Globular Cluster Systems, Galaxy Halos, and Galaxy Formation

Does Dark Matter Control GC Populations? (Directly? Indirectly? If so, how?)

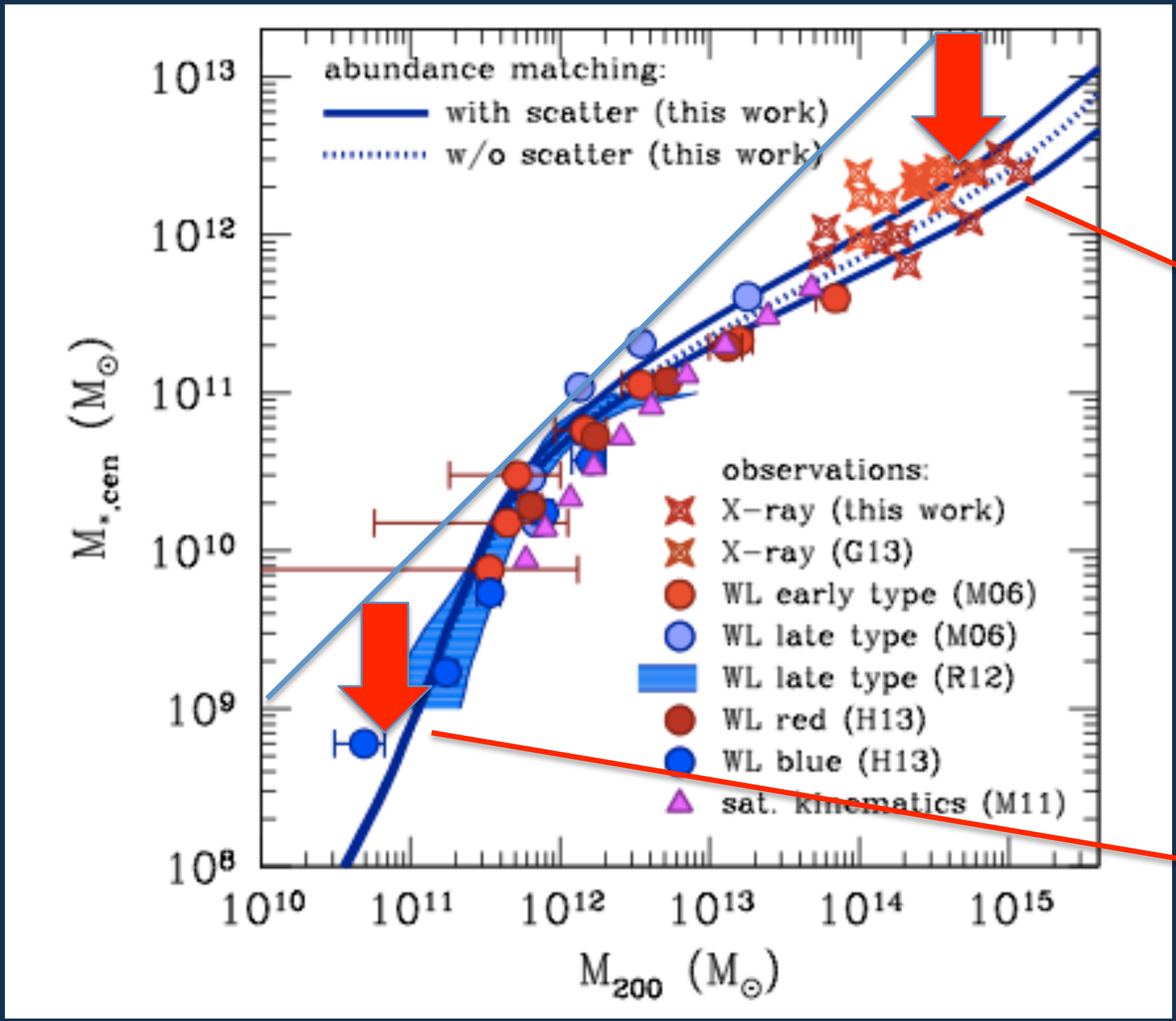
How do we gauge the net effect of feedback during galaxy formation?

What were the formation conditions for globular clusters (and galaxy halos)?

McMaster, April 2015

Colleagues: Mike Hudson, Gretchen Harris

M(stellar) strongly nonlinear function of M(halo)
Dominance of dark matter highest for either dwarfs or supergiants



Strong differences in types and level of feedback

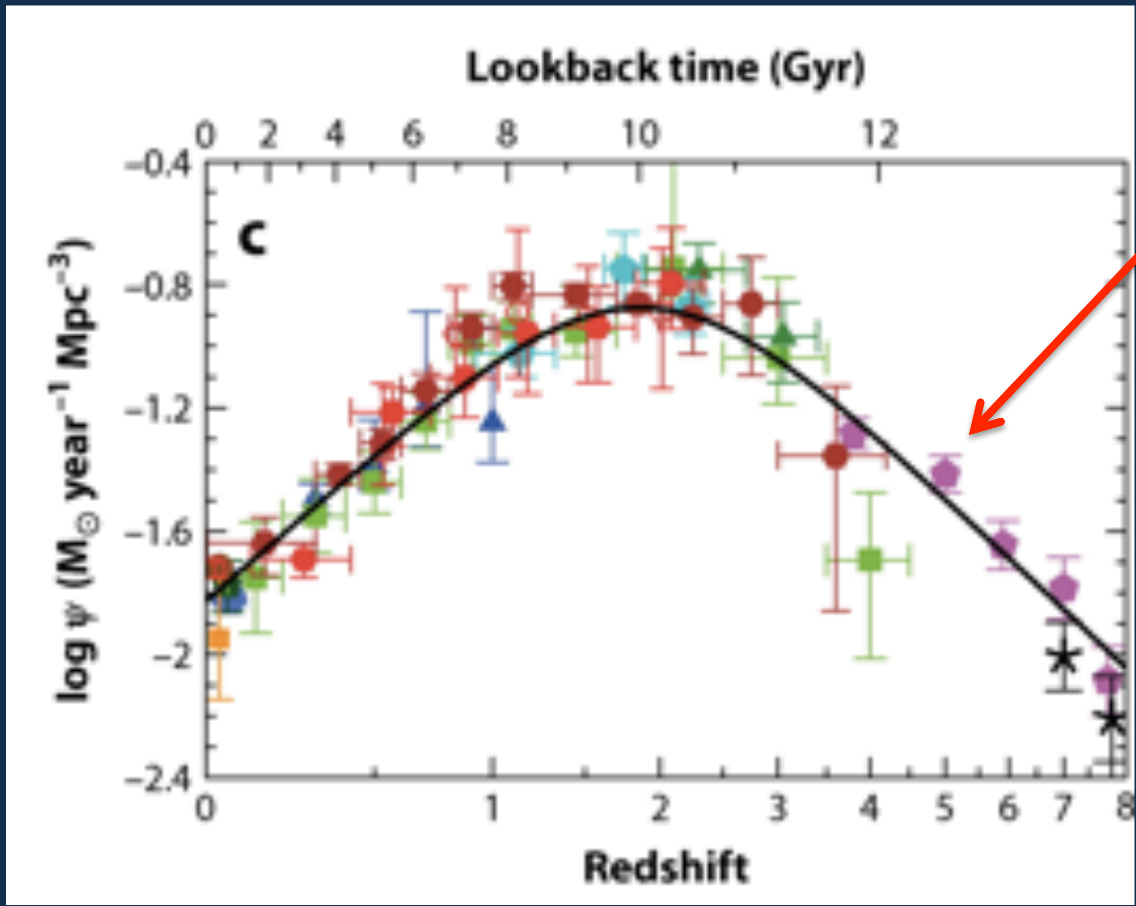
AGN heating, infall heating

Stellar winds, SNII heating, reionization ??

Kravtsov et al. 2014 (1401.7329)

But then, *is there* any *stellar population that forms in direct proportion to halo mass?*

Globular cluster formation epochs are   z = 2 – 8   (ages 10-13 Gyr), perhaps before much feedback reduces SFE globally



Most GCs form before the peak

Madau & Dickinson 2014, ARAA 52, 415

Massive (and supermassive) star clusters provide …

Fundamental testbeds for evolution of stars

Unique hosts for exotic objects: millisecond pulsars, LMXRBs, IMBH' s, blue stragglers

Internal dynamics and mass profile of galaxy' s halo --> accurate assessment of dark matter

Unique windows on earliest star formation in galaxies

Testbeds for dynamics of high-density N-body systems (N--> 10^7)

Relic glimpses of the pregalactic clouds at the beginning of hierarchical merging

Tests of starburst, merger, and chemical evolution histories of galaxies

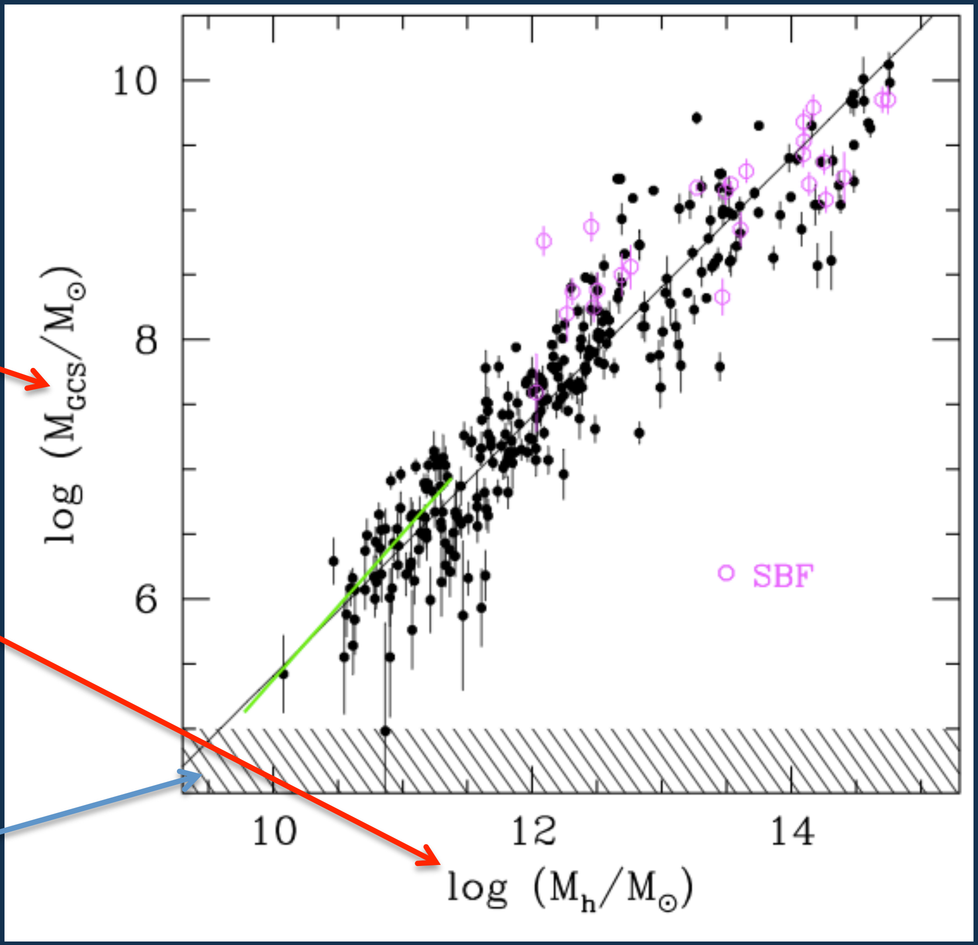

A globular cluster system (GCS) is the ensemble of all GCs in its host galaxy
M87 (CFHT)

The observed trend for all galaxies to date with measured GCSs:

Total mass in all globular clusters

Halo mass, from weak lensing

N < 1 GC



The literature on this topic:

Observationally based arguments

Blakeslee, Tonry, & Metzger 1997, AJ 114, 482
Blakeslee 1997, ApJL 481, L59
McLaughlin 1999, AJ 117, 2398
Blakeslee 1999, AJ 188, 1506
Kavelaars 1999, in Galaxy Dynamics, ASP Conf Ser 182, p.437
Spitler et al. 2008, MNRAS 385, 361
Peng et al. 2008, ApJ 681, 197
Spitler & Forbes 2009, MNRAS 392, L1
Georgiev et al. 2010, MNRAS 406, 1967
Harris, Harris, & Alessi 2013, ApJ 772, 82
Hudson, Harris, & Harris 2014, ApJ 787, L5
Durrell et al. 2014, ApJ 794, 103
Forte et al. 2014, MNRAS 441, 1391
Harris, Harris, & Hudson 2015, ApJ submitted

Theory

Kravtsov & Gnedin 2005, ApJ 623, 650
Moore et al. 2006, MNRAS 368, 563
Bekki et al. 2008, MNRAS 387, 1131
Katz & Ricotti 2014, MNRAS 444, 2377
Kruijssen 2014, MNRAS submitted

