Are globular clusters simple* after all?

Nick Choksi (UC Berkeley)
with Oleg Gnedin (U Michigan)

*to first order

A quick review of GC formation ideas…

high Jeans mass in DM mini-halos (e.g., Peebles & Dicke 68)

DM-baryon streaming velocity at recombination (Naoz & Narayan 14)

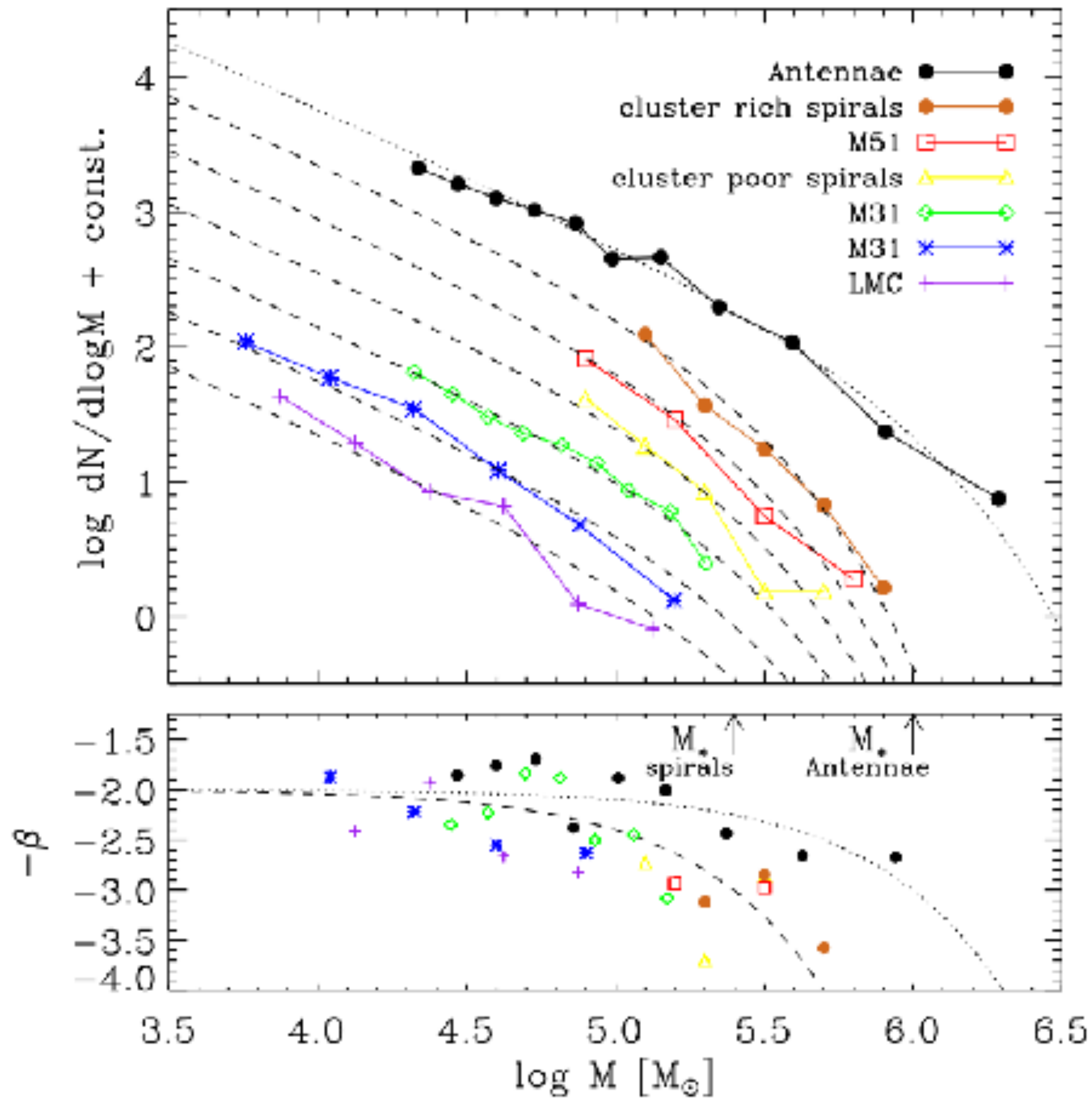
in-situ formation in cold IGM streams (Mandelker+ 17)

natural extension of "regular" star formation
(this talk; also: Kruijssen 15, Choksi+ 18, Pfeffer+ 18, El-Badry+ 19…)

Ubiquitous local proto-GC analogs

young (bound) clusters surrounded by large (unbound) SF complexes, typically in starbursting/interacting galaxies

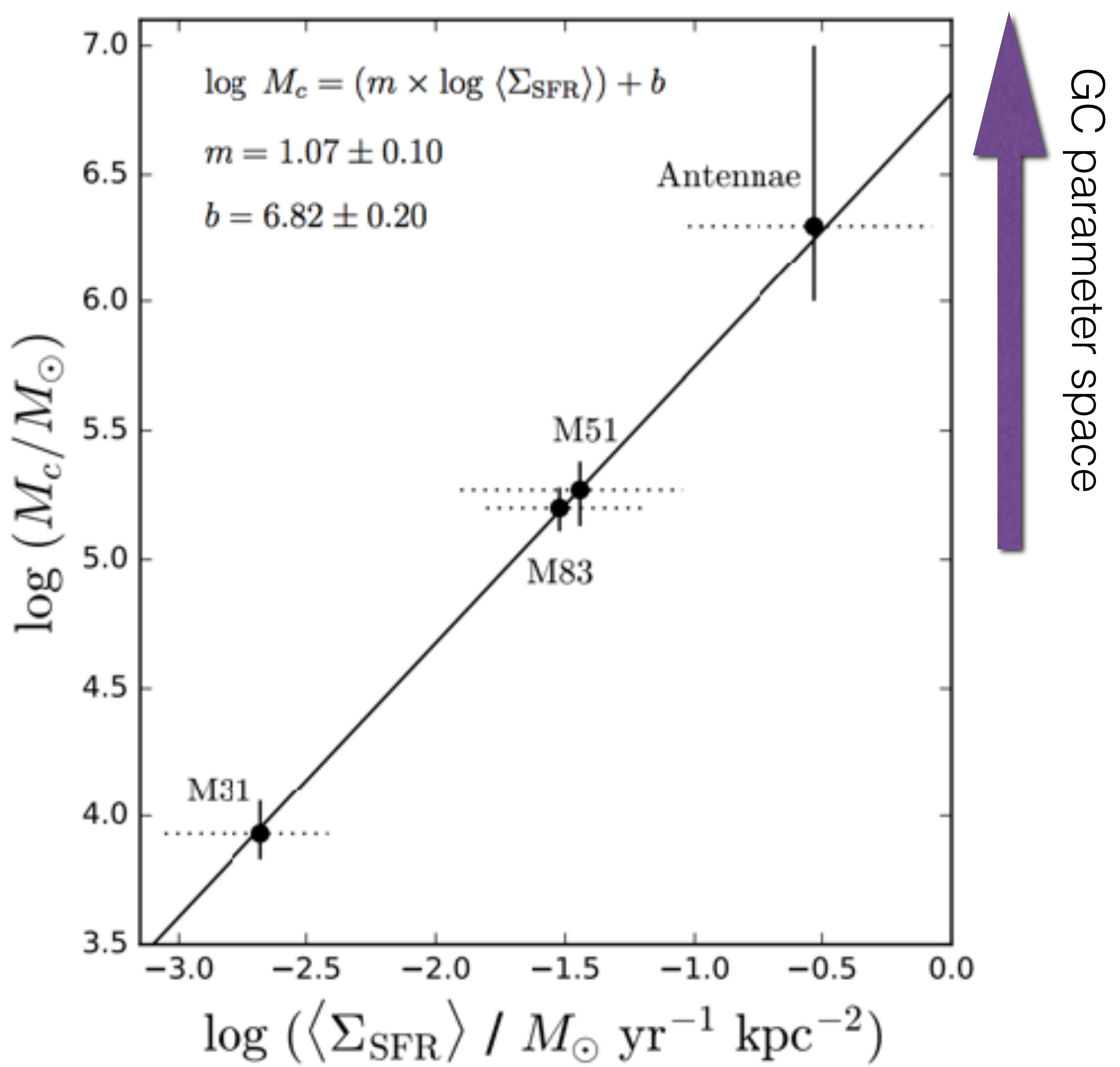
(Whitmore+ 99, Zepf+ 99, Zhang+ 01, Bastian+ 13, Longmore+ 14…many more)



Portegies-Zwart+ 10

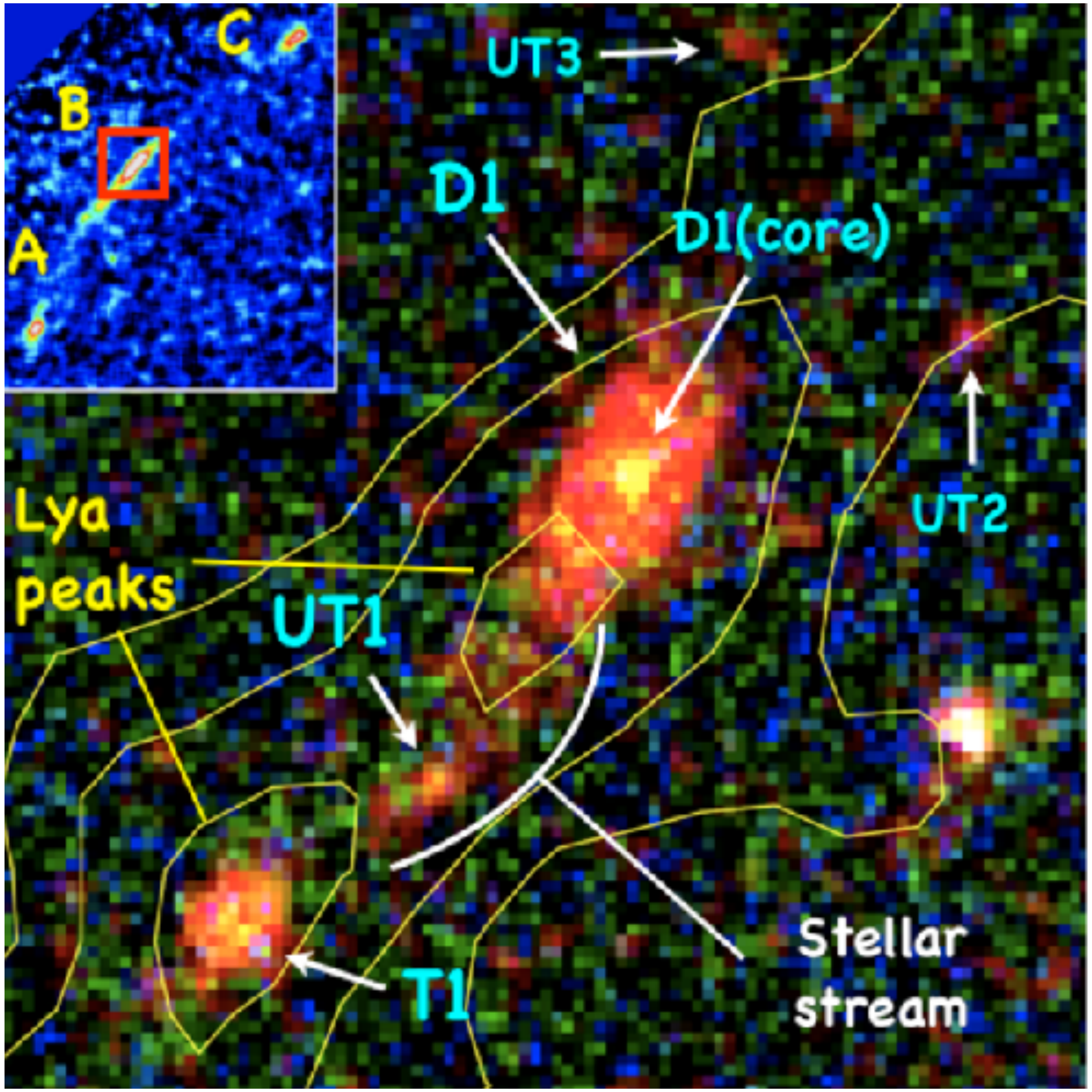
Young cluster and galaxy-scale properties correlate

$dN/dM \propto M^{-2}e^{-M/M_c}$



Johnson+ 17

Catching GC formation in the act at high-z?

