McMaster University

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)?

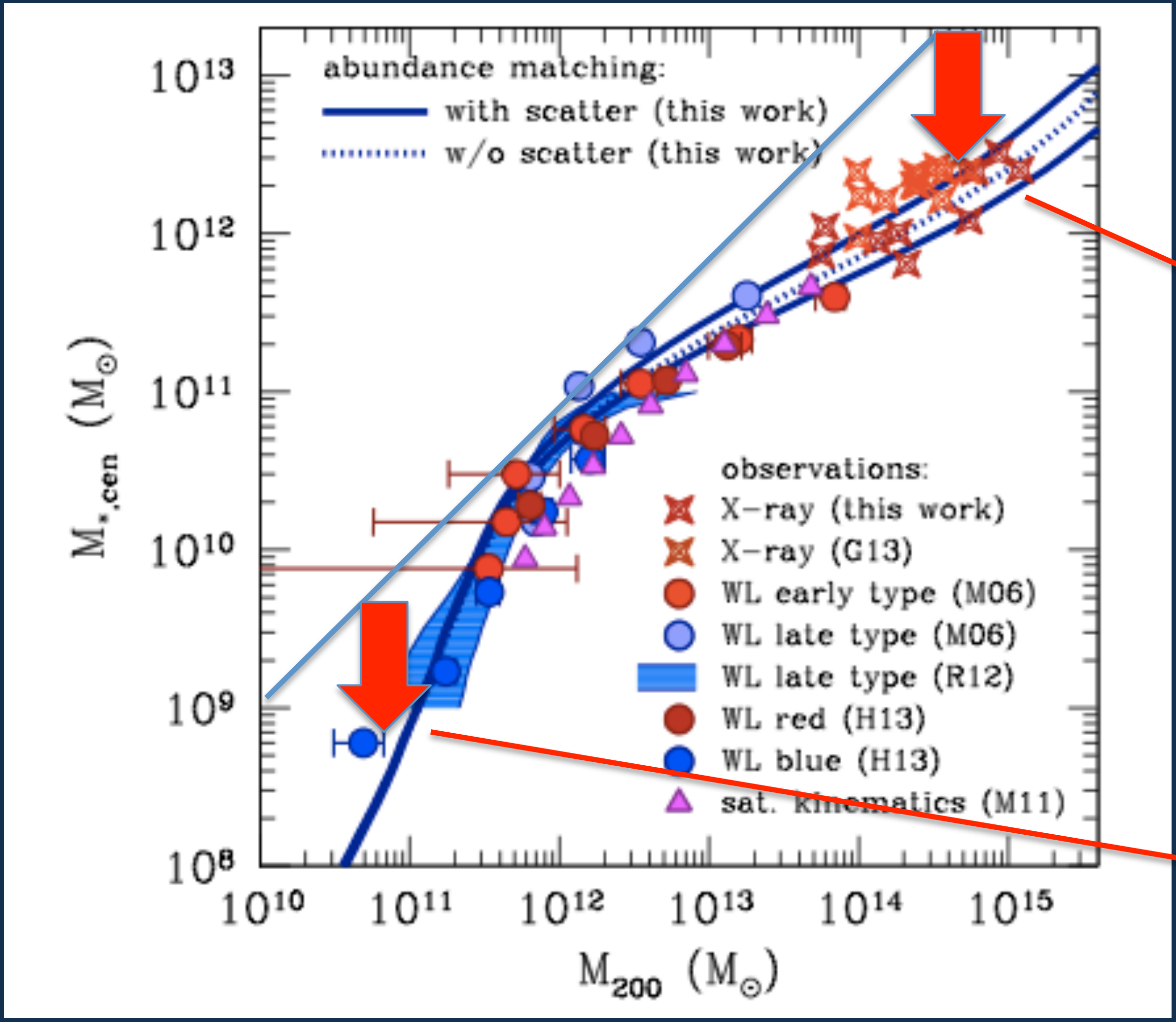
ESO, Feb 2015

Colleagues: Mike Hudson, Gretchen Harris

Outline

(1) Define the central correlation
(2) Characterize it observationally
(3) Link to current models: Interpretation
(4) Conclusions

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)

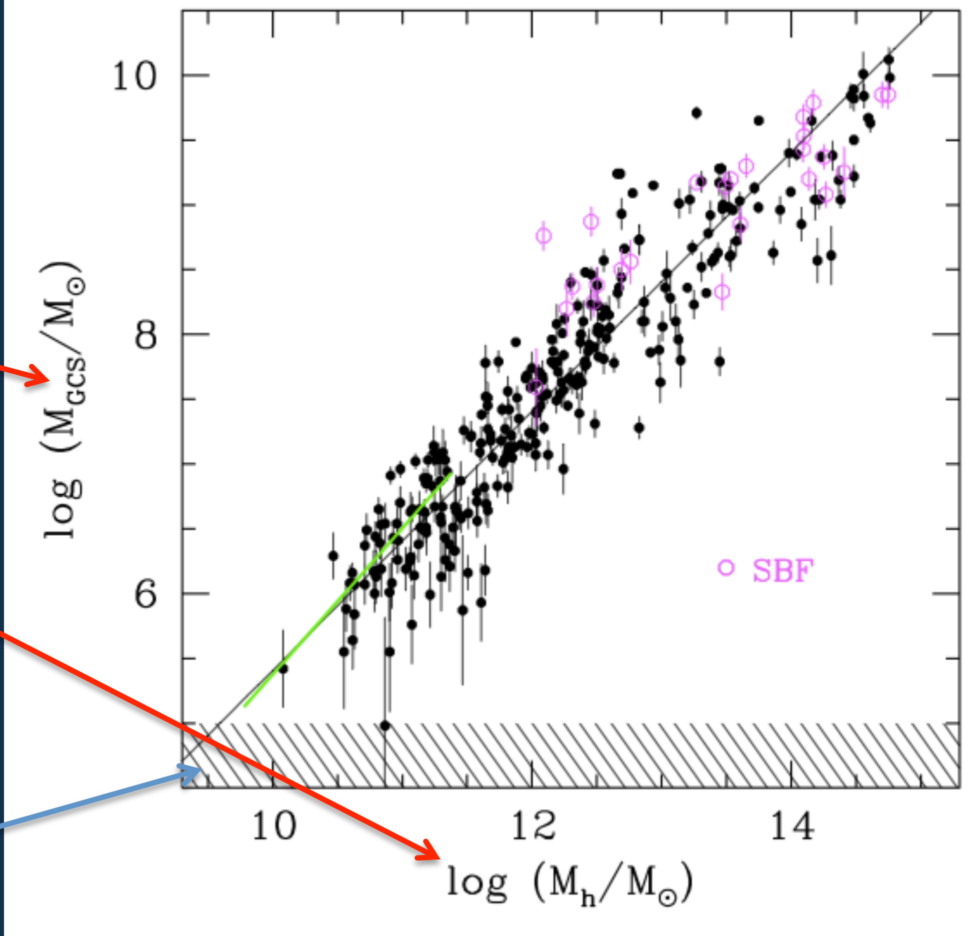
Is there any stellar population that correlates linearly with halo mass?

