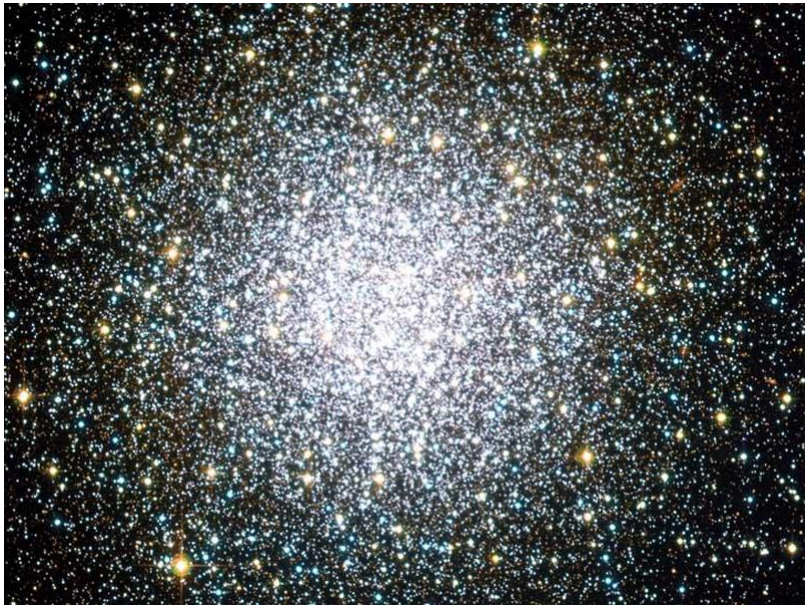
The Cosmological Origin of The Globular Cluster Metallicity Distribution.



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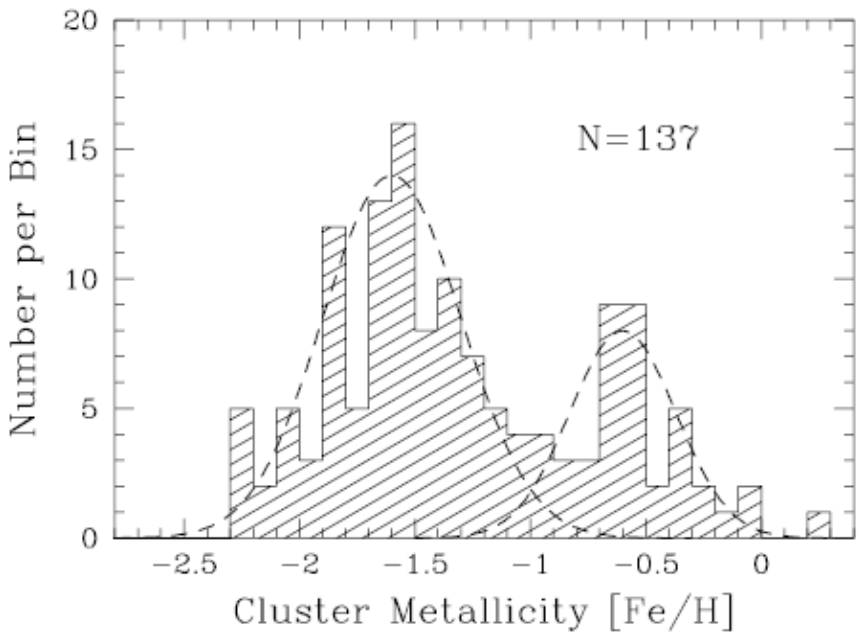
Globular Cluster Bimodality

- Milky Way GC's demonstrate a trend of bimodality both in color and metallicity. This is a feature now known to exist in many external galaxies.

- Models of galaxy formation -both simulations and semi-analytical- have thus far been unable to reproduce this feature



Harris (2001)