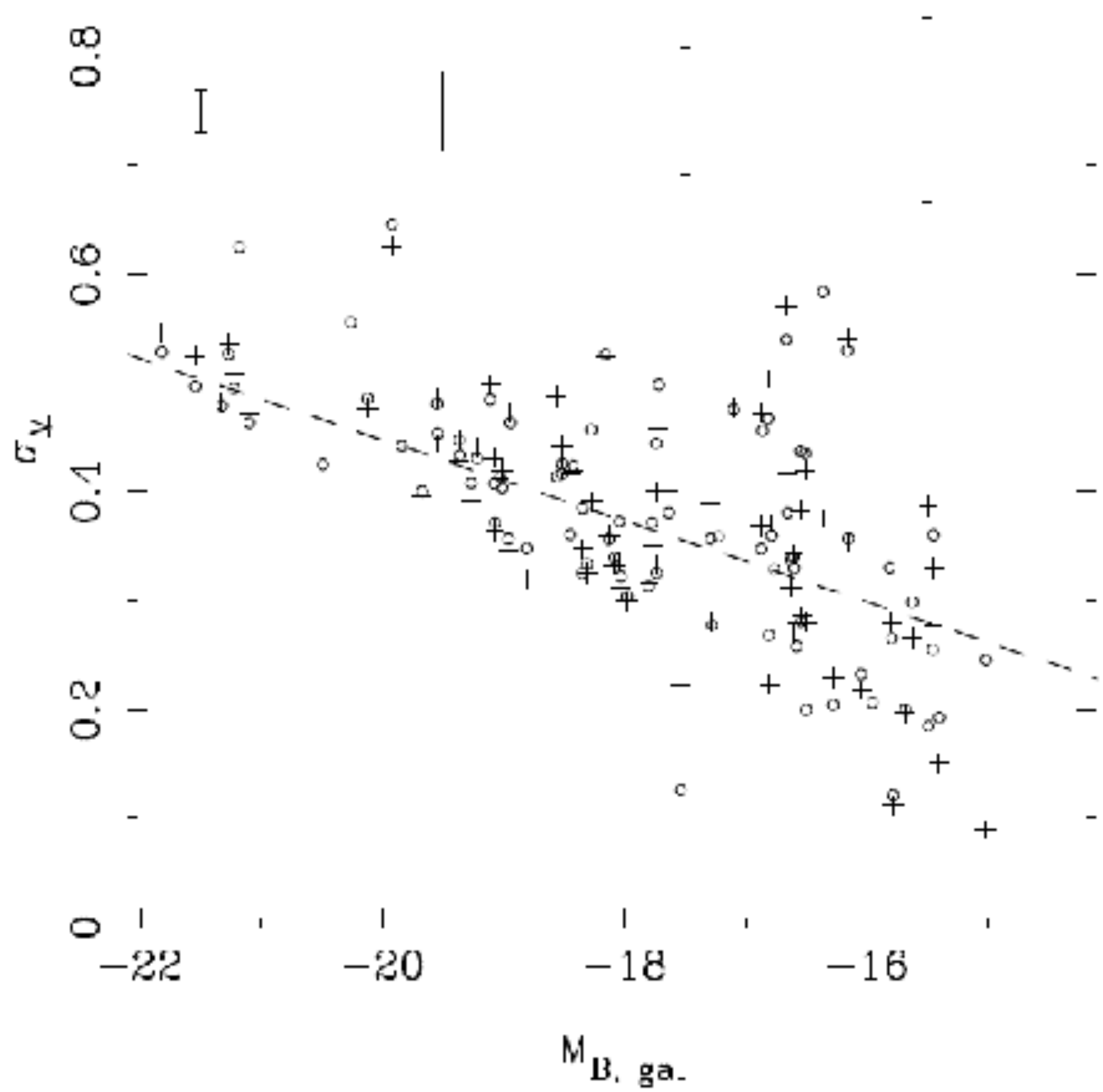


Sigma SFR ~ 10 $M_{sun}/kpc^2/yr$!