Globular clusters are a logical possibility.
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 the $M_{GCS} \sim M_{halo}$ correlation:

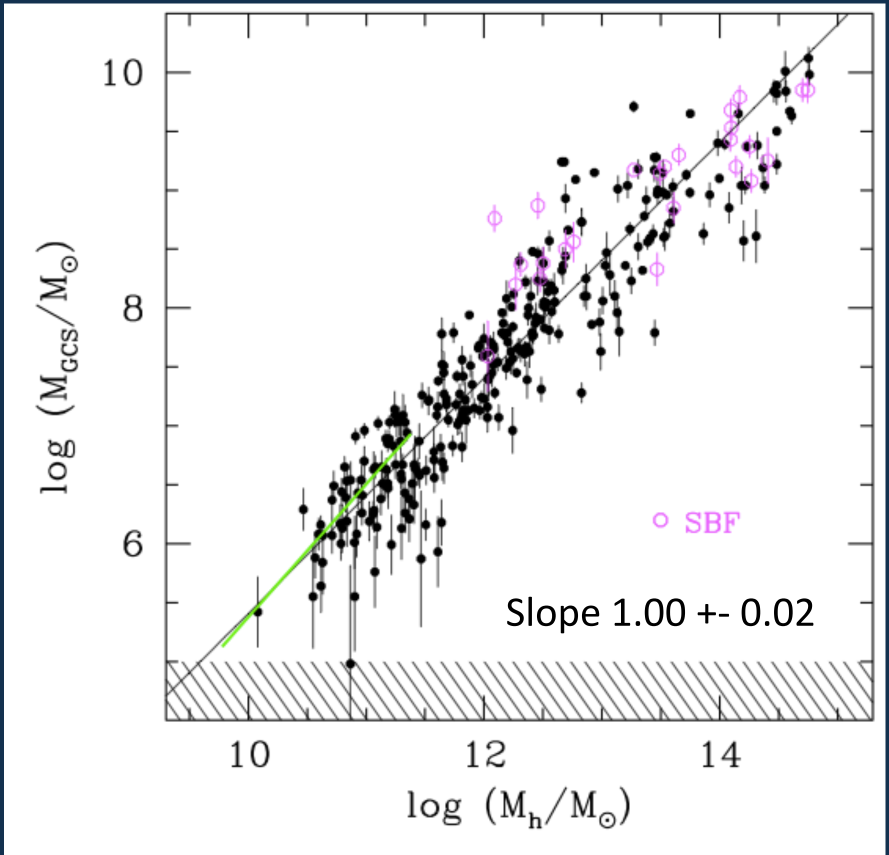
Observationally based arguments

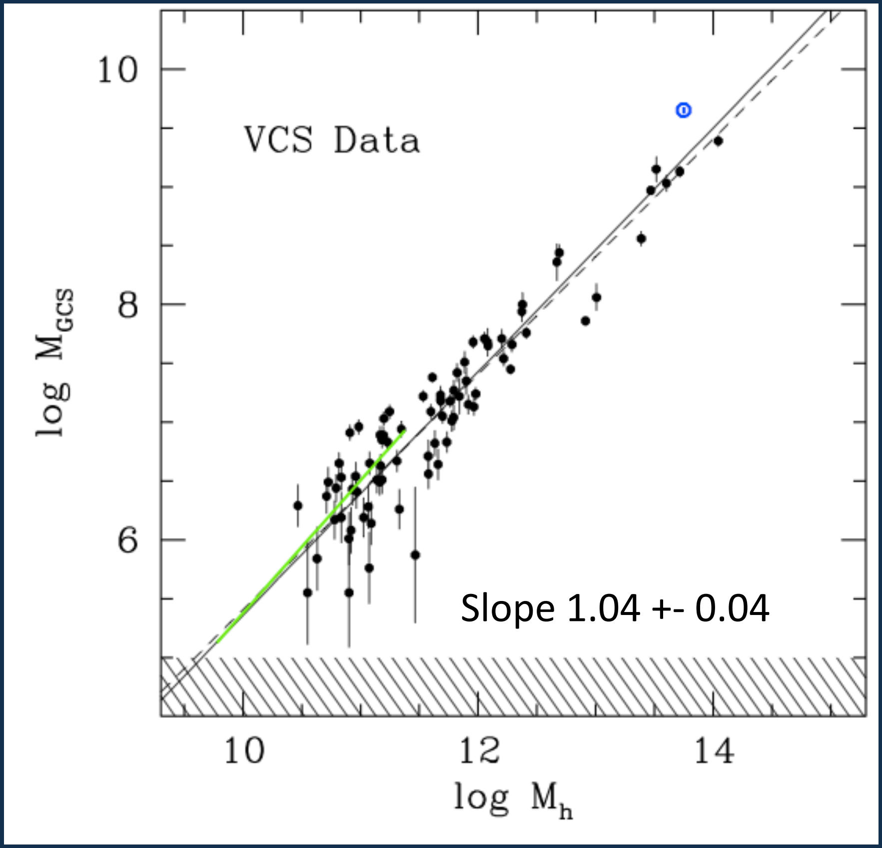
Blakeslee, Tonry, & Metzger 1997, AJ 114, 482
Blakeslee 1997, ApJL 481, L59
McLaughlin 1999, AJ 117, 2398
Blakeslee 1999, AJ 188, 1506
Kavelaars 1999, in Galaxy Dynamics, ASP Conf Ser 182, p.437
Spitler et al. 2008, MNRAS 385, 361
Peng et al. 2008, ApJ 681, 197
Spitler & Forbes 2009, MNRAS 392, L1
Georgiev 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