Our Recipe For Cluster Formation

- Massive clusters are formed according to the observed CIMF

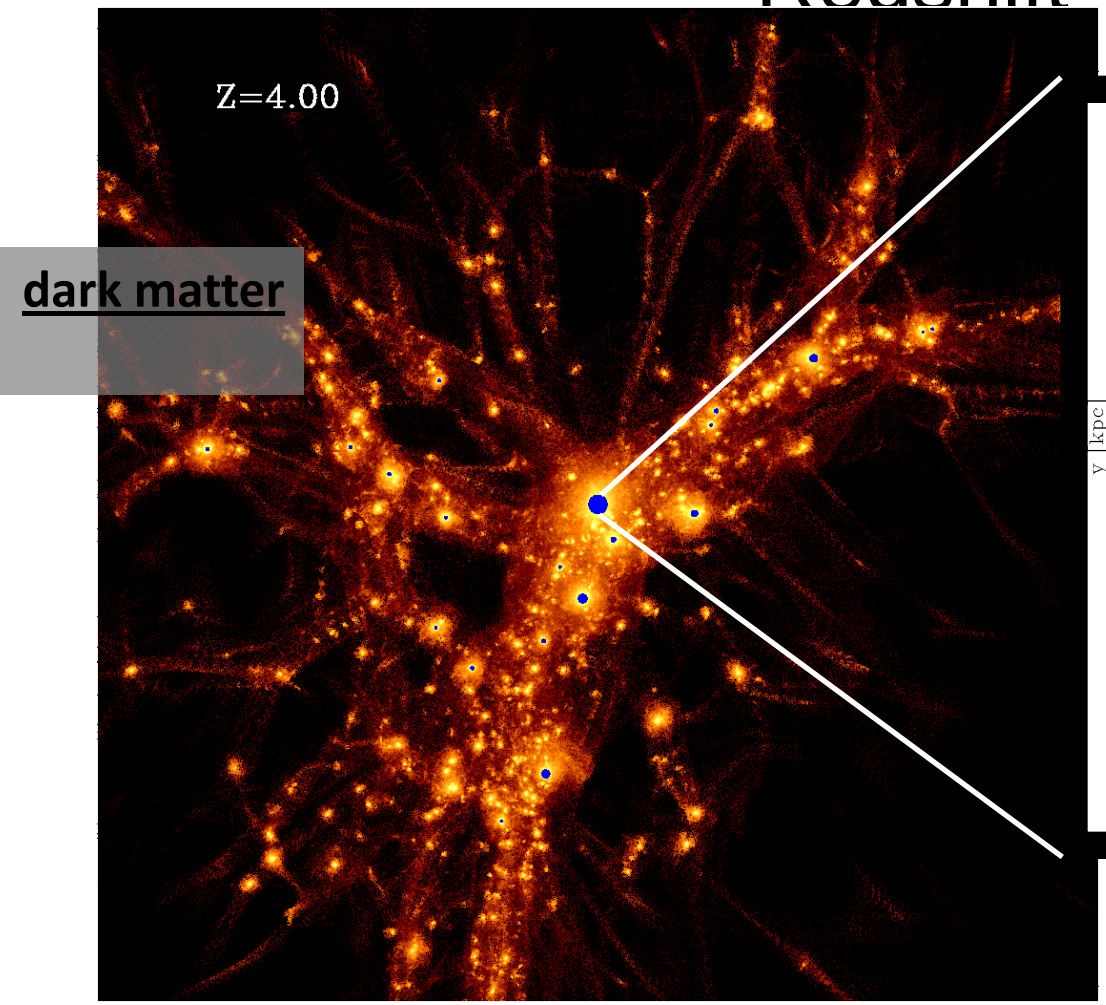
$$\frac{dN_{cl}}{dM} = N_0 M^{-2}$$

The formation efficiency of GC's relative to gas mass is taken from hydro simulations. (Kravtsov & Gnedin 2005)

$$M_{GC} = 3 * 10^6 M_\odot \left(\frac{M_h f_{gas}}{10^{11} M_\odot} \right)$$

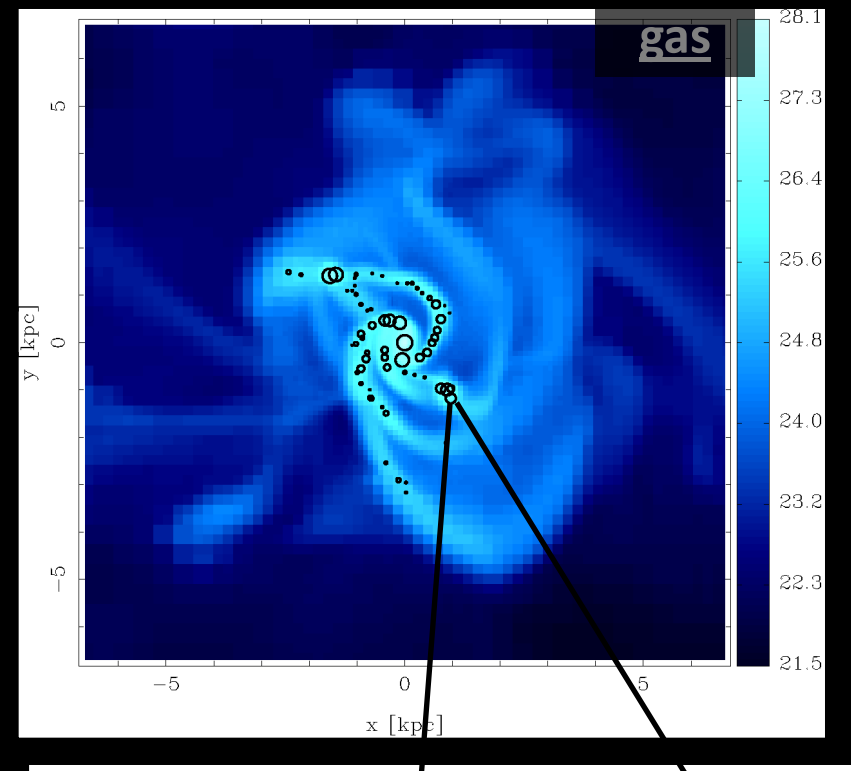
- Mass assembly histories taken from DM-only cosmological N-body simulations. (Kravtsov et al. 2003)
- We use scaling observed relations to get gas fraction and metallicity for each DM halo.
- Major merger criterion: GC formation is triggered by merging gas-rich progenitor galaxies. The nature of this criterion is a parameter in the model

Progenitor Galaxy + Gas Distribution at High Redshift



300 kpc (physical)

