Formation of Globular Clusters: A Possible Origin of Bimodality

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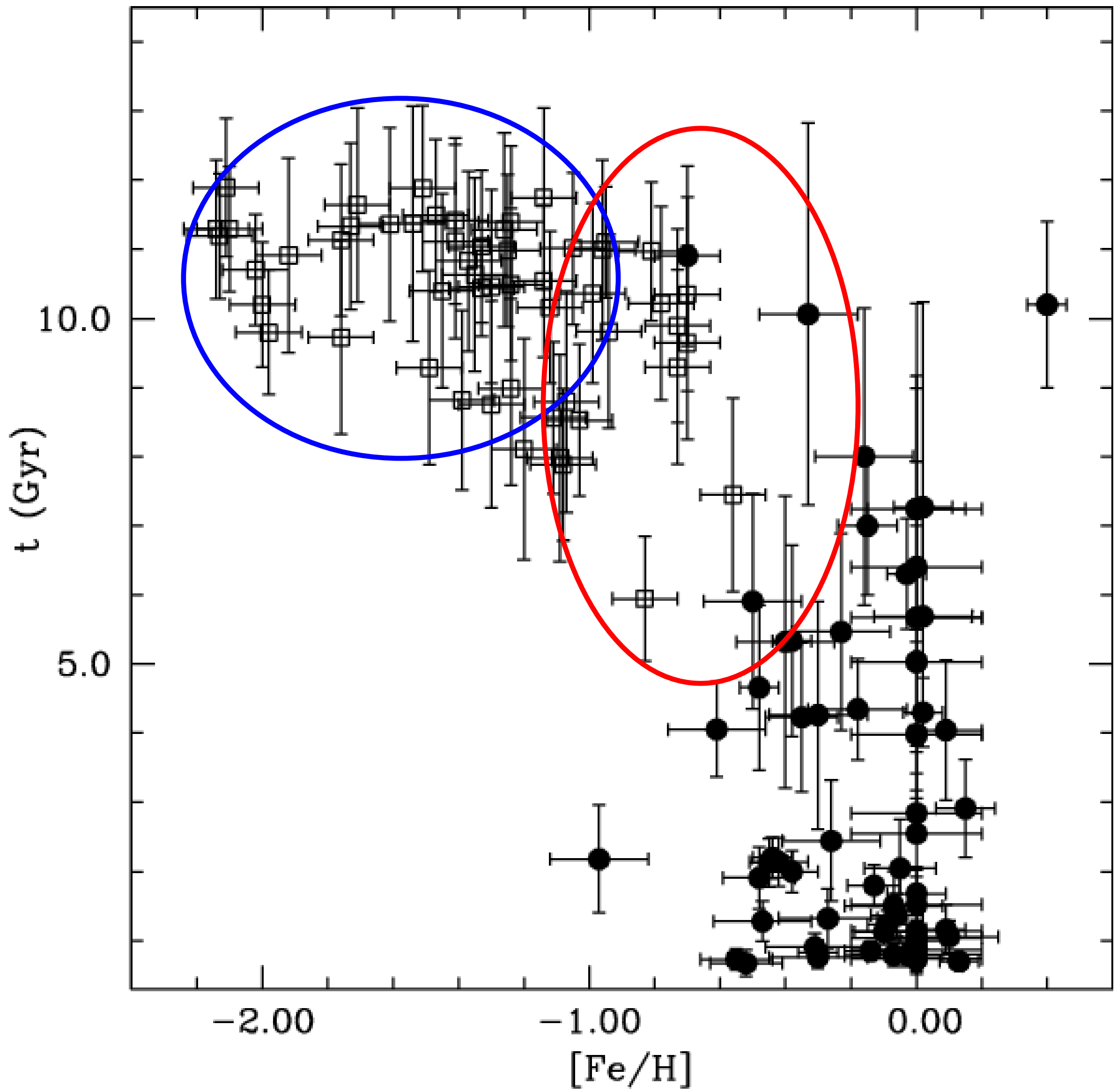
GCs have a spread of ages and not too low metallicity



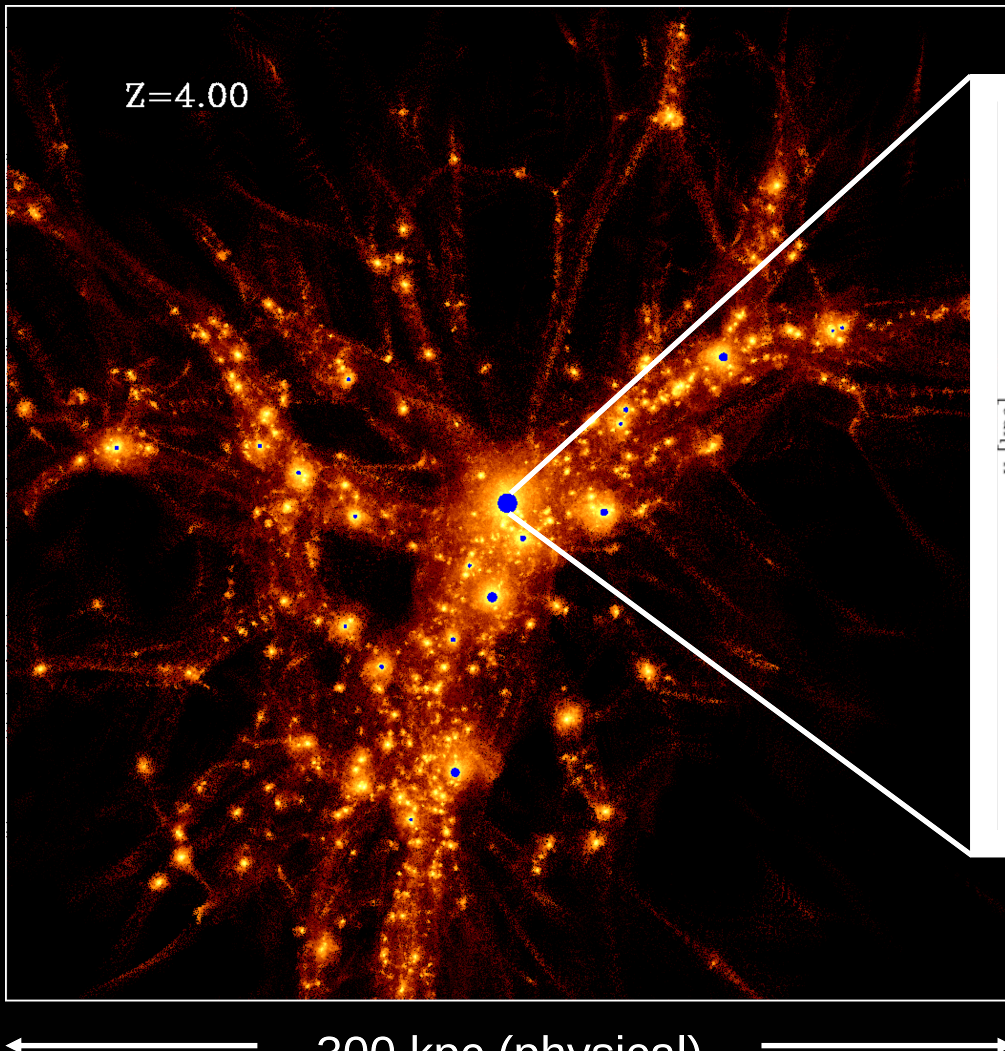
Percival & Salaris

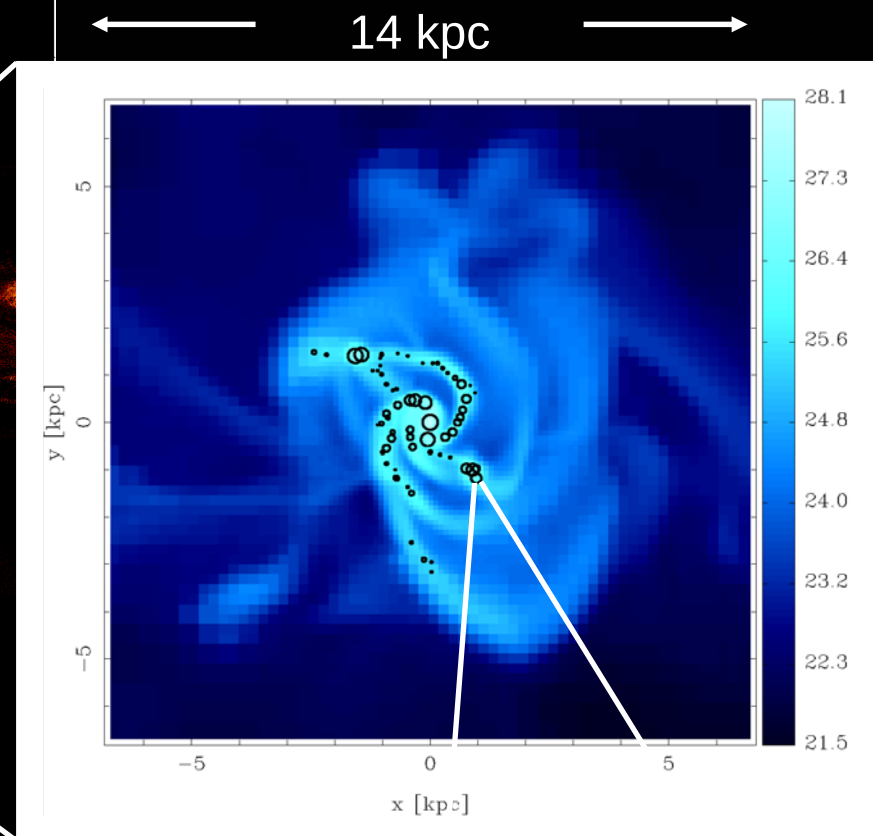
Color and Metallicity Bimodality

- Overwhelming observational evidence: in most galaxies
- Many interpretations:
    - *Red clusters formed in mergers of spirals, blue clusters formed somehow before that in host galaxies*
    - *Red clusters are associated with host galaxy, blue clusters formed independently, etc.*
- Most ideas assume separate bursts of formation for red and blue clusters, a sequence in time

