Uncovering the Accretion History of the Milky Way Using Star Clusters and Dwarf Galaxies

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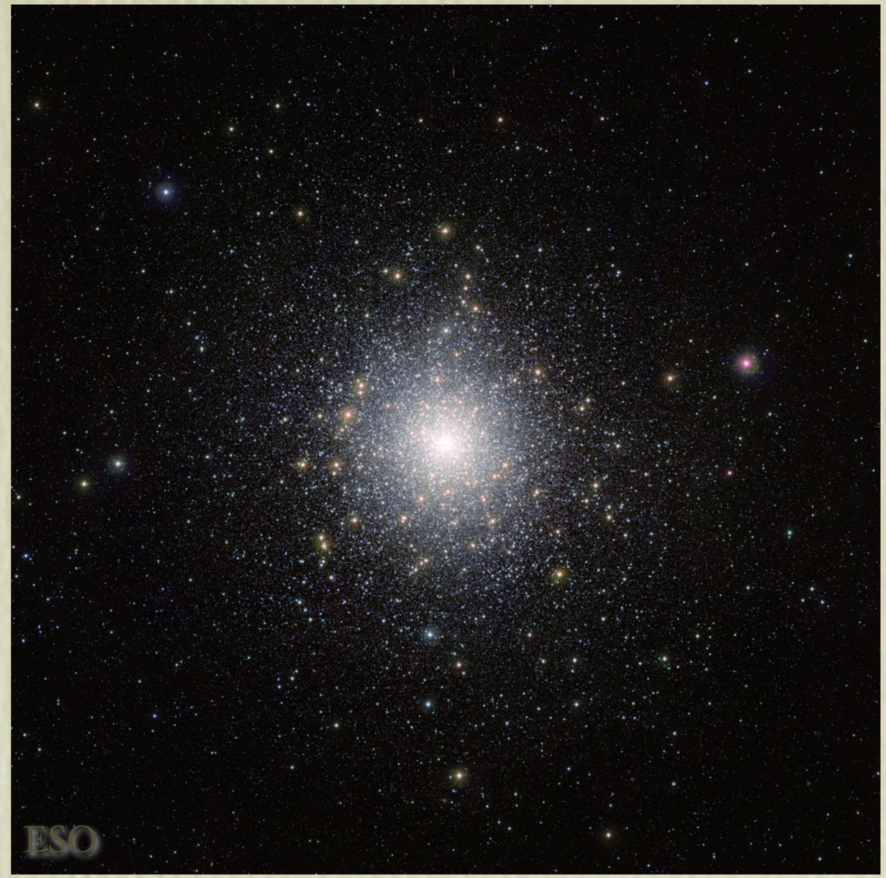
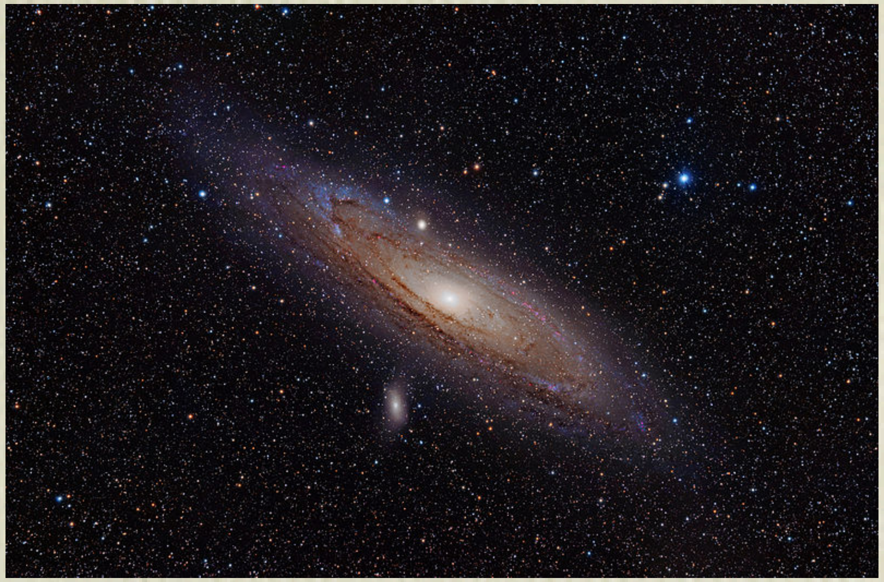
What Can we Learn from Globular Clusters?

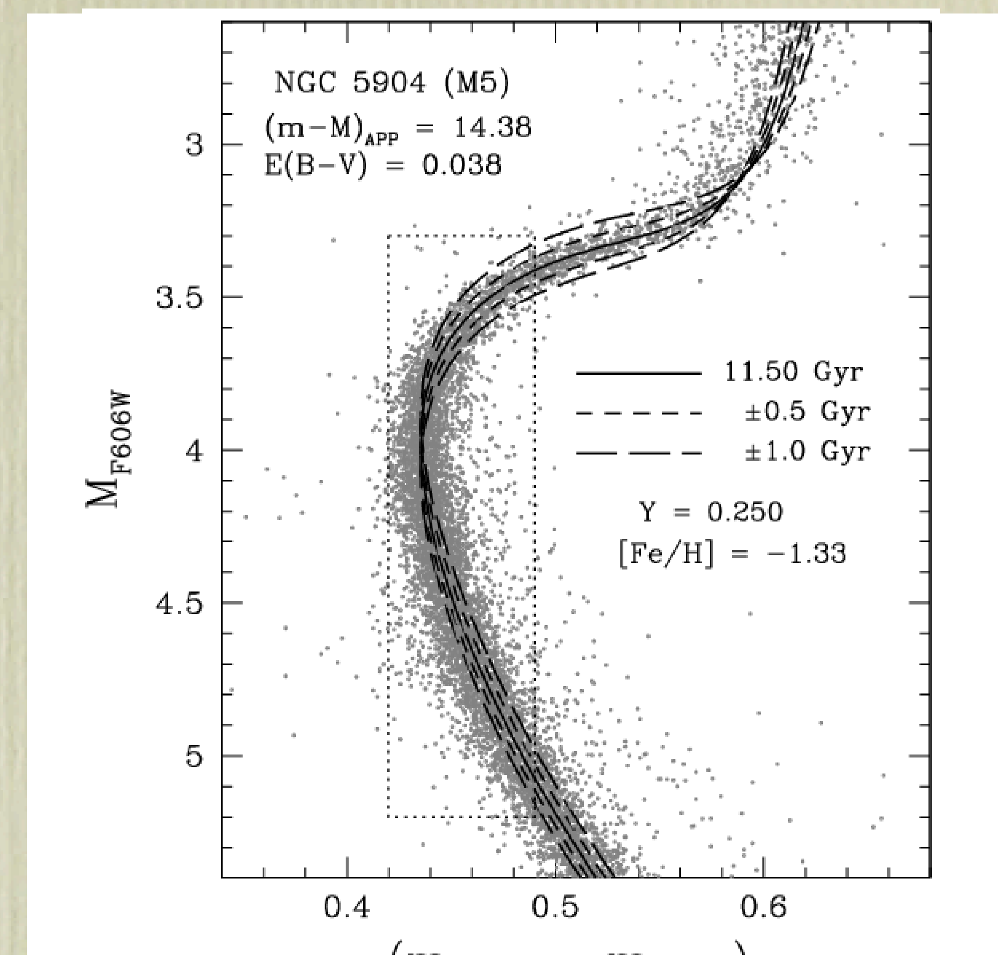
- How GCs form still unclear, but characterizing their age, orbits, metallicities can constrain whether some formed in-situ in the MW or were accreted (e.g., Côté et al. 1999).
- The in-situ GCs can provide insight into the chemical enrichment and peak SF epoch of their host galaxy.
- Similarly, any accreted GCs represent remnants of the hierarchical merger process which built up the host galaxy stellar halo.
- A census of the GC population within a galaxy offers a unique window into both baryonic processes (SF, chemical enrichment) and the dark matter driven accretion history in galaxies of many masses and types



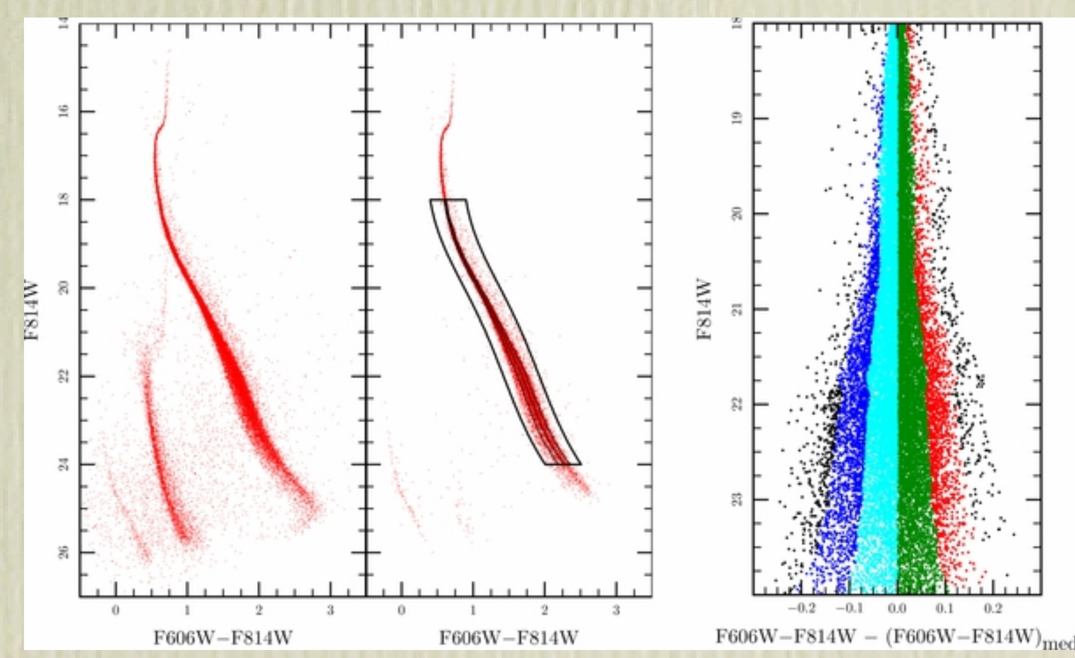


What Can we Learn from Globular Clusters?

- One of the best tools is to look at the GC formation times with an age-metallicity plot
- Large disagreement in the literature over the years as to the relative (let alone absolute) ages of GCs in the MW (e.g., Rosenberg et al. 1999, VandenBerg 2000, Salaris & Weiss 2002, De Angeli et al. 2005)
- Age studies used inhomogeneous photometry, metallicity measurements, variety of techniques...
- However most studies implied that GCs are extremely old with little variation.
- Gold standard arrived with homogenous HST treasury program of GC photometry (PI: Sarajedini)



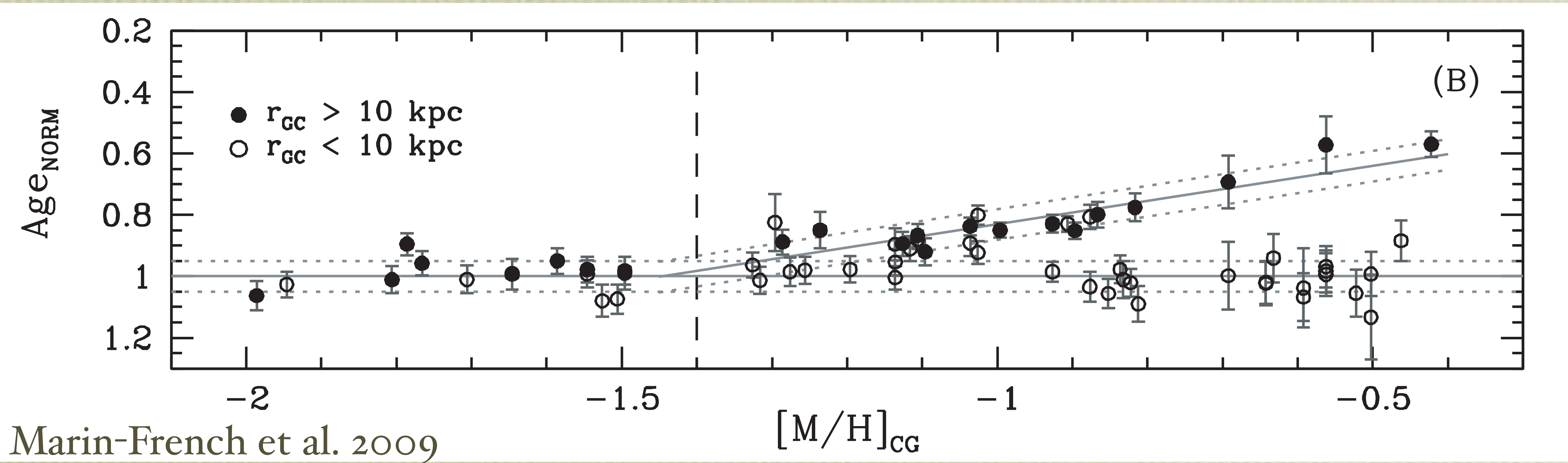
VandenBerg et al. 2013



Richer et al.

