Modeling the Globular Cluster System - Halo Mass relation

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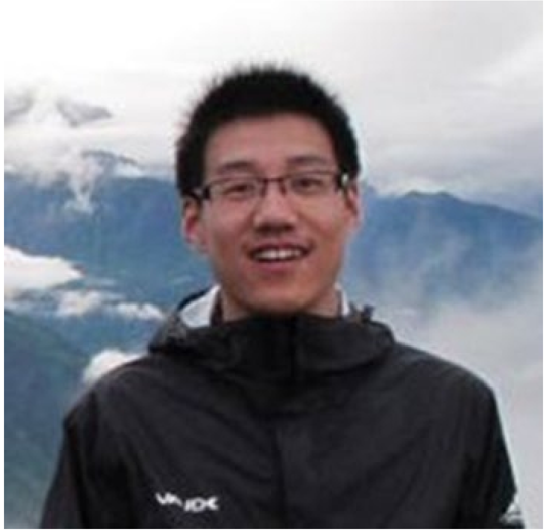
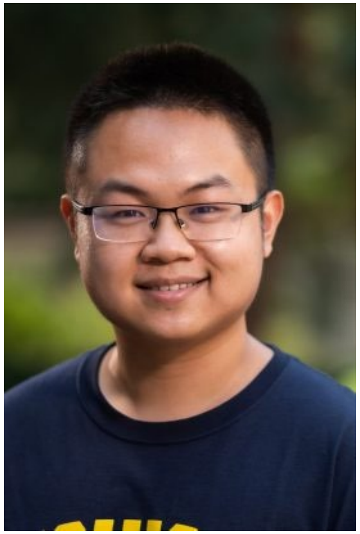
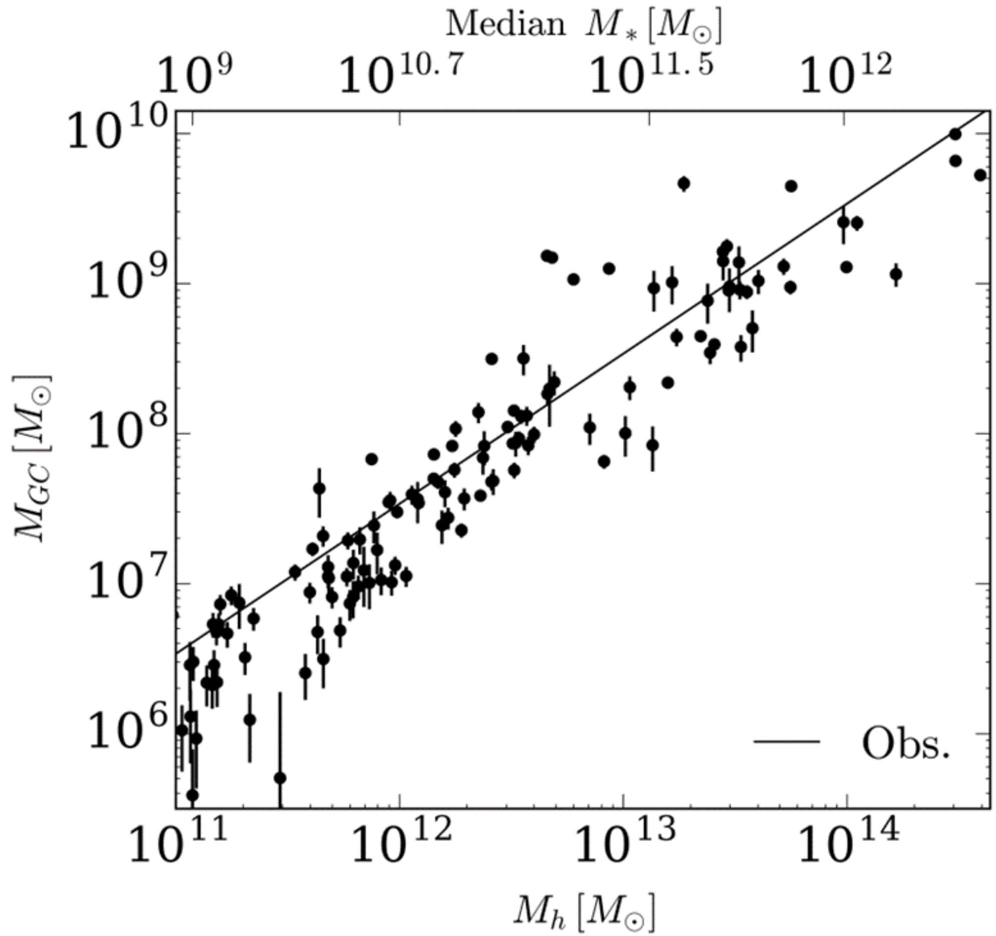


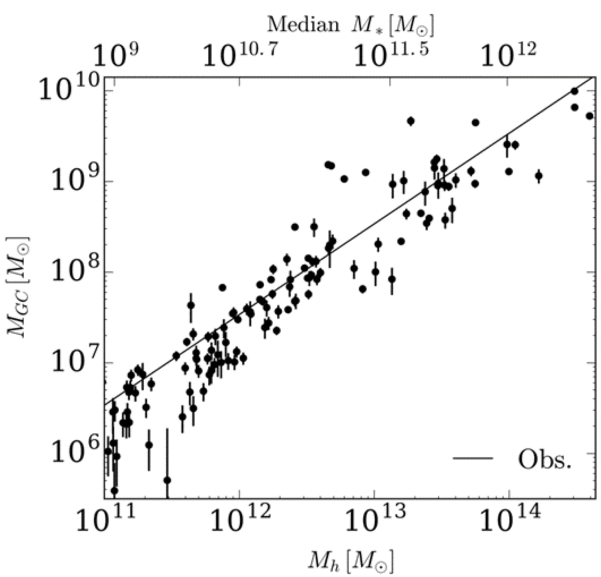


Setting the stage: Counting GCs in a central galaxy provides an estimate of the host halo mass

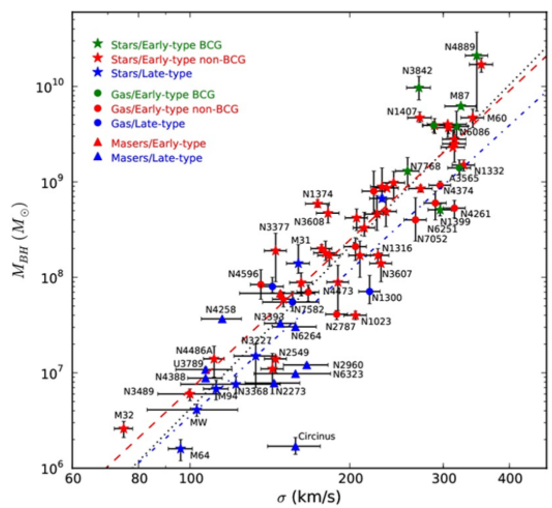
- $M_h \approx 3 \times 10^4\ M_{GC}$
- Observed scatter 0.28 dex (Harris et al. 2017) which includes 0.2 dex scatter in M_{GC} and 0.2 dex scatter in M_h (based on CFHTLenS lensing mass + dynamics)

