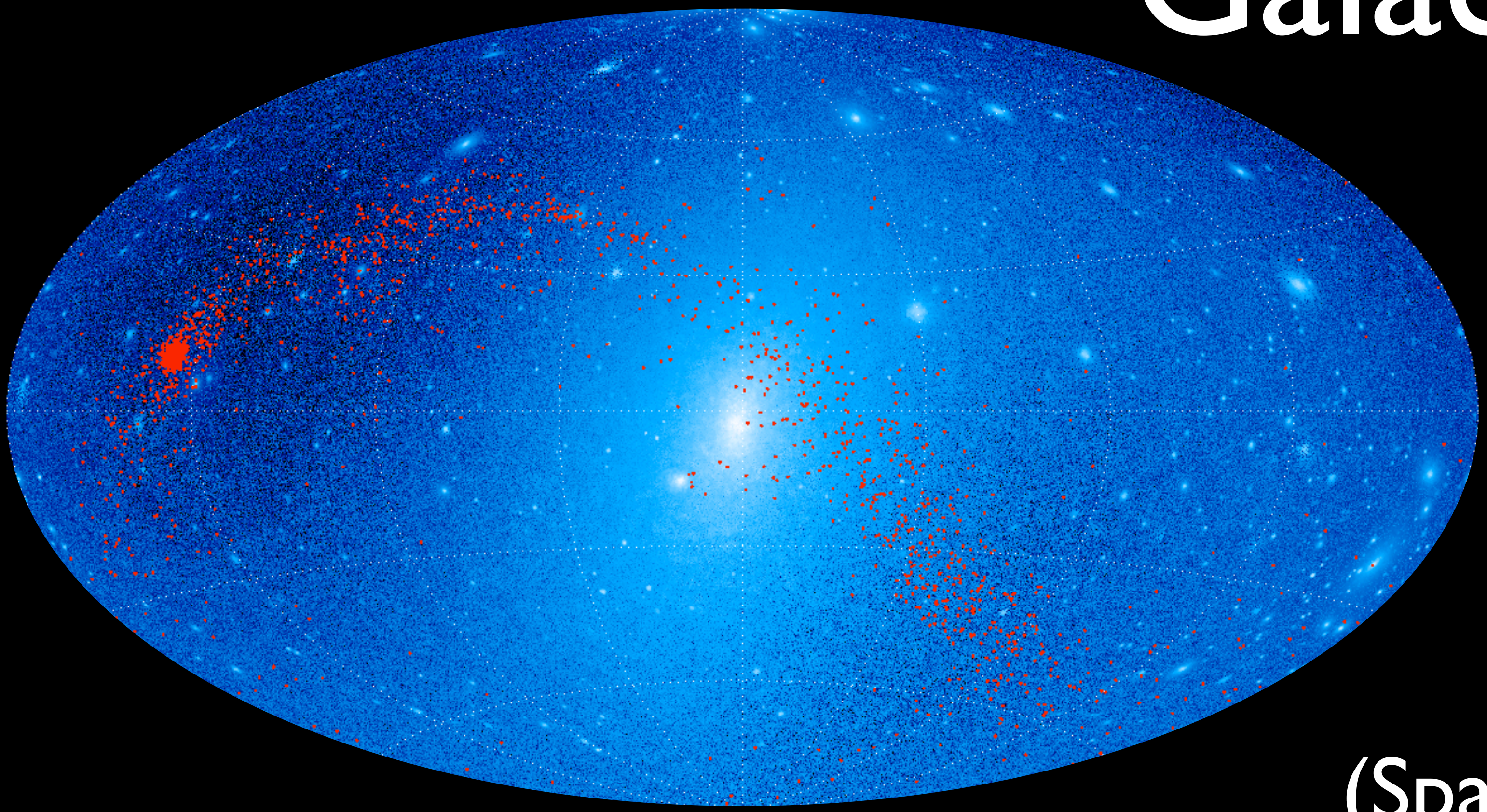
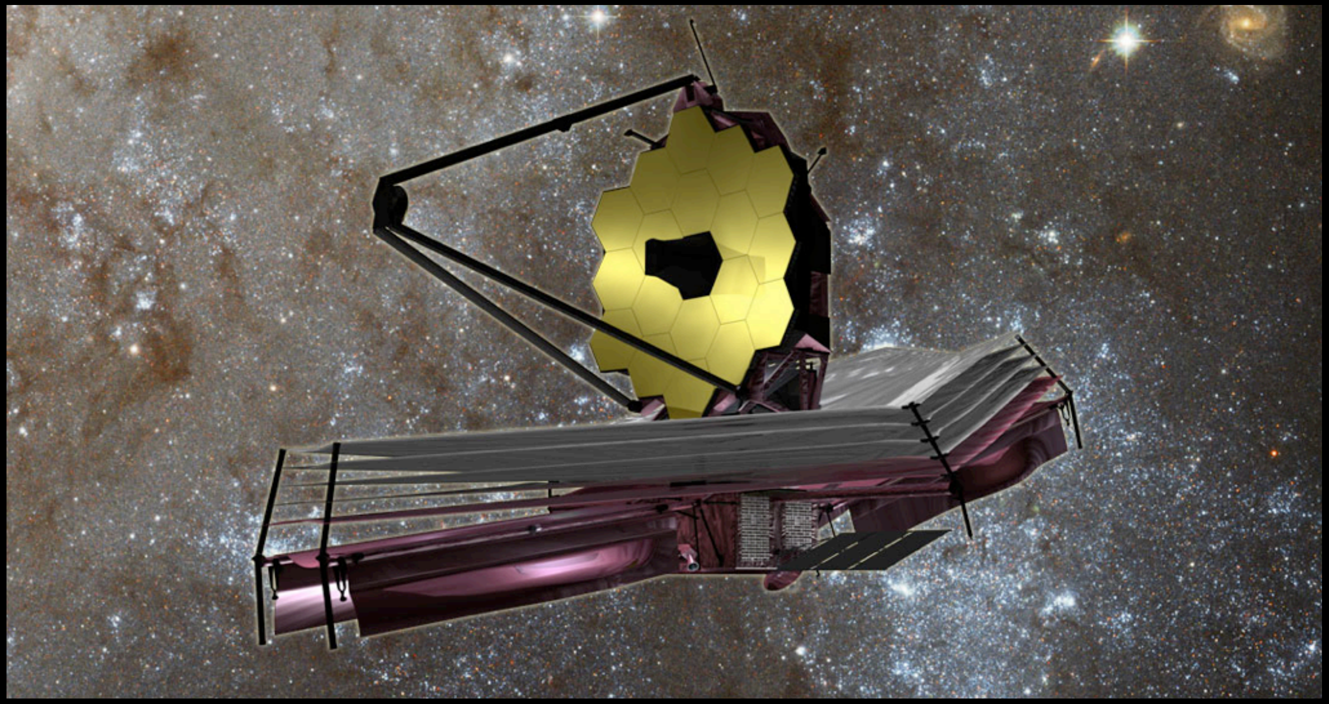


Galactic Archaeology and the First Galaxies

Jason Tumlinson
(Space Telescope Science Institute)



The Big Idea

How can we exploit the revolution in surveys of Galactic structure and chemical evolution to learn about the Epoch of First Light?

Hot Topics in the Study of the "First Stars"

1. *What was the IMF of primordial stars?*

   - Numerical simulations (Abel et al. 2002, Yoshida et al. 2006, O'Shea et al. 2007, Tan & McKee 2007) indicate mass scales of 10s to 100s of $M_\odot$ owing to inefficient cooling in primordial gas. But these will be extremely faint at high redshift!

   - Chemical abundance evidence considered alone favors yields from 10 - 40 $M_\odot$ (Tumlinson et al. 2004; 2006), but are we really looking at "second stars"?

2. *When and how did the first low-mass stars form?*

   - Theory-defined "critical metallicity", Z_{crit}, ~ 10^{-4} $Z_\odot$, needed for fragmentation to low mass, but metallicity is one of many possible influences: local temperature, CMB.

   - Simulating this process in realistic cosmological conditions is extremely difficult, and observational tests are greatly desired. What's the lowest metallicity star in MW?

3. *Did the first stellar generations yield novel types of SNe?*

   - Primordial stars may end up as extremely energetic "Pair Instability Supernovae" or as "hypernovae" with big effects on local star formation and possibly visible to us at high redshift. Would these have distinctive yield patterns we could go out and find?

Three Questions for Galactic Archaeology

1. Where are the "first galaxies" today?

2. How can we isolate their surviving stellar populations?

3. What might we learn when we do this?

Key Idea I: Where are the first galaxies today?

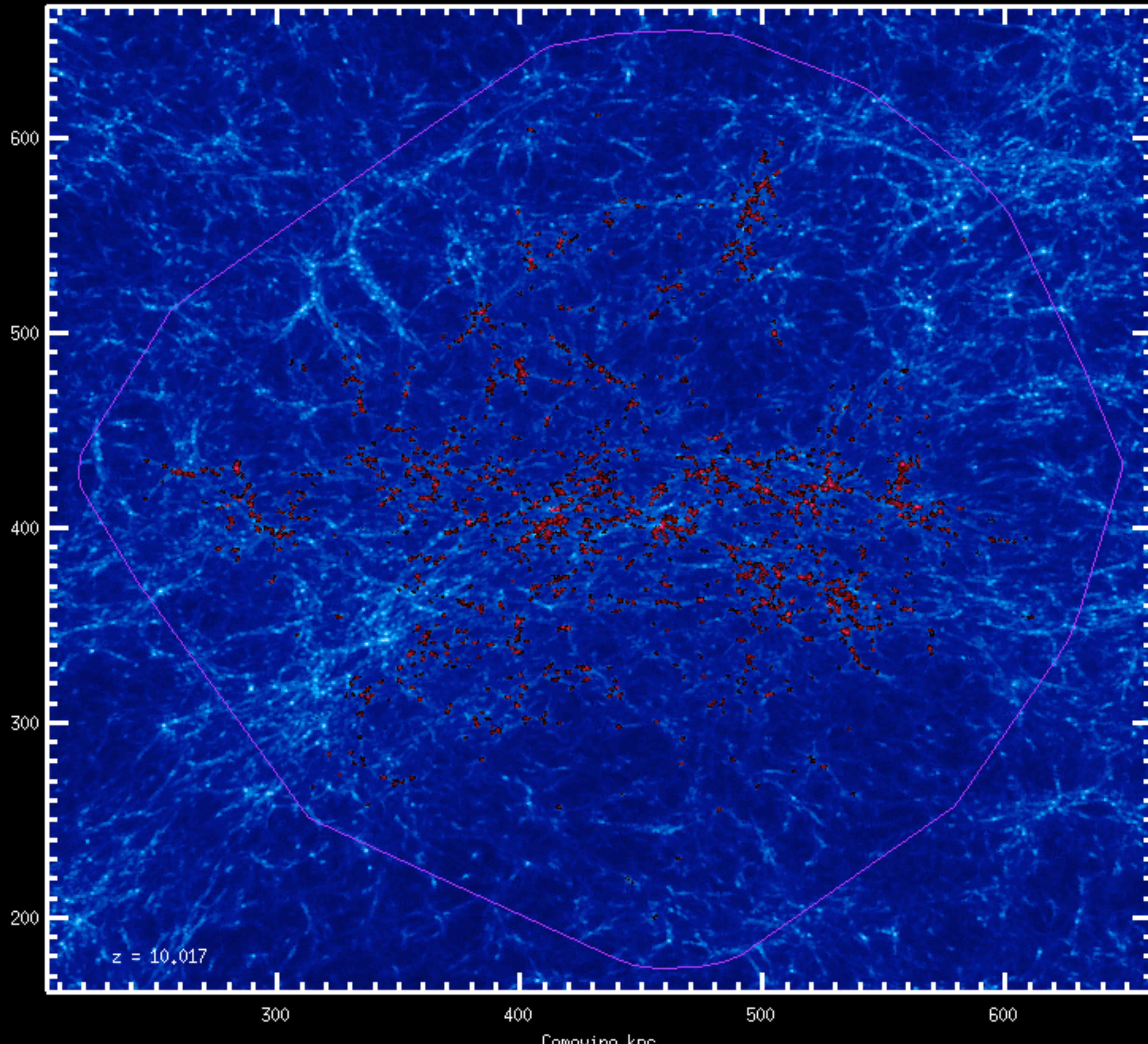
Key Idea I: Where are the first galaxies today?

Without any modeling of gas, we can assess the assembly history of the MW halo and place it in a high-redshift context, in two steps:

1. Run DM-only simulations of MW-like halos, with fine mass and time resolution. From these, make catalogs of bound halos.

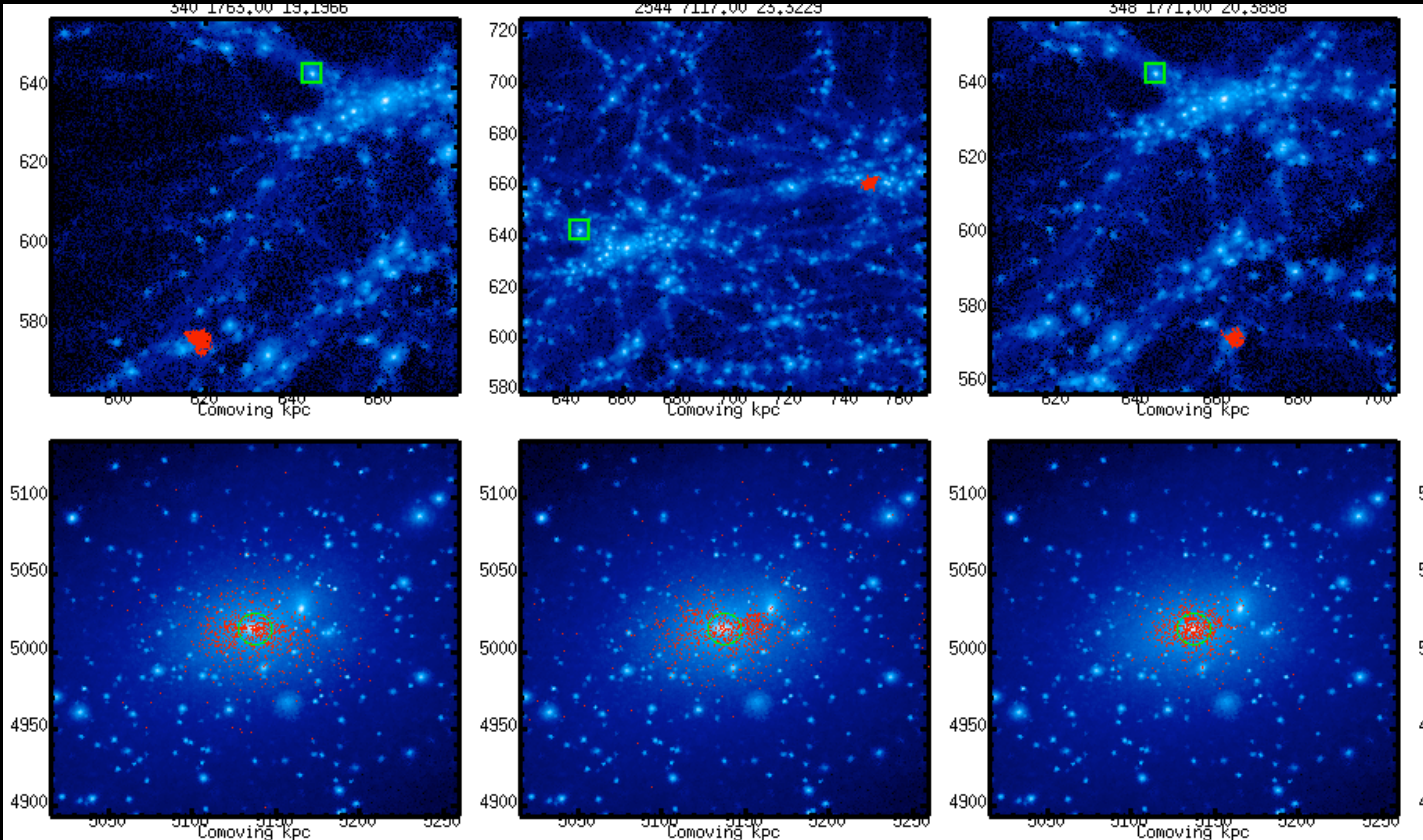
   Details: Gadget2 simulations, $M_{vir} = 1 - 2\times10^{12}\ M_\odot$, $M_{DM} = 2.6\times10^5\ M_\odot$, 6-8 million particles inside $R_{vir} \sim 350$ kpc, last major merger > 10 Gyr ago.