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



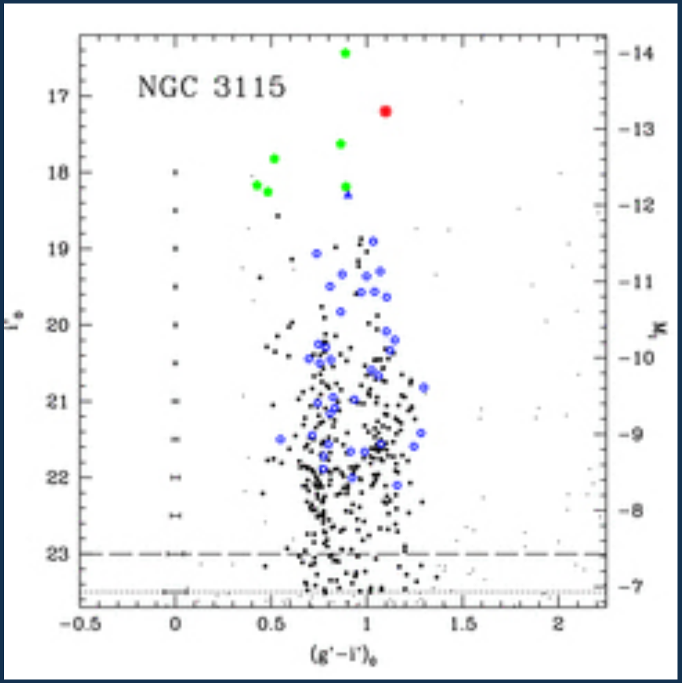


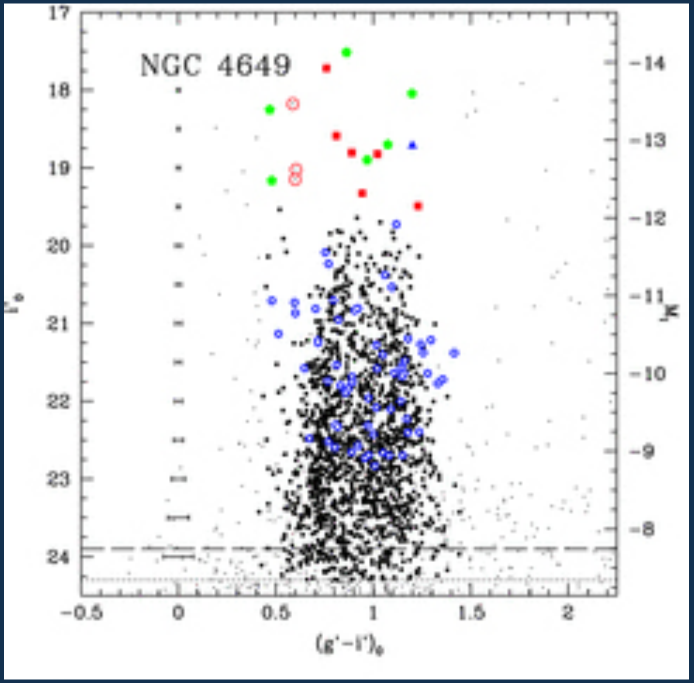
If a correlation is real, higher quality data will show it more clearly.
If *not* real, better data will tend to make the supposed correlation fall apart.

HST Virgo Cluster Survey only (Peng et al. 2009). Internally much more homogeneous

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

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





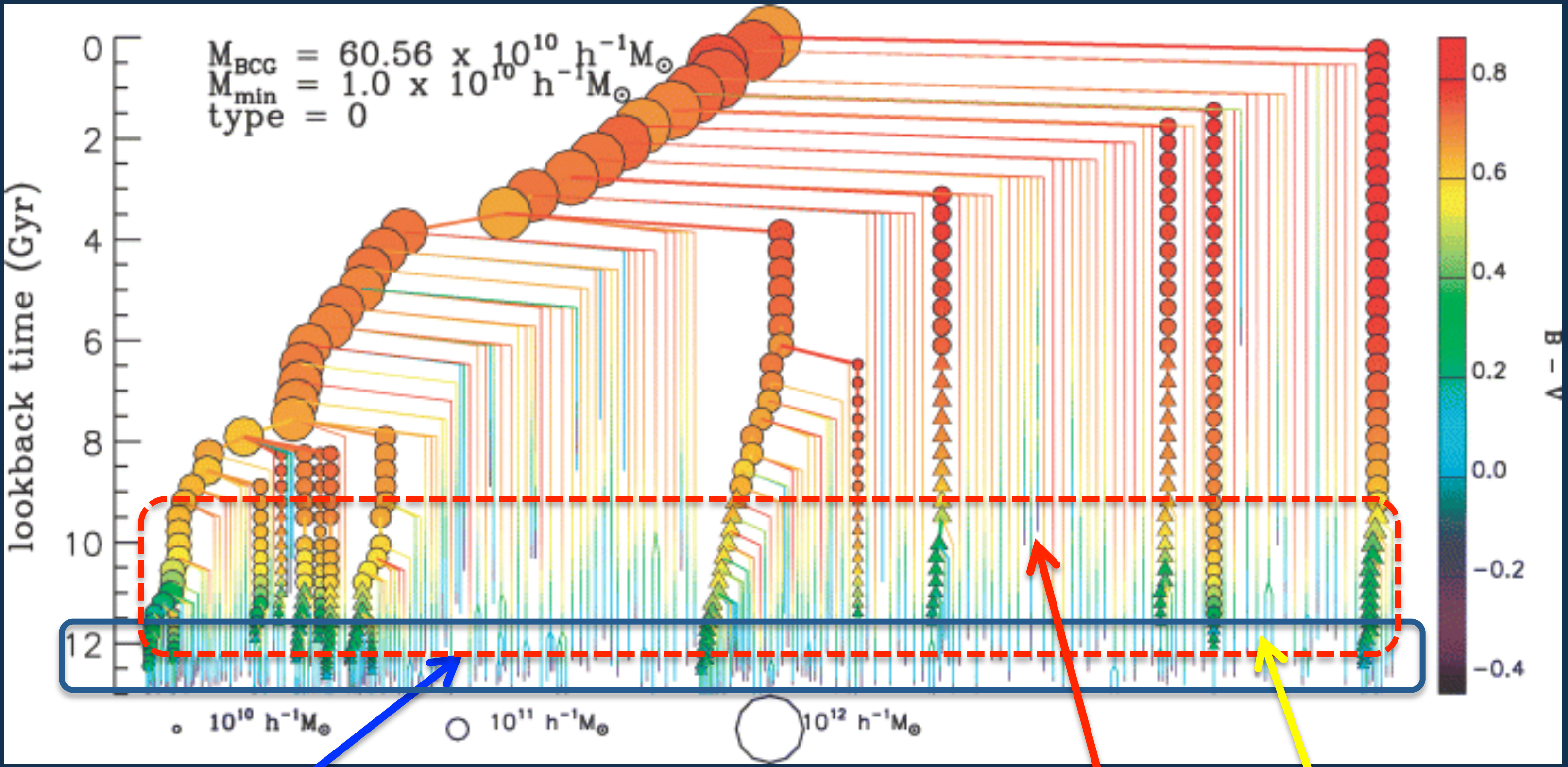
Faifer et al. 2011, MNRAS 416, 155

- 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)