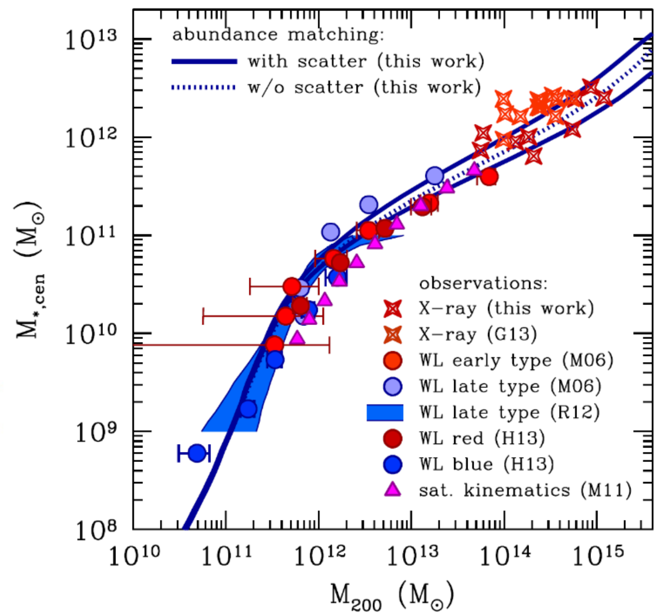


- Independent of other methods of measuring halo mass
- Scatter is comparable or smaller than for other scaling relations
- (Almost) linear trend vs. non-linear M_* - M_h relation
- Practical application at distances < 300 Mpc, to resolve GC population with HST and JWST imaging



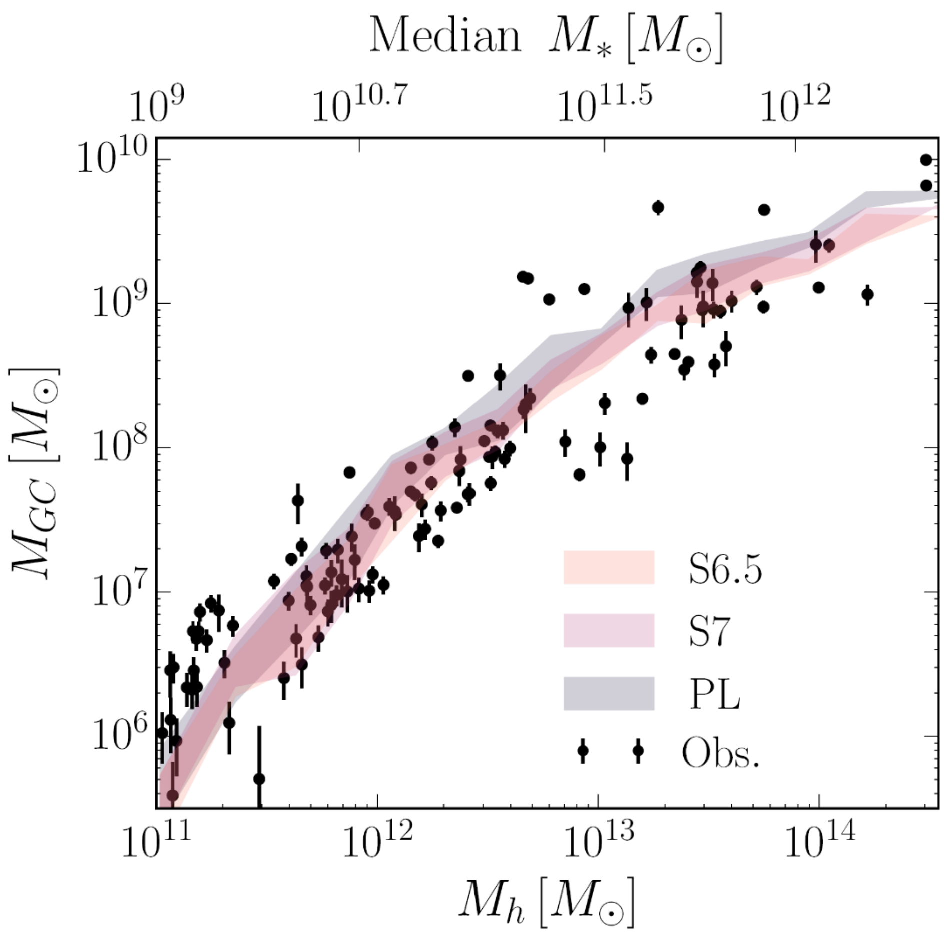
Black hole mass – velocity dispersion





Stellar mass – halo mass

Is this relation expected from models of globular cluster formation?



Choksi & OG (2019a):
shape of the relation is not explicitly modeled but comes out as a robust prediction