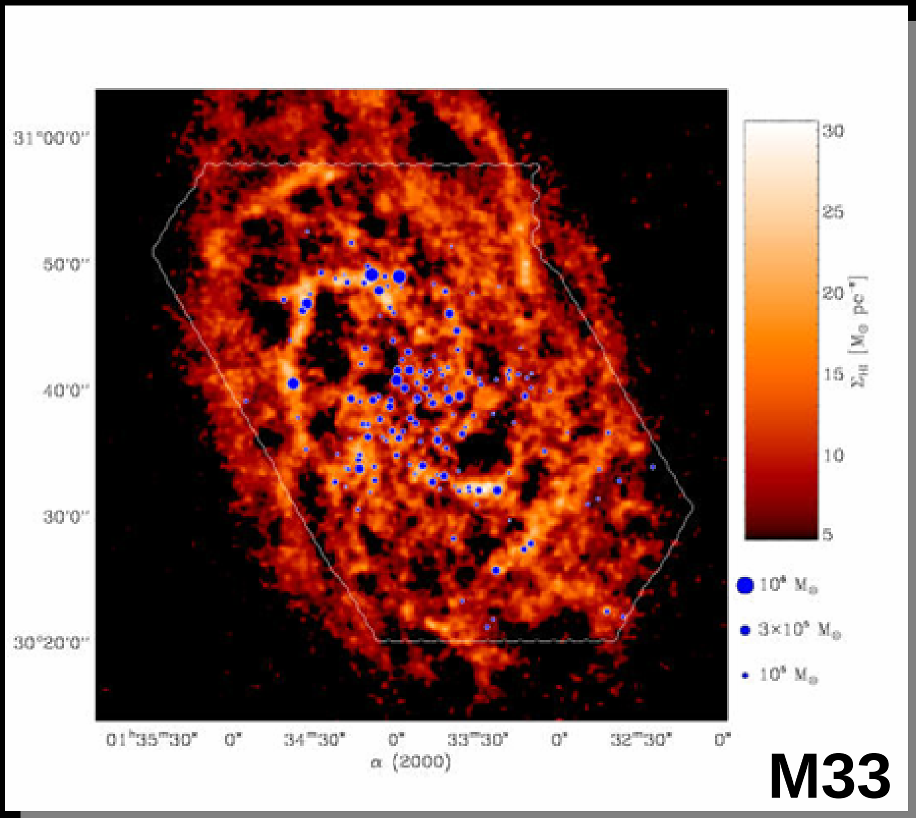
<u>Need to understand in the global context of galaxy formation</u>

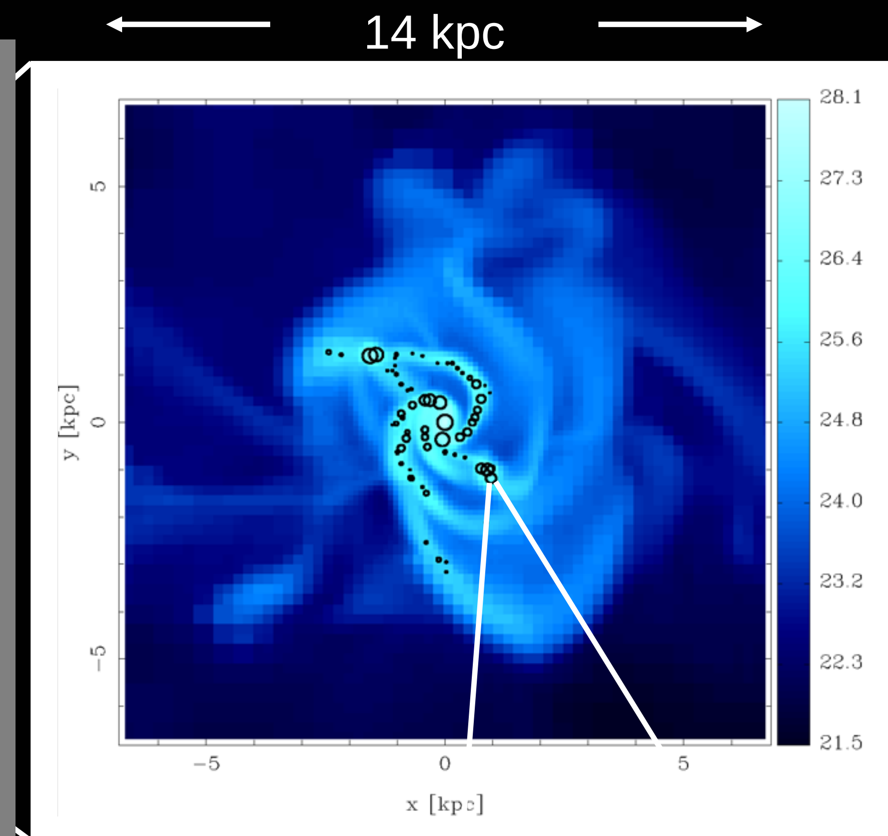
Use hydrodynamic AMR simulations to find molecular clouds





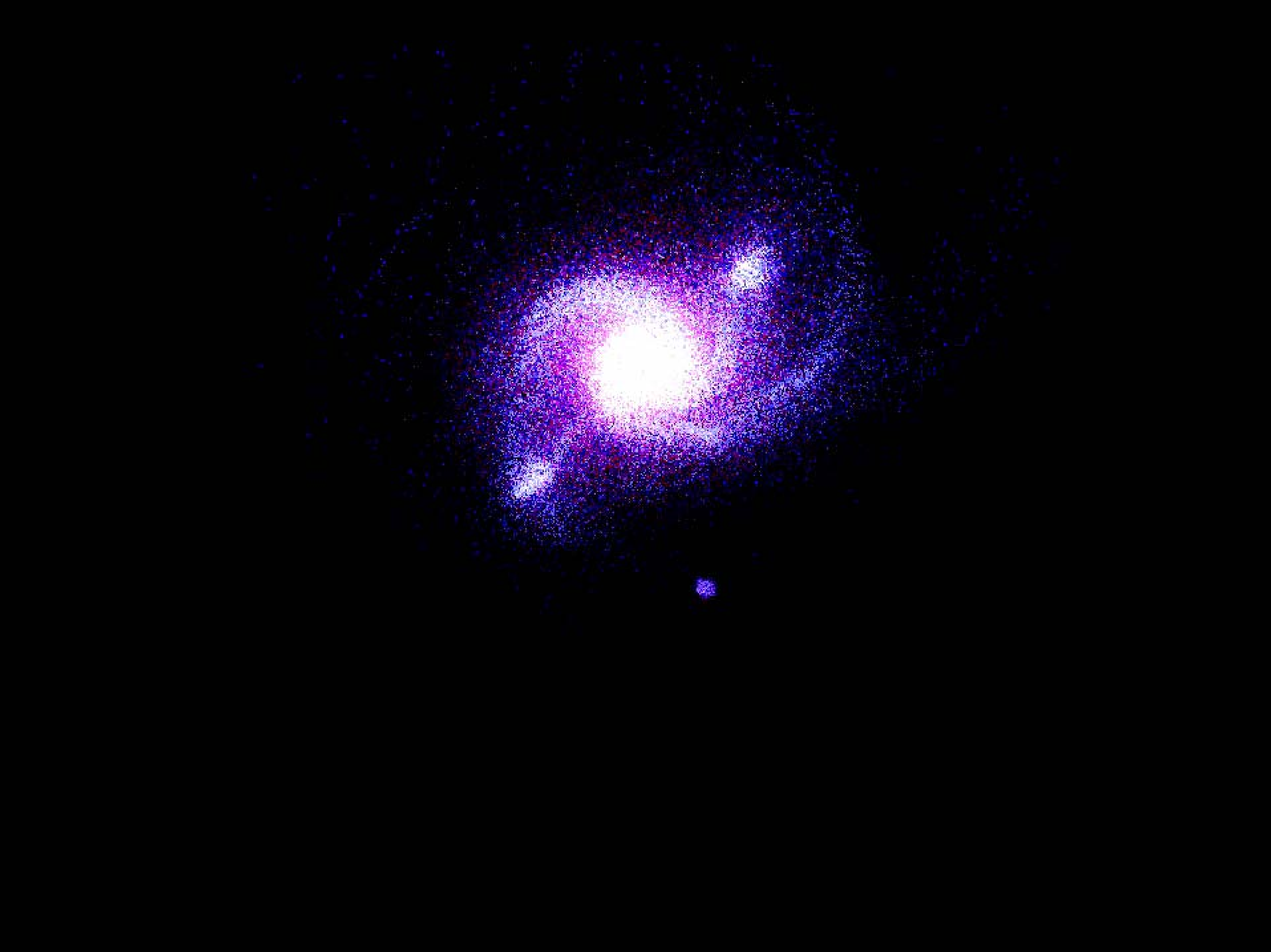
Kravtsov & OG (2005)



