Current models for globular cluster formation throughout cosmic time

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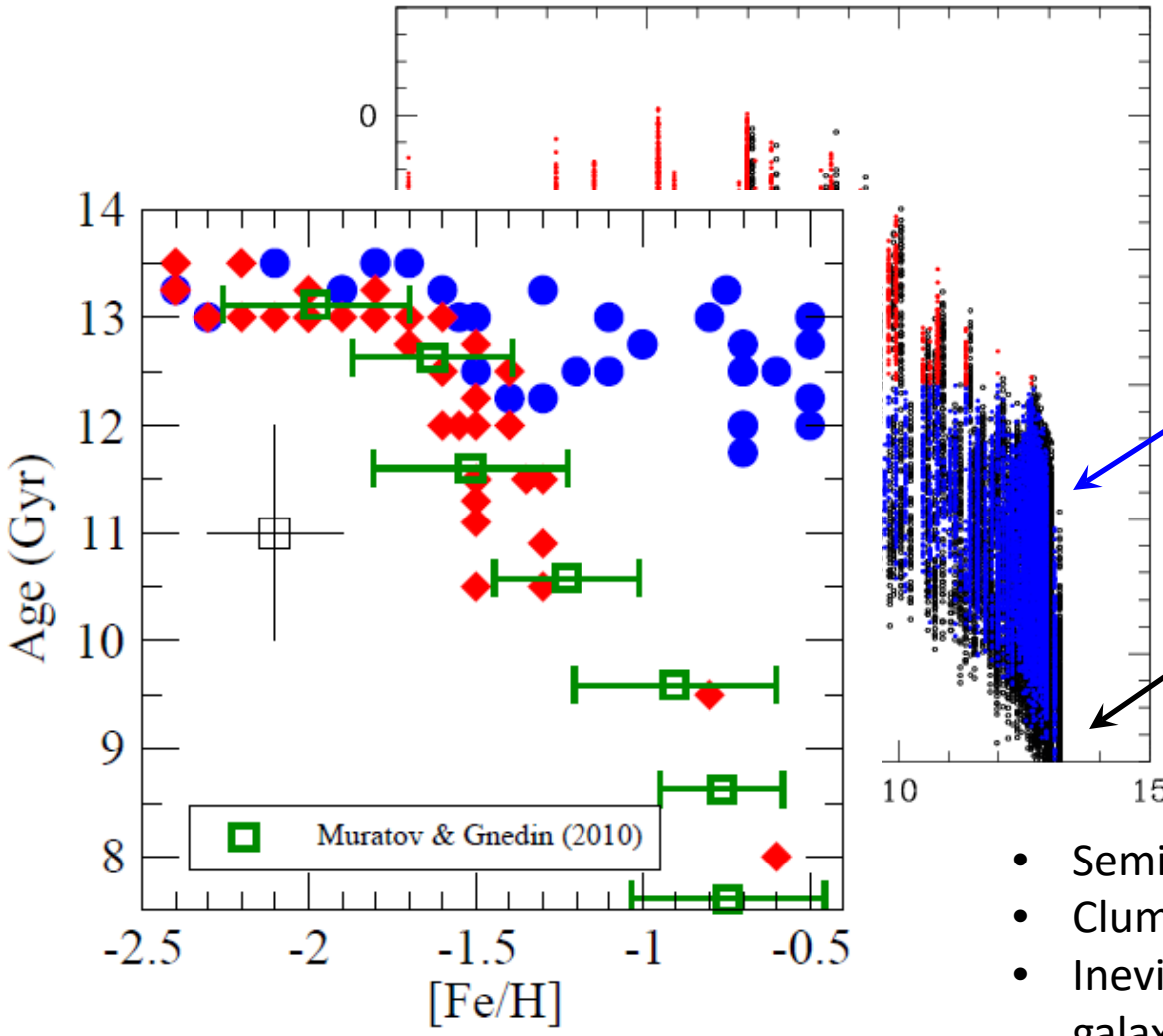
Setting the scene:

Average metallicity of GCs is lower than average metallicity of host galaxy
$\Rightarrow$ in terms of chemical evolution GCs form before majority of stars

Does it necessarily imply the offset in formation epoch?
$\Rightarrow$ need to understand the age-metallicity relation of GCs and field stars

Difference between the build-up of GCs and stars is real but subtle
$\Rightarrow$ opportunity to learn about galaxy formation at high redshift

Age - Metallicity Relation (AMR) for Galactic Globular Clusters



Muratov & OG 2010

(64 random realizations of each cluster)