Red particles are bound at z = 10



Red particles are bound at z = 10

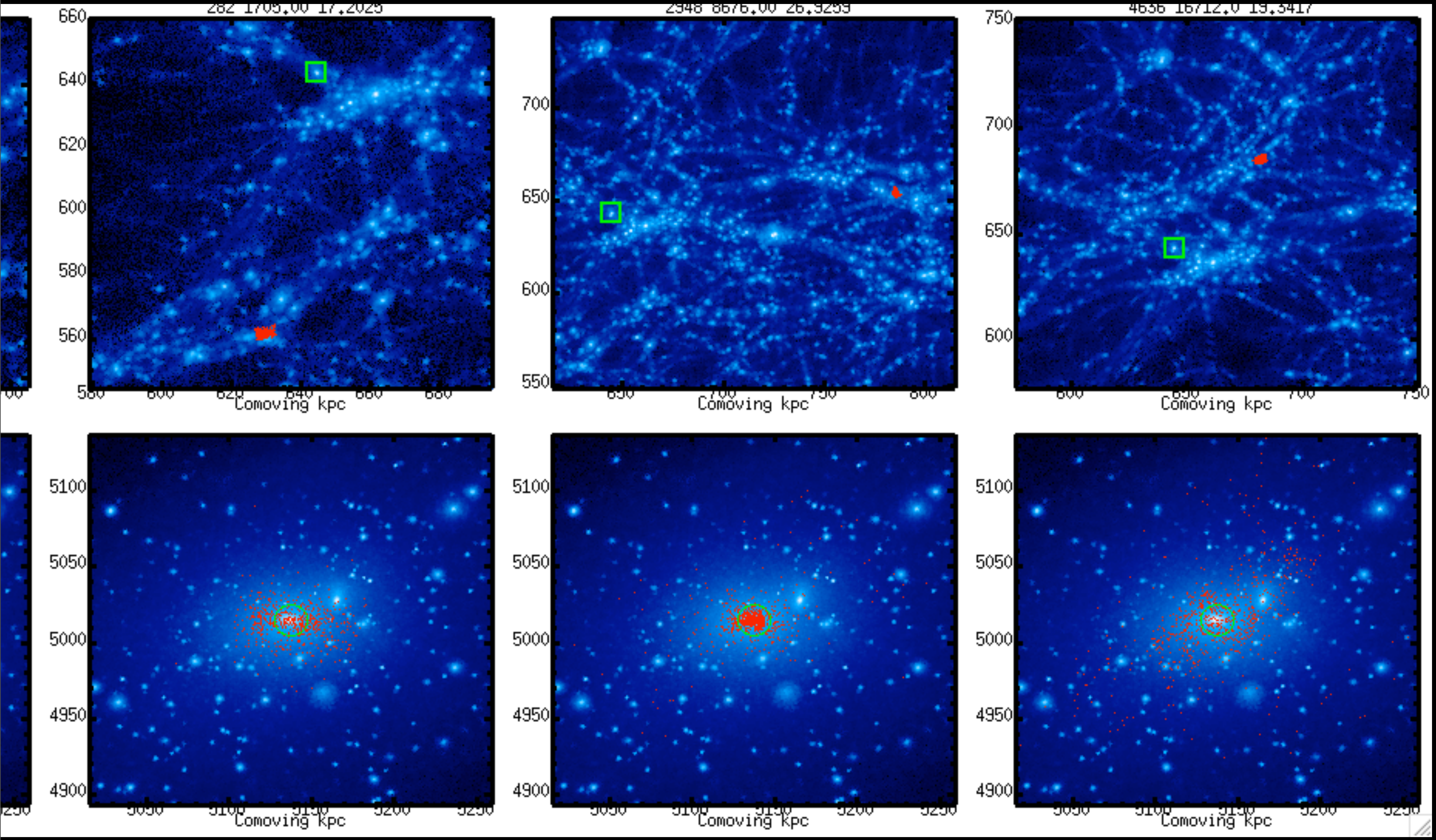
6 most massive progenitors at z = 6



Their particles at z = 0

R =10 kpc

6 most massive progenitors at z = 6



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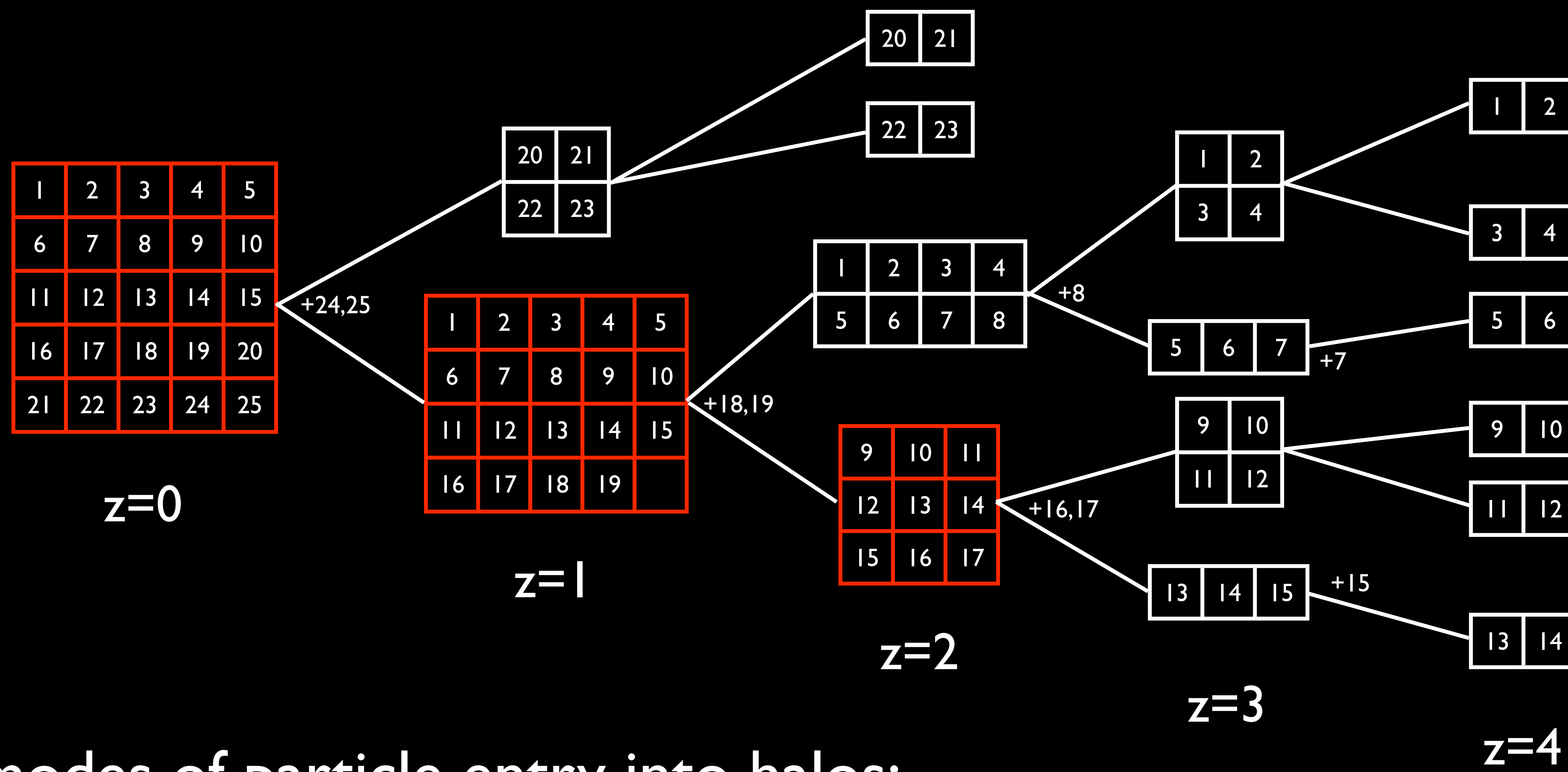
2. Construct a merger tree for all halos that presently lie inside R_{vir}, and analyze the mass assembly history of the host, its substructure, and the solar shell, R = 7-10 kpc.

   With *merger trees*, we can distinguish between mass acquired by mergers (likely to bring in stars) and mass acquired by "smooth accretion" (not likely to bring in stars).

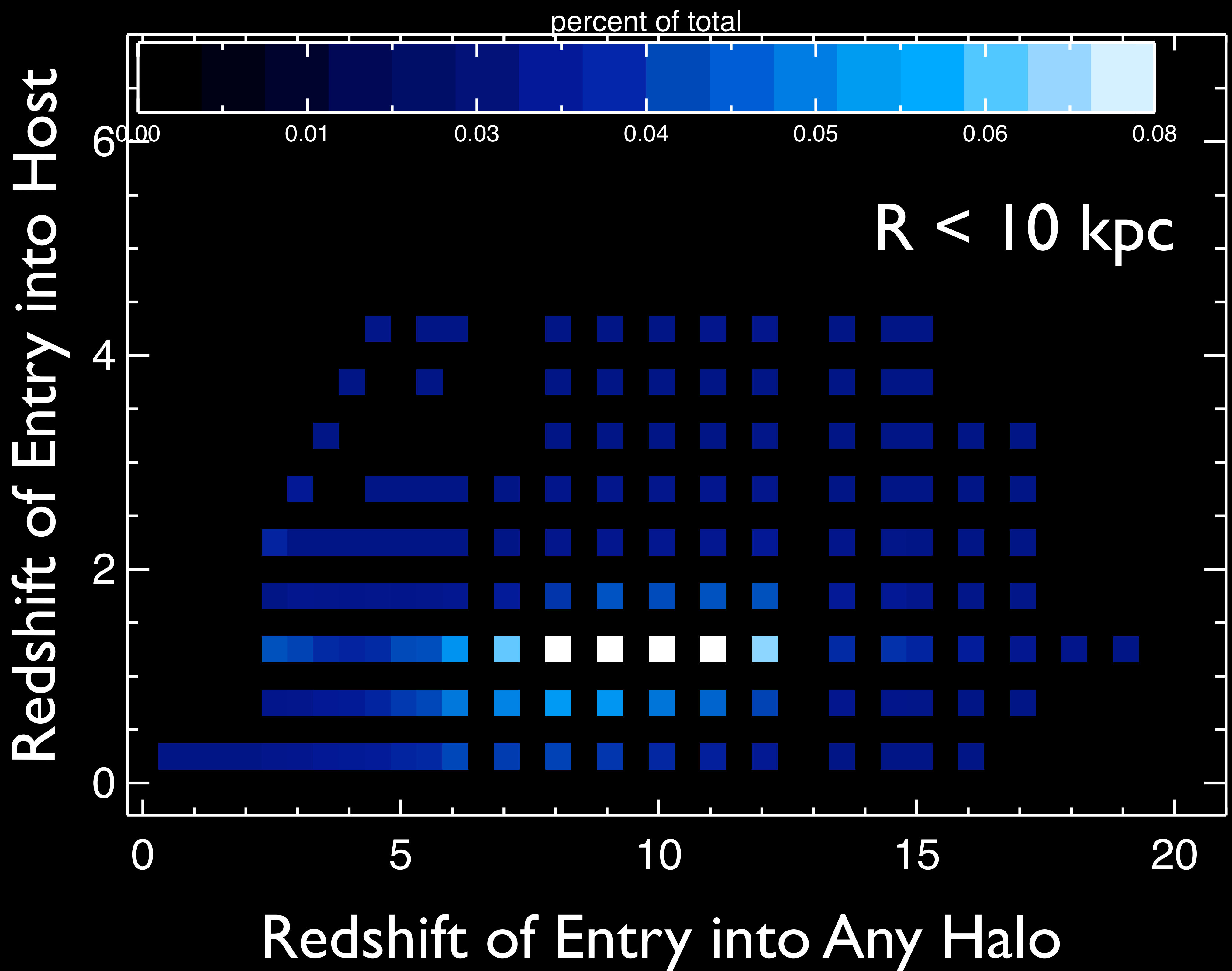


Two modes of particle entry into halos:

- z_{entry} = redshift of entry into any bound halo.
- z_{host} = redshift of entry into host halo (in red)
- Examples: Particle 21: z_{entry} = 2, z_{host} = 0

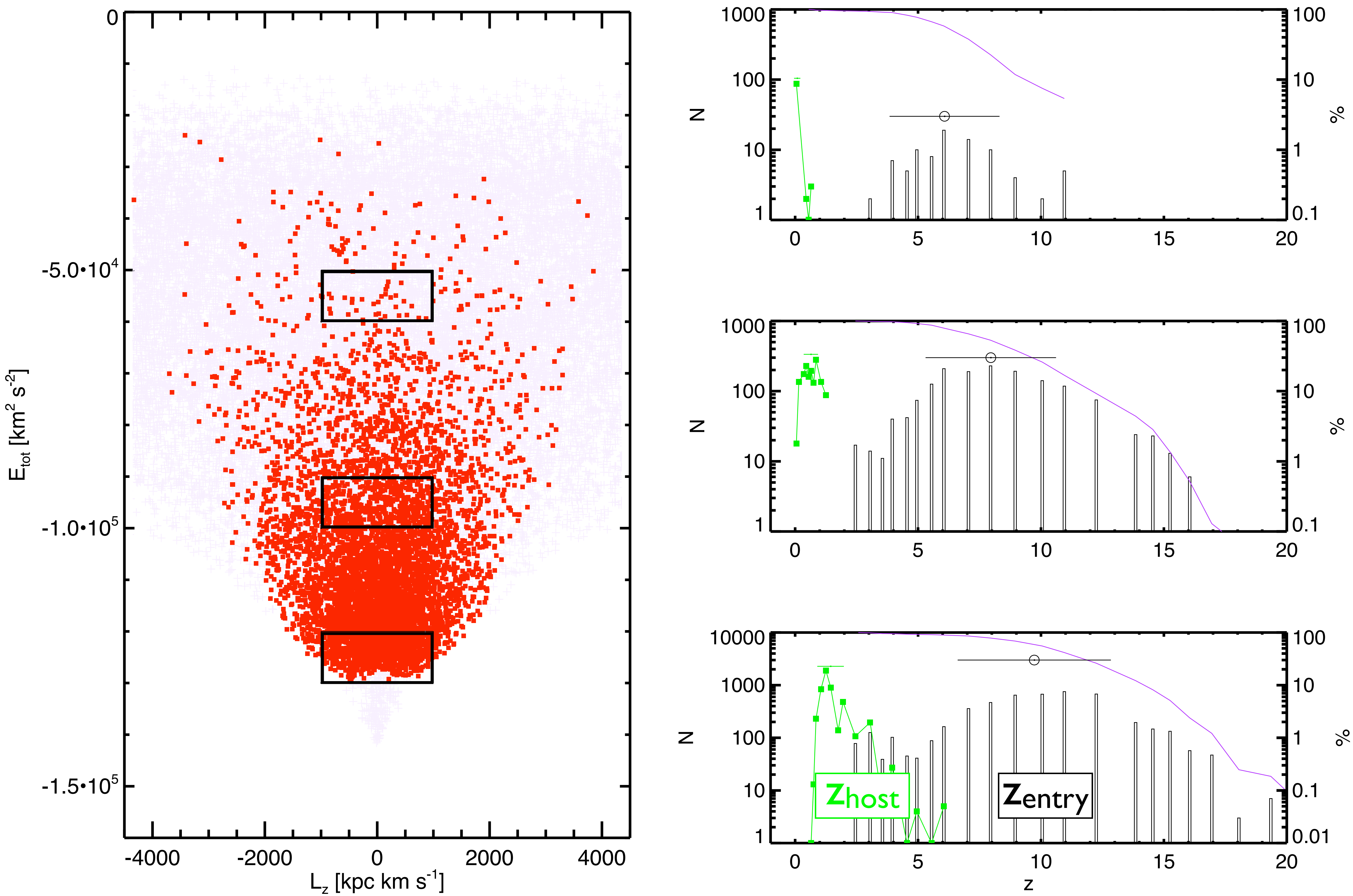
  Particle 14: z_{entry} = 4, z_{host} = 2

Simple rule: z_{entry} sets the age of the oldest (metal-poor) stars a particle can associate with.



The Solar Shell is built from particles that entered the host around the last major merger (z ~ 1.5), but which were incorporated into bound objects at z = 6 - 12.
<u>This is the essence of the hierarchical picture of structure formation.</u>

Mean z_{entry} increases for more tightly bound orbits, but is still ~ 6 for all "solar shell".



excludes "smooth accretion" particles

Three Questions for Galactic Archaeology

1. Where are the first galaxies today?

   Even without any modeling of gas processes, we can draw two important conclusions about the assembly history of the Milky Way halo:

   - The $z > 6$ progenitors of the MW survive today in the center of the halo (this is well-known; Helmi et al., Scannapieco et al. 2006; Diemand et al. 2007). However, they may have accreted into the host halo well after $z = 6$. Material in the solar shell first entered a bound object at $z > 4 - 10$.

   - These "first galaxy" remnants are centrally concentrated, but they highly overlapping with each other and with later accretions into the halo. So. . .

2. How can we isolate their surviving stellar populations?

3. What might we learn when we do this?

Key Idea II: How can we isolate the first galaxies?

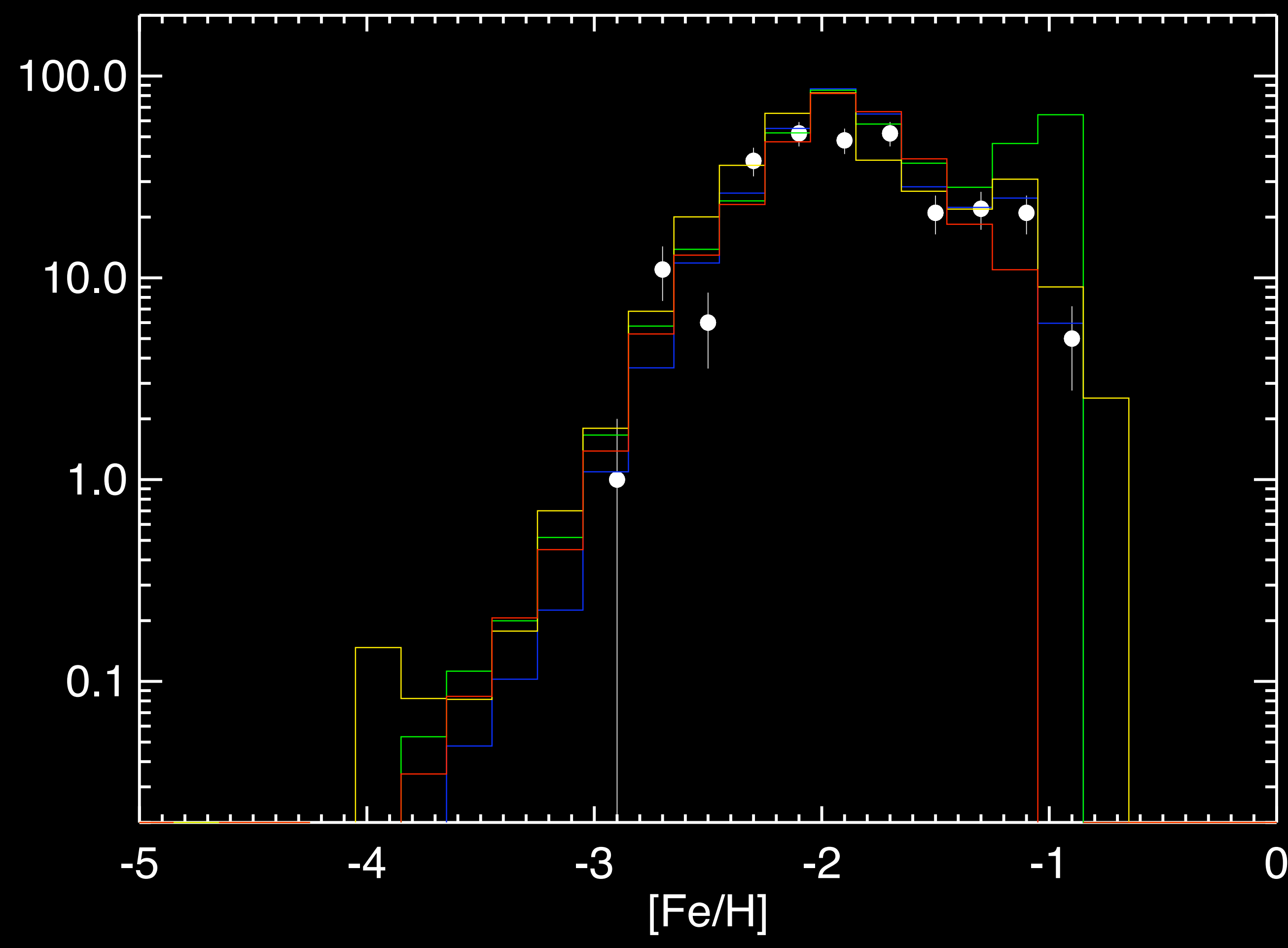
Simple analysis of DM simulations using z_{entry} and zhost no longer suffice - we must add modeling of gas processes in a hierarchical, stochastic model of chemical evolution.