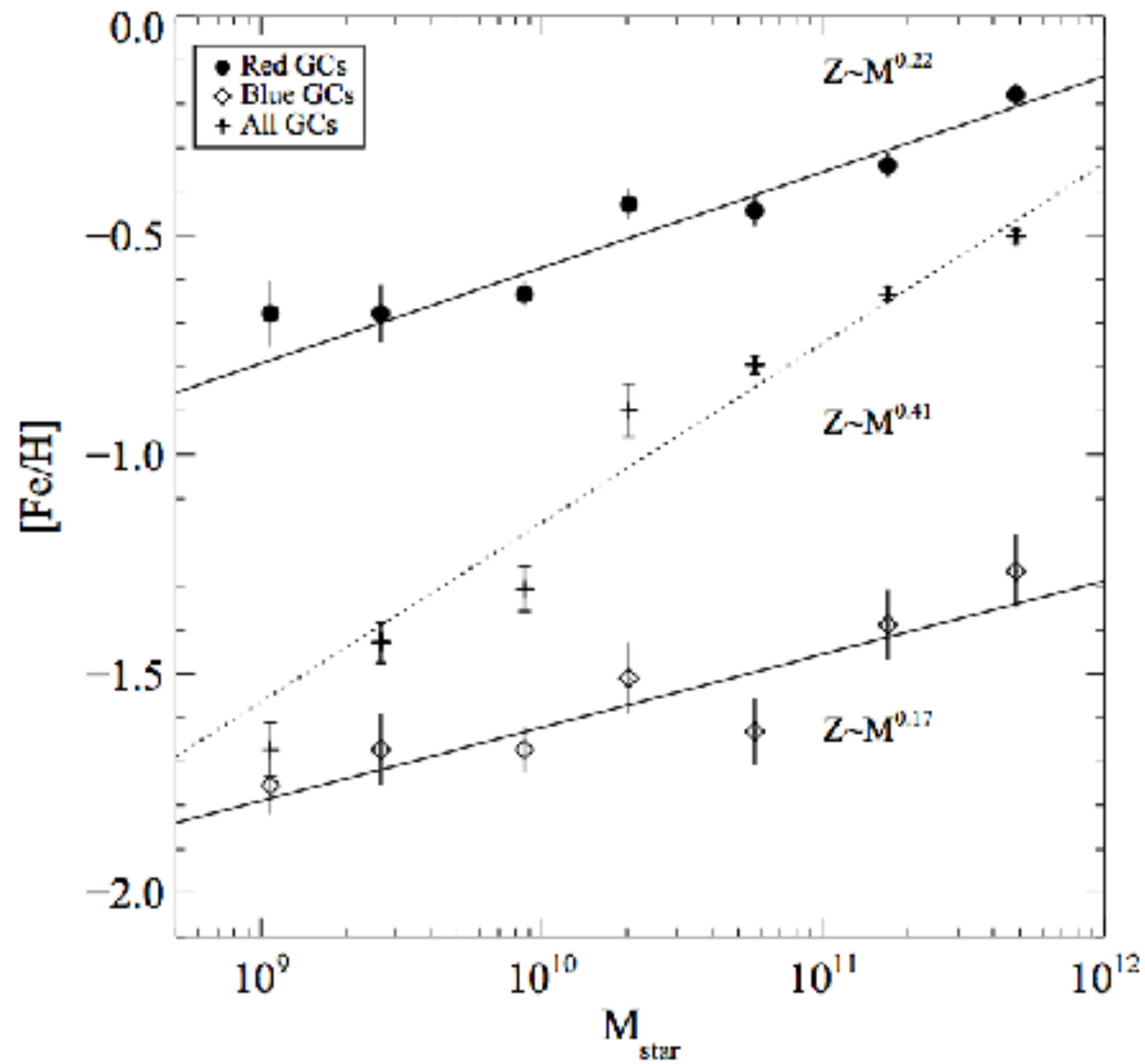
Vanzella+ 18
also Bouwens+ 17

GC system and galaxy properties correlate

width of GC system mass function



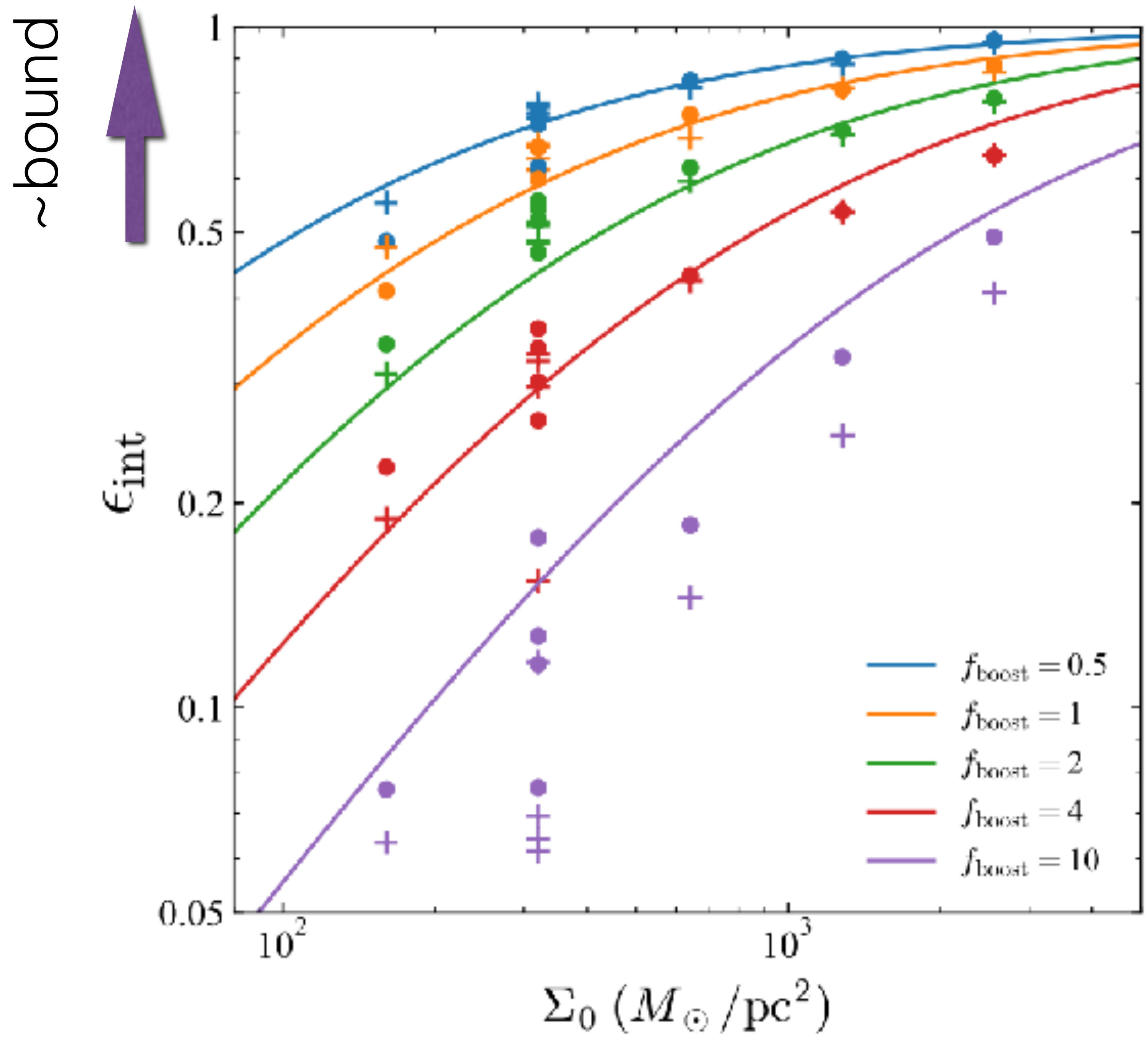
mean of GC system metallicities



Jordan+ 07

Peng+ 06

Dense GMCs form bound star clusters



Li+ 19
also: Kruijssen 14, Grudic+ 18

Many disparate observations hint at a non-exotic origin for GCs

Does it actually work?
Components of a “vanilla” GC formation model:

Dark matter halos
(simulations or Press-Schechter)
+galaxy properties
(paint on with scaling relations or use hydro sims)
+criterion for GC formation
(e.g., ISM pressure/density, accretion, mergers)

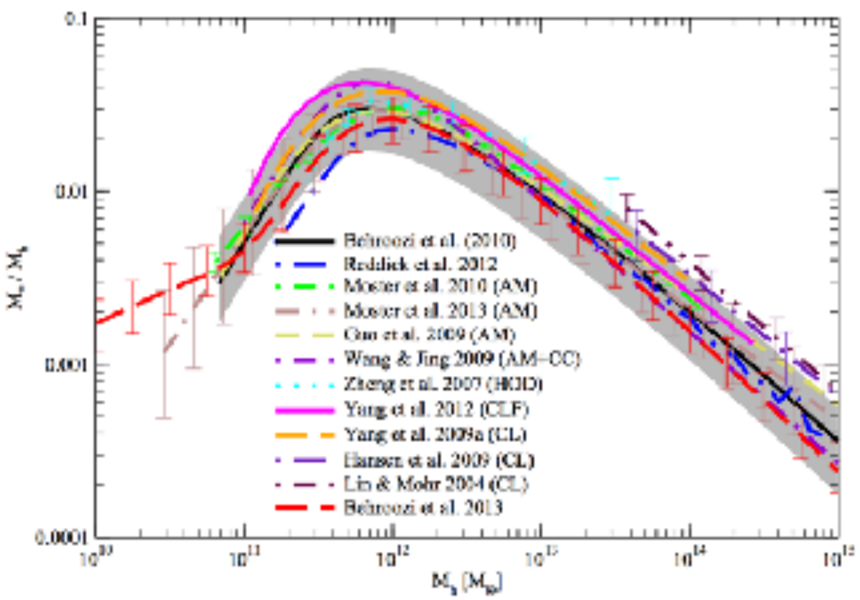
HUMMUS:

Hierarchical **U**nified **M**ultiscale **M**odel (of) **U**nresolved **S**tar-clusters

Cluster formation if: $(dM_h/dt)/M_h > p_3$

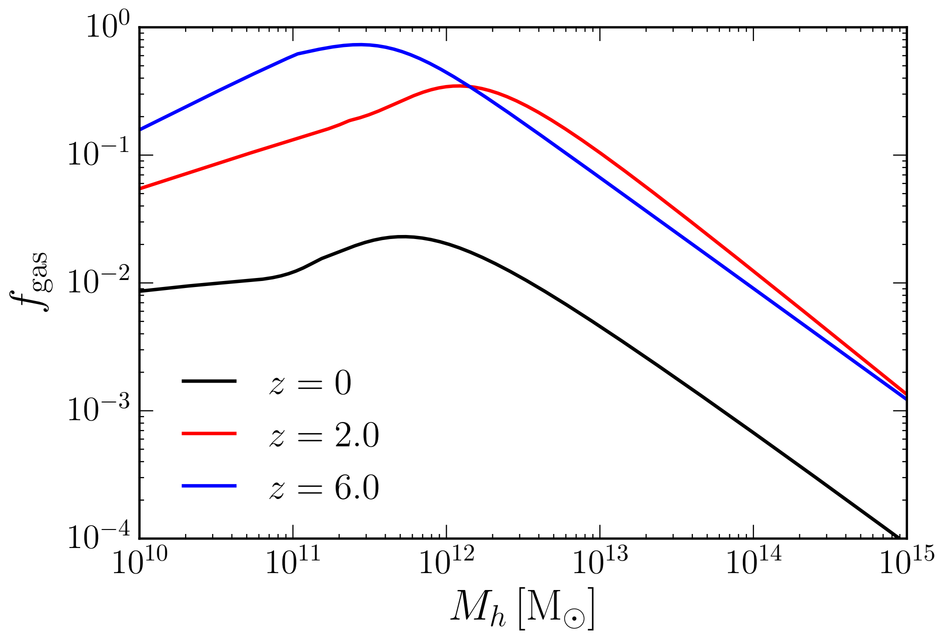
$M_{tot} = 1.8e\text{-}4 p_2 M_{gas}$

p_2, p_3 are free parameters



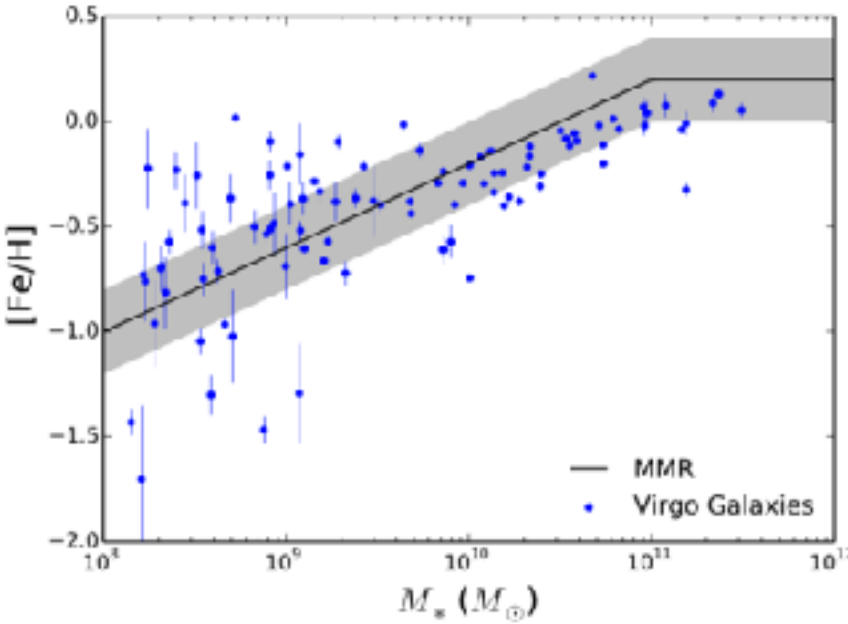
M_{star}-M_h

(Behroozi+ 13)



M_{gas} - M_{star}

(Lilly+ 13, Genzel+15, Tacconi+ 17)



M_{star}-[Fe/H]

(Kirby+ 13, Ma+ 14)

Draw from Schechter cluster IMF

dynamical + stellar evolution prescriptions

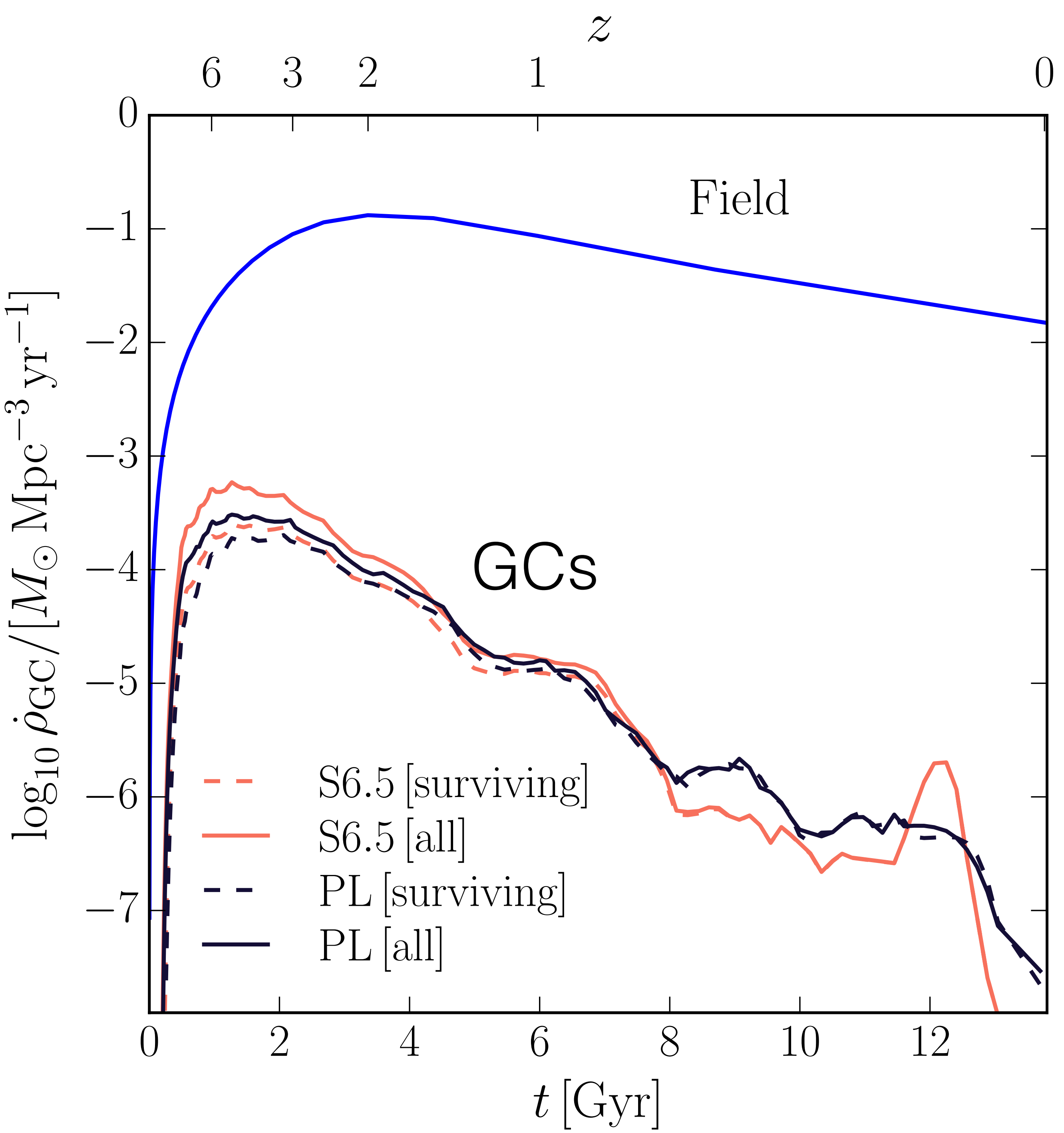
Choksi, Gnedin, Li 18 (1801.03515)

