Fossils of the First Galaxies in the Local Group: True Fossils and Ghost Halos

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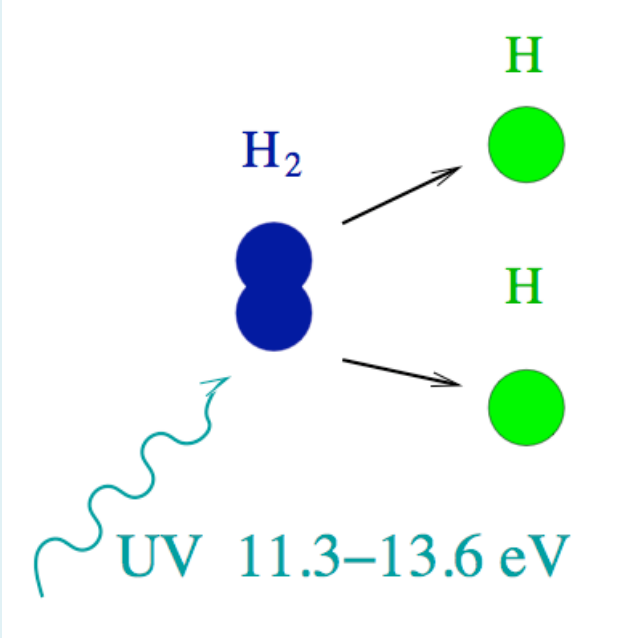
The Smallest Galaxies

Minihalos DO NOT initiate gas condensation by Lyman-α cooling.

$T_{vir} < 10{,}000$ K or $M_{dm} < 10^8\ M_\odot$ or $v_{max} < 20$ km/s

They are extremely sensitive to feedback effects and will not form stars unless they can form and retain significant amount of H_2.



H_2 photo-dissociation:Negative feedback
Suppress galaxy formation

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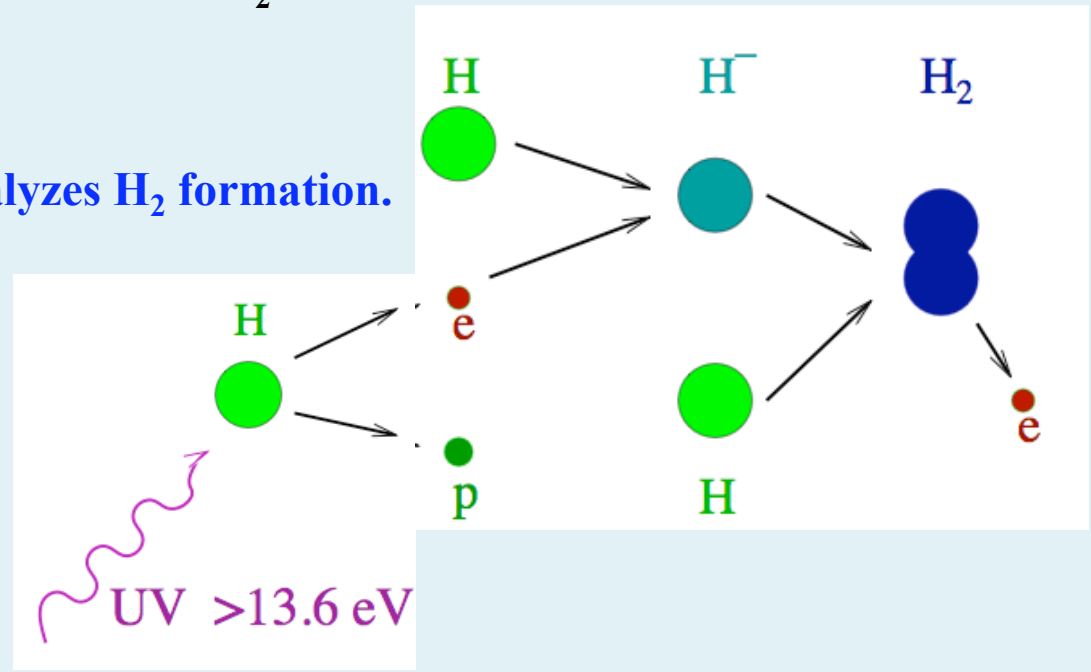
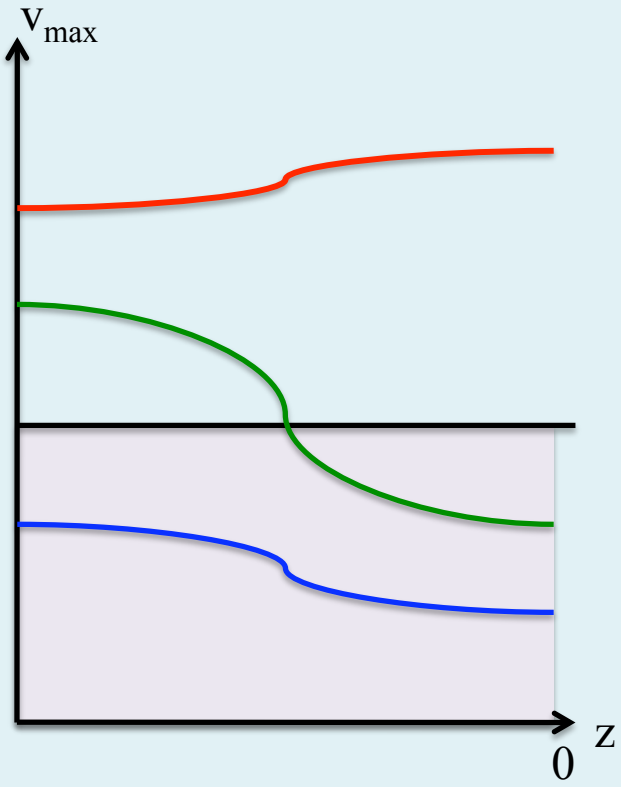
Ionizing UV radiation catalyzes H_2 formation.



What is a Fossil?

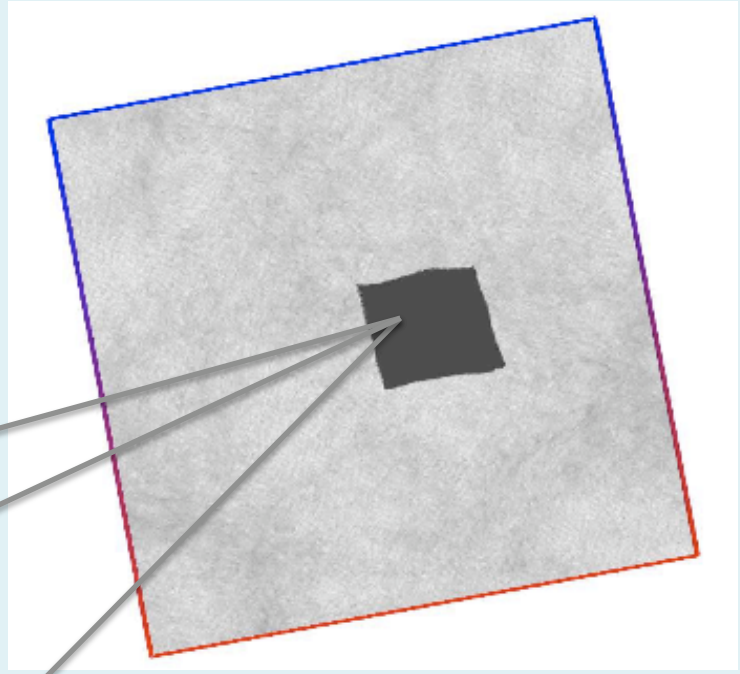


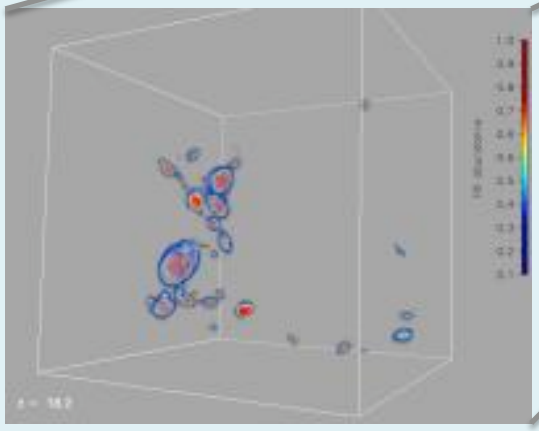
	Theory	Observation
non-fossil	$v_{max}(z=0) > v_{filter}$	ie. SMC
polluted fossil	$v_{max}(z=0) < v_{filter}$ **but ..** $max(v_{max}) > v_{filter}$	ie. Pegasus
true fossil	$v_{max}(z=0) < v_{filter}$ **AND** $max(v_{max}) < v_{filter}$	ie. Draco and CVn I

Hybrid Initial Conditions

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 $l > 1$ Mpc.