So, add some parameterized "rules" (Tumlinson 2006) for gas processes:

1. Accrete baryons smoothly in fixed proportion to DM mass.
2. Form stars in discrete parcels in fixed, parametric proportion to gas mass.
3. Eject metals into the "ISM" by SN II, SN Ia, and AGB stars with appropriate time delay.
4. Allow selective ejection of metals and gas into "IGM", with more efficient ejection from small halos with shallow gravitational potential wells.
5. "Paint" stellar populations onto particles in proportion to their halo mass.

These rules are similar to the semi-analytic prescriptions employed by Bullock & Johnston (2005), Robertson et al. 2005, and Font et al. (2006) in their semianalytic modeling of MW halos.

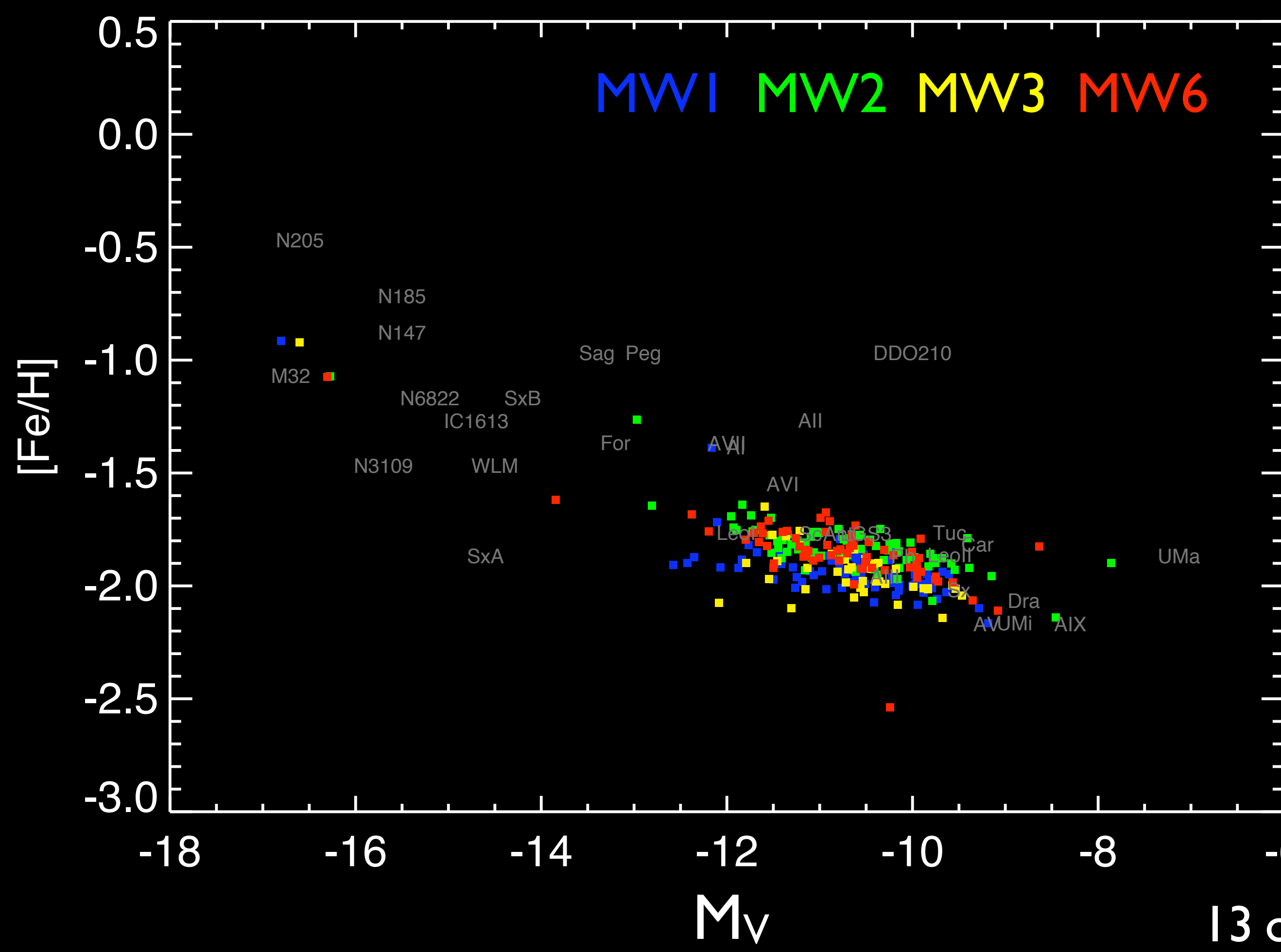
This modeling is very important, because while the "second stars" should be metal-poor, not all metal-poor stars will be "second stars", and we need some way of separating them.



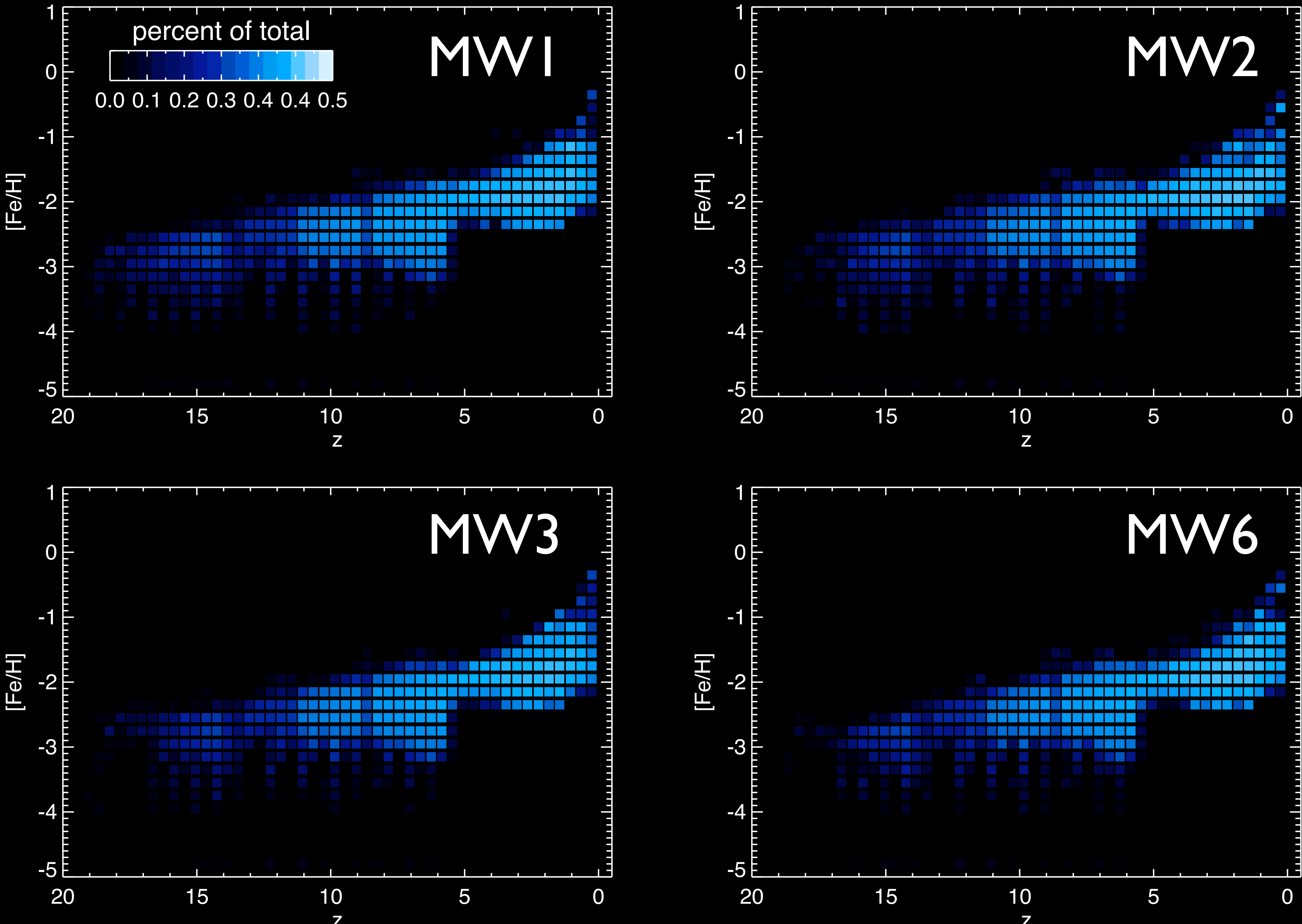
Calibrator 1
Match the halo MDF

("outer halo" from SDSS study by Carollo, Beers et al. 2007).

Calibrator 2
Match L-Z relation for surviving dwarf satellites.



MW Halo Chemical Evolution Histories



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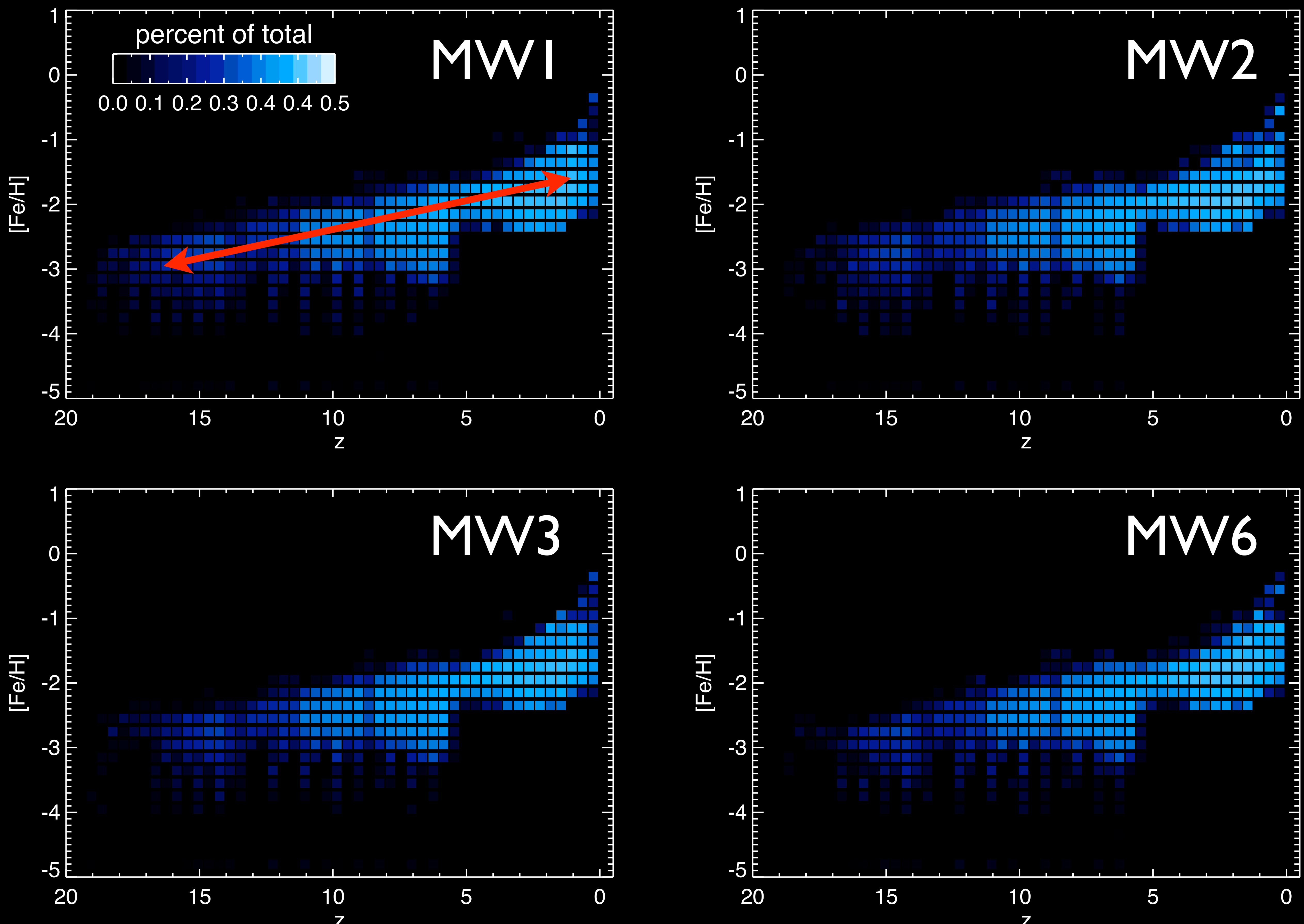

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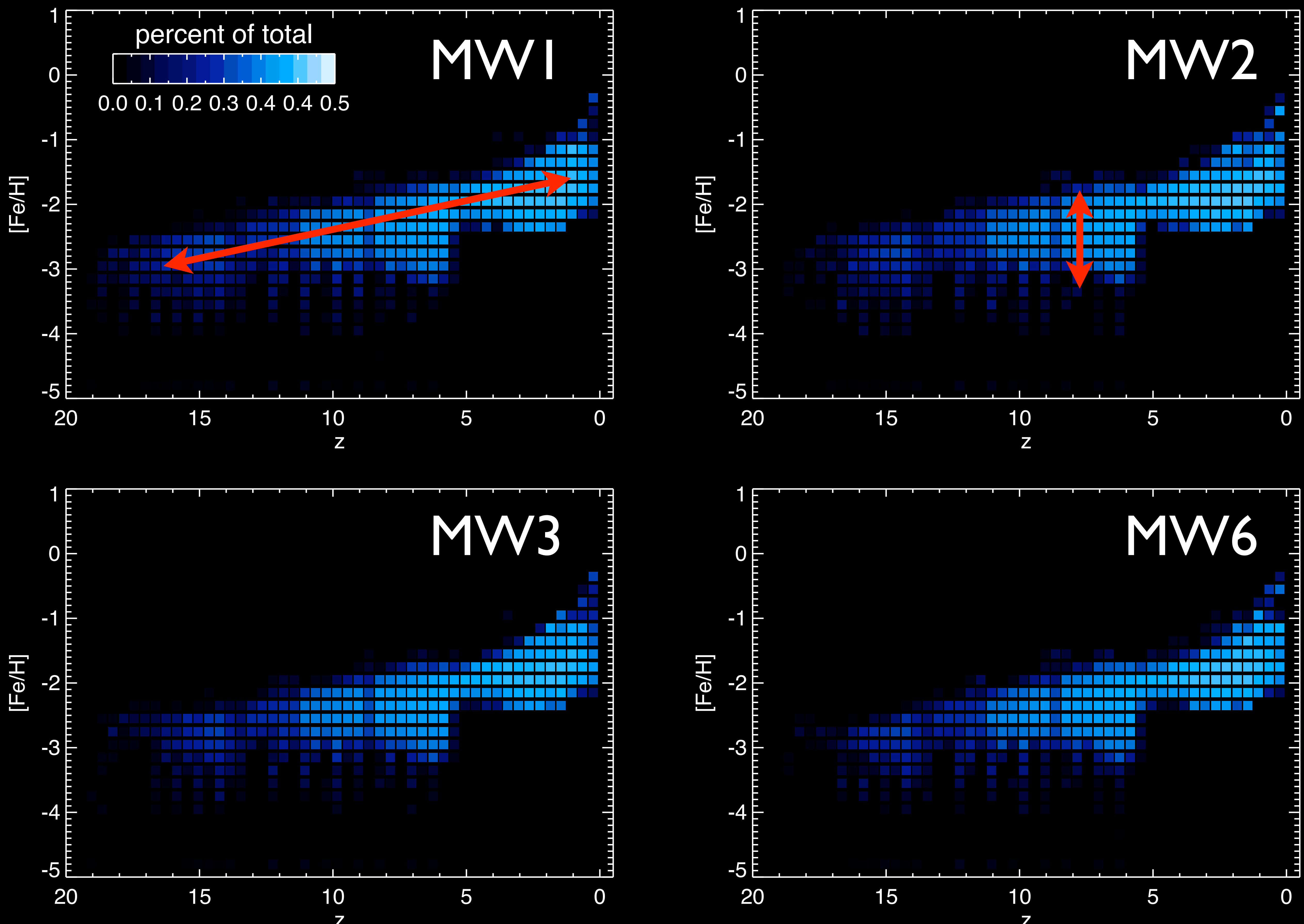