14 kpc

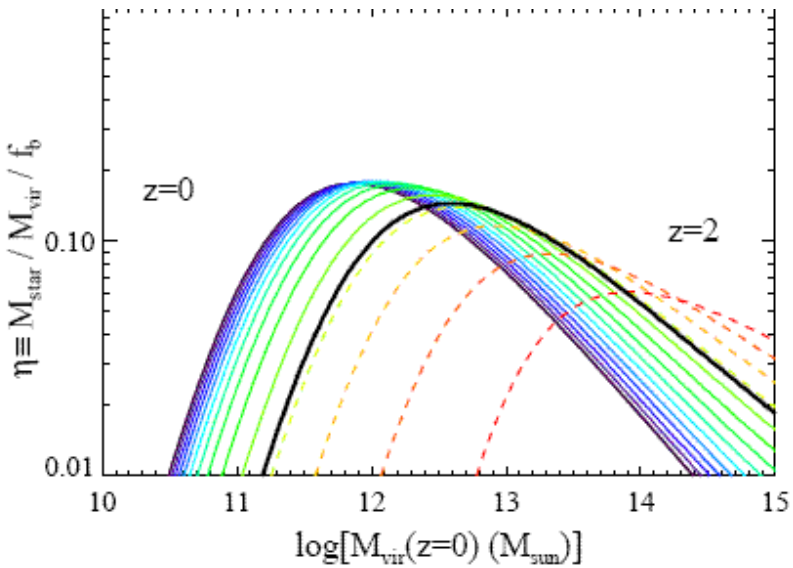


20 pc

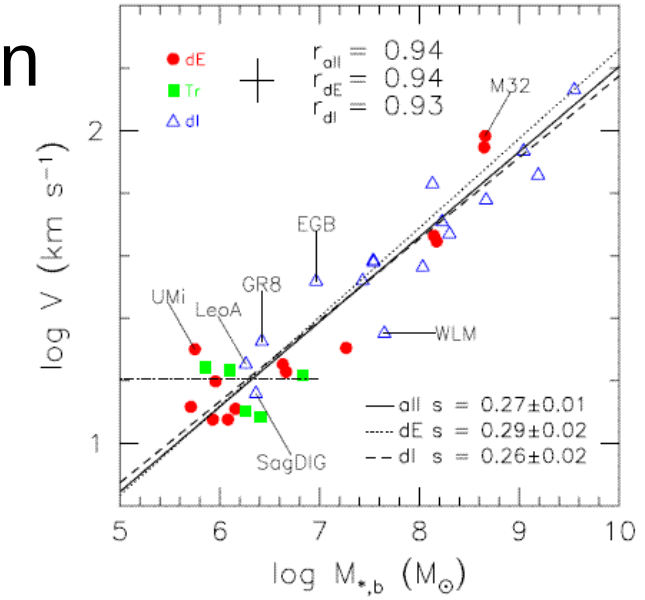
Kravtsov & Gnedin (2005)

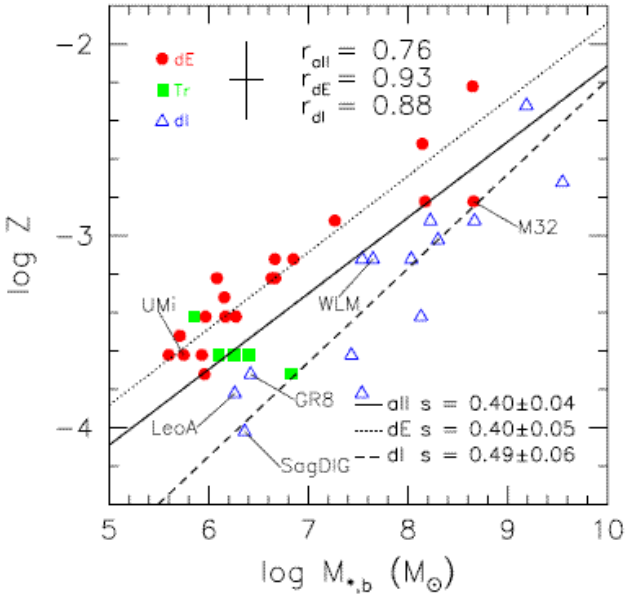
Parameterizing The Cold Gas Fraction And Metallicity

- We use scaling relation of Milky Way dwarf galaxies to get M_{star}-M_h and [Fe/H]-M_{star} (Woo et al. 2008). Another study gives us M_{gas}-M_{star}. (McGaugh 2005)
- We consider their evolution with cosmic time (Conroy & Wechsler 2008)