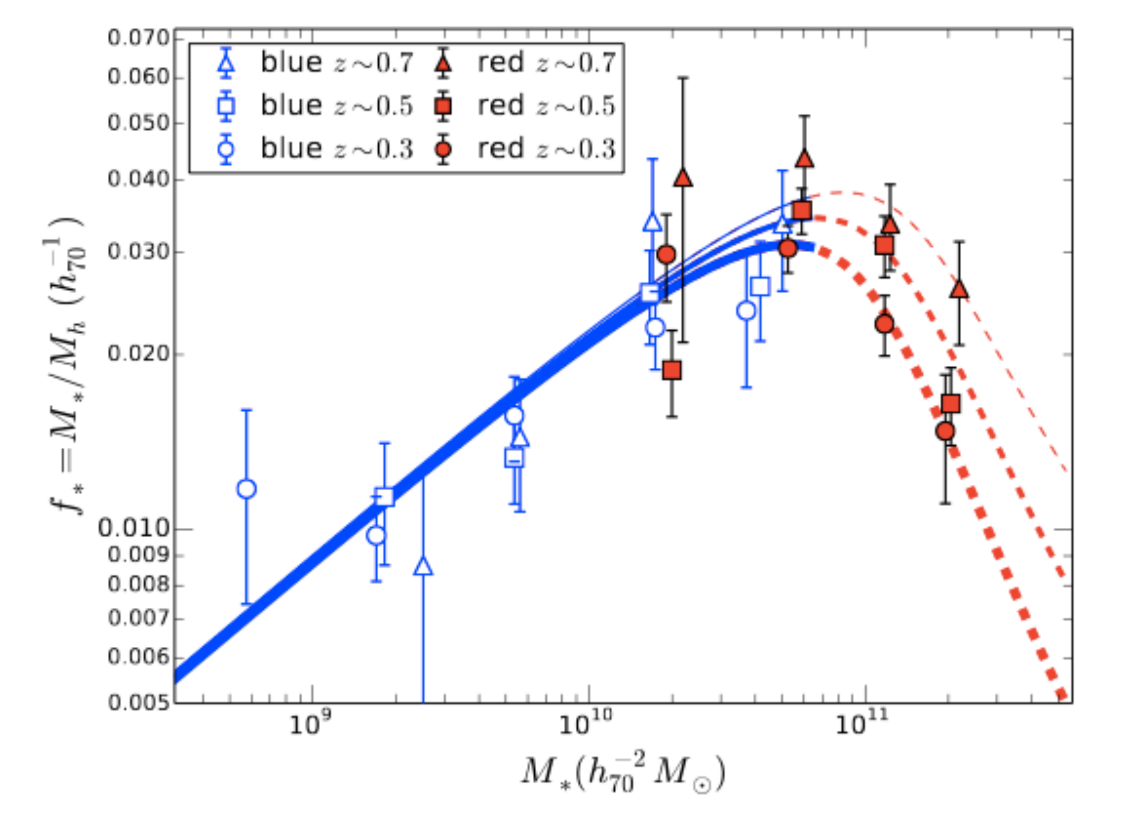
Assembling the data: (1) Galaxy halo masses

- M(halo): weak lensing measurements from CFHLens project
- 2×10^6 lenses over redshift range $0.2 < z < 0.8$, $i'_{AB} < 23$

Lenses stacked and $\langle M_h \rangle$ derived in 13 M_r bins and 3 redshift bins

- M(stellar): $M_* = L_K \cdot (M/L)_K$

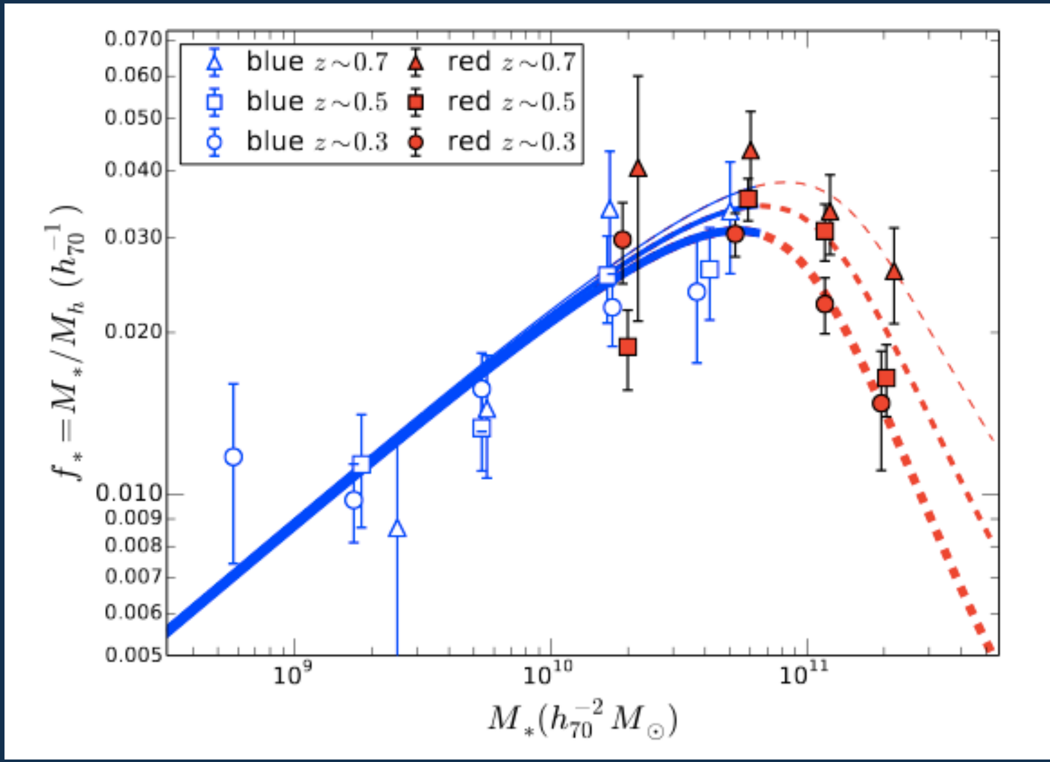
SHMR curve:
(M_*/M_h)
versus M_*
("absolute" star formation efficiency)



Hudson et al. 2015, MNRAS 447, 298

Stellar mass based on K-band luminosity

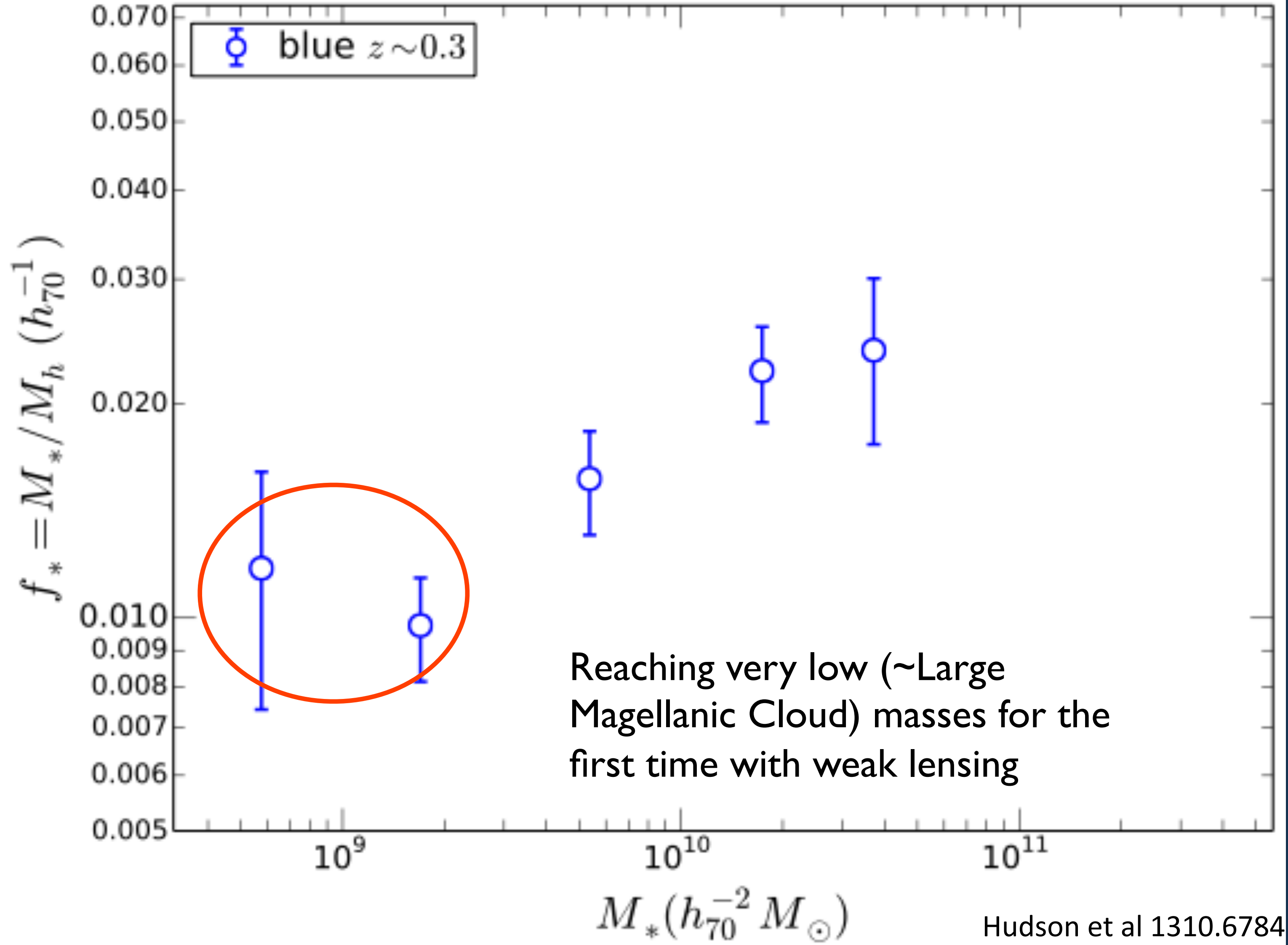
$M_K \rightarrow M_* \rightarrow M(\text{halo})$



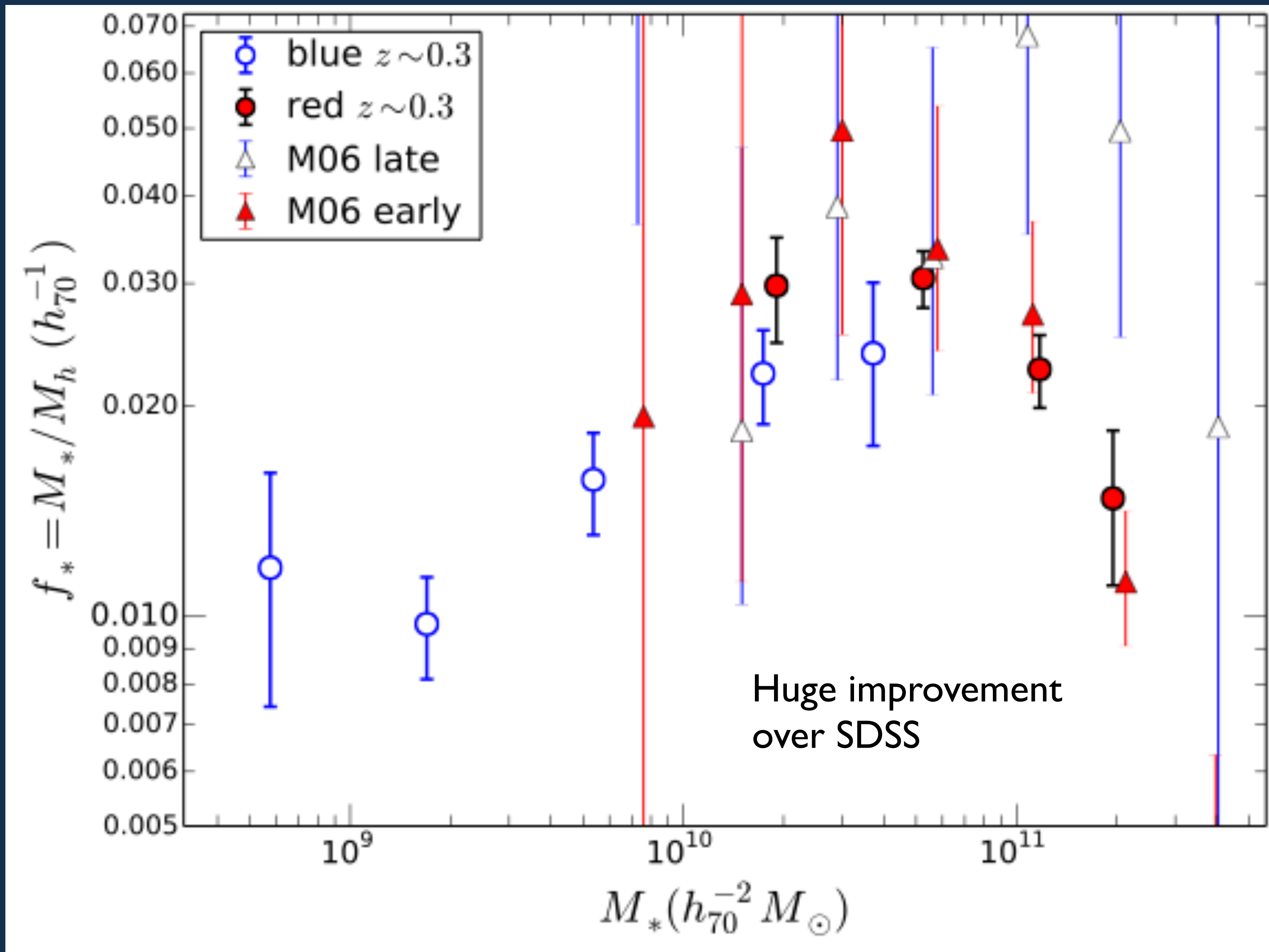
Yang et al. 2003 parametrization with β= 0.68, γ = 0.8

$$f_* = \frac{M_*}{M_h} = 2f_1\left[\left(\frac{M_h}{M_1}\right)^{-\beta} + \left(\frac{M_h}{M_1}\right)^{\gamma}\right]^{-1}$$