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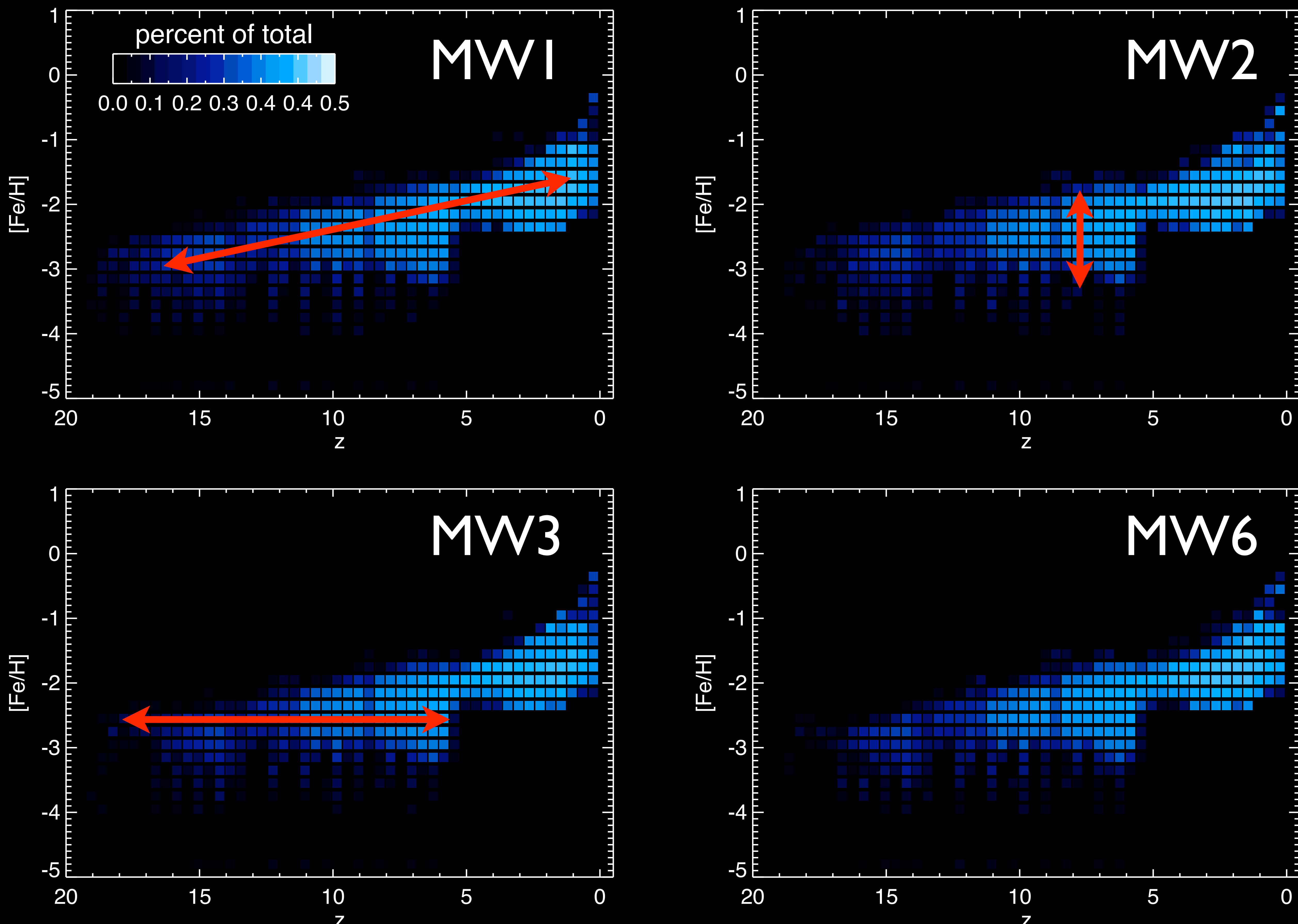
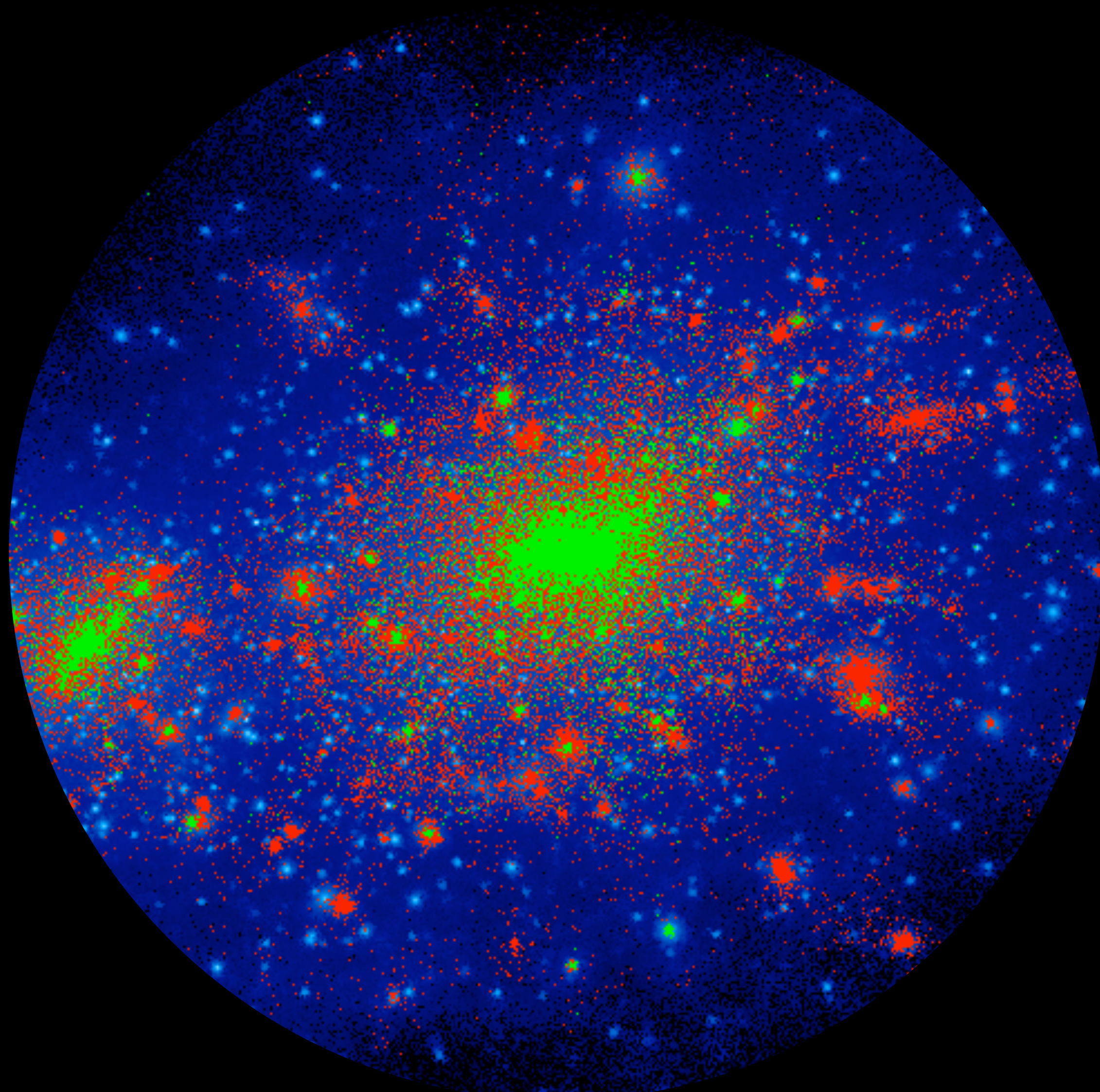


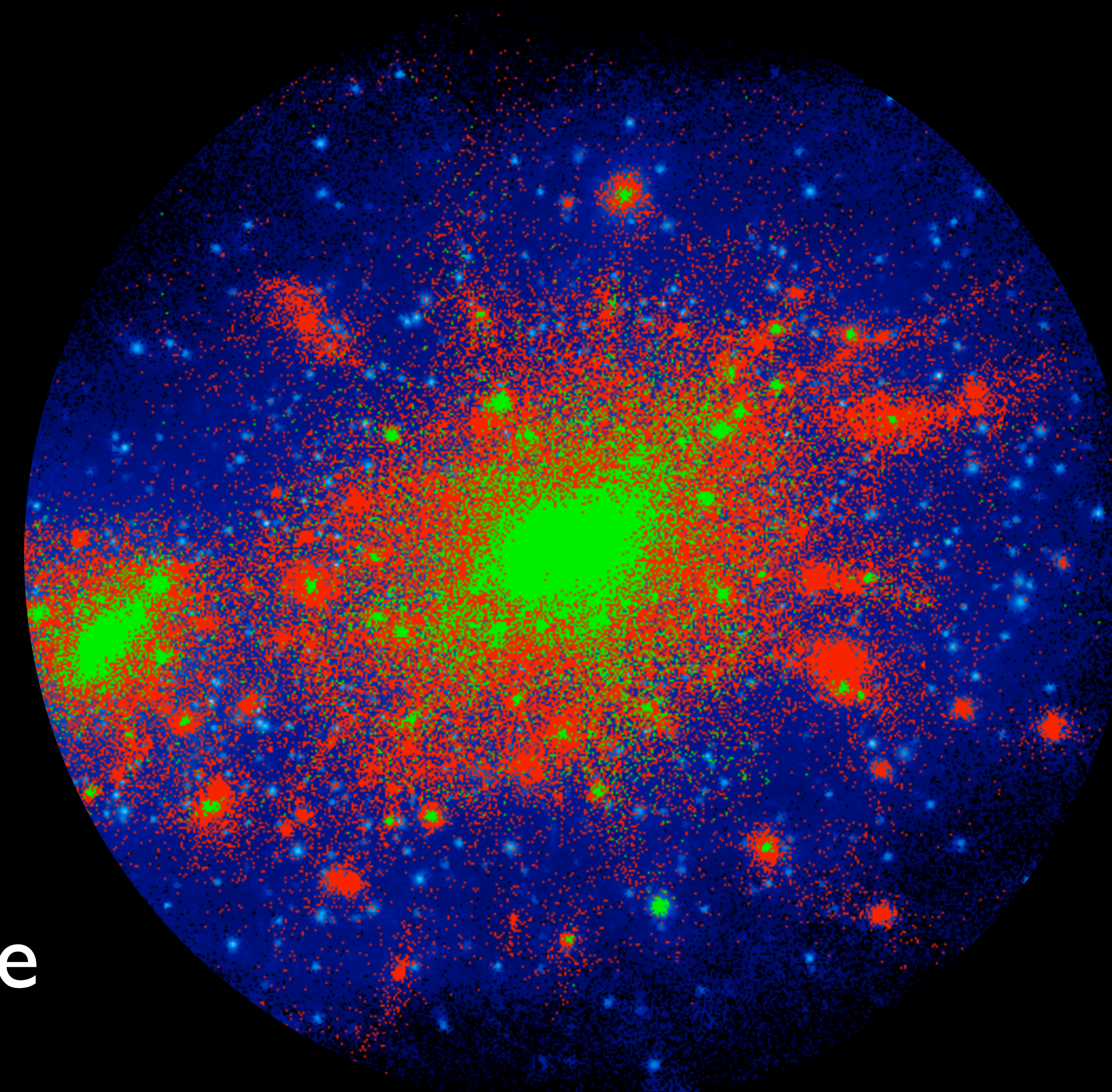
[Fe/H] < -3.5



stars formed z > 10

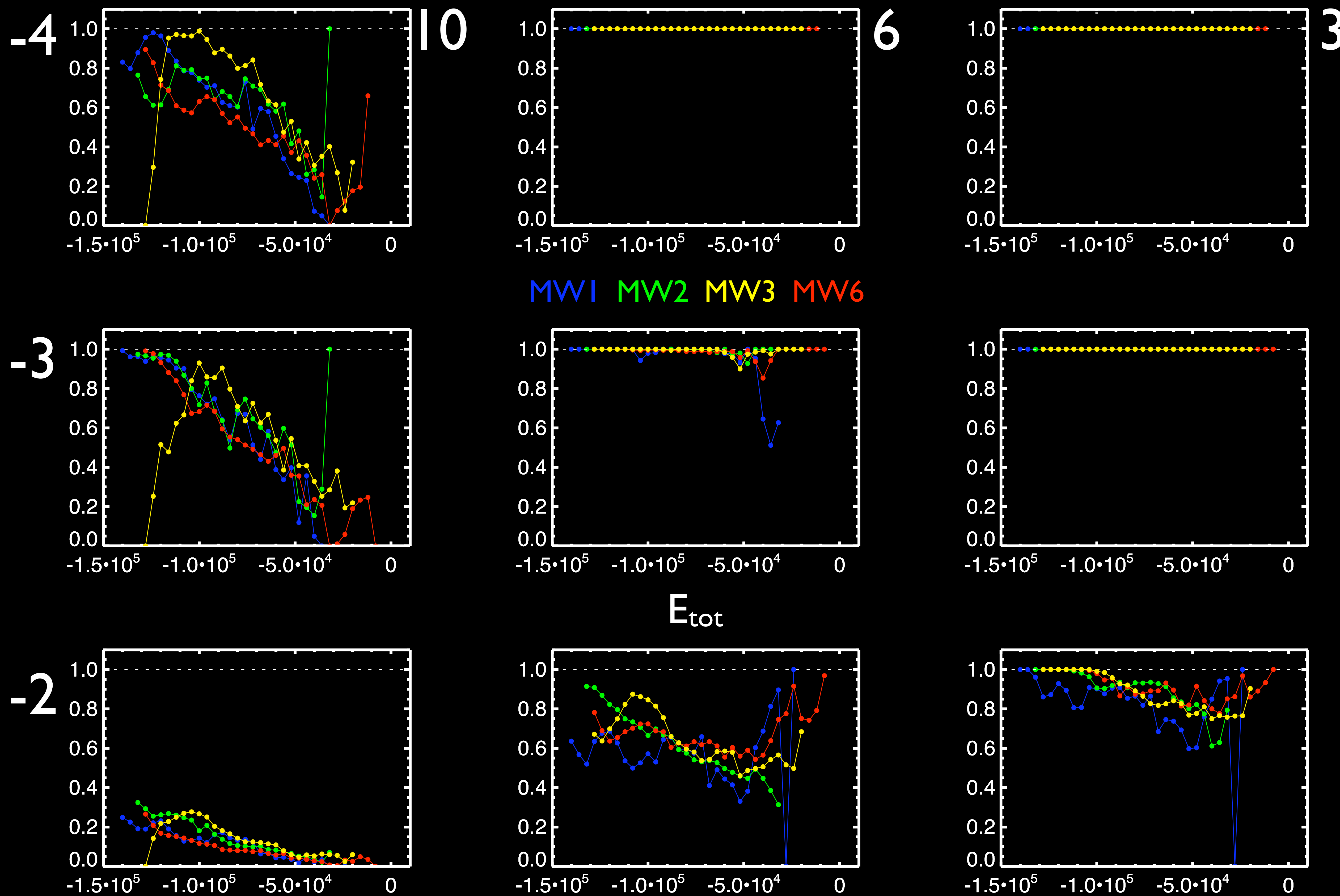
stars formed at all z

[Fe/H] < -2.0



Chronologically older stars are more centrally concentrated.

Number from z > 10,6,3 divided by number from all z



The fraction of stars that formed at high redshift increases as metallicity declines, and as orbits become more tightly bound.

Three Questions for Galactic Archaeology

1. Where are the first galaxies today?

Even without any modeling of gas processes, we can draw two important conclusions about the assembly history of the Milky Way halo:

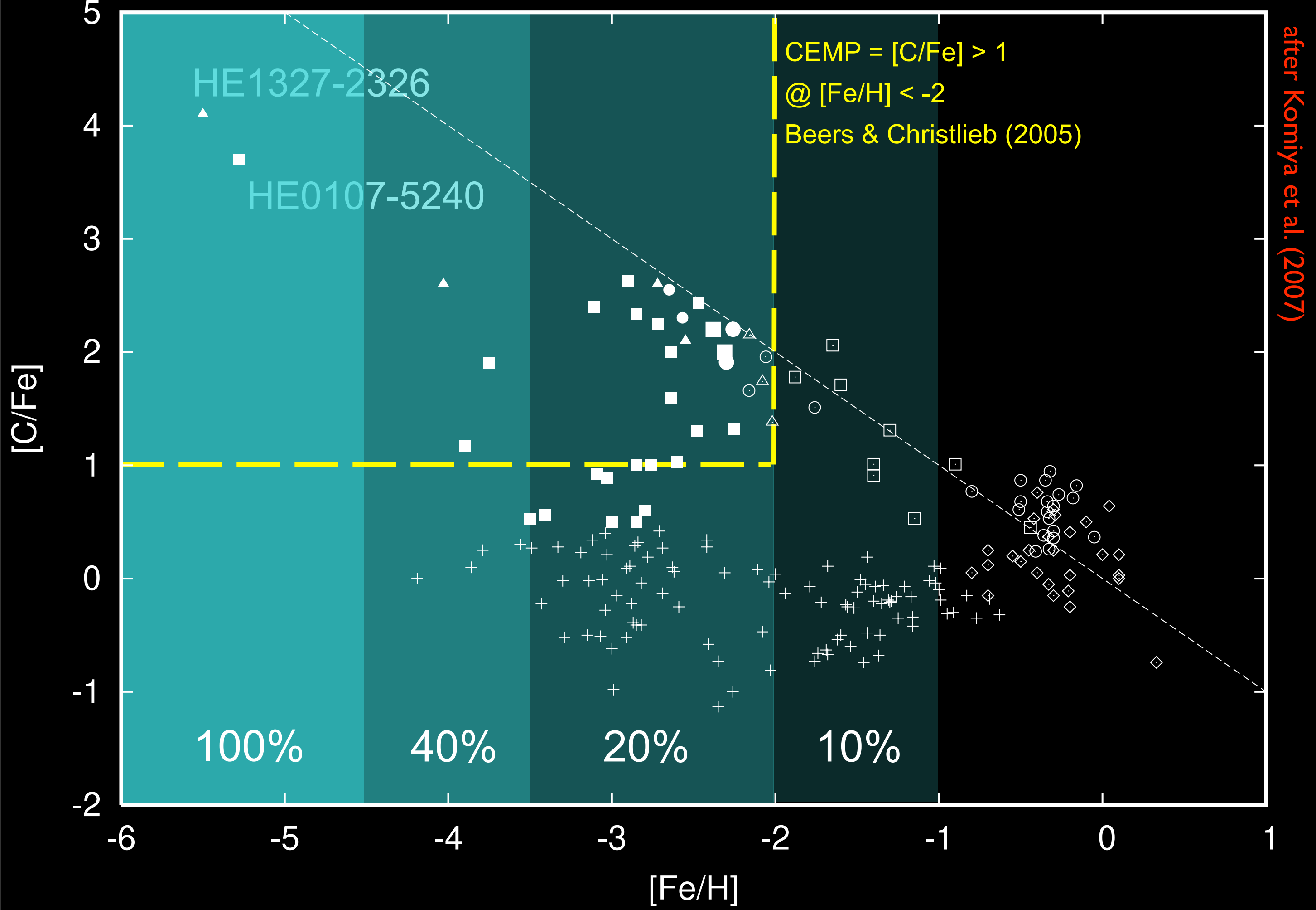
- The inner halo is built from pieces whose earliest antecedents arose at $z > 10$ (this is well-known; Helmi et al., Diemand et al.)
- Most of the material deposited in the solar shell first entered a bound object (and so becomes associated with stars) at $z > 4$, increasing to $z \sim 10$ as the present orbits become more bound.

2. How can we isolate their surviving stellar populations?

- Adding simple gas models reveals that significant fractions of low-metallicity stars formed at this epoch, and that they are not completely obscured by populations that formed and/or accreted later.
- Furthermore, we can “distill” a sample, increasing its fraction of the oldest stars, by using lower metallicities and selecting for more tightly bound orbits. It should be possible get > 50% “yield”.
- Note that “tightly bound = forms early / accretes early” but “loosely bound” means “accretes late”, not necessarily “forms late” - these late-accreting subhalos can have very old stars in them too.

3. What might we learn when we do this?

CEMPs. . .