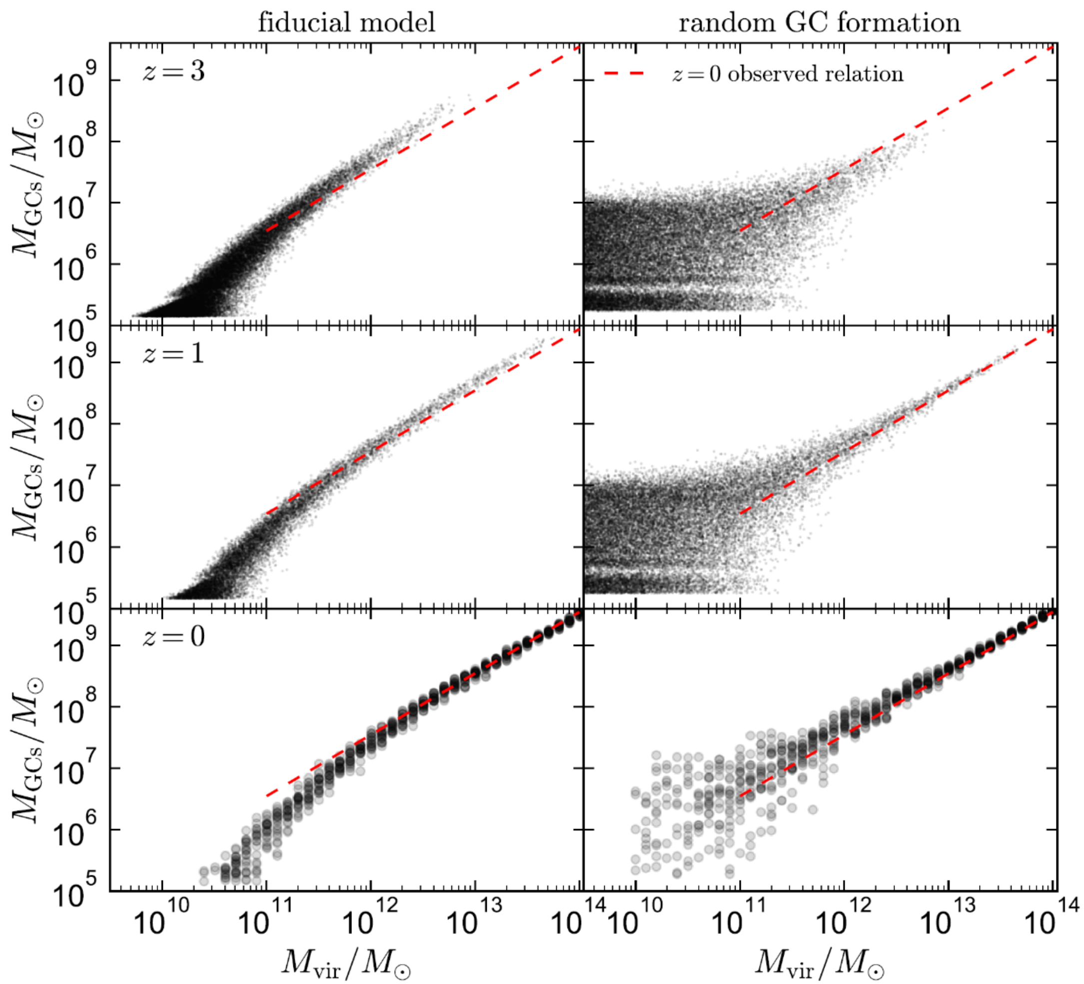
Observed scatter < 0.3 dex

Model scatter is also about 0.3 dex, due to different galaxy assembly histories

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

The relation also appears in other models:

El-Badry et al. (2019) merger-based semi-analytical model and a random merging model (also Bastian et al. 2020)



Model with updated galaxy scaling relations circa 2022

Model has three adjustable parameters:

$$M_{\rm GC} = 1.8 \times 10^{-4} p_2 M_g$$

GCS rate scales with cold gas mass

$$R_m \equiv \frac{M_{h,2} - M_{h,1}}{t_2 - t_1} \frac{1}{M_{h,1}}.$$

GCs form when halo is actively growing (often due to mergers)

Cluster formation is triggered if $R_m > p_3$

The rest are published galactic scaling relations:

Lilly+13, Genzel+2015, Tacconi+2017

$$\frac{M_g}{M_*} \equiv \eta(M_*, z) = \eta_9 \left(\frac{M_*}{10^9\, M_\odot} \right)^{-n_m} (1+z)^{n_z}$$

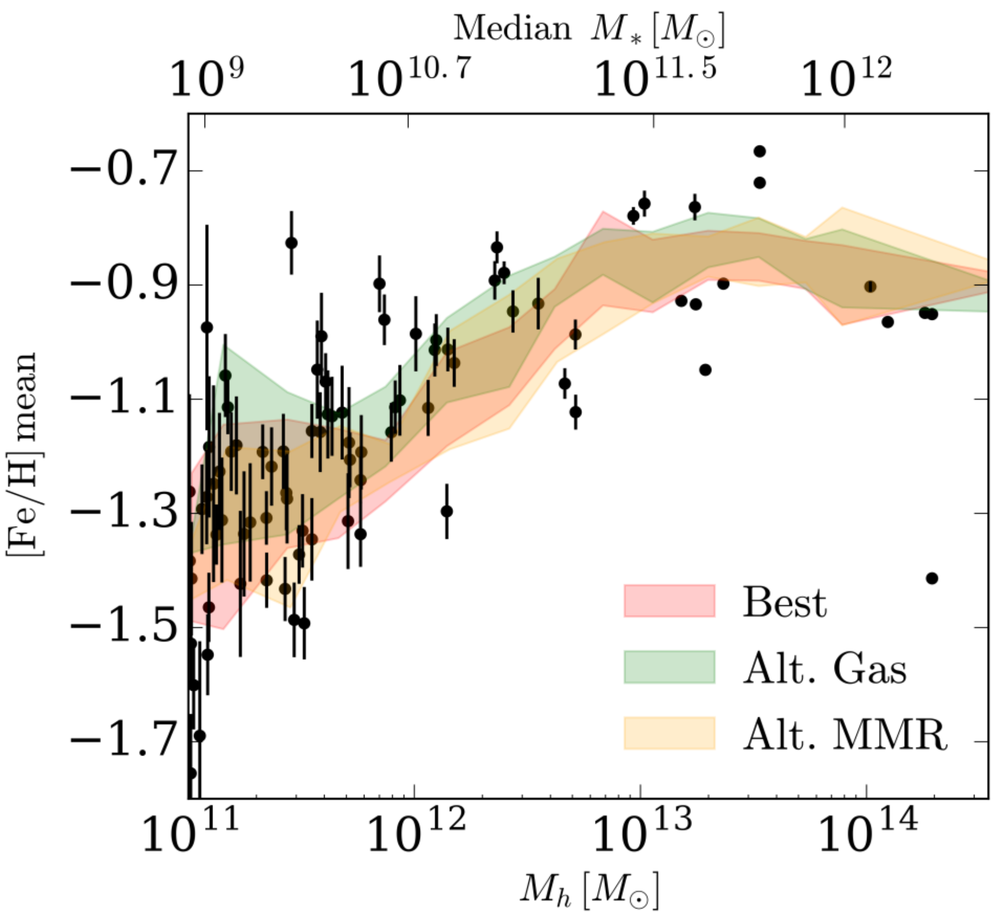
evolution of cold gas fraction

Mannucci+2009, Kirby+13, Ma+16

$$[\mathrm{Fe/H}] = \log_{10} \left[\left(\frac{M_*}{10^{10.5} M_\odot} \right)^{\alpha_m} (1+z)^{-\alpha_z} \right]$$