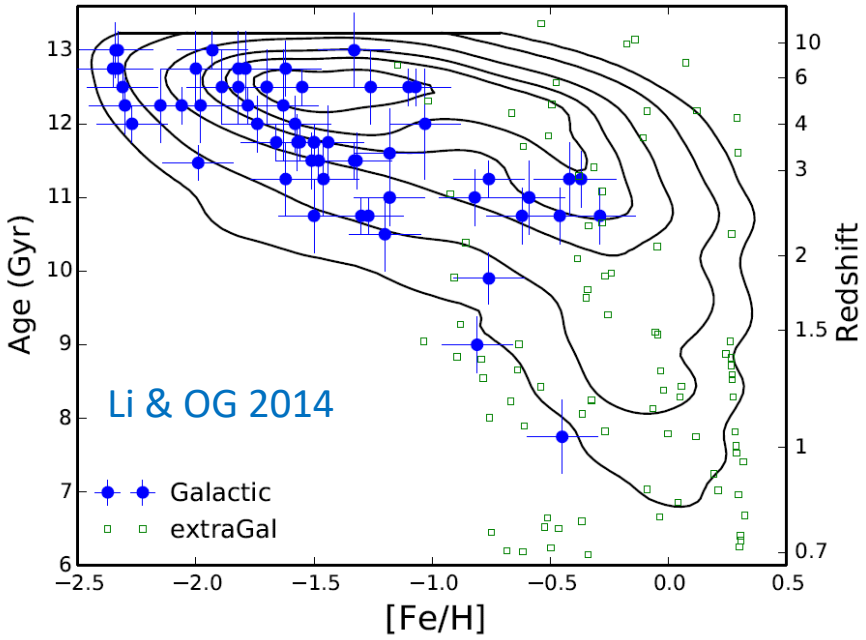
surviving GCs

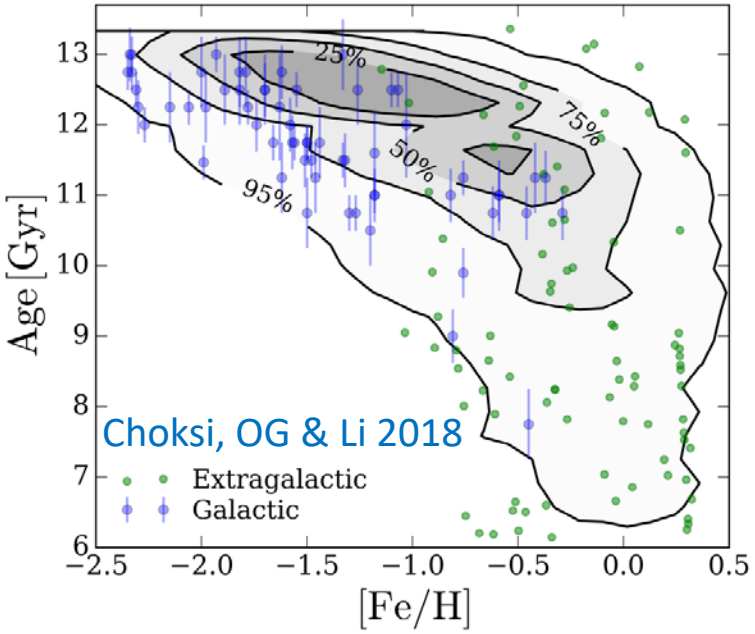
disrupted GCs

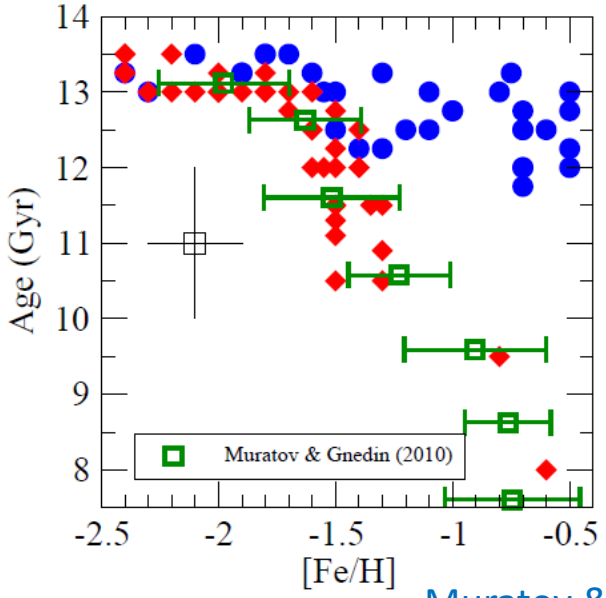
- Semi-analytical model
- Clumsy, many parameters
- Inevitable prediction of connecting galaxy formation and GC formation
- Motivated by Beasley et al. 2002

from resolved CMD with HST: Dotter et al. (2011)

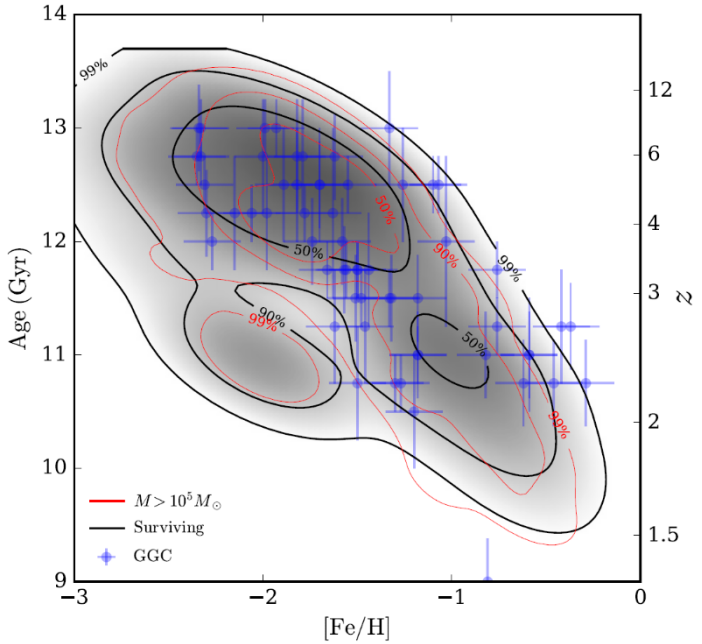
Later versions of the model predicted similar AMR





