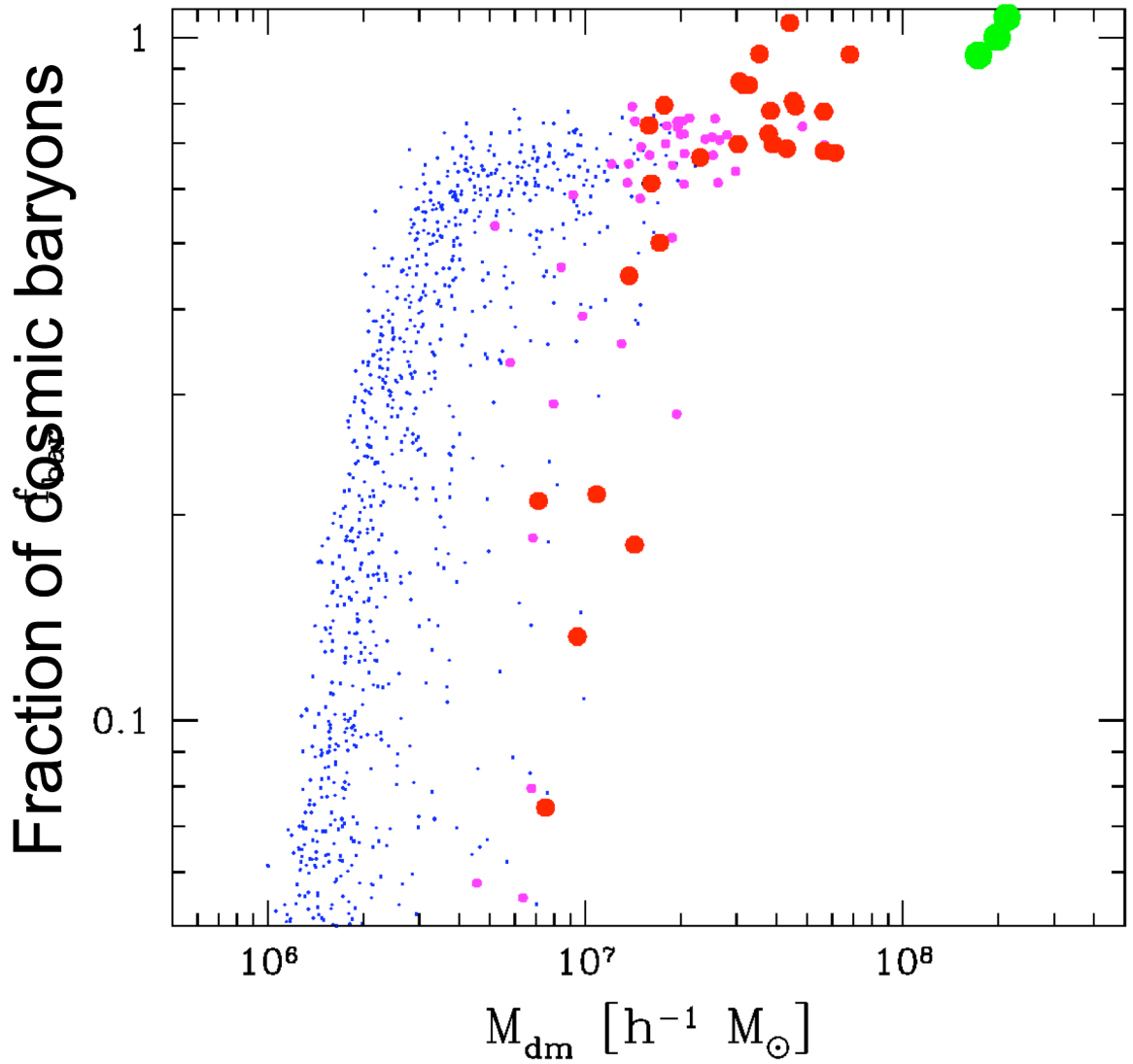
First population:
SFR depends on the IMF and Fesc

Second population:
SFR depends on the SFE



Feedback: Internal vs. external

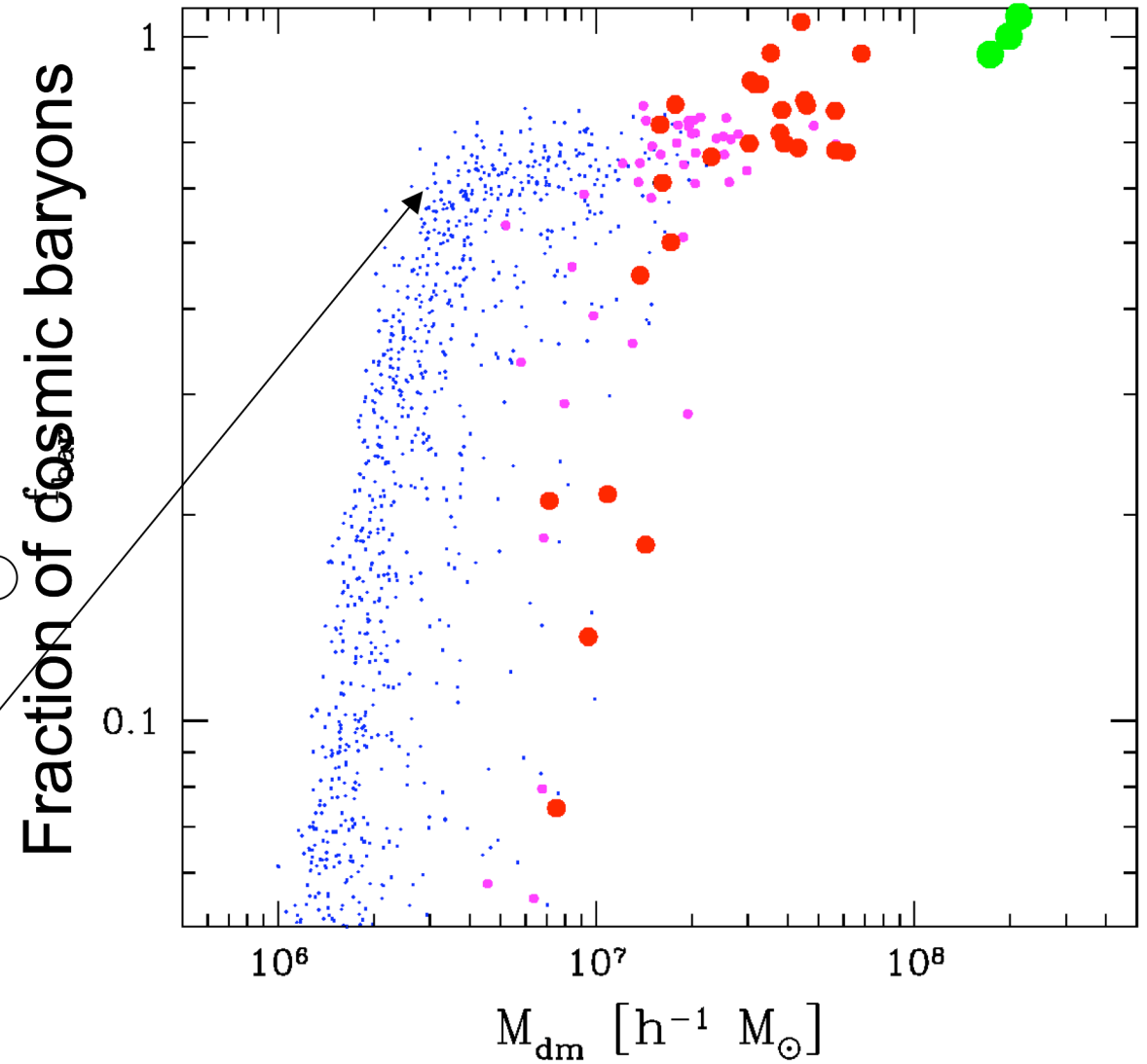
- → no stars
- → few stars
- → more stars
- → many stars



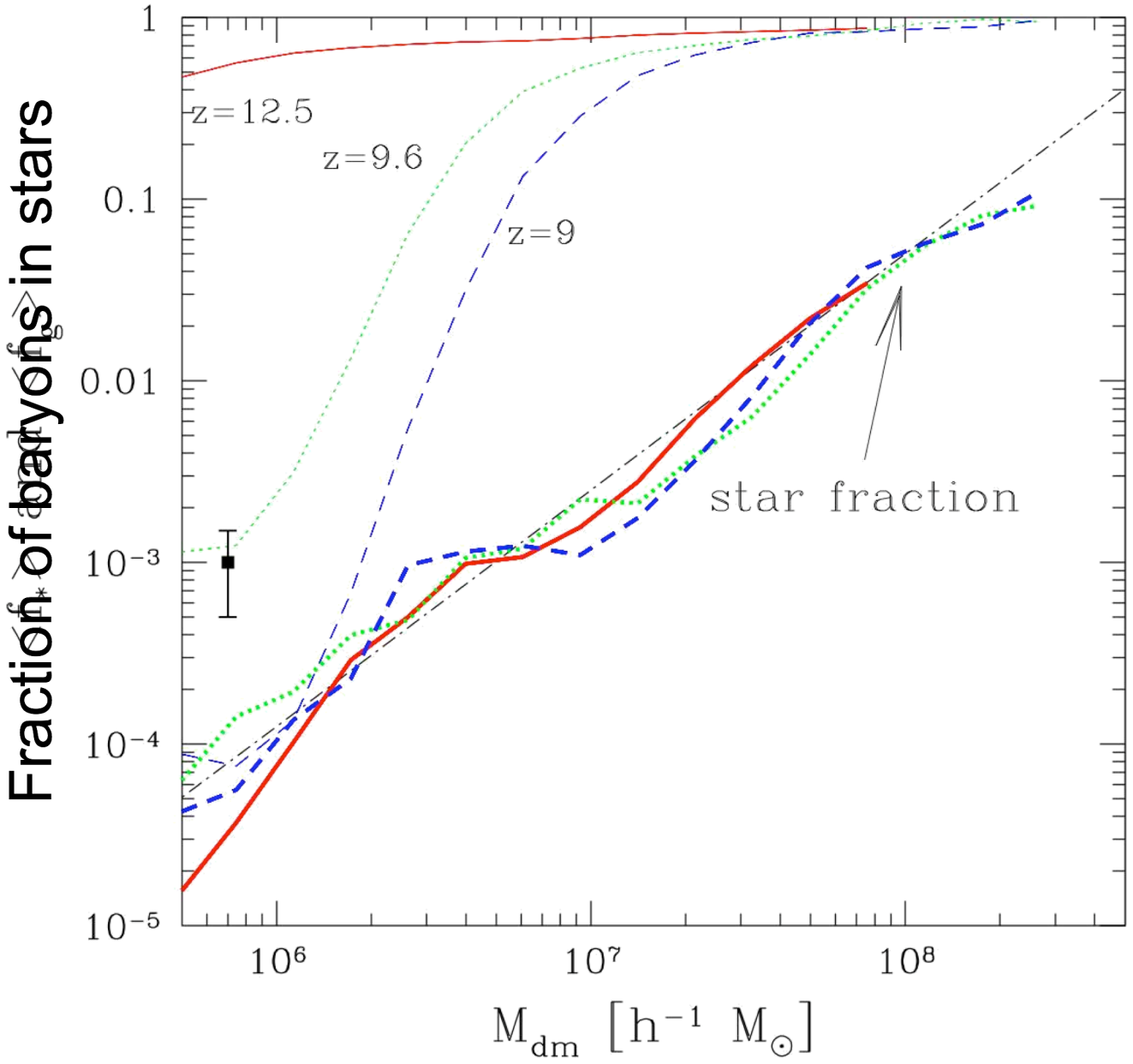
Feedback: Internal vs. external

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

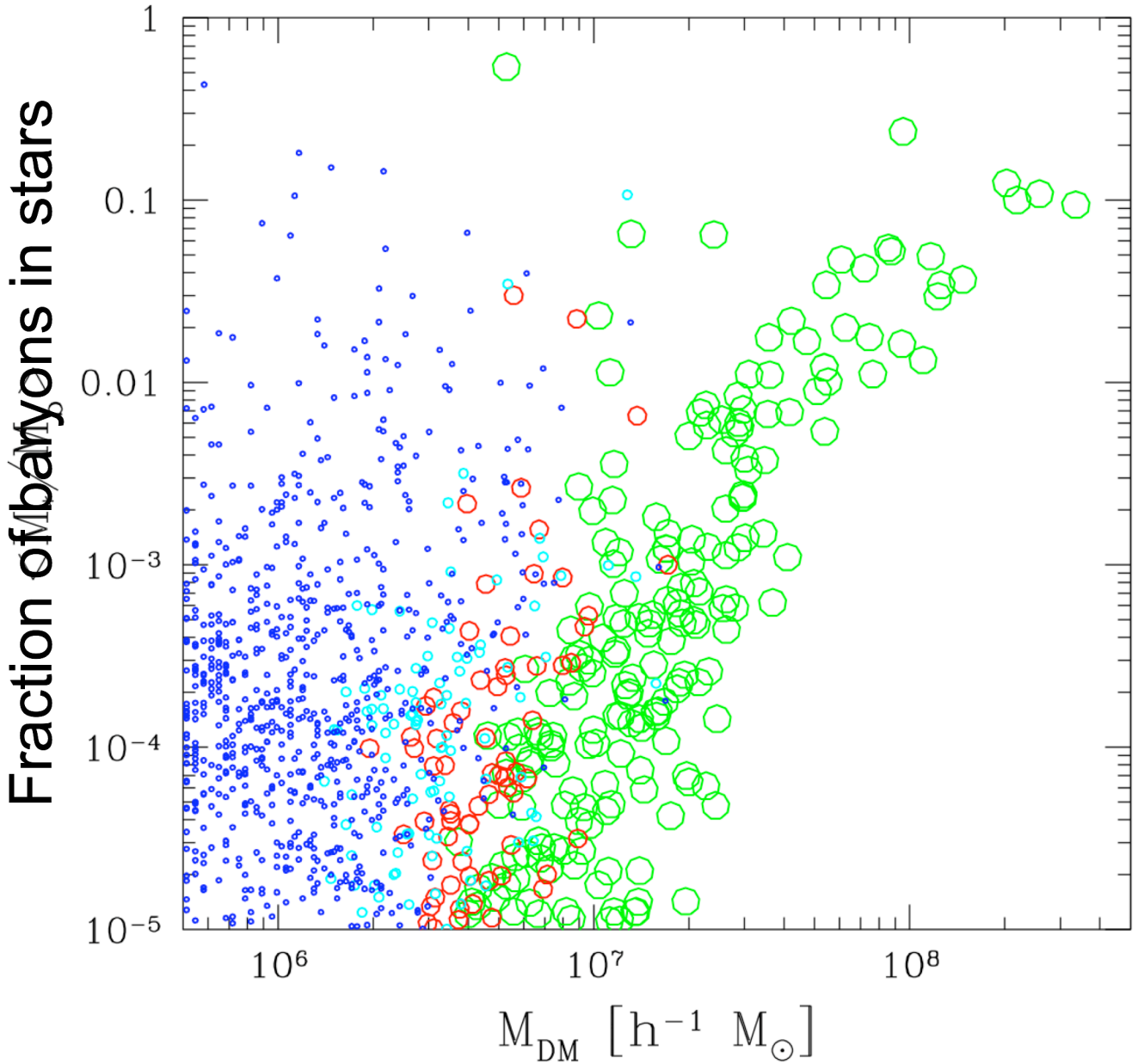
Dark galaxies retain more gas



Star formation efficiency



Star formation efficiency

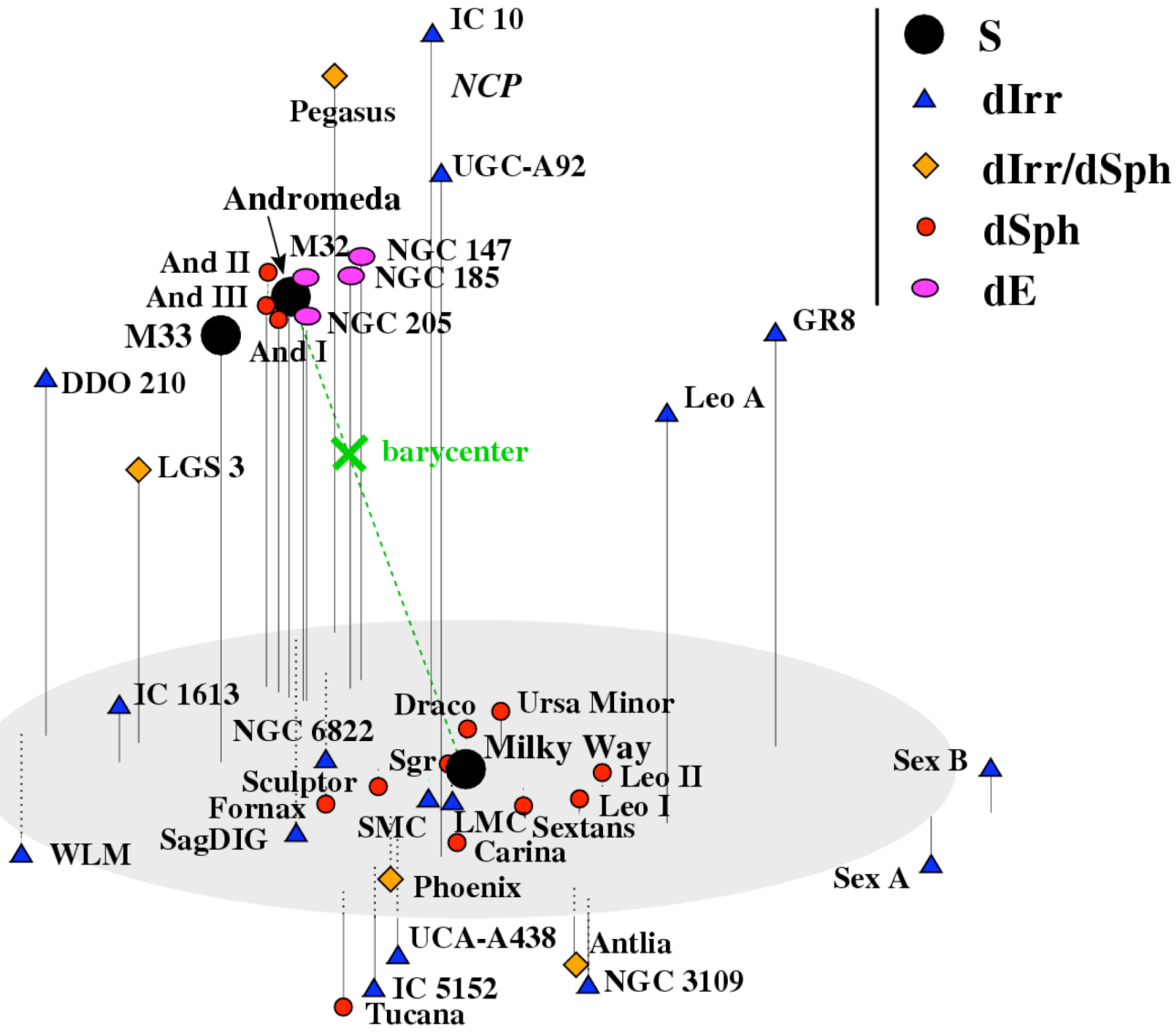


Can we test our simulations ?