mass-metallicity relation

Model is tested on predictions for GC age-metallicity distribution



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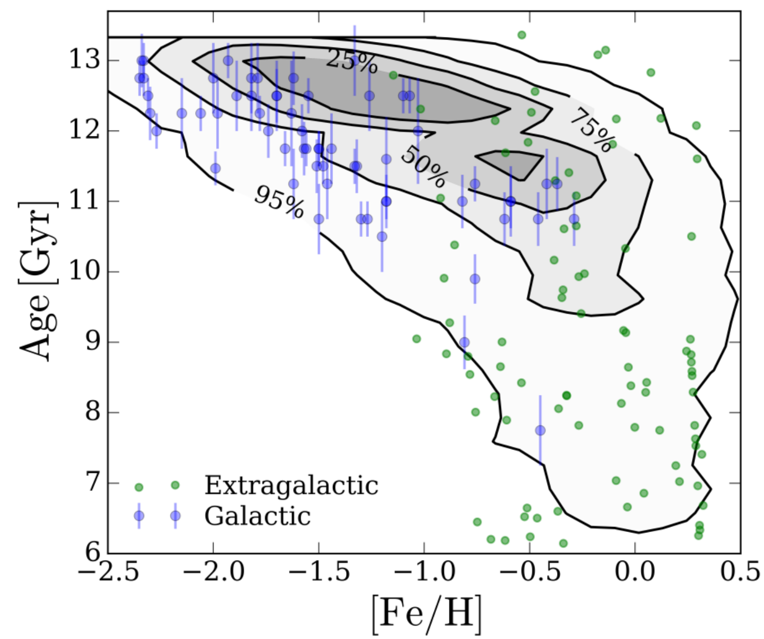
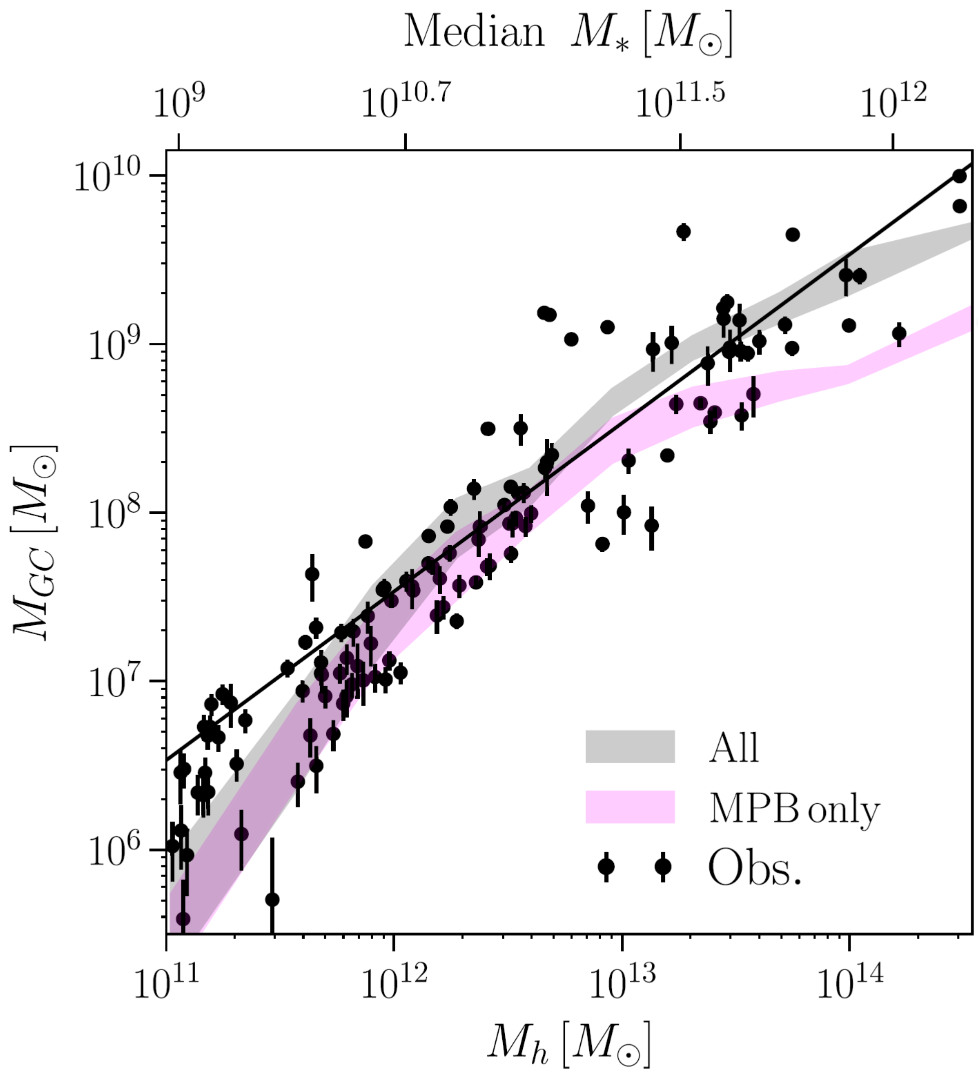


Choksi, OG & Li 2018

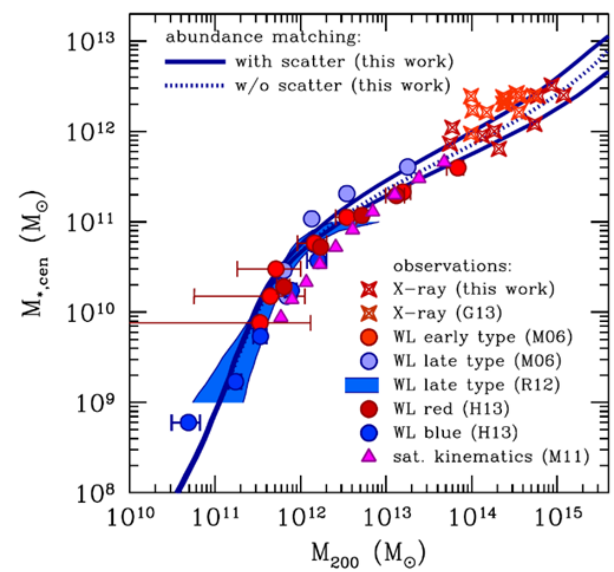
Most GCs in galaxy groups and clusters are formed in satellite galaxies that merge into the central galaxy



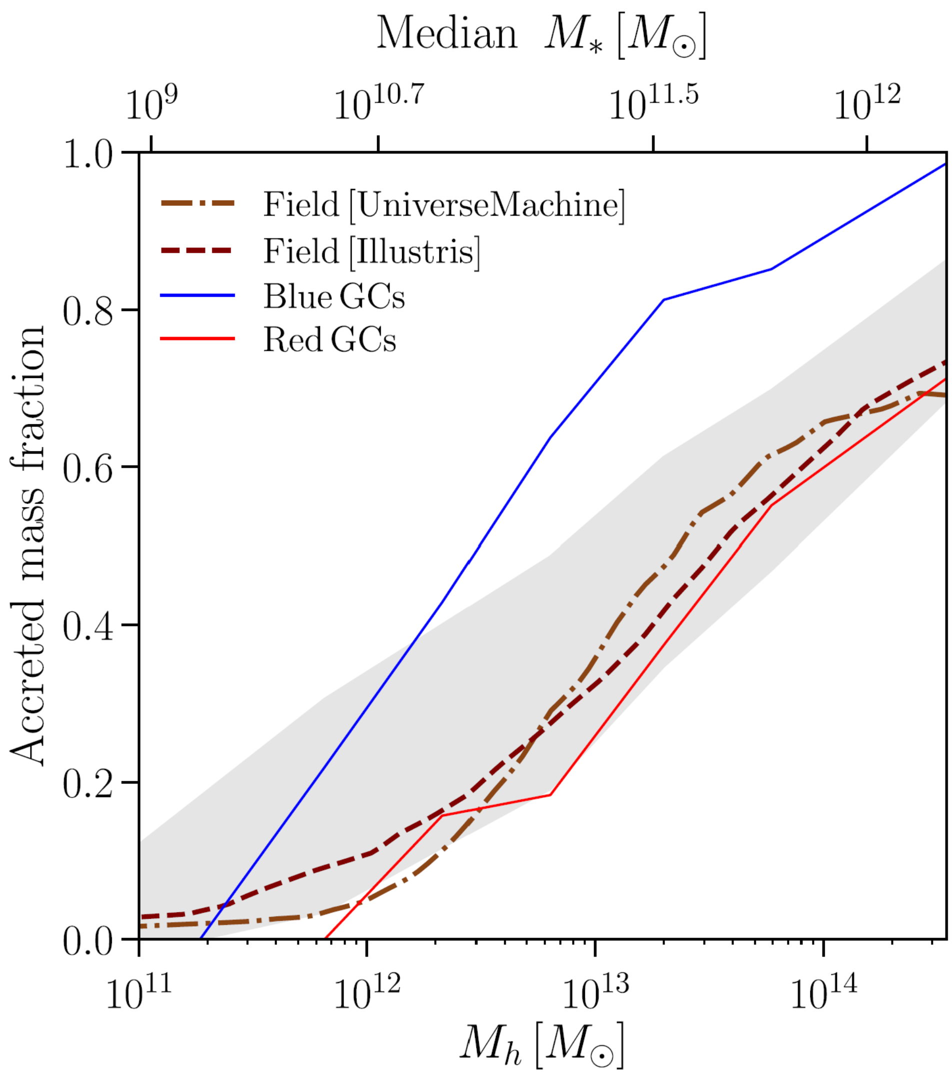
total for central galaxy

formed in-situ only

In-situ similar to field mass accumulation in central galaxies:



Accretion of satellites (ex-situ clusters)



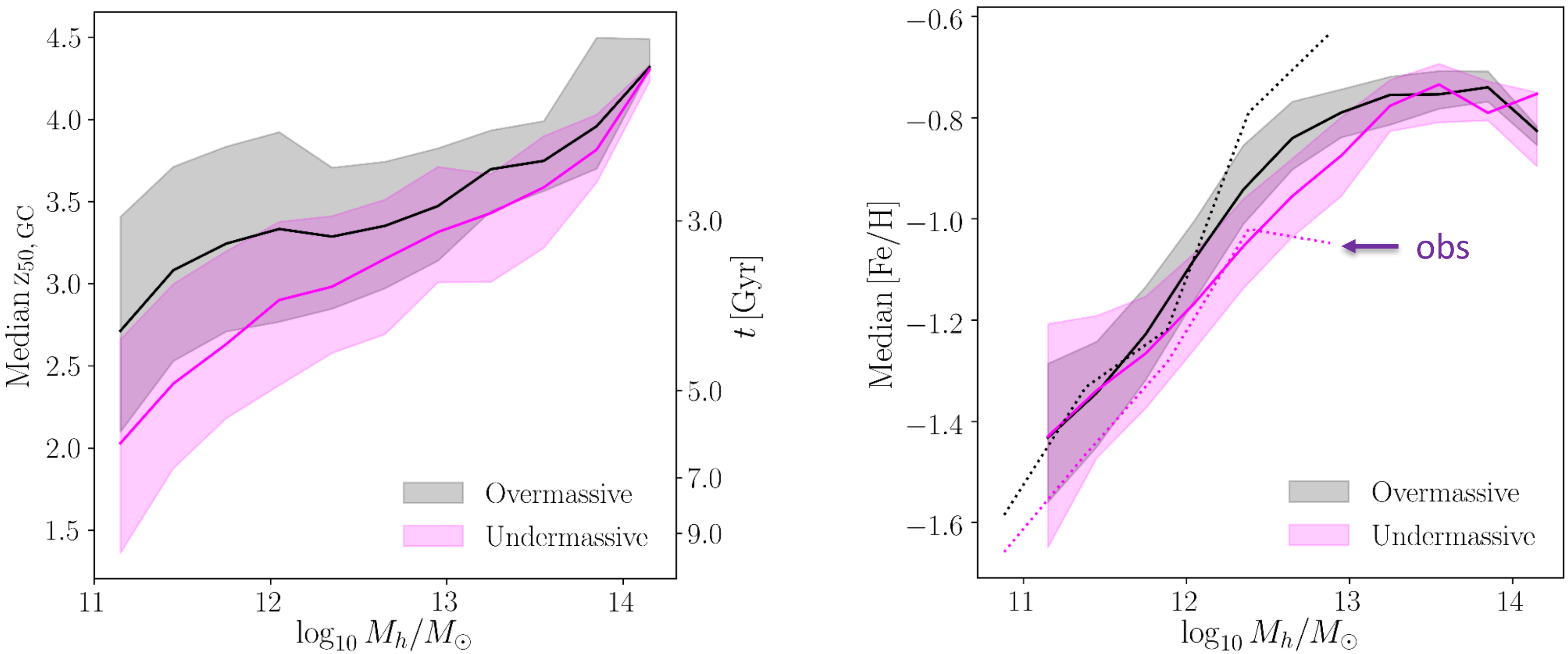
More important for GCs than for field stars

Satellites responsible for straightening the M_{GC}-M_h relation at high mass

Scatter at highest masses is real and due to differences in the assembly history

Choksi & OG 2019b

Systematic properties of M_{GC}-M_h relation

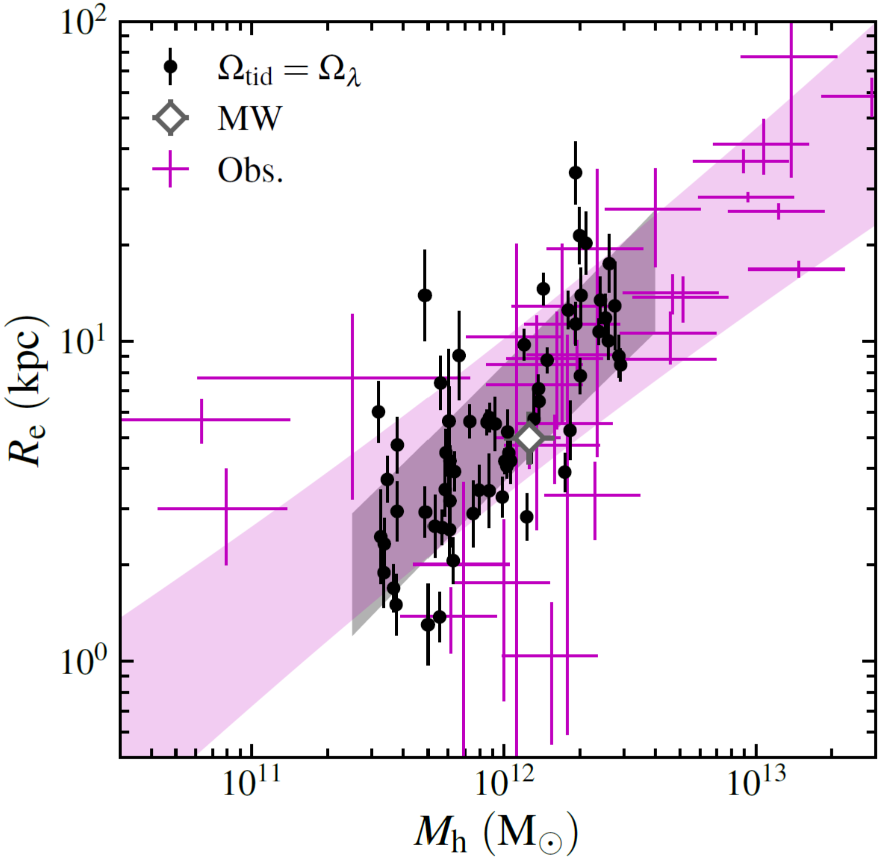


GC systems above the mean relation are expected to form 1-2 Gyr earlier, with 0.1 dex higher [Fe/H]