Ricotti et al (2002a,2002b)

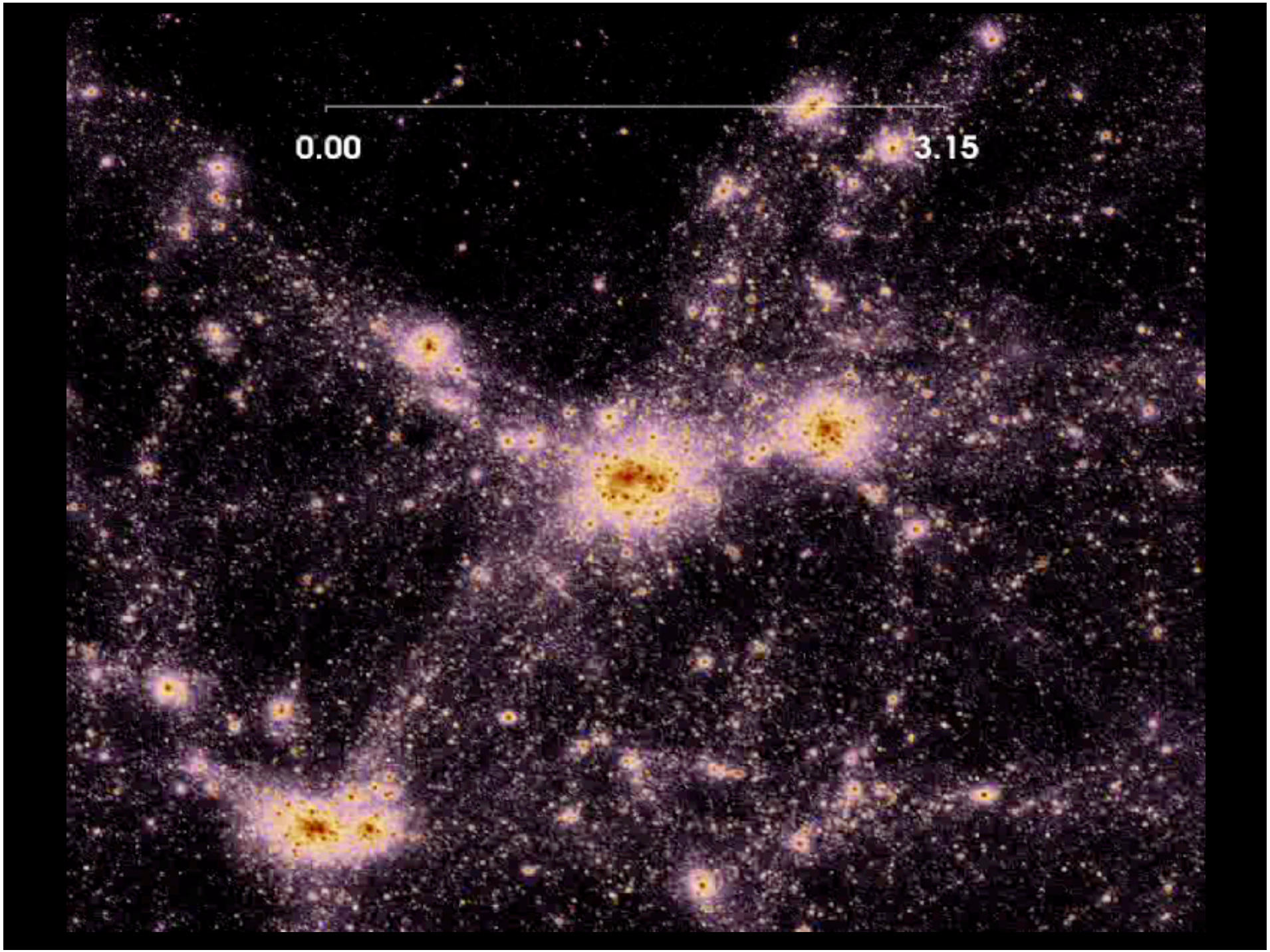
Each HR particle in the resulting N-body simulation represents a pre-reionization halo.

Unique IDs allow us to retrieve the stellar properties at $z = 0$ of halos $> 3 \times 10^6 M_\odot$.

Simulations

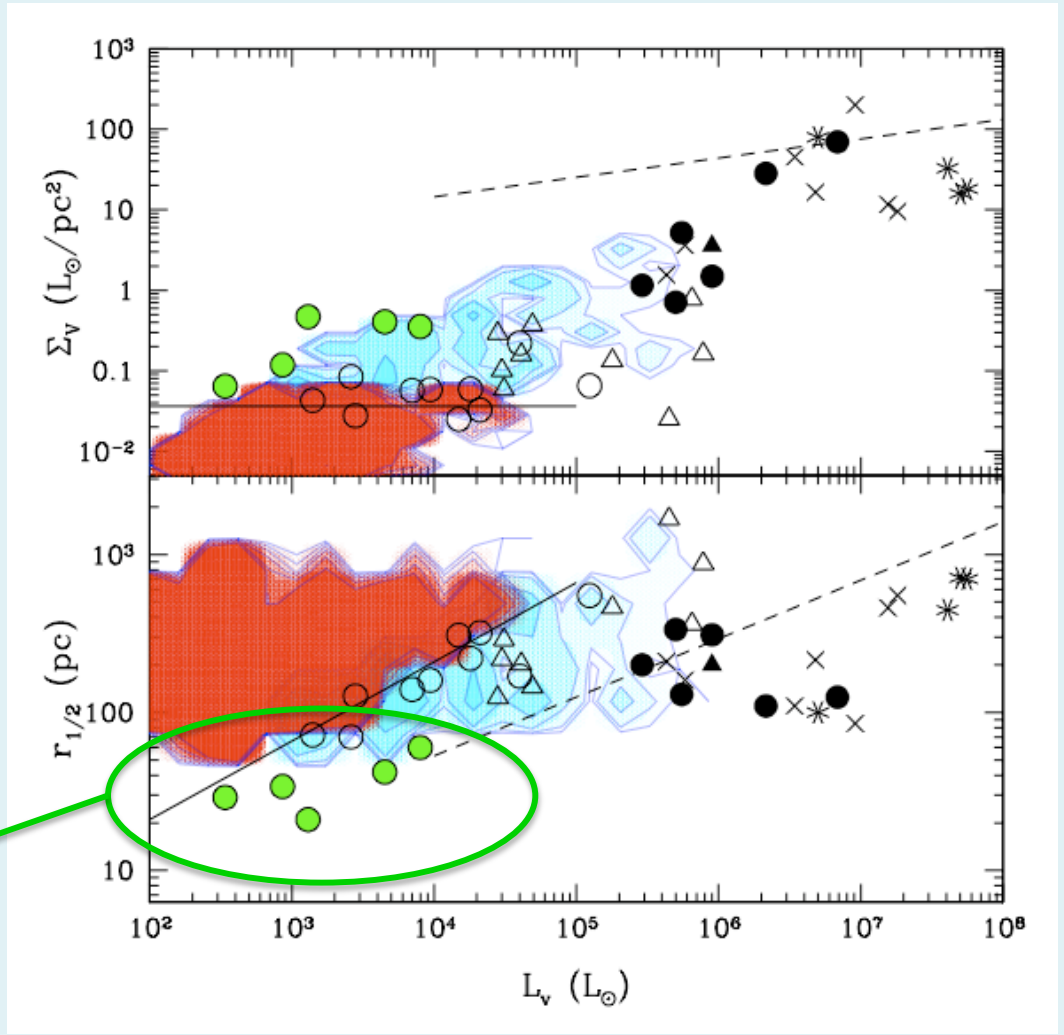
Run with Gadget 2 (Springel, 2005) on the University of Maryland HPCC Deepthought and analyzed with AHF (Knollmann & Knebe, 2009).