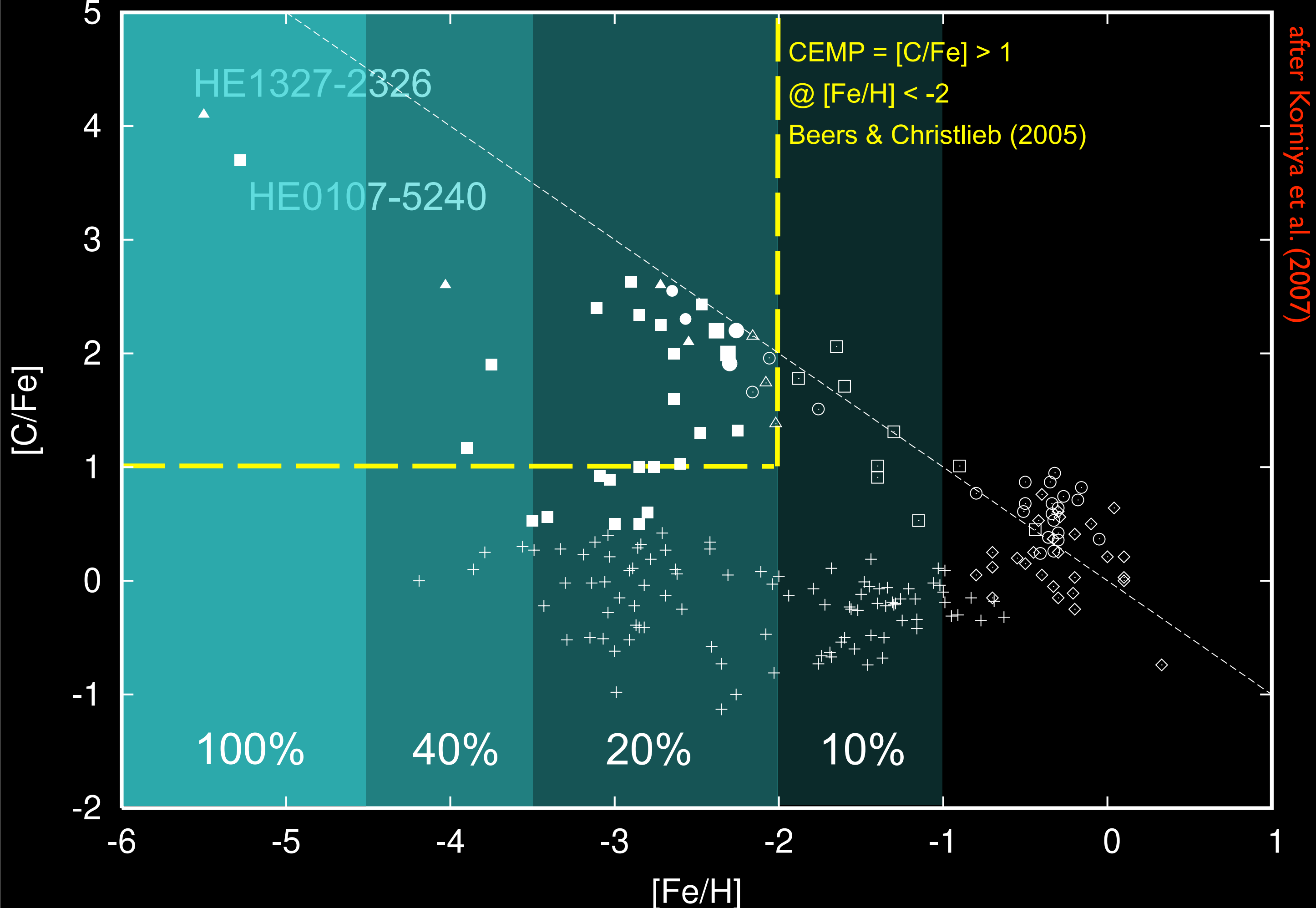


At least 80% of CEMP stars are born as low-mass partner in a binary.

CEMPs are thus a sensitive probe of IMF in the range 1 - 8 M⊙.

CEMPs also become more common in more metal-poor populations.

CEMPs. . . . . . and a CMB-mediated IMF?



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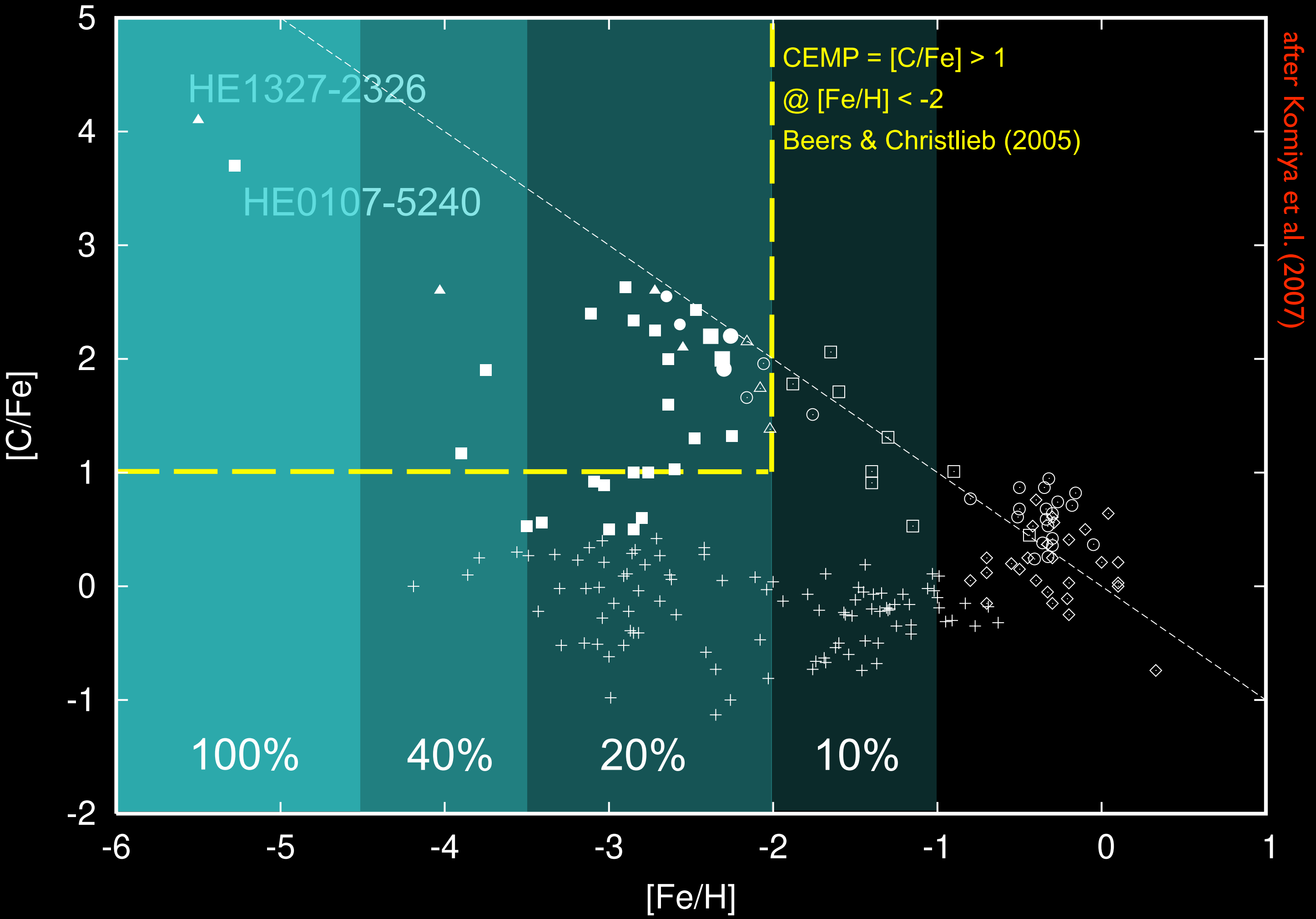

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At low redshift, gas and dust cooling set $T = T_{min} = 10$ K.

But at high z, the CMB sets $T_{min} = 2.73(1+z)$ K!

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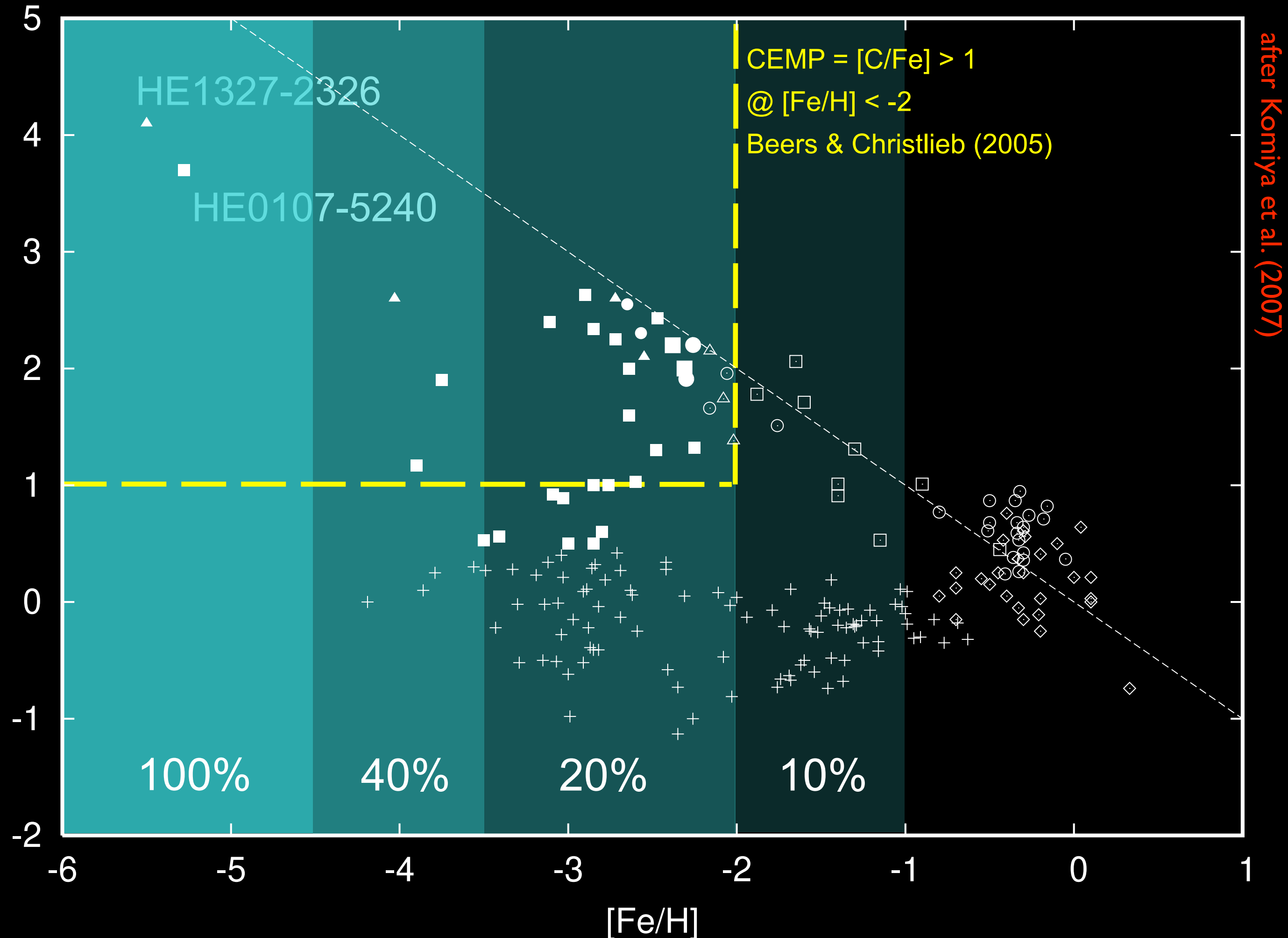

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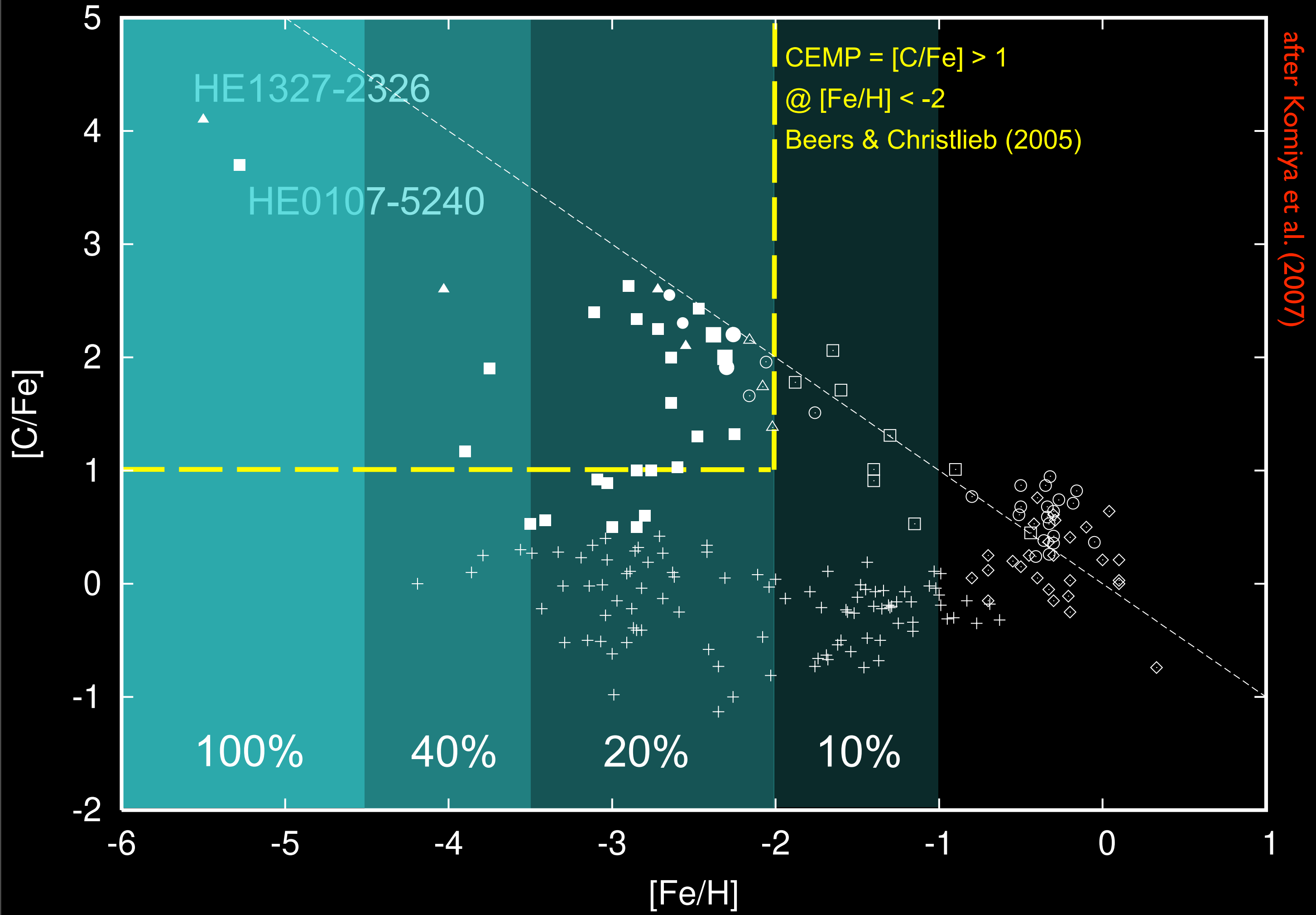

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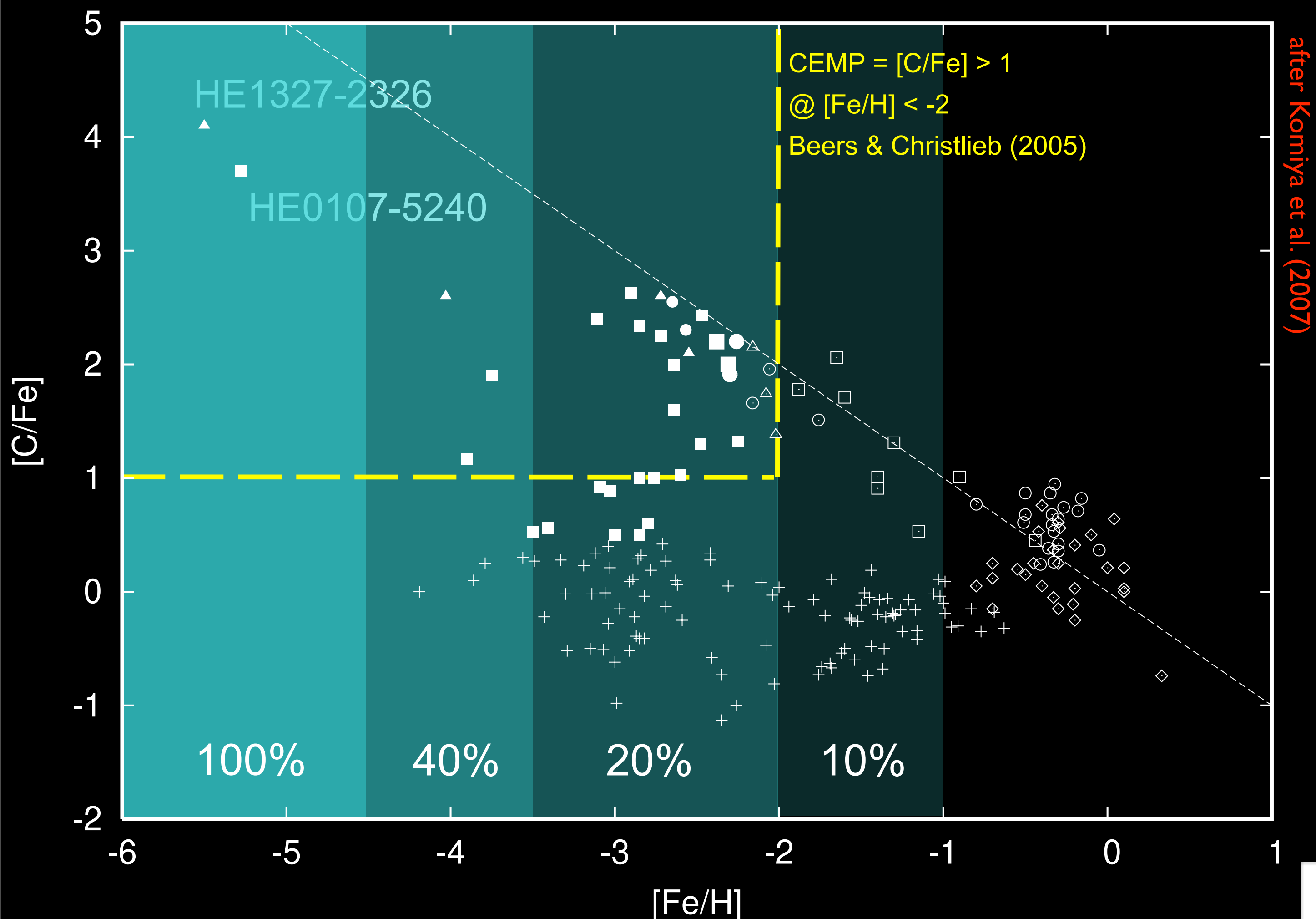
CEMPs... ...and a CMB-mediated IMF?