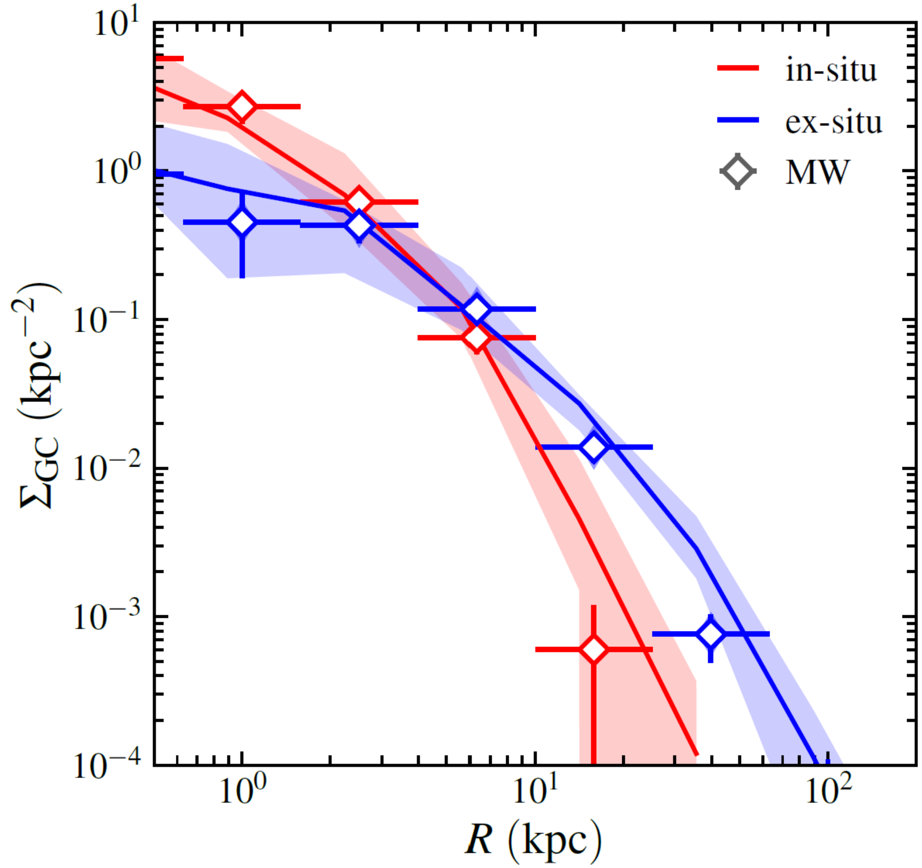
(because of higher gas mass and density at higher z)

New version of the model: Chen & OG (2022)

includes cluster disruption based on local tidal field
predicts spatial and kinematic distribution of GC system



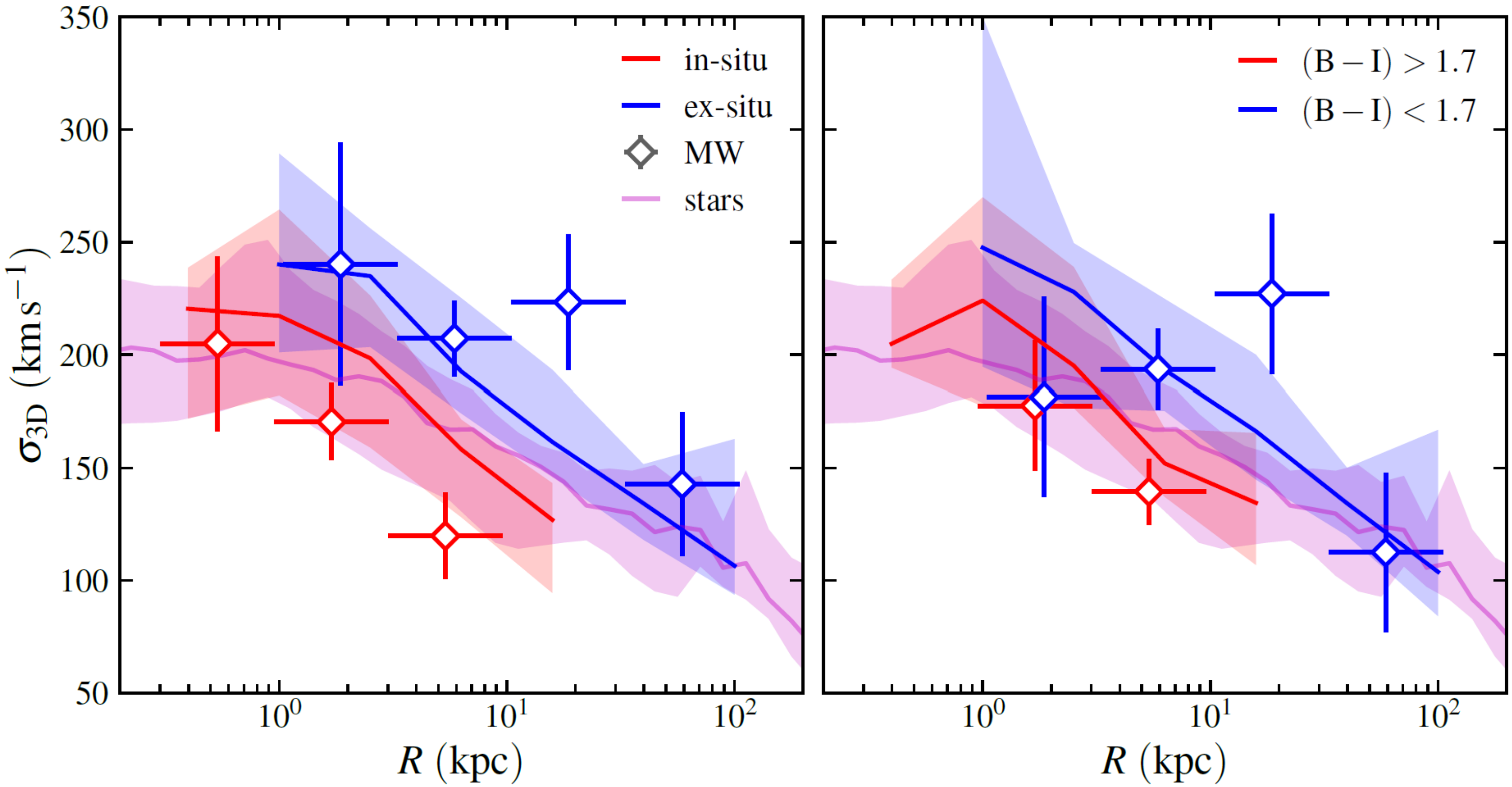
Effective radius of the whole GCS, based on de Vaucouleurs fit