Choksi & Gnedin 19 a, b (1810.01888, 1905.05199)

similar "vanilla" approaches: Pfeffer+ 18, El-Badry+ 18, Li+ 18

GC formation roughly traces overall star formation

GC formation rate



Choksi & Gnedin 19a

similar results:
Reina-Campos+ 19
El-Badry+ 18
Li+ 17

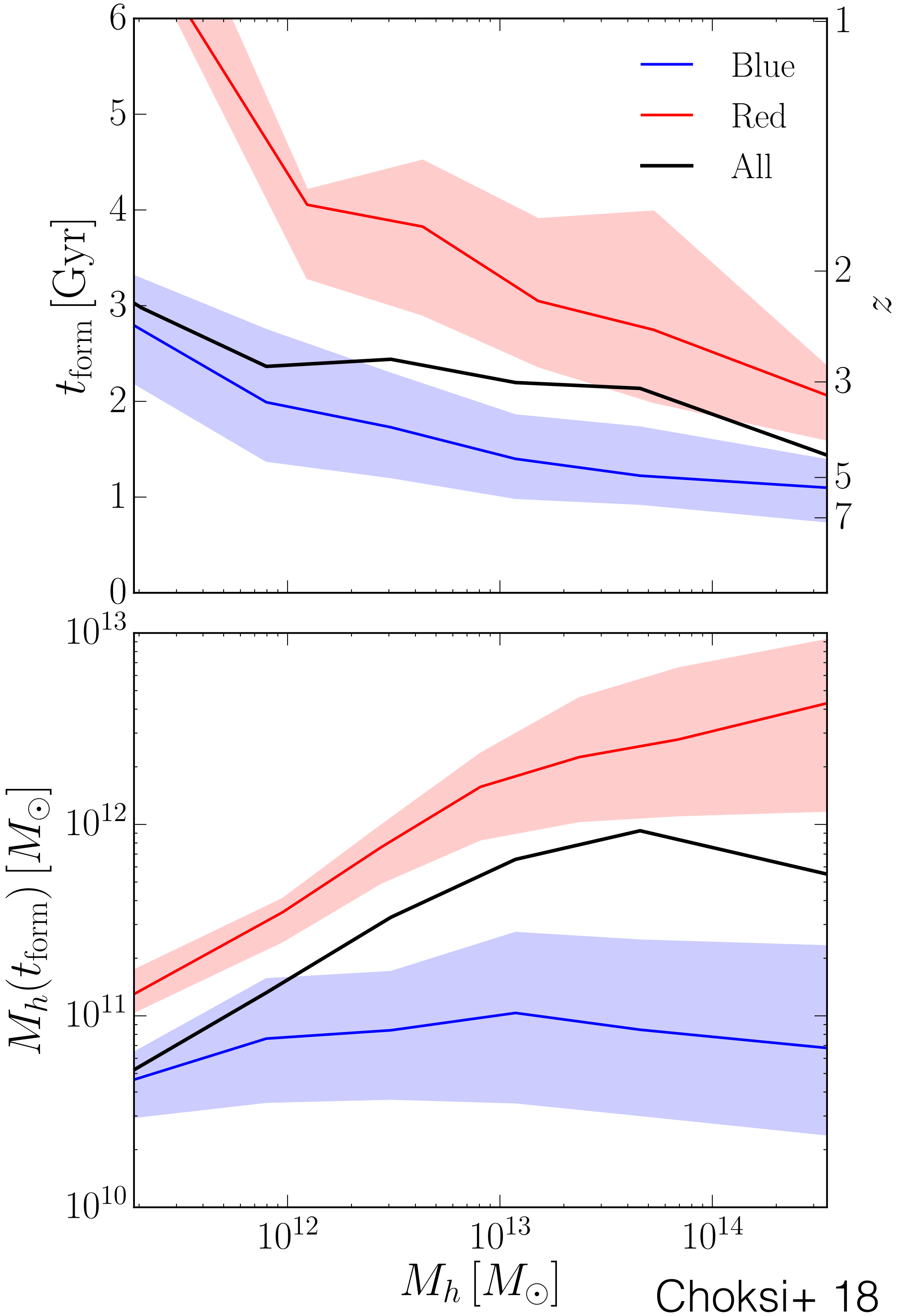
Formation epochs and sites

“Downsizing” effect, similar to overall buildup of galaxies

Metal-poor clusters form at z~3-5 in low-mass halos

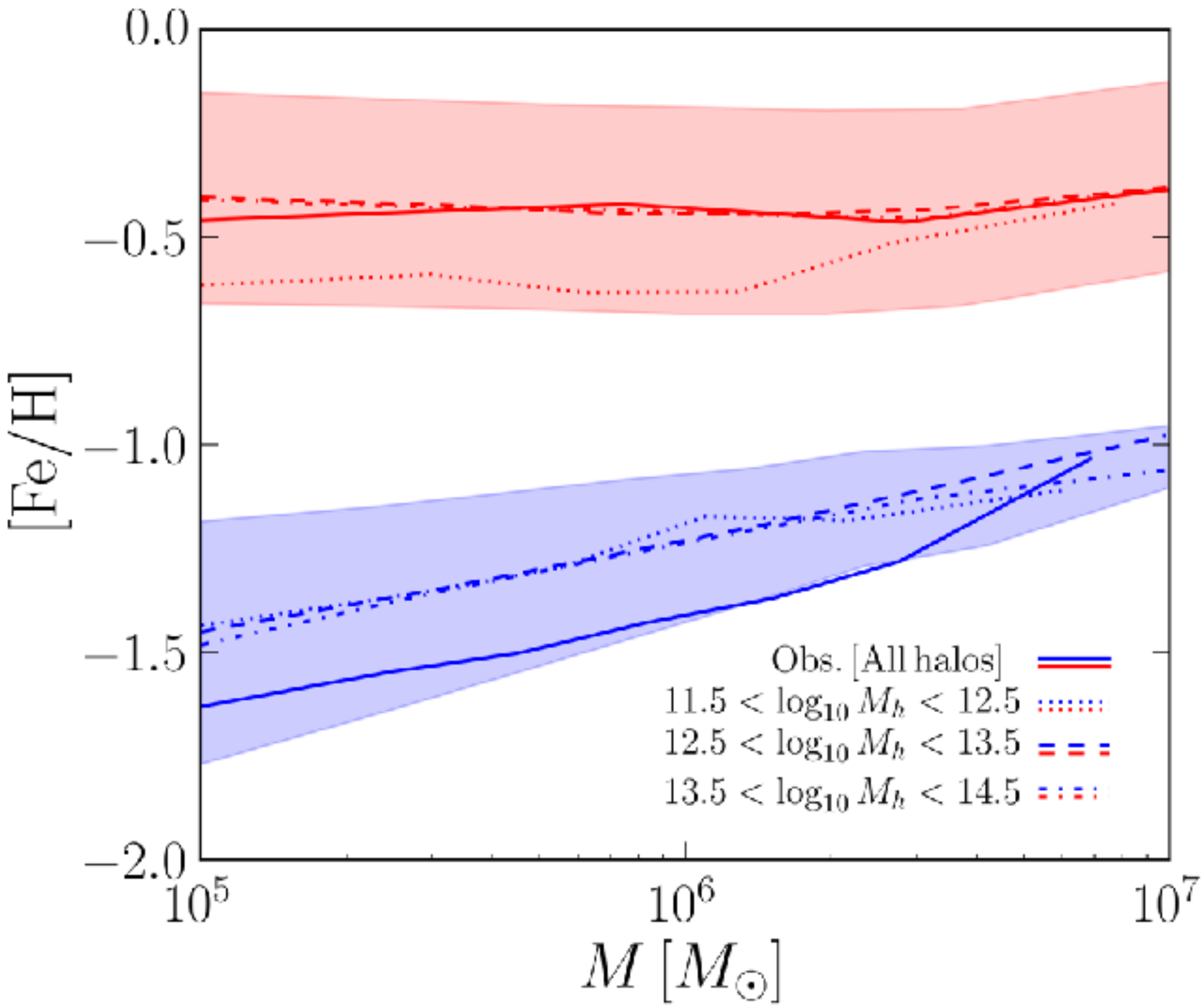
shaded region: 25th-75th percentile
solid curves: median trend