Small extrapolation to zero redshift



Hudson et al 1310.6784


blue $z \sim 0.3$
red $z \sim 0.3$
M06 late
M06 early
Huge improvement over SDSS
$f_* = M_*/M_h\ (h_{70}^{-1})$
$M_*(h_{70}^{-2}\,M_\odot)$
0.070
0.060
0.050
0.040
0.030
0.020
0.010
0.009
0.008
0.007
0.006
0.005
10^9
10^{10}
10^{11}

Assembling the data: (2) GC system total mass

Catalog of globular cluster systems in 419 galaxies (Harris, Harris & Alessi 2013).

- Extracted from ~110 individual papers
- Covers entire luminosity range except very smallest dwarfs that have no clusters
- 245 E, 93 S0, 81 S/Irr

Sum over GCLF, including known trend of "turnover" magnitude and LF dispersion with galaxy size (giant galaxies have broader, brighter GCLFs)

$$M_{GC} = \left(\frac{M}{L}\right)_V \int L \cdot n(L)\, dL$$

$(M/L)_V = 2$

Define $\eta = M_{GC}/M_h$

M_{GC} = total mass in globular clusters, M_h = halo mass

Estimates of η in the literature

	η (10^{-5})
Blakeslee && 1997	~ 10-20
Spitler et al. 2008	3.2
Spitler & Forbes 2009	7.1
Georgiev et al. 2010	6 +- 1
Harris et al. 2013	6
Hudson et al. 2014	3.9 +- 0.9
Durrell et al. 2014	2.9 +- 0.5
Harris et al. 2015	3.4 +- 0.4

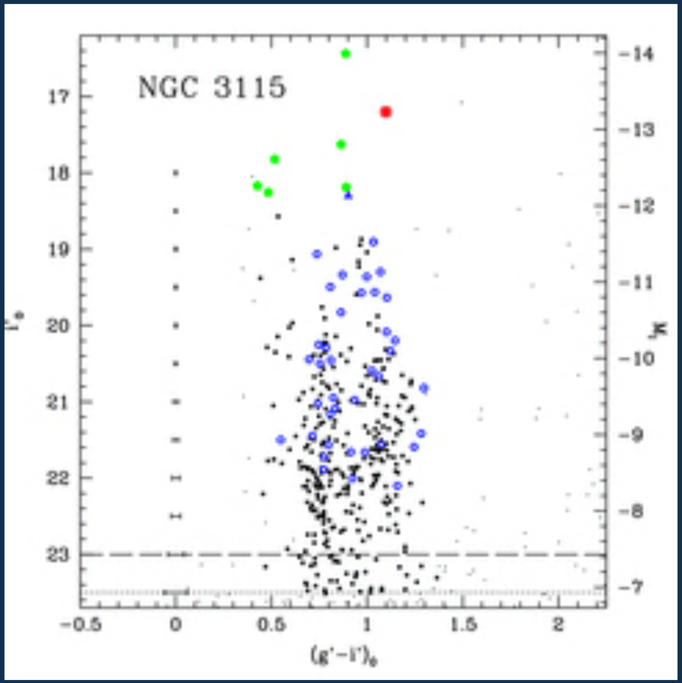
Main differences due to

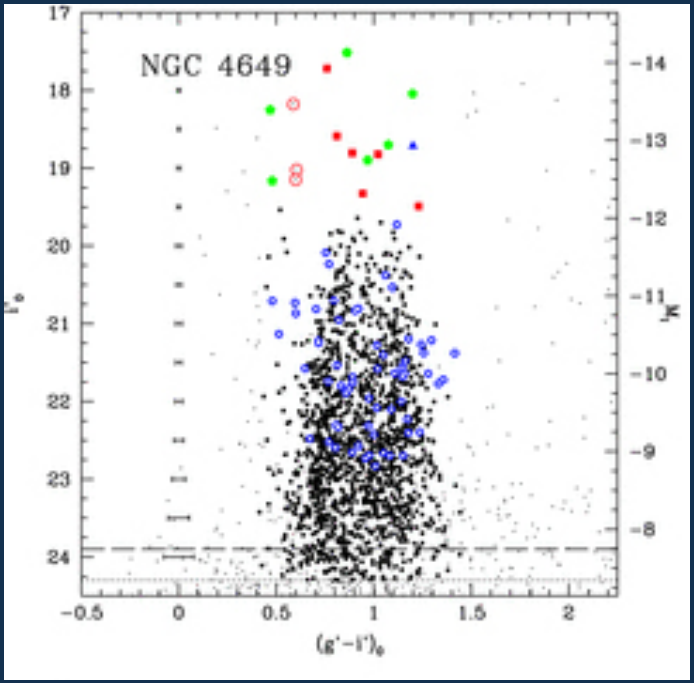
- method and zeropoint for calculating halo mass
- method for calculating M(GCS) (mainly assumptions about mean GC mass)

What else can be done for observational characterization of this phenomenon?

In almost all galaxies there exist "blue" and "red" GC **
subpopulations (bimodal distribution in color or metallicity)

** (really more like "yellow" and "orange")





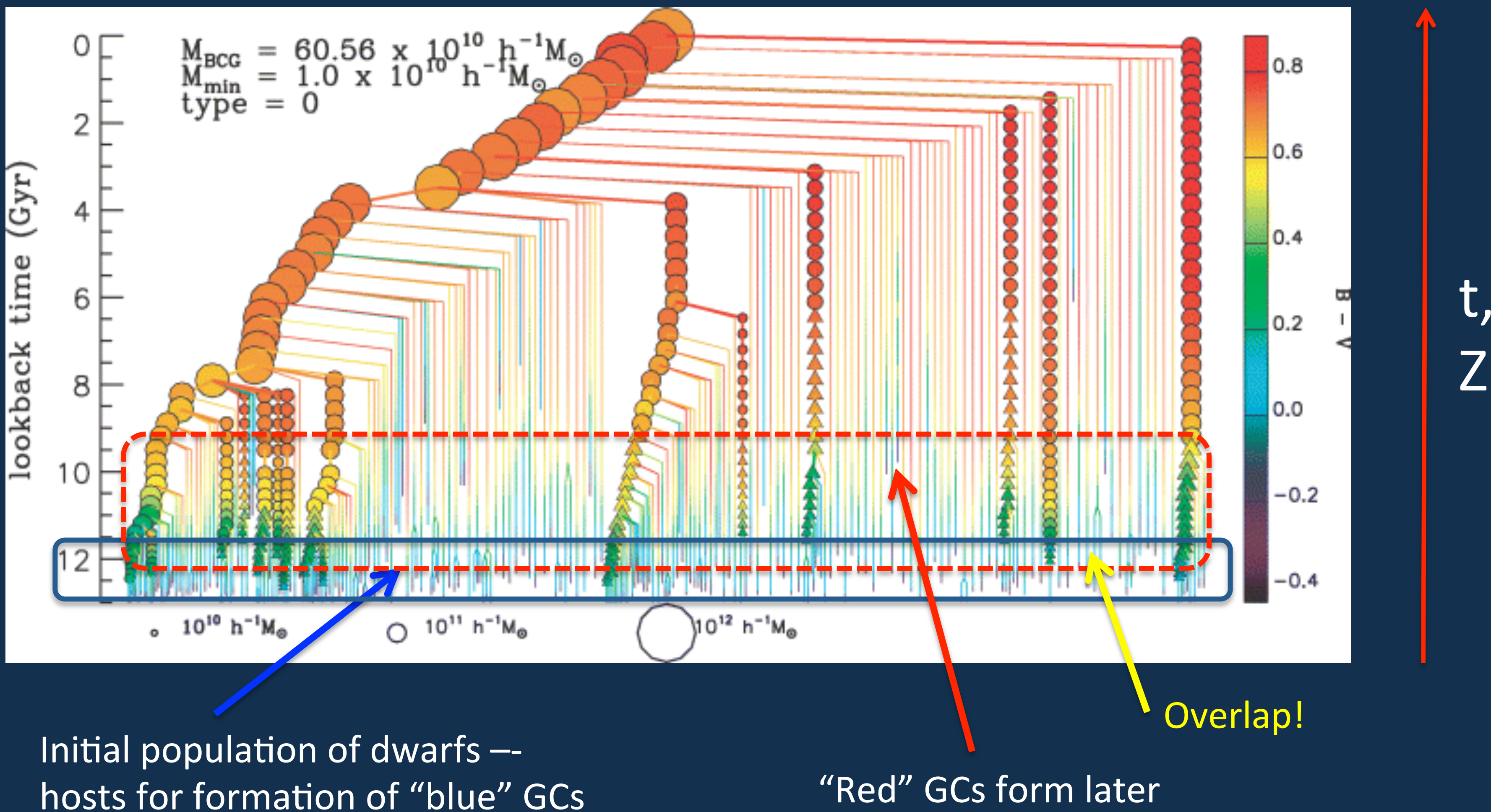
Faifer et al. 2011, MNRAS 416, 155

- Calibrations in nearby galaxies indicate "blue" GCs are on average older (by 2-3 Gy) and more metal-poor; also more spatially extended in the halo

- "Red" GCs progressively more prominent in bigger galaxies with longer, more complex star formation histories

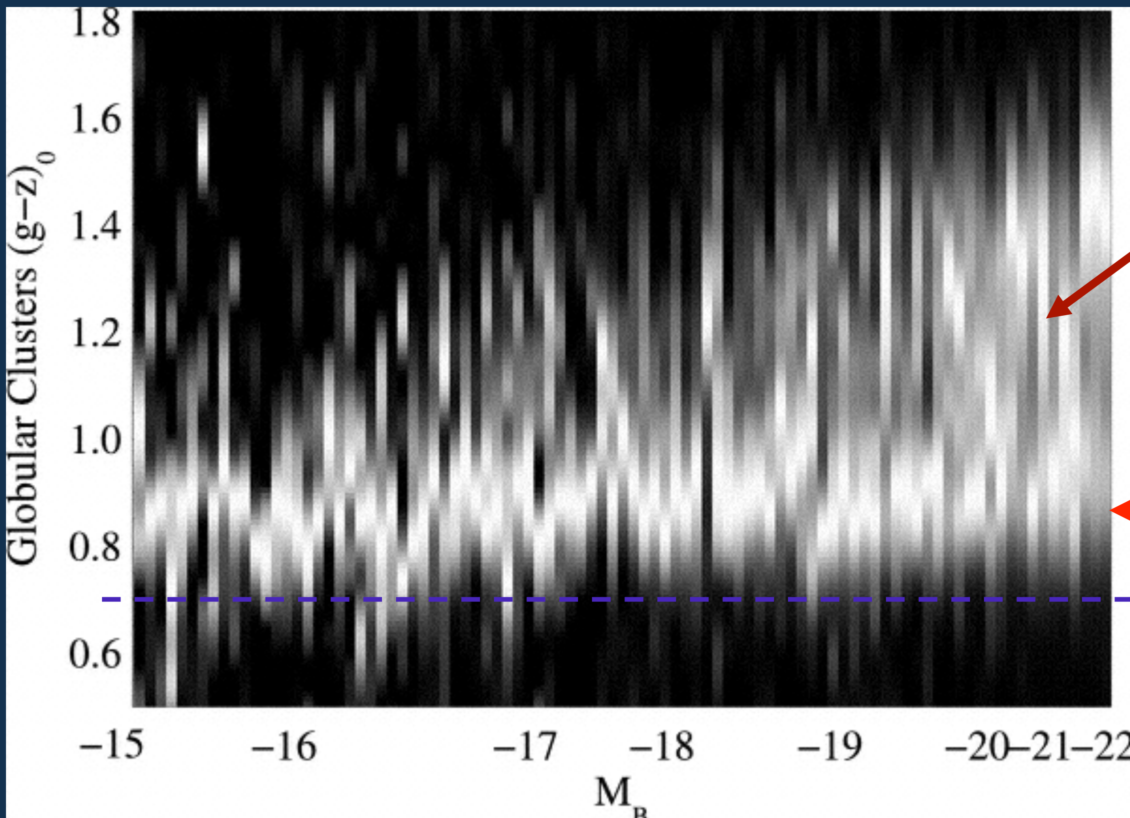
Fit into standard hierarchical-merging picture of galaxy formation.