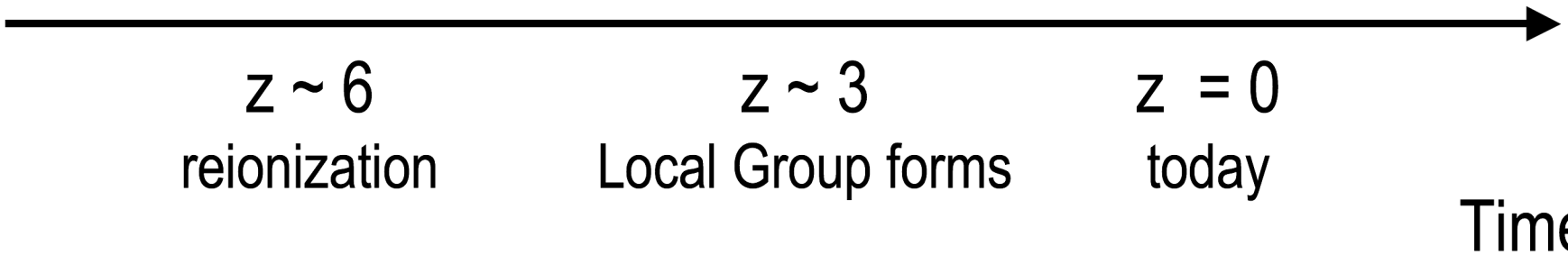
- ~100 dwarfs per comoving Mpc^3 at z=10
- Most are distroyed by z=0 but 5-10% survive
- Where are the fossils of the first galaxies?

- Dwarf Spheroidal galaxies are among the oldest and smallest bound stellar objects we know
- Perfect candidates to be the fossils of the first galaxies.
- The Local Group is a crucial benchmark to test the theoretical models of the formation of first stars and galaxies

The Local Group (not up to date)



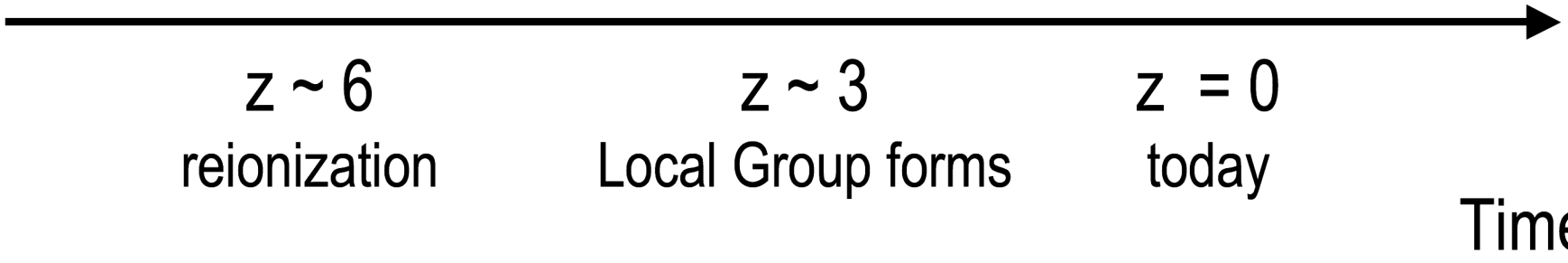
Origin of Dwarf Spheroidals



(Credit: N. Gnedin)

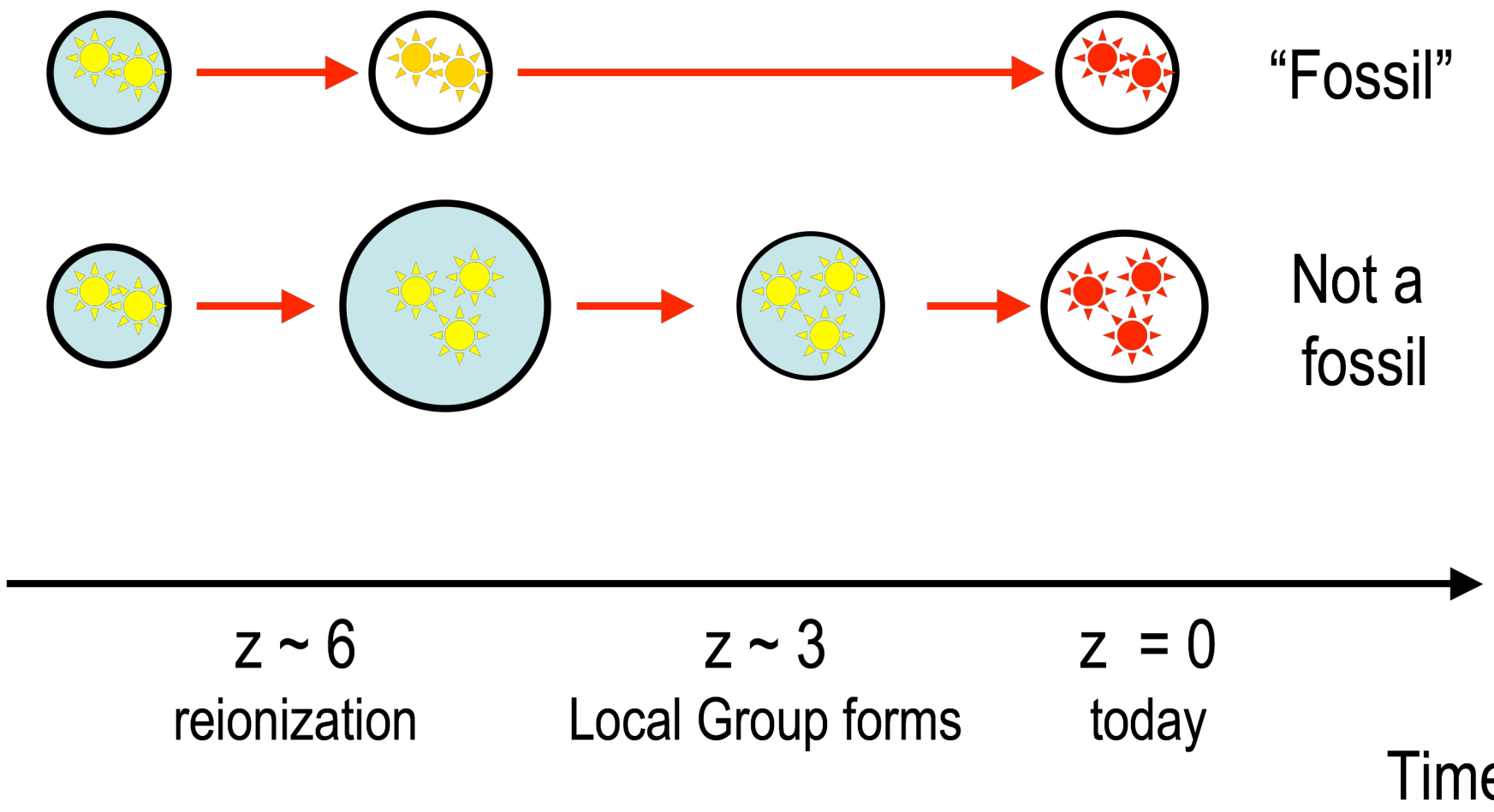
Origin of Dwarf Spheroidals

"Fossil"



(Credit: N. Gnedin)

Origin of Dwarf Spheroidals

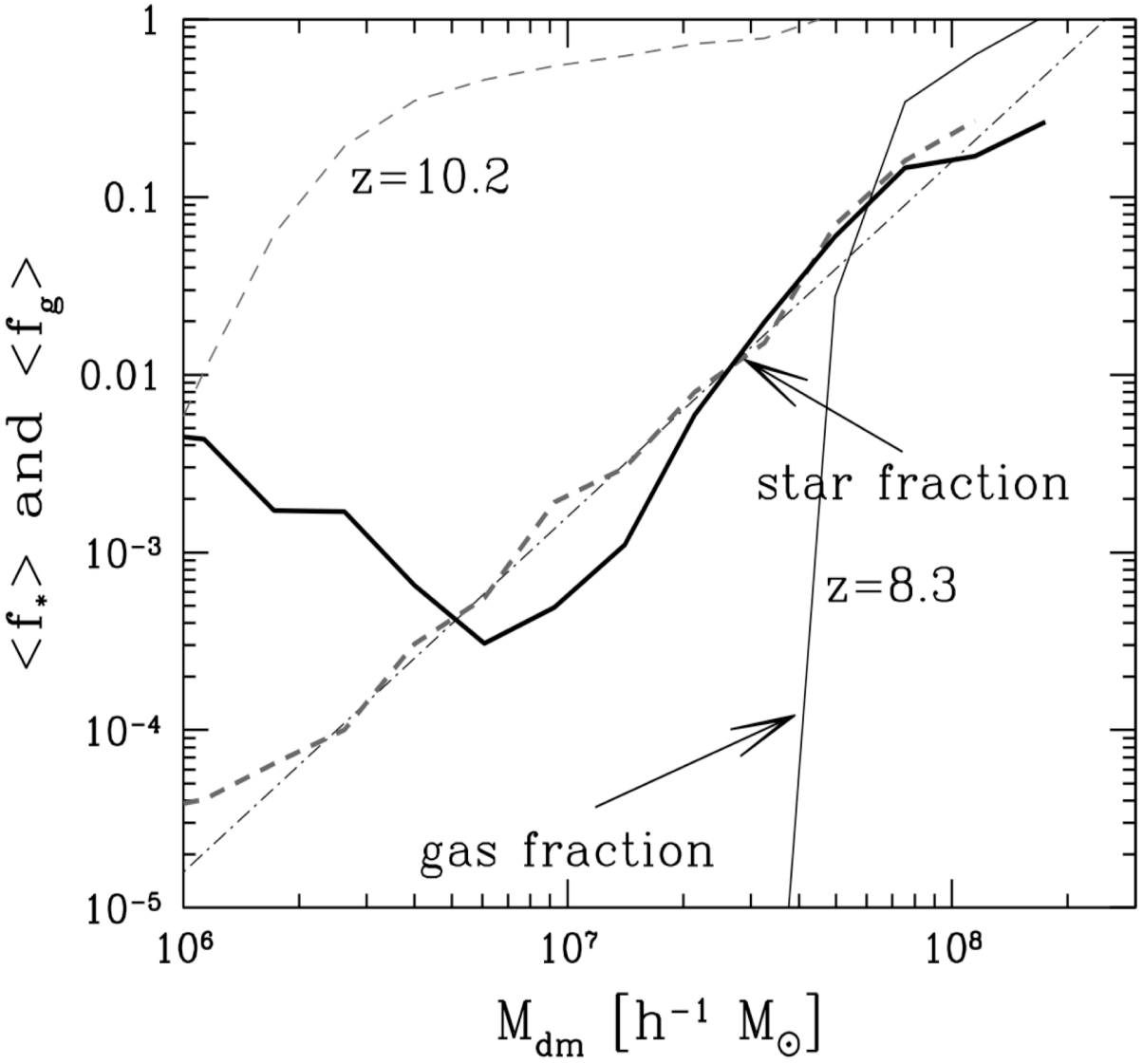


(Credit: N. Gnedin)

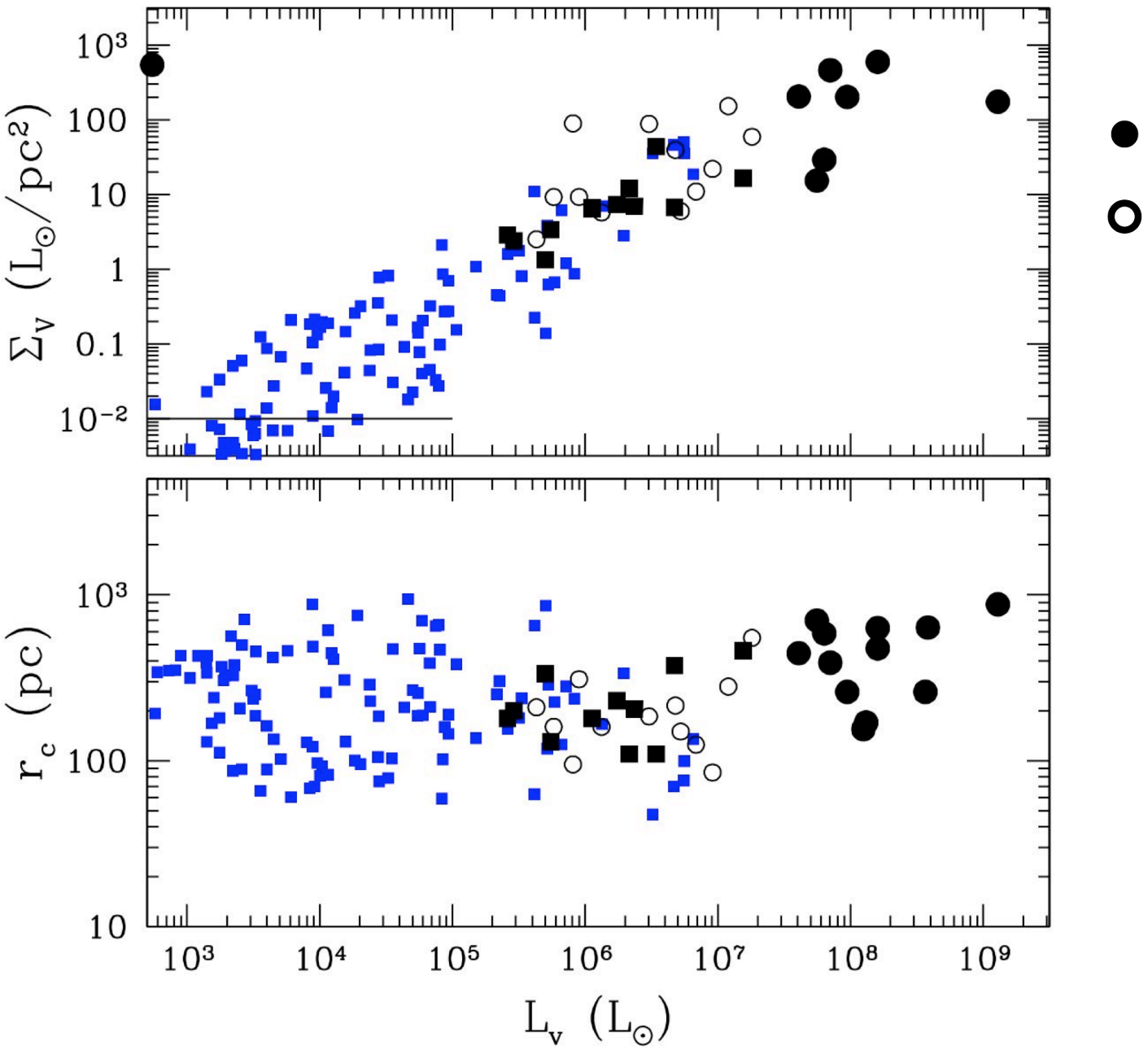
Simulating the effect of Reionization

1. We insert a bright source at redshift z=9 that reionizes the IGM.
2. We compare simulated galaxies at z=8.3 to dwarfs in the Local Group.

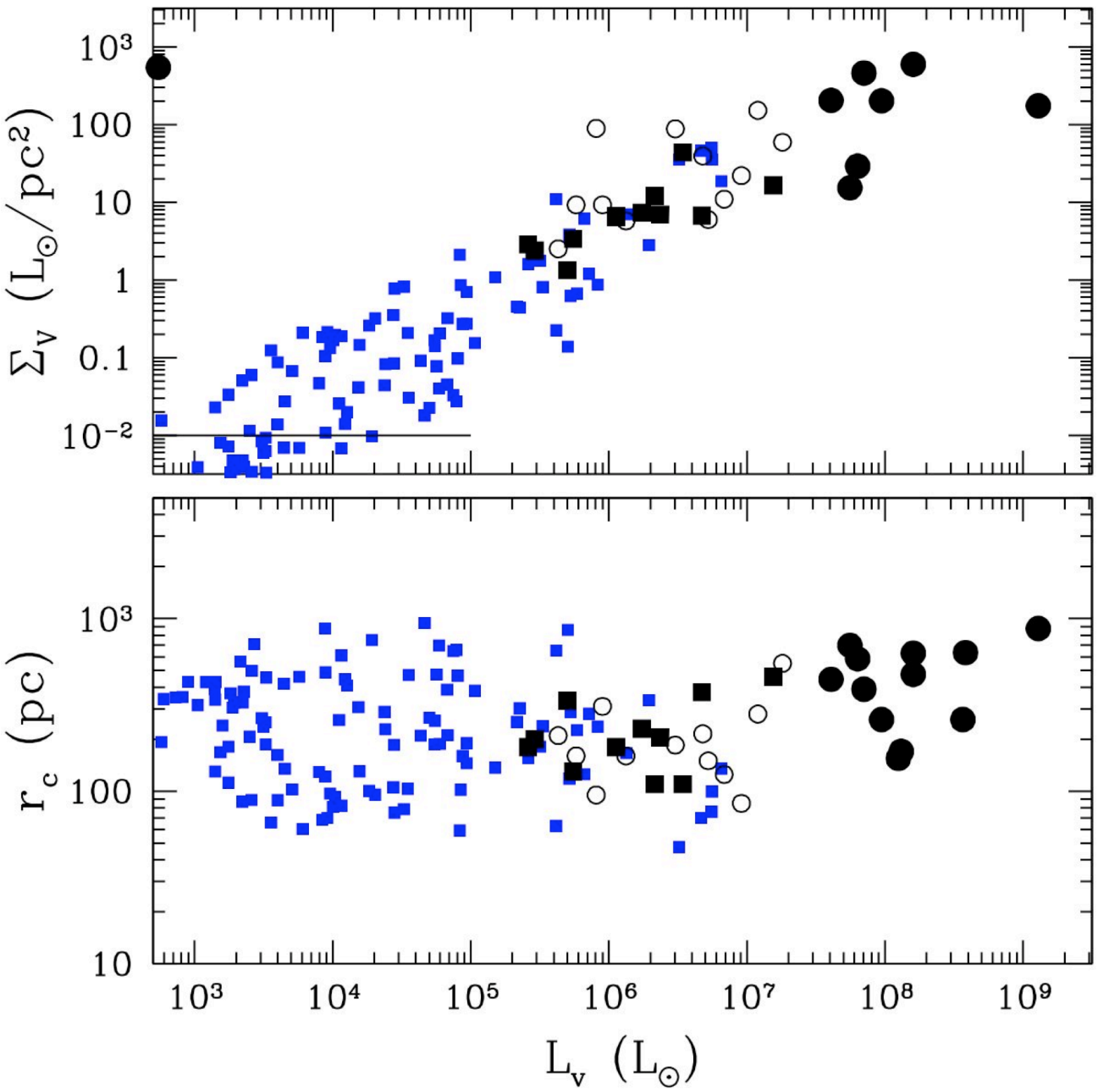
Note: at z=10, before reionization, the galaxies have about the same properties as after reionization.