Metal-rich clusters form at z~1-3 in massive halos



Choksi+ 18

A blue-tilt, but no self-enrichment

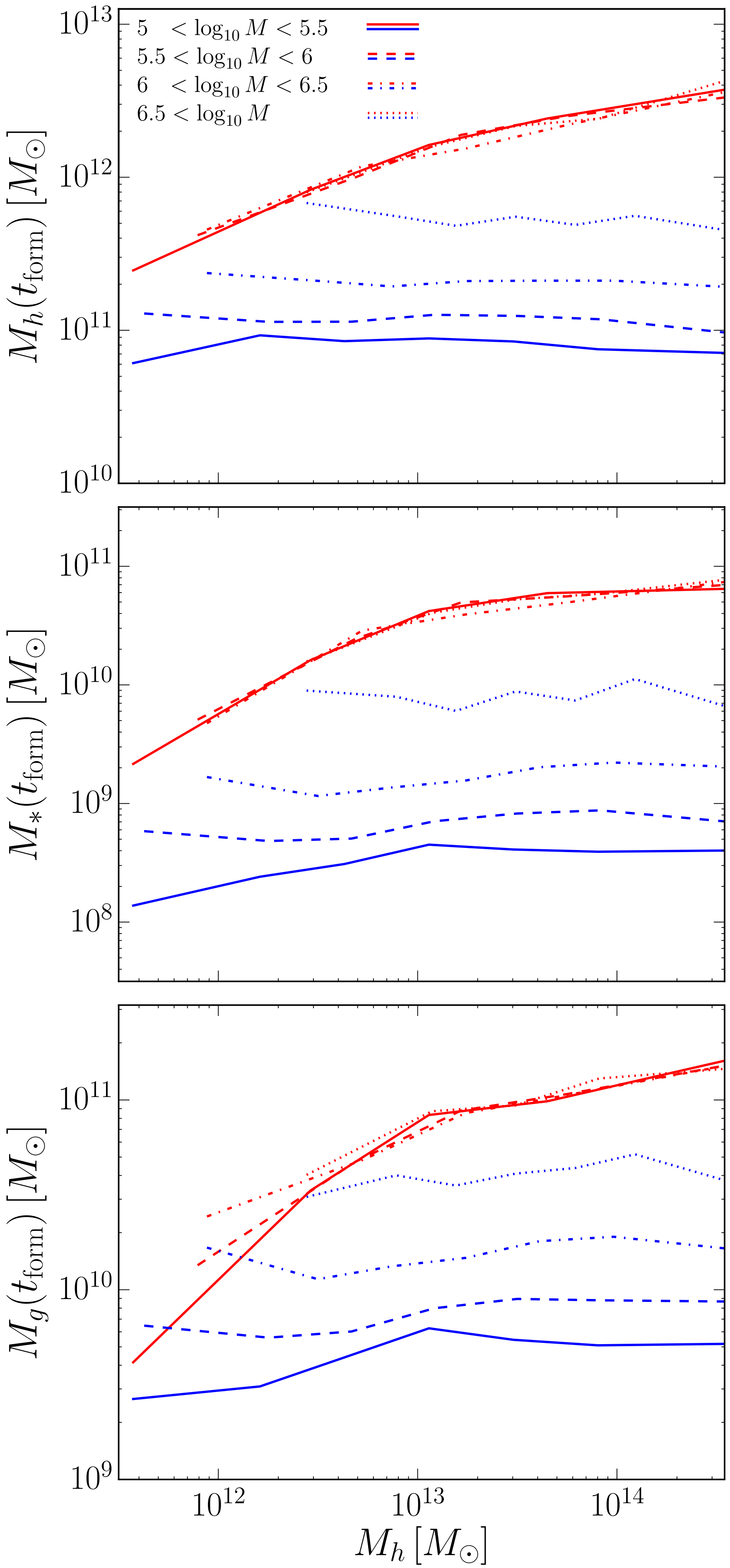


no tilt

blue tilt

Choksi+ 18

Blue-tilt as a gas supply effect



halo mass at time of cluster formation

logM > 6.5

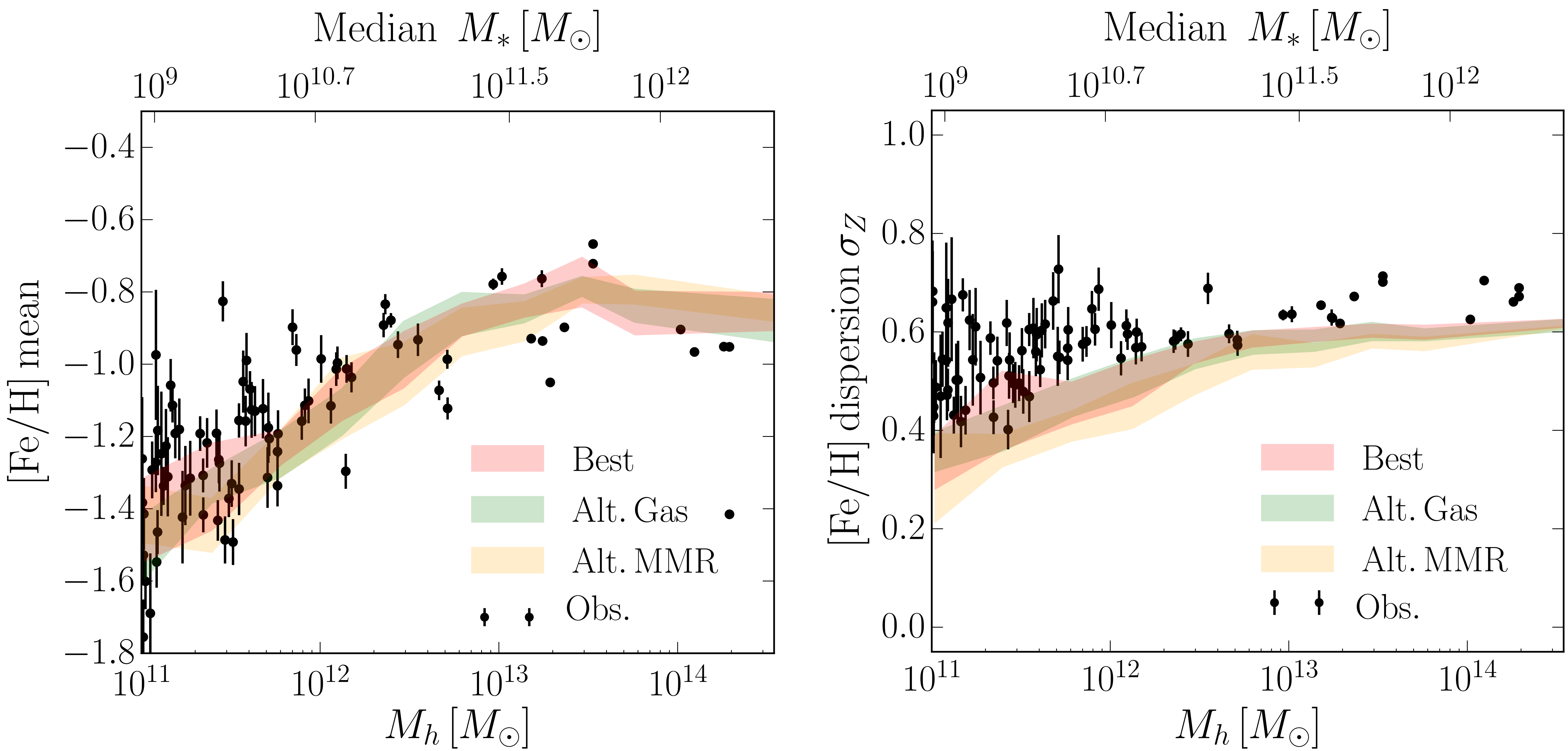
5.5 > logM > 5

galaxy **stellar mass** at time of cluster formation

galaxy **gas mass** at time of cluster formation

- Metal-poor GCs form in **gas-limited** halos
  - massive MP GCs can **only** form in higher mass halos
  - higher host mass <—> higher metallicity (adopted scalings)
- Metal-rich clusters form in more massive halos w/ more gas
  - —> cluster IMF fully sampled when metal-rich GCs form

Mean properties of metallicity distribution depend on galaxy mass

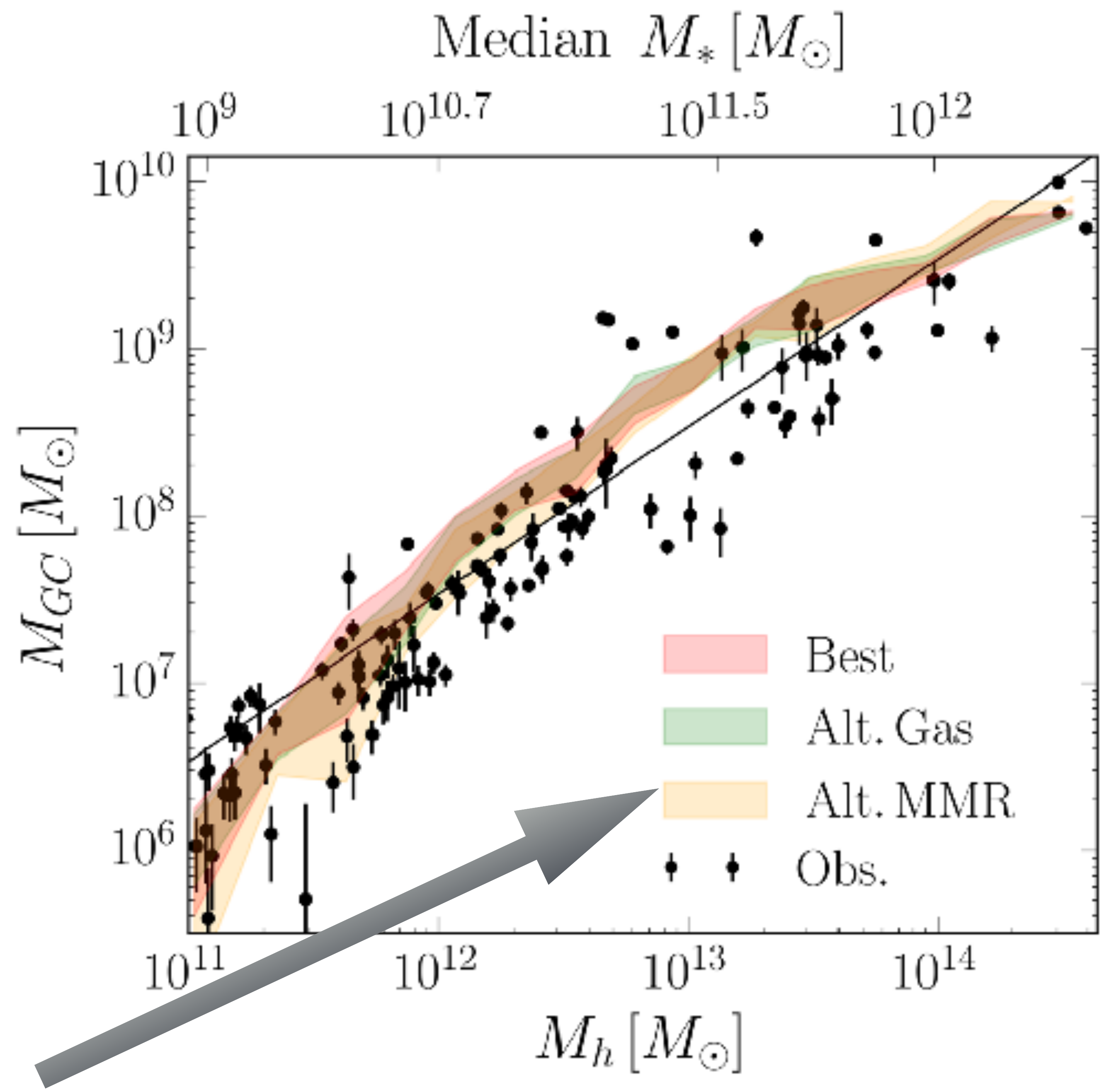


Choksi+ 18

Combined mass in GCs scales (nearly) linearly w/ host halo mass

Obs. show: $\mathbf{M_{GC} \sim 3.5 \times 10^{-5} M_h}$
(over ~4 dex in halo mass!)
0.3 dex scatter (including obs. errors)