Run C	Run D
box = 50^3 Mpc^3 h^{-3}	box = 50^3 Mpc^3 h^{-3}
PR outputs used = 8.3	**PR outputs used = 8.3, 10.2, 12, 14**
z_{init} = 8.3	z_{init} = 10.2
$m_{high\ res}$ = 3 x 10^5 – 3 x 10^8 $M_\odot$ m_{min} = 3 x 10^5 $M_\odot$	**$m_{high\ res}$ = 3 x 10^5 – 3 x 10^8 $M_\odot$** m_{min} = 3 x 10^5 $M_\odot$
ε= 1 kpc	ε = 1 kpc
MW.1 = 1.82 x 10^{12} $M_\odot$	MW.2 = 0.87 x 10^{12} $M_\odot$ **MW.3 = 1.32 x 10^{12} $M_\odot$**


0.00
3.15

The Ultra-Faint Dwarfs as Fossils of the First Galaxies

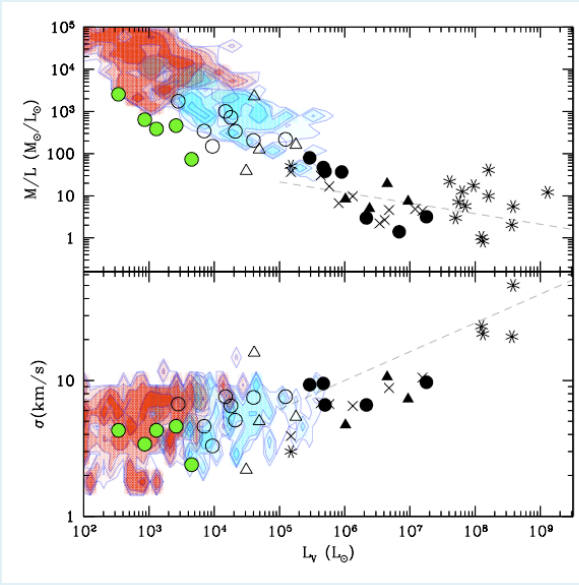
- dIrr
- dE
- classical MW dSph
- MW ultra-faints
- classical M31 dSph
- M31 ultra-faints
- fossils detectable by SDSS
- fossils ***not*** detectable by SDSS

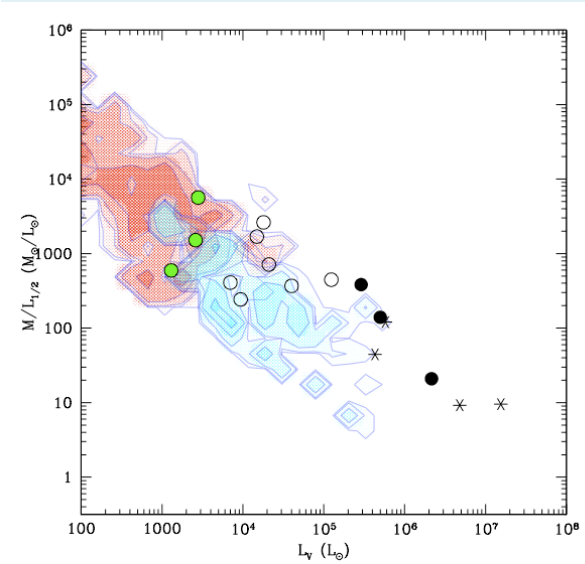


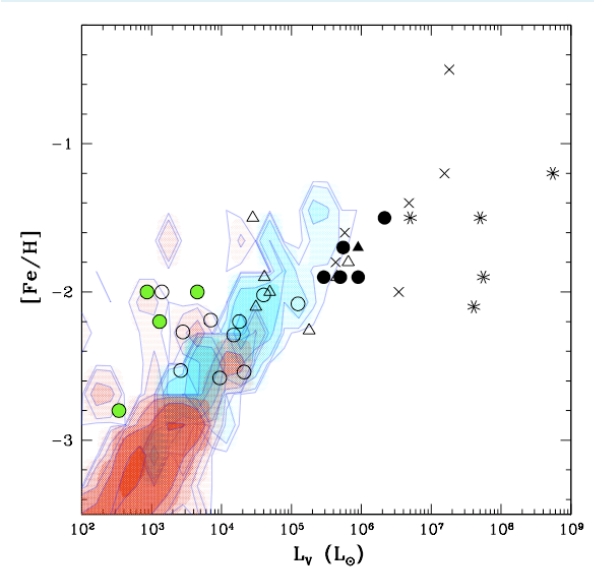
Σ_V and r_{hl} are not in agreement with predictions for true fossils.

Bovill & Ricotti (2009, 2010a-in prep)

The Ultra-Faint Dwarfs as Fossils of the First Galaxies







Bovill & Ricotti (2009, 2010a-in prep)

Undetected dwarfs have higher M/L but the *same* velocity dispersion!

Match of ultra-faints in M/L is independent of mass estimator.

Undetected dwarfs would have [Fe/H] < -3

[Fe/H] of the "green" dwarfs are consistent with a primordial fossil origin.

Observational Sample

An observed fossil dwarf is defined as:

~ dSph (no gas, diffuse, roughly spherical stellar population)

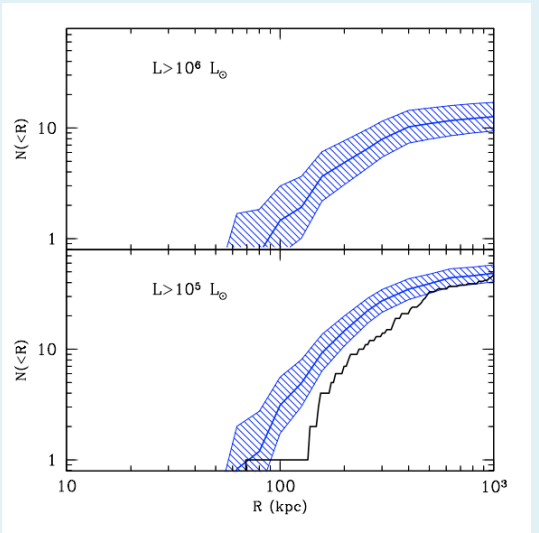
~ SFH dominated by an old, metal poor population

~ $v_{max} < 20$ km s^{-1} : $\sigma_* <$ ~ 10-15 km s^{-1}

Classical dwarfs: fossils as defined in Ricotti & Gnedin (2005) with $L_V < 10^6\ L_\odot$.