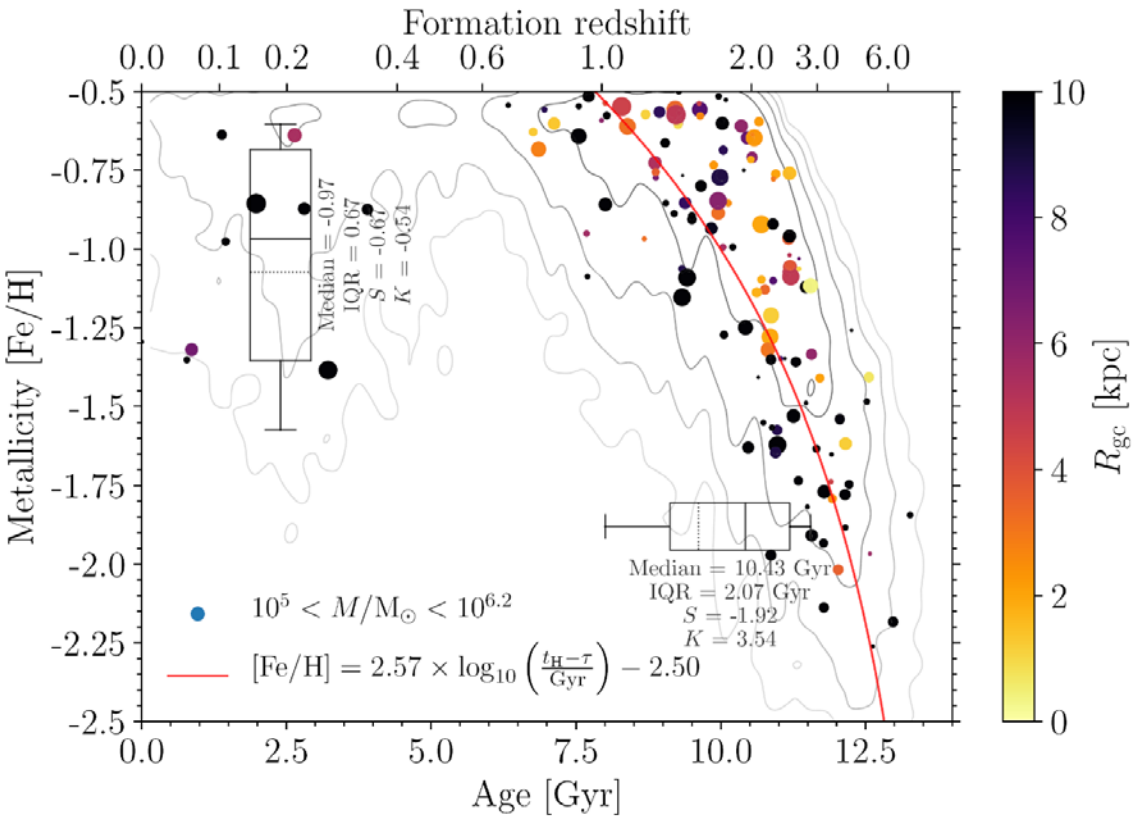


Muratov & OG 2010

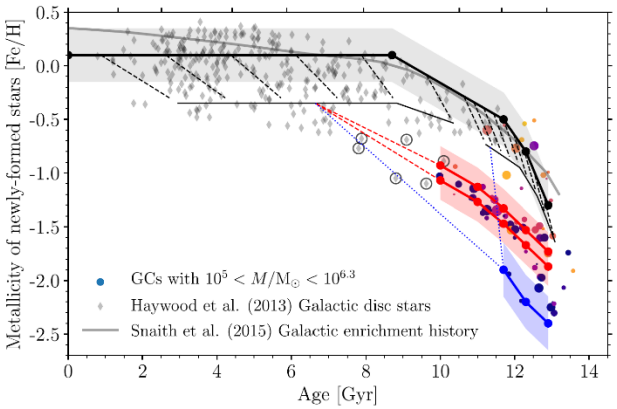


Li & OG 2019
(simulation)

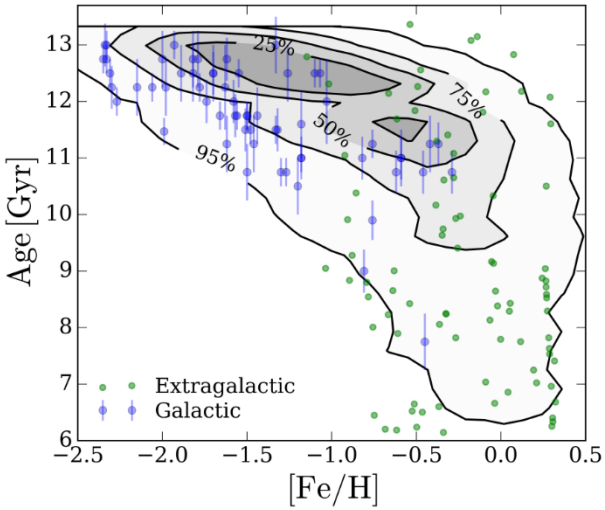
Similar AMR from E-MOSAICS project



Kruijssen et al. 2019



reconstruct accretion events



Choksi, OG & Li 2018

Everything looks similar.

Are we done modeling GC formation?

Origin of the age-metallicity relation in detail

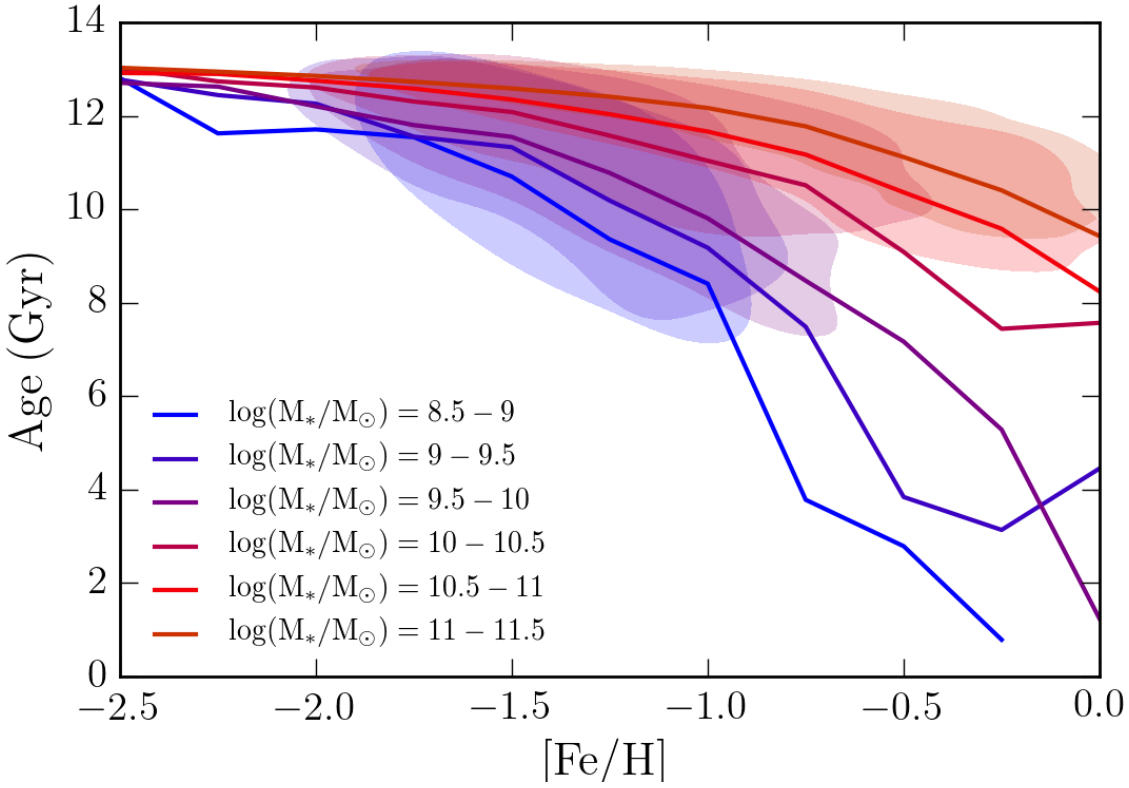
To predict the GC AMR, models need to determine:

- When massive star clusters form (age)
- How many clusters form (distribution)
- How many get disrupted (distribution at z=0)
- What metallicity they get (met)