Past HST MW GC Age Metallicity Relations

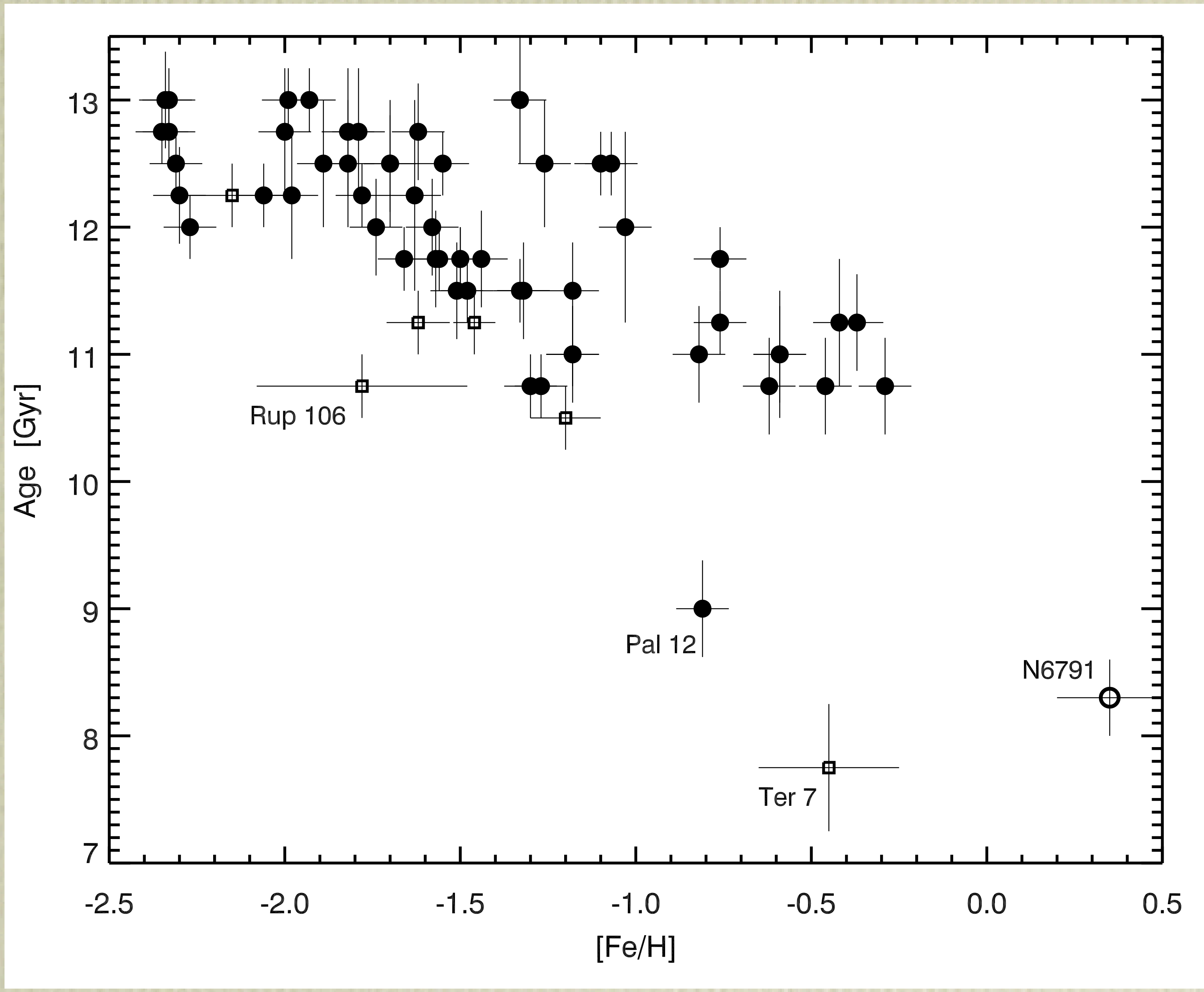
- Marin-French et al. (2009) AMR showed co-eval population of old globular clusters at all metallicities.
- The very small spread in ages (~0.5 Gyr) also implied that GC formation was quite rapid.
- Models to explain this typically invoke reionization to truncate the formation of GCs - but younger GCs associated with the Sgr dSph complicated this (e.g., Beasley et al. 2002).



Marin-French et al. 2009

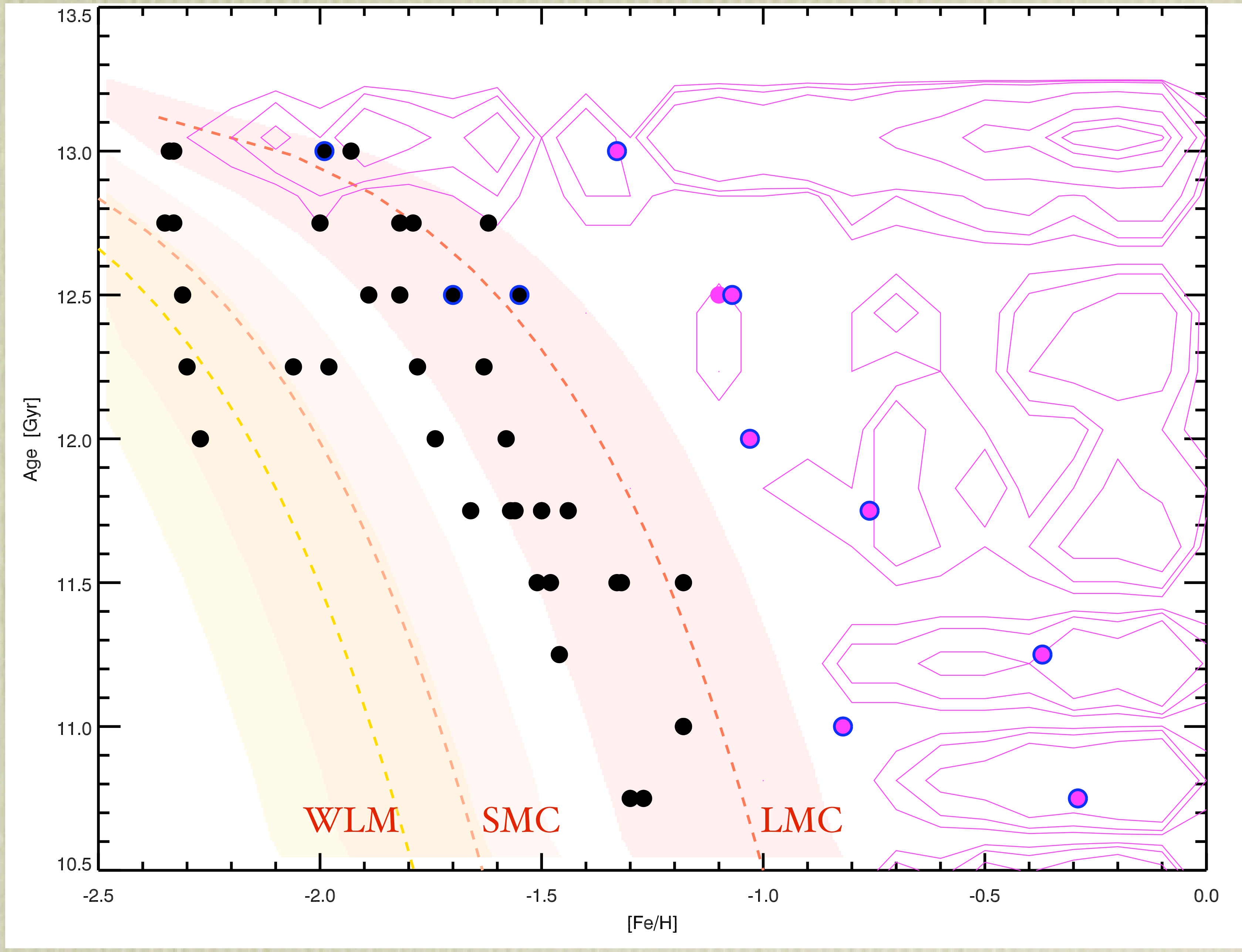
New MW GC Age Metallicity Relation

- New AMR shows two parallel sequences, each with significant age range, but offset at all ages by ~0.6 dex in [Fe/H].
- No longer required to shut off GC formation, and reignite it in preferred environments.
- Likely problematic to have both sequences of GCs form in-situ.



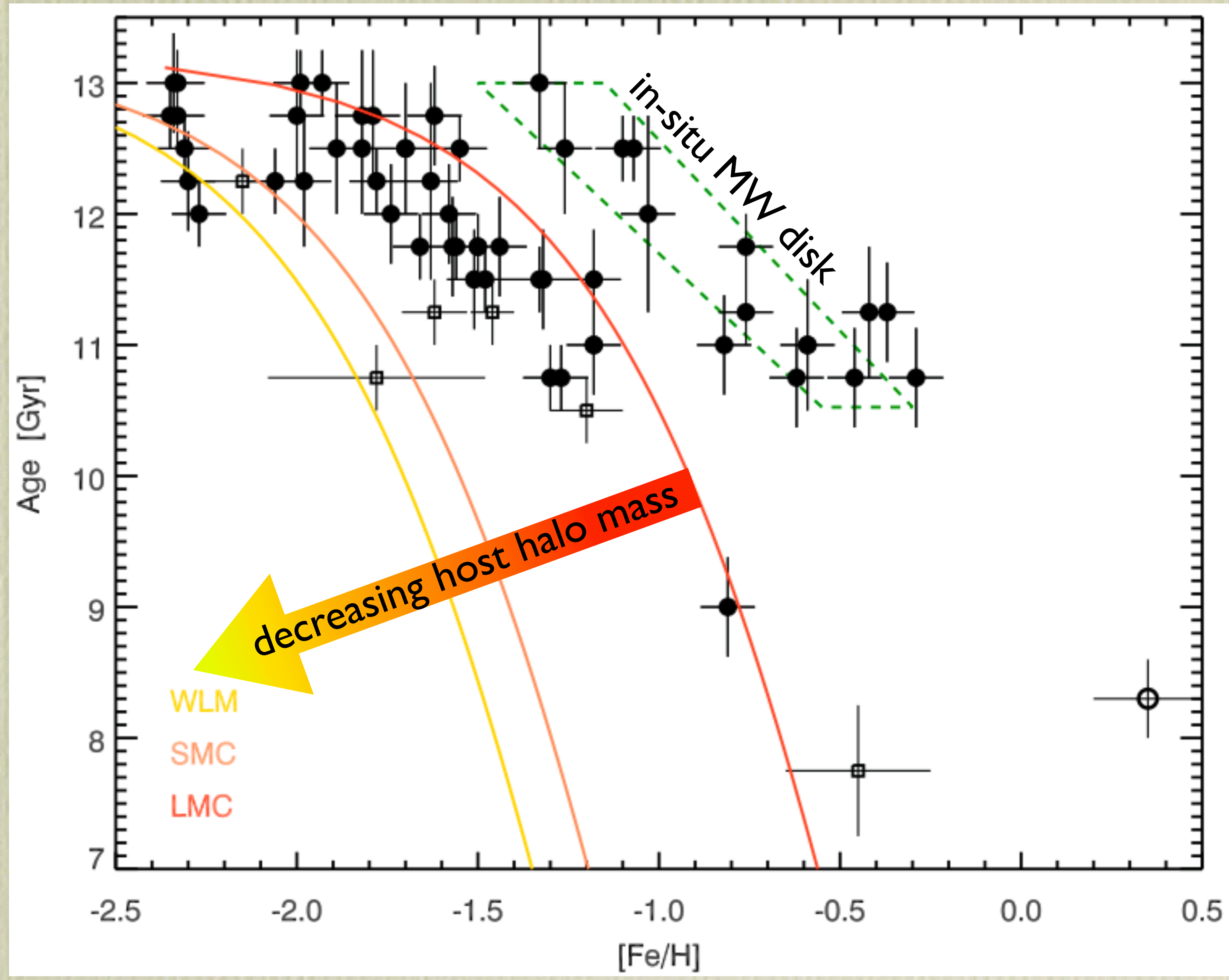
Separating In-situ and Accreted GCs

- Assume stellar density profile and velocity ellipsoid for MW halo and disk components (Juric et al.), determine GC membership via Bayesian inference
- Phase-space data indicates that GCs with disk-like orbits (in-situ) occupy the more metal rich arm, while (accreted) halo GCs the metal poor arm.

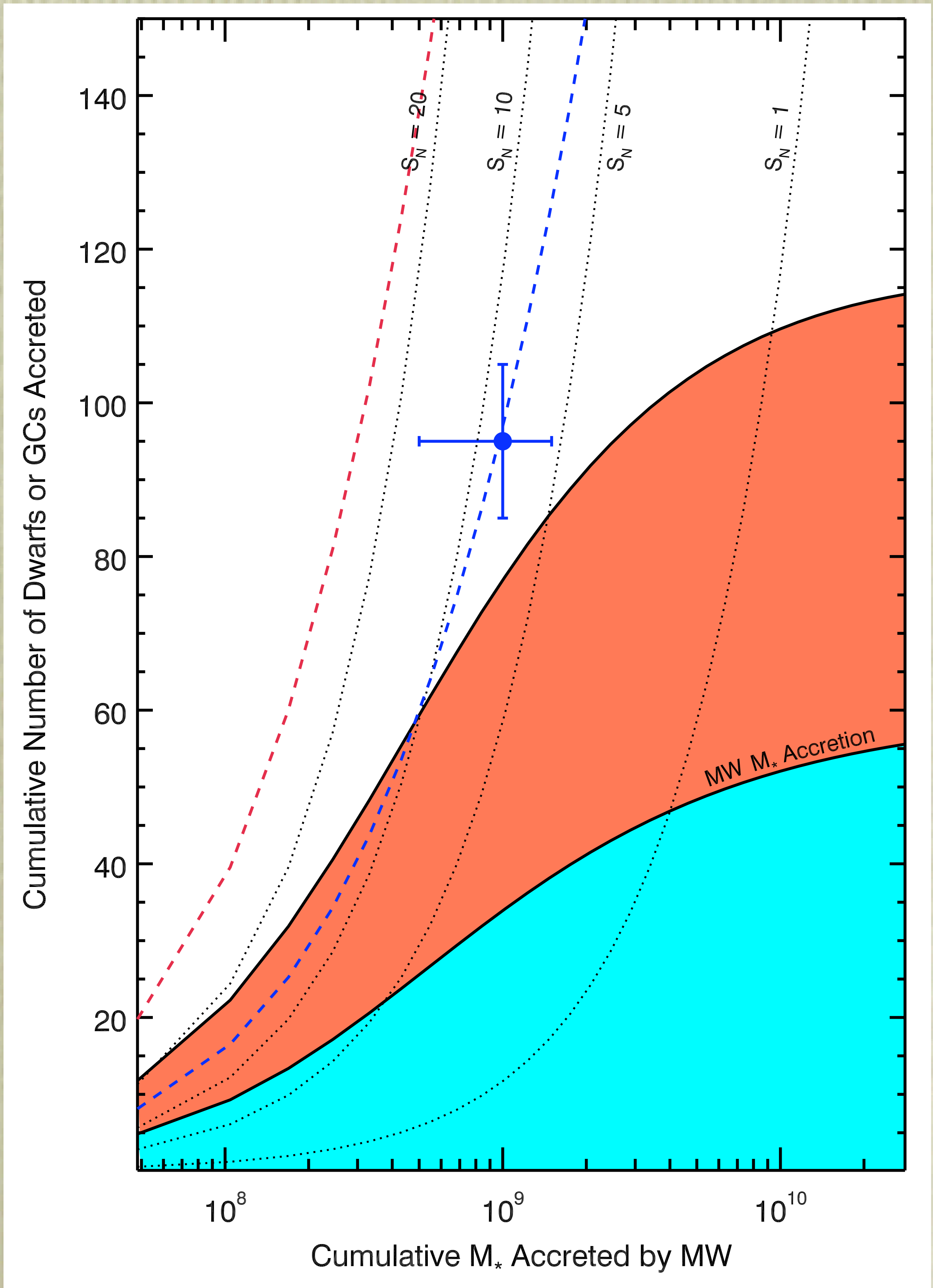


Progenitor Galaxy Masses for Accreted GCs

- Offset of sequences a result of the mass difference of the GC's progenitor (dwarf) galaxies. This effect due to the mass-metallicity relation for galaxies.
- With this picture we can assign each accreted halo GC a progenitor galaxy of a given mass.