FossiL's Properties



FossiL's Properties



Non-fossils

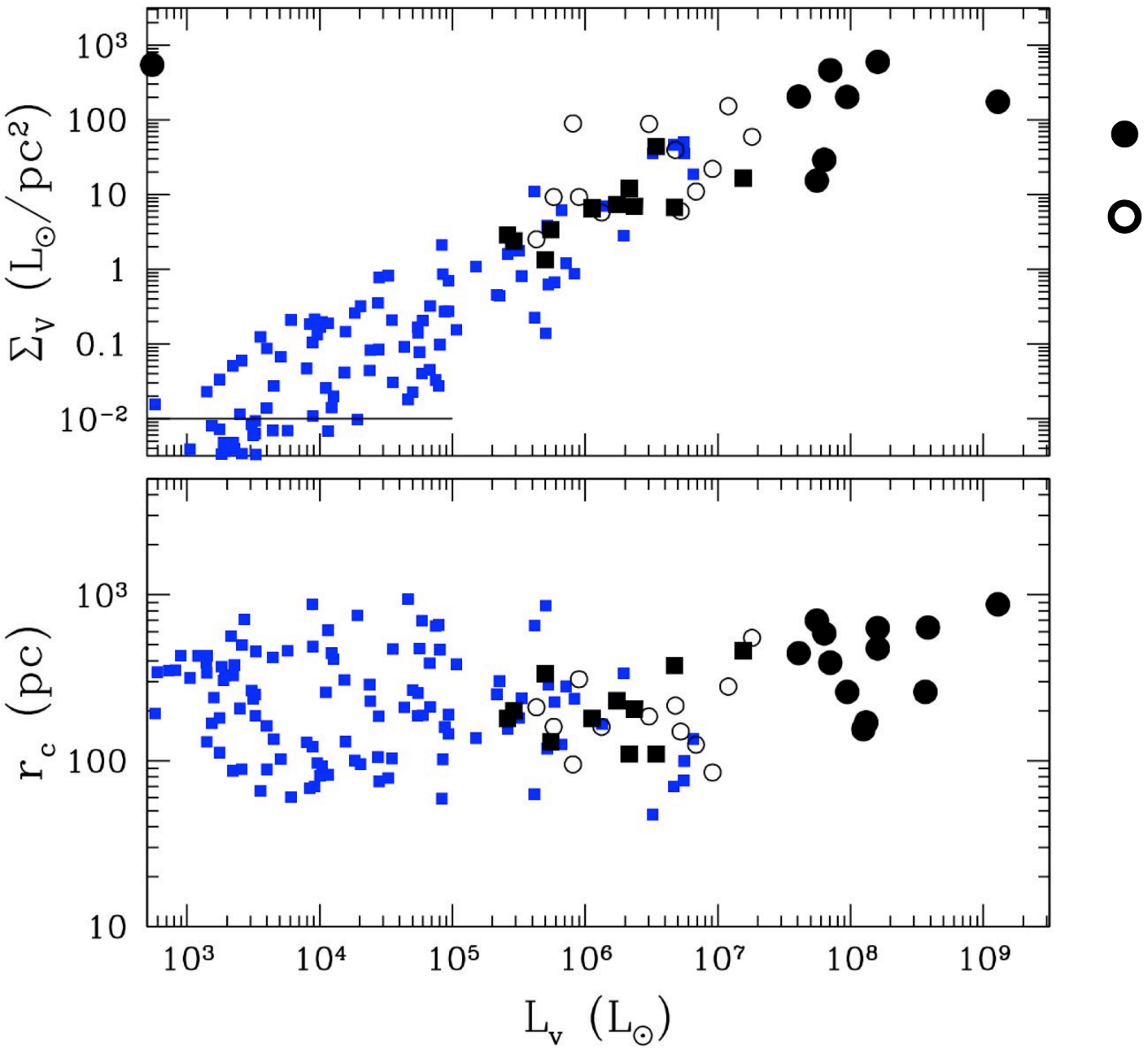
Fossils

Virtual dwarfs

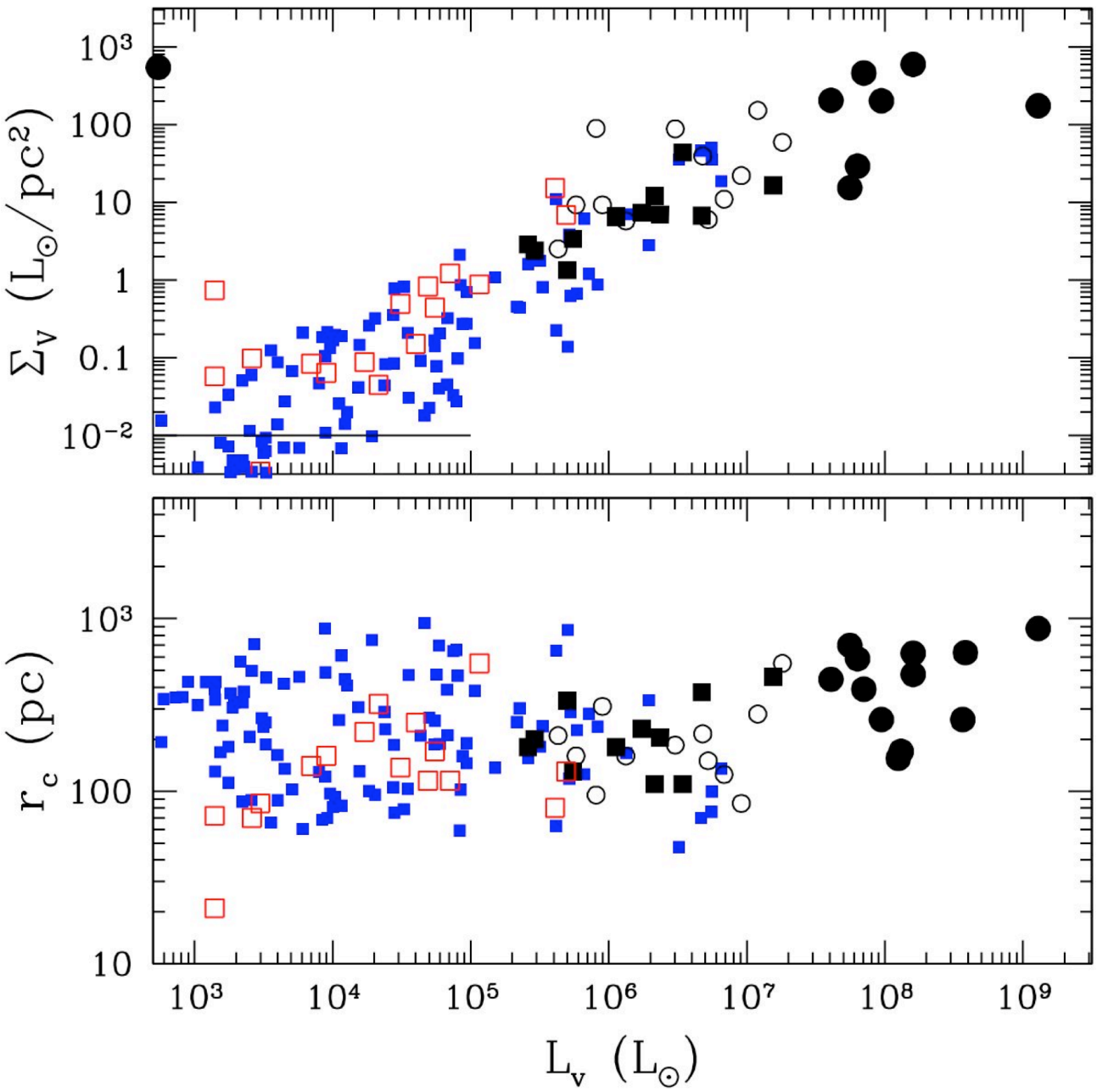
Missing dwarfs discovered!!

- Since 2005 about 16 Ultra-faint new dwarfs have been discovered! (# from 32 to 48)
- Star counts in SDSS data and deep imaging around Andromeda(Willman etal 05; Zuckert etal 06; Belokurov etal 06,07; Martin etal 06; Irwin etal 07; Sakamoto & Hasegawa 07;Malewski etal 07;Ibata etal 07; Walsh etal 07; Simon & Geha 07)
- Only 1/4 of the sky around M-W and Andromeda surveyed!
- Correcting for completeness we expect >60 new ultra-faint dwarfs
- Inferred # of dwarfs today: approaching 100 and growing !

FossiL's Properties



FossiL's Properties



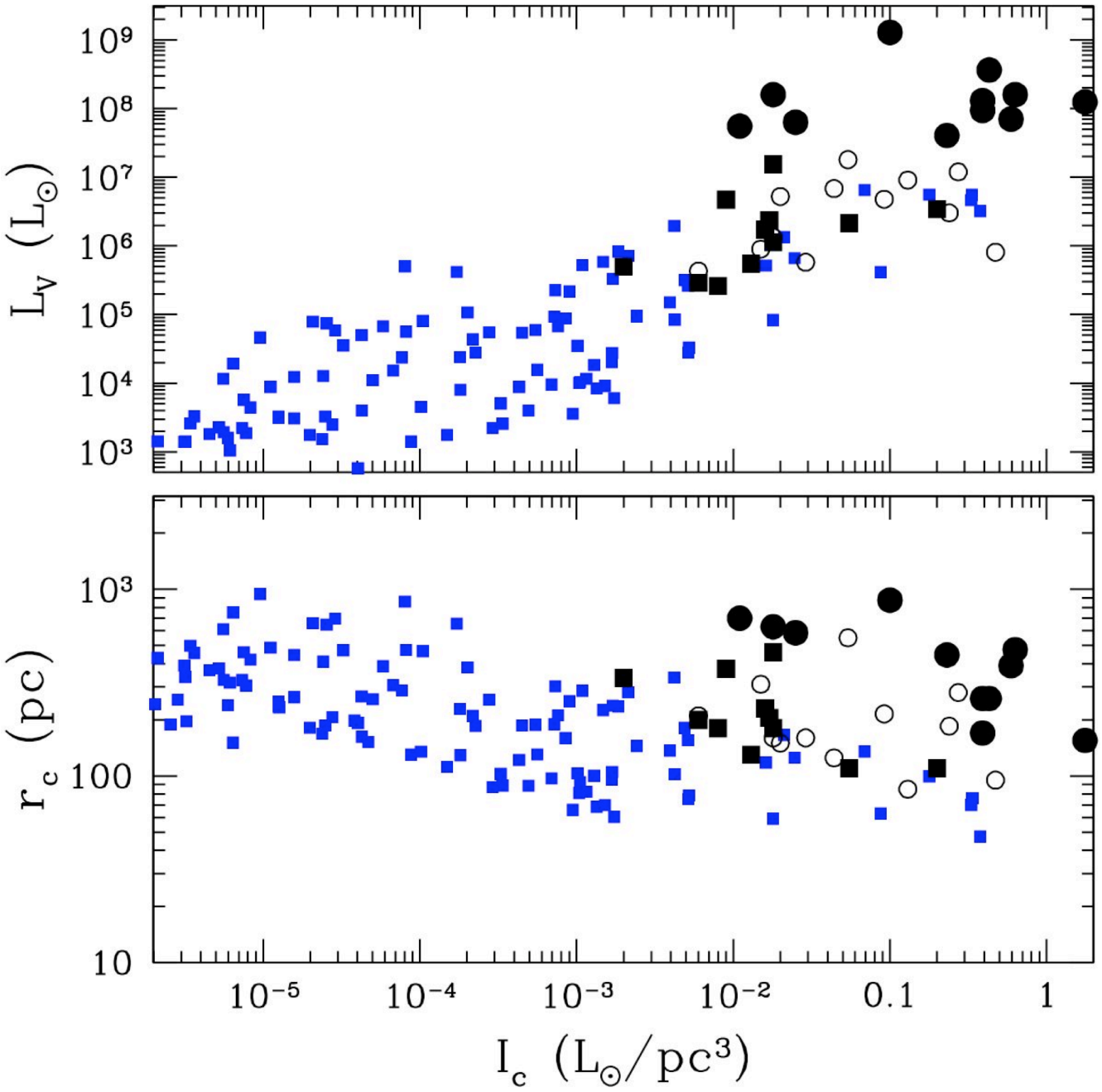
Non-fossils

Fossils

New dwarfs

Virtual dwarfs

FossiL's Properties (cont.)

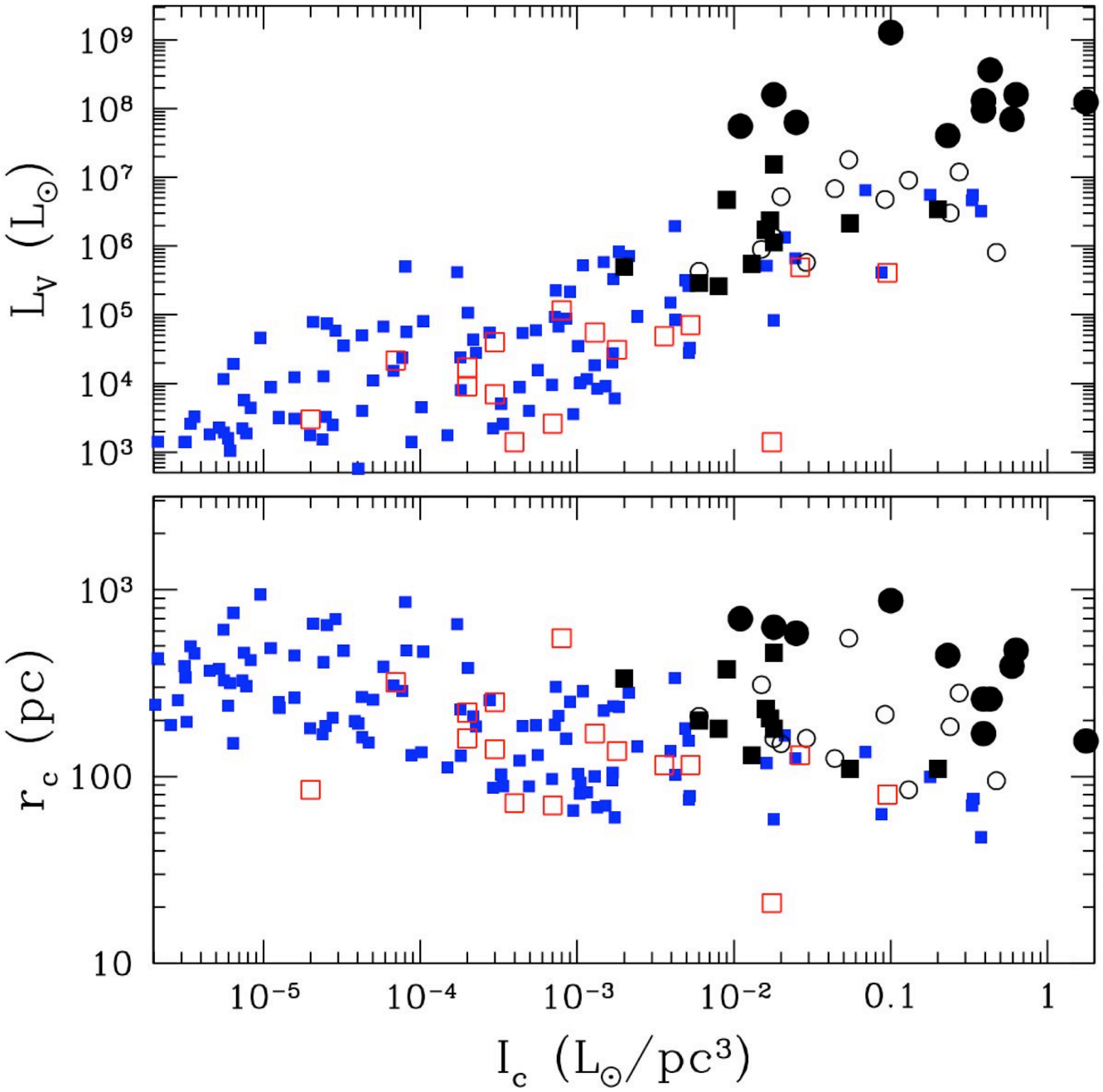


Non-fossils

Fossils

Virtual dwarfs

FossiL's Properties (cont.)