	Choksi model	E-MOSAICS
Age	Based on rate of host halo mass assembly (*model assumption*)	Based on *EAGLE model* of galaxy formation
Distribution	Proportional to cold gas mass supply (*from empirical galaxy scaling relations*)	*EAGLE* SFR times cluster formation efficiency Γ based on P_{gas} and ρ_{gas}
M_c	Fixed $\sim 10^7\ M_\odot$	Based on Γ and M_{GMC}
Distribution at z=0	Disruption model based only on cluster mass, plus stellar evolution	Mass-dependent relaxation, *tidal shocks*, plus stellar evolution
Metallicity	*Empirical galactic mass-metallicity relation*	*EAGLE model*
Currently applied	Wide range of host mass from giants to dwarfs, plus many statistical realizations to account for uncertainty of scaling relations	25 Milky Way-sized galaxies and dwarf satellites

Also: Boylan-Kolchin 2017; El-Badry et al. 2019; Katz & Ricotti 2014; Renaud et al. 2017; Trenti et al. 2015

AMR as a function of host galaxy mass



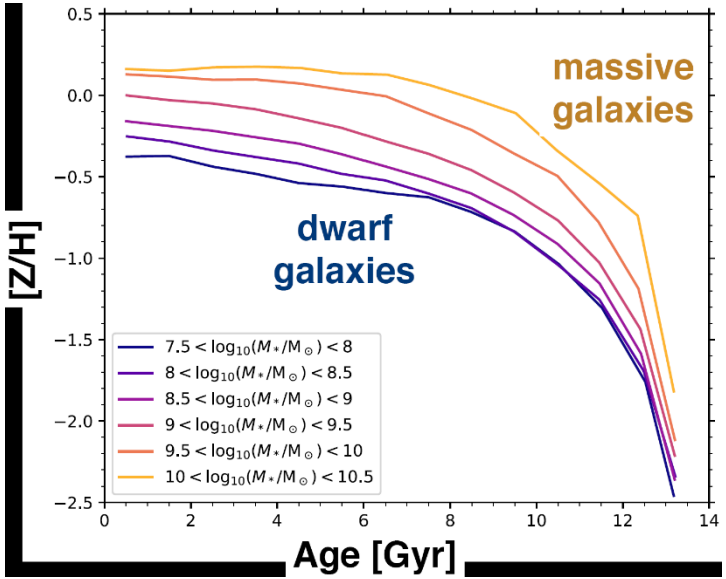
Choksi model

<u>For meaningful tests of models we need age accuracy of 1 Gyr.</u>

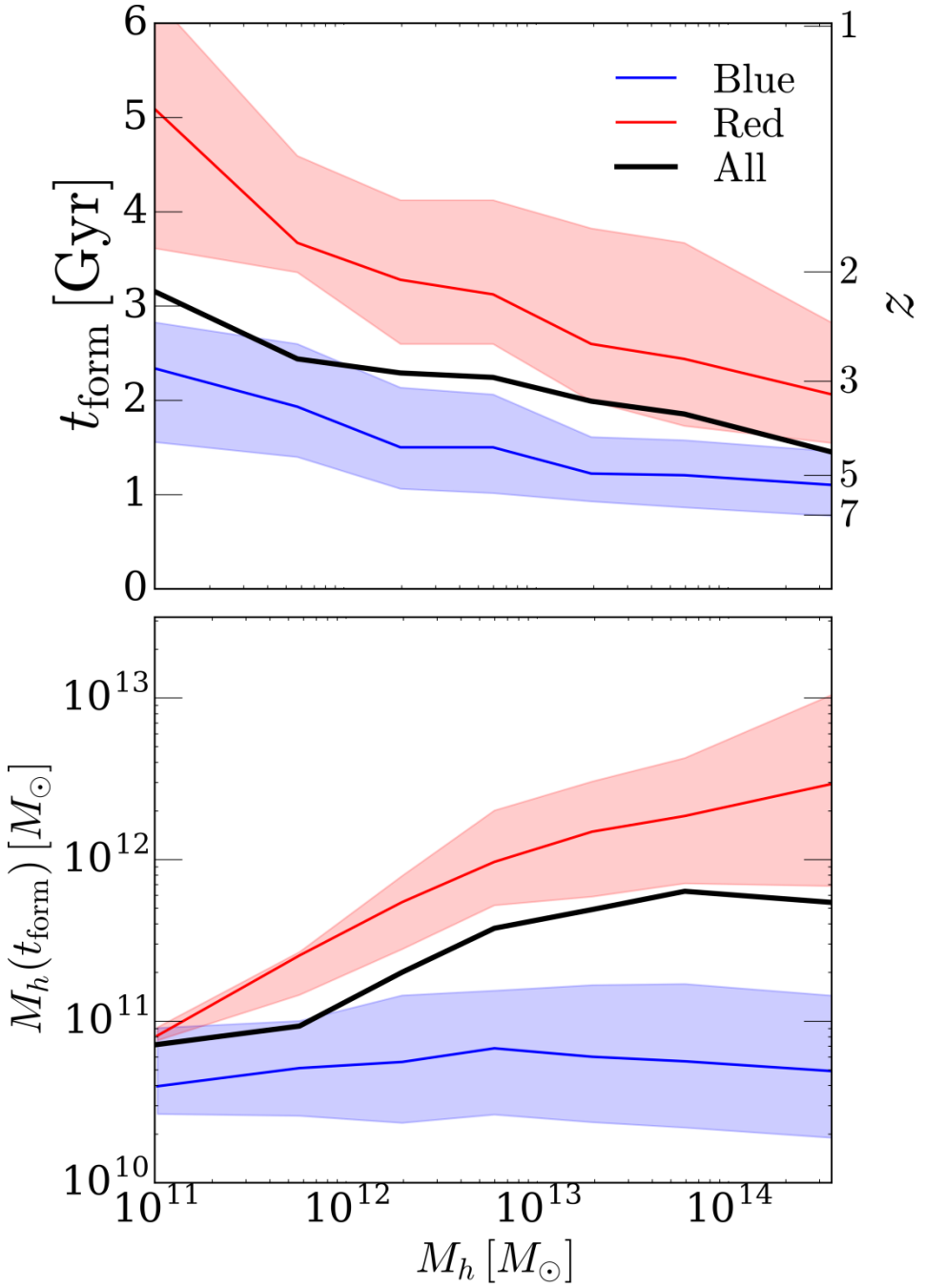
Need extragalactic GC systems.

Relative ages suffice for testing host galaxy environment.

Distributions overlap: need good statistics.