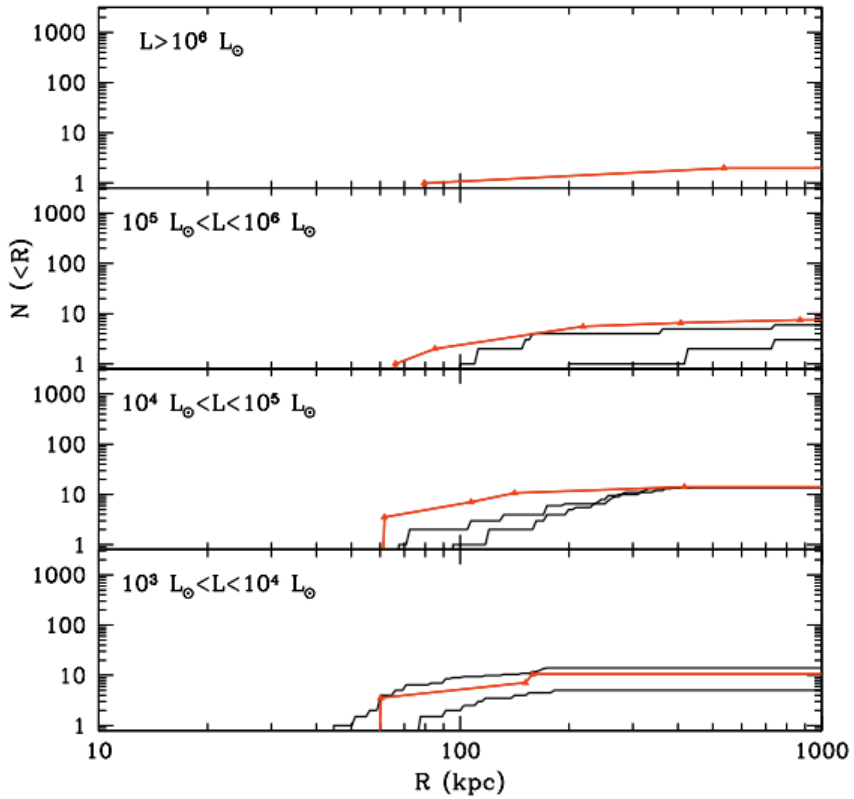
Ultra-faint dwarfs: R > 50 kpc whose stellar properties are consistent with our true fossils.

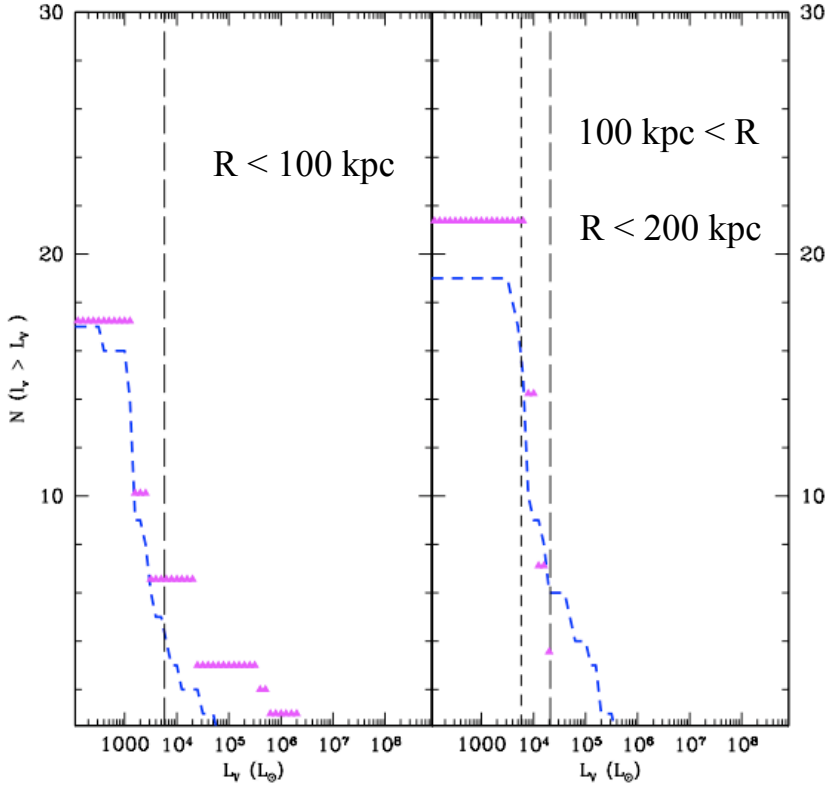
	R < 50 kpc	R > 50 kpc
tidal	Ursa Major II, Segue I & II, Willman I	Pisces II
non-tidal	Coma Ber.	Bootes I & II, CVn I & II, Hercules, Leo IV, Leo T, Ursa Major I



Gnedin & Kravtsov (2006), MSB & Ricotti (2010a,in-prep)

Fossil Distributions

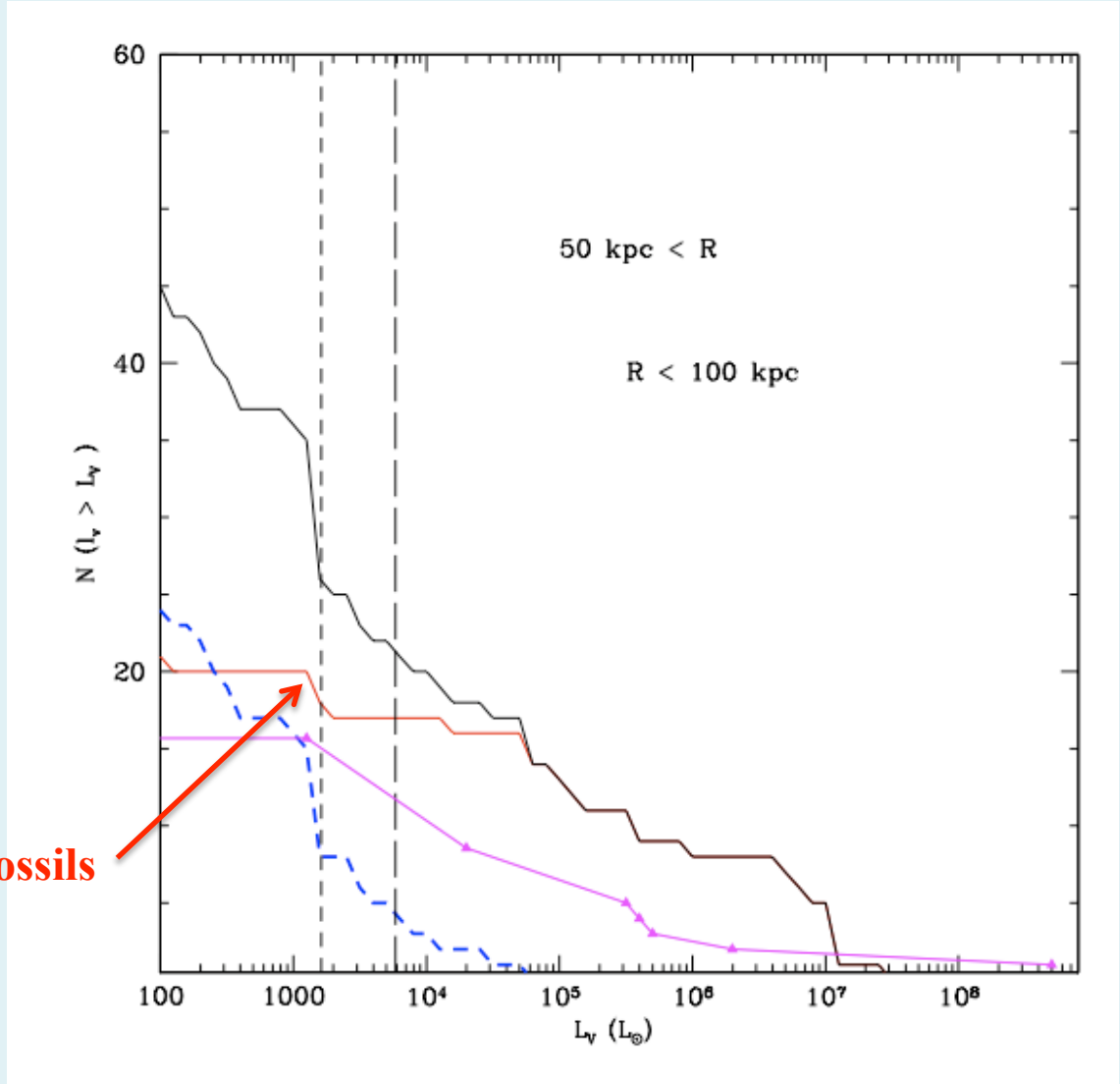




Bovill & Ricotti (2010b-in prep)