t, Z

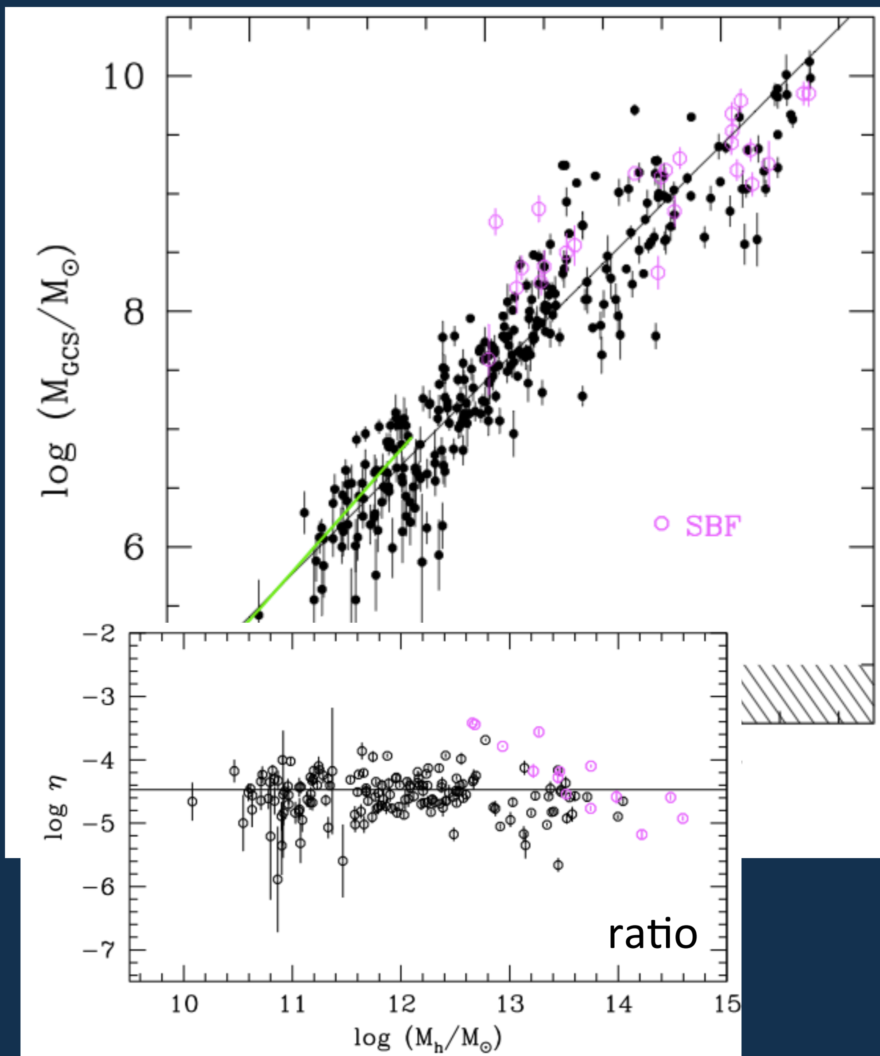
Overlap!

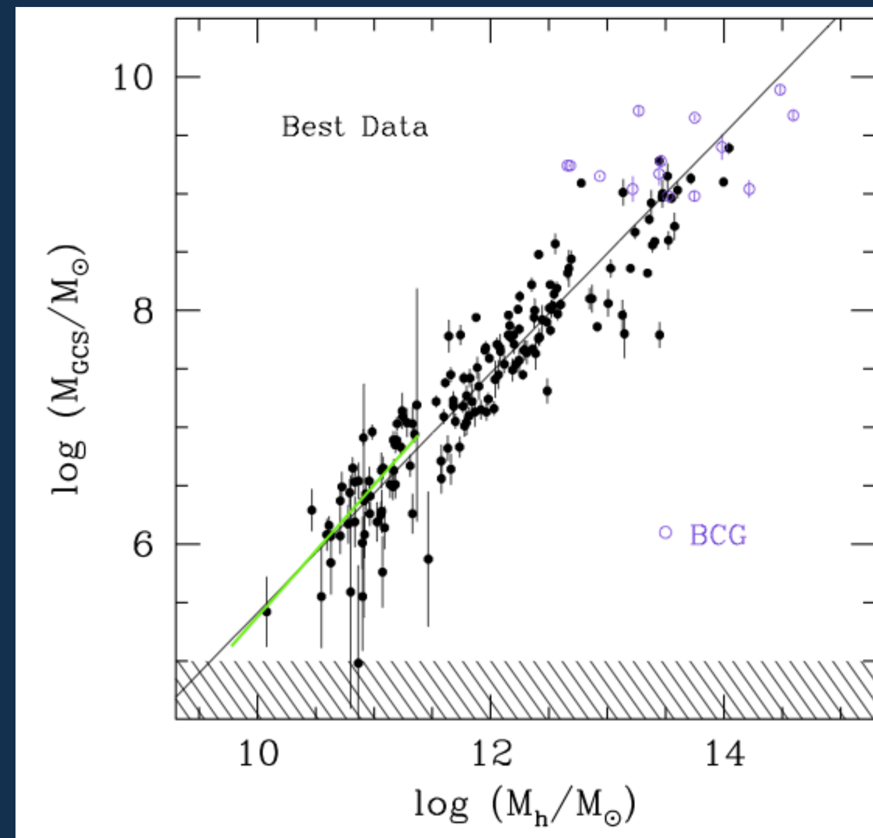
Initial population of dwarfs –- hosts for formation of "blue" GCs

"Red" GCs form later

Also see Kruijssen 2014

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

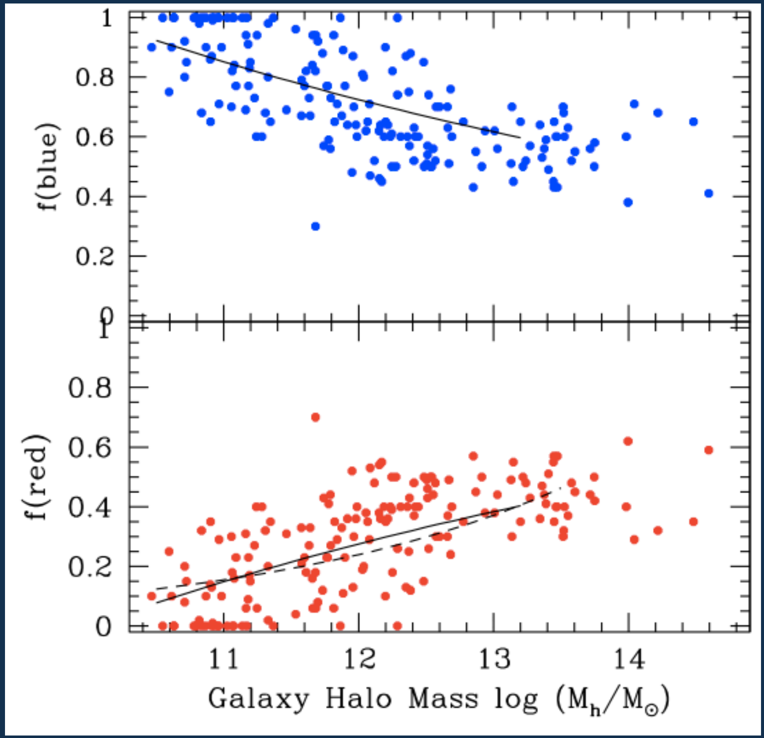
Estimates of $\eta = M_{GC}/M_h$ in the literature:

	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

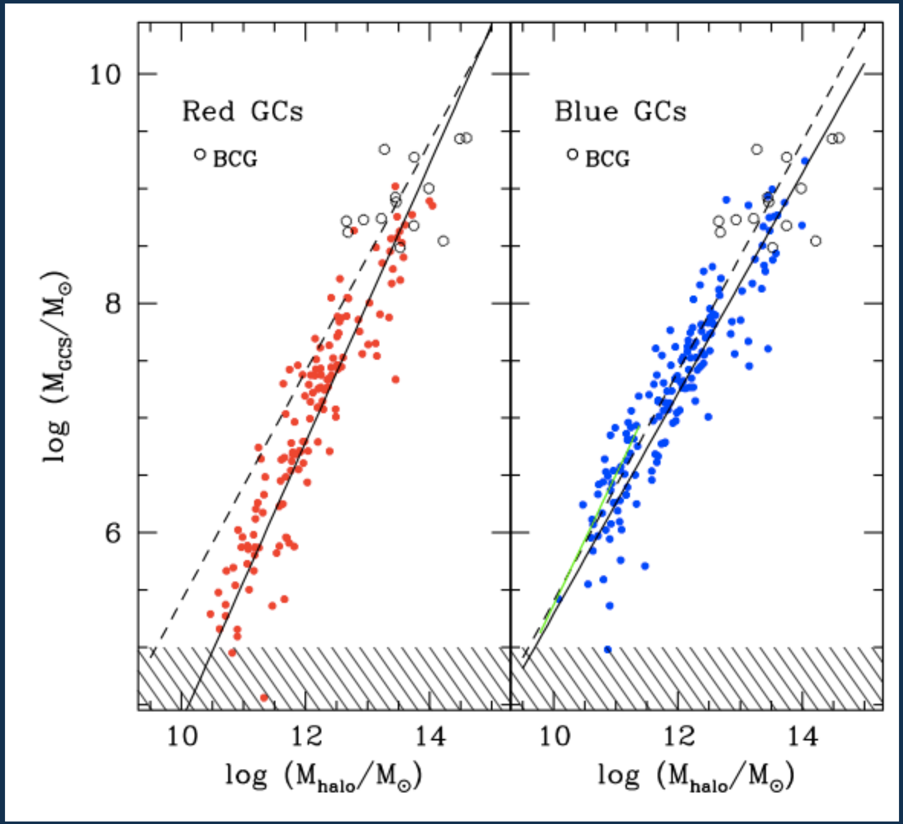
- method and zeropoint for calculating halo mass
- method for calculating M(GCS) (mainly assumptions about mean GC mass)

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



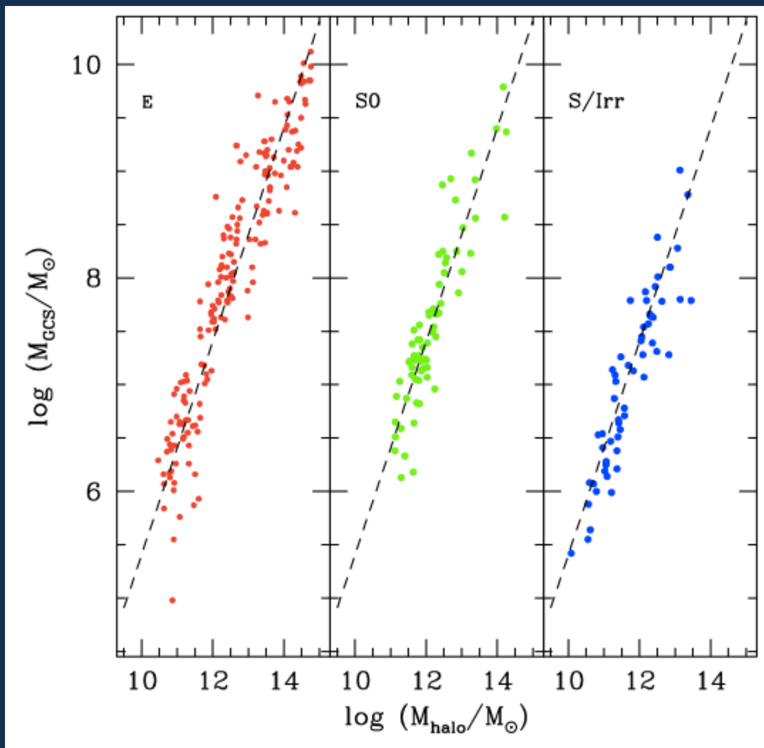
$$f_{blue} = \left(\frac{M_h}{10^{10} M_\otimes}\right)^{-0.07}$$

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



$$M(GCS)_{blue} \sim M_h^{0.95}$$
$$M(GCS)_{red} \sim M_h^{1.19}$$

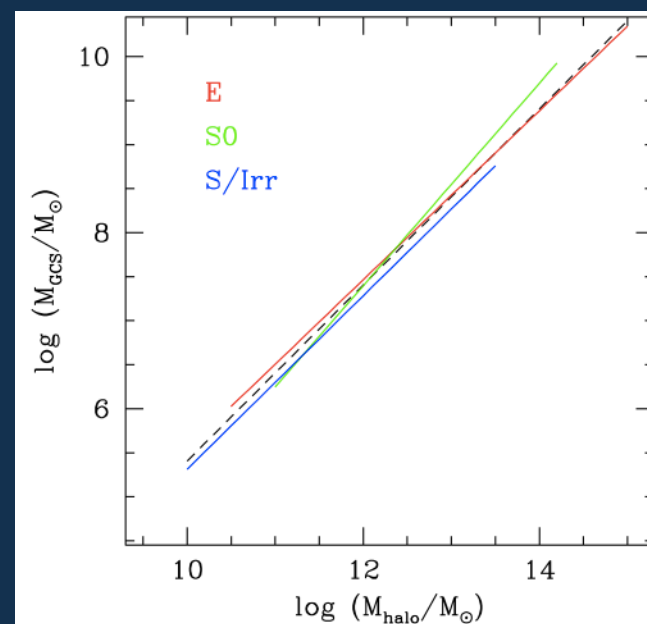
What about host galaxy type (morphology)?



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

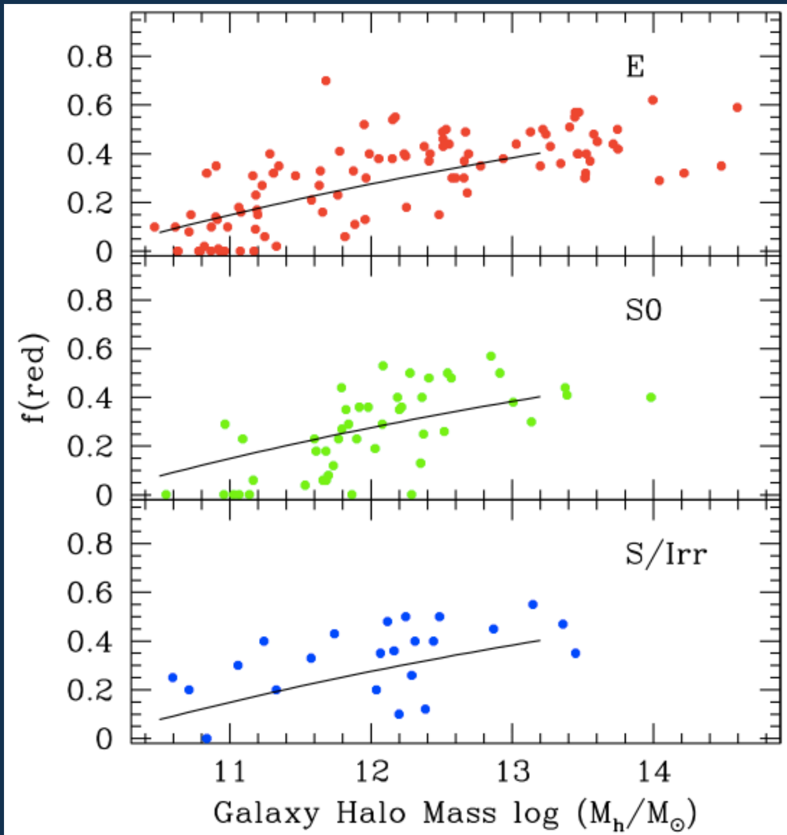
$$M(GCS) \sim M_h^{1.15\pm0.05} \quad S0's$$