EAGLE sims: Pfeffer



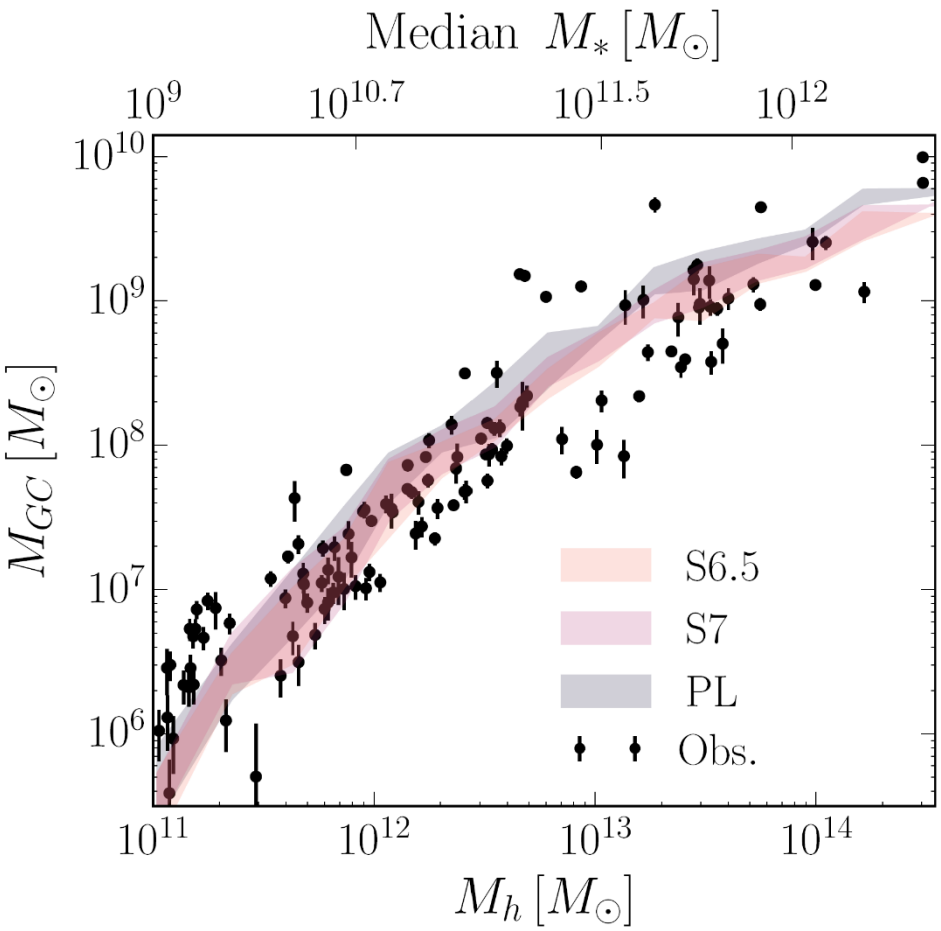
Most blue clusters form when halo mass is $2\times10^{10} - 10^{11}$ $M_\odot$ at redshifts *z = 3-7*

Red clusters form at *z = 2-4* in most massive galaxies, and at *z = 1-2* in dwarfs *(downsizing effect)*

Age differences are easier to measure for red clusters and in less massive galaxies.

25% - 75% range of all clusters formed (and survived to z=0) within a galaxy of mass M_h (Choksi, OG & Li 2018)

Globular cluster system mass – Host halo mass relation



Observations include:
- Milky Way, M31
- Virgo Cluster galaxies
- Brightest Cluster Galaxies

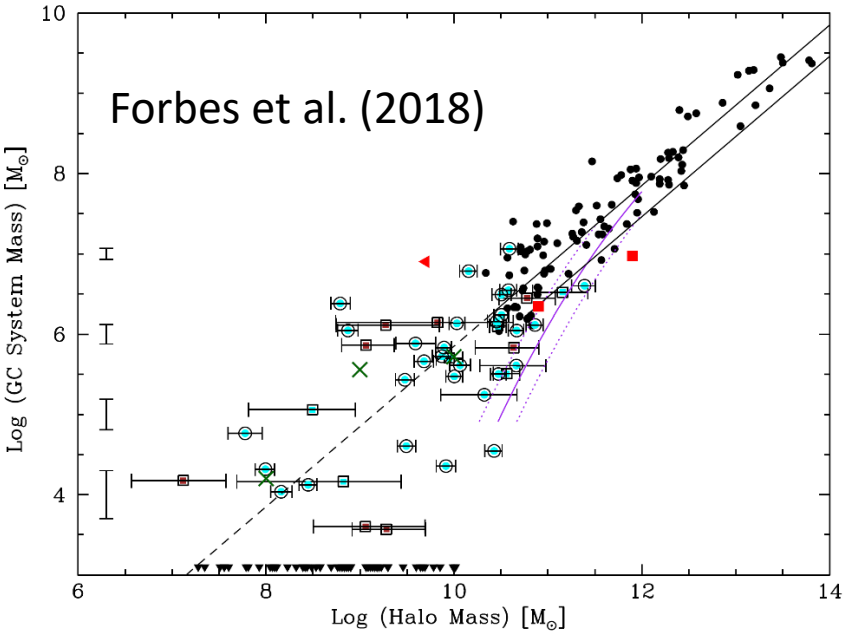
Choksi, OG & Li (2018)

New tight scaling relation to determine halo mass.

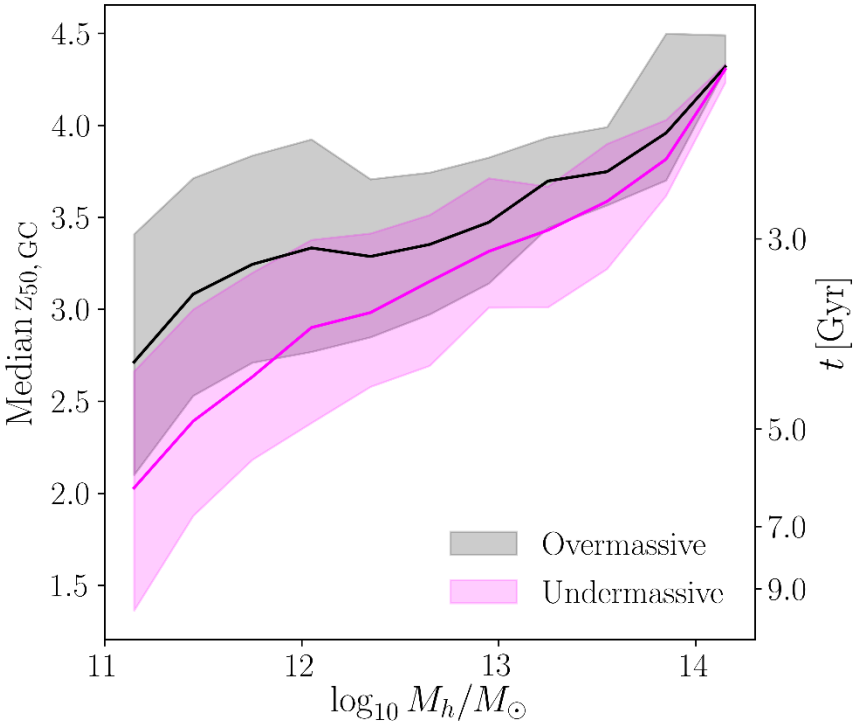
Observed scatter < 0.3 dex, intrinsic scatter consistent with zero.