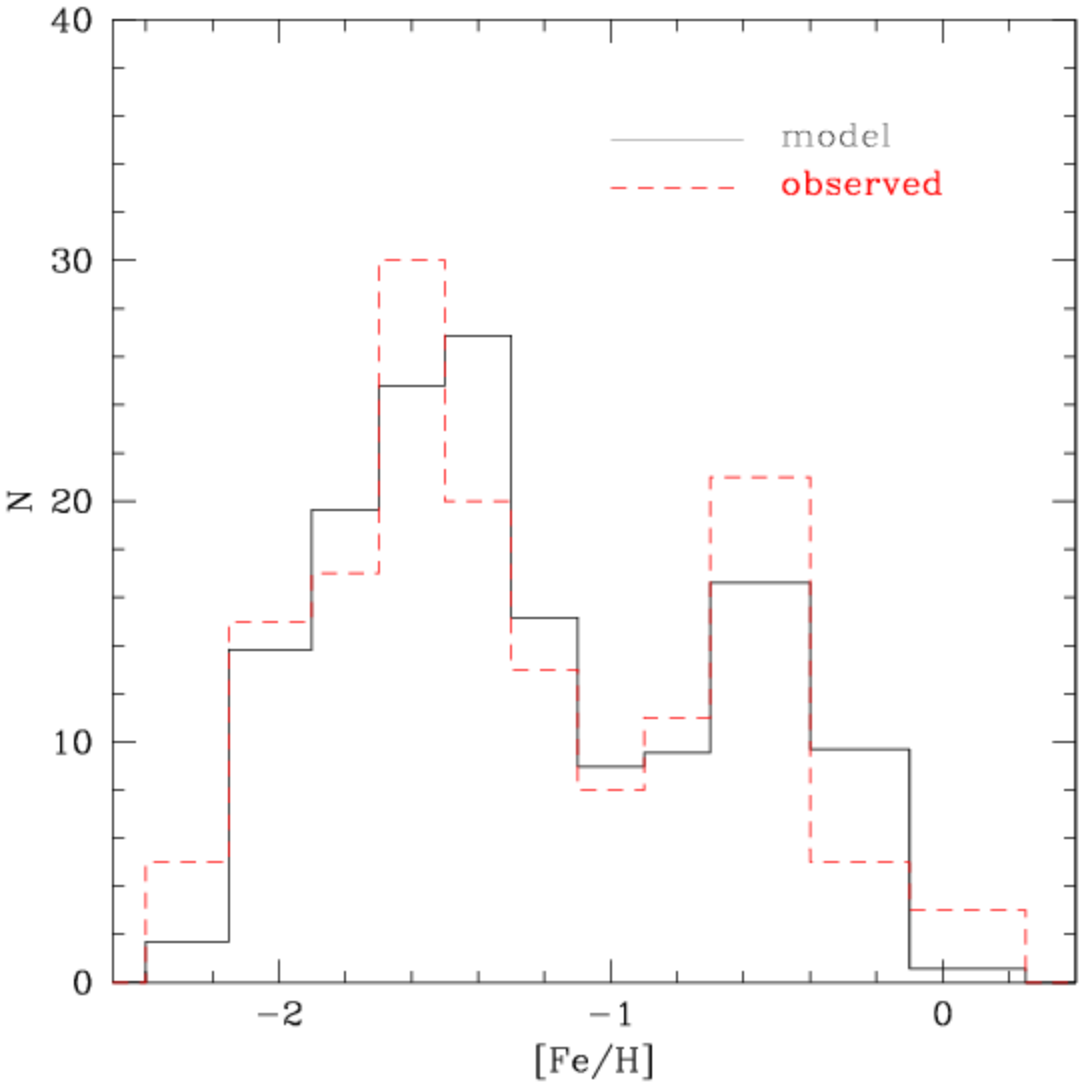
Conroy & Wechsler (2008)





Woo et al. (2008)