Representative merger tree for giant (De Lucia & Blaizot 2007)



Also see Kruijssen 2014

The bimodality question: “red” and “blue” GC subpopulations. Is one correlated better with M(halo)?

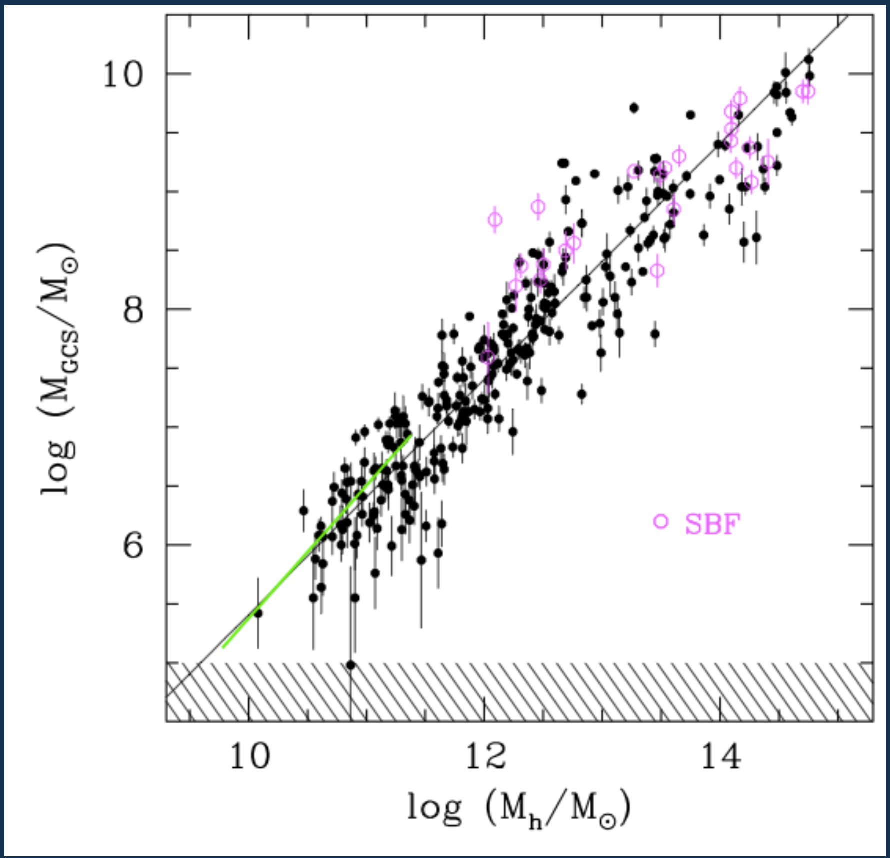


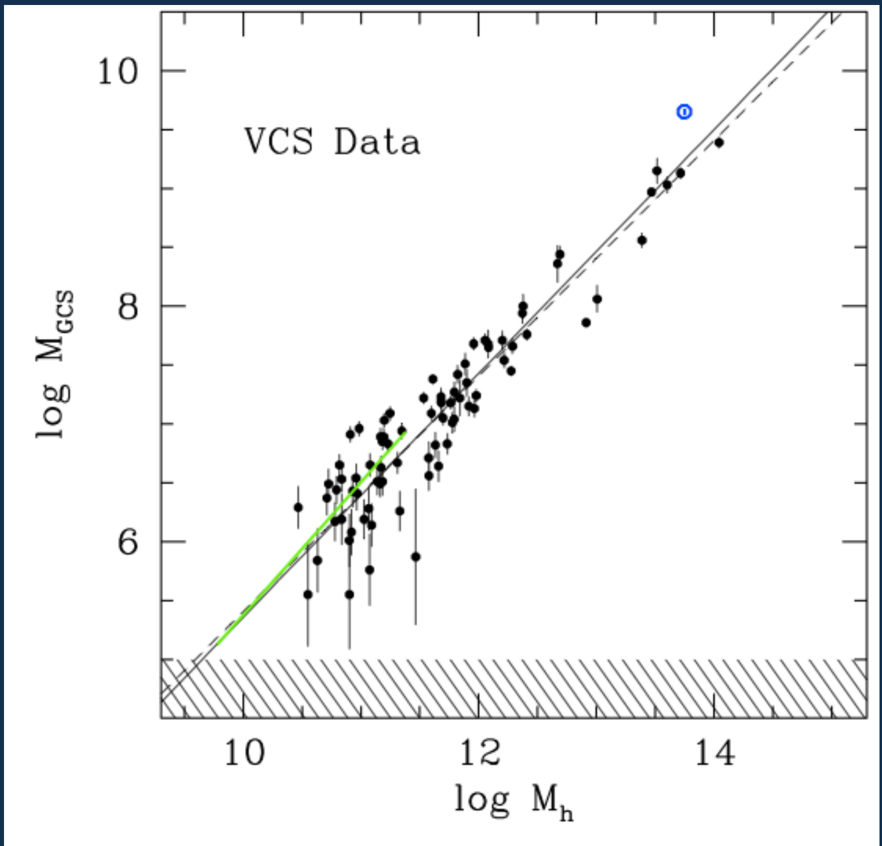
Peng et al. 2006, ApJ 639, 95

Dwarfs: N(red) ~ 0

Even in most giant galaxies, N(blue) still the majority

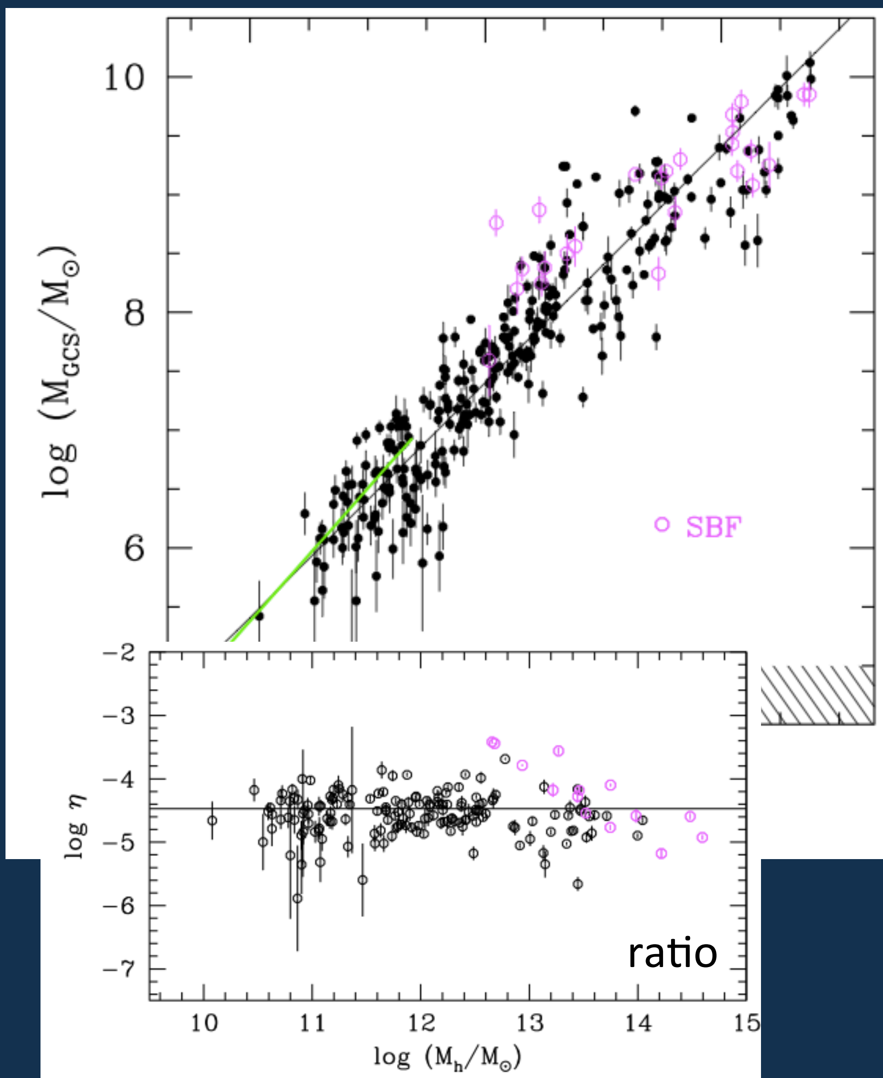
Scatter around the 1:1 line: inhomogeneity in the database? Intrinsic?

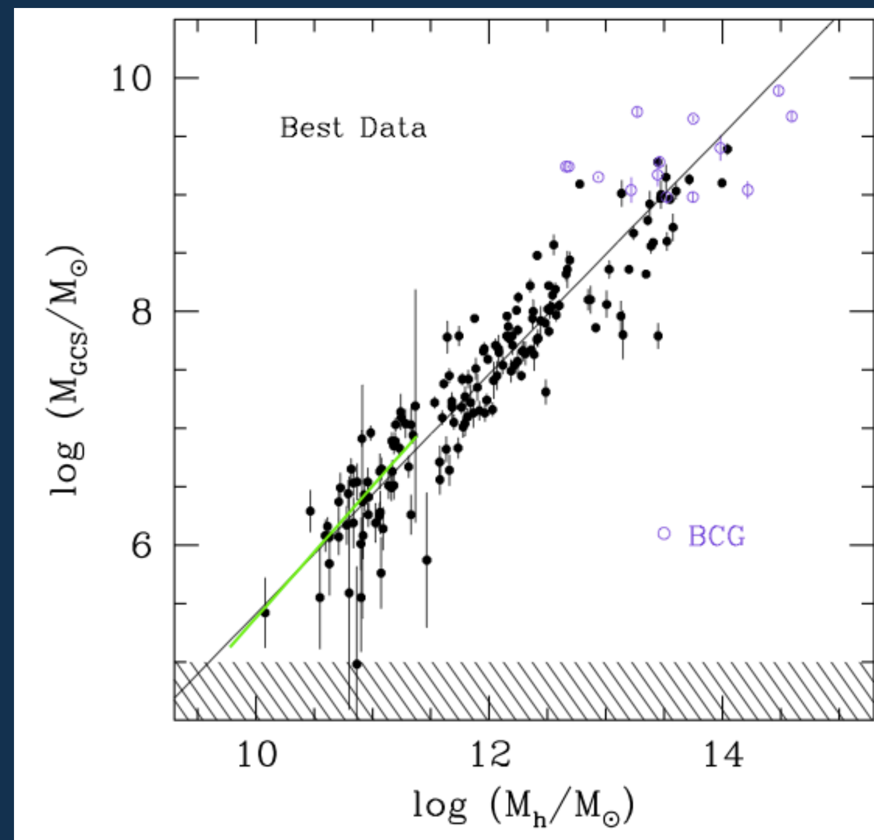




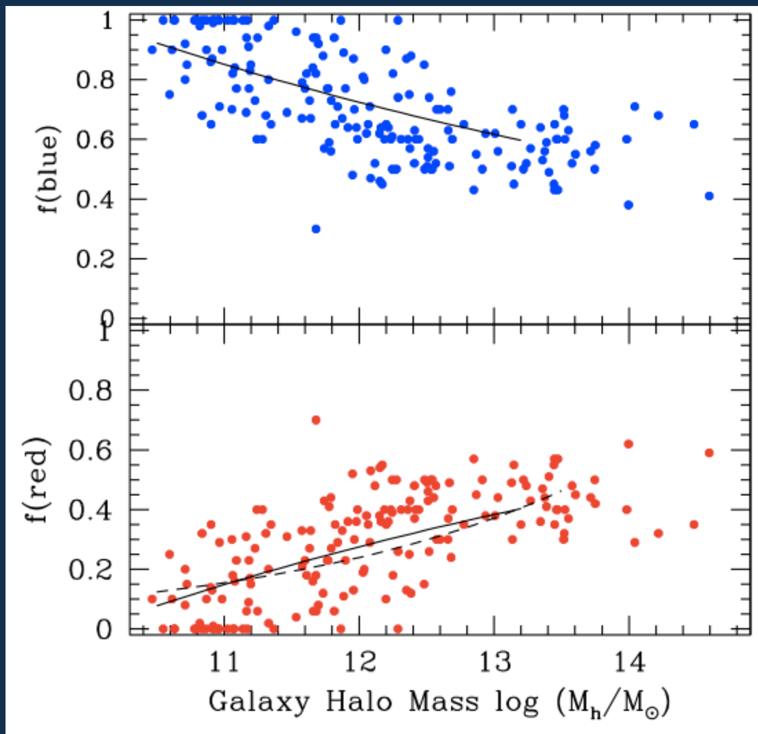
HST Virgo Cluster Survey only. Internally much more homogeneous