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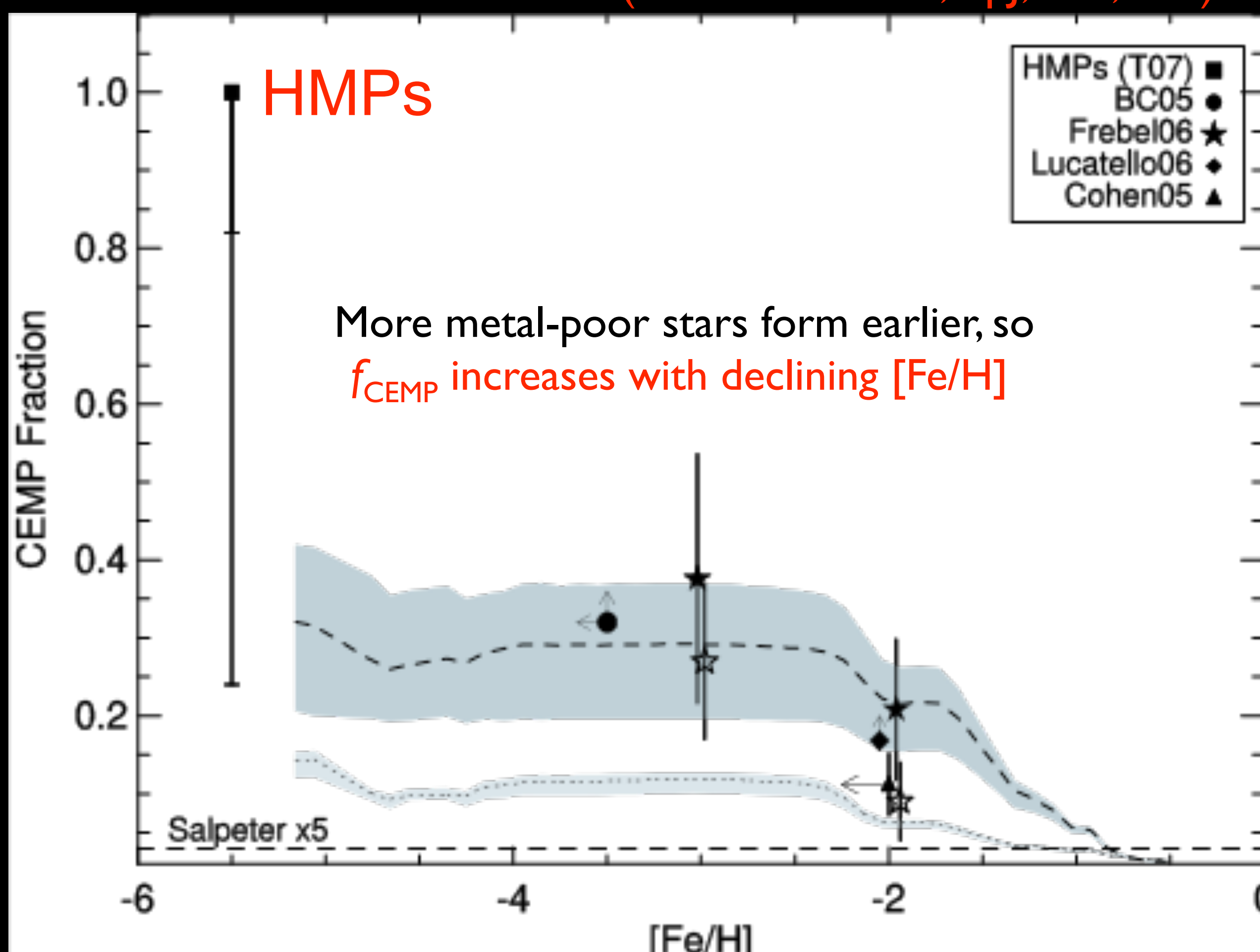
(Tumlinson 2007, ApJ, 664, L63)



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The implication of the CMB-IMF is that . . .

. . . earlier stellar populations see a <u>hotter CMB</u>, have a <u>high characteristic</u> mass, and so exhibit a <u>higher fraction of CEMPs</u>.

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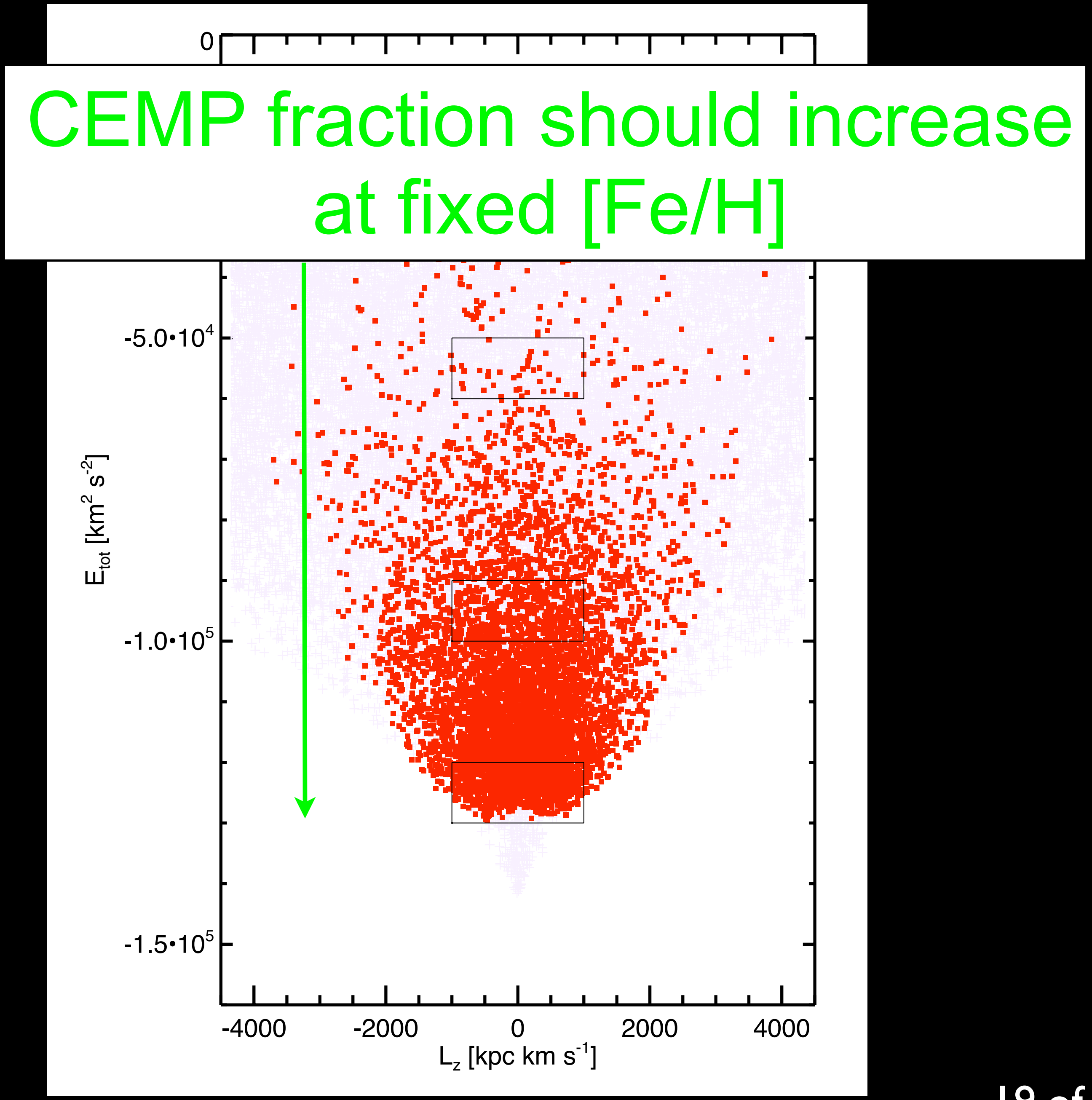

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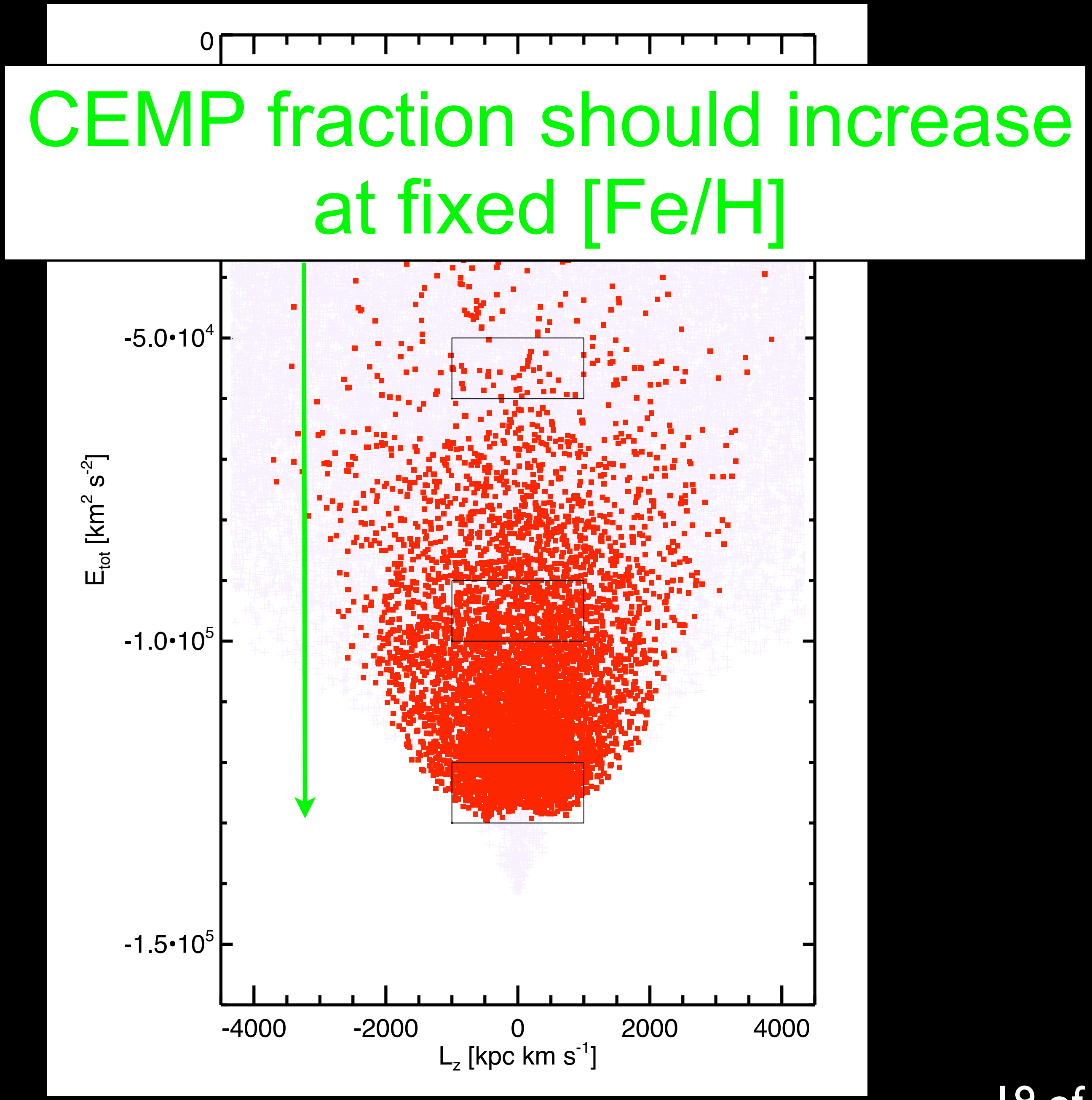
To test this, survey the inner regions of the galaxy for CEMPs. These extremely metal-poor stars will be "in the bulge" but not "of the bulge".



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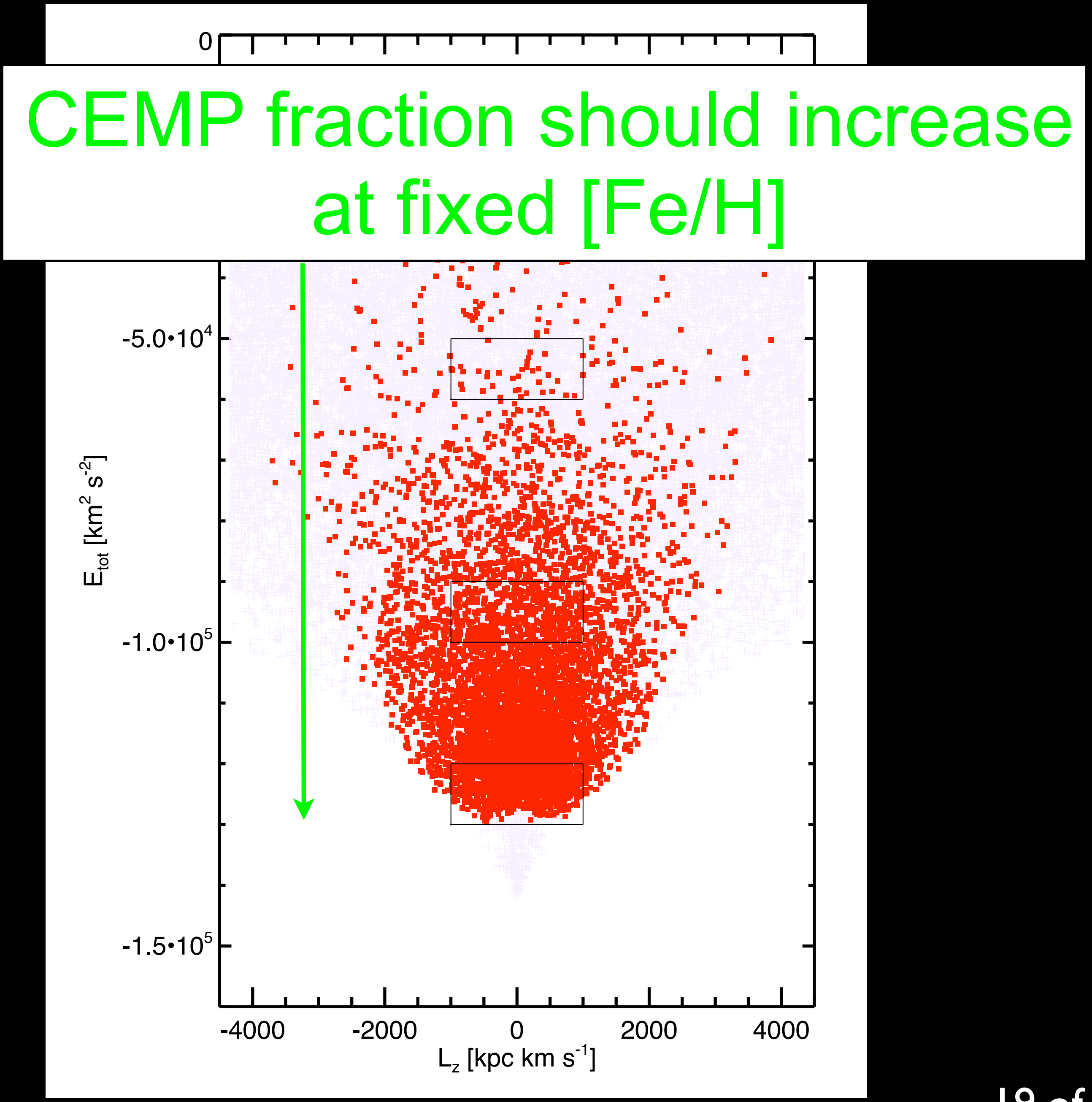
The SDSS-III APOGEE Survey (2011 - 2014)

- 300-fiber NIR spectrograph, resolution R~20,000, S/N=100
- Abundances 15+ elements in 100,000 2MASS-selected giant stars to H=13.5



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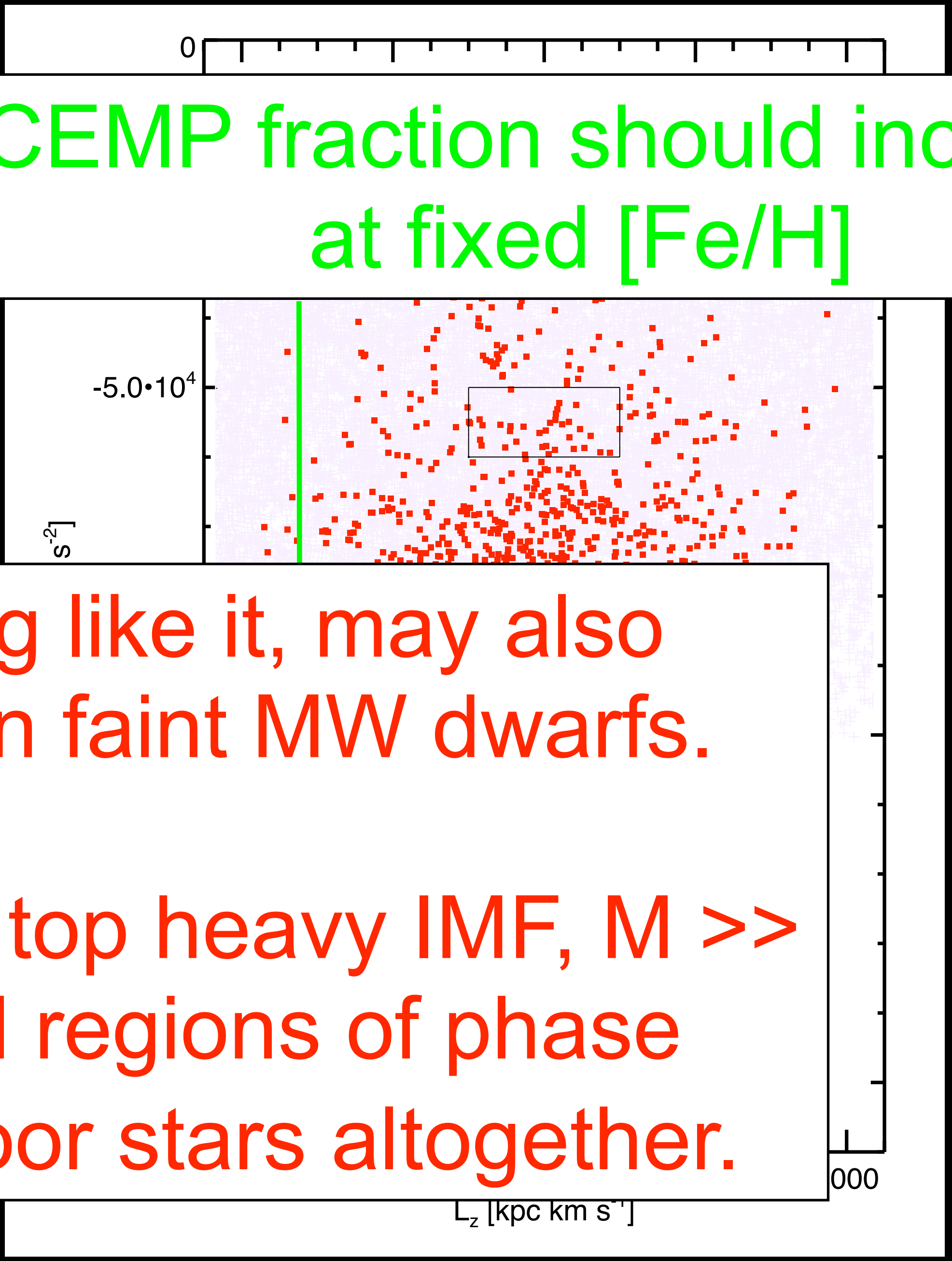