Main Result: Bimodal Metallicity Distribution

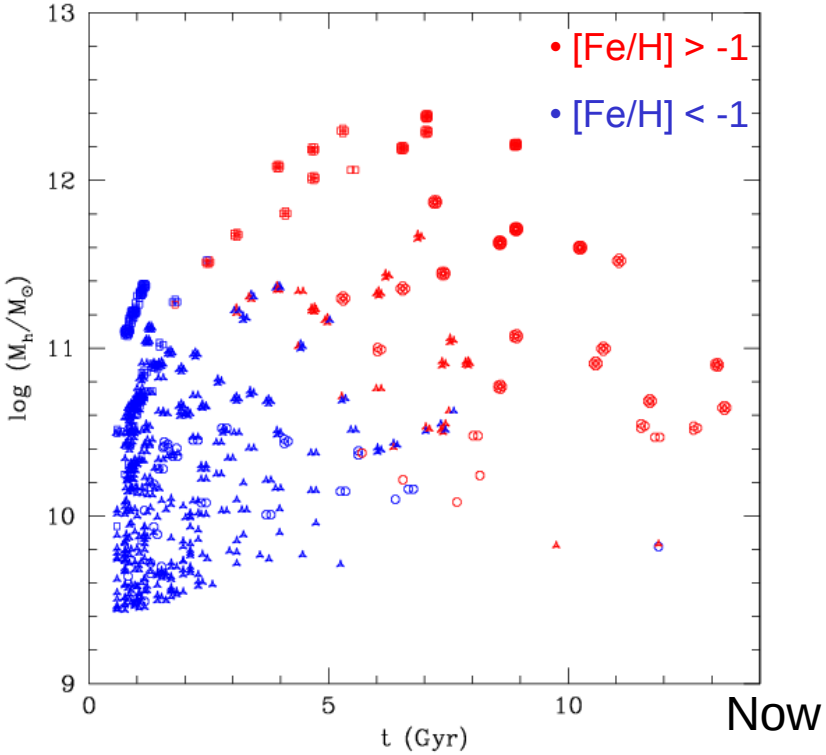


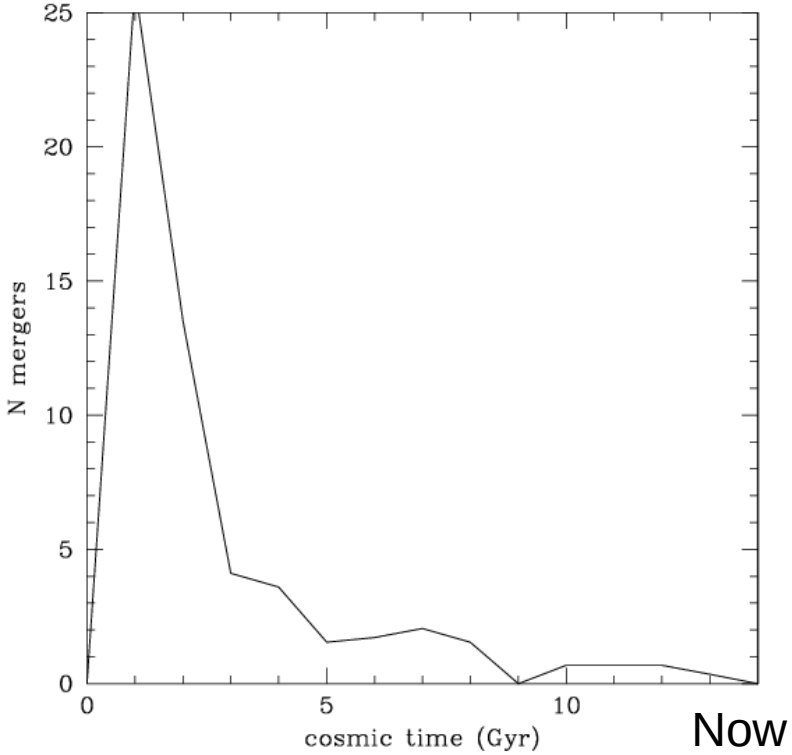
KS Test: 80%
Dip Test 99%

Muratov & Gnedin 2010

The Origin of Bimodality In Our Model

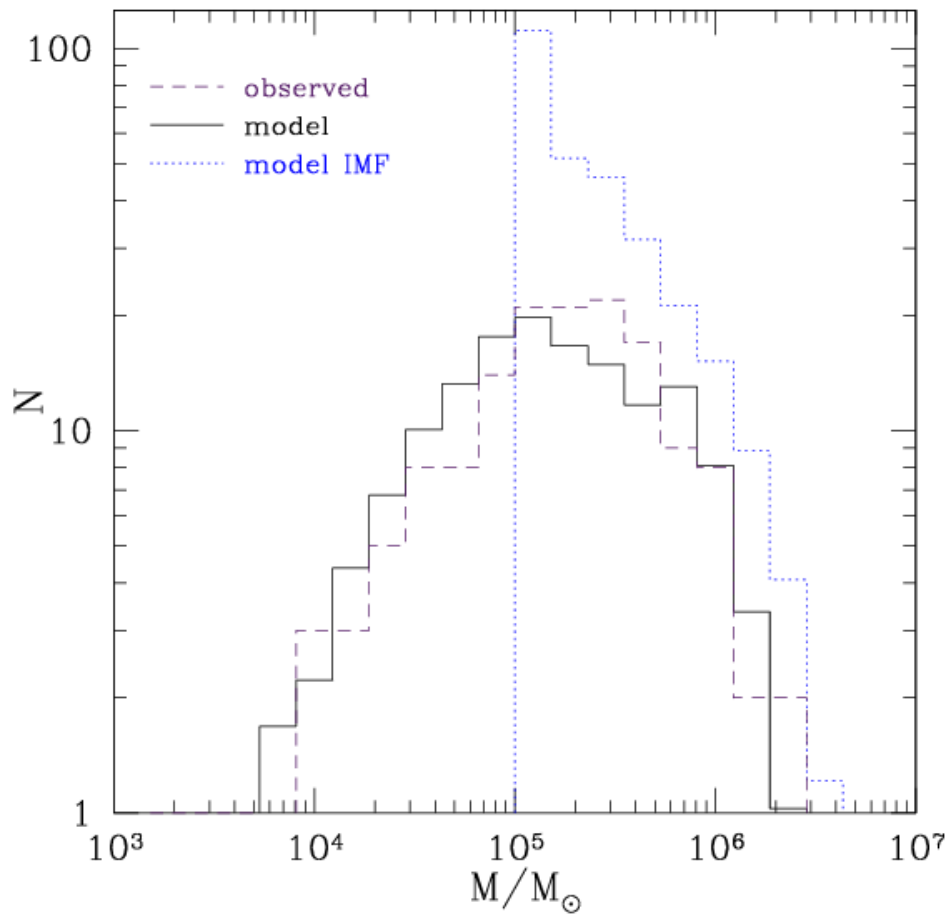
- In hierarchical galaxy formation, it is expected that the galaxy will undergo several phases of mergers.
- Early phase: frequent mergers of low-mass, gas-rich, metal-poor halos.
- Late phase: sparse mergers of high-mass halos with enriched gas.





Mass Function of GC's

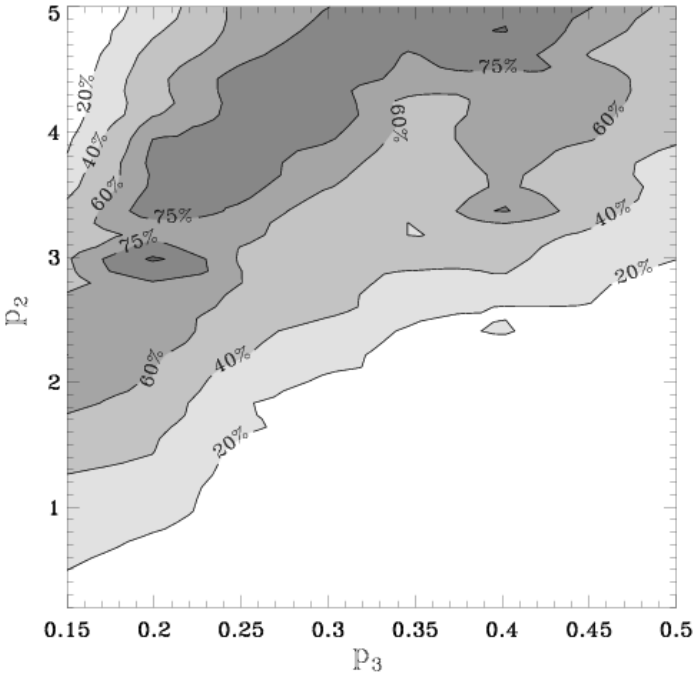
- Initially, each halo has a power law distribution of clusters dN/dM ~ M^{-2}. But, globular clusters are prone to mass loss and disruption over time.
- We include effects of two-body relaxation and stellar evolution. The results look OK.
- KS test: 7.4%
- Comparable means and dispersions



Muratov & Gnedin 2010

Is The Distribution Unique?