Highlights non-linearity
0.2 dex scatter

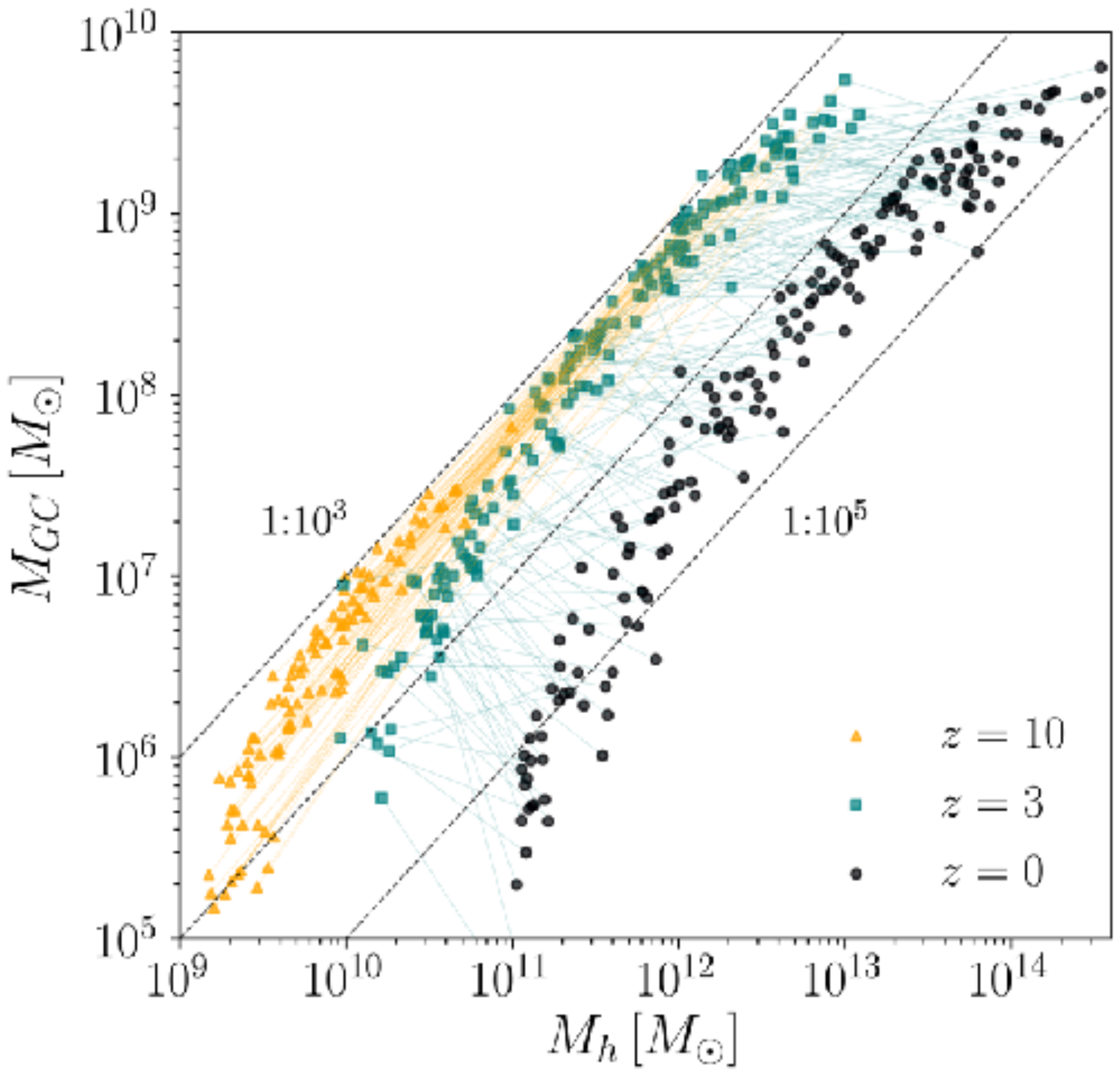


"Alt. Gas": lower gas fractions at high-z
"Alt. MMR": higher metallicities at high-z

Choksi+ 18

obs. data: Peng+ 06, Spitler+ 09, Harris+ 10, 15,16

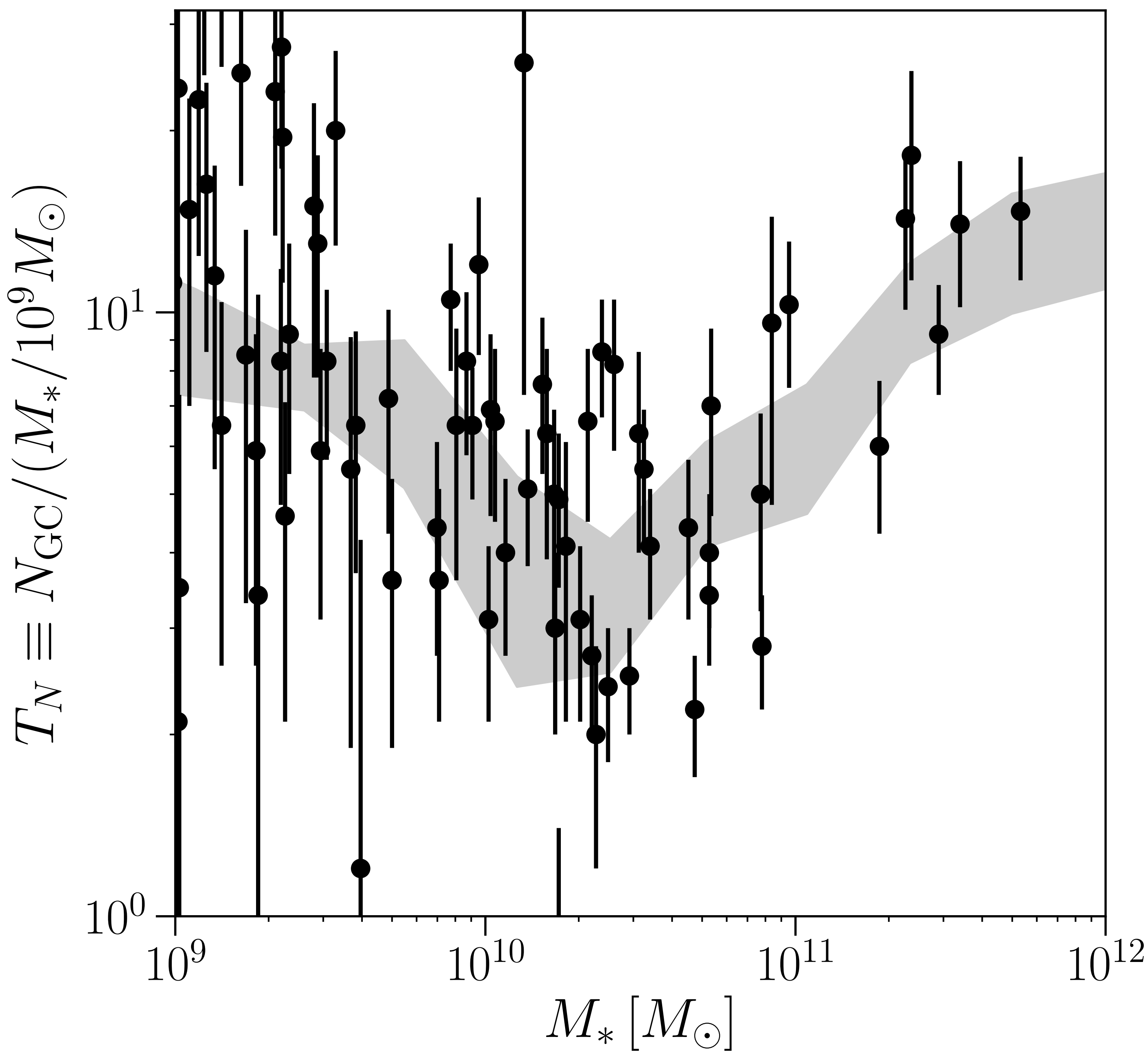
M_{GC}-M_h relation evolves by ~10x over cosmic time



Shape set by relation btw. *cold gas mass and halo mass*

Choksi+ 19b

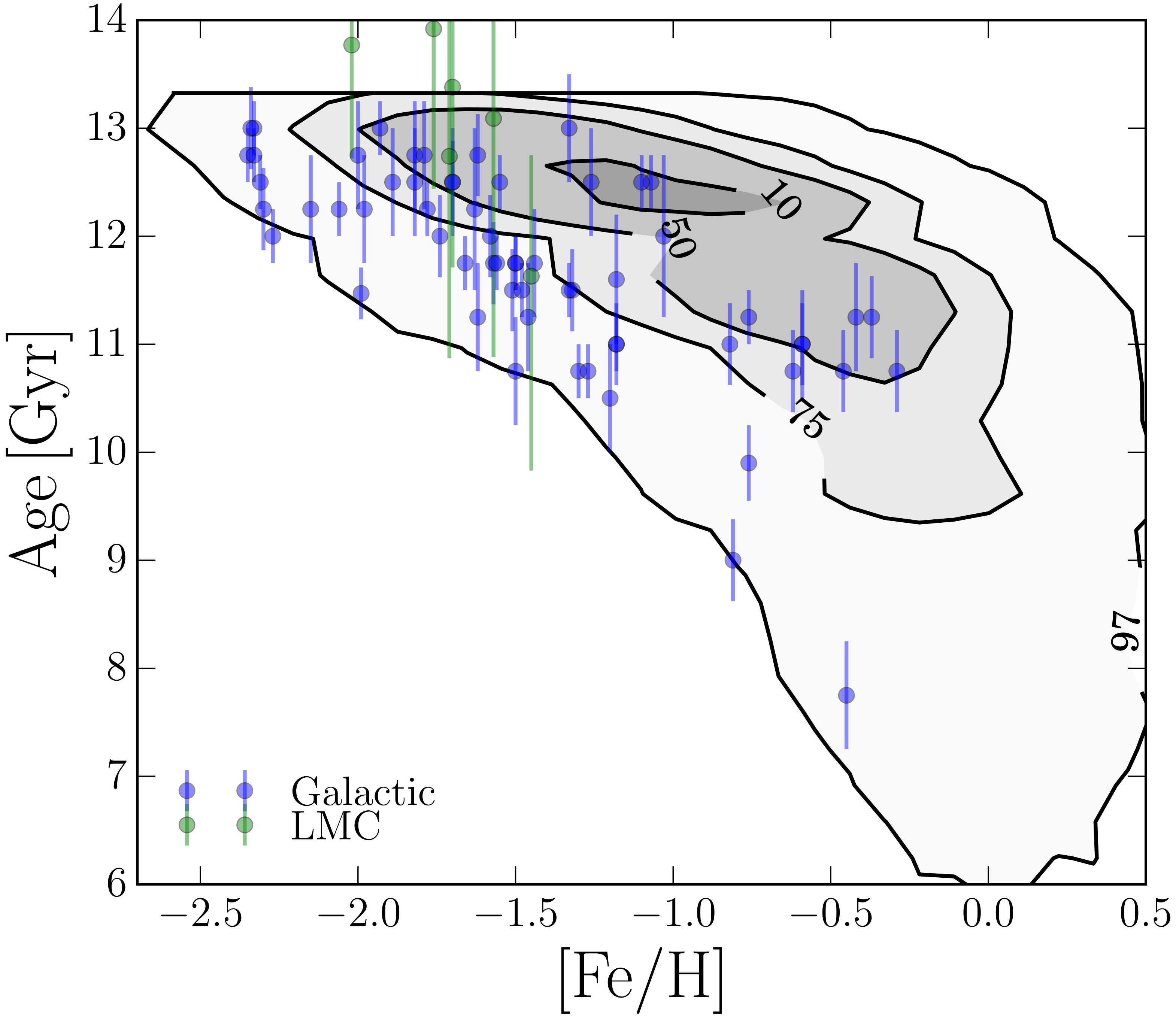
“Specific frequency” of Gas



Choksi & Gnedin 19b

Nick Choksi (Berkeley)