Select the ~200 galaxies with photometry good enough to define the red/blue fractions   f(red), f(blue)



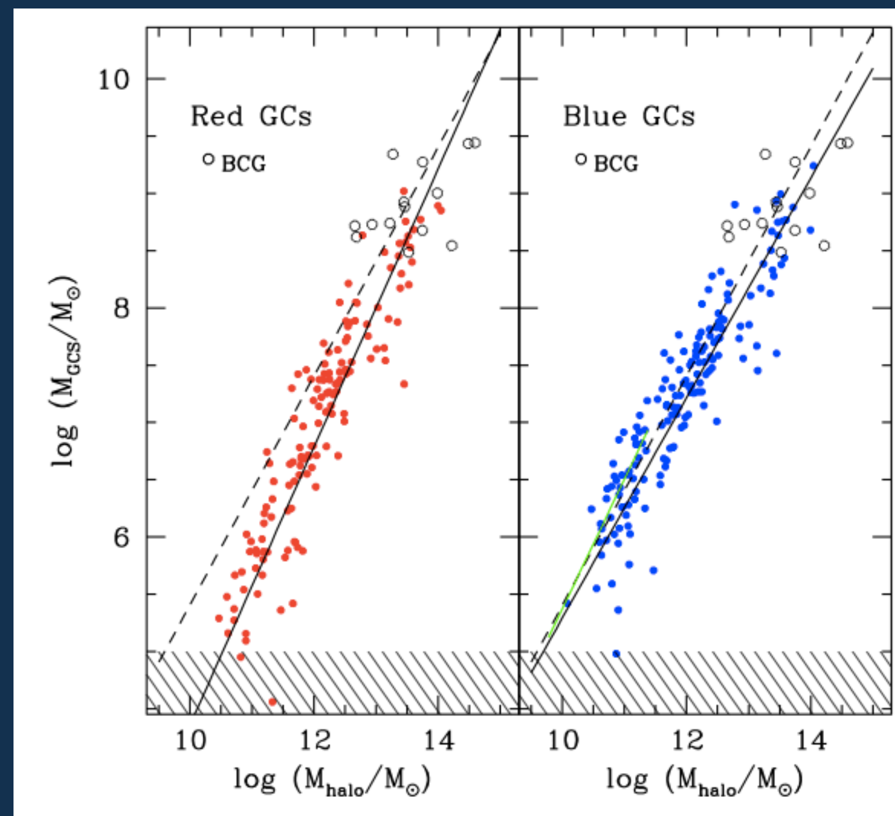


f(red, blue) known.
Same scatter as Virgo subset, and better coverage



$$f_{blue} = \left(\frac{M_h}{10^{10} M_{\otimes}} \right)^{-0.07}$$

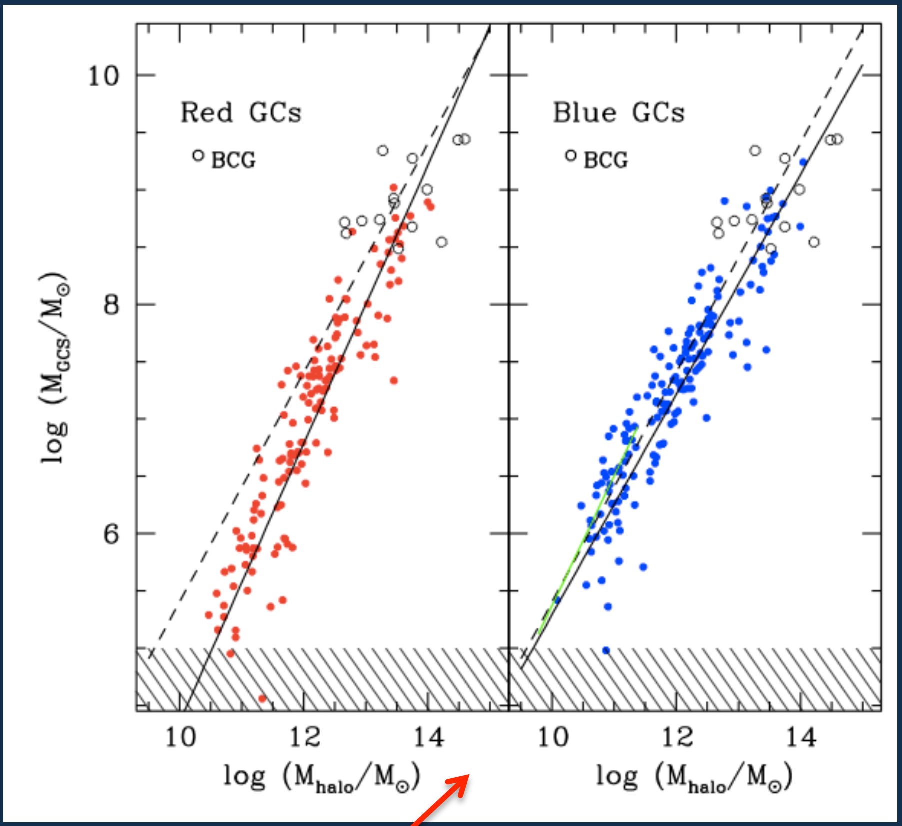
Valid for $M < 10^{13} M_0$

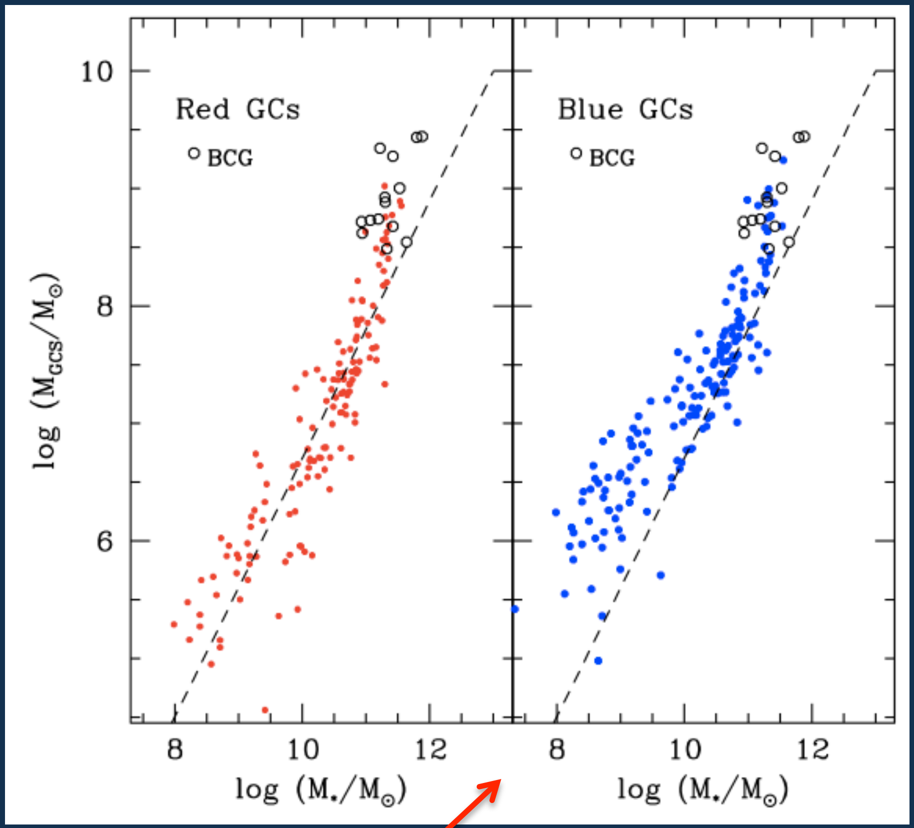


$$M(GCS)_{blue} \sim M_h^{0.95}$$

$$M(GCS)_{red} \sim M_h^{1.19}$$

The classic "specific frequency problem" is essentially the correlation of M(GCS) (or number) with galaxy stellar mass (or luminosity)

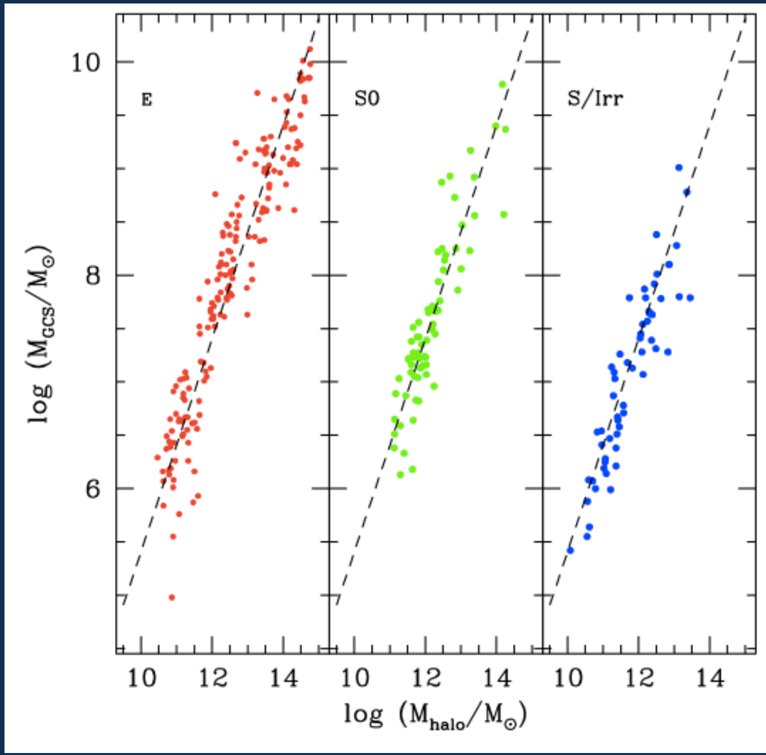




Halo mass

Stellar mass

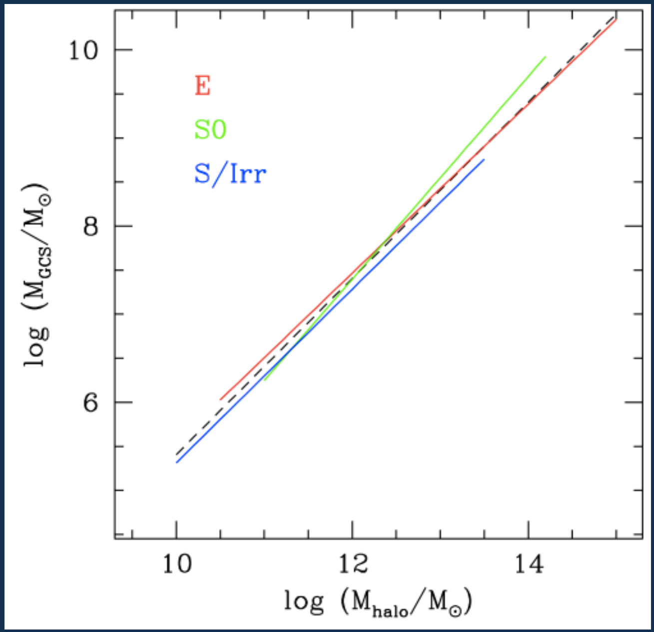
What about host galaxy type (morphology)?



$$M(GCS) \sim M_h^{0.96\pm0.02} \quad Ellipticals$$

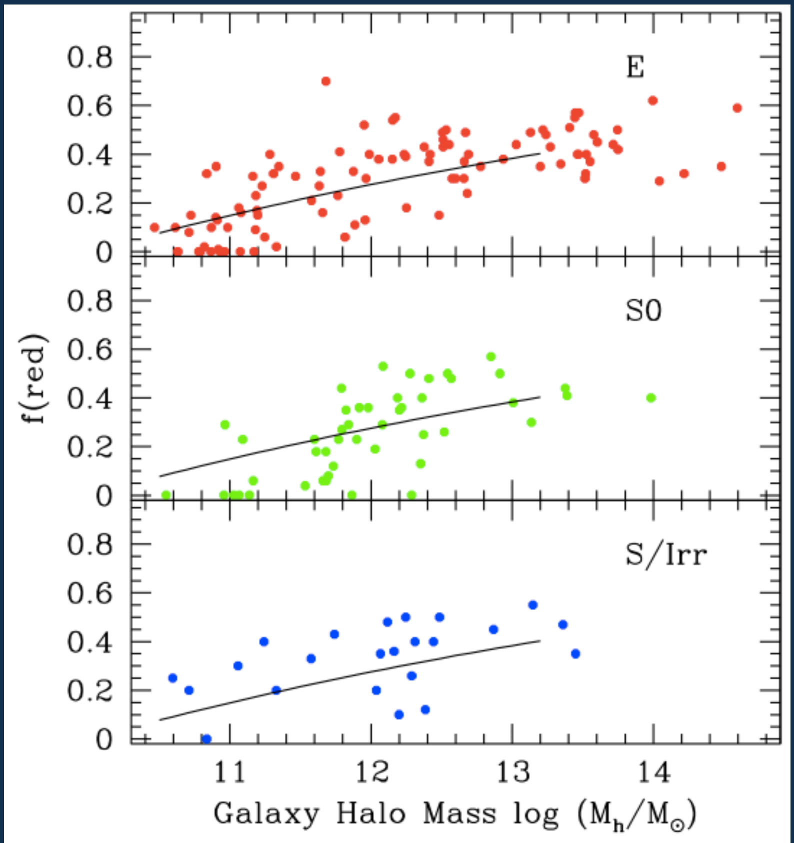
$$M(GCS) \sim M_h^{1.15\pm0.05} \quad S0's$$