Surface number density for in-situ and ex-situ GC in MW mass galaxies

Kinematic signatures of in-situ and ex-situ clusters

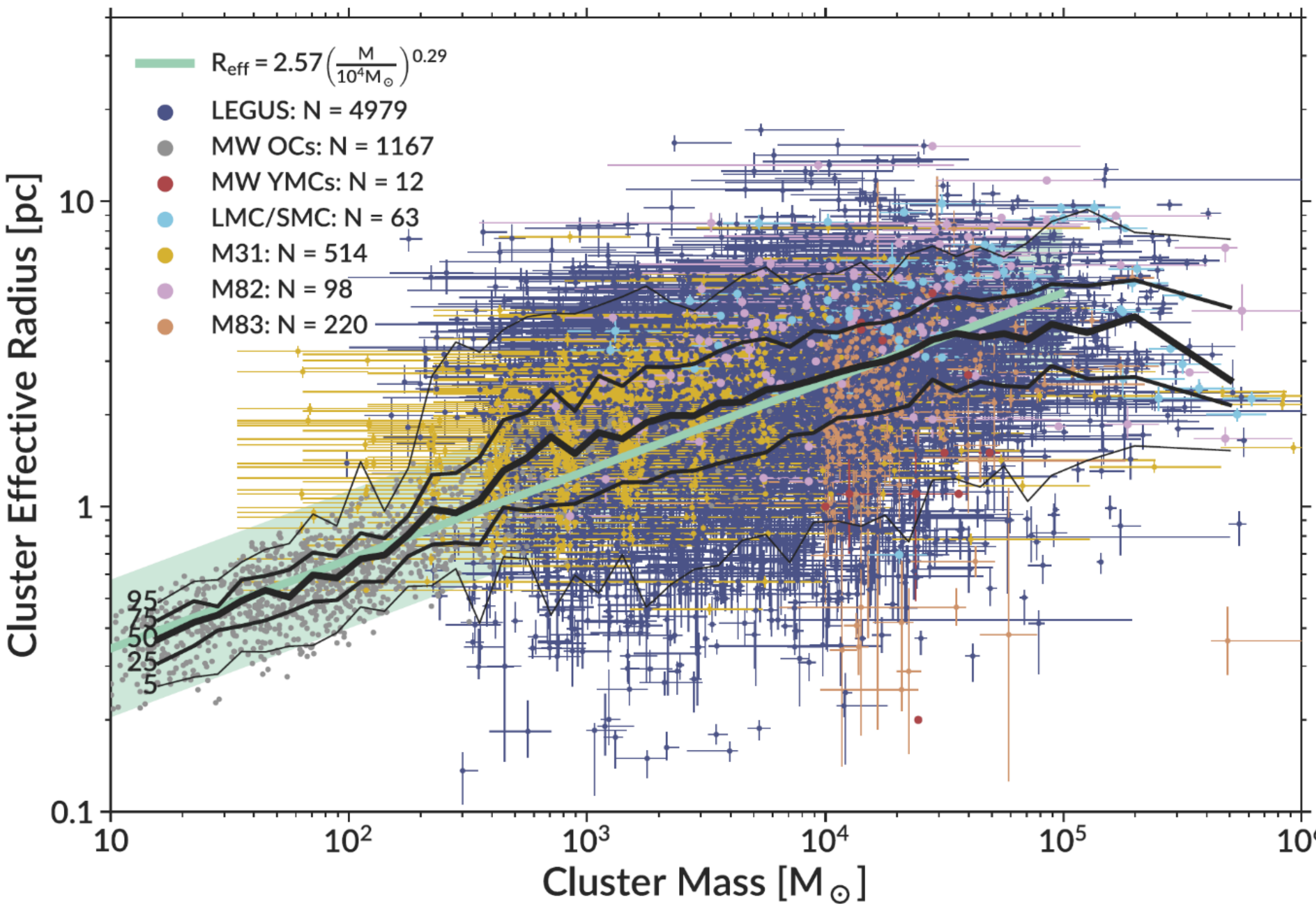
Ex-situ GCs have higher velocity dispersion than in-situ GCs or field stars; can only approximately be described by a color cut; both trends are same as observed in the MW



Chen & OG 2022

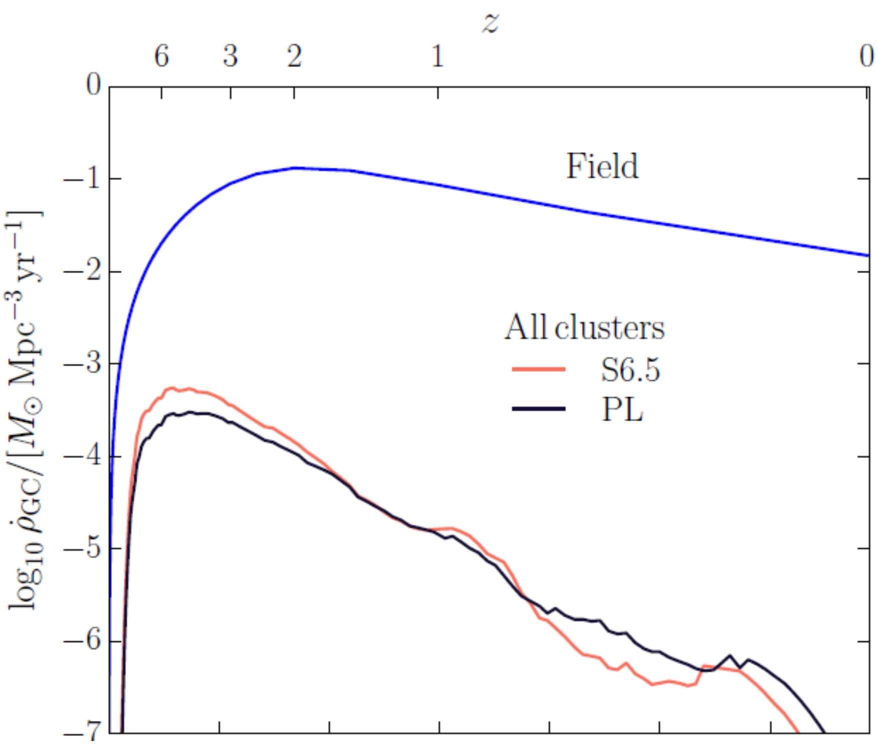
Includes size – mass relation for young star clusters