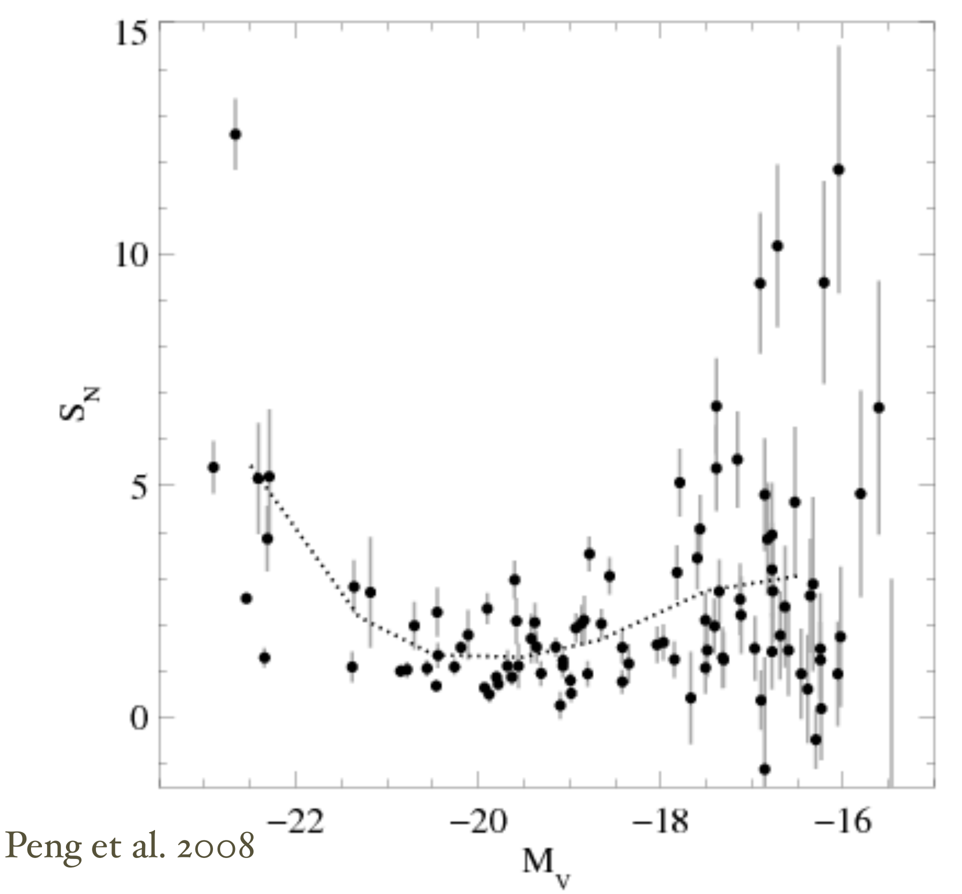


Accretion History for the MW



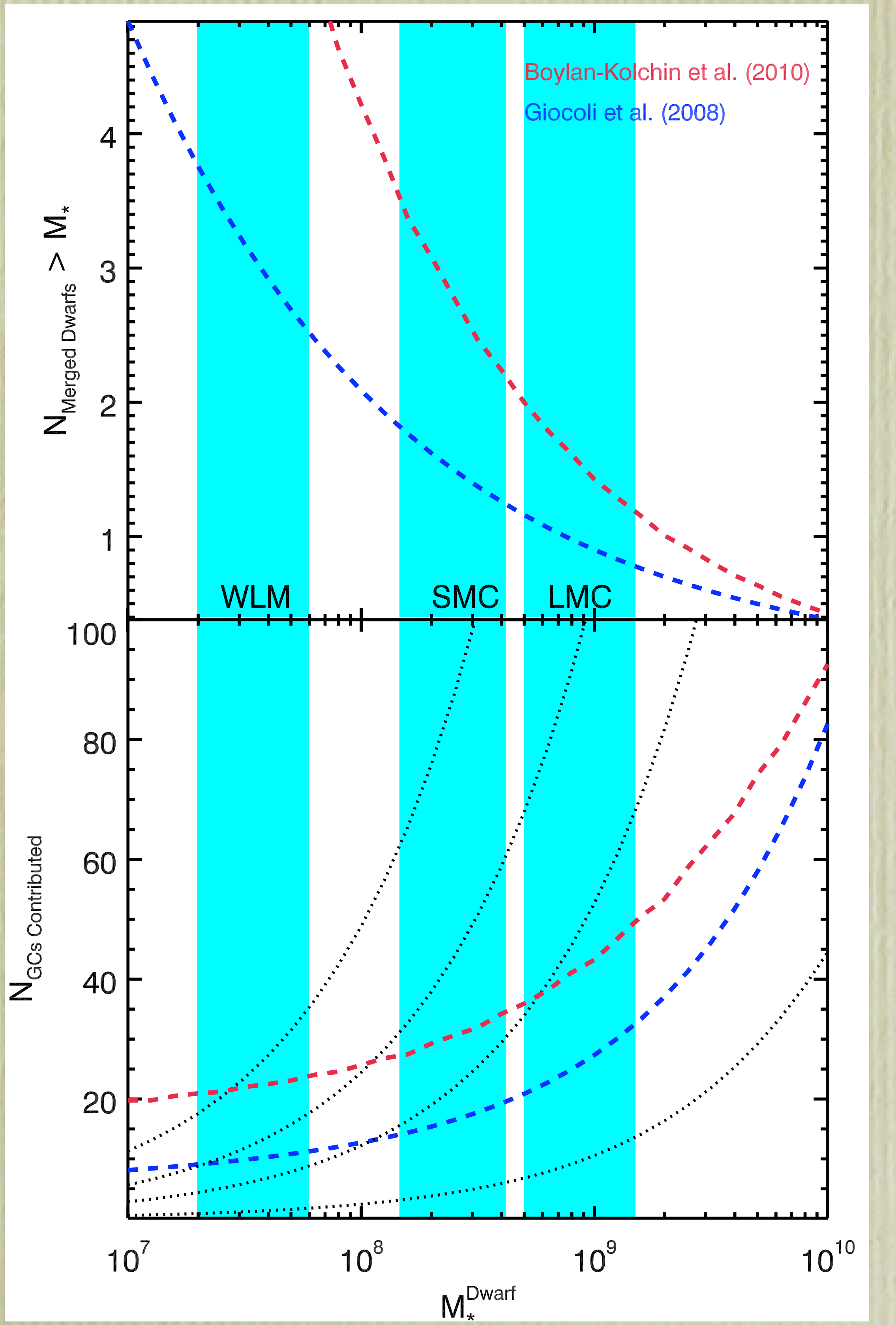
- Using subhalo mass function, stellar-halo mass relation, various specific frequencies, can study whether the MW's stellar halo and GC system can be self-consistently accreted

$$S = N \times 10^{0.4(M_V + 15)},$$



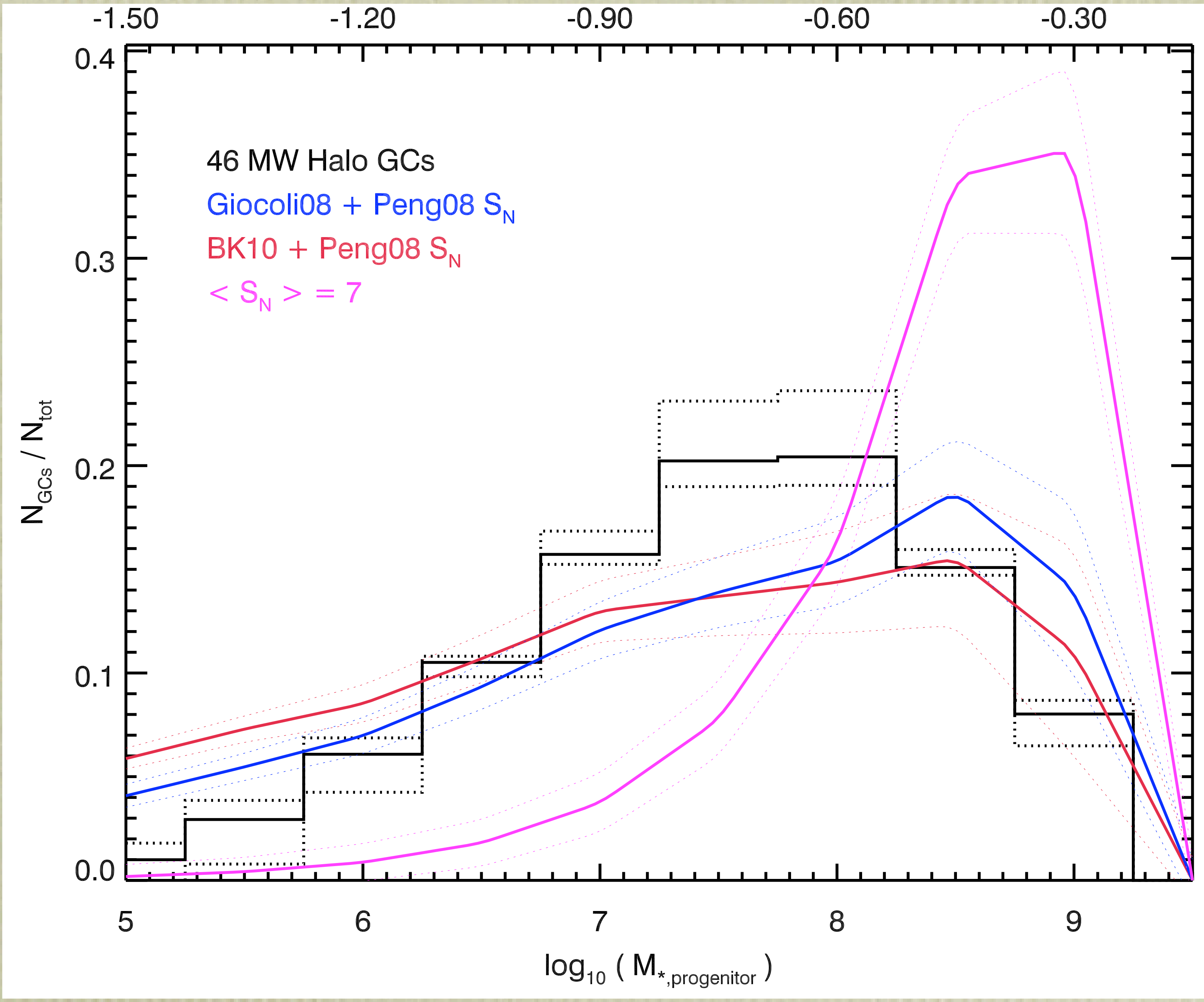
Peng et al. 2008

Constraints on the Subhalo Mass Function



- Want to know not just how many total mergers, but how many of a given mass.
- Which were the most important for contributing mass to the halo? For contibuting GCs? (see also, Forbes & Bridges 2010; Mackey & van den Bergh 2005)
- Expectations from simulations: many more low mass mergers, but these only contribute a few percent of the GCs.