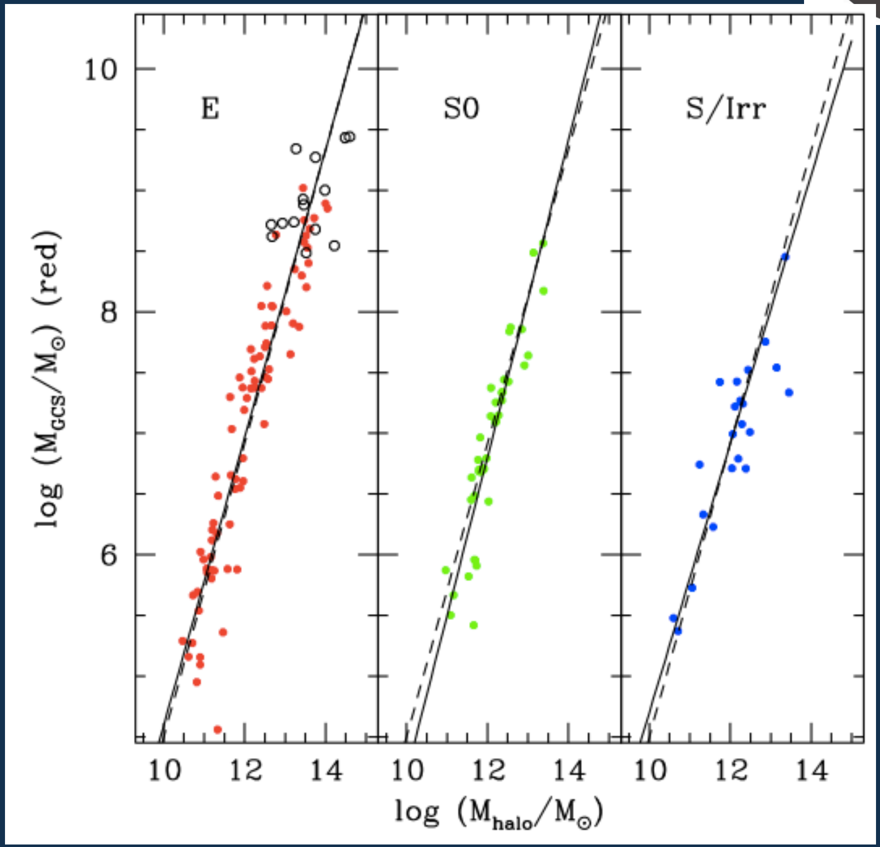
$$M(GCS) \sim M_h^{0.99\pm0.08} \quad S/Irr$$



S/Irr offset (0.18 +- 0.06) dex below E/S0 types. Globally "less efficient" at forming GCs? (by 30-40% nominally)

Some more second-order trends --





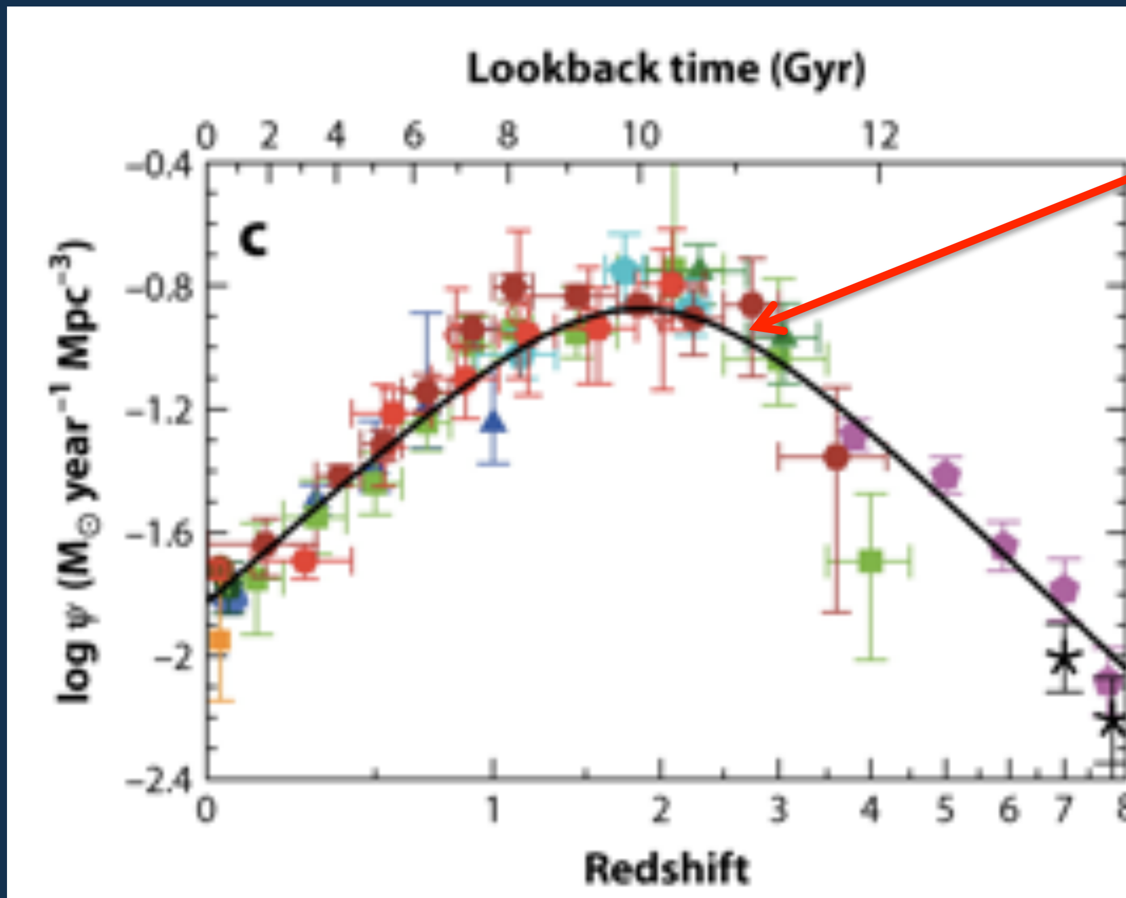
Spirals have a slightly *higher* fraction of metal-rich GCs, by $\Delta f \sim 0.1$

Did they experience fewer satellite accretions than E/S0's ?

This difference cancels the slightly lower total M(GCS) in spirals, leaving same M(GCS)(red) vs M(halo) trend for all types

But wait: Shouldn't the red (metal-richer) GCs track the total *stellar* mass better instead?

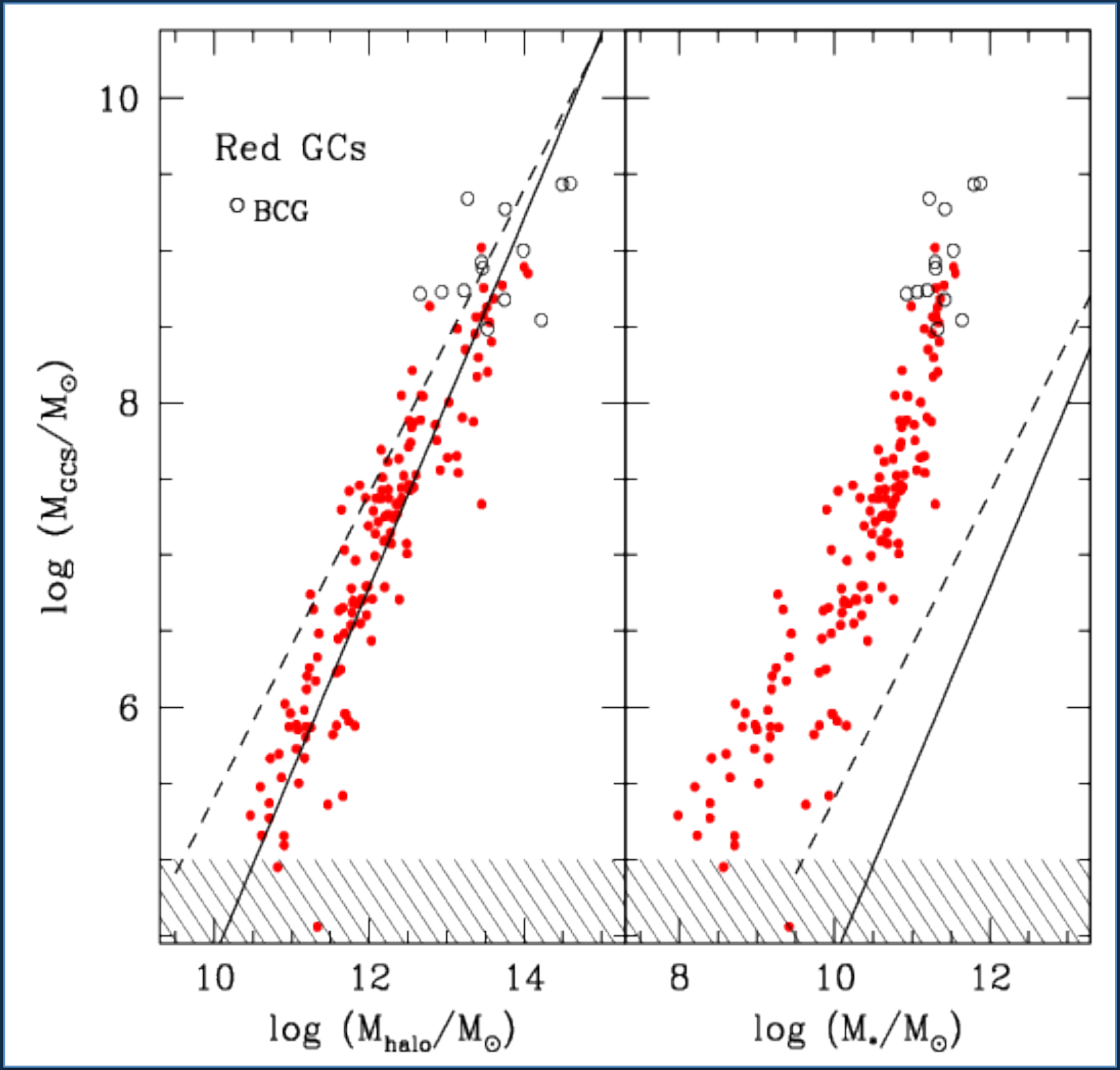
Globular cluster formation epochs are z = 2 – 8, but red GCs mostly formed in z = 2 – 4 , not far from peak of cosmic SFR



Bulk of stellar mass in galaxies built in this range

Madau & Dickinson 2014, ARAA 52, 415

Compare red GCs vs. halo mass, then stellar mass



What does the correlation mean?

We should get the result we see, if two conditions hold:

$$M_{GCS} \sim M_{gas}(init) \sim M_h$$

GC formation is largely immune to the feedback that damages field-star formation, or happened before feedback got started

The *absolute value* of η also means something.
A simple argument to understand the basic correlation:

$$\eta \equiv \left(\frac{M_{GCS}}{M_h}\right) \sim \left(\frac{M_{bary}}{M_h}\right) \times \left(\frac{M_{GMC}}{M_{bary}}\right) \times \left(\frac{M_{PGC}}{M_{GMC}}\right) \times \left(\frac{M_{GC}}{M_{PGC}}\right)$$

$$\sim 0.15 \times 0.01 \times 0.1 \times 0.3 \sim 4 \cdot 10^{-5}$$

GMCs large enough to build GCs

Massive dense proto-GCs

Infant mortality and long-term dynamical evolution (more appropriate to high-M clusters dominating η)

An interesting detour:

The ratio η can be used to estimate galaxy masses (Spitler & Forbes 2009):

How well does it do for the Milky Way?