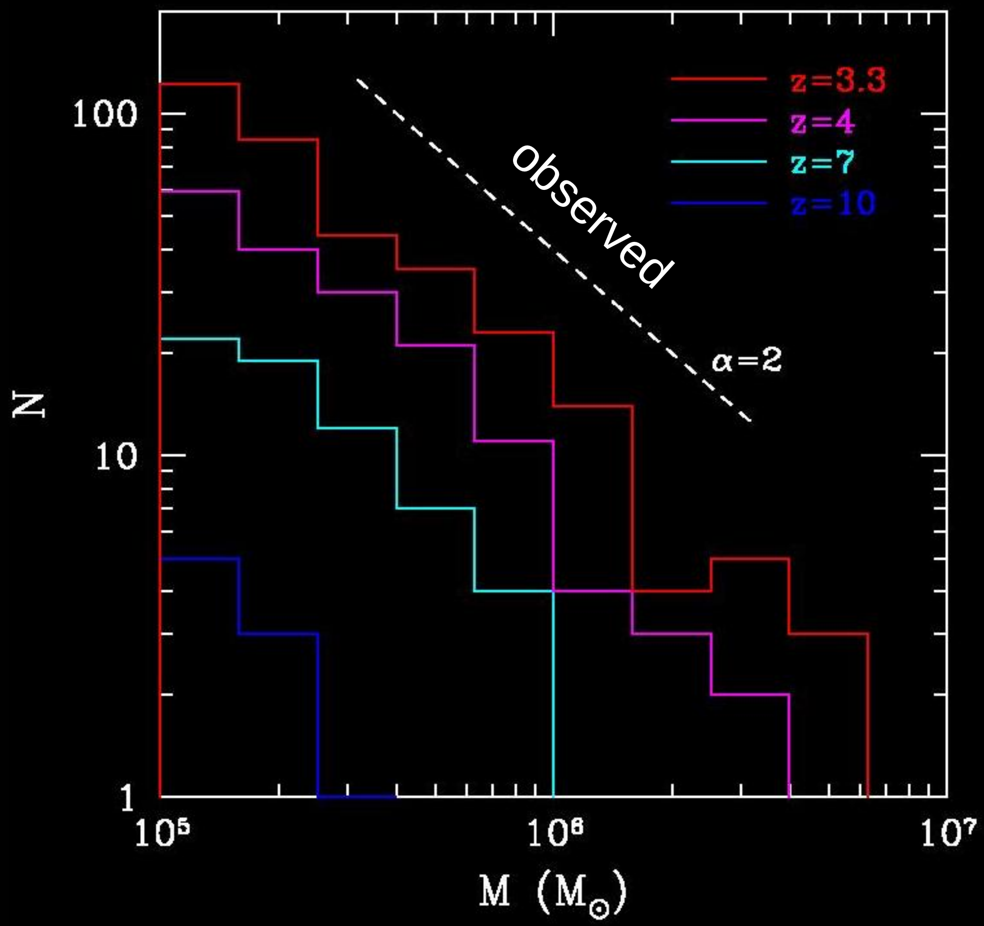


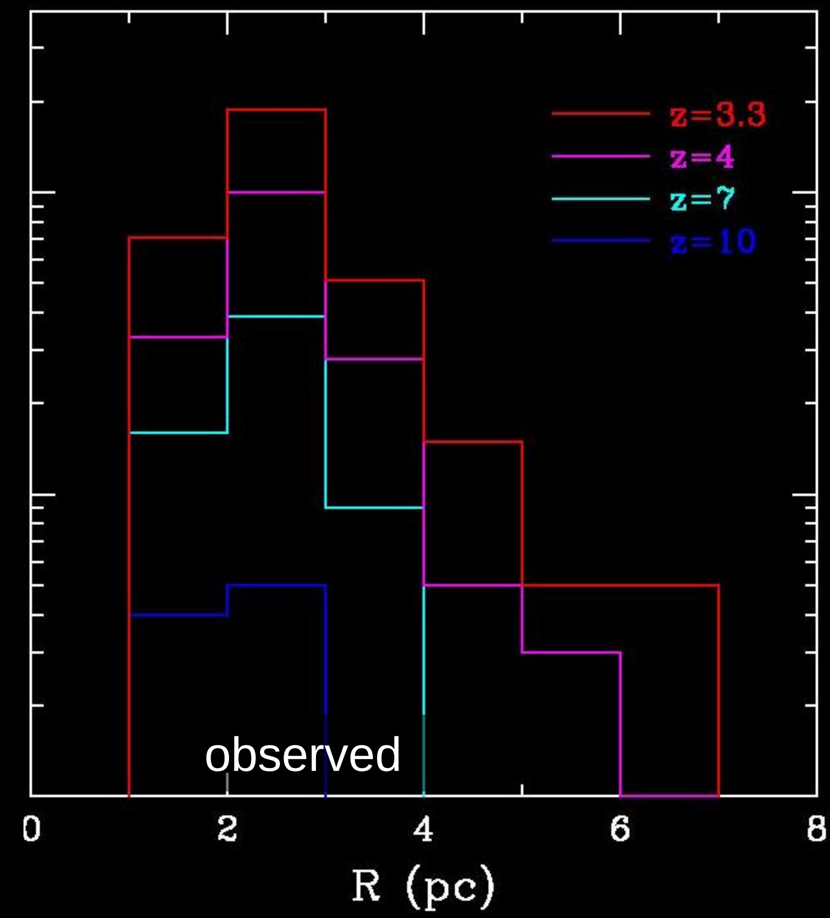
density threshold in the cloud core: $10^4\ M_\odot\ \mathrm{pc}^{-3}$

this enforces same average density ρ_h



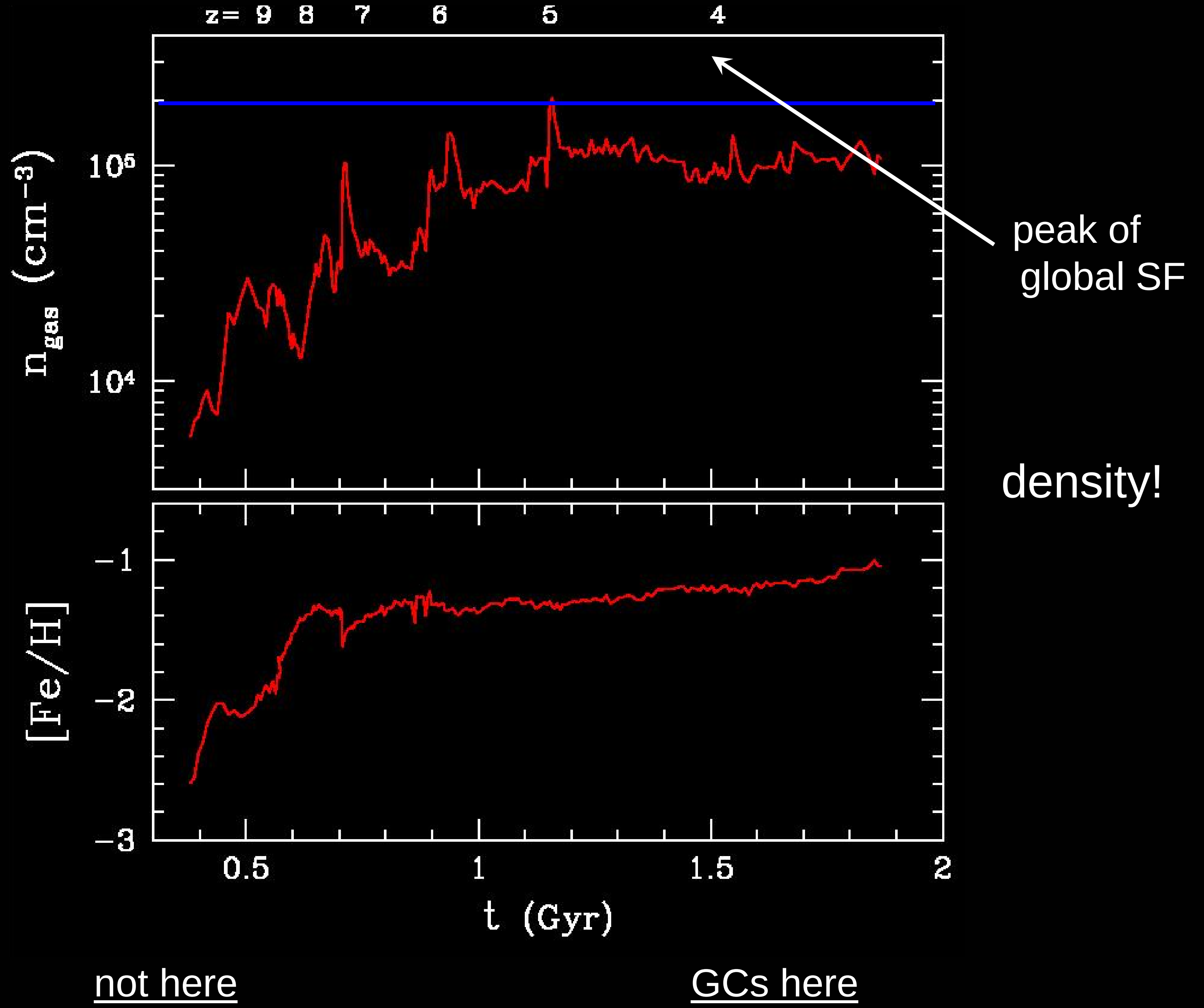
Initial masses and sizes of model GCs are in excellent agreement with the observations of young clusters