MW.2 and MW.3 from Run D with SDSS detection limits applied (Walsh et al, 2009)

"Primordial" Luminosity Function

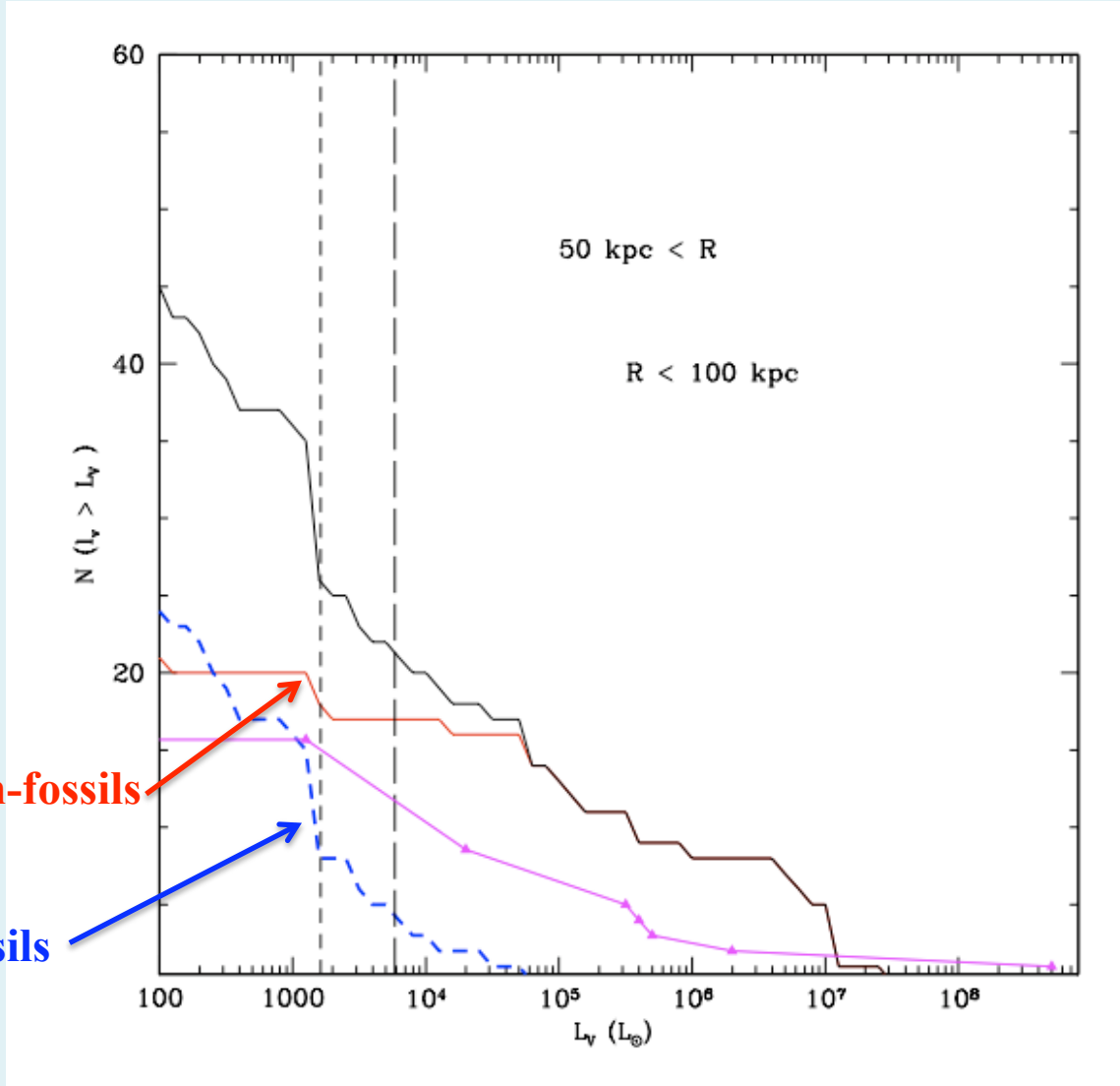


non-fossils

Non-fossils are any subhalo which was able to form stars after reionization.
All of the non-fossils contain a primordial population.

CAUTION: Since these objects may have formed stars after reionization, the z=0 luminosity function will shift to the right with a lower slope relative to the primordial one.

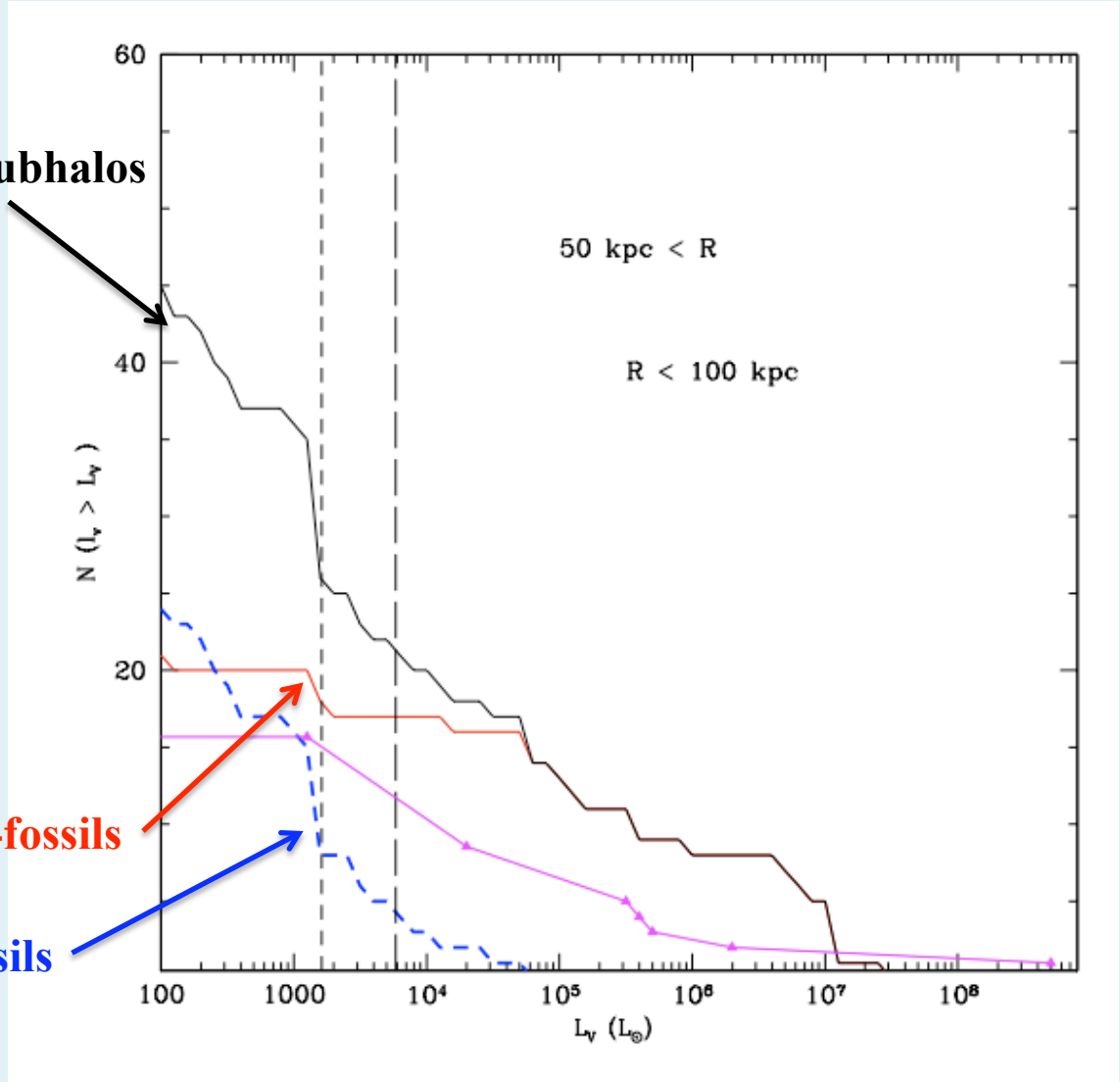
"Primordial" Luminosity Function



Fossils have undergone no significant baryonic evolution after reionization.