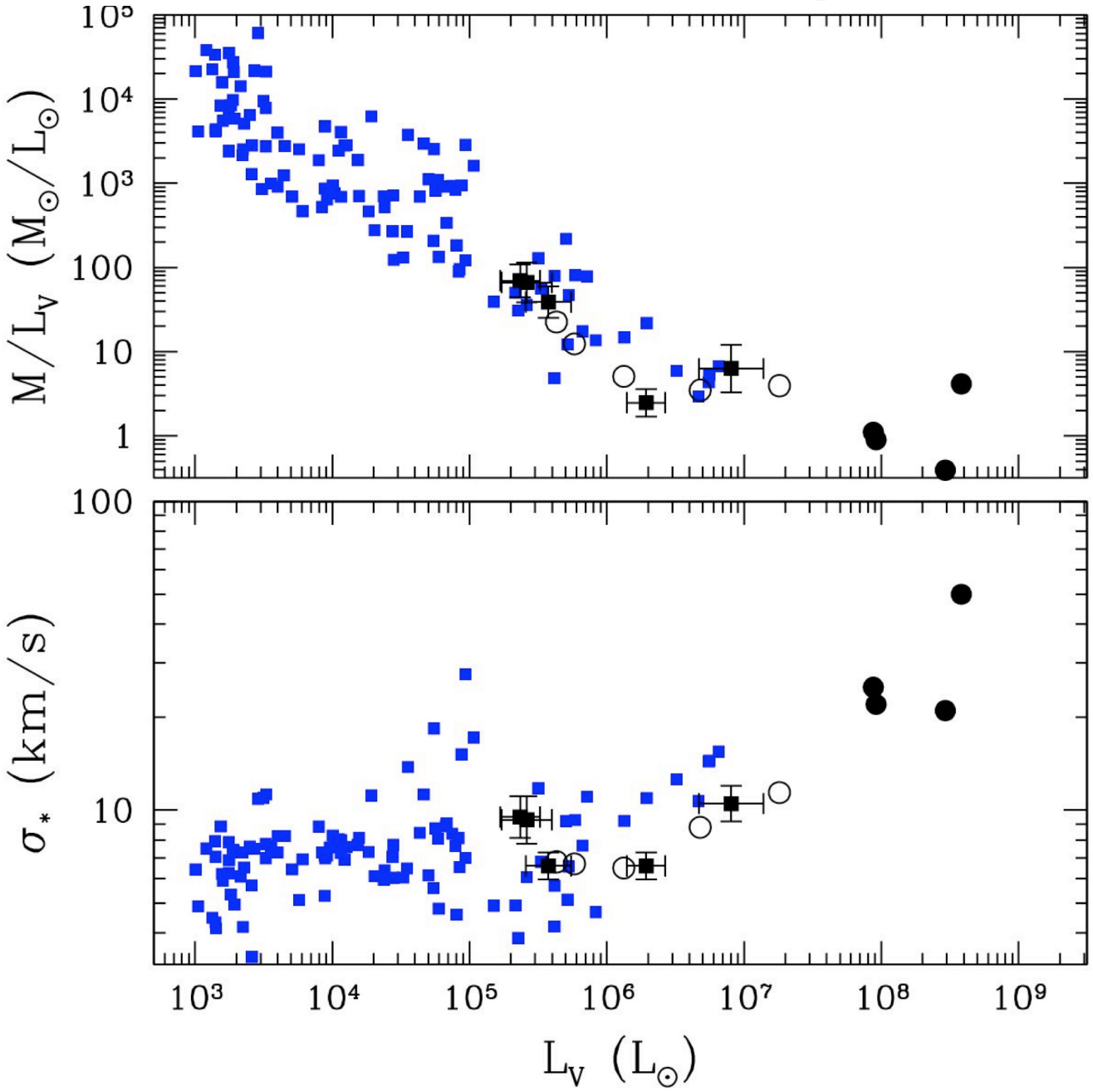
Non-fossils

Fossils

New dwarfs

Virtual dwarfs

FossiL's Properties (cont.)

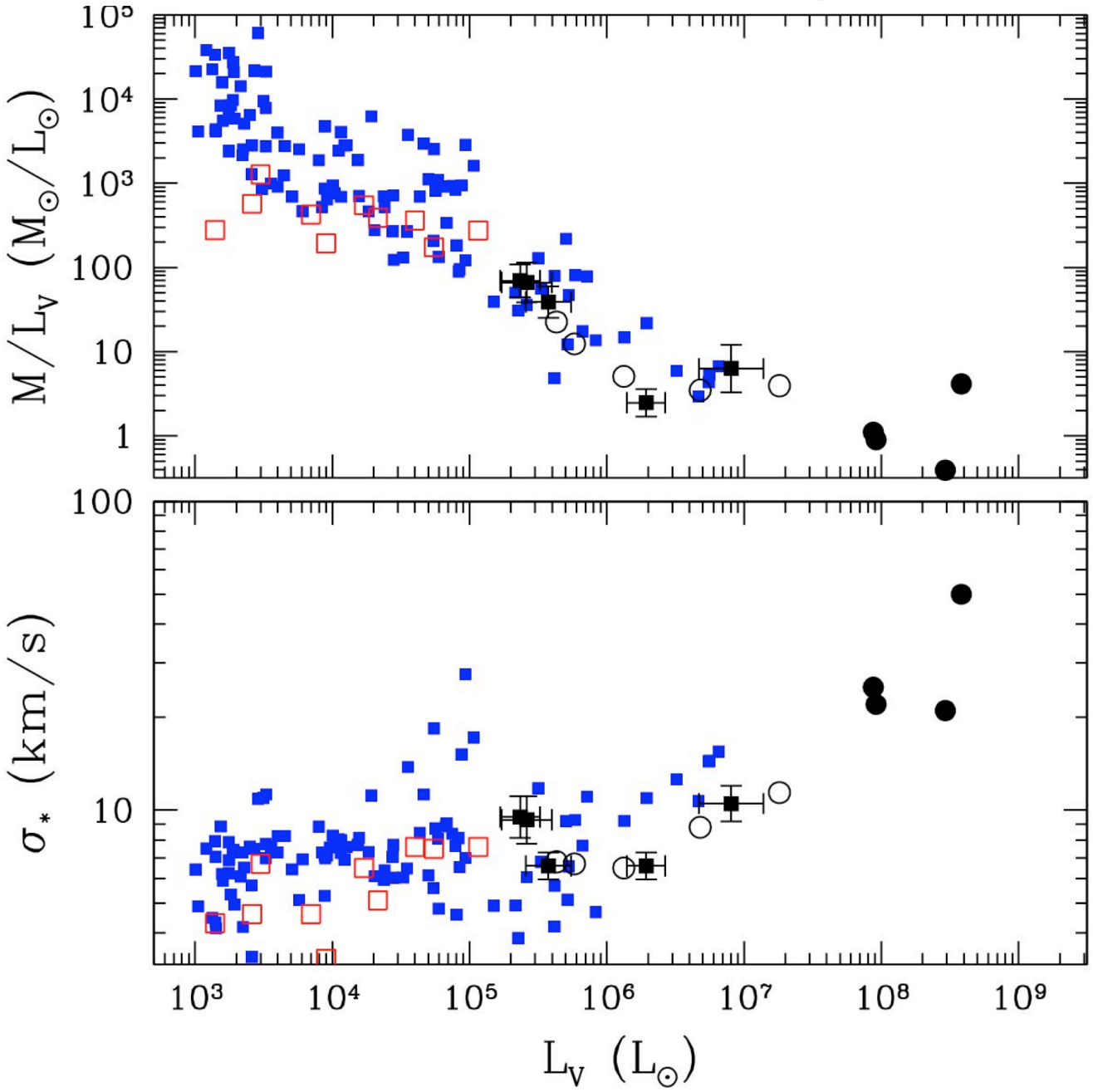


Non-fossils

Fossils

Virtual dwarfs

FossiL's Properties (cont.)



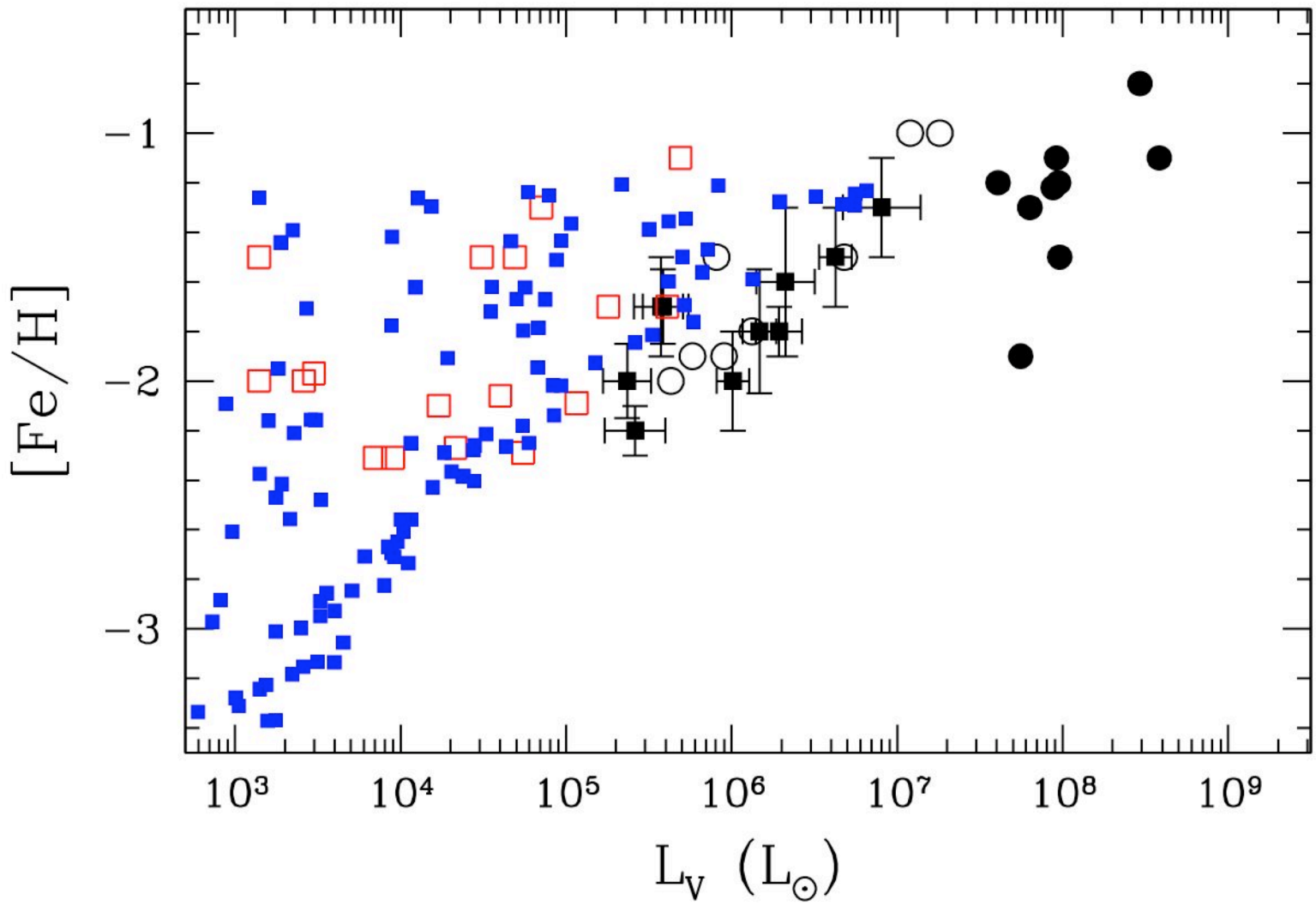
Non-fossils

Fossils

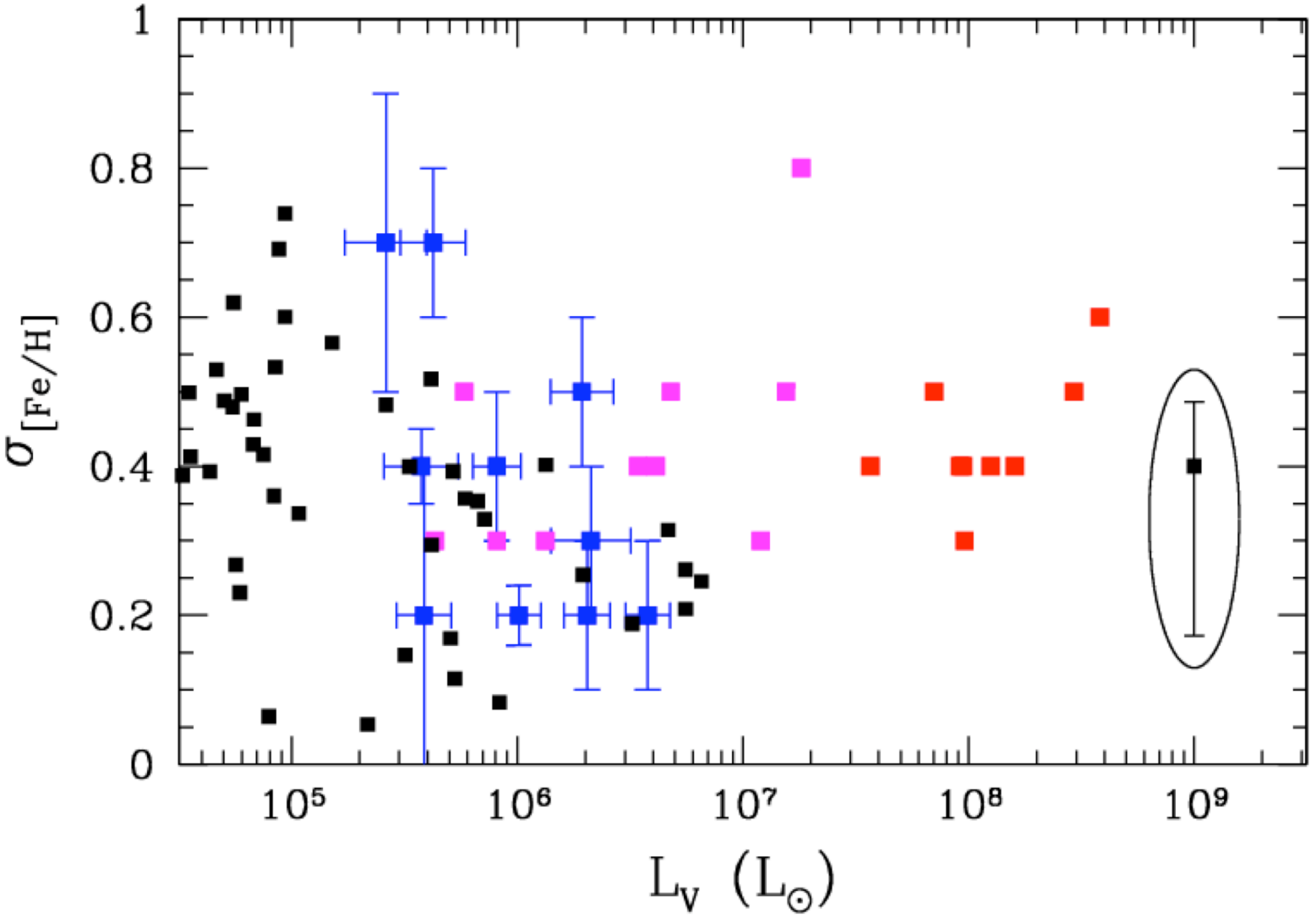
New dwarfs

Virtual dwarfs

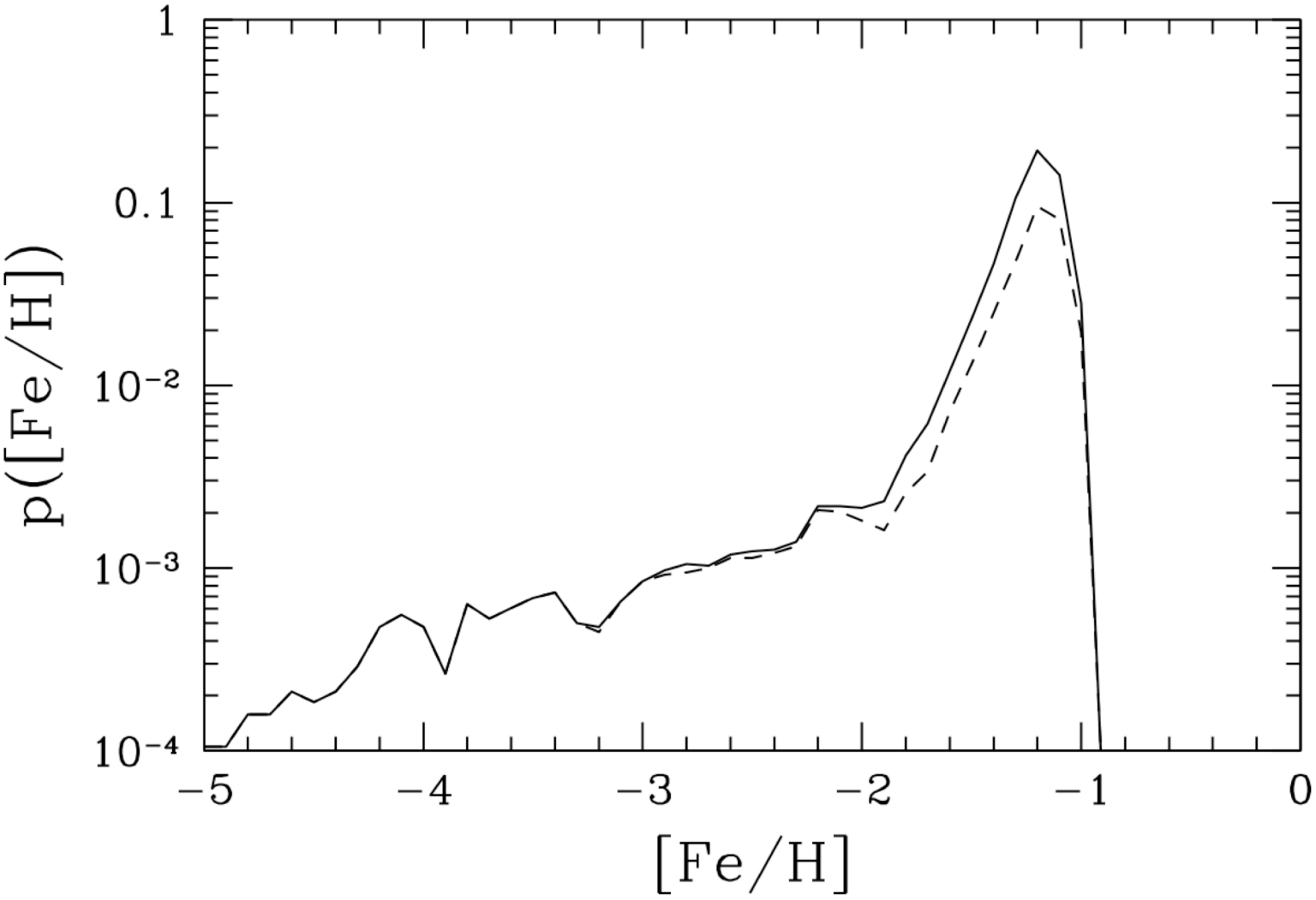
Metallicity



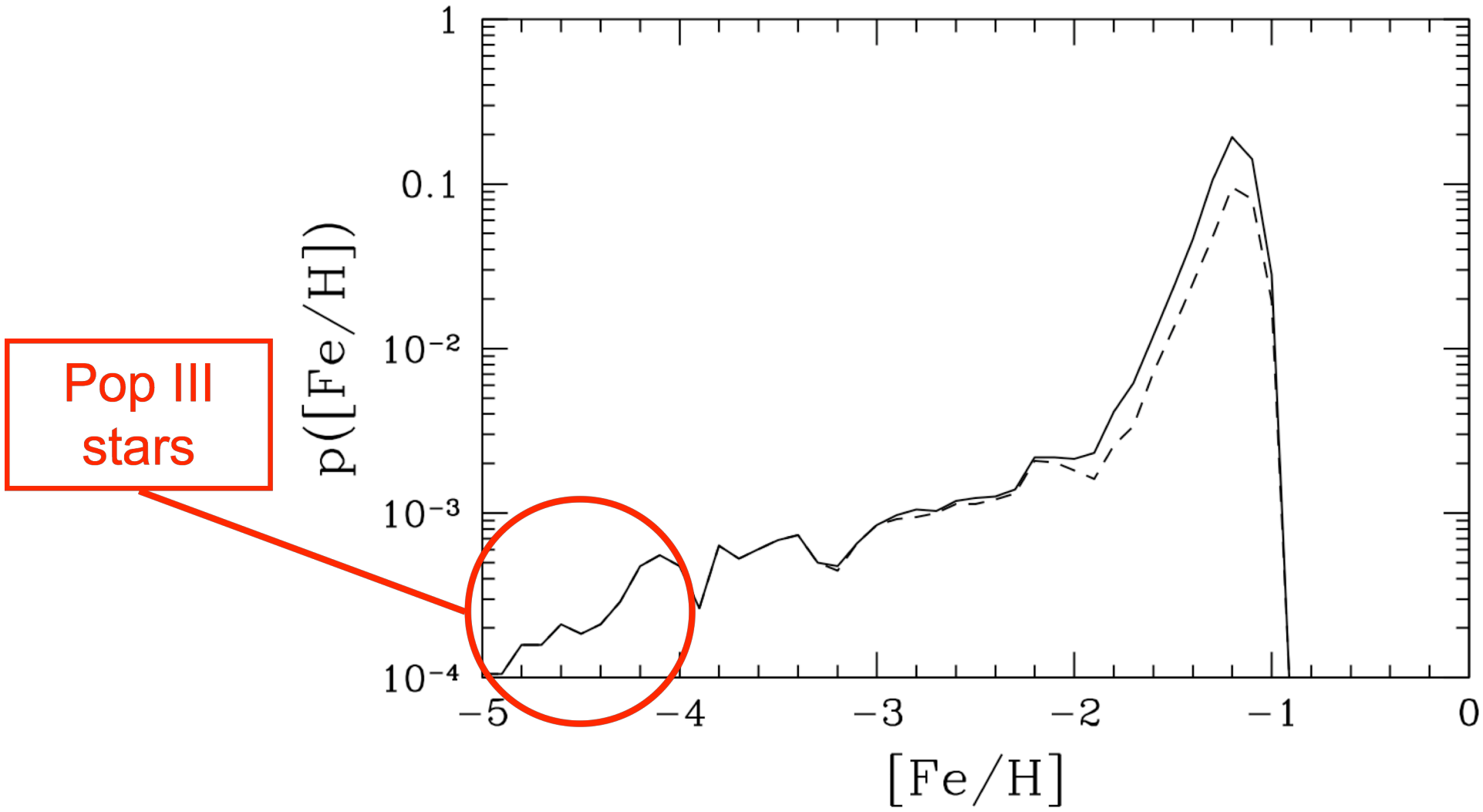
Metallicity Spread: a feature Not a problem!