$M_{GC} \propto M_{host}$

(cumulative distributions accumulated by a given epoch)



z= 9 8 7 6 5 4
n_{gas} (cm^{-3})
10^5
10^4
[Fe/H]
−1
−2
−3
0.5
1
1.5
2
t (Gyr)
peak of
global SF
density!
not here
GCs here

Dynamical evolution removes most low-mass clusters

Jose Prieto & OG (2008)

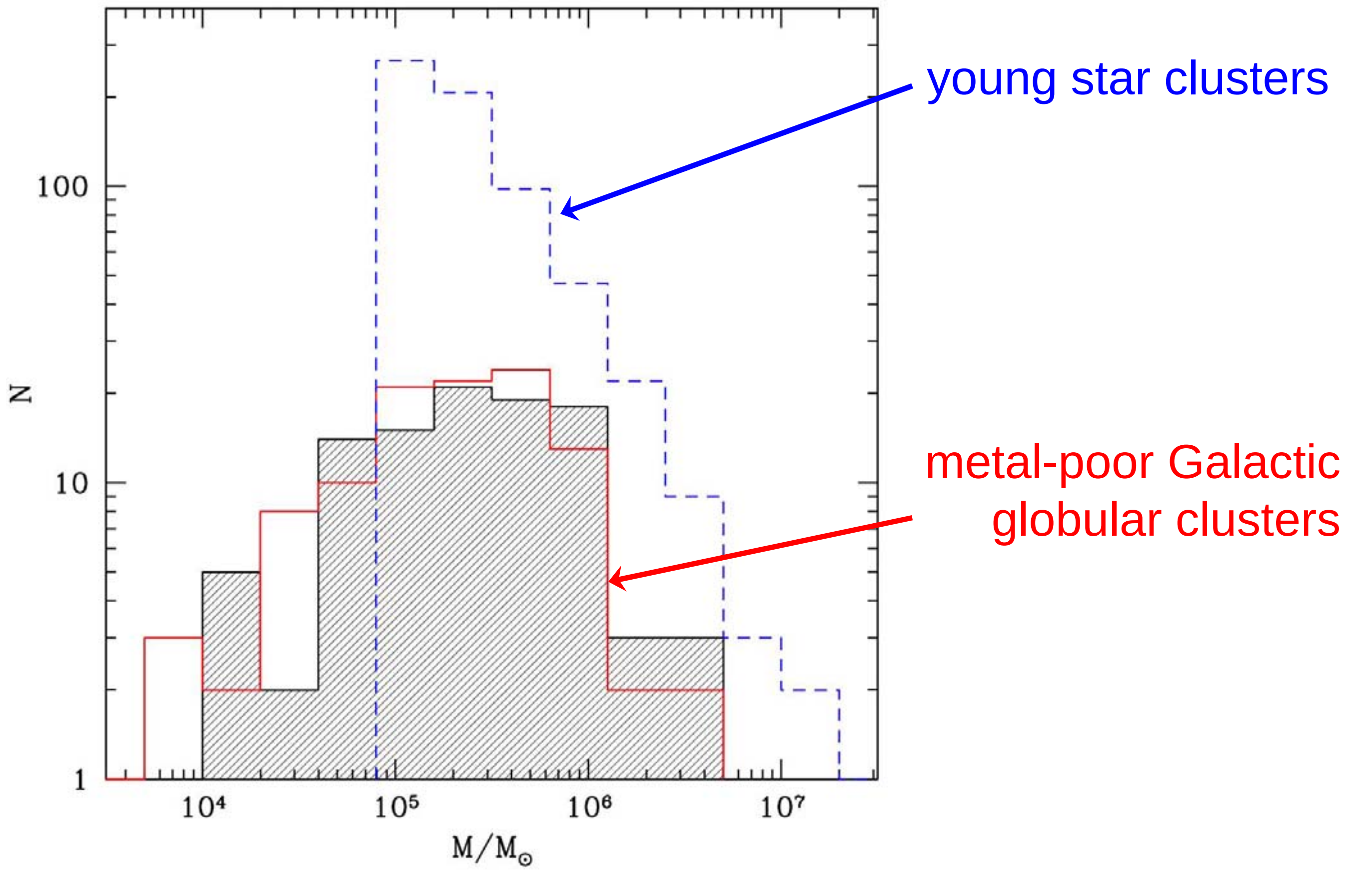
Stellar evolution + relaxation + tidal shocks

$\xi_e = const$

$R_h(0) \propto M(0)^{1/3}$

$R_h(t) \propto M(t)^{1/3}$

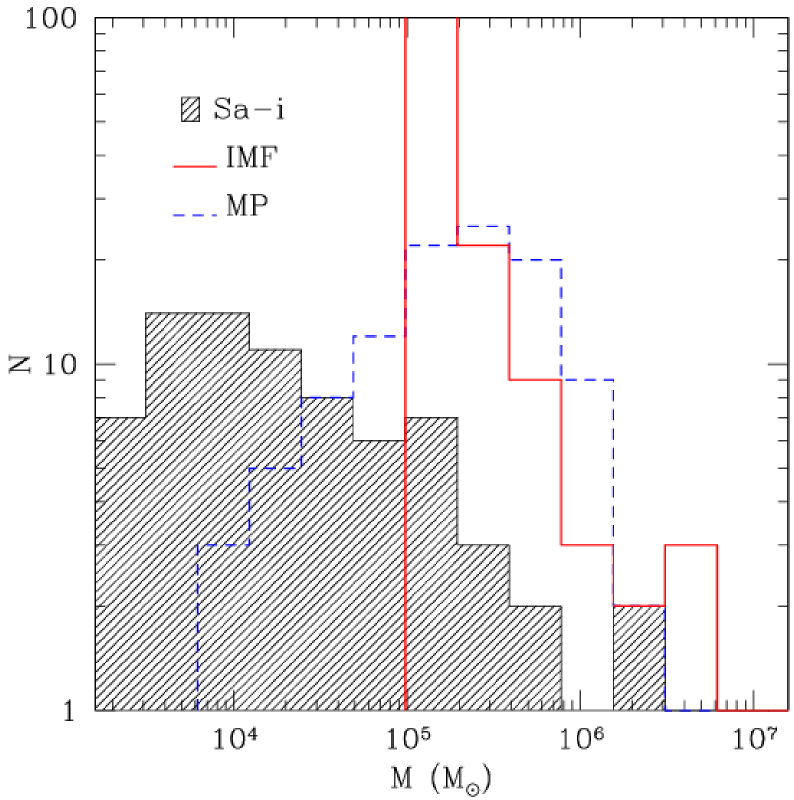
average density is constant



final/initial mass = 0.46   final/initial number = 0.16

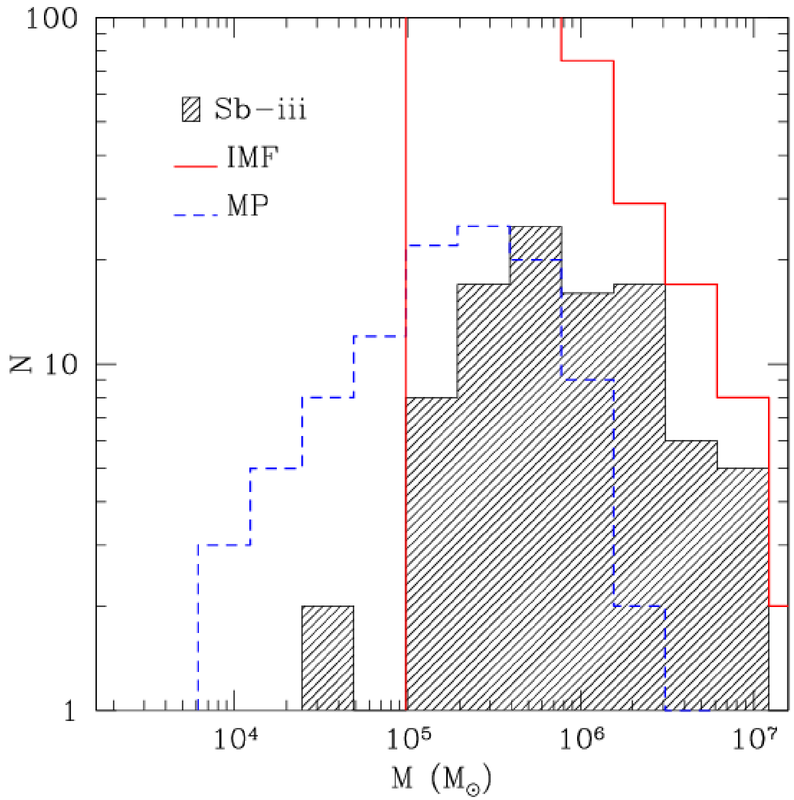
Not all R–M relations are consistent with the observed mass function