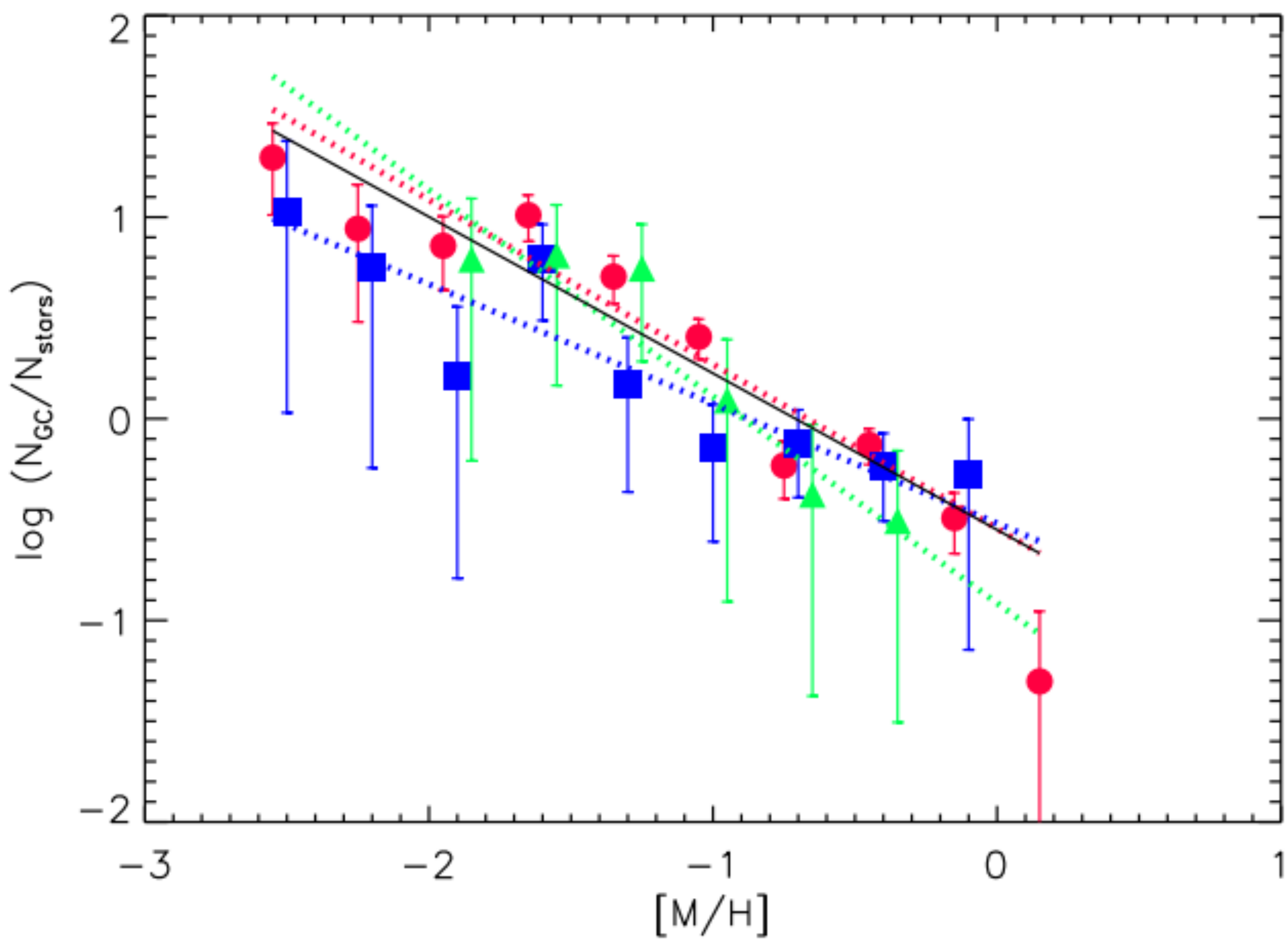
A bifurcated age-metallicity relation



obs. data Leaman+ 13, Wagner-Kaiser+ 17

Choksi+ 18

GC specific frequency in stellar halos decreases w/ [Fe/H]

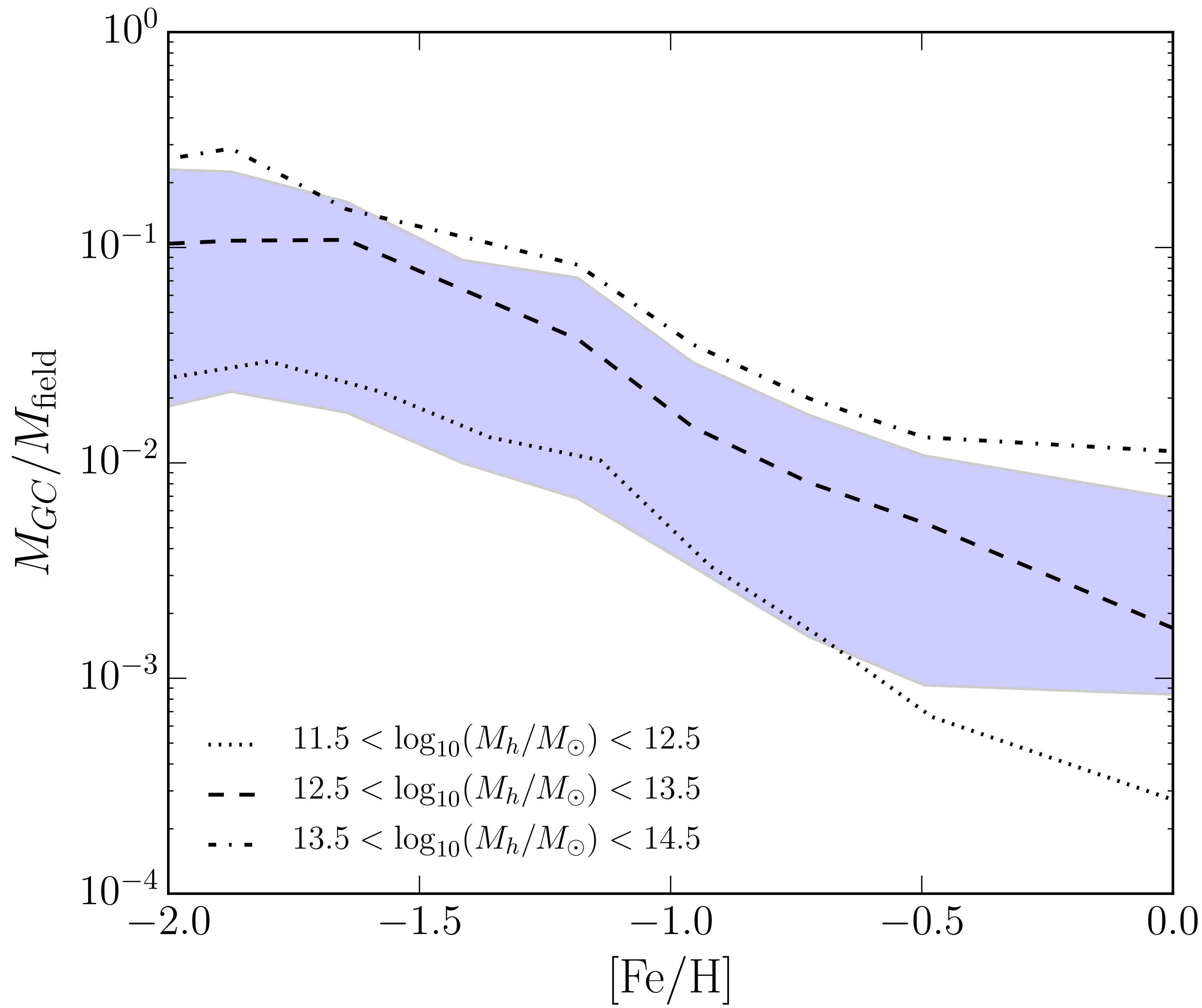


Lamers+ 17

GC specific frequency decreases w/ [Fe/H]