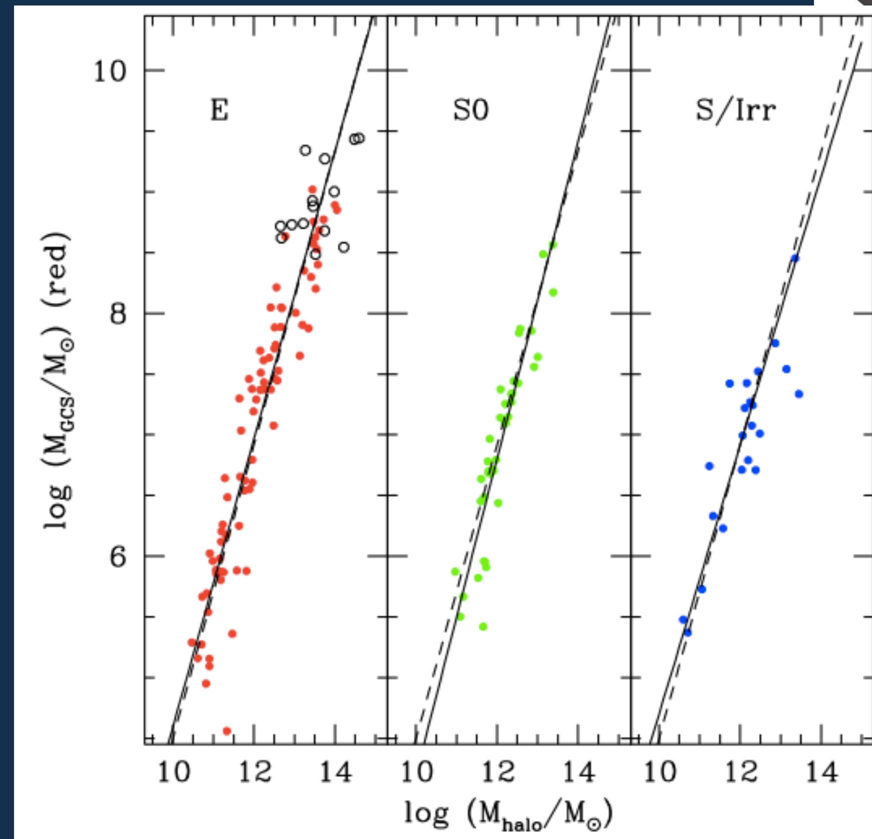
$$M(GCS) \sim M_h^{0.99\pm0.08} \quad S/Irr$$



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

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

This has been an observationally driven subject.

We desperately need some theory

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

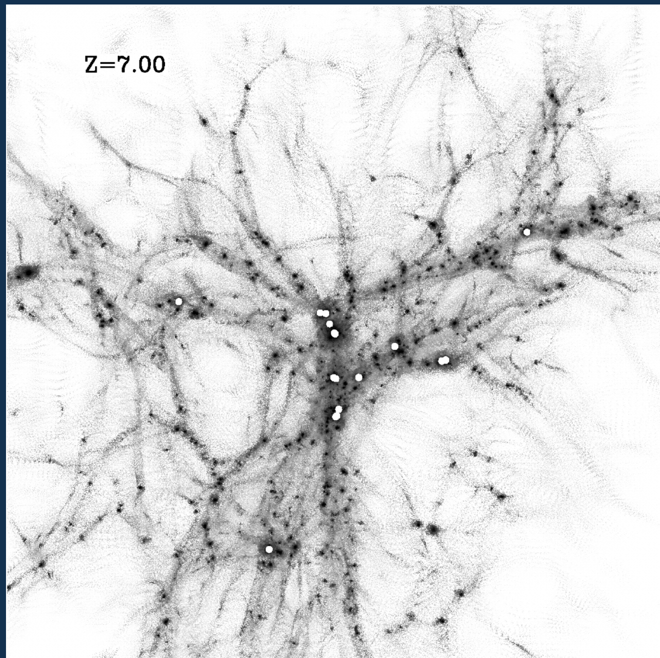
George E.P.Box

in *Empirical Model Building and Response Surfaces*

limited by – input assumptions

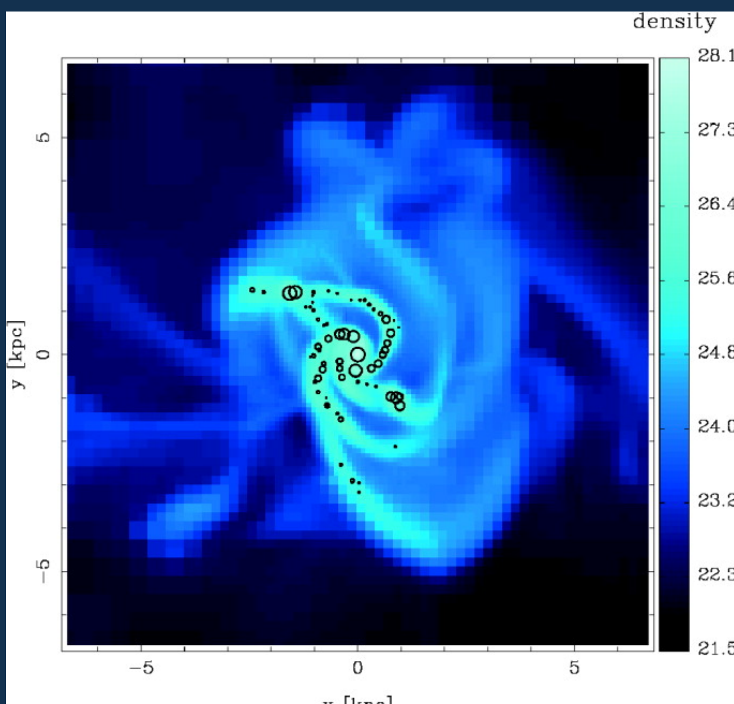
-- input physics

-- computational power



KG05 is a ***useful*** model

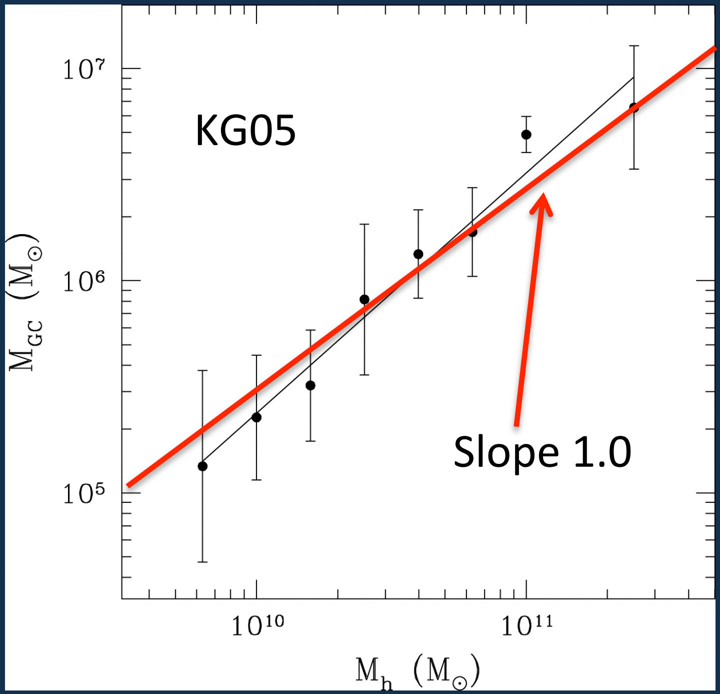
- Hydro + AMR simulation of a ~1 Mpc box followed from z = 11.8 to 3.35
- Inclusion of feedback from stellar winds, SNe, UV background
- SFR ~ local gas density
- Minimum grid resolution ~30 pc, enough to find *sites* of GC formation within GMCs, but not the proto-GCs themselves