$R_h(0) = R_h(t) = \text{const}$



final/initial mass = 0.29
final/initial number = 0.54

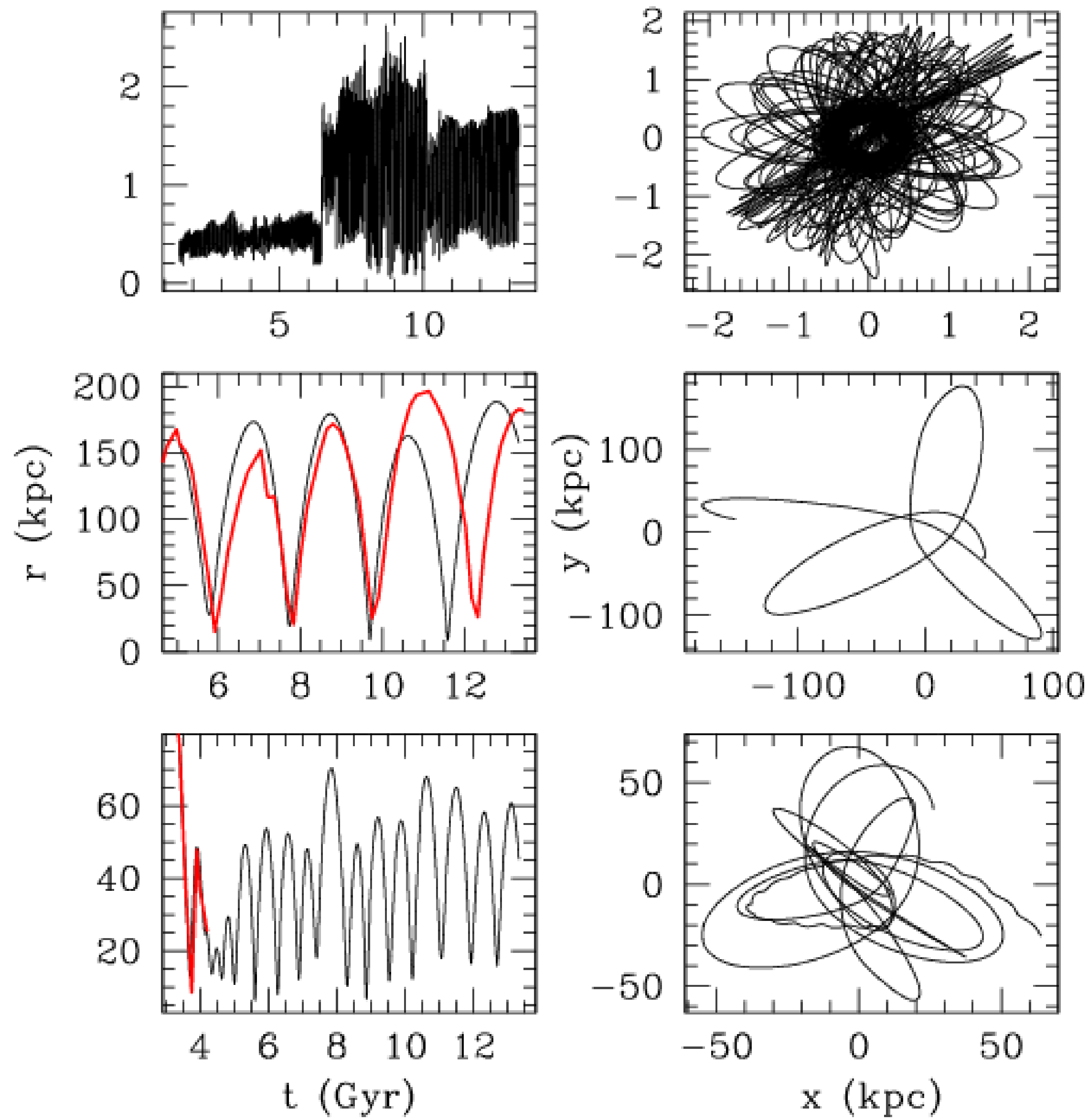
$R_h(0) \propto M(0)^{1/3}$, $R_h(t) \propto M(t)$



final/initial mass = 0.54
final/initial number = 0.09

Different types of orbits of globular clusters at z<3

Jose Prieto & OG (2008)



main disk

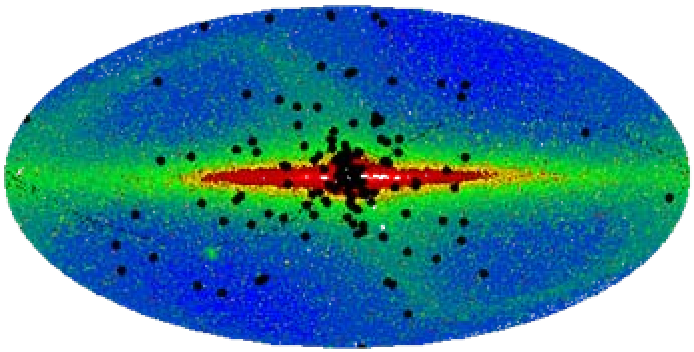
surviving satellite galaxy (red)

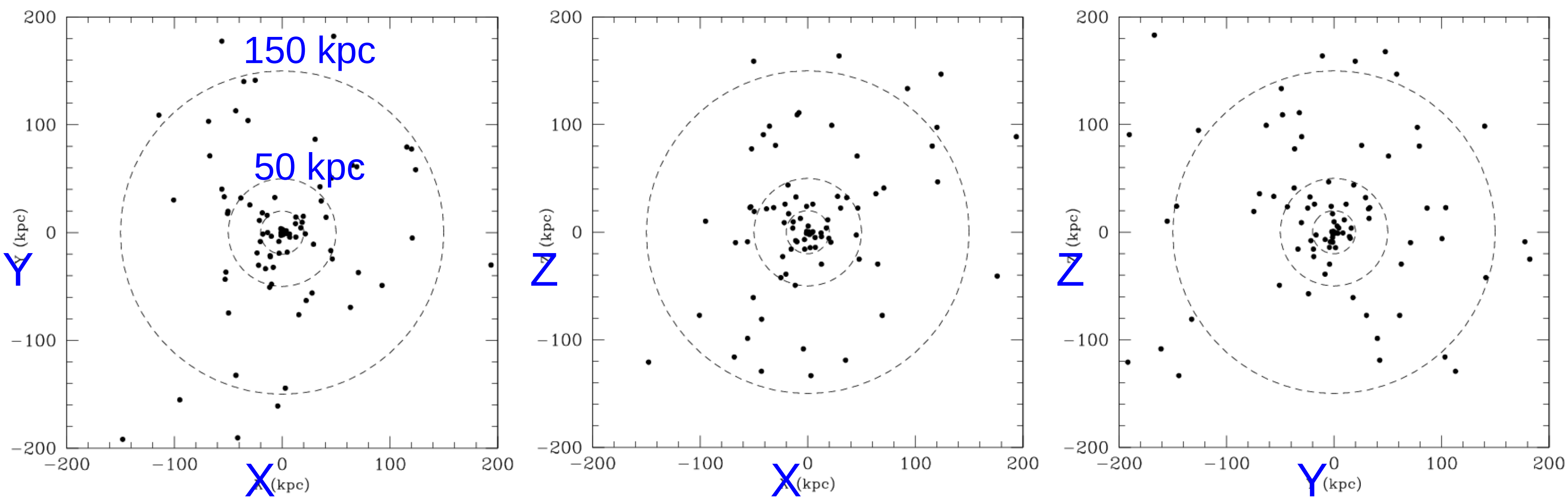
disrupted satellite galaxy

Mergers of host galaxies of GCs result in a spheroidal distribution of the overall GC system *now*