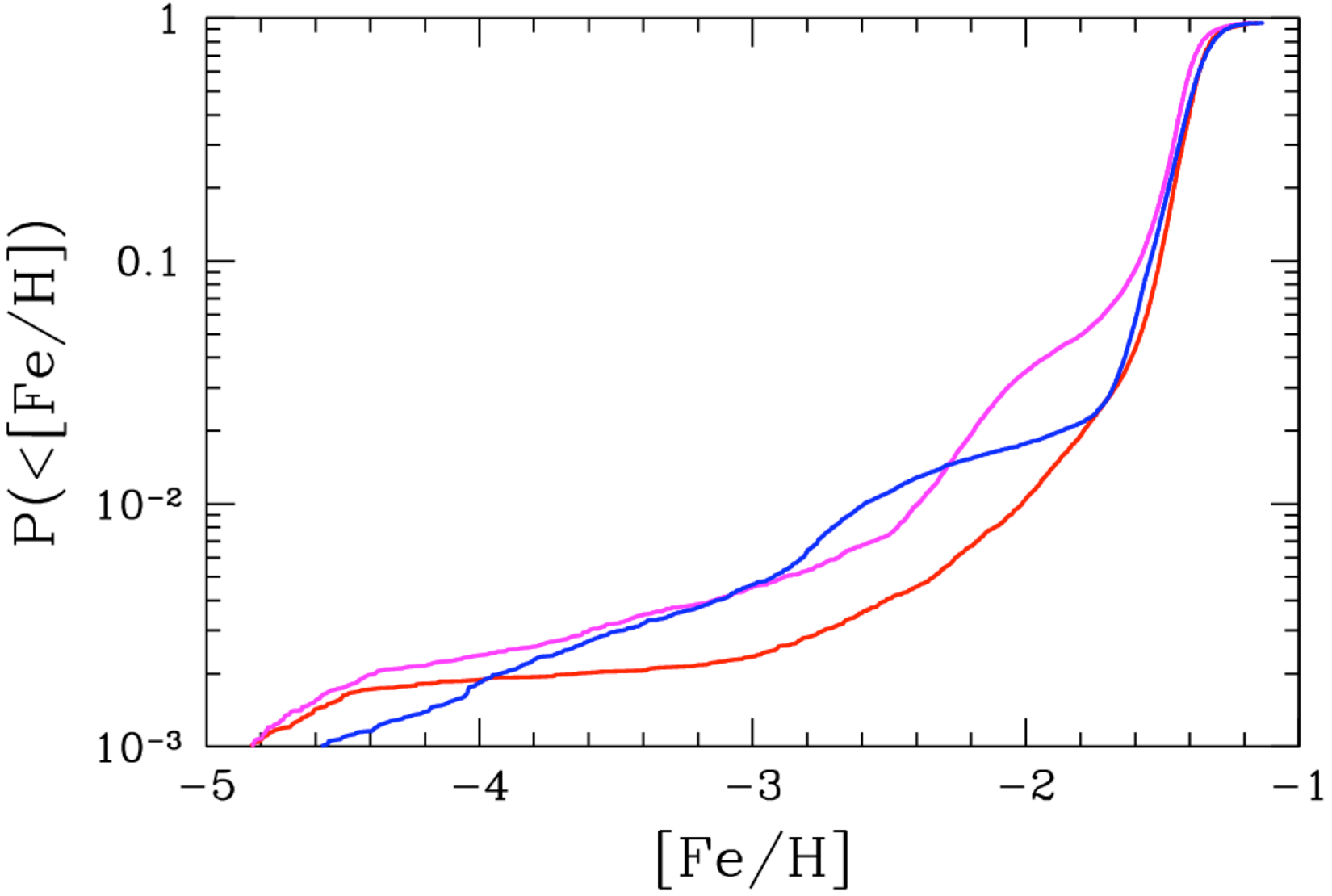
Metallicity Distribution: an example



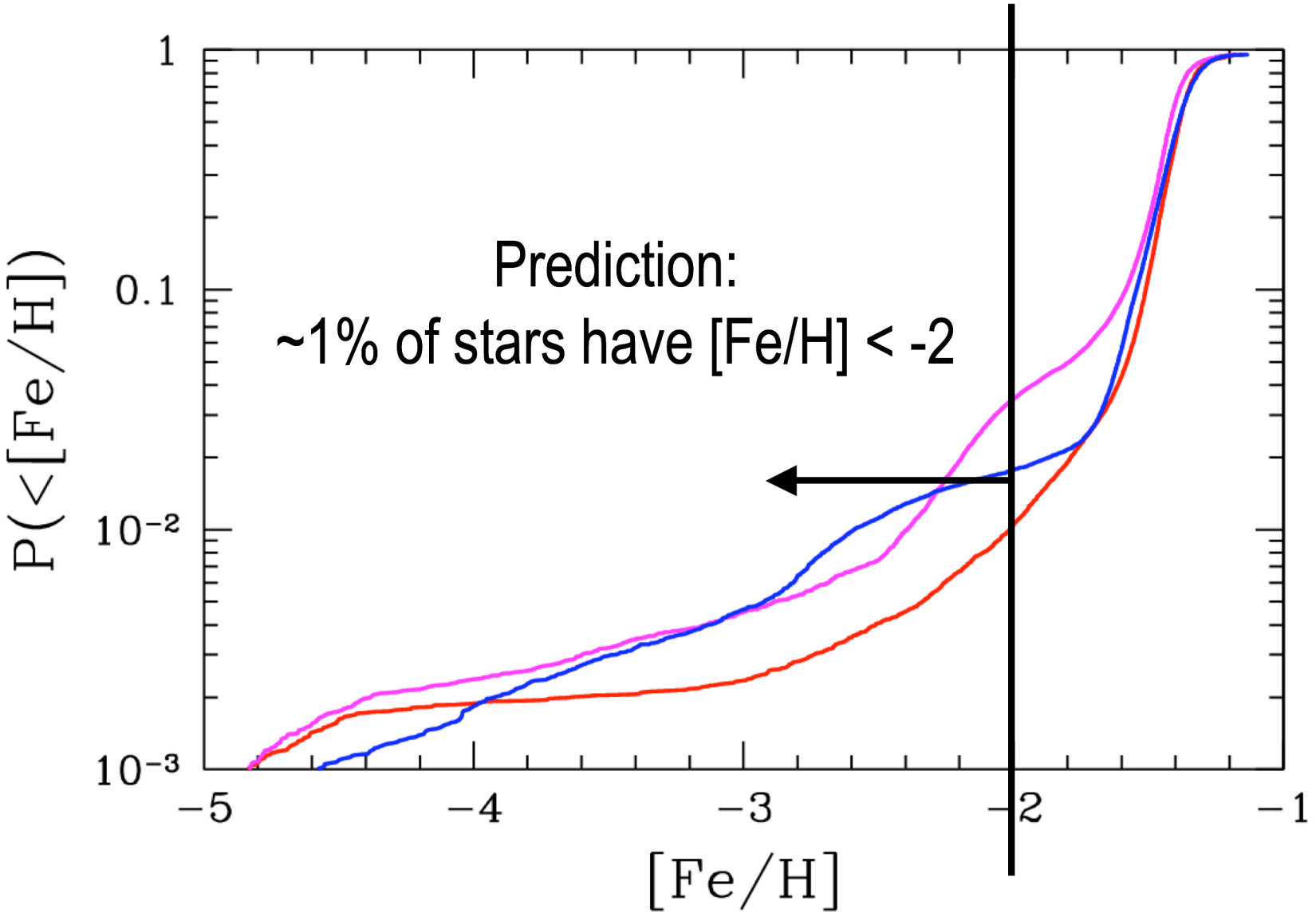
Metallicity Distribution: an example



Cumulative Distribution



Cumulative Distribution



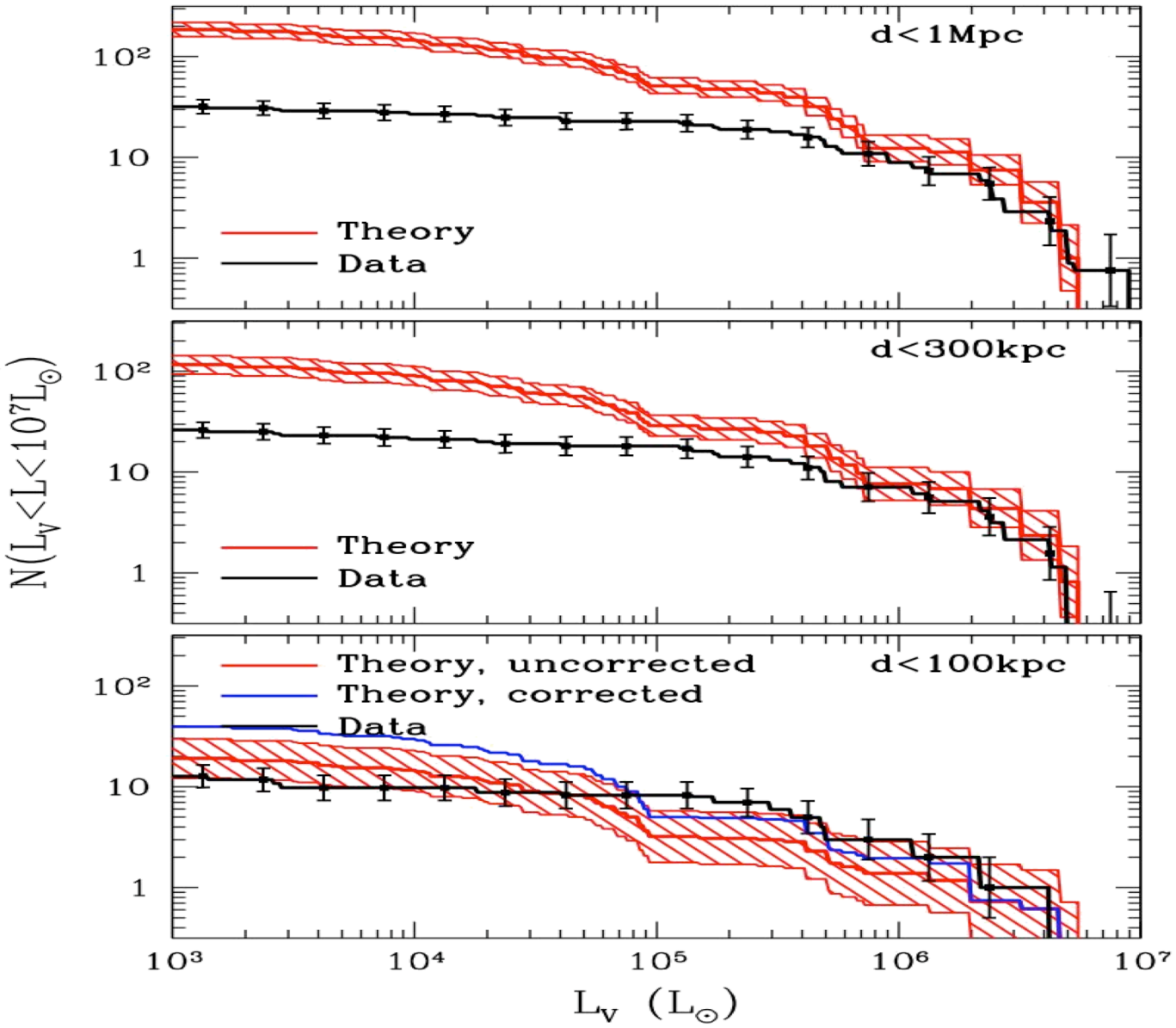
How massive are their DM halos?

- There are only ~40 halos in the Milky Way and Andromeda with V>20 km/s
- Some ultra-faint dwarfs must be in mini-halos with V<20 km/s
- First evidence for star formation in primordial dwarfs and importance of positive feedback?

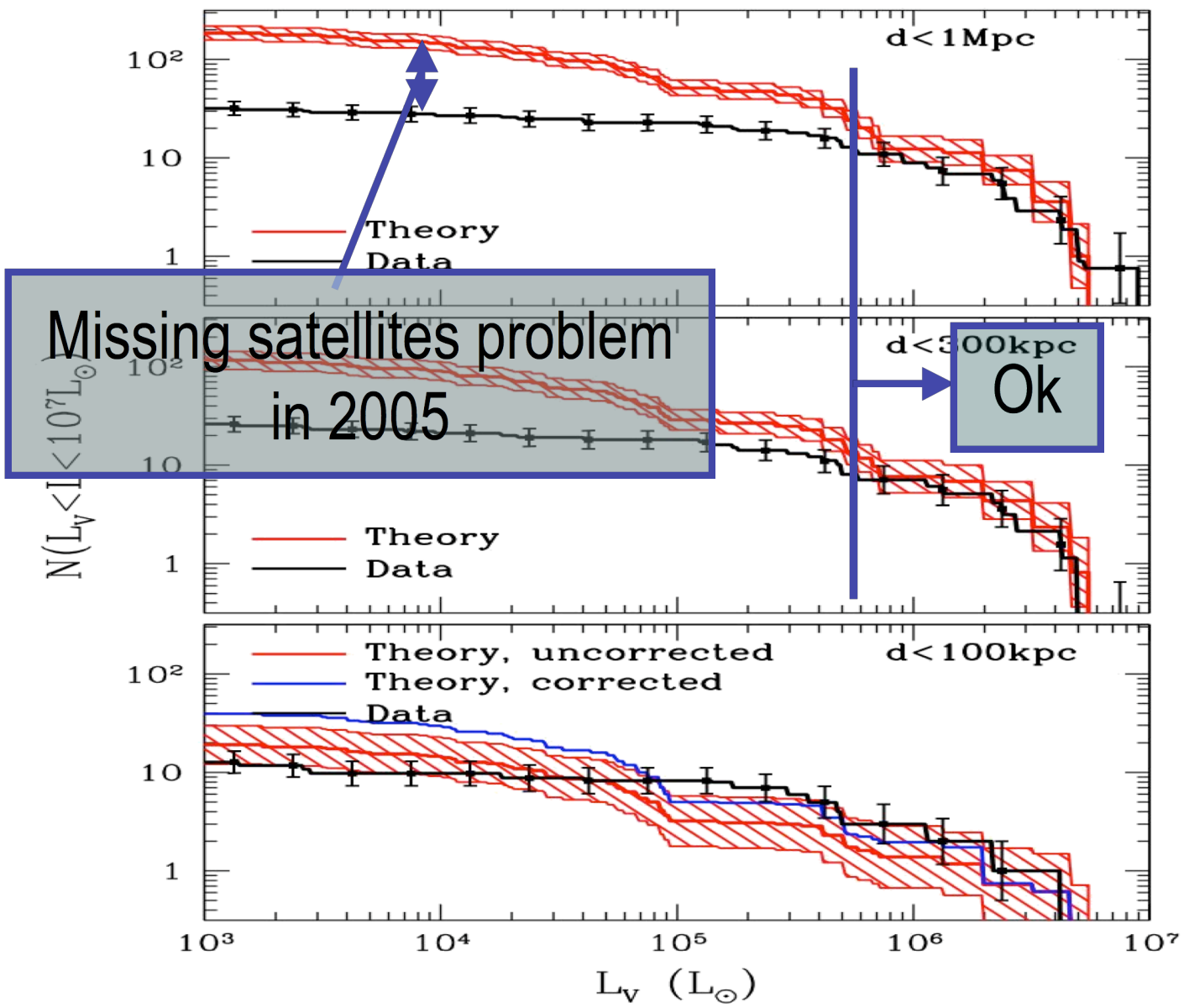
Distribution around MilkyWay and Andromeda

- Use N-body simulation of the Milky-Way combined with data on first galaxies to predict luminosity function at z=0 (Gnedin and Kraztov 2006)
- Similar procedure used to predict Luminosity functions in the Voids (Bovill and Ricotti, in preparation)