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

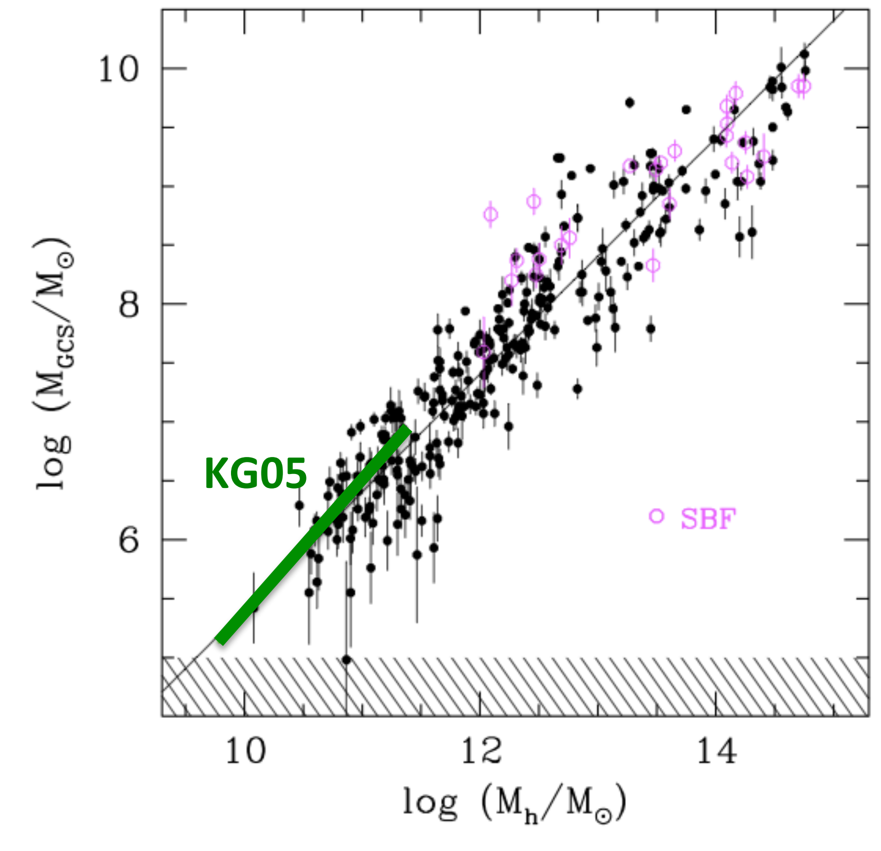


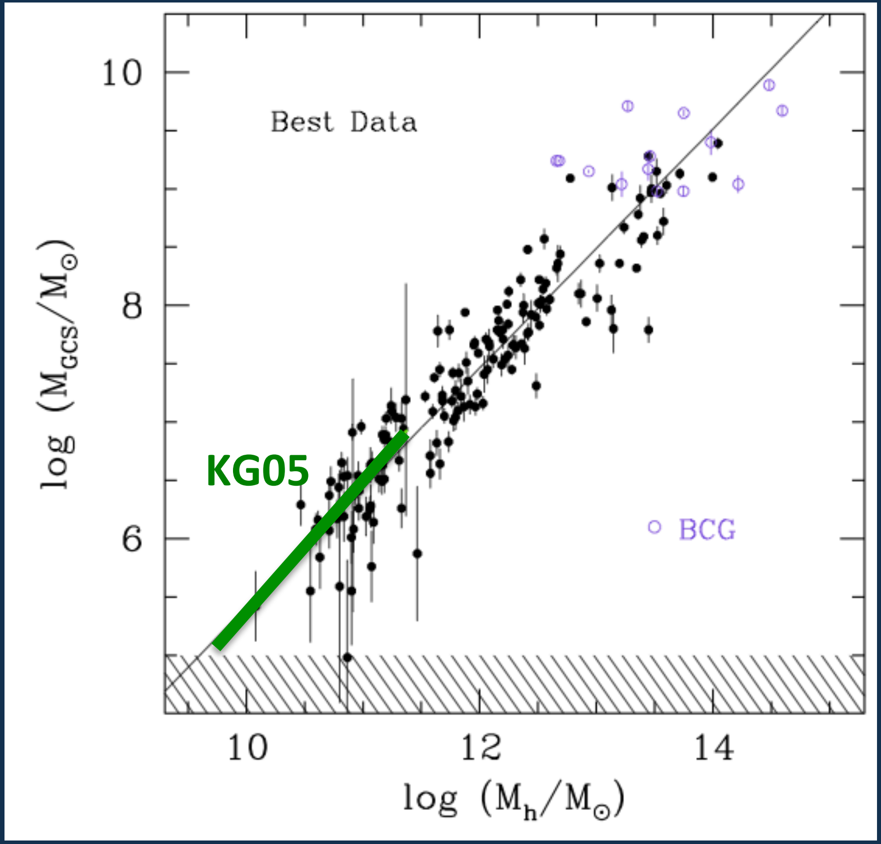
$$M_{GCS} \sim M_h^{1.13\pm0.08}$$

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

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

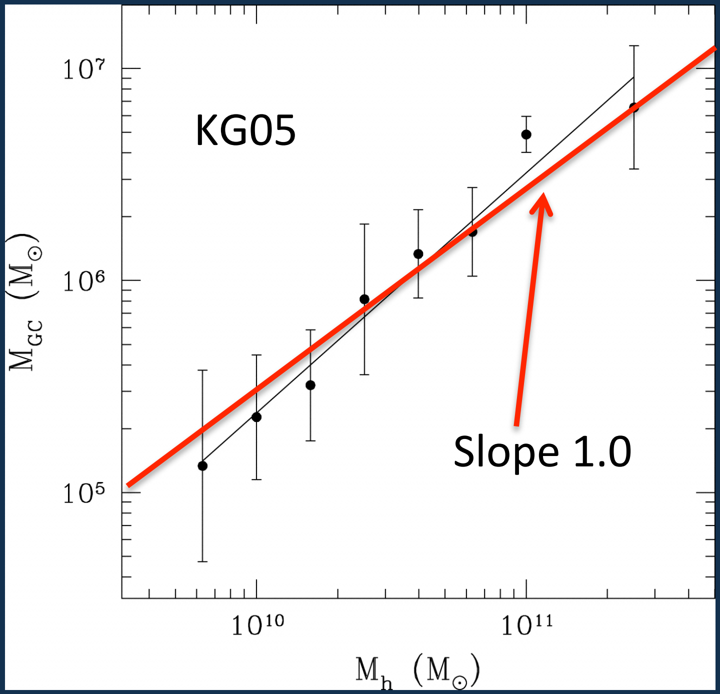
Comparison of KG05 model with data