CEMP fraction should increase at fixed [Fe/H]

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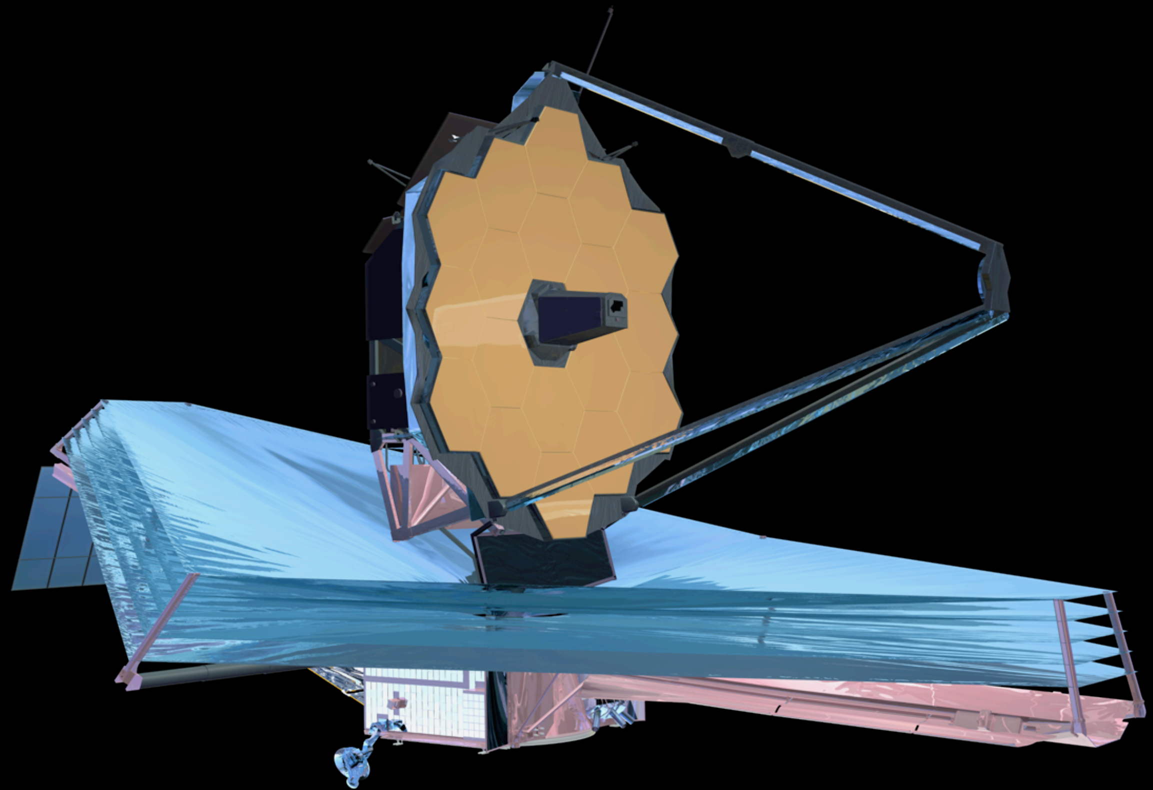
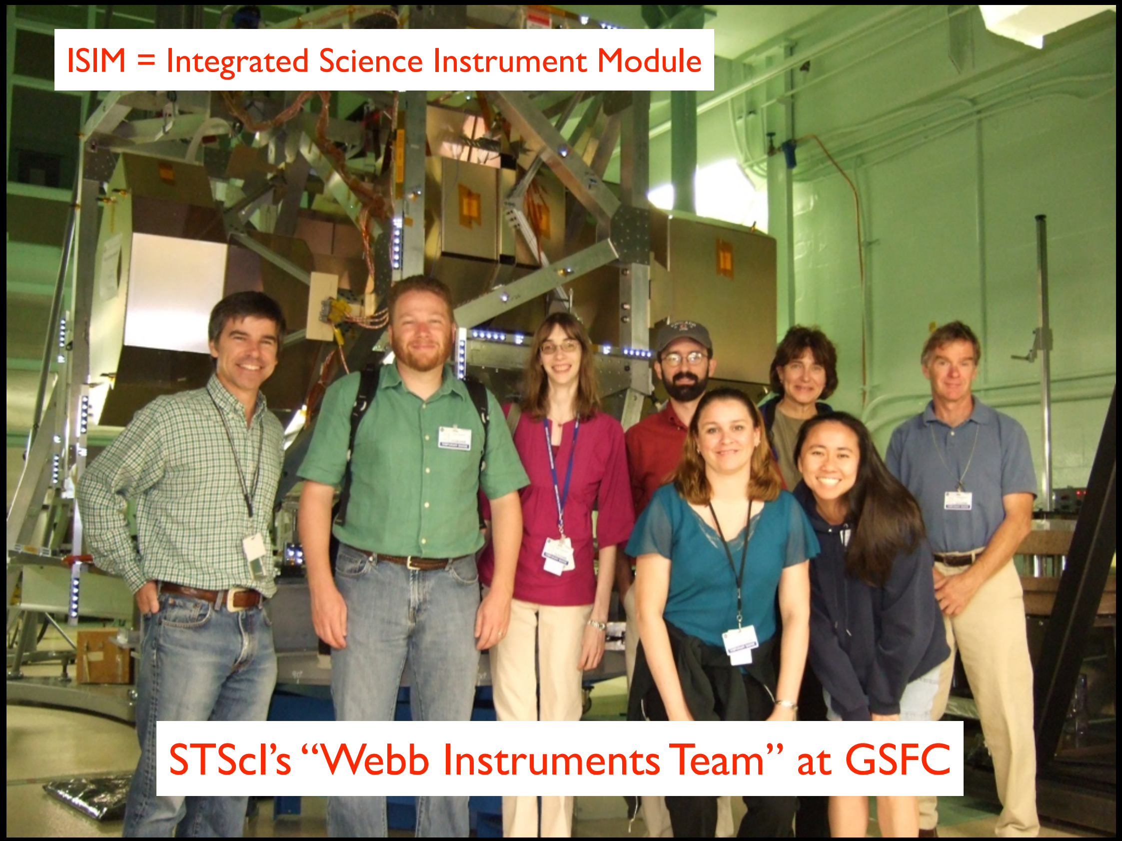
CMB-IMF, or something like it, may also explain high M/L ratios in faint MW dwarfs.

In the "extreme case" of a top heavy IMF, M >> 10 M☉, the most bound regions of phase space may lack metal-poor stars altogether.

James Webb Space Telescope - "The First Light Machine"





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- Cycle 1 GO Proposal Deadline: Sept 30, 2012. Get ready!
- Four science cases:
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  2. The Assembly of Galaxies
  3. The Birth of Stars
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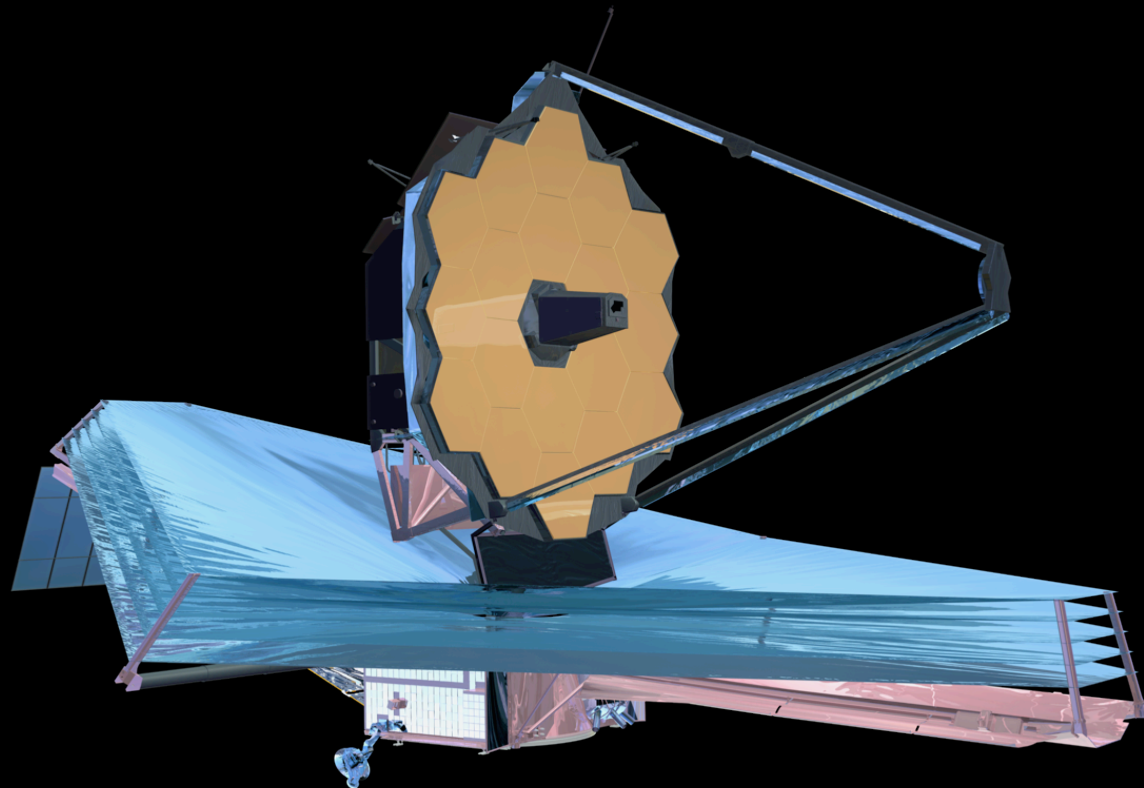

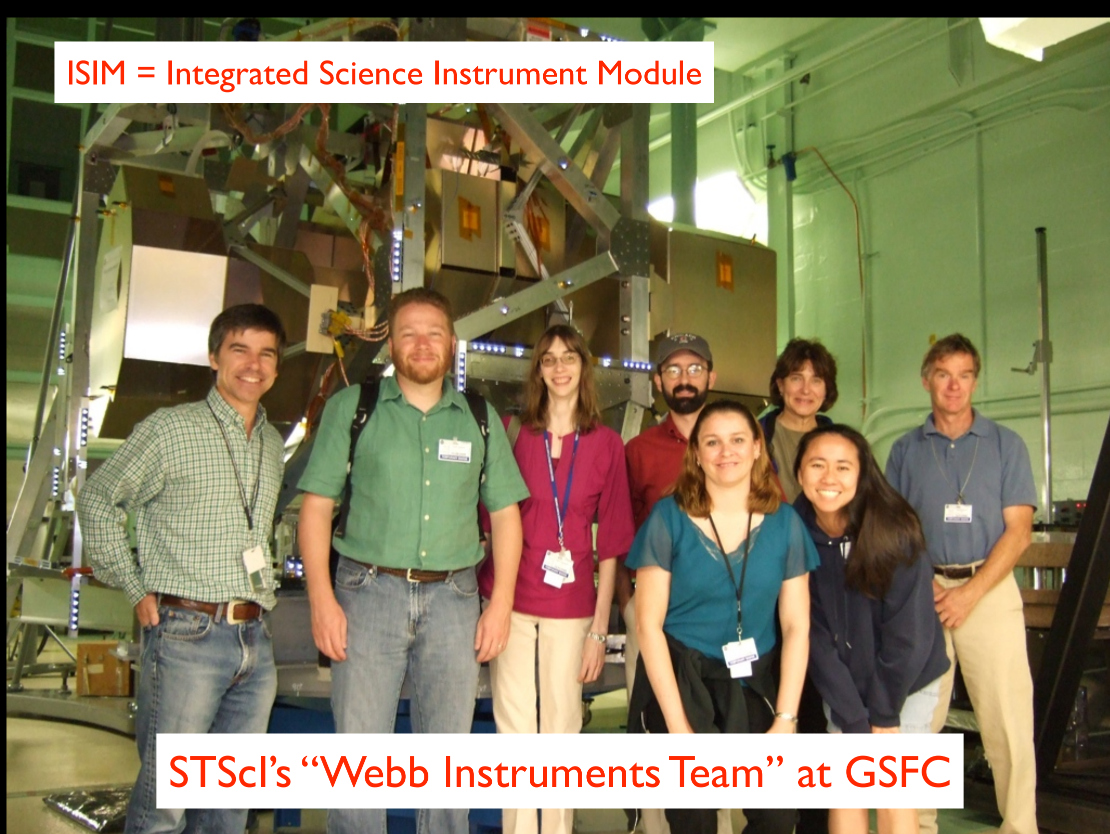

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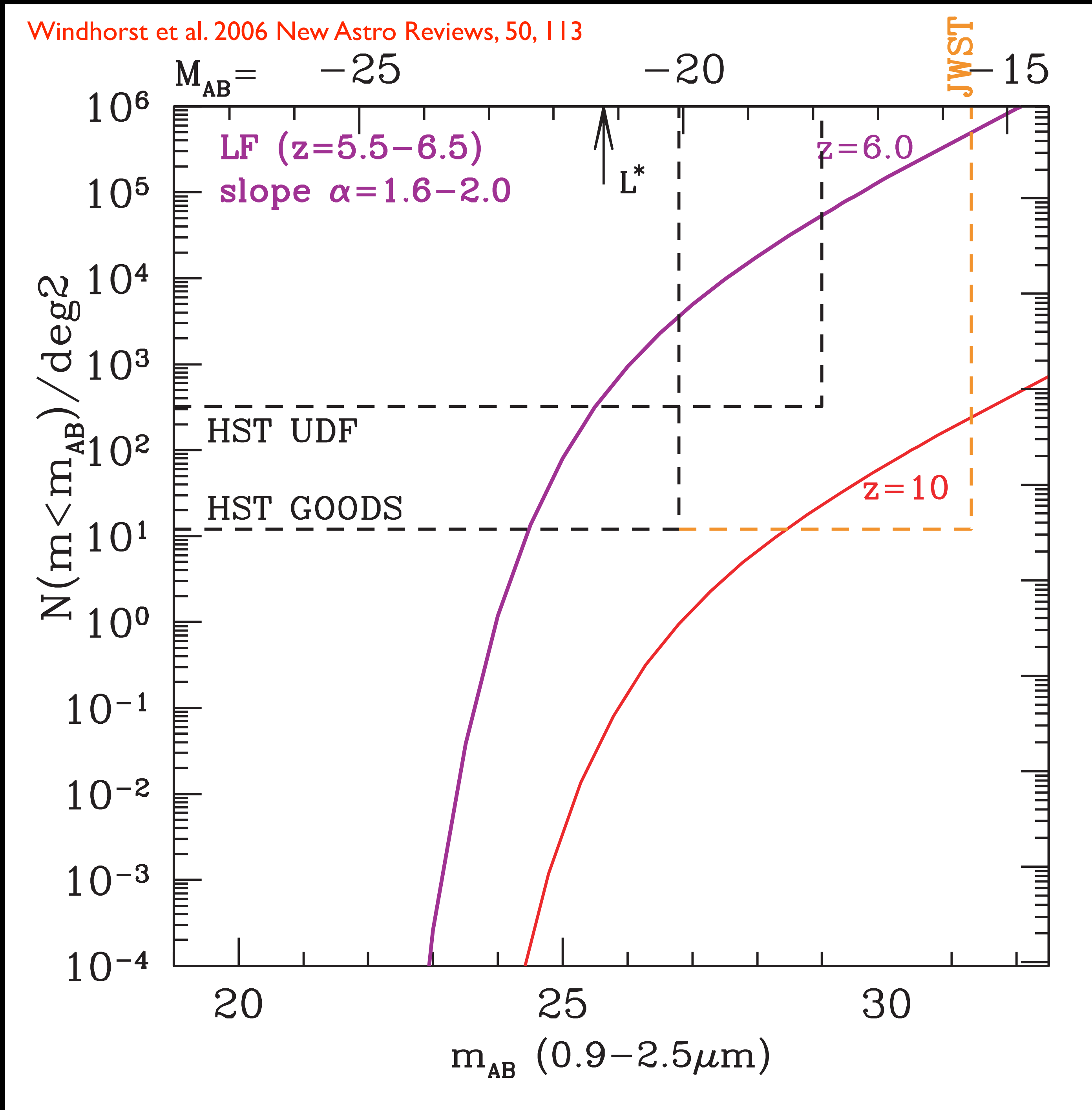
But will JWST see the z > 6 progenitors of the MW?