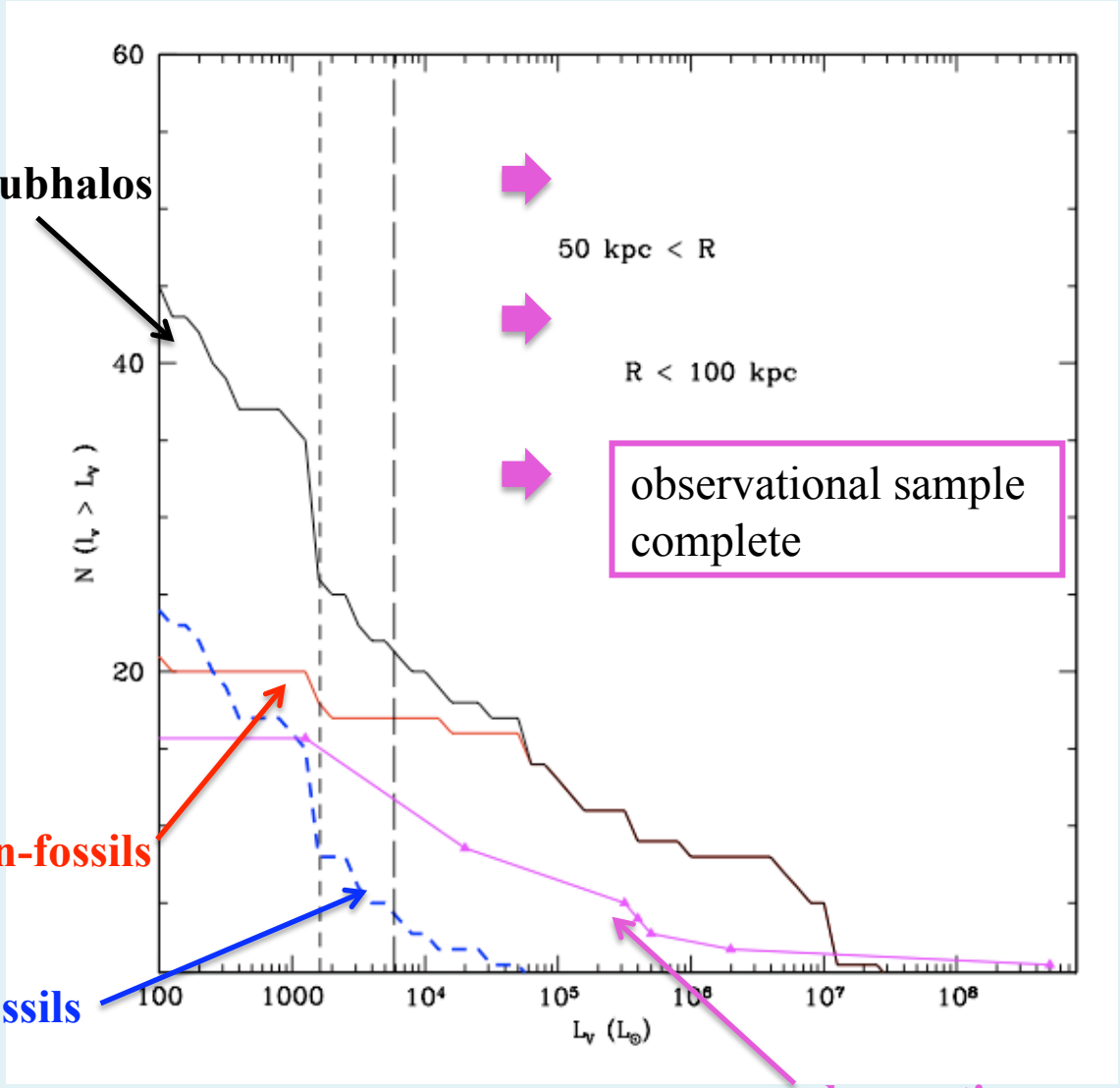
Unlike the non-fossils, their primordial luminosities directly determine the z=0 luminosity function.

"Primordial" Luminosity Function



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

"Primordial" Luminosity Function

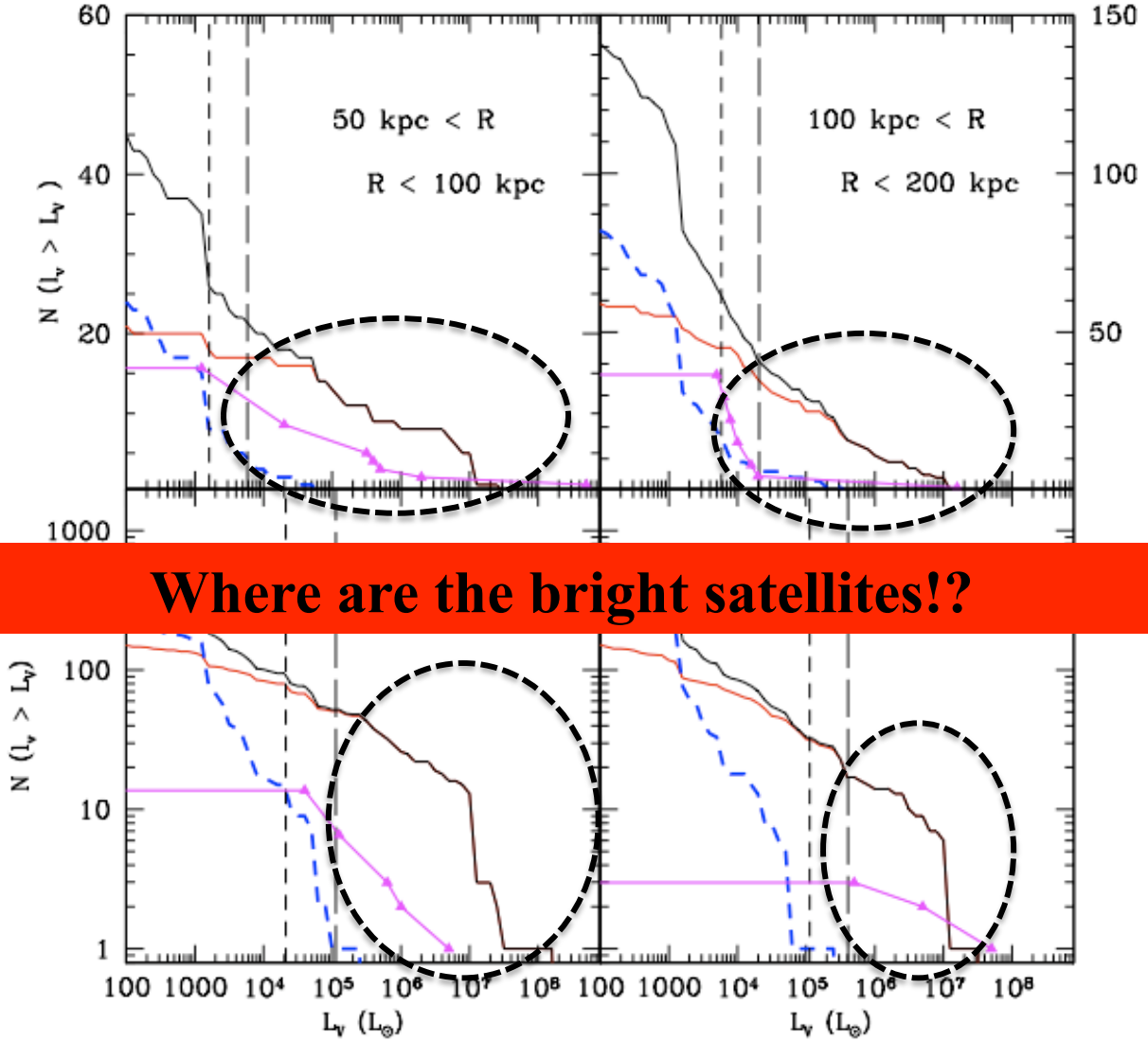


Includes all known dwarfs with R > 50 kpc.