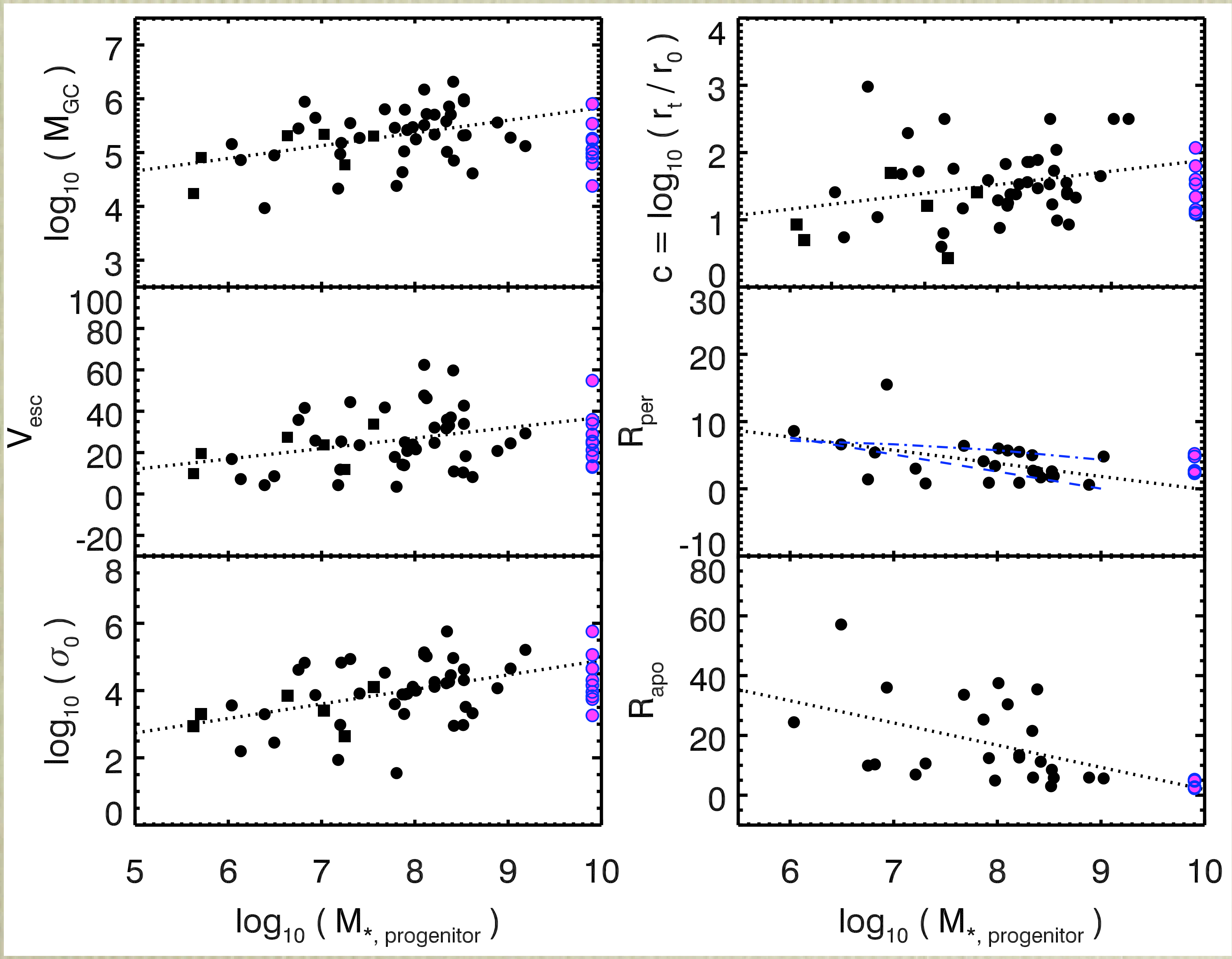
Constraints on the Subhalo Mass Function



$$N_{sig} = \frac{(\Sigma m_{*,progenitor})^2}{\Sigma m_{*,progenitor}^2}.$$

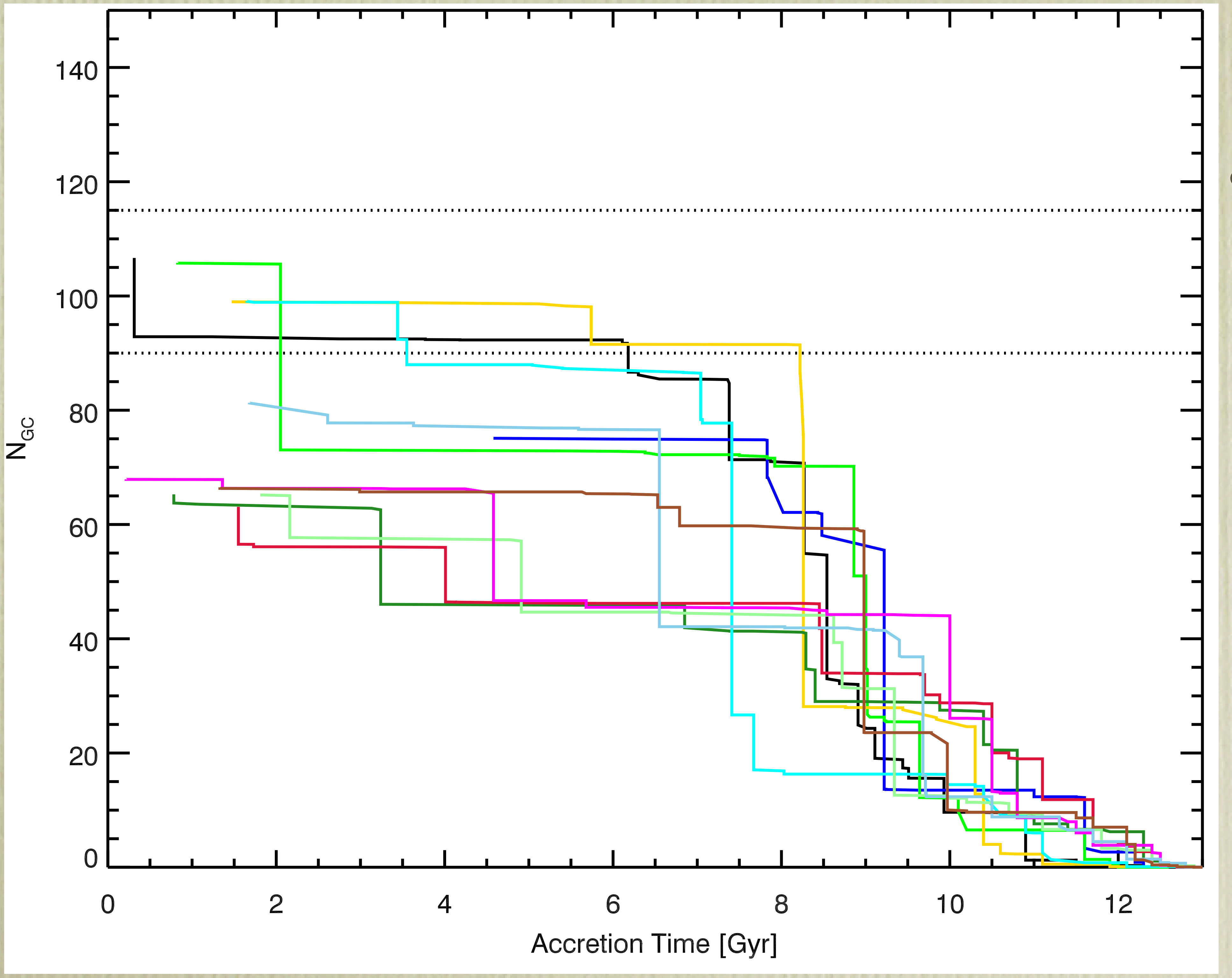
- How do simulations compare with the distribution of progenitor masses implied by the halo GC AMR offsets. Model independent check.
- Excellent agreement with numerical simulations in a differential sense.
- Rules out a constant specific frequency - implies that GC formation efficiency more closely linked to dark matter mass than stellar mass (also implied from different arguments by Georgiev et al., Spitler et al.)

GC Properties & Host Galaxy Mass Correlations



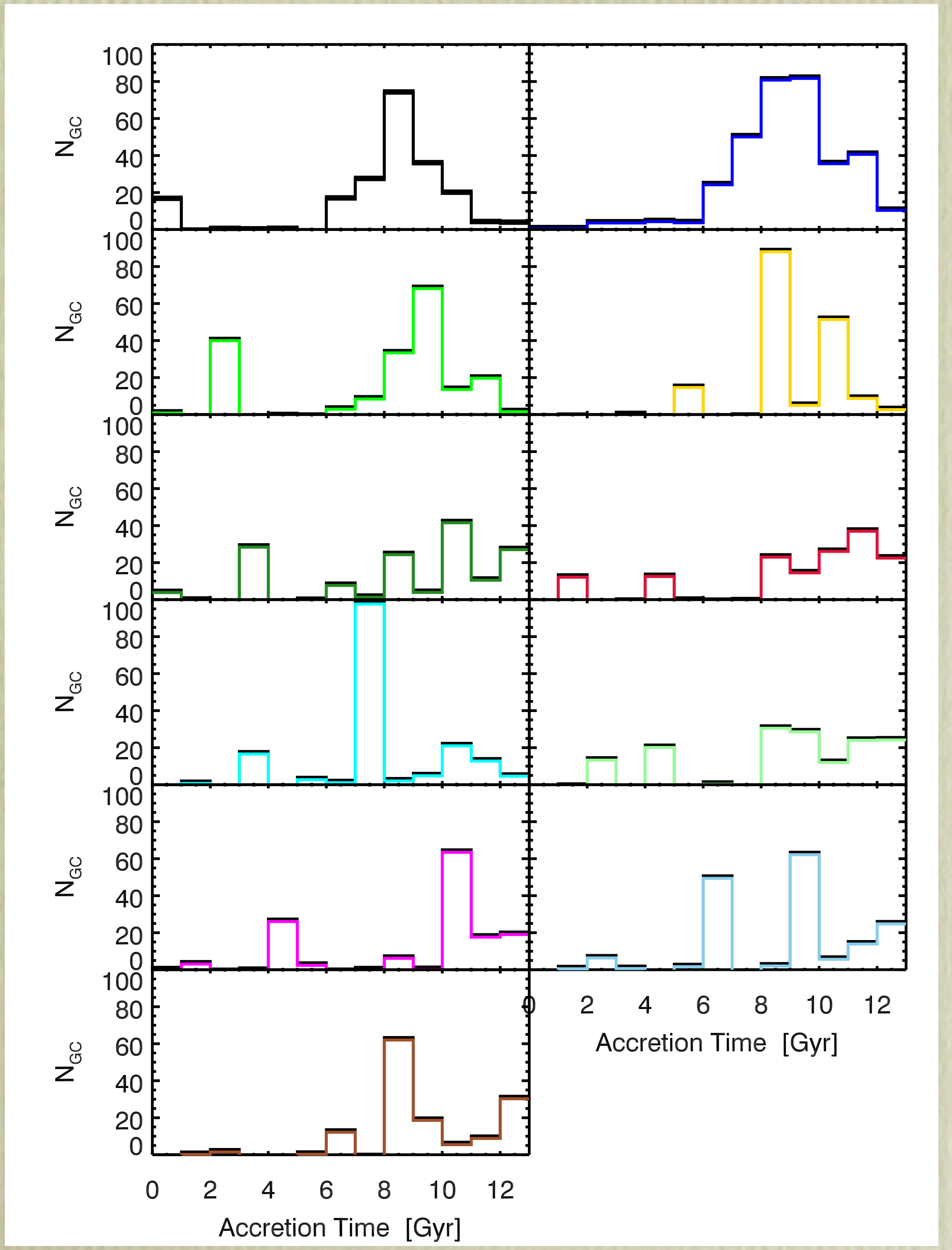
- Orbital properties consistent with dynamical friction operating on GCs which came from highest mass progenitors
- This, and correlations of GC mass/density with the progenitor mass suggests the interpretation of AMR in terms of progenitor host mass may be appropriate. Tests of M_{prog}-M_{GC} correlation?

A Look at the Assembly of a Simulated MW



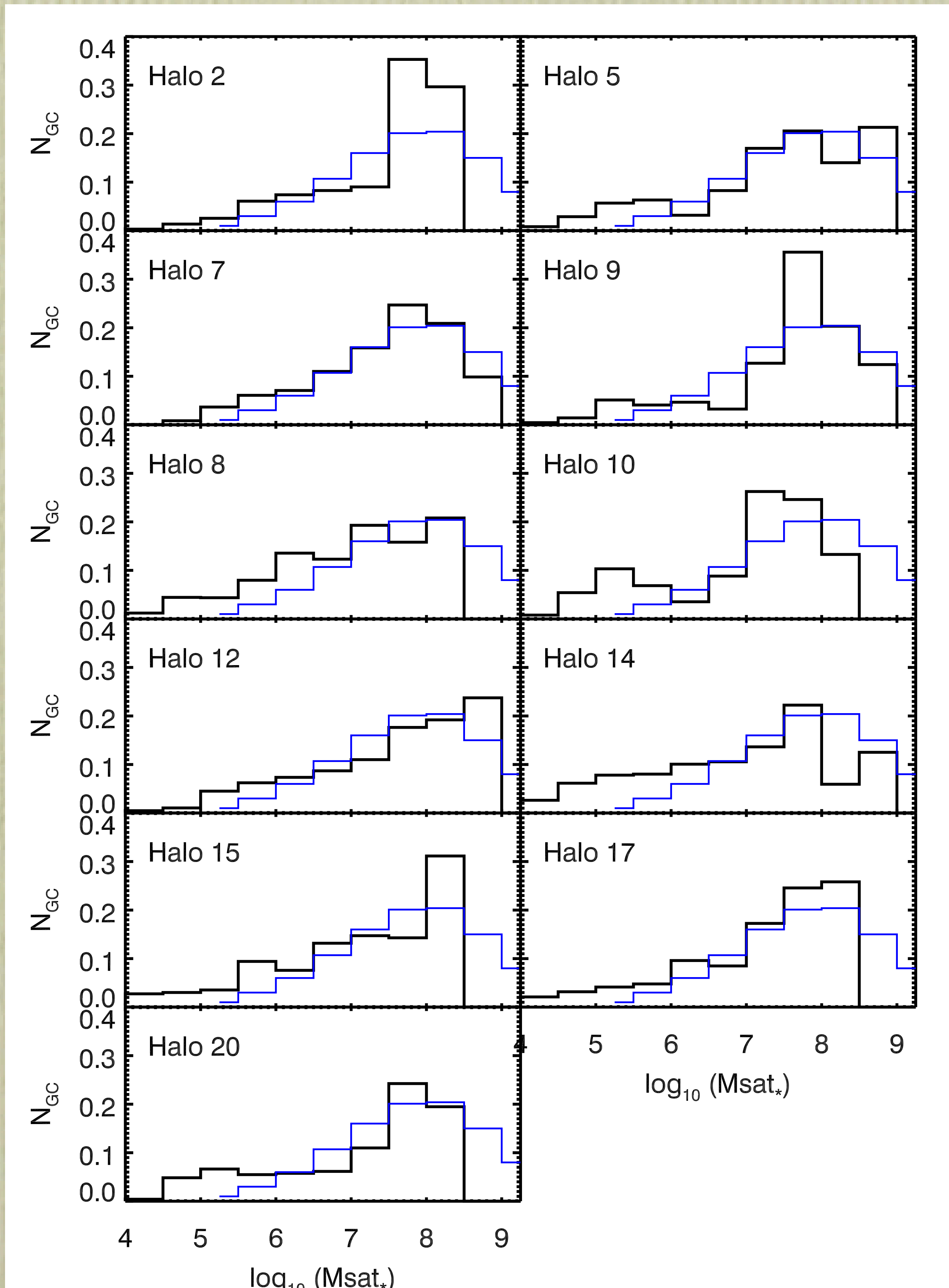
- Using the Bullock & Johnston (2005) and Font et al. (2008) simulations, can we identify a simulated MW with the accretion history most similar to what we infer based on the MW GCs?