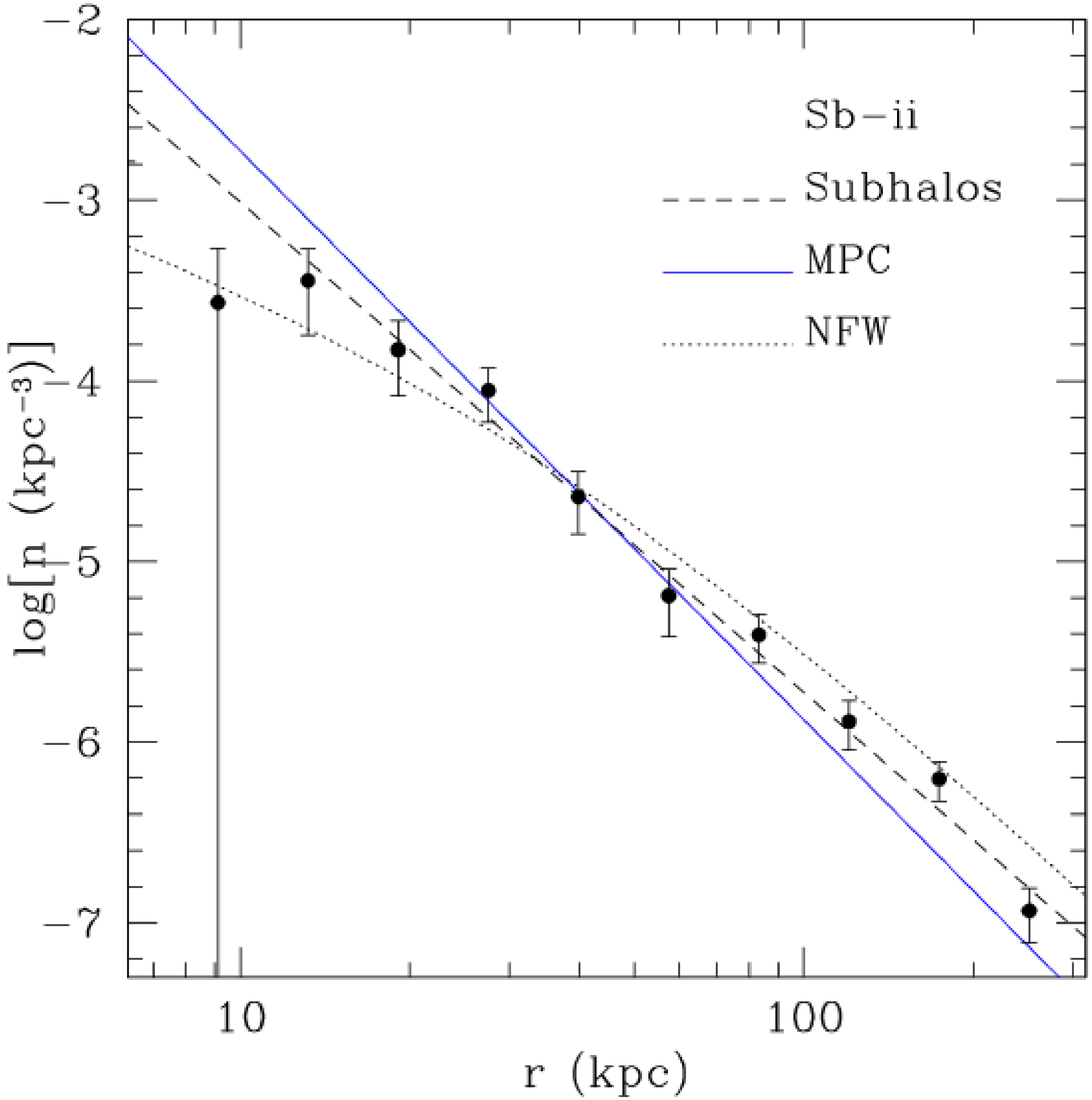
number density is consistent with a power-law, slope ≈ –2.7

(observed ≈ – 3)