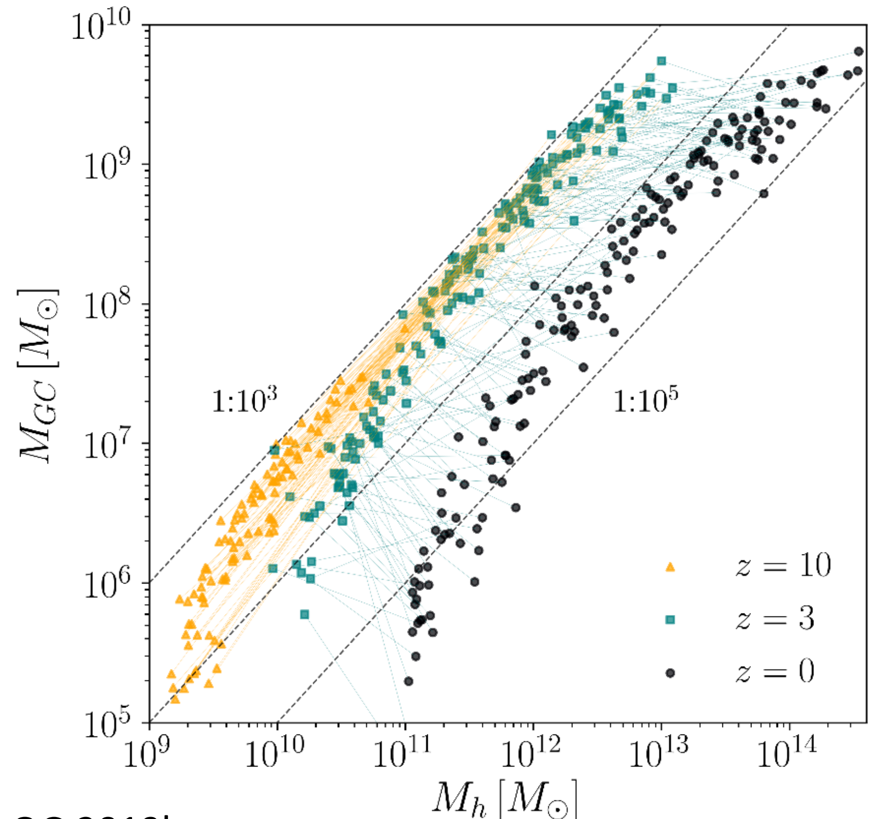
Uniform measurement of half-mass radii in the LEGUS HST survey, plus other published samples



Brown & OG 2021

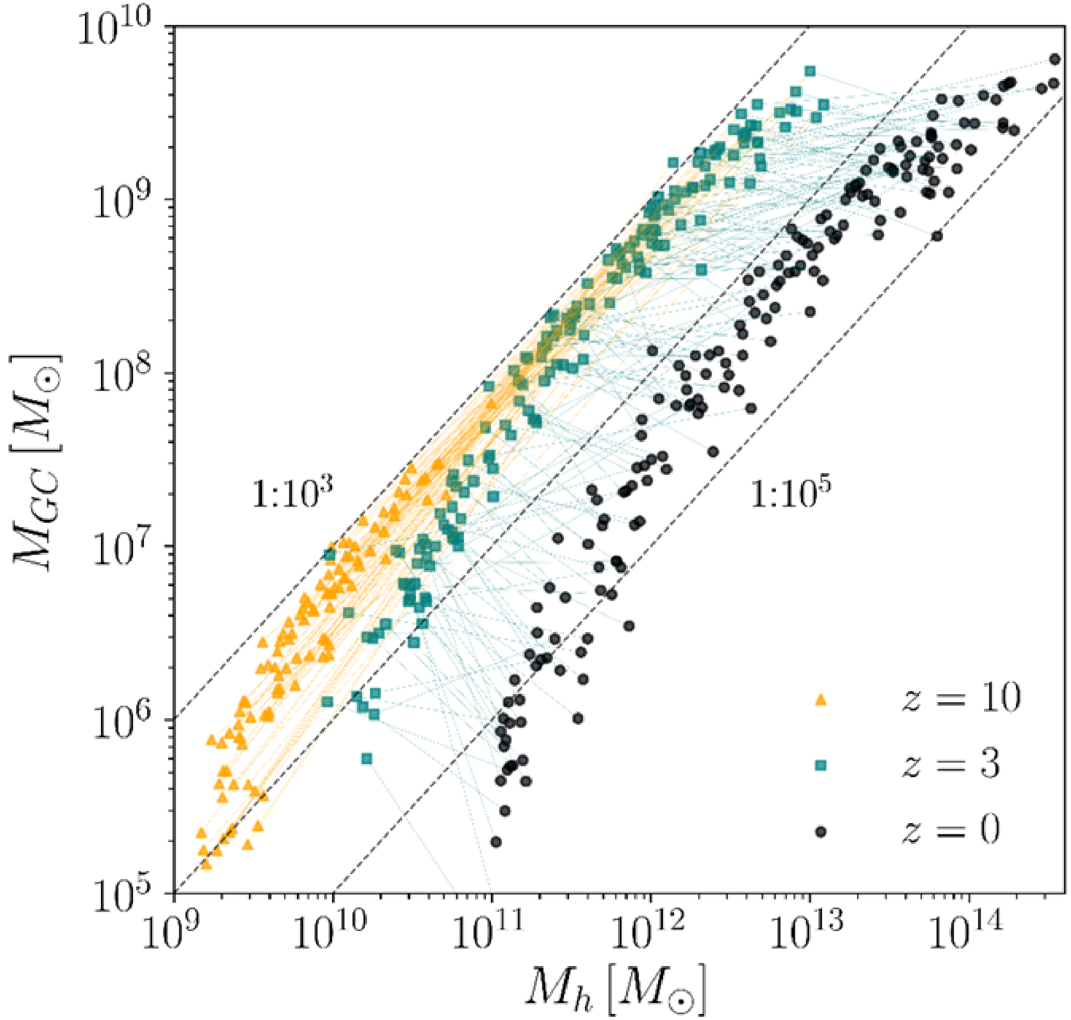
At redshift z > 3 massive star clusters (> 10^5 M_{sun}) constitute a much higher fraction of galactic star formation than now. These are epochs when JWST has unique advantages over HST or ground-based facilities.





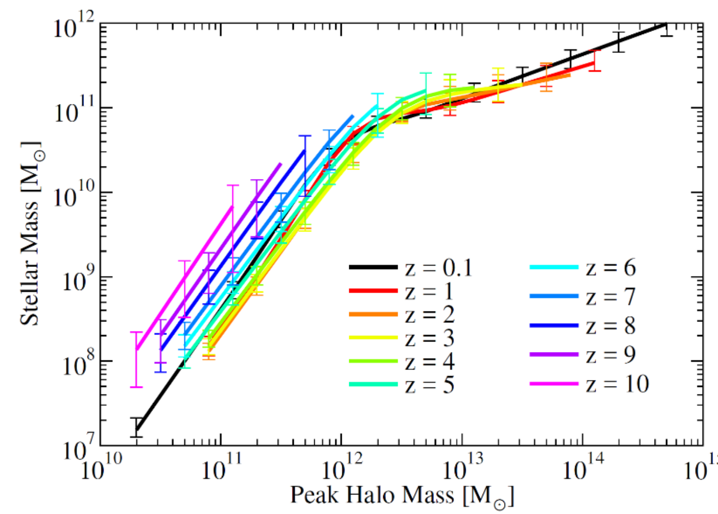
Choksi & OG 2019b

Evolution of the GCS mass – halo mass relation: order of magnitude offset at redshifts z=3-10



Choksi & OG 2019b

mostly due to late growth of halo mass and cluster disruption (similar to field stellar mass offset but over a wider range of halo mass):



Summary

- M_{GC} - M_h relation is robustly predicted by models of GC formation and evolution (Choksi, OG, Li 2018; Choksi & OG 2019a)

- Accretion of satellite systems straightens the relation relative to stellar mass – halo mass relation (Choksi & OG 2019b)

- Normalization of M_{GC} - M_h relation is expected to increase with redshift, by up to an order of magnitude (Choksi & OG 2019b)

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

- Density profiles and kinematic signatures of ex-situ clusters (Chen & OG 2022)

- Largest sample of young cluster sizes (Brown & OG 2021)