A Look at the Assembly of a Simulated MW



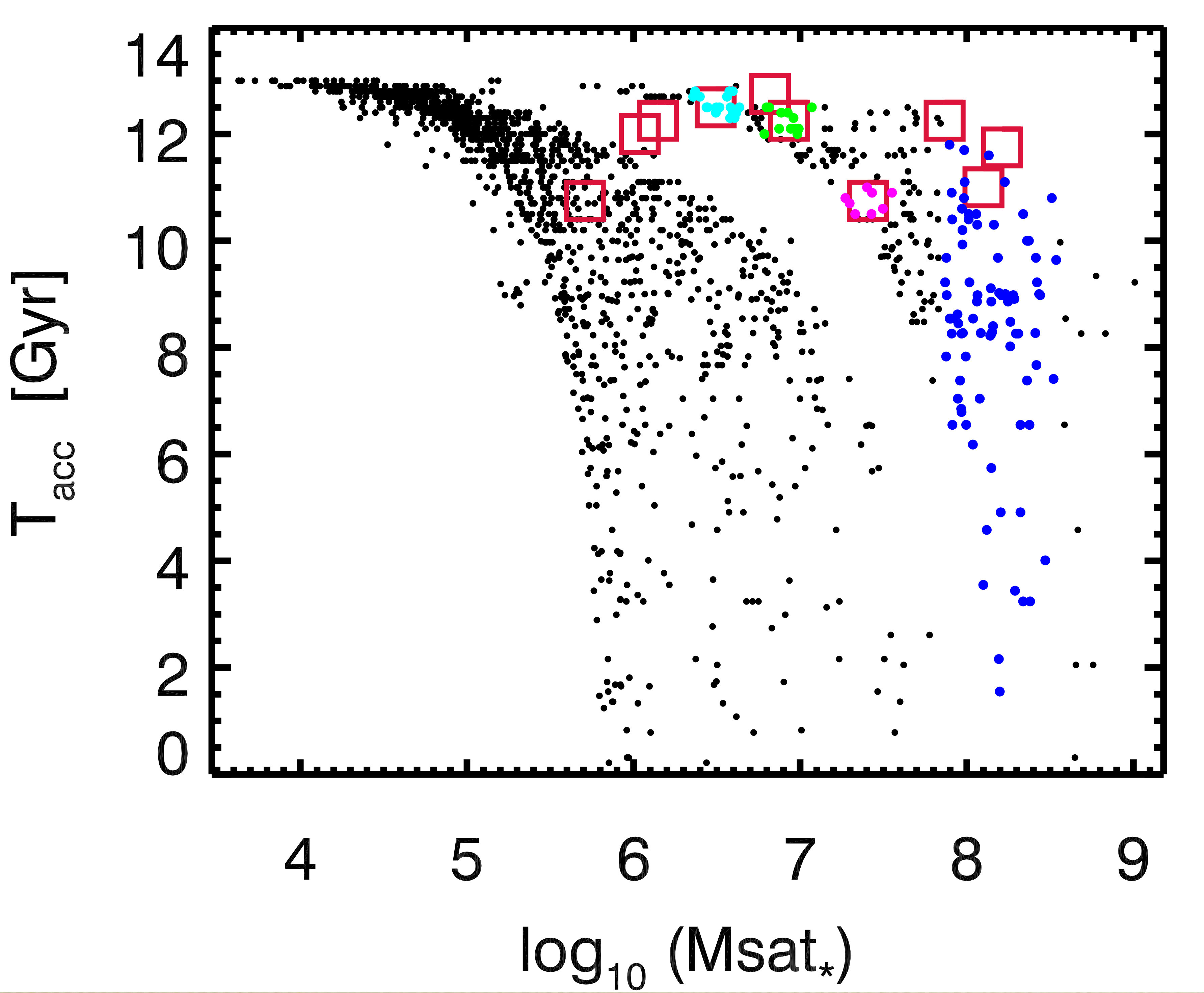
- Can use the Bullock & Johnston (2005) and Font et al. (2008) n-body+SAM simulations of 11 realizations of the MWs hierarchical buildup.
- Applying the same specific frequency arguments, can identify a simulated MW with the accretion history most similar to what we infer based on the MW GCs?

A Look at the Assembly of a Simulated MW



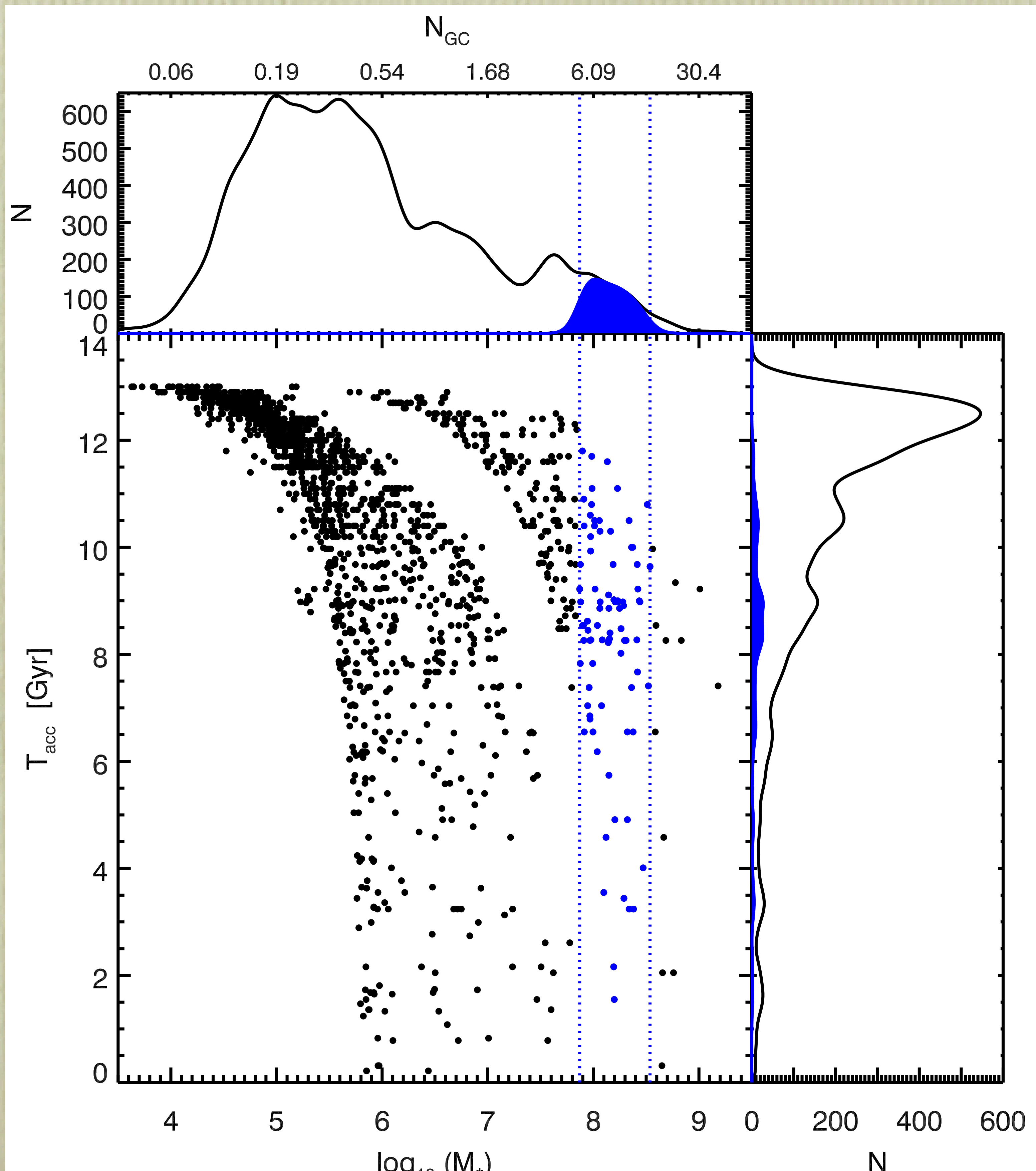
- Several halos do show similar distributions of accreted subhalo masses.
- While they might be the 'correct' mass distribution, are the subhalos merging at the correct time?
- How can we test this?

Observational Tests of the Accretion Time?



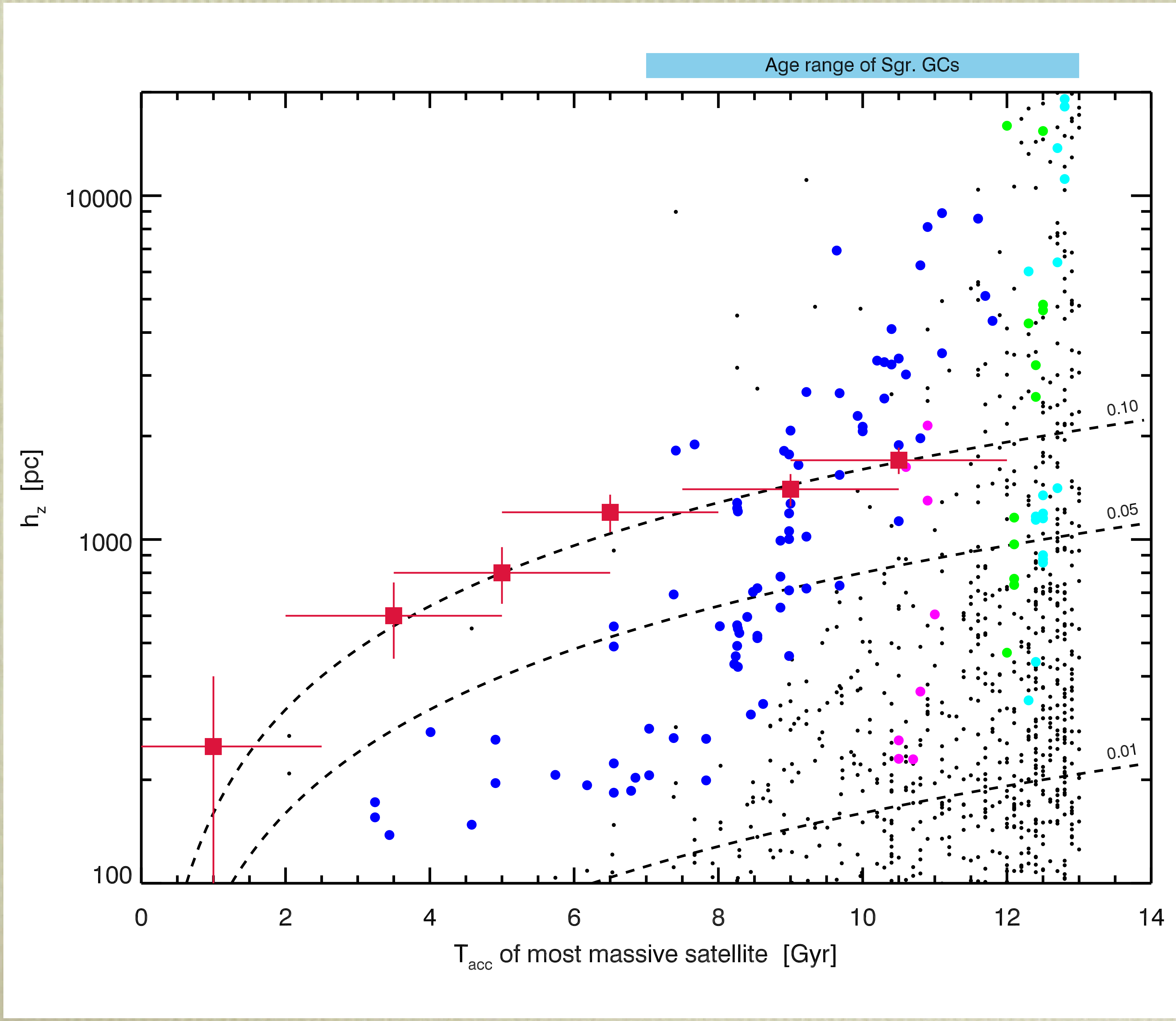
- **Method 1:** Assuming that the accreted GCs couldn't have formed after accretion to the MW, some GCs have ages and progenitor masses which constrain their accretion time.
- e.g., if a GC is 12.5 Gyrs old, it must have come from a satellite which was accreted later than that (12.0 Gyrs ago for example)

Observational Tests of the Accretion Time?