M (10^{12} M_{sun})	Source	Method
1.2 +- 0.5	Hudson && 2014	GCS mass
0.9 +- 0.3	Watkins && 2010	halo satellite tracers (isotropic)
0.4	Deason && 2013	(R < 50 kpc) halo BHB stars
1.2 +- 0.6	Battaglia && 2005	halo satellite velocity dispersion
1.6 +- 0.6	Boylan-Kolchin && 2013	Leo I motion + simulations
3.1 +- 1.4	Sohn && 2013	Leo I timing
(>0.8)	Li & White 2008	calibrated timing argument
1.4 +- 1	Gonzalez && 2014	entire Local Group
1.4 +- 0.2	Eadie && 2015	satellite motions + Bayesian/MCMC

This has been an observationally driven subject.

We desperately need some theory

All models are ~~wrong~~, but some are useful.

George E.P.Box

in *Empirical Model Building and Response Surfaces*

limited by – input assumptions

-- input physics

-- computational power

30 Doradus + R136 (J.P.Gleason)

R136 within 30 Doradus (LMC).

R136 ~ 2-Myr age
50000 M(Sun)
will produce a *small* GC

NB Kruijssen (2014) argues that sites of GC formation were much denser than GMCs today – CFE much higher than ~0.01 now

GC formation in a semi-cosmological framework (aimed at blue, metal-poor GCs) – high redshift + before reionization

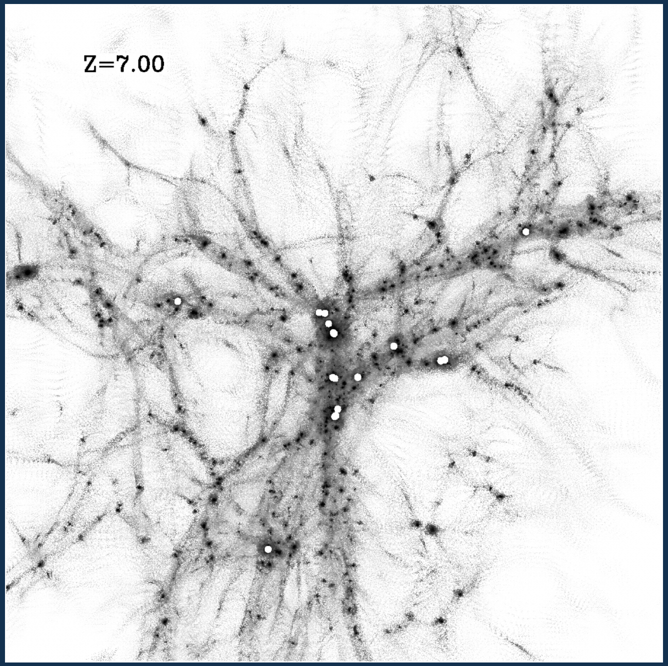
Peebles & Dicke 1968
Peebles 1984
Fall & Rees 1985
Moore et al. 2006
Boley et al. 2009
Corbett Moran et al. 2014

If blue and red GCs form by different routes, no context for understanding the close physical similarities of GCs with different metallicities (mass distribution, scale sizes, King-type structures)

GC formation during hierarchical merging

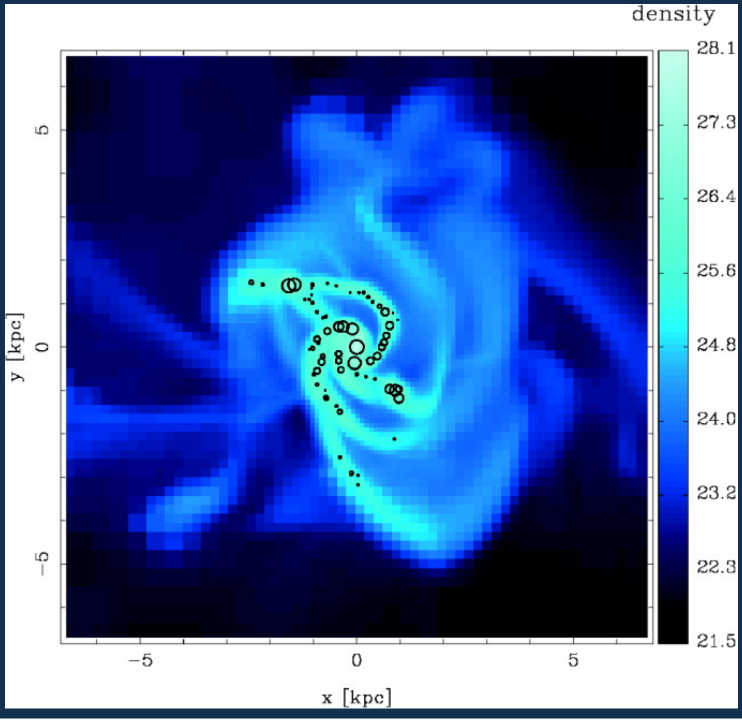
Beasley et al. 2002
Kravtsov & Gnedin 2005 (KG05)
Moore et al. 2006
Bekki et al. 2008
Muratov & Gnedin 2010
Griffen et al. 2010
Tonini 2013
Li & Gnedin 2014

Proto-GCs emerge as dense massive clumps in large GMCs (whenever and wherever enough gas can be assembled)



KG05 is a ***useful*** model

- Hydro + AMR simulation of a ~1 Mpc box followed from z = 11.8 to 3.35
- Inclusion of feedback from stellar winds, SNe, UV background
- SFR ~ local gas density
- Minimum grid resolution ~30 pc, enough to find *sites* of GC formation within GMCs, but not the proto-GCs themselves



Snapshot at z = 4. "Final" galaxy is Milky Way sized, ~10^{12} M_0

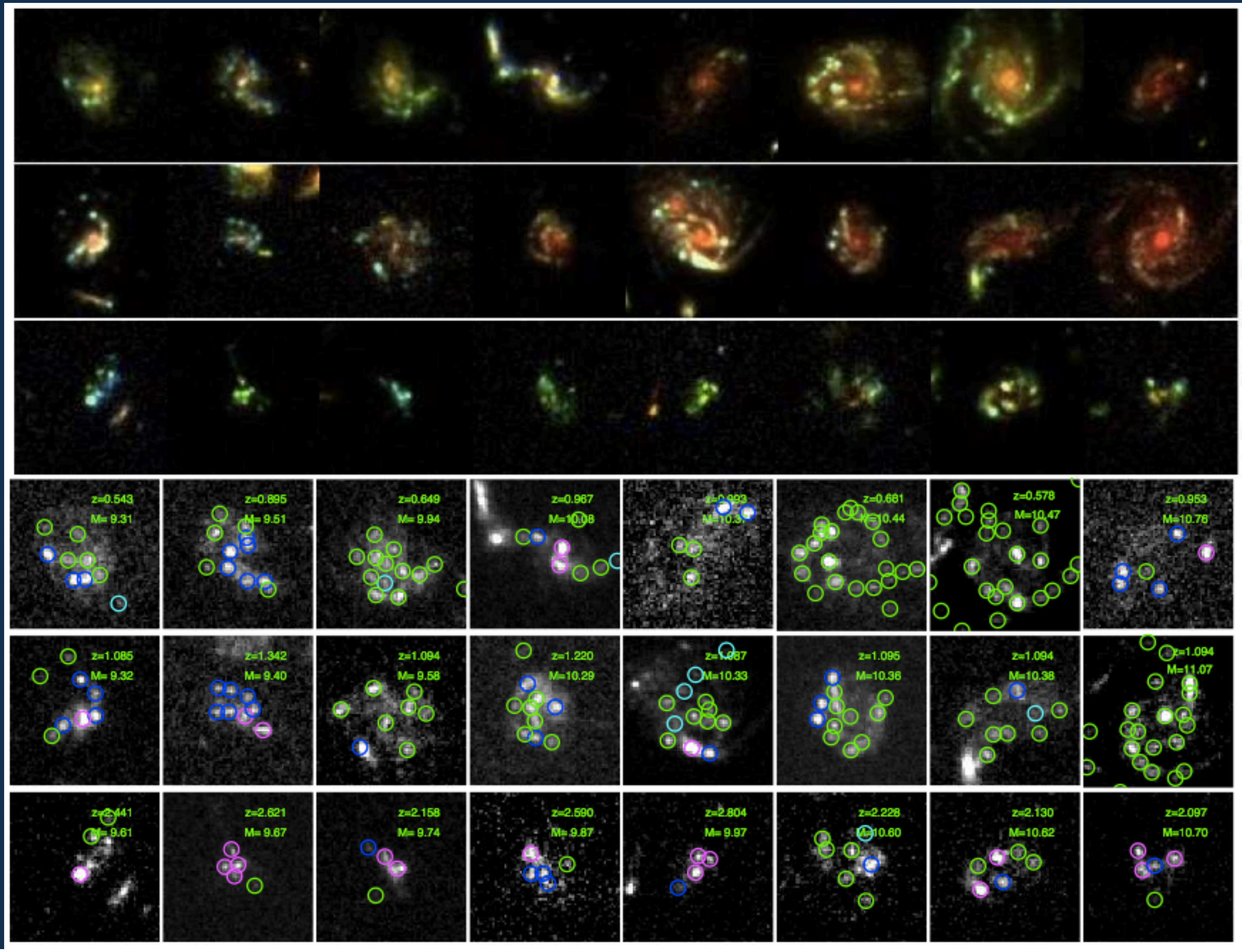
Proto-GCs marked as densest cores within GMCs if density above threshold $\rho > 1\ M_0/pc^3$

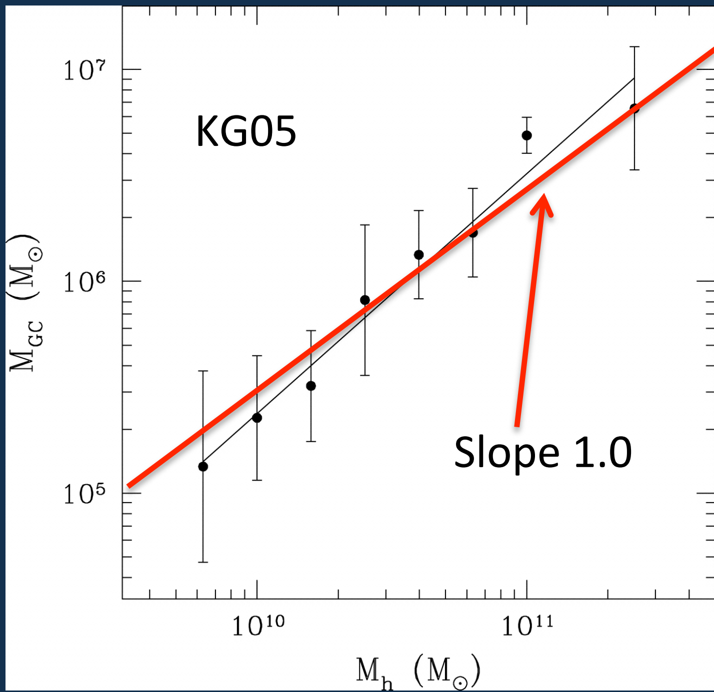
Metallicities reach [Fe/H] = -1 at end of run

Massive star forming clumps in 0.5 < z < 3 galaxies. Strongly resemble the ‘SGMCs’ of Harris & Pudritz 1994, Kravtsov&Gnedin 2005 as sites of GC formation

Guo et al. 2015, ApJ (1410.7398)

HST BVI imaging (CANDELS)