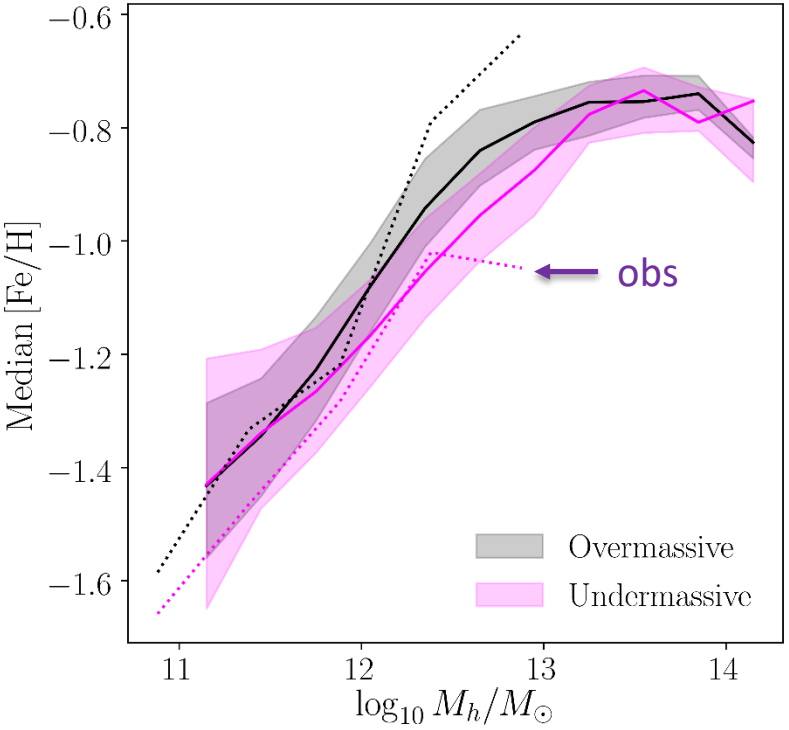
Model scatter is due to different galaxy assembly histories.

<u>What about dwarf galaxies?</u>



Systematic properties of M_{GC}-M_h relation

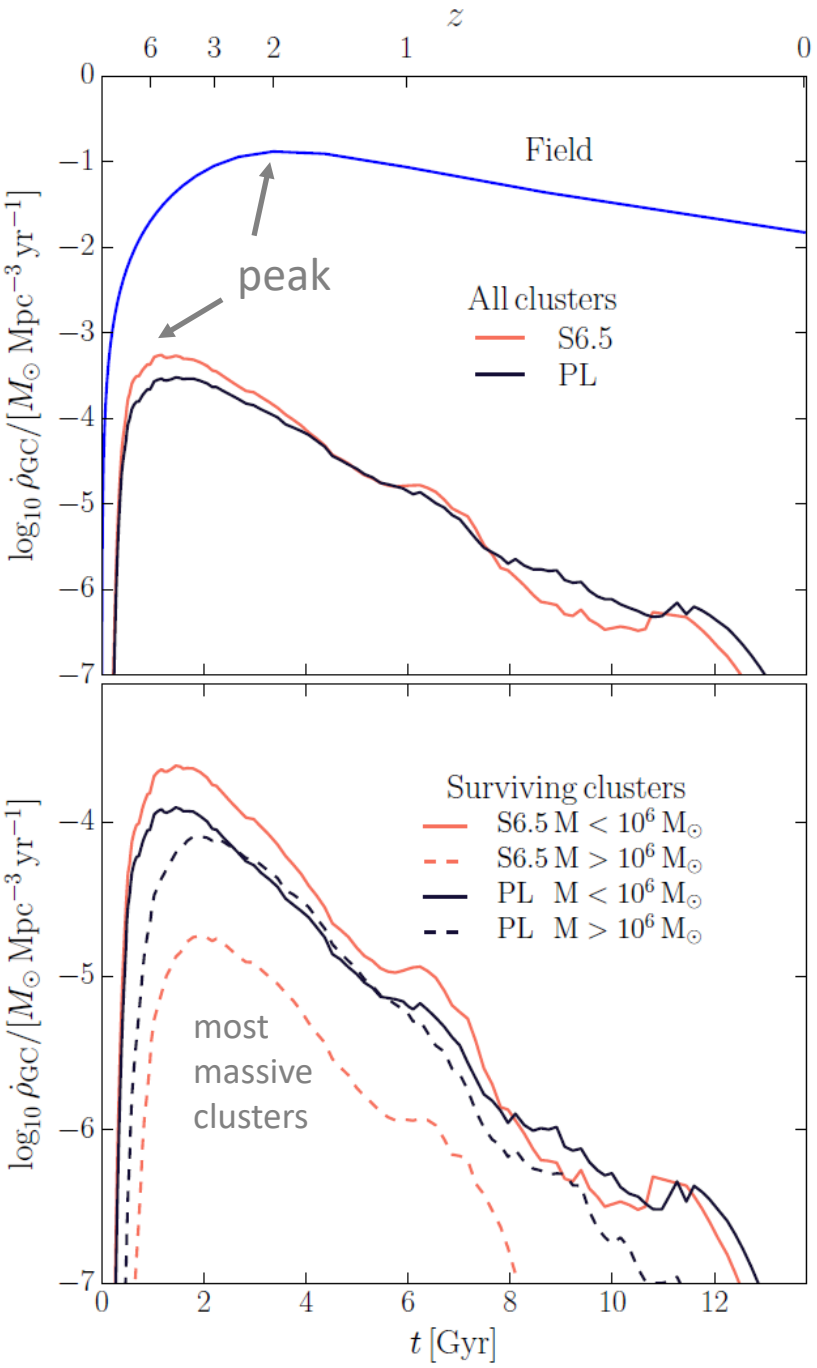




Choksi & OG in prep.