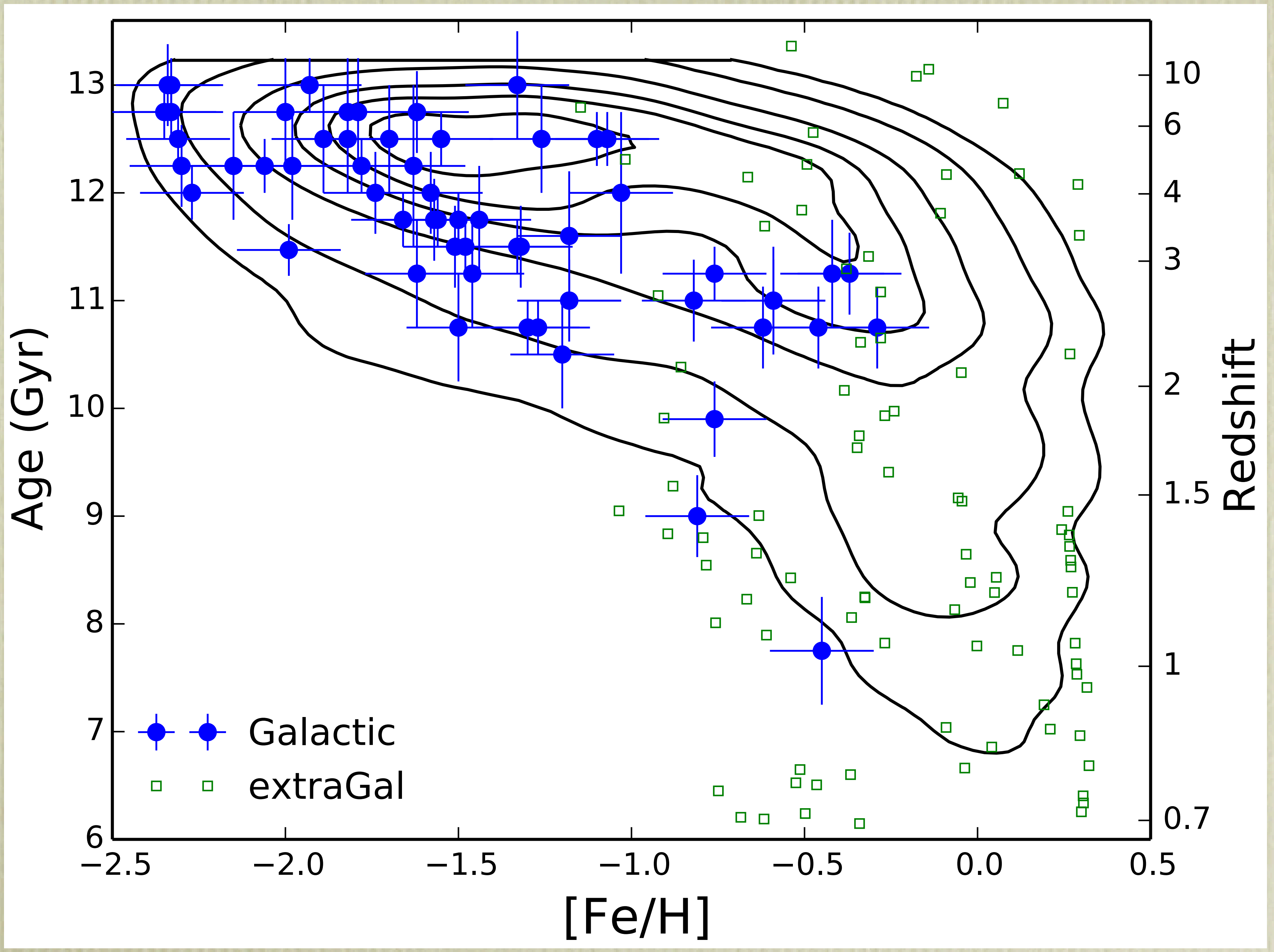
- **Method 2:** Use the photometrically constrained mass of the Sagittarius progenitor (i.e., Niederste-Ostholt et al. 2012) to tag similar subhalos in the simulations. See what the typical accretion times were for the likely 'Sgr.' subhalos.

Observational Tests of the Accretion Time?



- Using disk scale heights for different mono-age populations (Bovy et al., Stinson et al. 2013), and analytic disk heating prescriptions (Benson et al. 2004, Helmi et al. 2011), can ask if the candidate Sgr. subhalos would have been too destructive to the MW disk

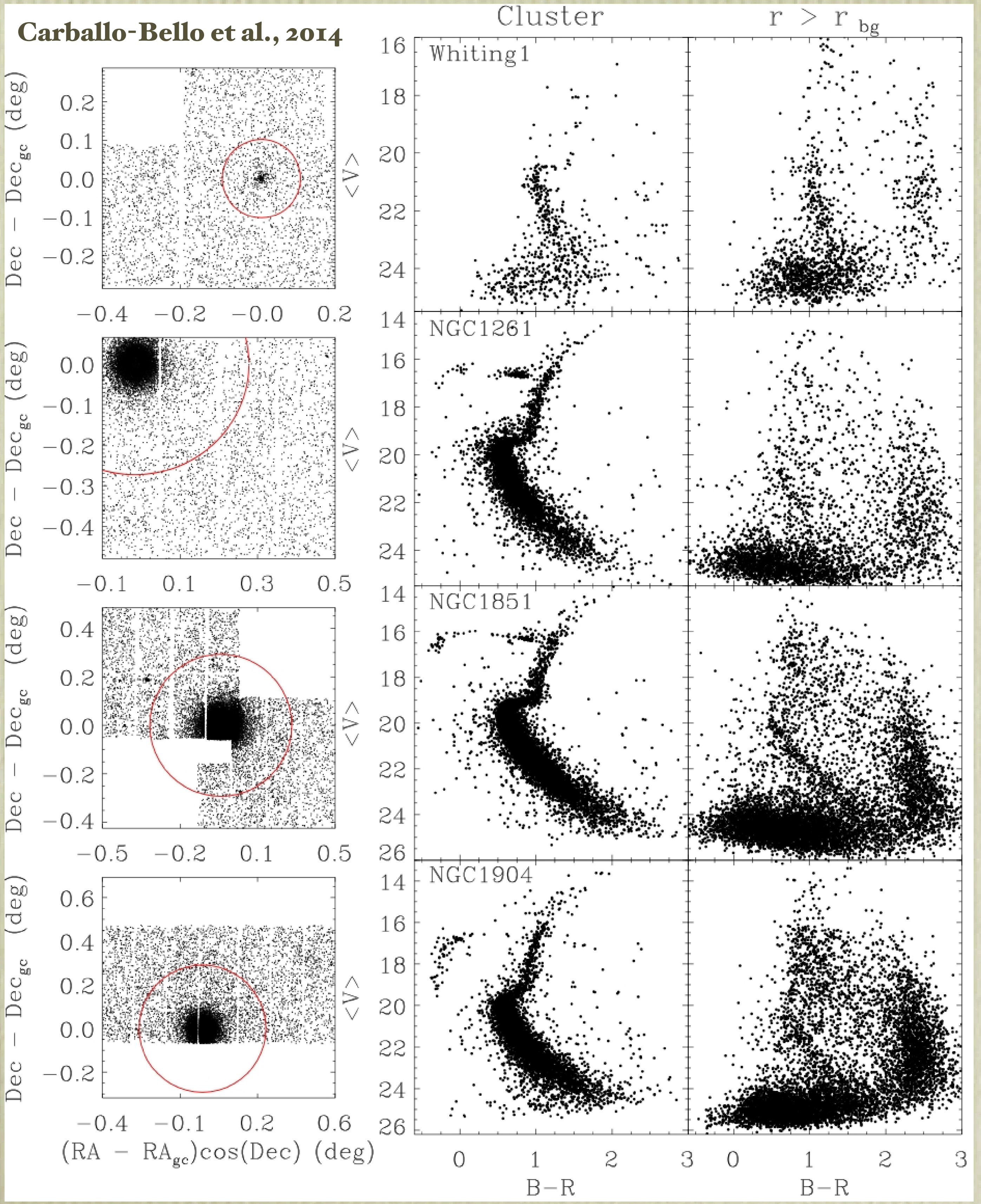
Observational Tests of the Accretion Time?



- Further insight possible by comparing with semi-analytic models
- Additional constraints from more massive galaxies, will help clarify the trends with host galaxy mass.

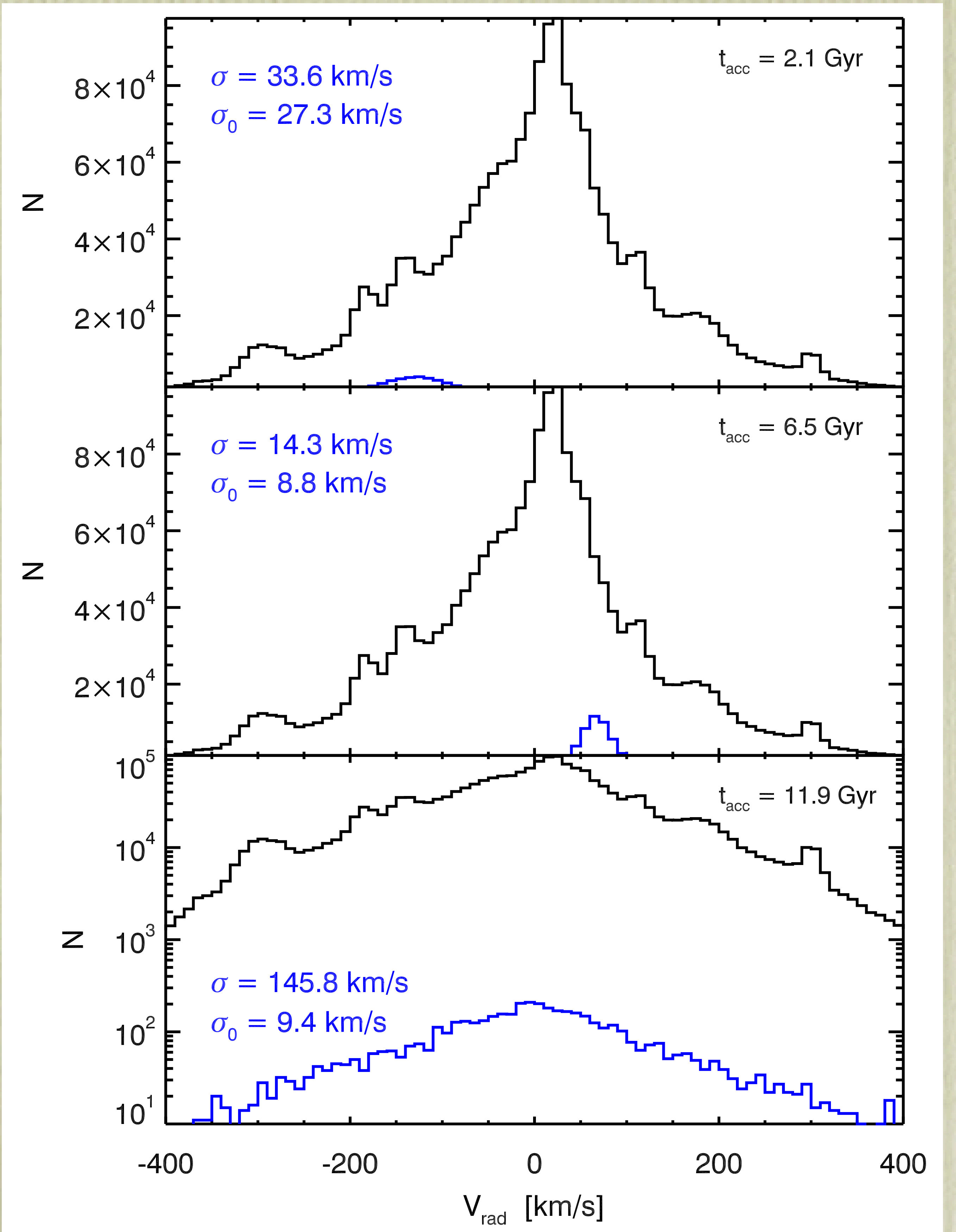
Li & Gnedin (2014)

Observational Tests of the Accretion Time?

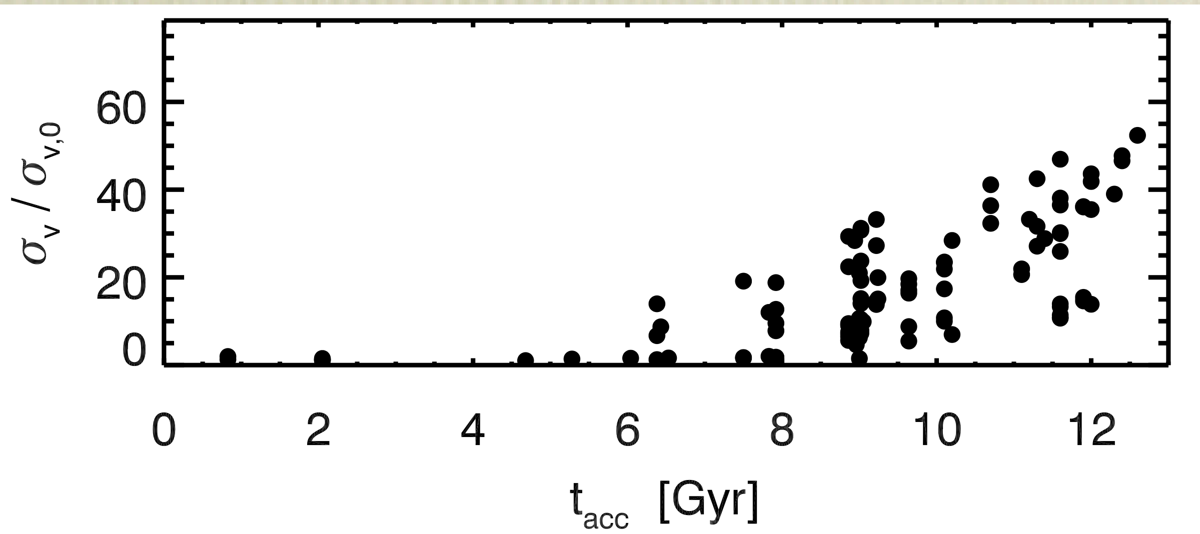


- Can start to apply this to observational constraints of outer halo GCs and extra-tidal GC stars. Carballo-Bello et al. 2014, and other surveys show that extra-tidal debris is sometimes not detected, even to low surface brightness limits.
- Is this consistent with CDM halo assembly?

Longevity of Accretion Signatures



- What are the **mass** regimes, and **accretion times** where we expect satellites to be dispersed, or coherent in position? velocity? phase space?
- Over time, dynamical mixing can wash out LOS observational signature for old (> 6 Gyr) events.