Luminosity Functions



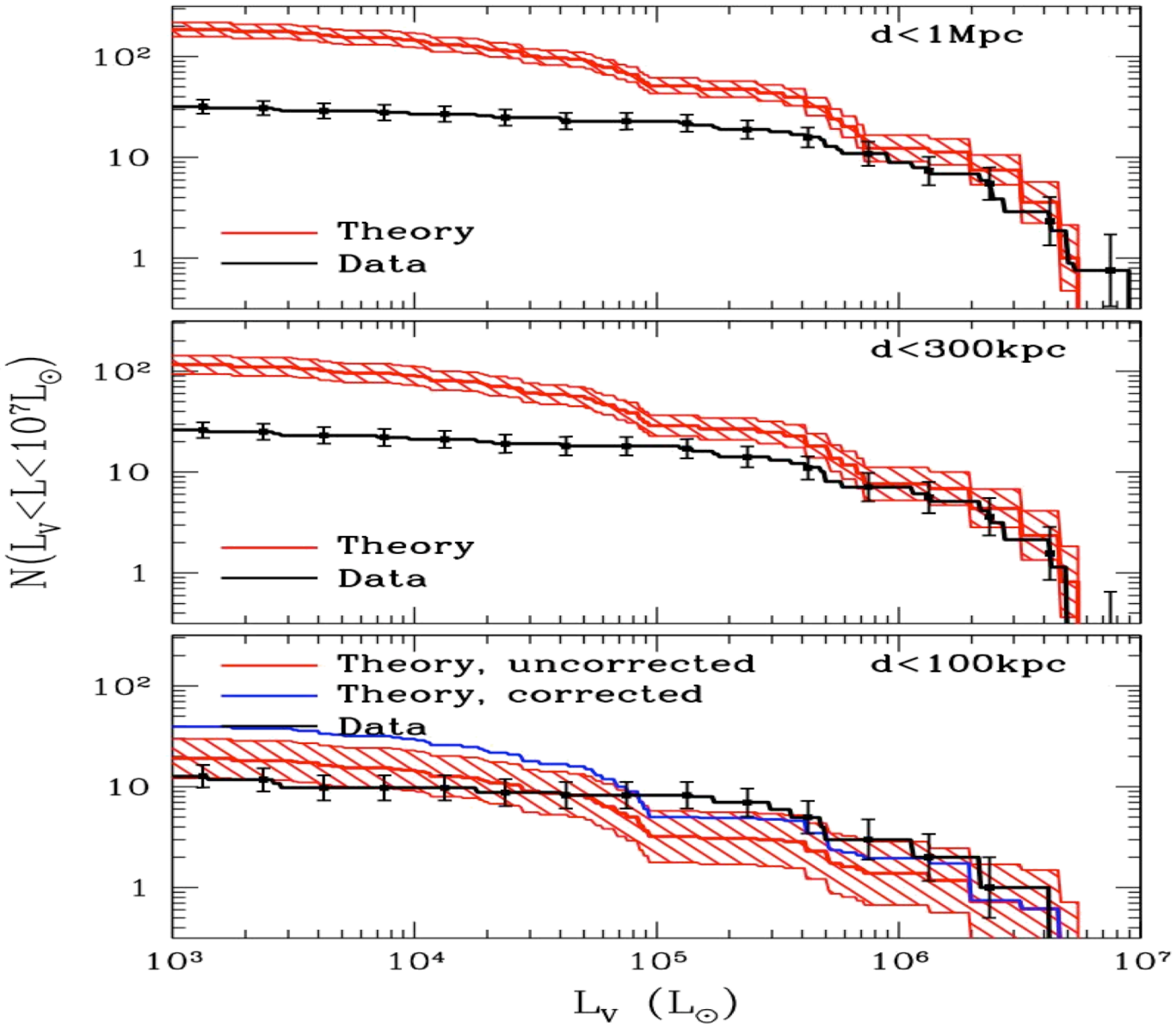
Luminosity Functions



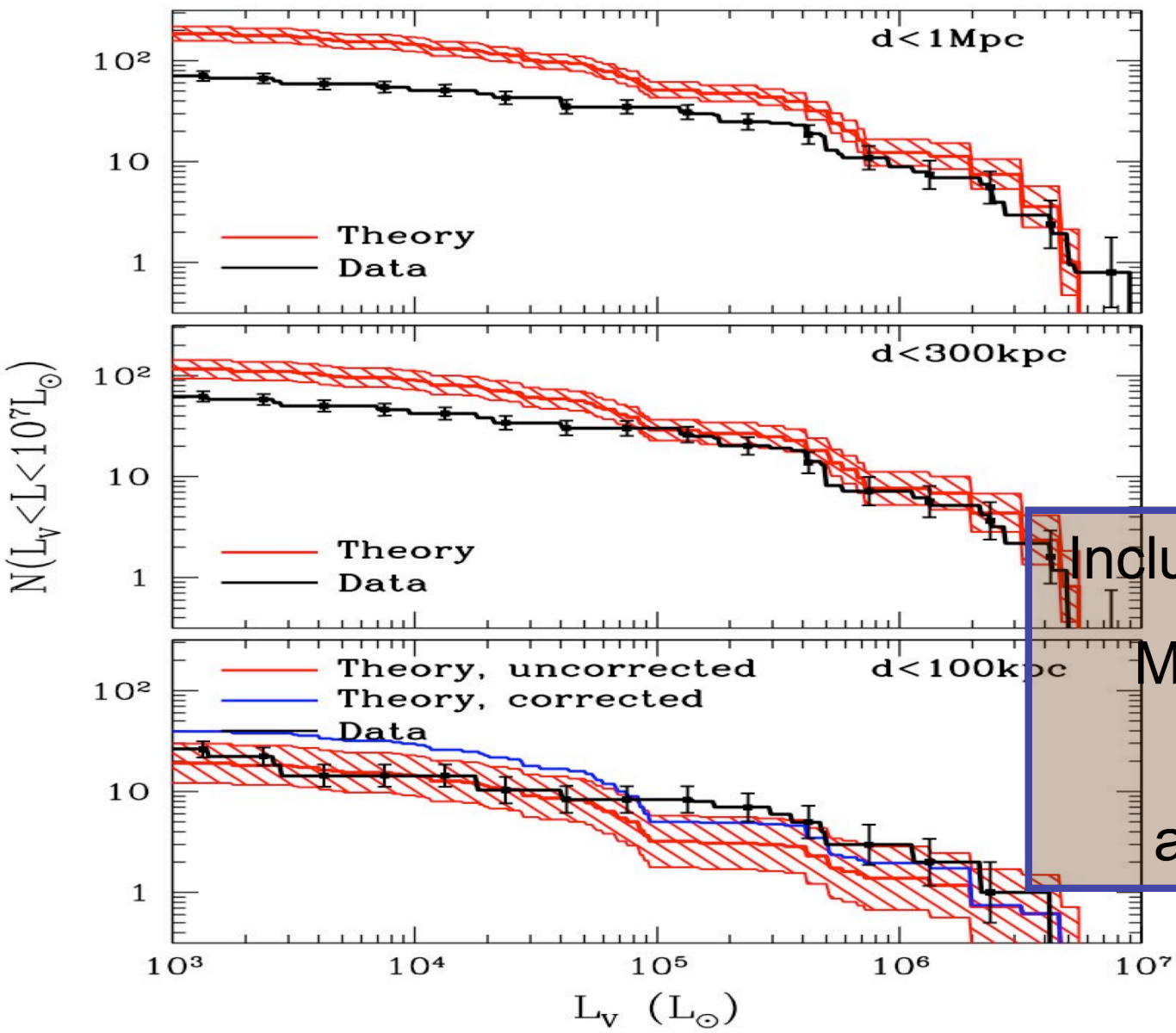
Missing satellites problem in 2005

Ok

Luminosity Functions



Luminosity Functions



Including new dwarfs

Missing satellite problem

almost solved!

Conclusions

Conclusions

Our simulations show that the first galaxies are very numerous and ultra-faint

Conclusions

Our simulations show that the first galaxies are very numerous and ultra-faint

• Many tens to a hundred of “surviving” fossils of the first galaxies should be in the Local Group and Local Volume

Conclusions

Our simulations show that the first galaxies are very numerous and ultra-faint

- Many tens to a hundred of "surviving" fossils of the first galaxies should be in the Local Group and Local Volume
- Resemble lowest mass dwarf spheroidals in almost all observable properties – is it a coincidence?

Conclusions

Our simulations show that the first galaxies are very numerous and ultra-faint

- Many tens to a hundred of "surviving" fossils of the first galaxies should be in the Local Group and Local Volume
- Resemble lowest mass dwarf spheroidals in almost all observable properties – is it a coincidence?
- Predicted ultra-faint dwarfs are being found!

Conclusions

Our simulations show that the first galaxies are very numerous and ultra-faint

- Many tens to a hundred of "surviving" fossils of the first galaxies should be in the Local Group and Local Volume
- Resemble lowest mass dwarf spheroidals in almost all observable properties – is it a coincidence?
- Predicted ultra-faint dwarfs are being found!
- Existence of reionization fossils in the Local Group is an hypothesis consistent with the data but can other formation scenarios also reproduce the data?

Conclusions

Our simulations show that the first galaxies are very numerous and ultra-faint

- Many tens to a hundred of "surviving" fossils of the first galaxies should be in the Local Group and Local Volume
- Resemble lowest mass dwarf spheroidals in almost all observable properties – is it a coincidence?
- Predicted ultra-faint dwarfs are being found!
- Existence of reionization fossils in the Local Group is an hypothesis consistent with the data but can other formation scenarios also reproduce the data?
- I hope that our hypothesis is correct because it will open up a new exciting window into the very first stages of galaxy formation.

THE END

Dwarf galaxies - first or second population?

Dwarf galaxies - first or second population?

- First Population (I.) - Issues:
  1. How small were the smallest luminous galaxies ?
  2. How many ? How did they look like ?
  3. Did they survive to redshift z=0 ?

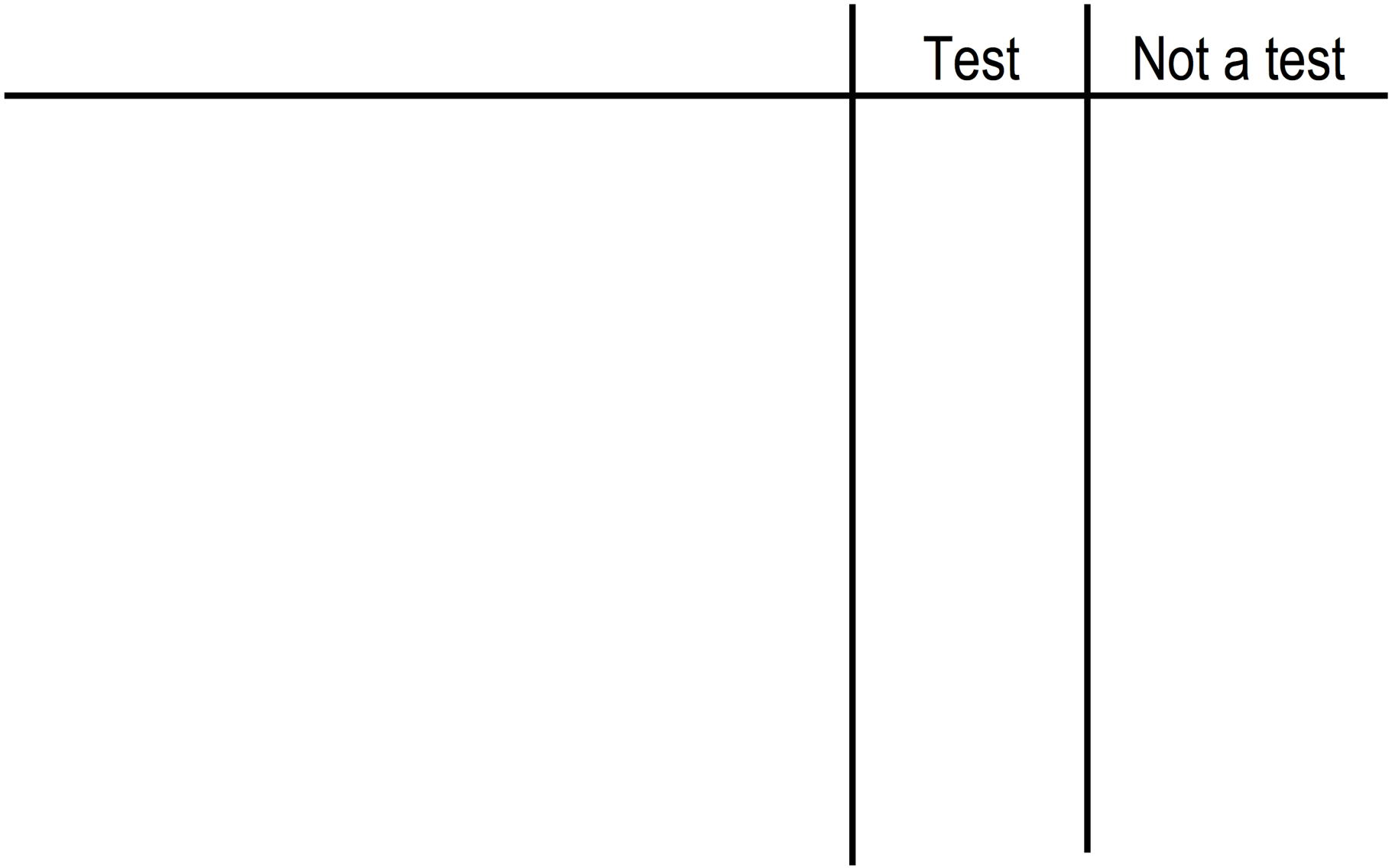
  (see Tassis et al. 2003 and Ricotti & Gnedin 2005)

Dwarf galaxies - first or second population?

- First Population (I.) - Issues:
  1. How small were the smallest luminous galaxies ?
  2. How many ? How did they look like ?
  3. Did they survive to redshift z=0 ?

  (see Tassis et al. 2003 and Ricotti & Gnedin 2005)
- Second population (II.) - Issues:
  1. Do they look like dwarf galaxies (dSph, Irr or dE)?
  2. Is their number density compatible with observations?
  3. Role of tidal stripping - only DM or also stars?

  (see Stroehr et al. 2002 and Kravtsov et al. 2004)


Test
Not a test

	Test	Not a test
Abundance spread		

	Test	Not a test
Abundance spread		x
α/Fe ratio		?

	Test	Not a test
Abundance spread		x
α/Fe ratio		?
MS Turnoff Spread	?	

	Test	Not a test
Abundance spread		✗
α/Fe ratio		?
MS Turnoff Spread	?	
>60 new faint dSph at d>200 kpc	✓	

	Test	Not a test
Abundance spread		✗
α/Fe ratio		?
MS Turnoff Spread	?	
>60 new faint dSph at d>200 kpc	✓	
S-process/r-process ratio	✓	

	Test	Not a test
Abundance spread		✗
α/Fe ratio		?
MS Turnoff Spread	?	
>60 new faint dSph at d>200 kpc	✓	
S-process/r-process ratio	✓	
Existence of [Fe/H]<-2,-3 stars	✓	

	Test	Not a test
Abundance spread		✗
α/Fe ratio		?
MS Turnoff Spread	?	
>60 new faint dSph at d>200 kpc	✓	
S-process/r-process ratio	✓	
Existence of [Fe/H]<-2,-3 stars	✓	

Summary

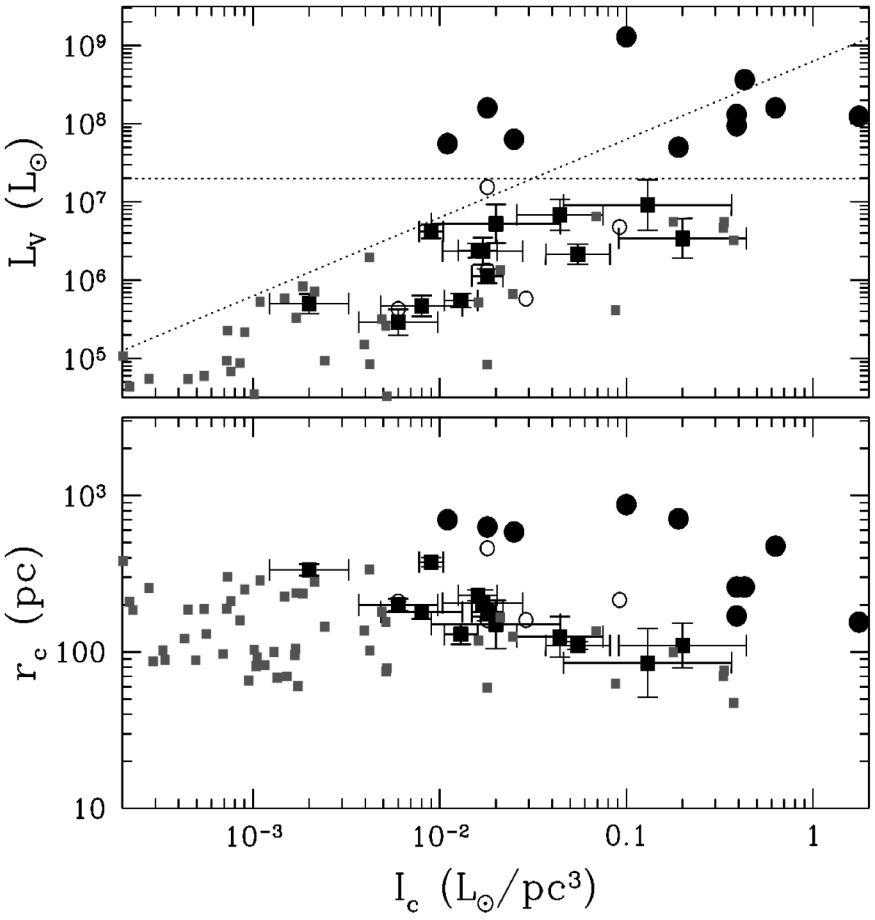
- The first population of galaxies has unique properties because of their small mass: inefficient cooling, chemical feedback and photo-evaporation.