- 6-dimensional parameter space leads to ‘slices’ of solutions within the parameters that all give viable results.
- How do we choose the best one for our Galaxy?
  - KS probability for both mass and metallicity
  - Constrain that N = 150 (as observed)

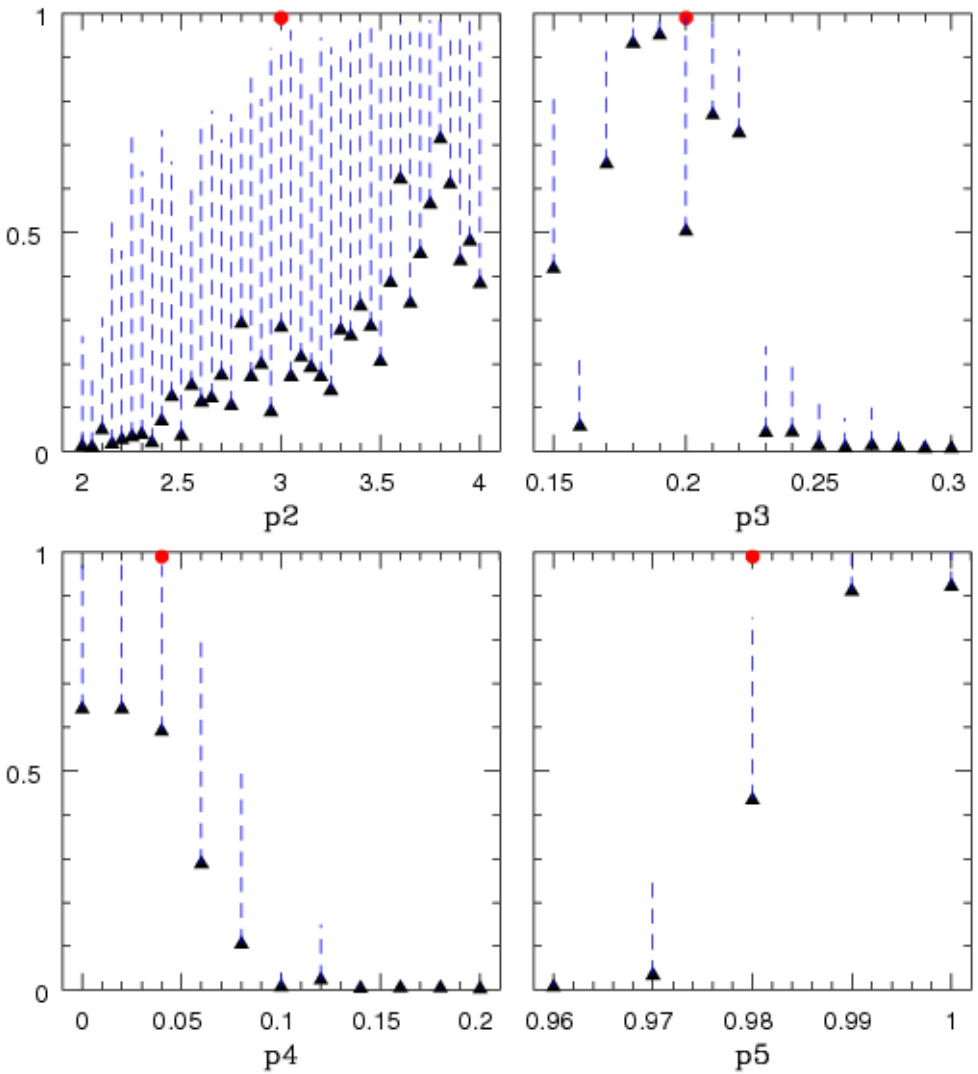


$$M_{h,i} > p_3 M_{h,i-1}$$

$$M_{GC} = 3 \times 10^6 \, \mathrm{M}_\odot \, (1 + p_2) \, \frac{M_g / f_b}{10^{11} \, \mathrm{M}_\odot}.$$