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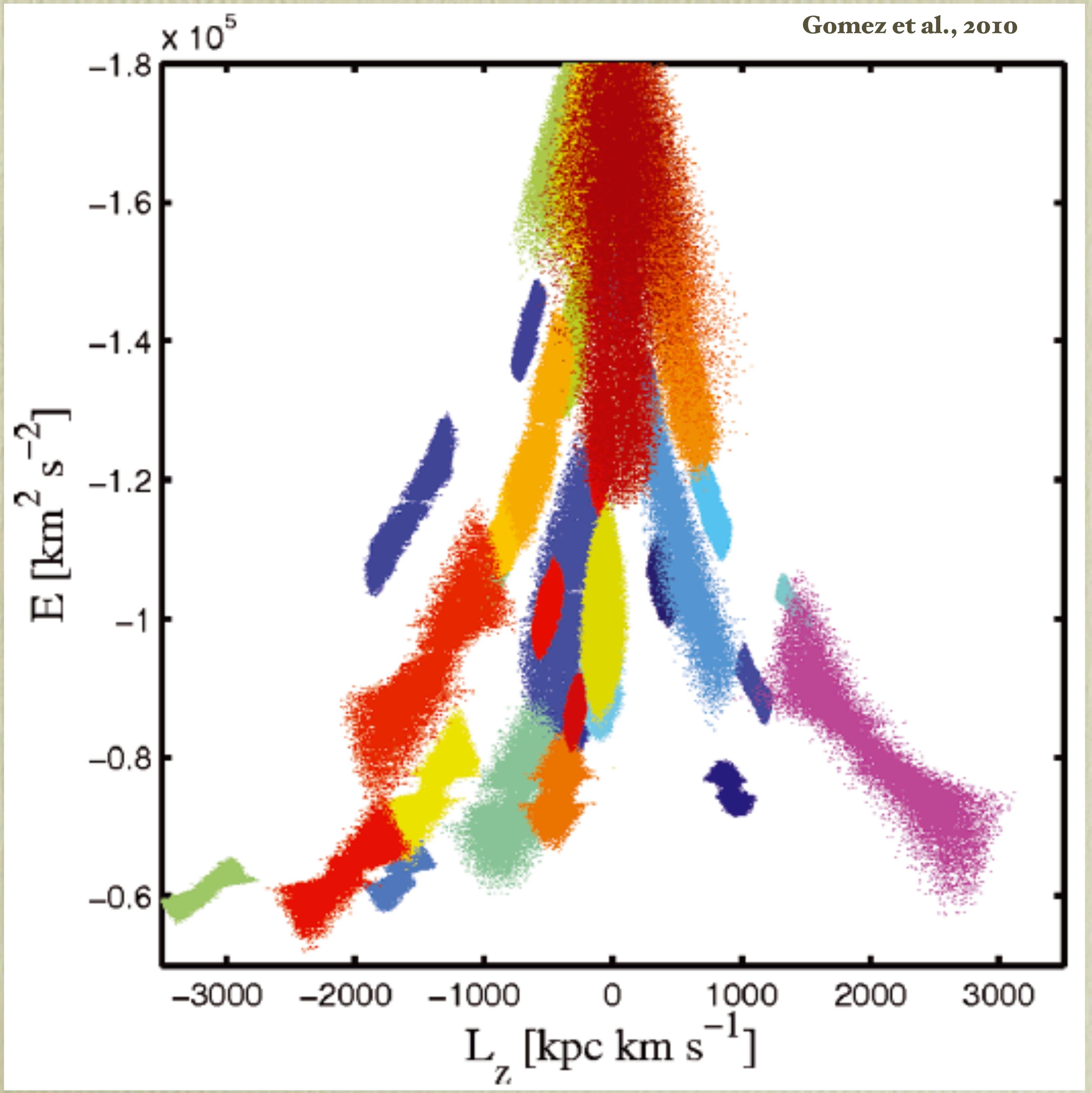


- With GAIA, possible to use full 6-D phase space information to construct integrals of motion
- These are conserved quantities and therefore subhalos should maintain coherence in this parameter space.
- Can be powerful when coupled with unique chemical tracers.

Summary

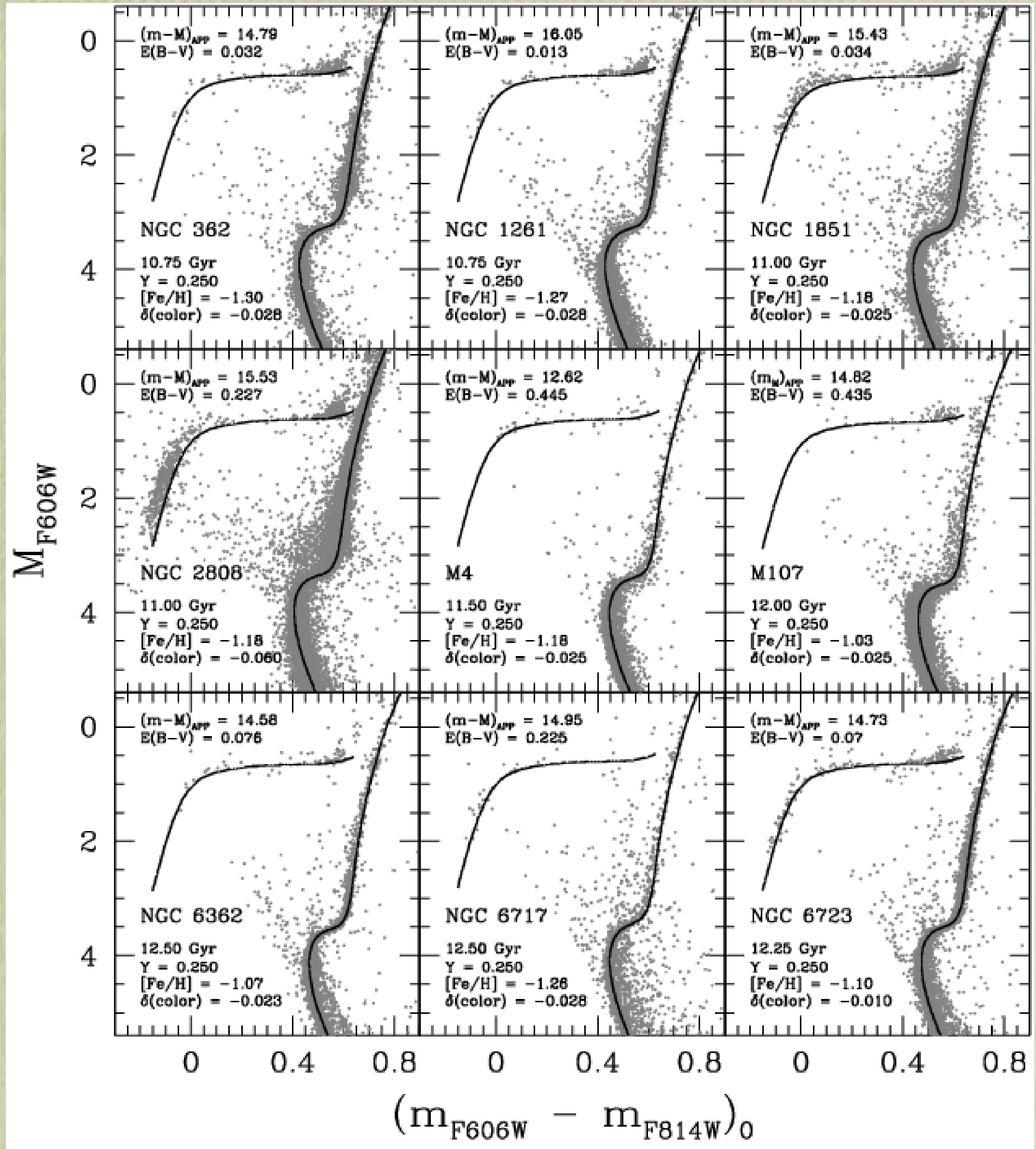
- New age dating analysis has revealed GC populations in the MW with significant age ranges - relax assumption that all GCs are old and coeval.
- Bifurcated AMR and kinematic information allow for separation into accreted/in-situ GCs. Age spreads and metallicity offset requires accretion origin for the more metal poor sequence from dwarf galaxies.
- Begin to constrain the total number, and number by mass of dwarfs that merged with the MW and compare to simulations of galaxy assembly.
- Correlations between progenitor galaxy mass and GC properties may shed light on GC formation mechanisms.
- Interpretive picture applied to Sag. and N-body simulations suggests it could have been too destructive to MW disk if it merged > 7 Gyrs ago.
- Next steps - use analytic merger histories to apply this to MW (with additional stellar stream info), M31, more distant galaxies.
- Need joint kinematic/chemical analysis of data and SAM+n-body to recover information on the oldest merger events.

Age Determinations of GCs

- Compile spectroscopic metallicities, higher order elemental abundances together with distance moduli, and reddening estimates.
- These allow you to fit isochrones to GCs to explore age-dependent morphological portions of the colour-magnitude diagram
- Not so simple... *almost* every portion of the CMD varies with age, metallicity, elemental-abundances, Helium, and colour-temperature relations.
- In addition the choice of stellar evolutionary model will influence your determination. Model ingredients can differ and impact the isochrone morphology - most importantly the inclusion of metals diffusion, convective mixing treatment, radiative levitation, atmospheric boundary conditions, even interpolation methods from the theoretical to observed planes.

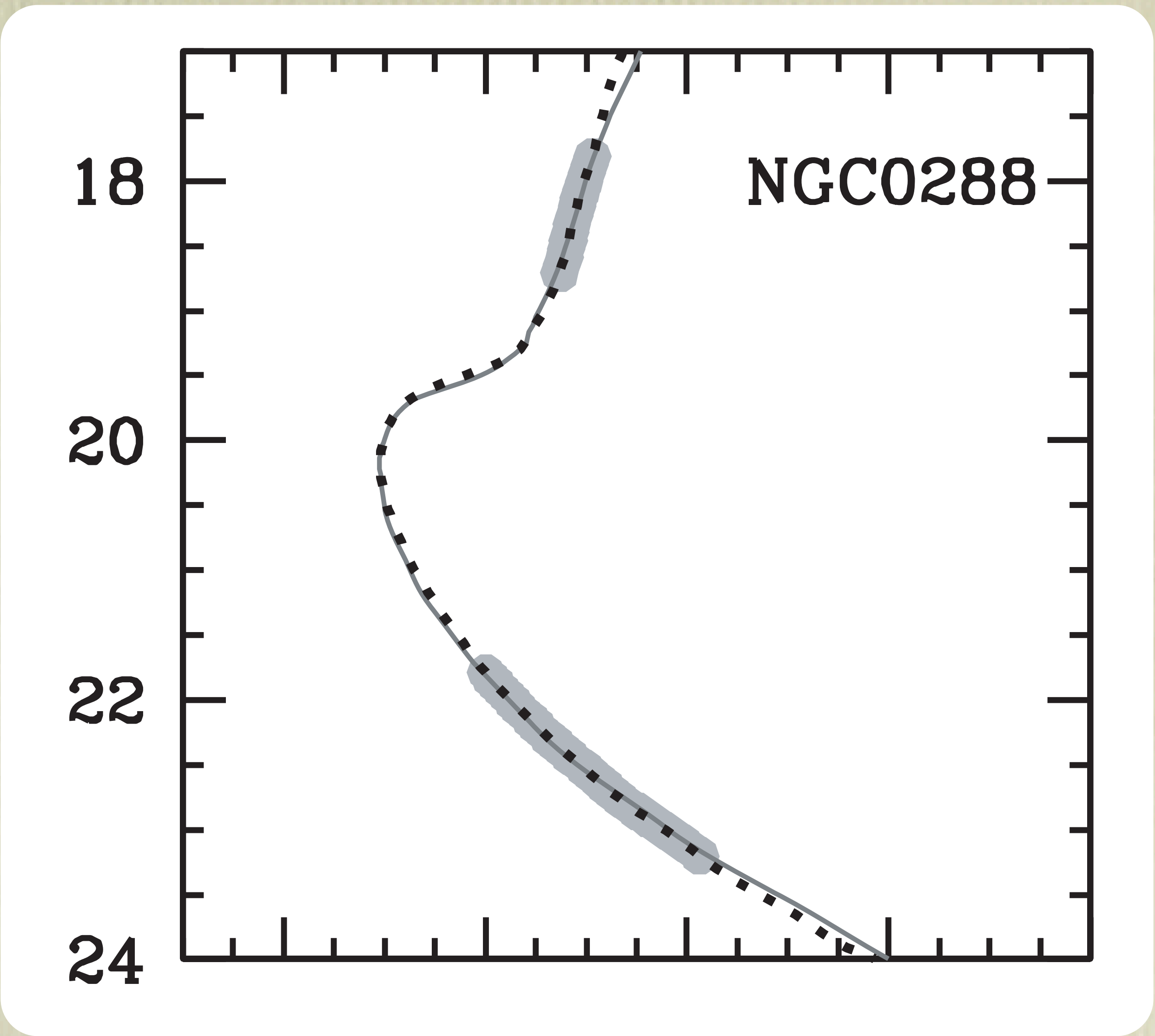
Age Determinations of GCs

- What you want...
- Deep colour magnitude diagram (reflects the current luminosity and temperature of the star, i.e. its evolutionary state)
- Isochrone (describes the evolutionary position for stars of different mass at a common age and metallicity)



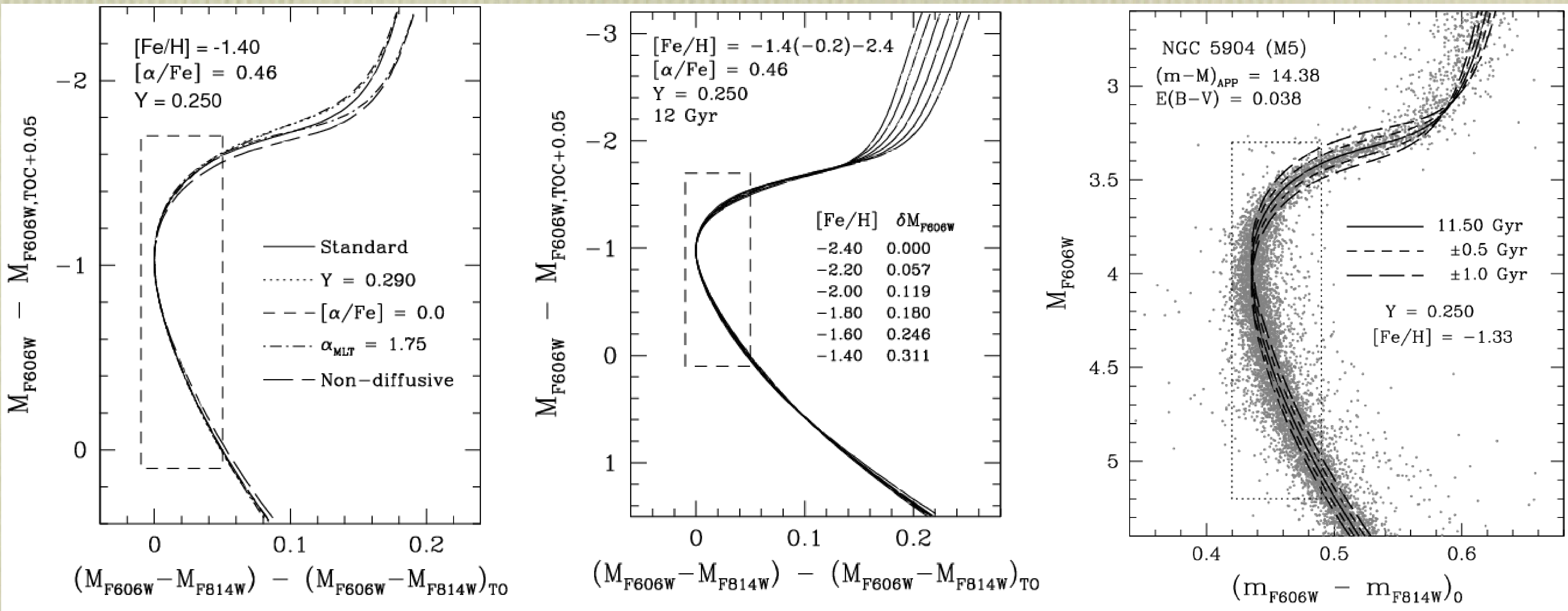
Relative MS Fitting Method

- How to get it...?
- Marin-French et al. presented the relative MS Fitting method in their large analysis of the HST treasury photometry of MW GCs.
- Advantage is that it is distant independent, but relies on matching GCs at the lower MS and RGB.
- These features have a dependence on cluster [Fe/H], alpha-elements, treatment of convection, colour-temperature relations...
- Authors removed metallicity dependence by linking clusters of similar metallicity. Fine until [Fe/H] scale changes...