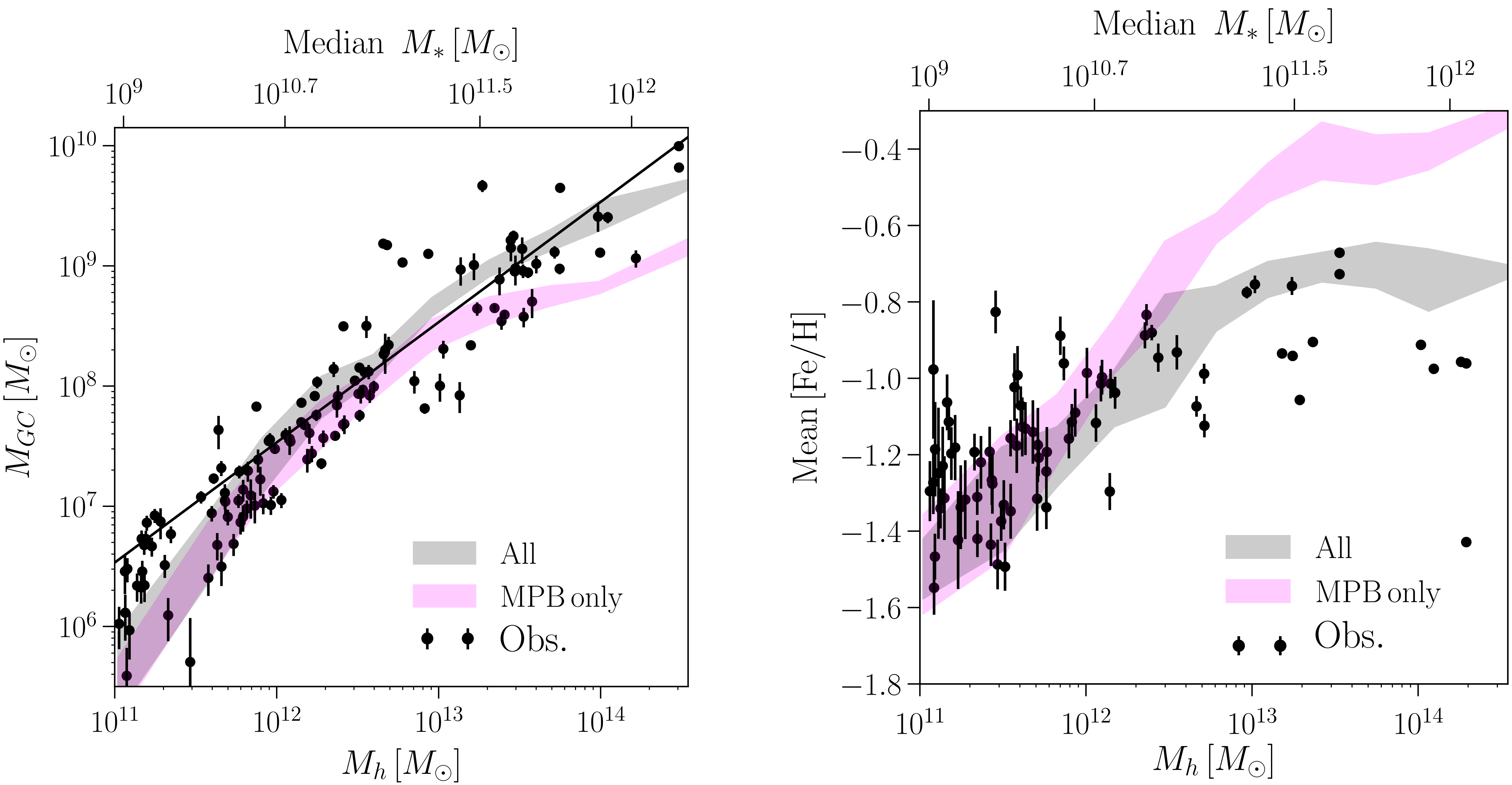
M_{GC}/M_{field} **higher** in **more massive** galaxies

Defining a stellar halo is hard!



Choksi+ 18

Satellites are important for building GC systems

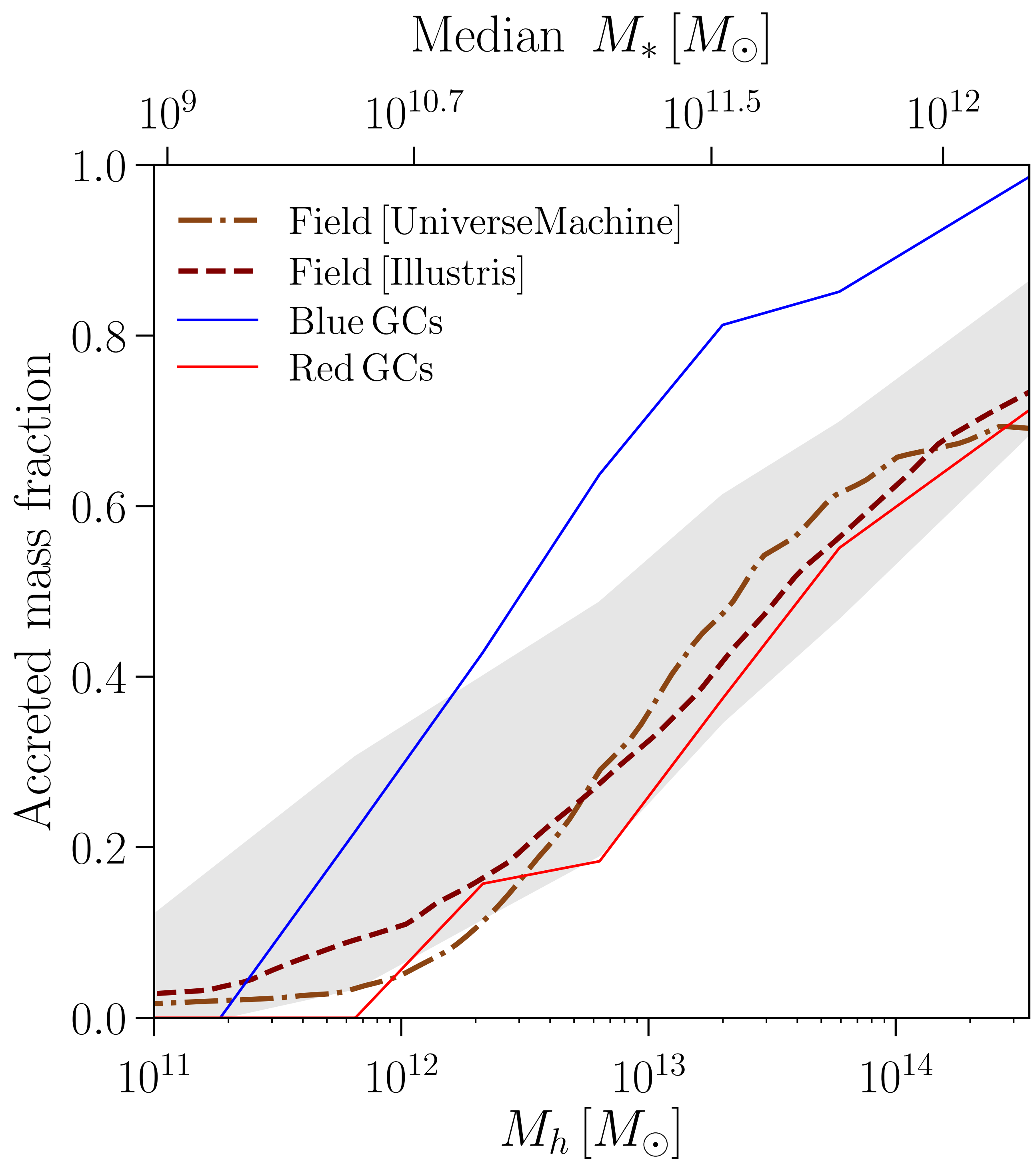


"All": including GCs formed in satellites

"MPB only": only GCs formed "in-situ" in main progenitor

Choksi & Gnedin 19b

Fraction of accreted GC mass scales strongly with host mass



Choksi 19b

What sets the minimum metallicity of GCs?

Min obs. **GC** metallicity [Fe/H] ~ -2.5 (e.g., Forbes+ 19, Beasley+ 19)

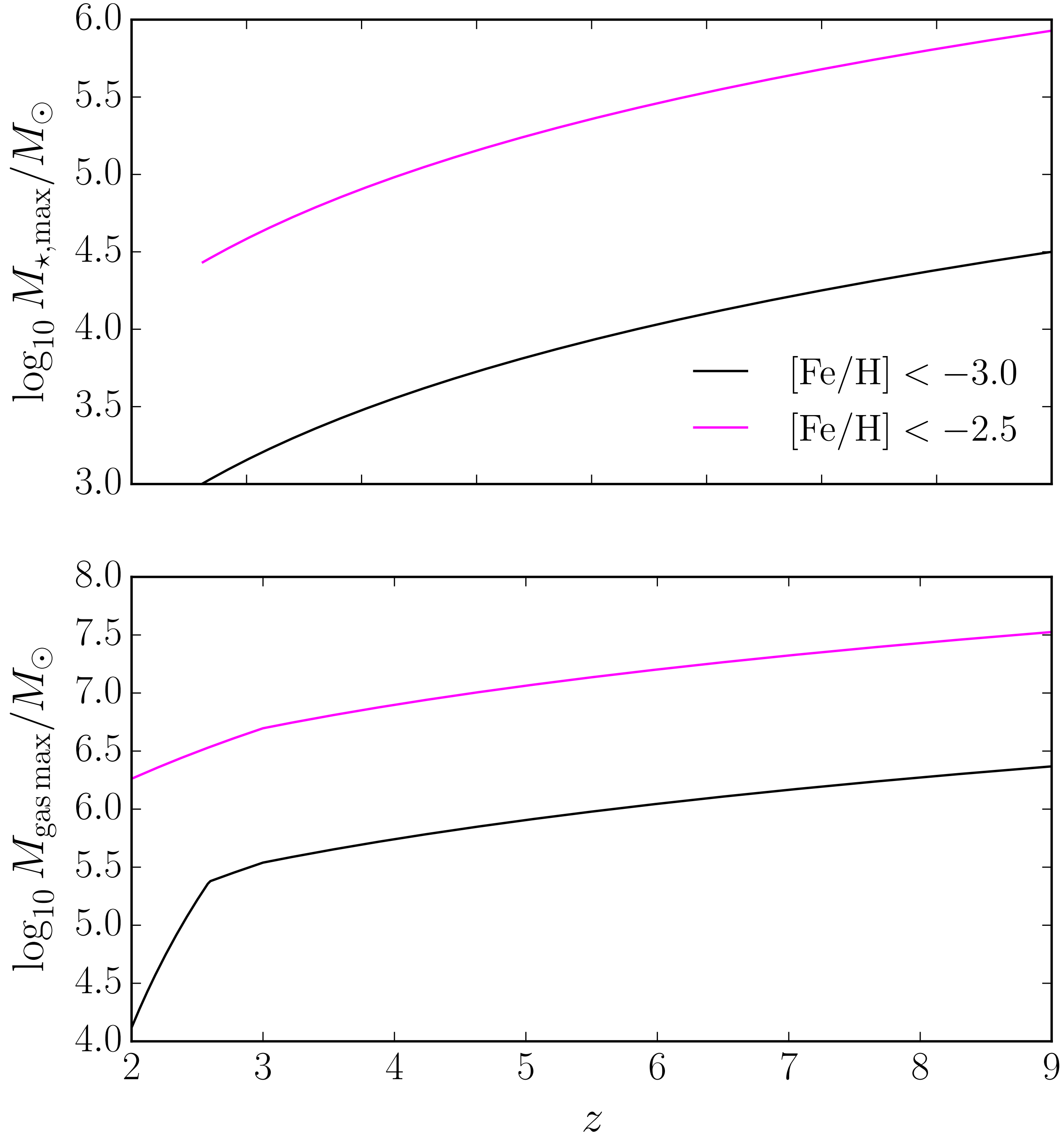
Min obs. **individual star** metallicity [Fe/H] < -4

But mean GC metallicity << mean field metallicity!

Galaxy mass-metallicity relation sets GC metallicity floor

max. M_{star}
for given [Fe/H]

max. M_{gas}
for given [Fe/H]



disrupted GCs
may be lower [Fe/H]

Choksi+ 18
see also: Kruijssen 19

Conclusions

GCs **most simply** explained as tracing overall star formation
…but, also **biased** towards earlier times
GC formation rate **peaks at z ~ 3-5**

Simultaneously explains many disparate observations, including:
metallicity distribution functions, specific frequencies, age-metallicity,
GC system mass - halo mass…

For Mh > 10^{13} M_{sun}, most GCs (and field) **form in satellites**

Mergers subdominant in triggering GC formation

GC metallicity floor because **small, metal-poor galaxies don't have enough gas to form GCs**