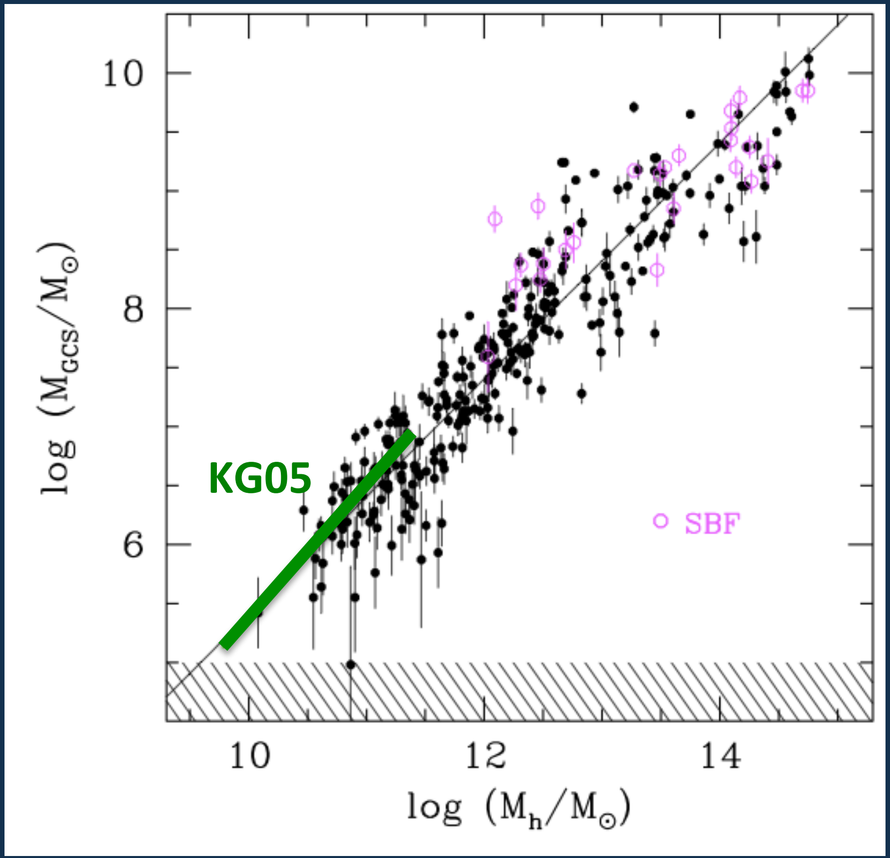


$$M_{GCS} \sim M_h^{1.13 \pm 0.08}$$

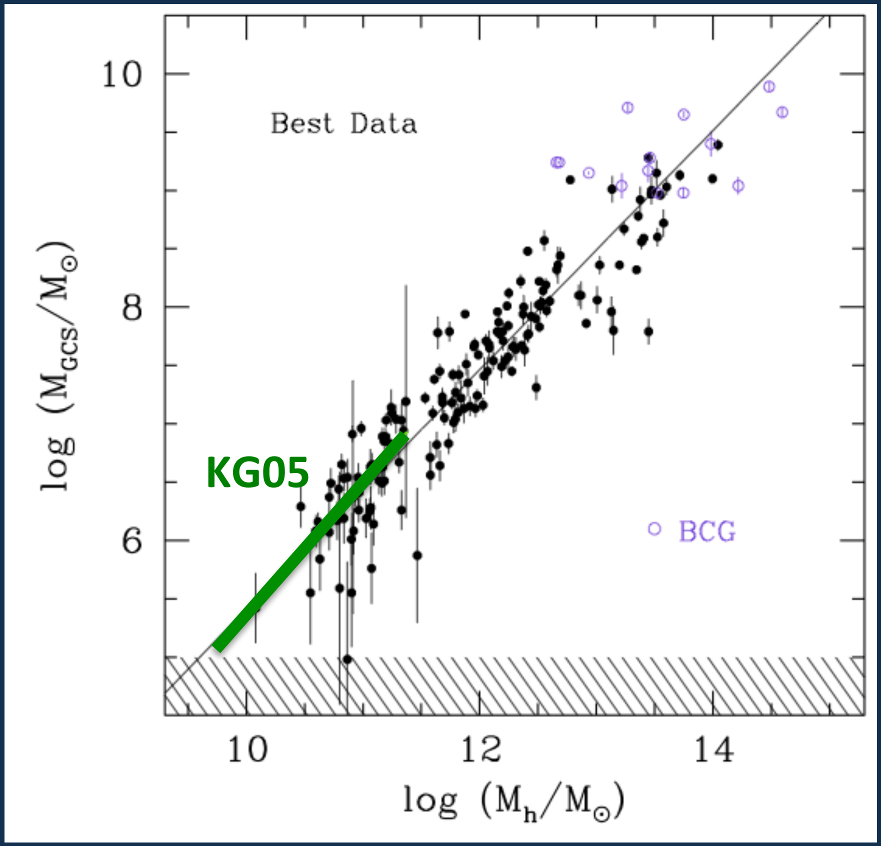
Should be comparable to the metal-poor GCs, [Fe/H] < -1

and applies to small halos $M_h < 3 \times 10^{11}\ M_0$

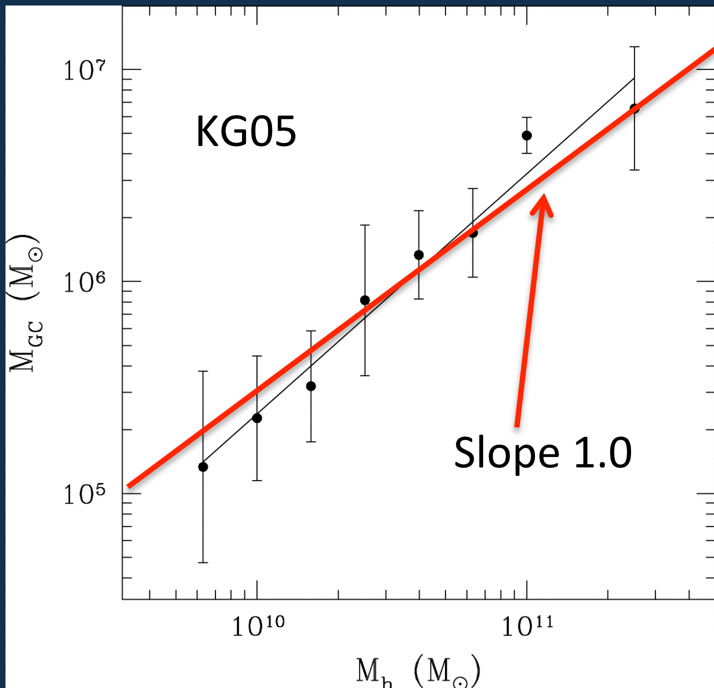
Comparison of KG05 model with data

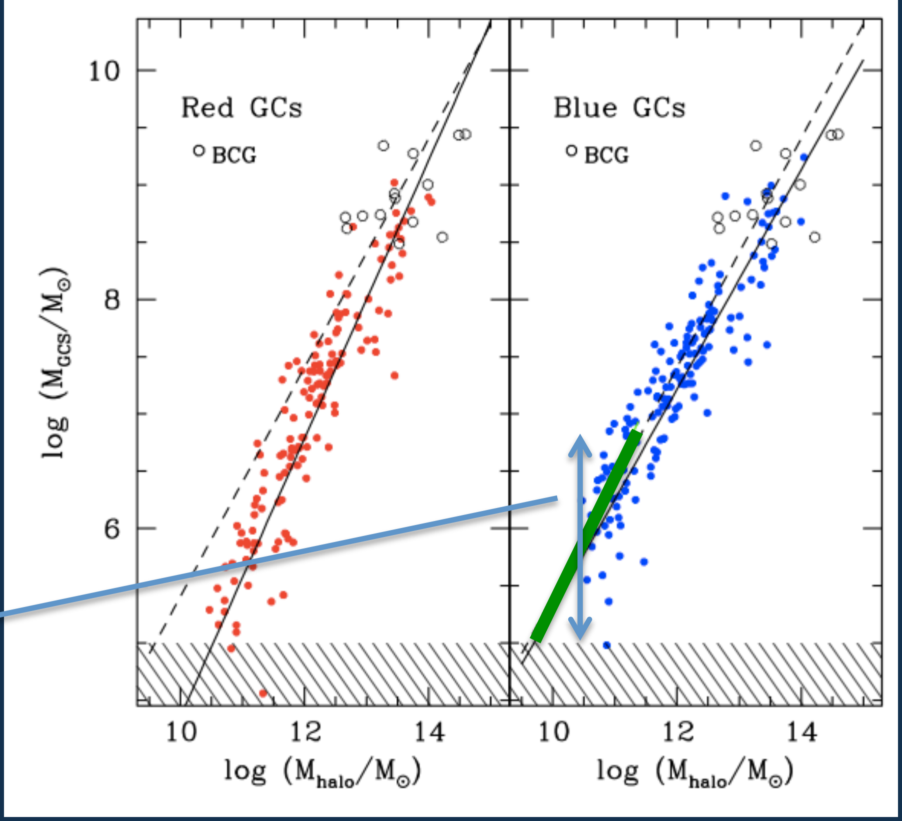


All data



f(red, blue) known.





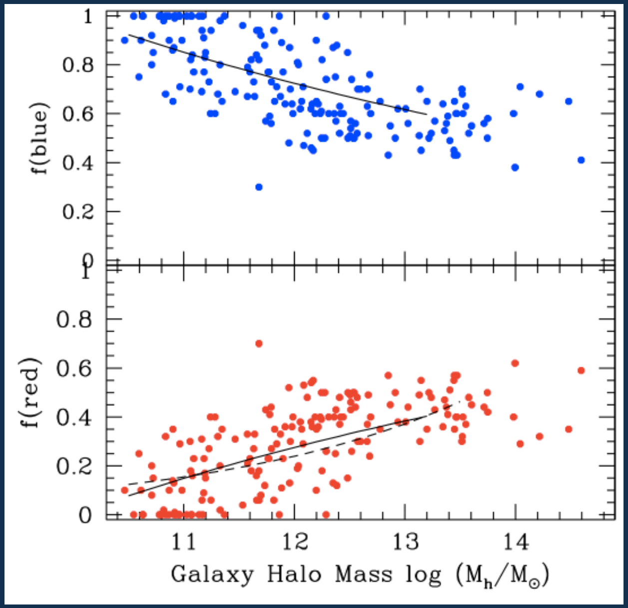
Zeropoint agreement is accidental!

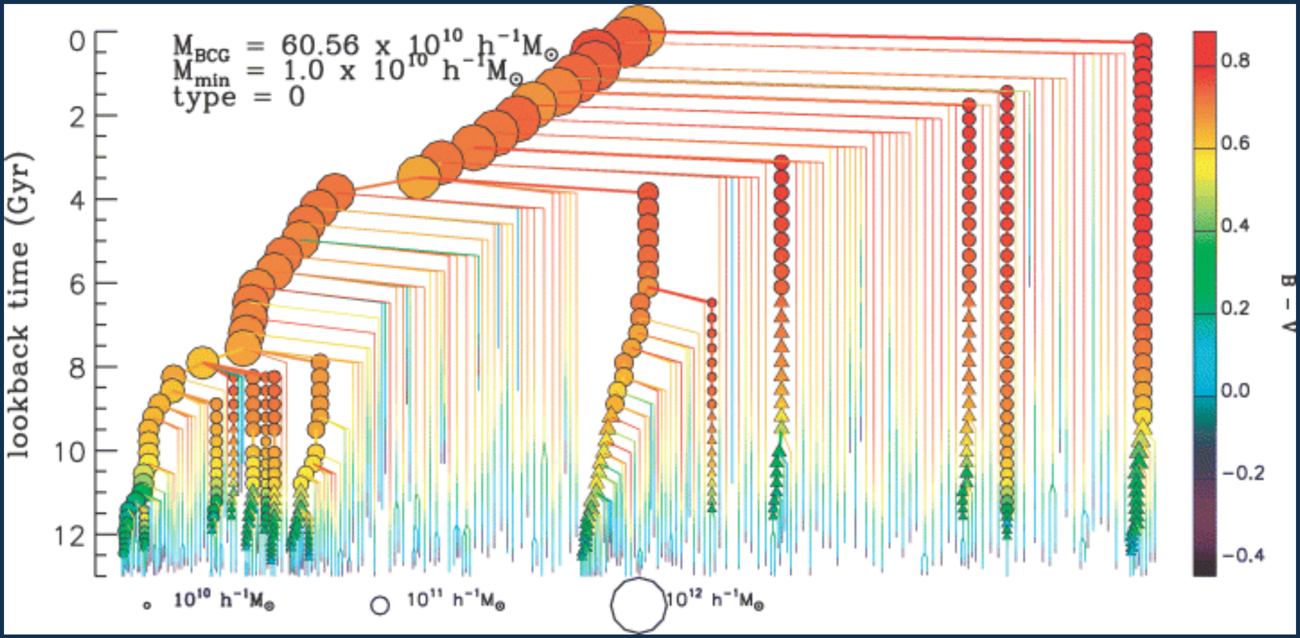
-- comparison of halo masses then vs . now
-- GC masses now vs. proto-GC masses then

Provides a mechanism for replicating the blue-GC mass line all the way up to the giants

The trend of red/blue fraction is the visible outcome of the merger-tree history for each individual galaxy.

A successful hierarchical model must correctly reproduce the trend! An important new constraint





What do we need next?

Observations/data

Homogeneous, accurate photometric studies of more galaxies, particularly in the moderate-to-high mass range

Data good enough for accurate red/blue fractions and covering wide field

Any correlation with environment?

Promising database: MATLAS survey material

Theory/modelling

Merger-tree models specifically aimed at incorporating GCs

Ultimately, hydro simulations at high enough resolution to isolate true GC formation sites

Conclusions (for now):

- The M(GCS) ~ M(halo) correlation gets stronger with increased size and precision of database. Two basic assumptions seem necessary to understand this:
  (a) M(GCS) ~ initial M(gas) ~ M(halo)
  (b) GC formation is largely immune to feedback

- M(GCS)(blue) ~ $M(\text{halo})^{0.96}$ and a plausible merger-tree model exists for reproducing it over its entire range

- M(GCS)(red) ~ $M(\text{halo})^{1.2}$, but we have no comparably good model
  The smallest halos capable of generating and holding metal-rich GCs (from the observations) are at ~10^{11} M_0.

- S/Irr galaxies have systematically higher fractions of red GCs. Did they experience relatively fewer satellite accretions?