Then use difference in MSTO magnitude as proxy for age. However the magnitude is sometimes also poorly defined as the TO can be nearly vertical

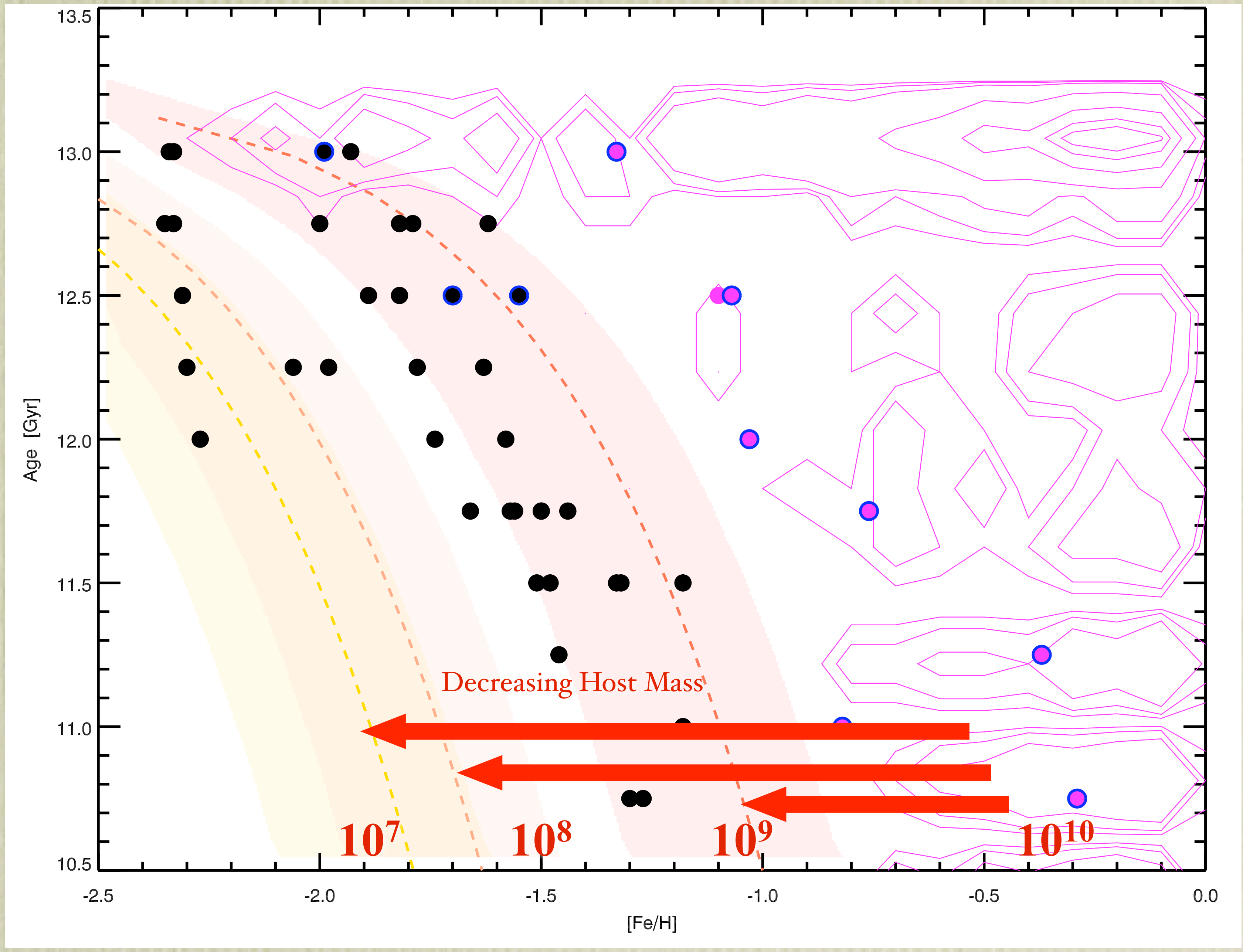
New Age Derivations



- Use MSTO colour as anchor point - morphology around turnoff independent of age, metallicity, alpha abundance, mixing/diffusive treatments
- SGB fitting easily yields best fit age
- Errors not any more precise, but robust to systematics.

Progenitor Galaxy Masses for Accreted GCs

- Offset of sequences a result of the mass difference of the GC's progenitor (dwarf) galaxies. This effect due to the mass-metallicity relation for galaxies.
- With this picture we can assign each accreted halo GC a progenitor galaxy of a given mass.



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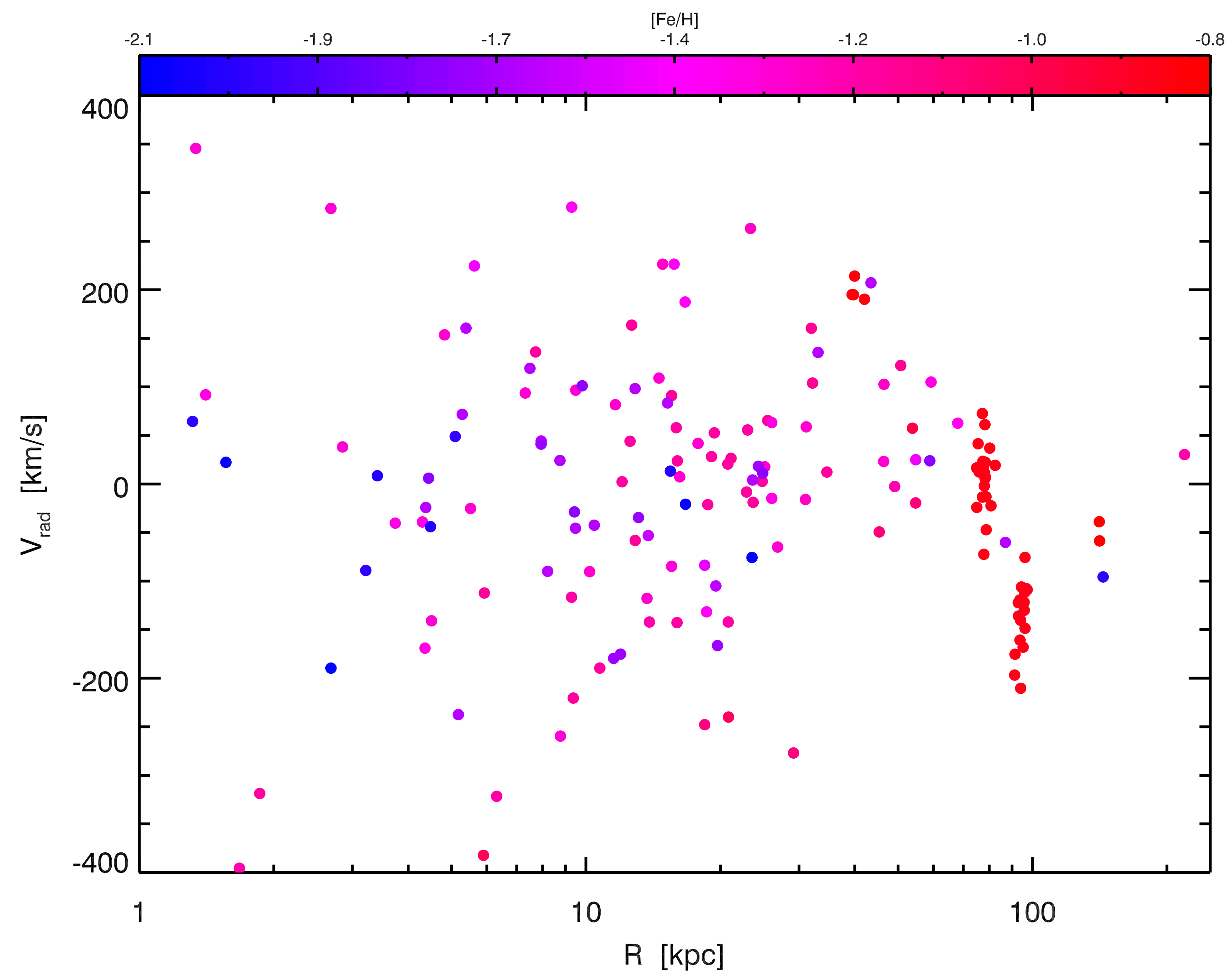
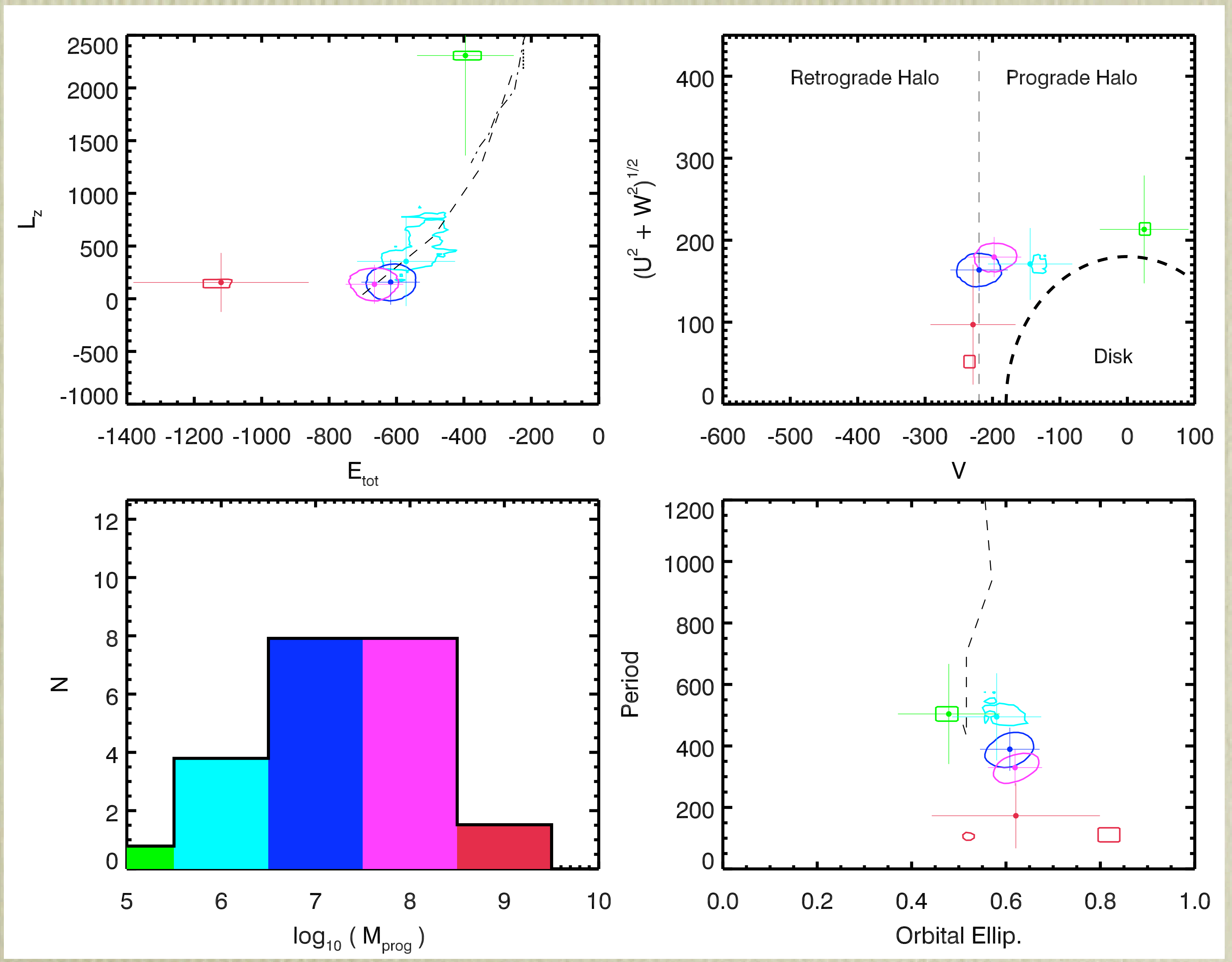


- In addition to stars from the host dwarf galaxy, can we associate multiple GCs from the same host?
- Possibly, but need to combine kinematics and chemistry

GC Properties & Host Galaxy Mass Correlations



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