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

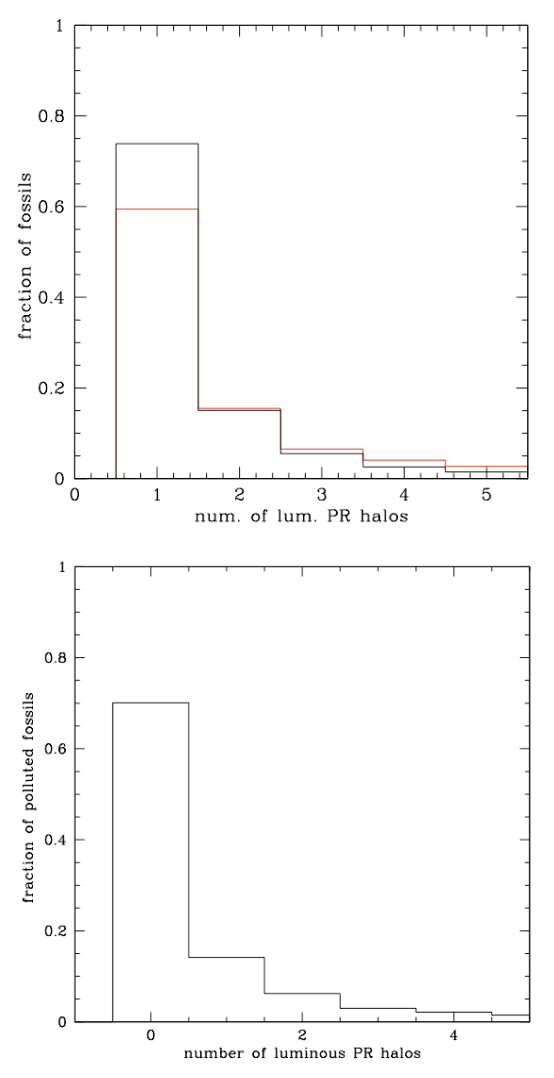
Sample is complete to the right of the dashed lines.

"Primordial" Luminosity Function

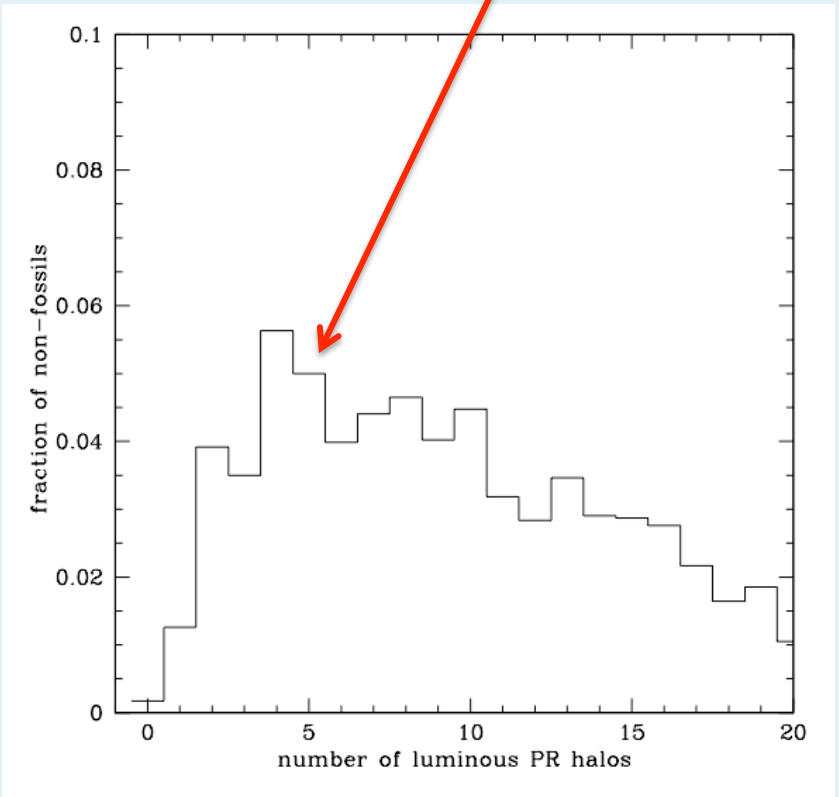


Where are the bright satellites!?

Which one is not like the others?

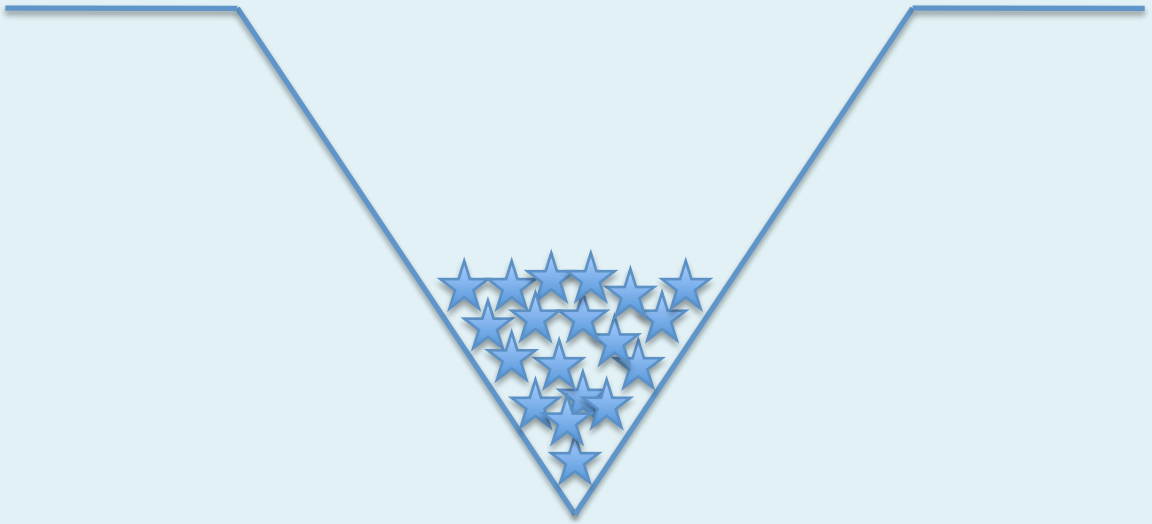


Majority of the non-fossils have undergone > 4-5 major mergers!