- The second population is not subject to these feedbacks and can form stars efficiently

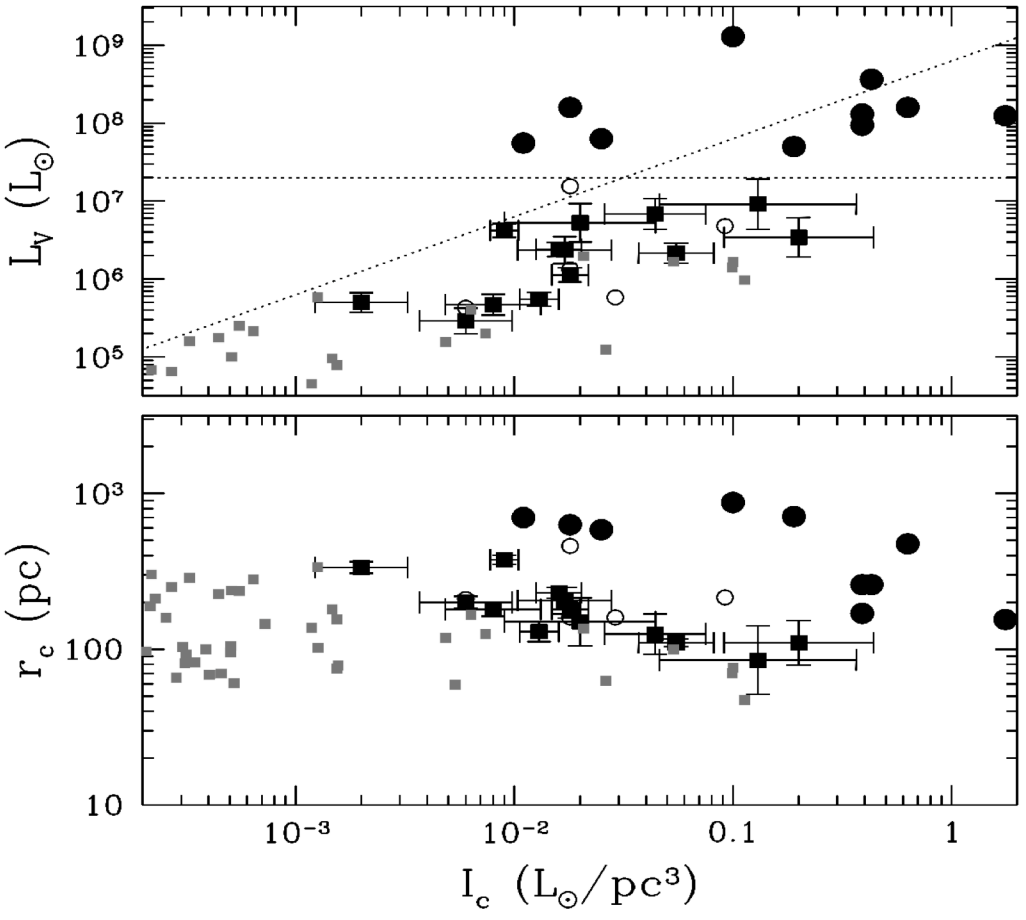
- The first population is remarkably similar to dSphs in the Local Group.

- The observed relationships for dSphs differ from other dwarfs in the Local Group. We propose that this could be the evidence for the existence of these two populations of primordial galaxies.

Result not sensitive to the assumed M/L ratio of the stars



$M_\odot/L=3$ for the stars



$M_\odot/L=10$ for the stars

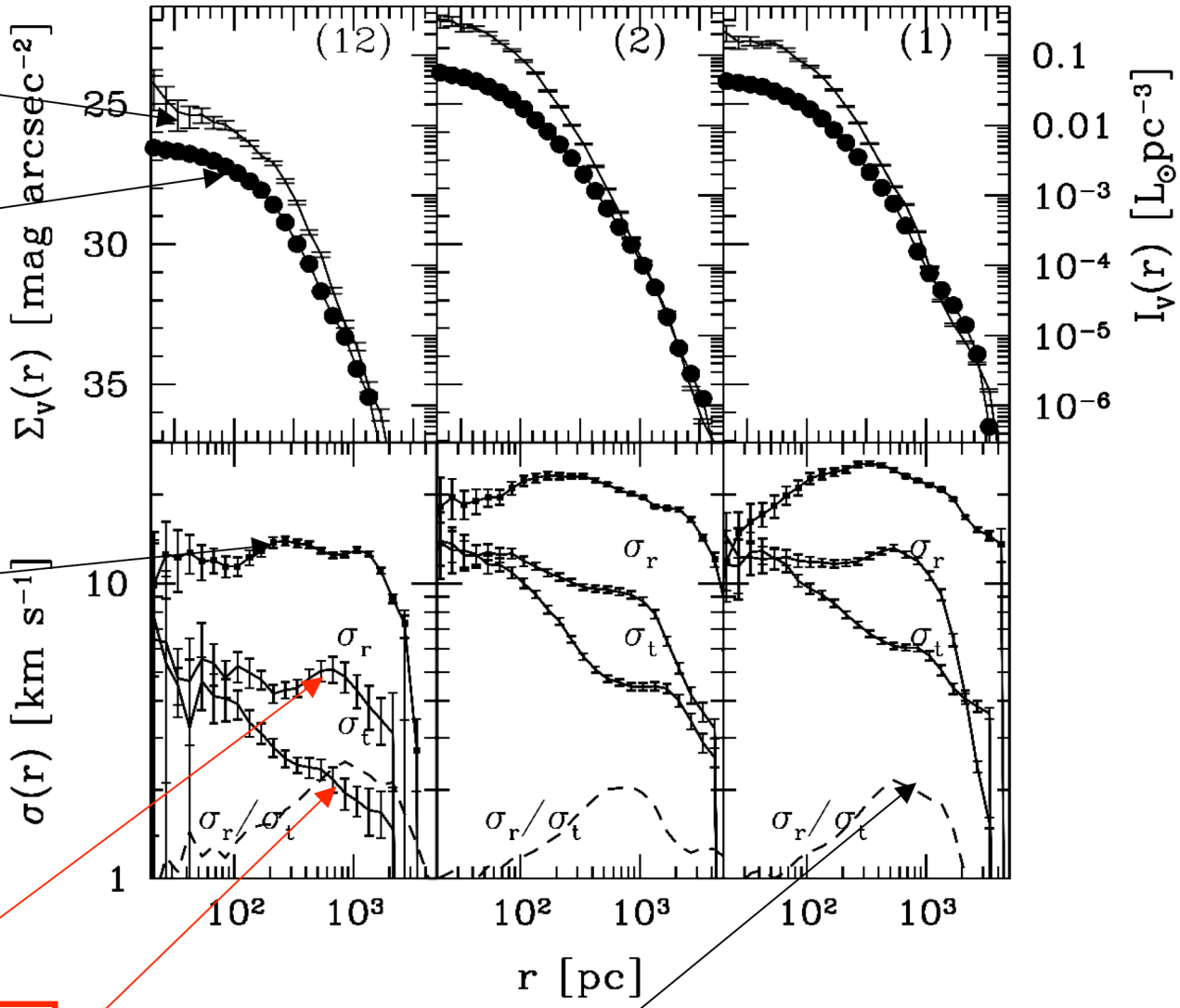
Velocity dispersion of the stars

Emissivity profile

Surface density profile

Velocity dispersion:

DM (isotropic)



stars

radial

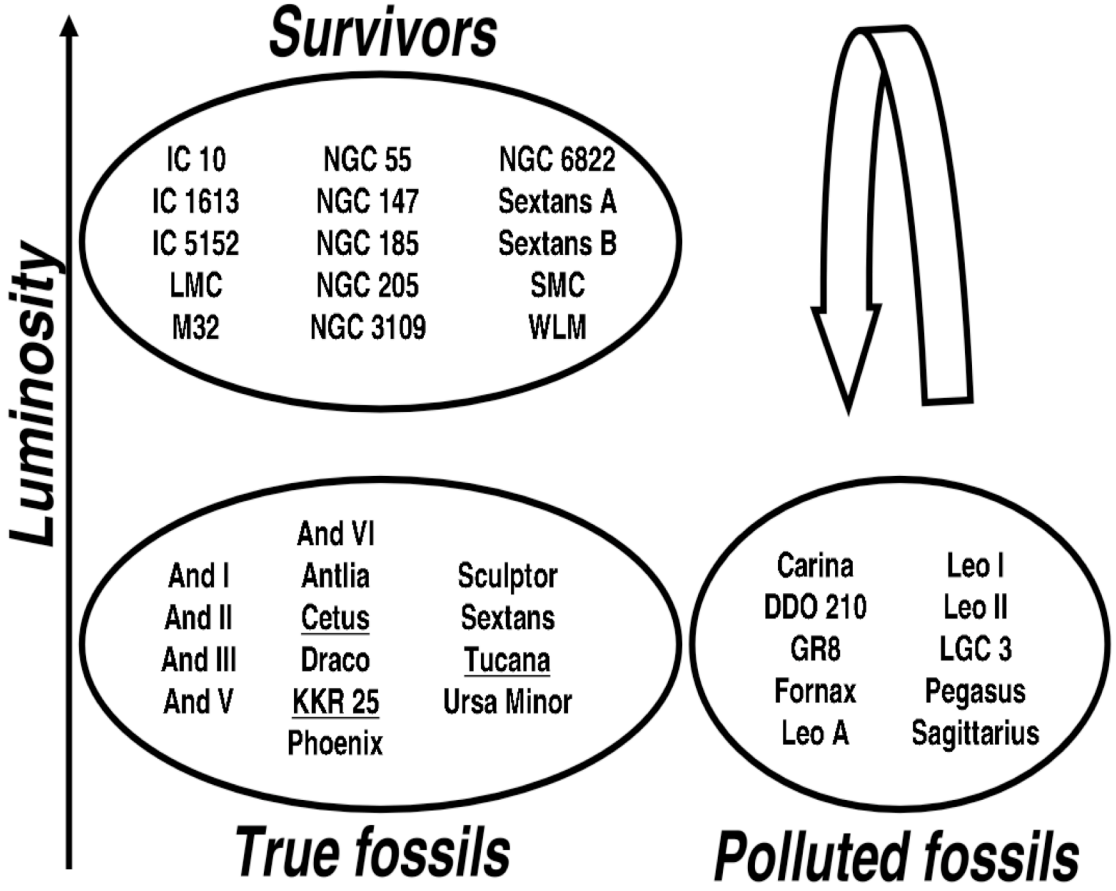
tangential

Anisotropy increases in the outer part

Tentative formation histories

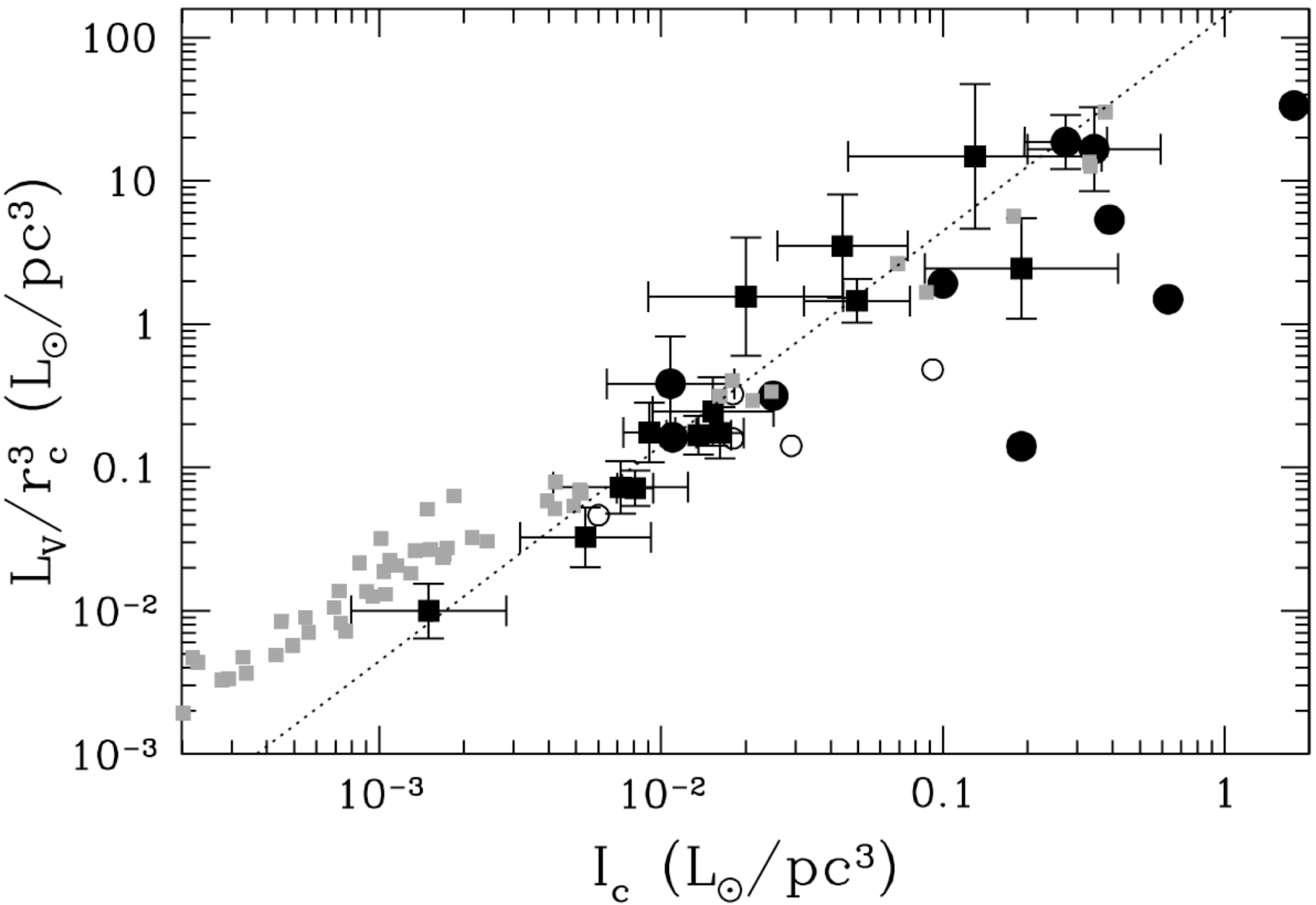
Classification based on:

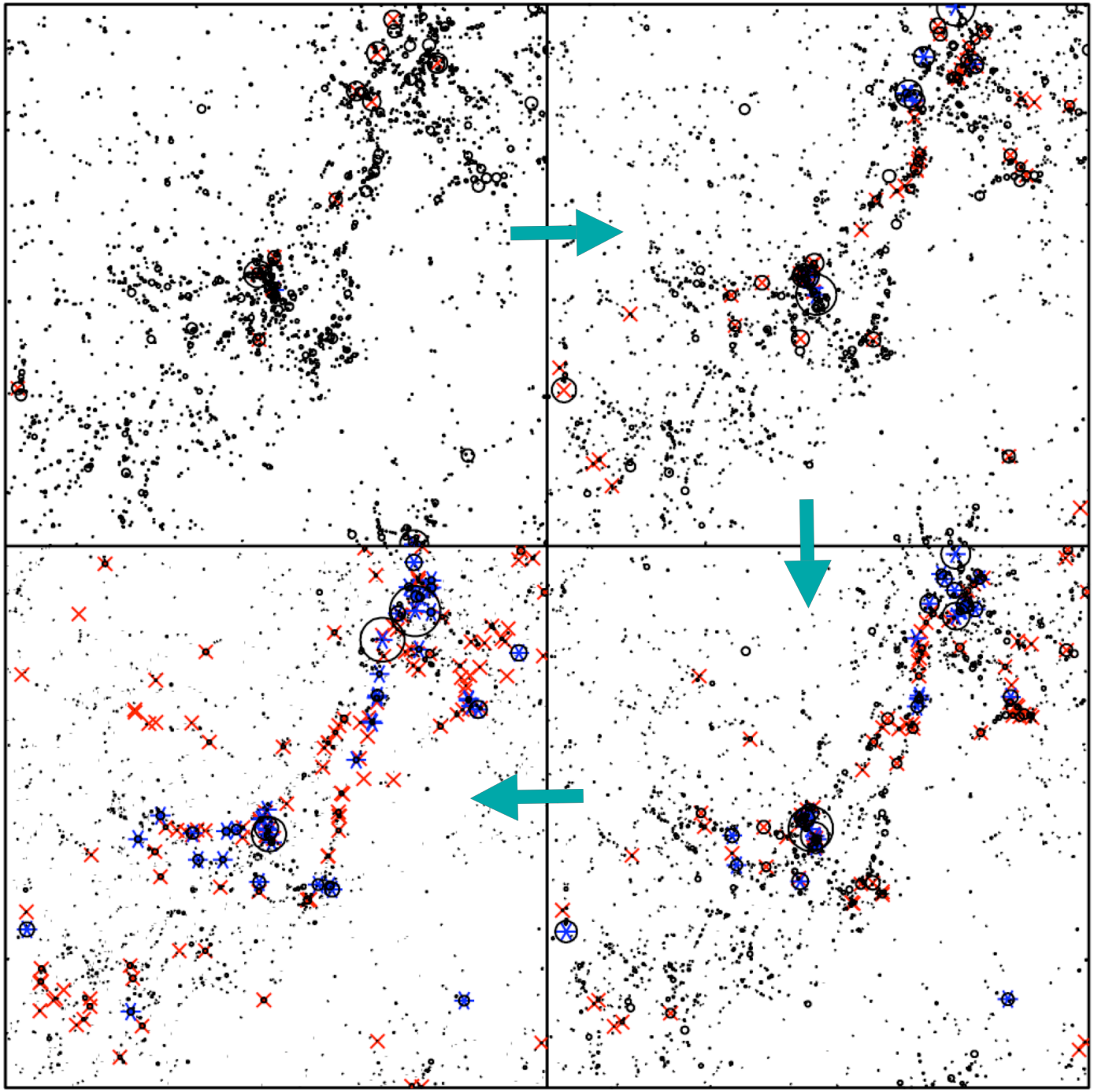
1. Similarity to simulated primordial galaxies
2. Age of dominant stellar populations (from Grebel & Gallagher 2004)