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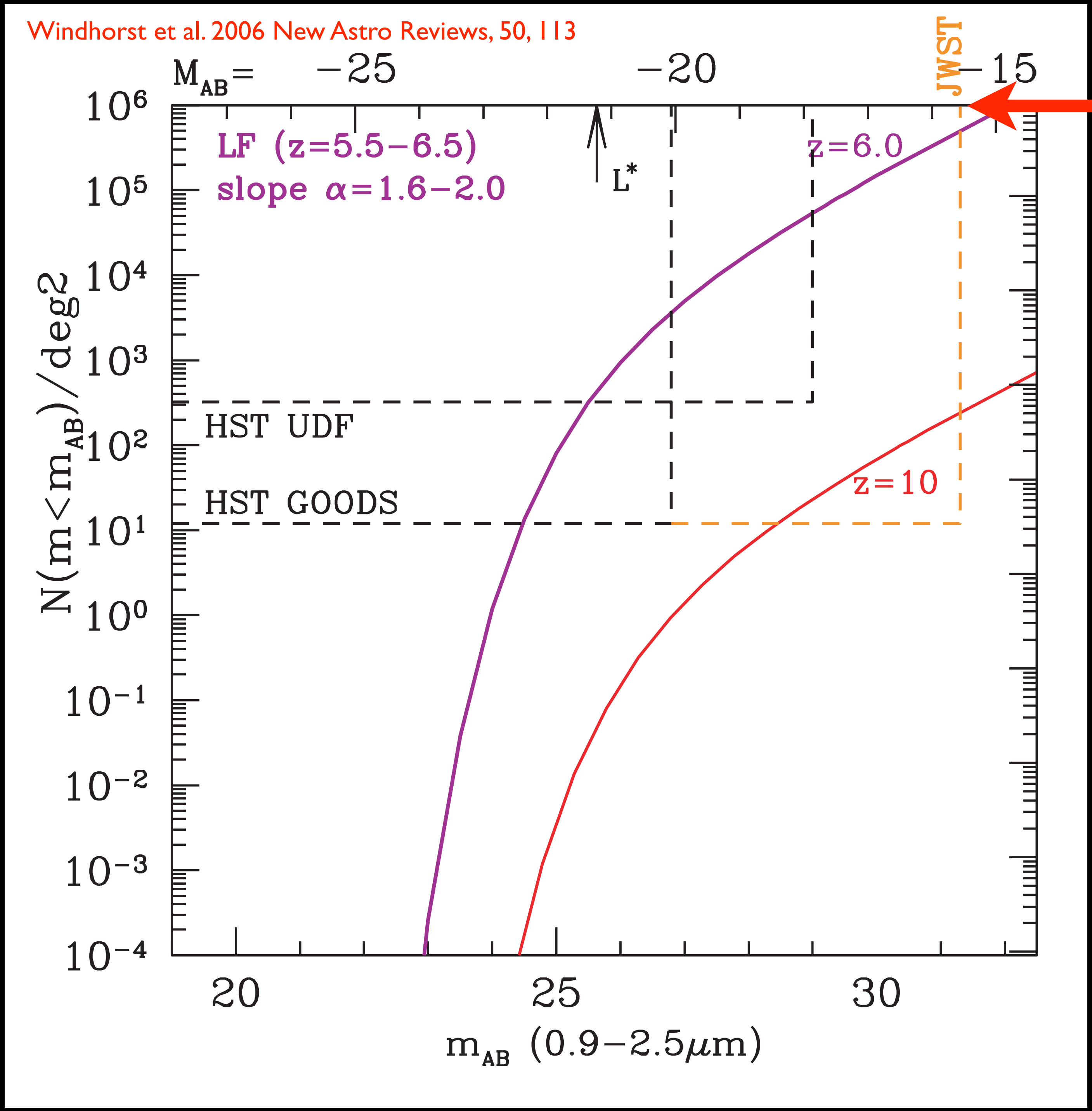

Range occupied by MW progenitors at z > 6

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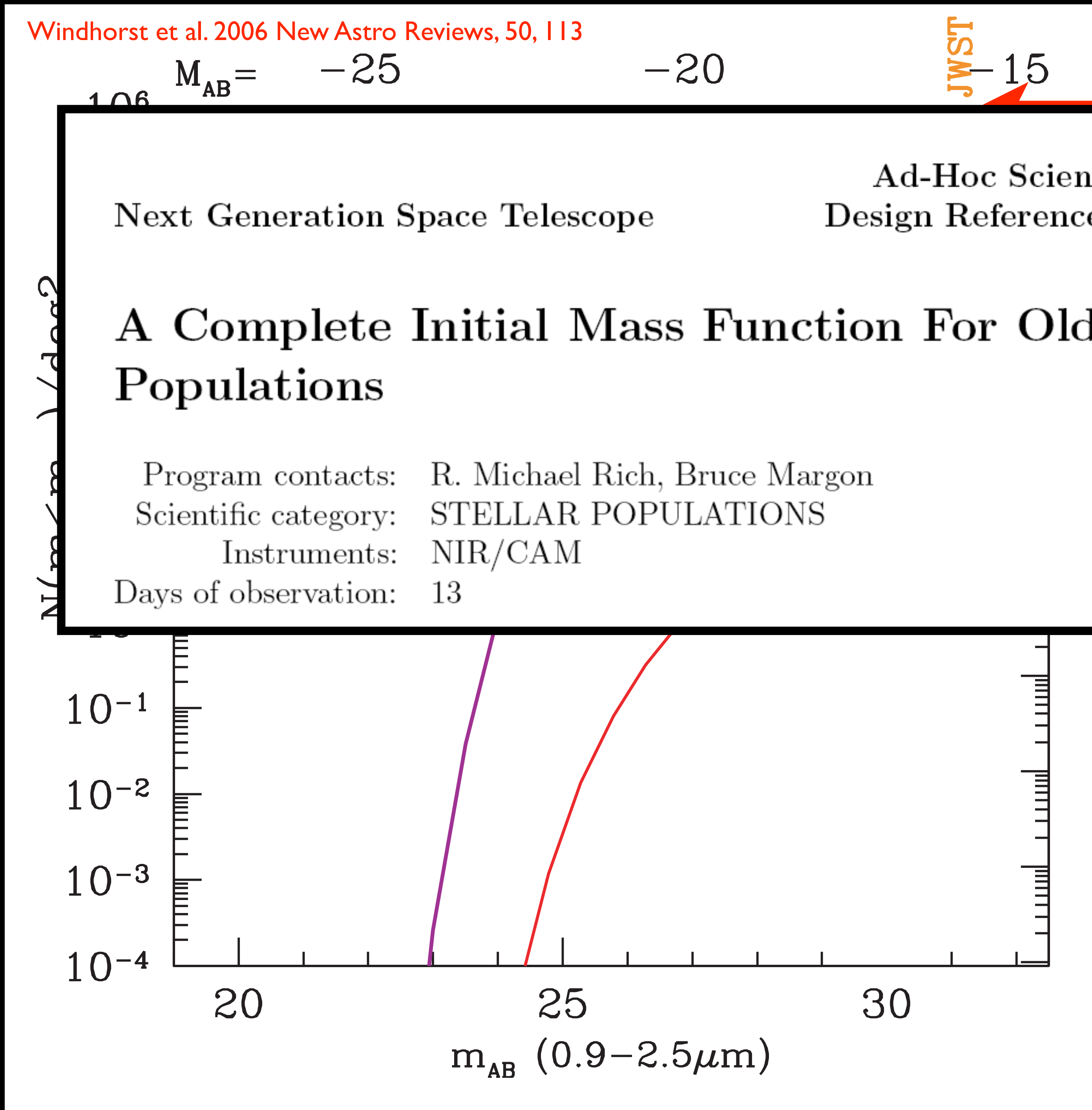

Next Generation Space Telescope

Ad-Hoc Science Working Group
Design Reference Mission Proposal

A Complete Initial Mass Function For Old Stellar Populations

Program contacts:	R. Michael Rich, Bruce Margon
Scientific category:	STELLAR POPULATIONS
Instruments:	NIR/CAM
Days of observation:	13

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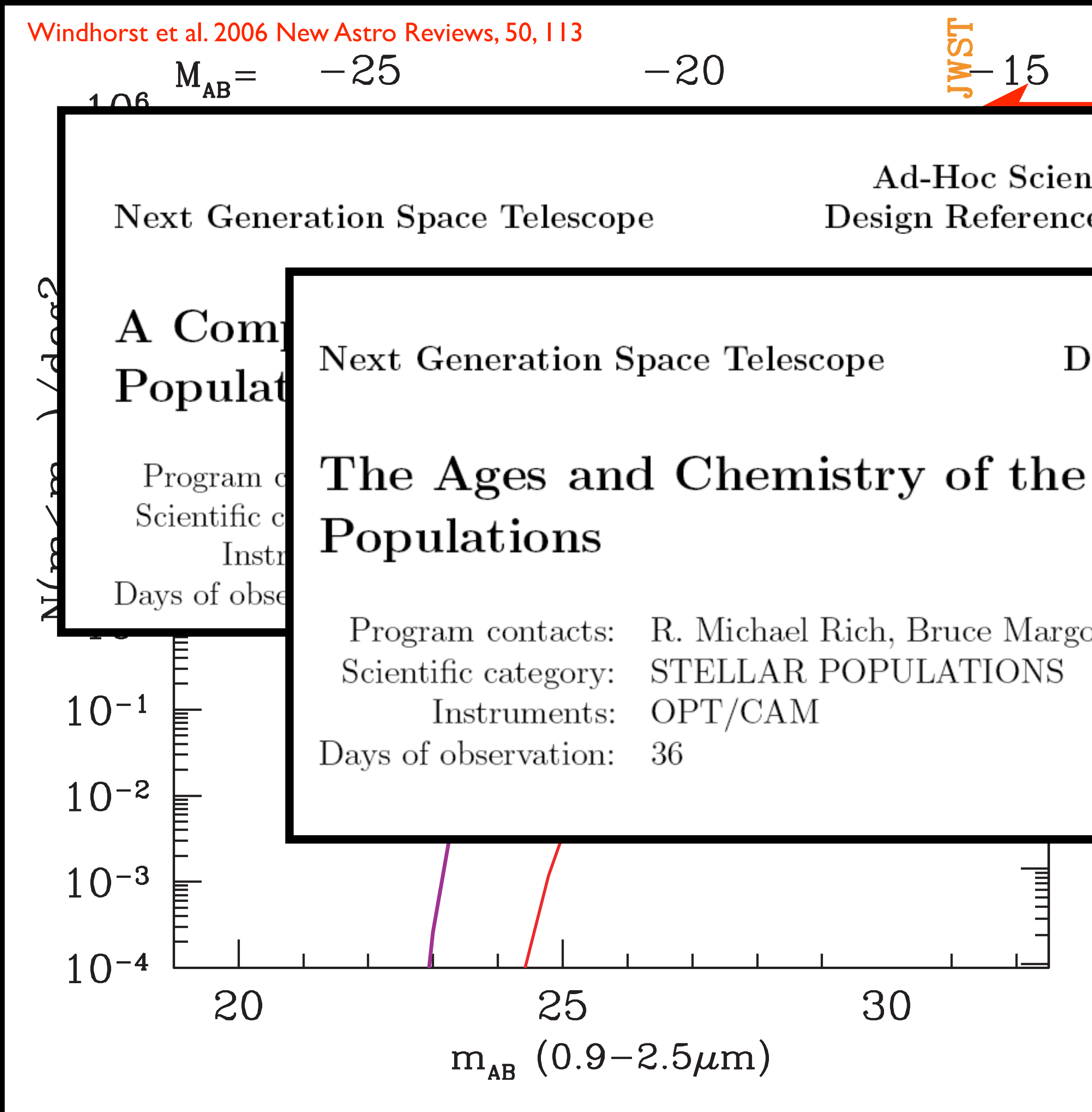

Next Generation Space Telescope

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Next Generation Space Telescope

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The Ages and Chemistry of the Oldest Stellar Halo Populations

Program contacts:	R. Michael Rich, Bruce Margon
Scientific category:	STELLAR POPULATIONS
Instruments:	OPT/CAM
Days of observation:	36

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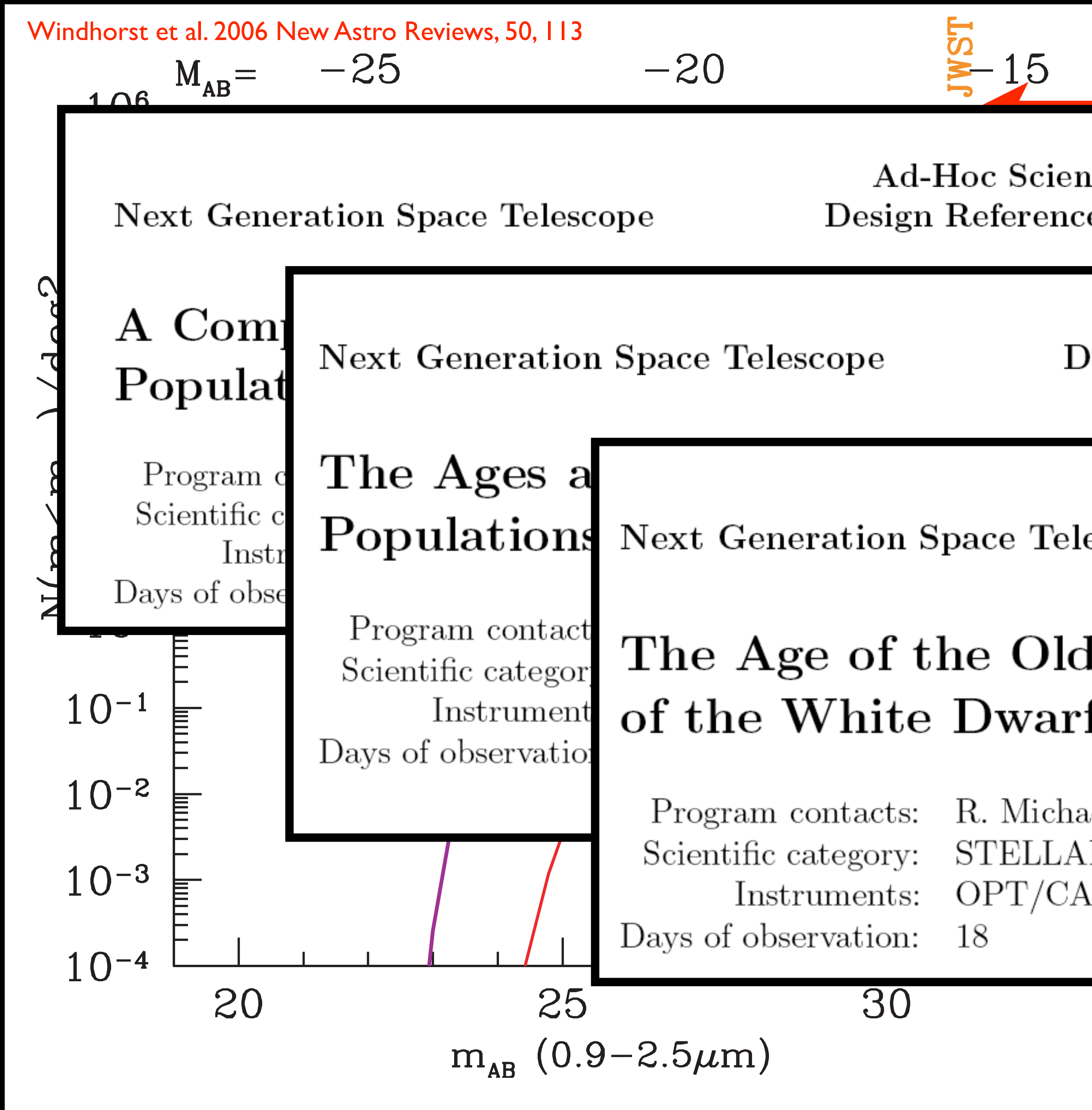
But will JWST see the z > 6 progenitors of the MW?



Next Generation Space Telescope

Ad-Hoc Science Working Group
Design Reference Mission Proposal

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Next Generation Space Telescope

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Design Reference Mission Proposal

The Age of the Oldest Stars from the Faint End Slope of the White Dwarf LF in Globular Clusters

Program contacts: R. Michael Rich, Bruce Margon, Harvey Richer
Scientific category: STELLAR POPULATIONS
Instruments: OPT/CAM, NIR/CAM
Days of observation: 18

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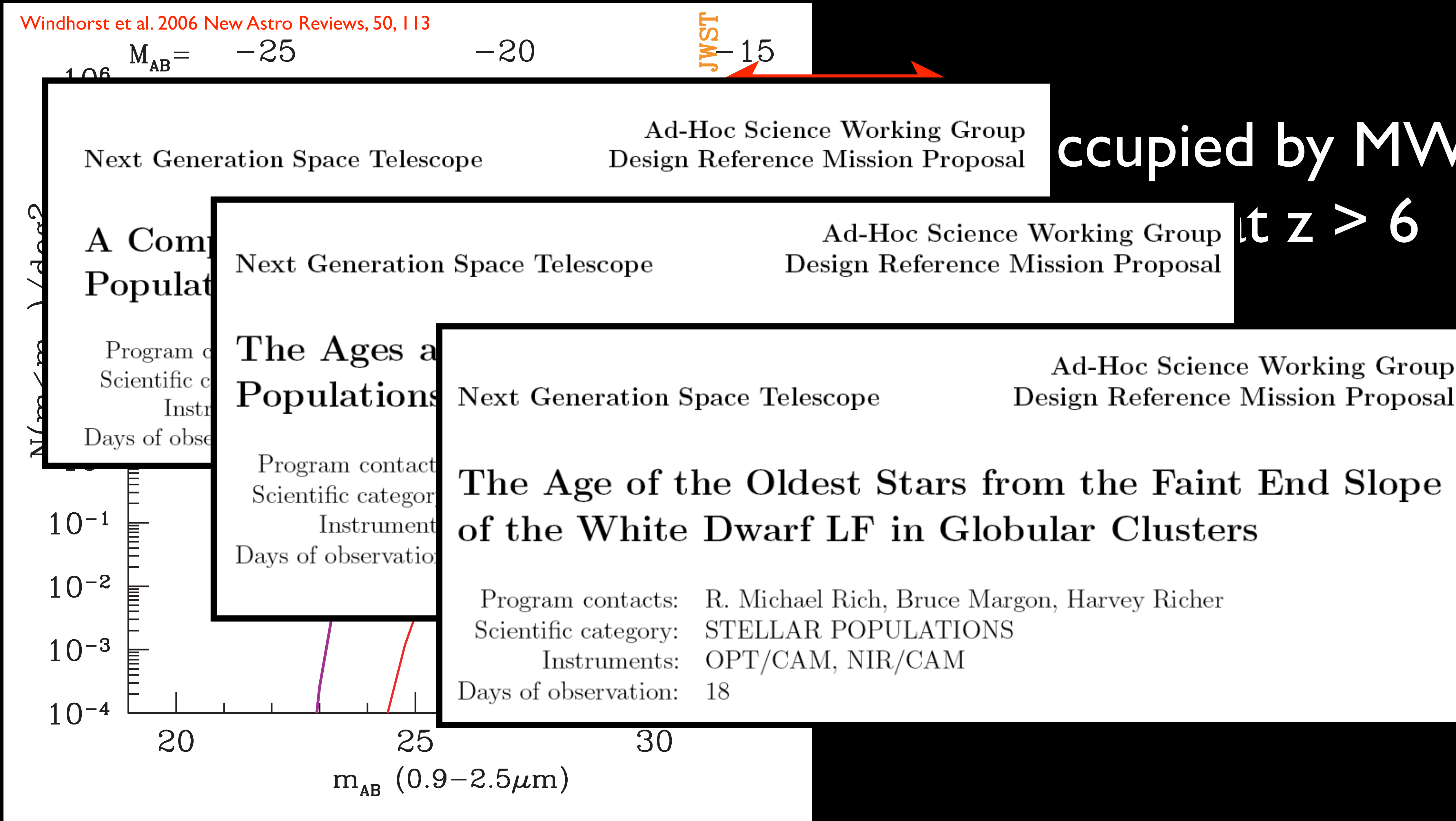
But will JWST see the z > 6 progenitors of the MW?



JWST will provide a lot of information on high-redshift galaxies…
but it may not see the z > 6 progenitors of the Milky Way …
so Galactic Archaeology may reveal information about galaxies that JWST will miss!
That is, "First Light", but not where you think!

Three Questions for Galactic Archaeology

1. Where are the first galaxies today?

   They're right here! We may already have some stars that formed at $z > 10$ in existing samples of metal-poor stars.

2. How can we isolate their surviving stellar populations?

   The best approach is to look in the tightly bound portions of the inner Milky Way halo.

   If chemical evolution works as we think it does, then $z > 6$ stars make up the majority of stars in this region and are relatively unobscured by stars formed and/or accreted later.

3. What might we learn when we do this?

   Is the IMF of the first stellar generations skewed by the CMB?

   Are there chemical abundance patterns that appear only in these distilled high-redshift populations, and if so do they suggest novel types of supernovae?

Perhaps most importantly, the coming revolution in Galactic surveys promises to reveal stars from galaxies that we cannot access any other way.