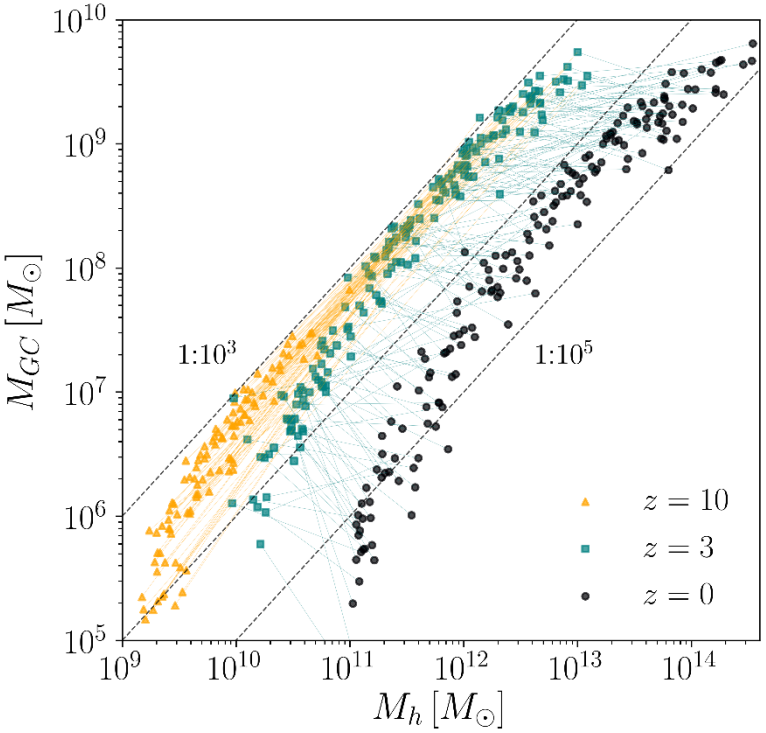
GC systems above the mean relation are expected to form 1-2 Gyr earlier, with 0.1 dex higher [Fe/H]

(because of higher gas mass and density at higher z)



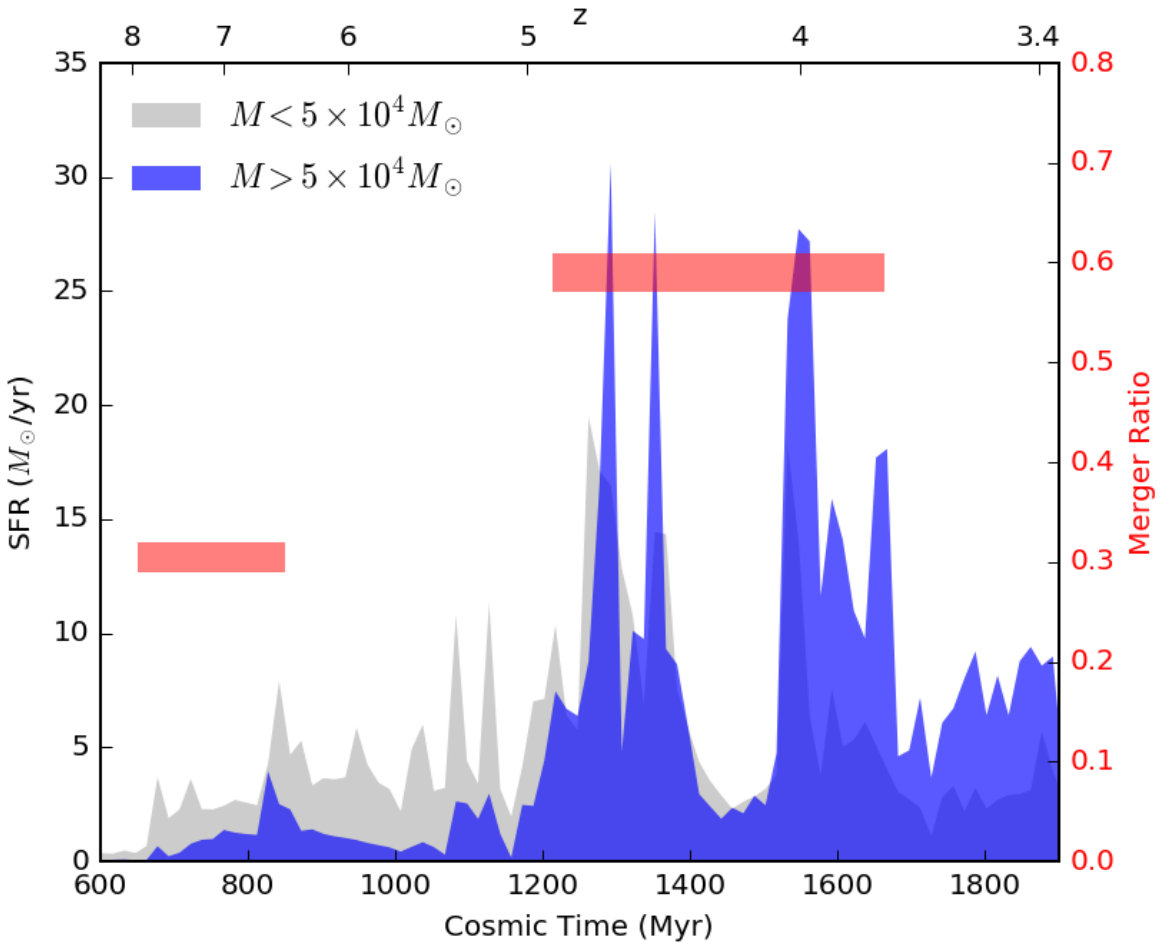
At redshifts z>3 young massive star clusters constitute a much higher fraction of star formation than now.