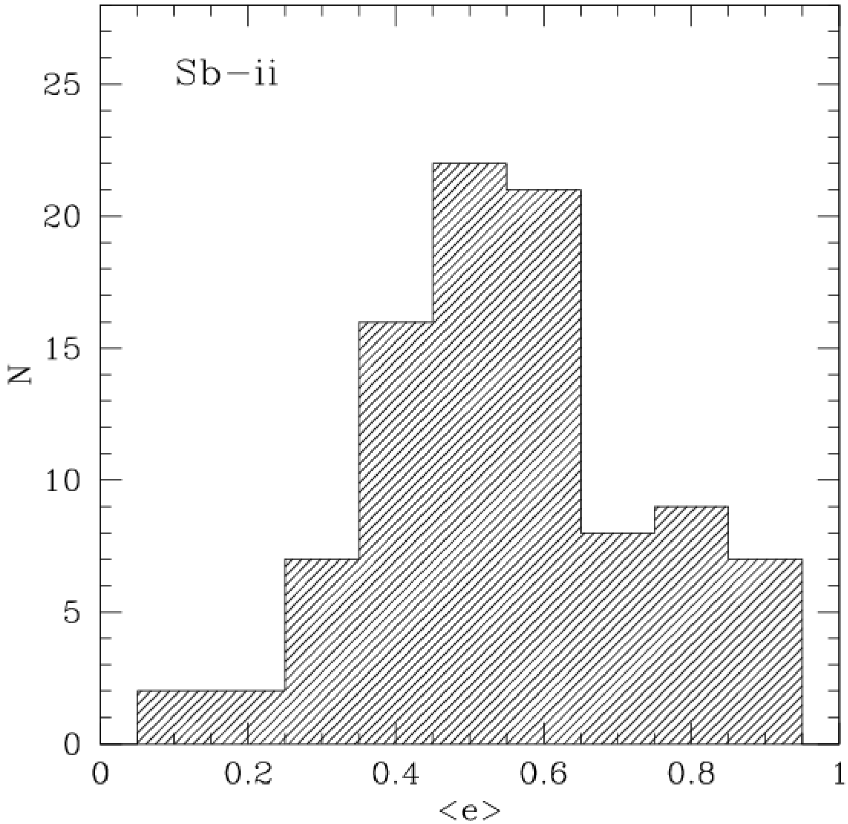


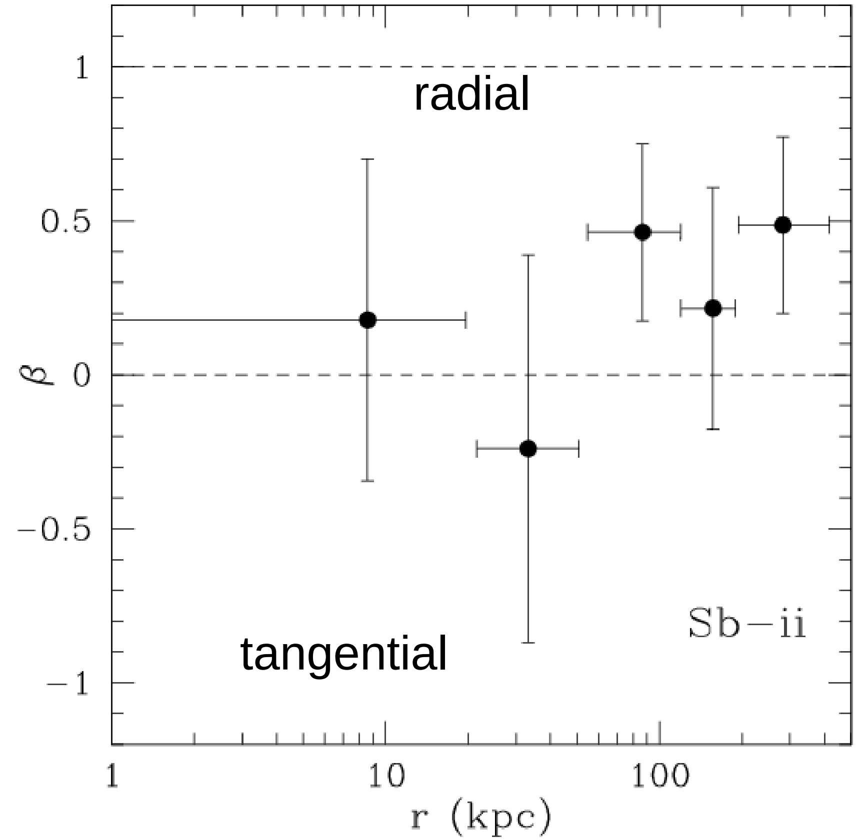


The slope of the spatial distribution is good but the size is wrong



Kinematics

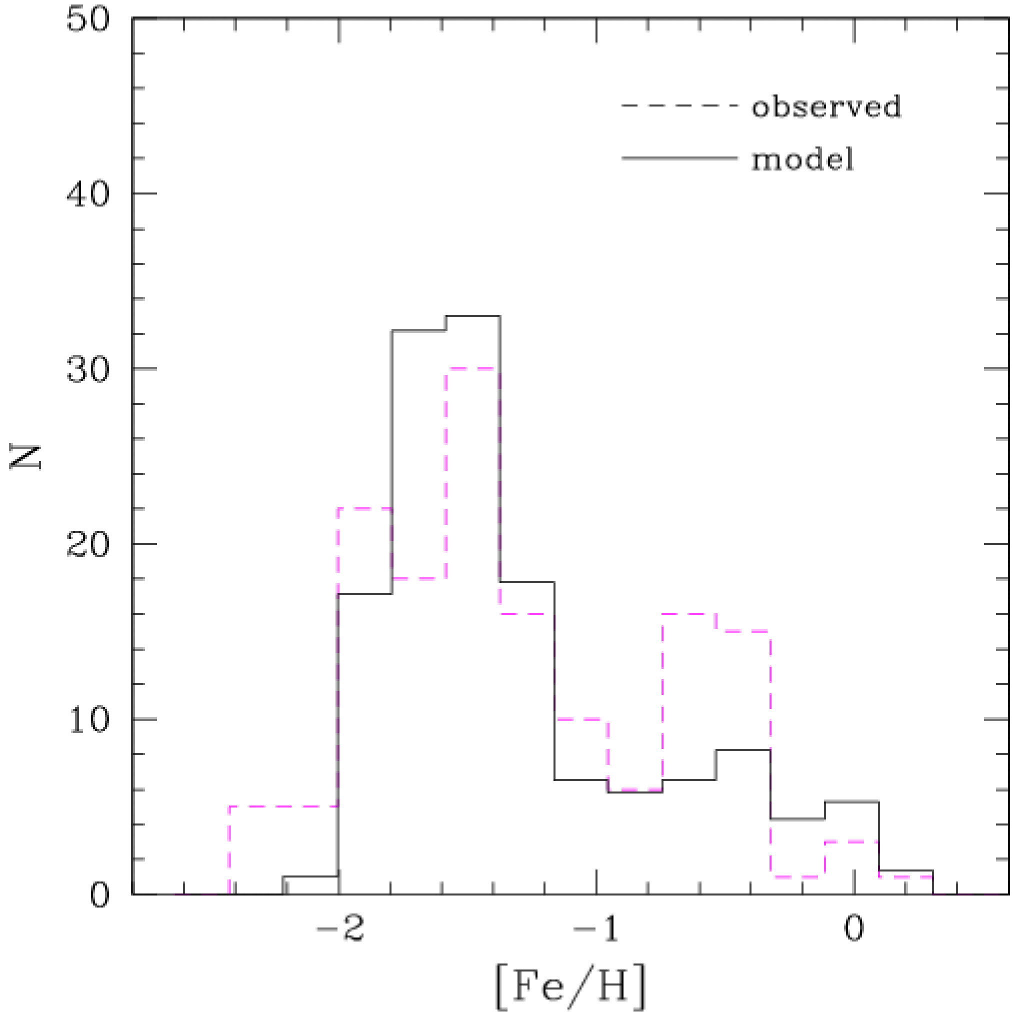




eccentricity
$e = (R_a - R_p)/(R_a + R_p)$

velocity anisotropy
$\beta = 1 - V_t^2 / 2 V_r^2$

Towards understanding metallicity bimodality



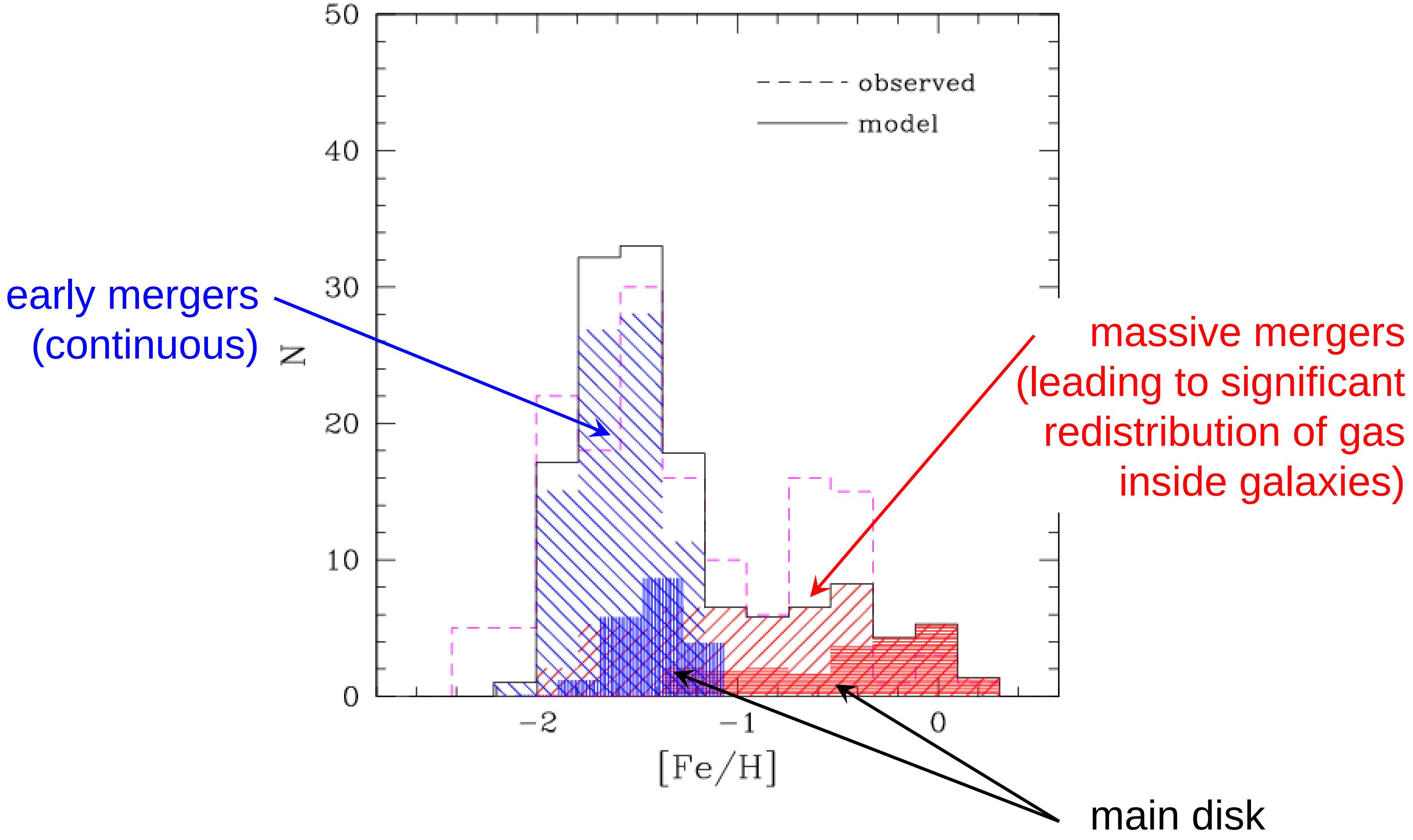
supplement halos with cold gas mass based on observ.

use M_{GC} - M_{gas} relation from sim.

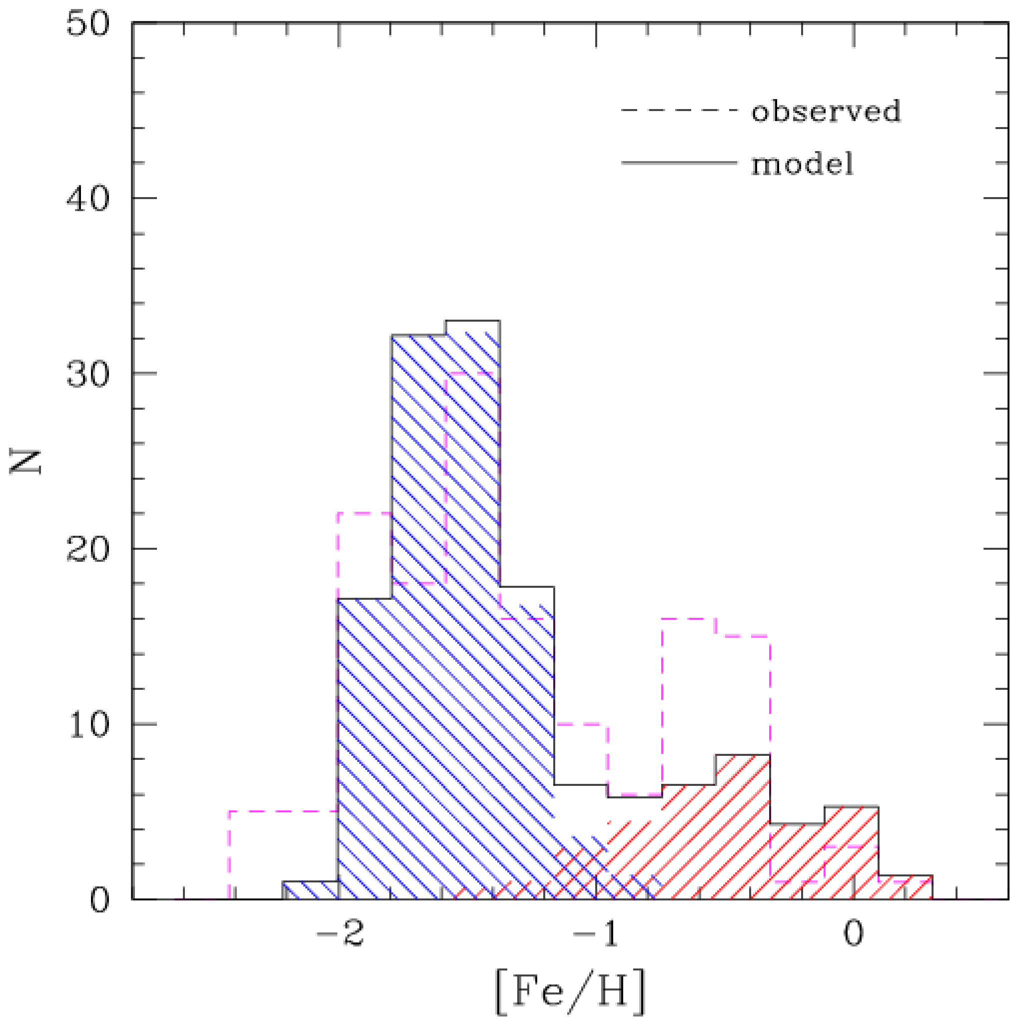
metallicity from observed M_*-Z relation for host galaxies, evolves with time

Sasha Muratov & OG, in prep.