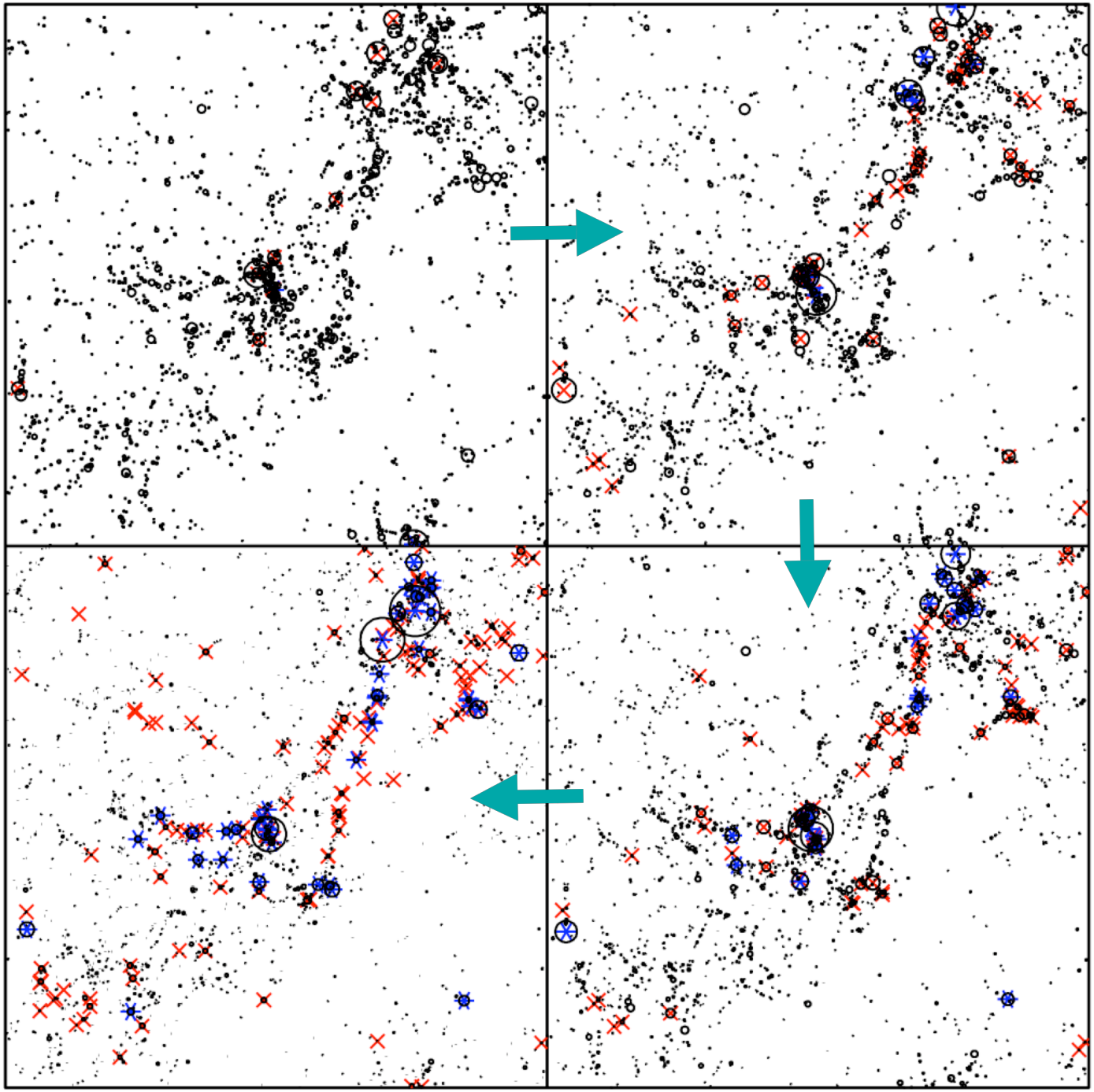


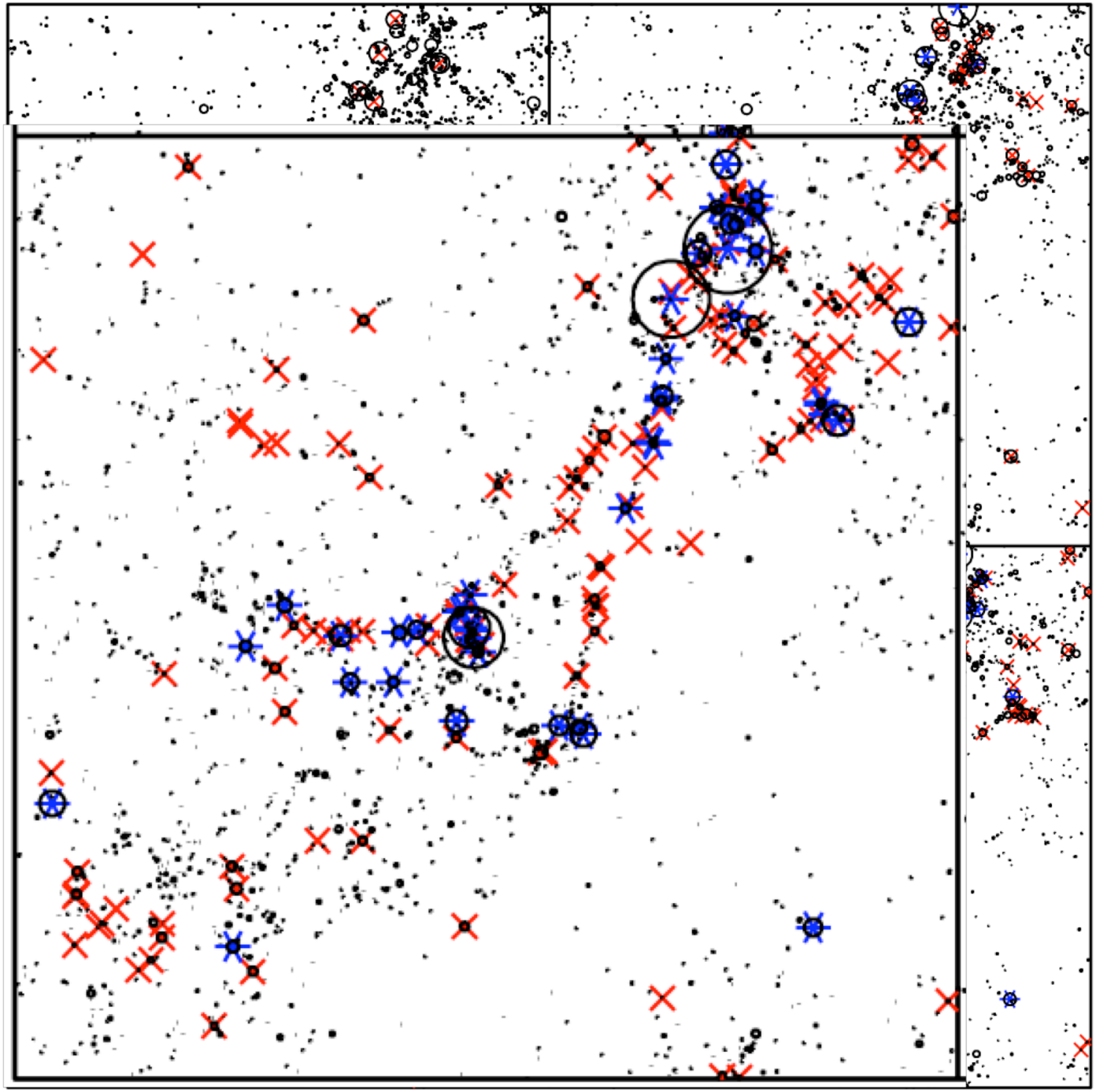
"True fossils":

3 (isolated, underlined names) + 5 (M31 satellites) + 6 (MW satellites)=14

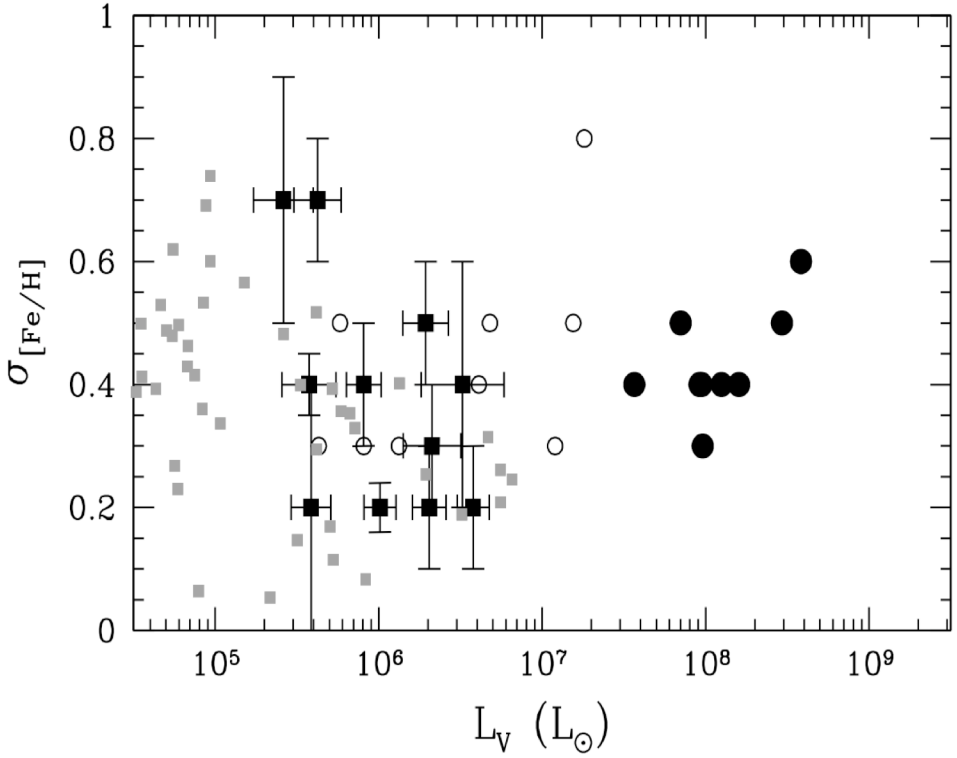

100
10
1
0.1
10^{-2}
10^{-3}
L_V/r_c^3 ($L_\odot/pc^3$)
10^{-3}
10^{-2}
0.1
1
I_c ($L_\odot/pc^3$)

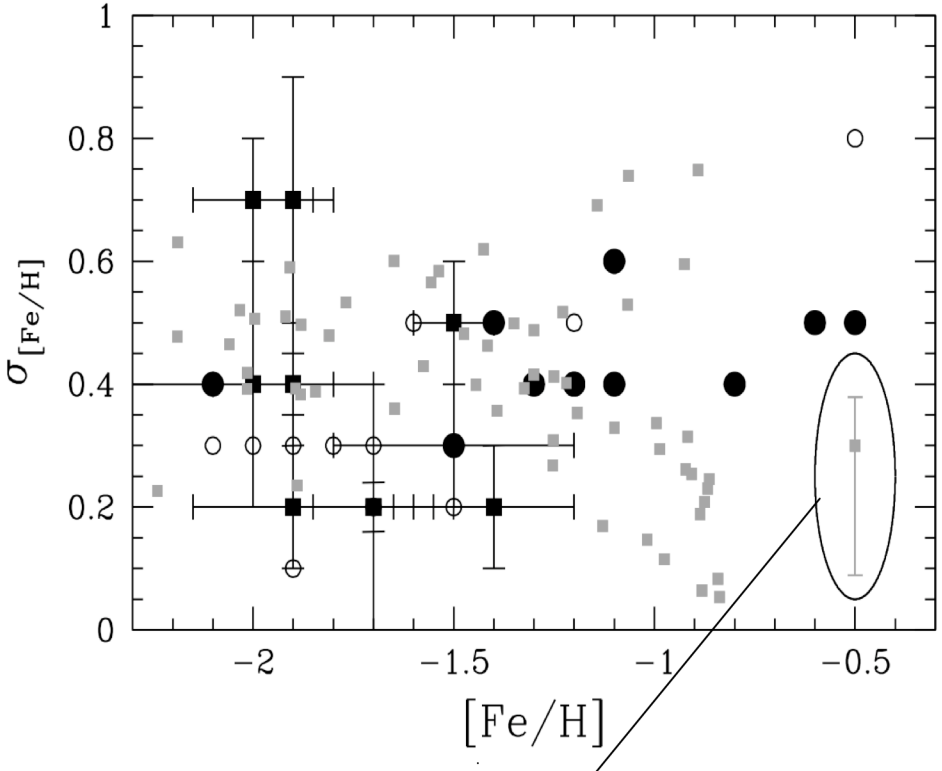






Metallicity spreads consistent with observations





NB:Time scale for Fe enrichment 40-50 Myr (instantaneous burst) (Matteucci & Recchi 2001)

Errorbar for simulated galaxies

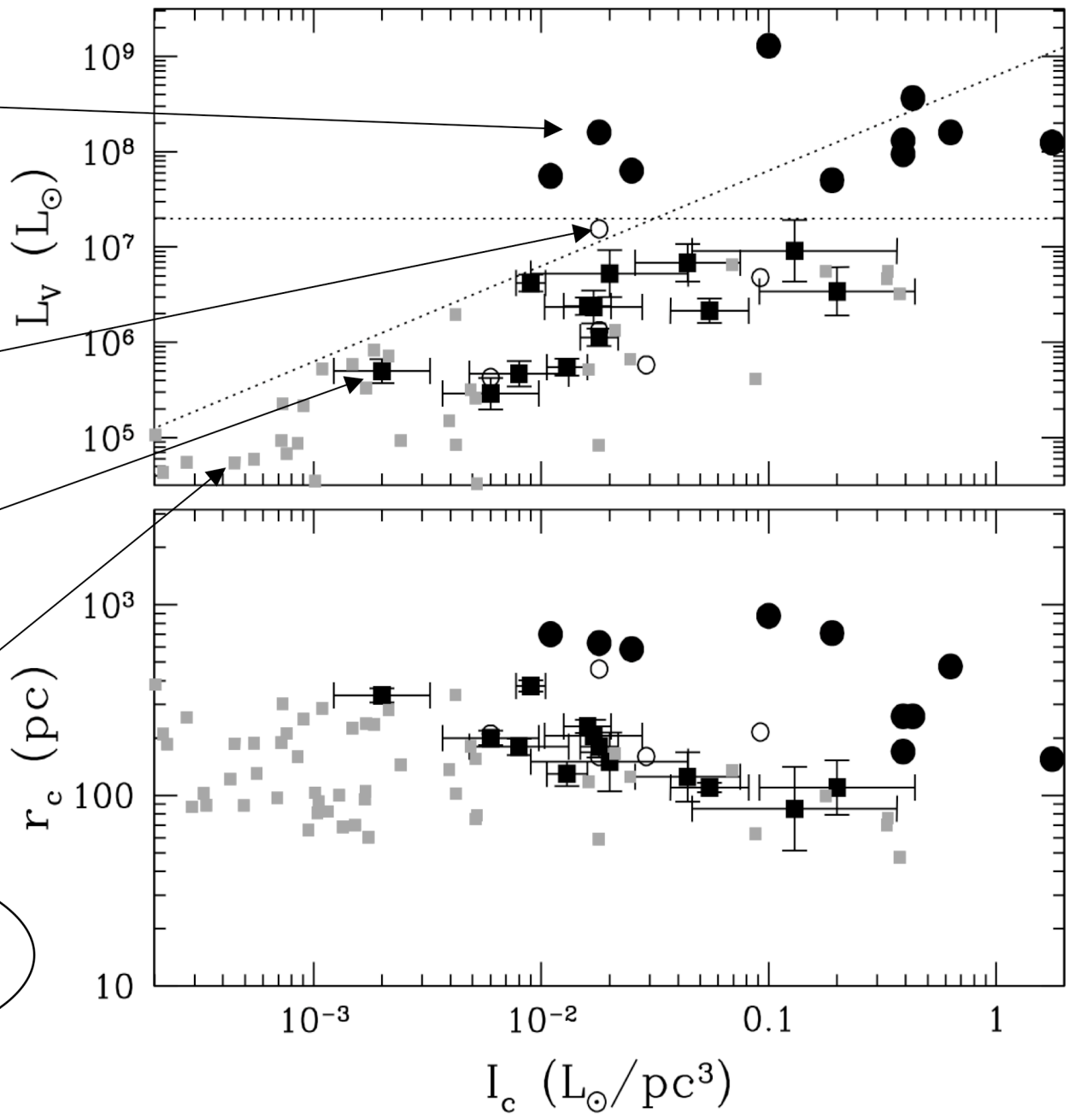
Ricotti & Gnedin 2005

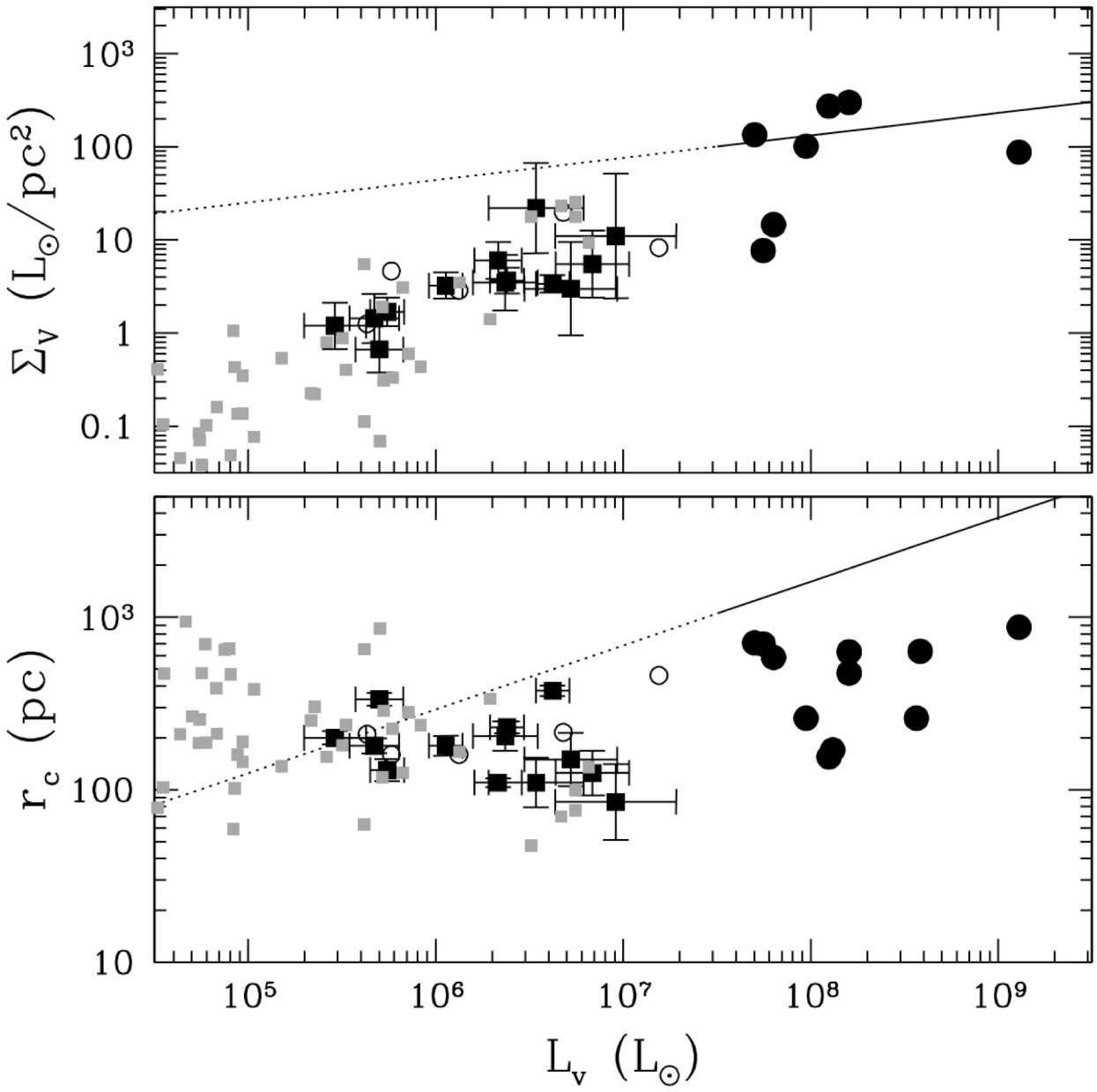
● Recent SF (dIrr and dE)

○ Mixed age populations (dIrr/dSph)

■ Predominant old population (dSphs)

▪ Simulated galaxies





Lines: scaling relationships for more luminous Sc-Im galaxies
(Kormendy & Freeman2004)