Bimodality Is Not Unique – It's Natural

Dip Test Probability

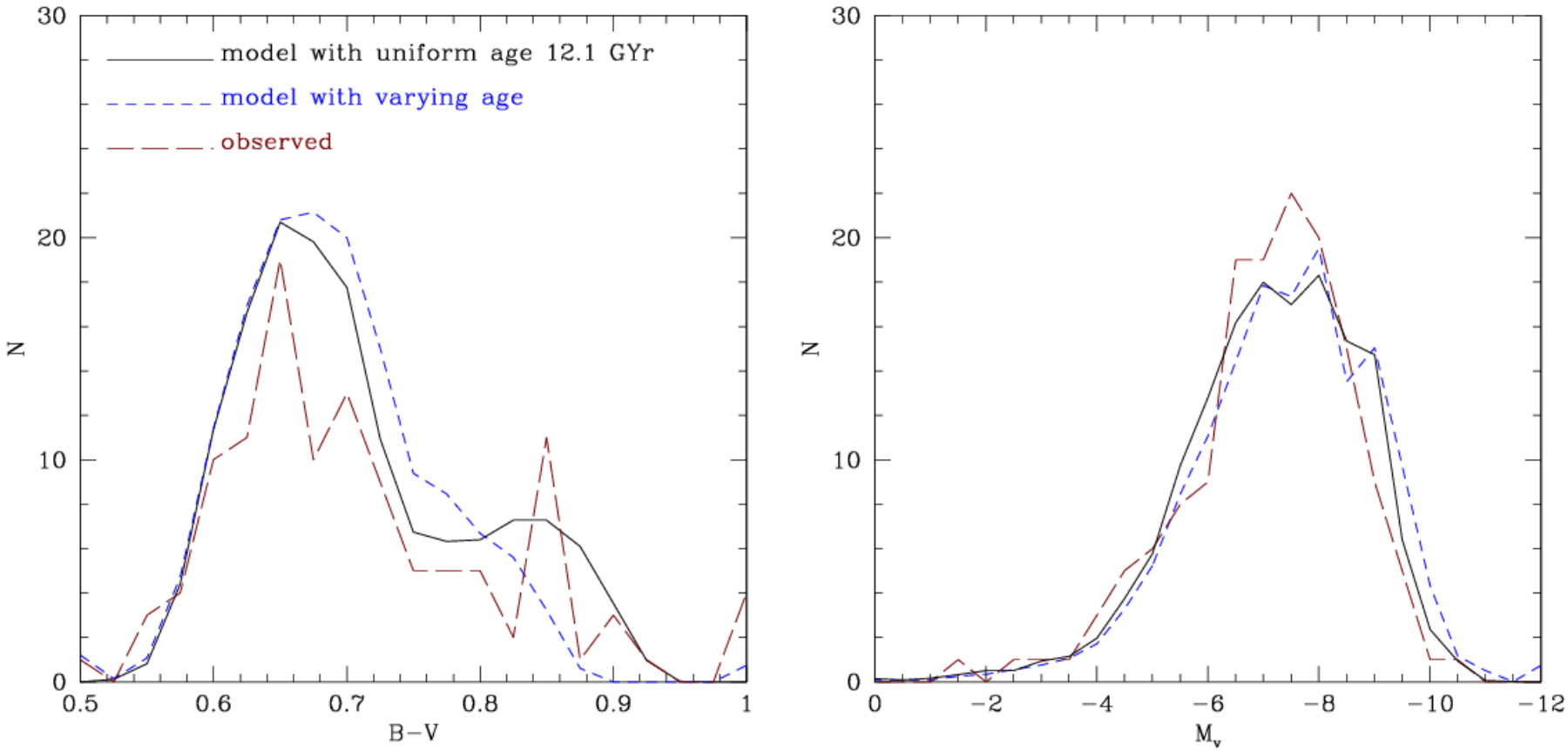


- Many realizations of our model are shown to be non-unimodal by the Dip Test.

Summary

- We present a prescriptive model for globular cluster formation that successfully reproduces a bimodal metallicity distribution.
- We have included a model for mass disruption. Our mass function is consistent with observations (more or less).
- Bimodality occurs for a wide range of model parameters. It is therefore a natural result for hierarchical galaxy formation.