Model: star cluster formation is triggered by gas-rich mergers of progenitor galaxies

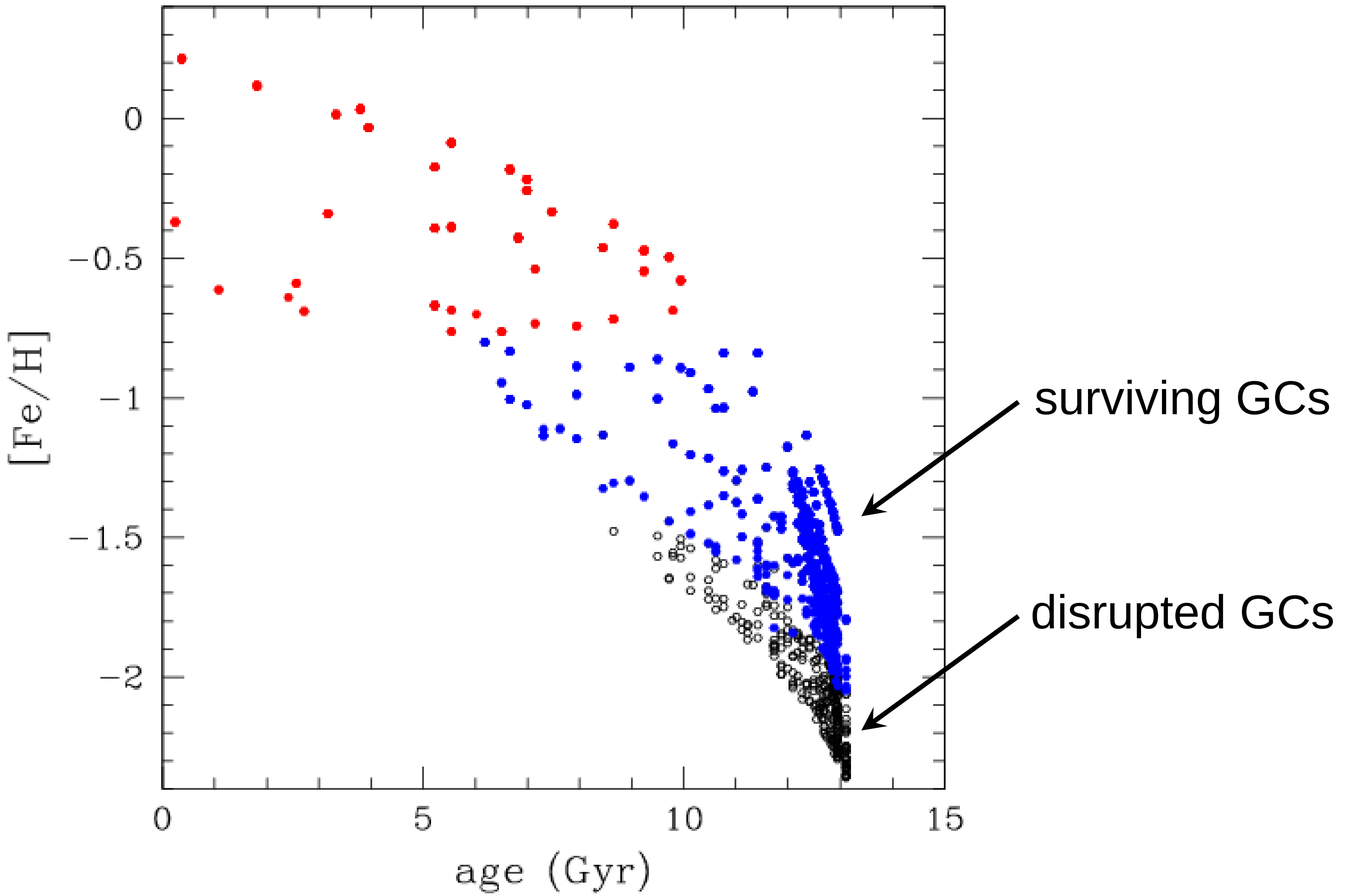


Blue clusters preferentially older, red clusters younger



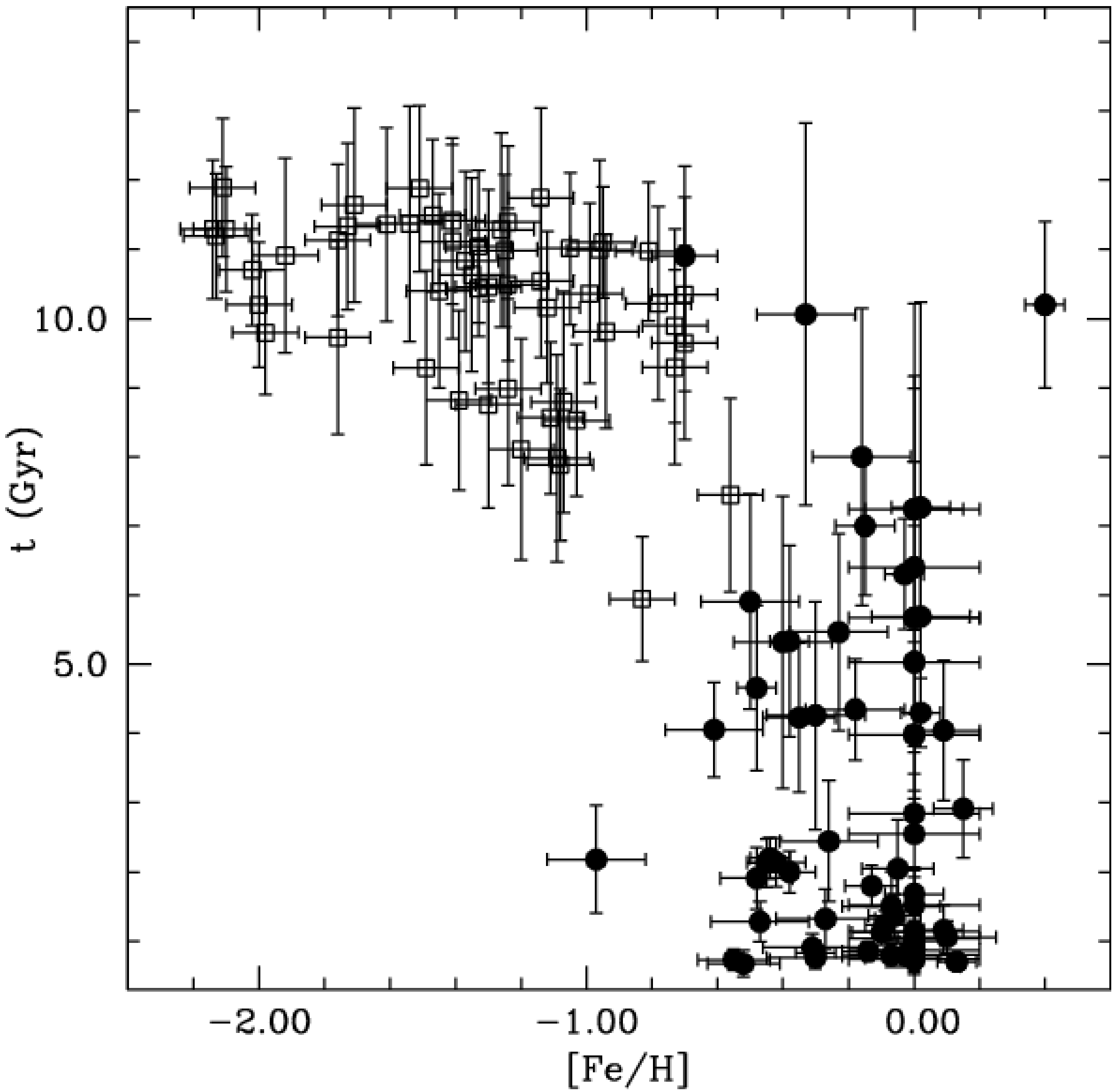
redshift>2 redshift<2

Spread of ages? Several Gyr



- Helps dilute gradient of the mass function: younger clusters form preferentially in inner Galaxy where disruption time is shorter

Not so impossible?



Percival & Salaris

Summary

•Globular clusters may form in giant molecular clouds in progenitor galaxies at intermediate redshifts

•Model explains observed *sizes, masses, ages, metallicities*

•Dynamical evolution explains the present mass function, but not all R-M relations work

•S*patial distribution*: isotropic but more extended than observed

•*Velocity distribution*: isotropic at the center, radial at large radii

•*Red clusters* in the Galaxy are due to massive late gas-rich mergers

•*Blue clusters* are mostly due to early continuous mergers, with some contribution of massive mergers

•Break between populations is due to few late massive mergers

•Massive mergers produce both red and blue clusters in almost equal amounts: in large elliptical galaxies expect red fraction ~ 50%