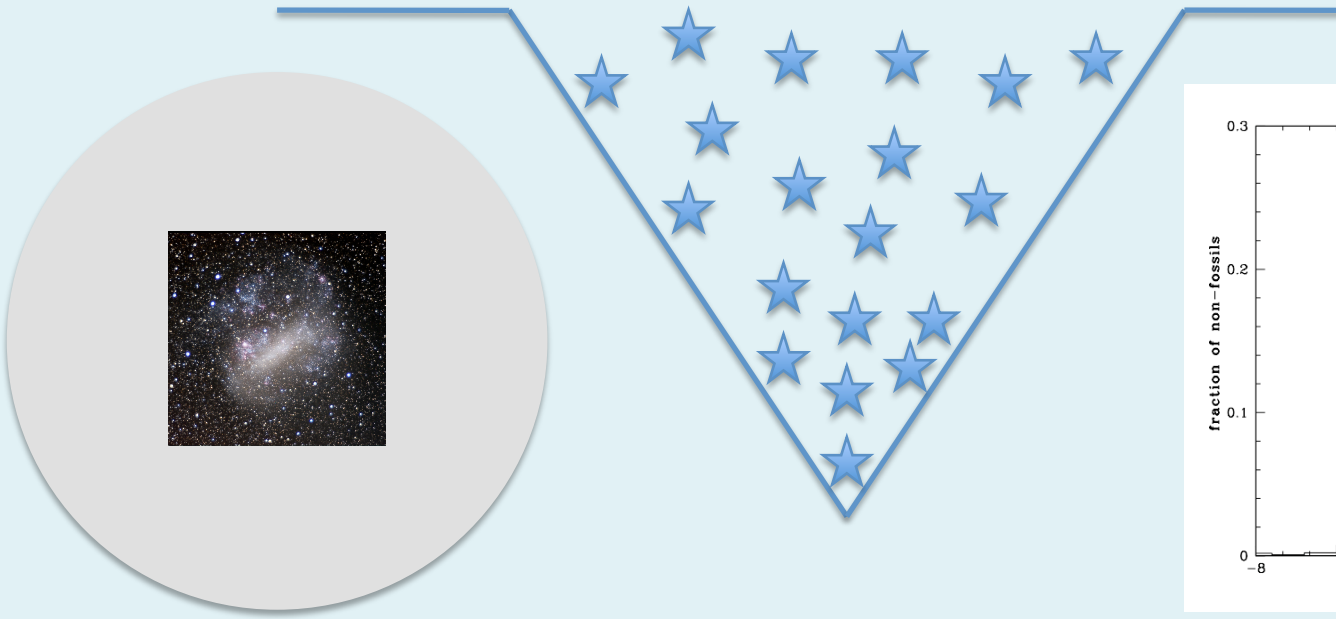
Fluffing the Non-Fossils

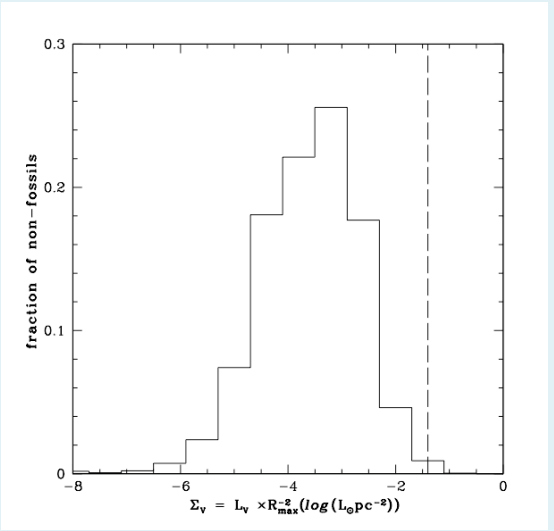
Stars initially form at the center of a dark matter halo.



Ghost Halos

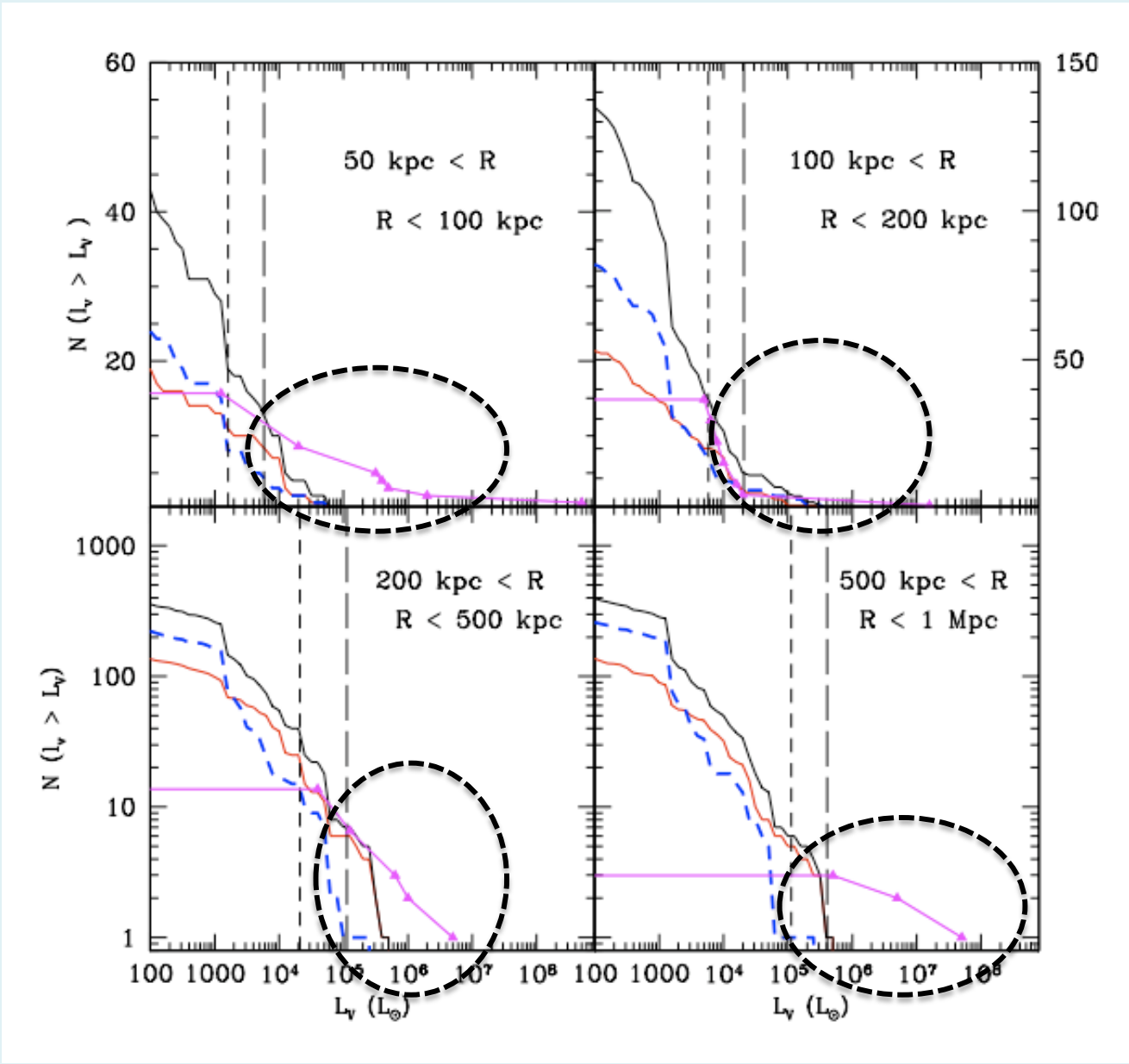
Kinetic energy from the repeated collisions heats the primordial stellar population.





Primordial stars become a diffuse “ghost halo” around a dIrr which is below the SDSS detection limits.

This ghost halo will be the first to go in an interaction with another halo.



Bovill & Ricotti (2010b-in prep)

Take Home Points

• The stellar properties of the ultra-faint dwarfs are consistent with those of a primordial population in size, luminosity, velocity dispersion, M/L and [Fe/H].

• **In the primordial model there is an undetected population of even dimmer dwarfs with higher M/L, [Fe/H] of -3 or lower, and the *same* σ_* as the ultra-faints.**

• True fossils in our simulation are able to reproduce the distribution of fossil satellites around the Milky Way and **there are no true fossils with $L_V > 10^6 L_\odot$.**

• We overproduce subhalos with $L_V > 10^4$-$10^5 L_\odot$ at all radii by as much as an order of magnitude.

• The most effective way to lower the number of luminous subhalos while preserving the fossil population is to assume that the non-fossils (dIrr and dE) near the MW lost > 99% of their primordial populations.

• **The primordial population of isolated non-fossils would be retained in a diffuse "ghost halo" of $\tau > 12$ Gyr, [Fe/H] < -2 stars.**


Questions?