Luminosity and Color Distributions

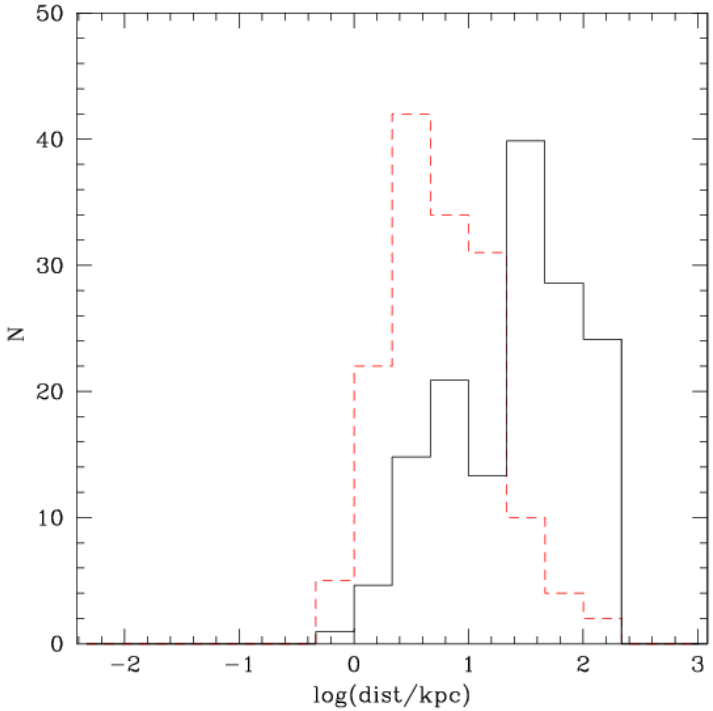


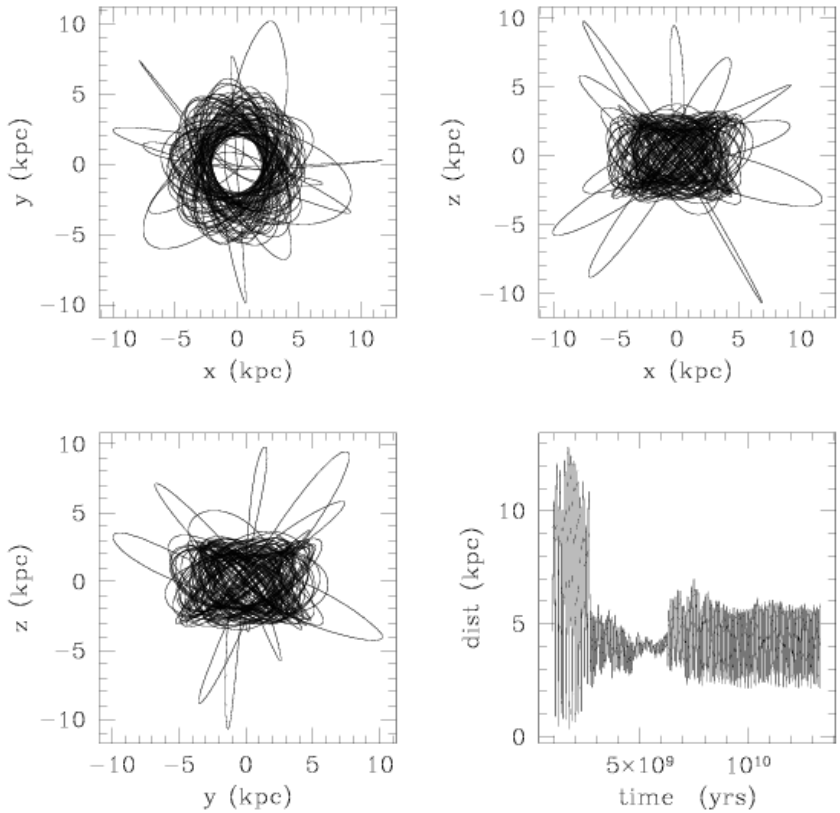
Obtained with the GALAXEV population synthesis code of Bruzual & Charlot (2003)

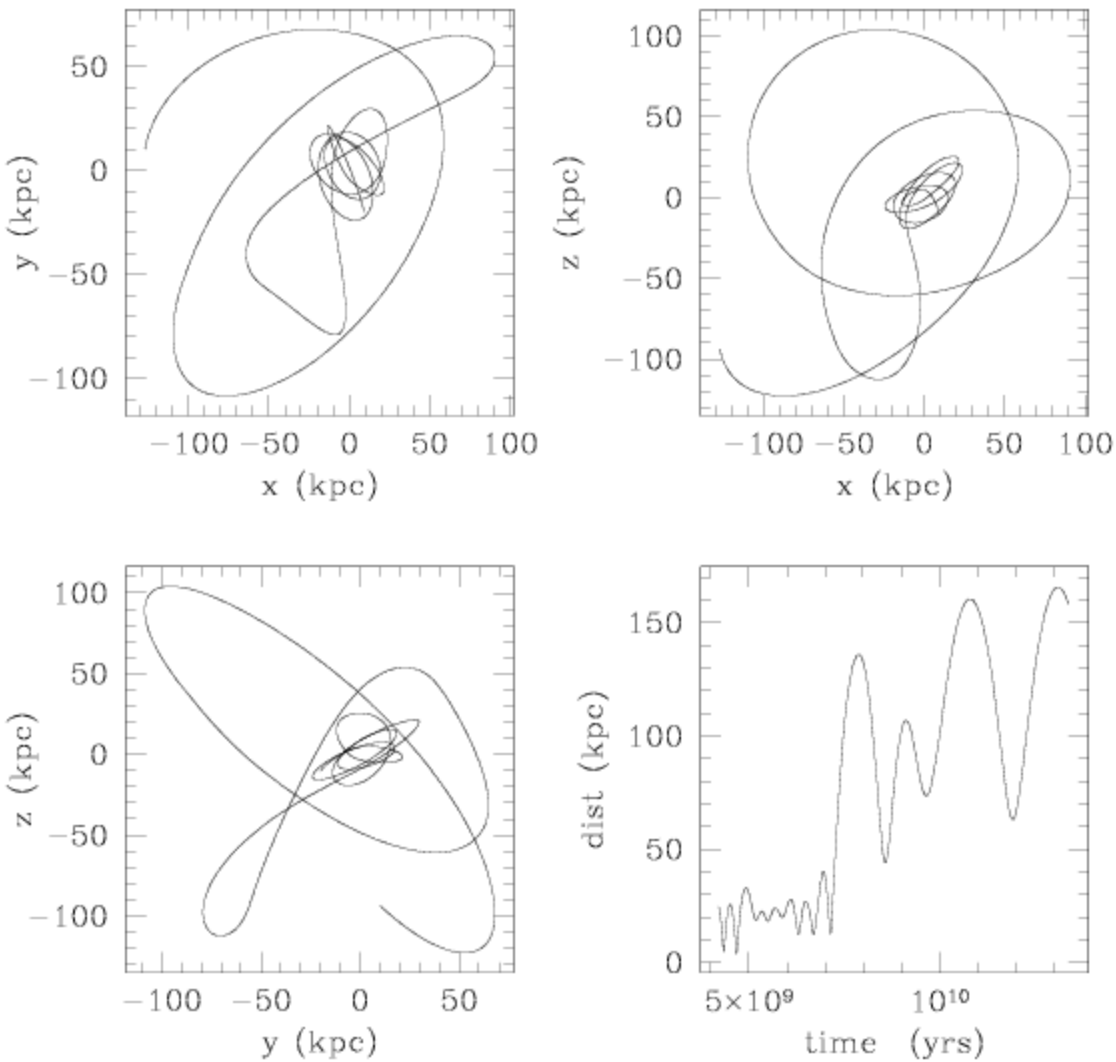
GALAXEV stole our bimodal distribution

The Radial Distribution of Clusters

- Inherent problem with hierarchical formation model: DM is too far out. That means GCs in our model are also too far out






y (kpc)
x (kpc)
z (kpc)
x (kpc)
z (kpc)
y (kpc)
dist (kpc)
time (yrs)
5×10⁹
10¹⁰

Globular Clusters vs Field Stars