<u>JWST will directly probe formation of proto-globular clusters.</u>



Choksi & OG 2019

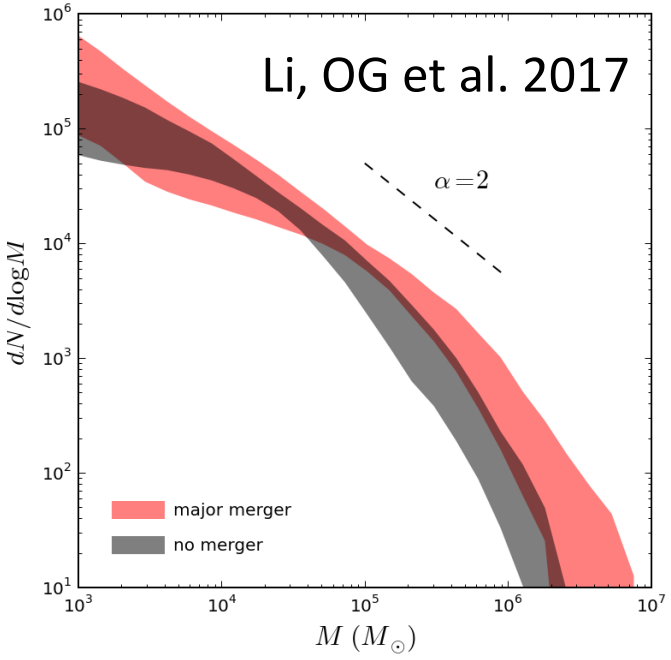
Gas-rich mergers of massive galaxies promote cluster formation



because they enhance SFR (M_c scaling: Adamo)

but mergers also enhance cluster disruption

<u>Need better understanding with high-res simulations</u>

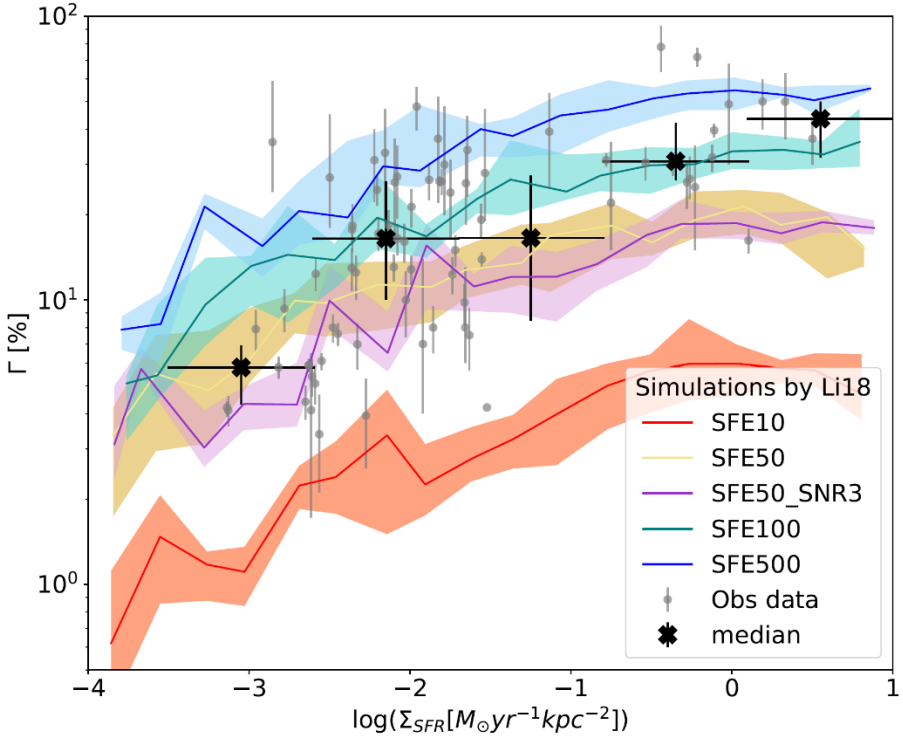


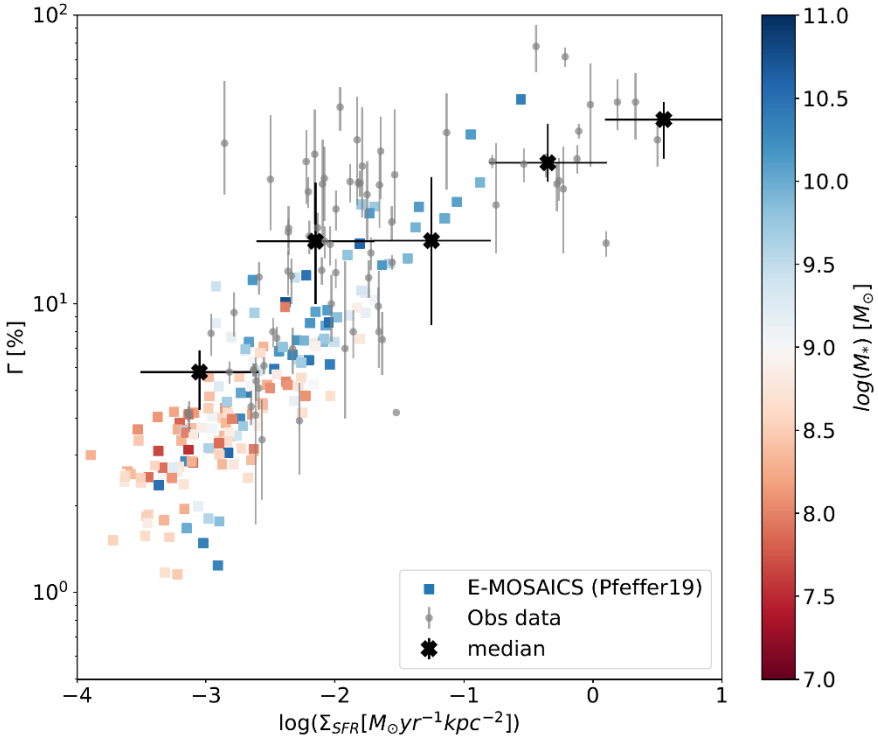
Cluster MF is more strongly truncated between mergers

Fraction of clustered star formation Γ

A new powerful test of galaxy formation simulations – constrain modeling of star formation and feedback

<u>Can this relation be probed on smaller scales?</u>





Adamo et al. 2020

Discussion points

Need to measure AMR in extragalactic GC systems to test models: relative age accuracy ~1 Gyr. Expect larger differences for red clusters and in smaller galaxies.

Need good statistics because AMR of galaxies of different mass overlap.

M_{GC}-M_h relation in dwarf galaxies: need to measure galaxy mass better.

Overmassive GC systems are expected to form 1-2 Gyr earlier, with 0.1 dex higher [Fe/H].

Normalization of M_{GC}-M_h relation is expected to be an order of magnitude higher at z>3. JWST will directly probe formation of proto-GCs.

Gas-rich mergers promote GC formation(?) Need better understanding from cosmological simulations with ultrahigh resolution and GC physics.