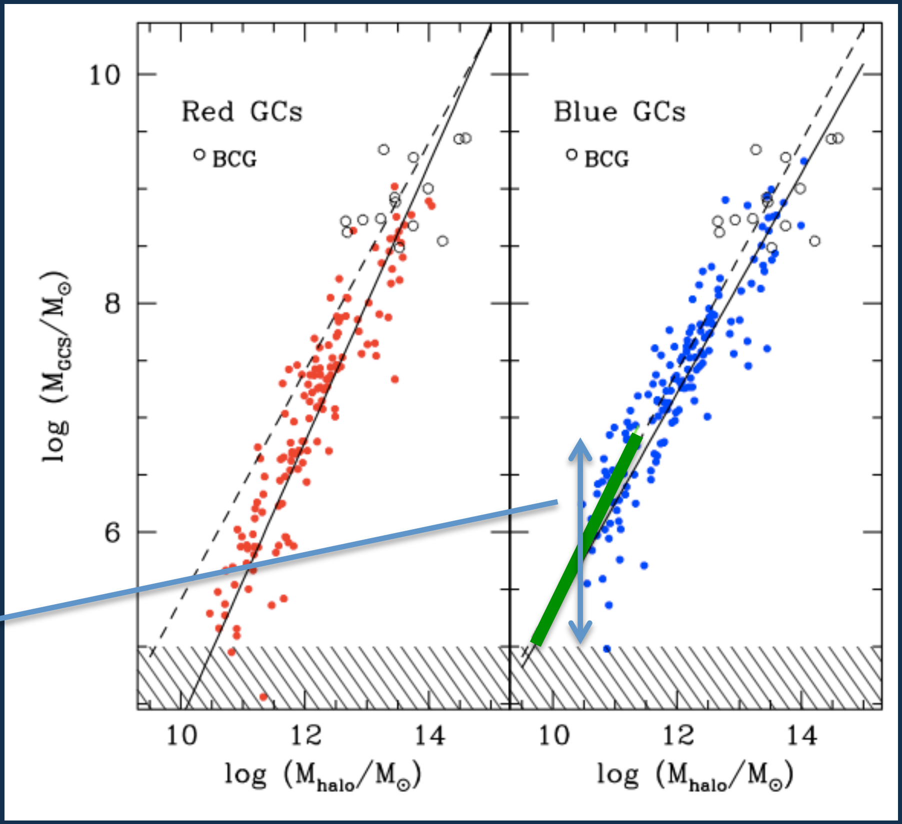




All data

f(red, blue) known.





Zeropoint agreement is accidental!

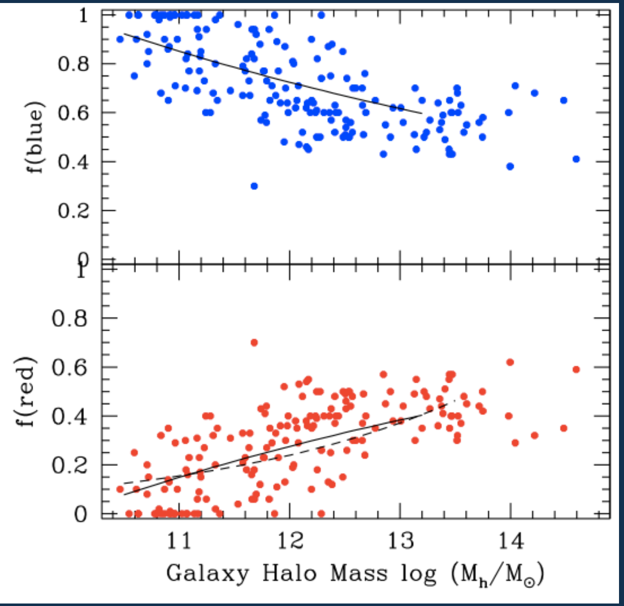
-- comparison of halo masses then vs . now

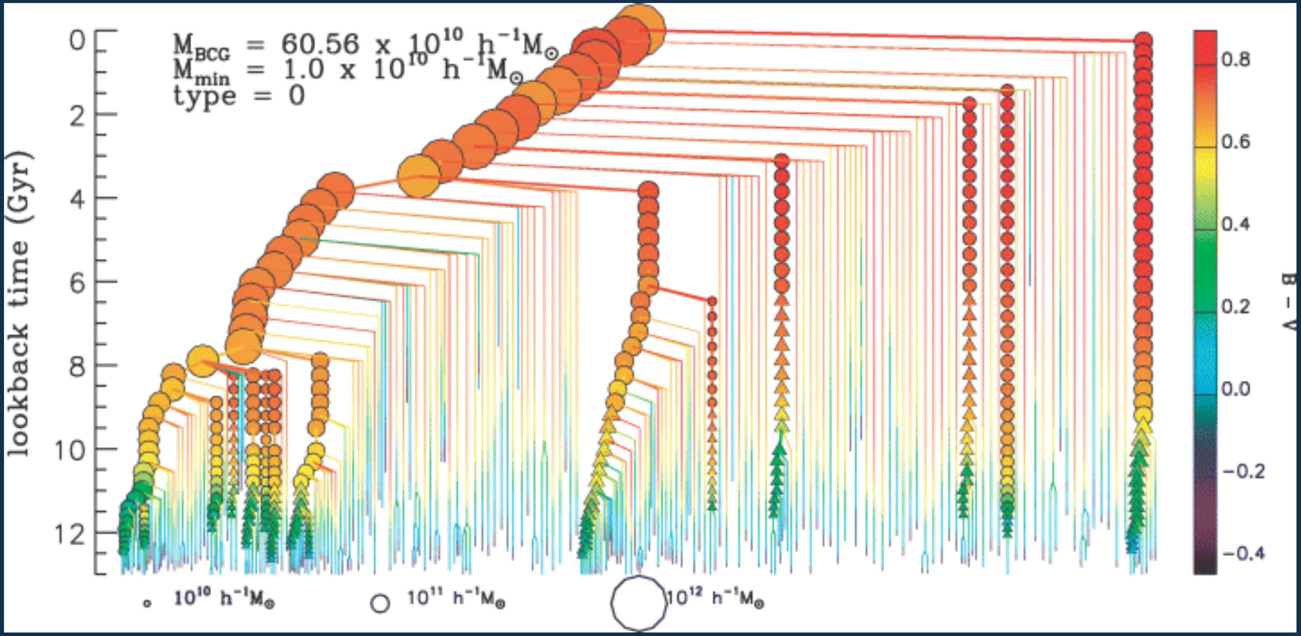
-- GC masses now vs. proto-GC masses then

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

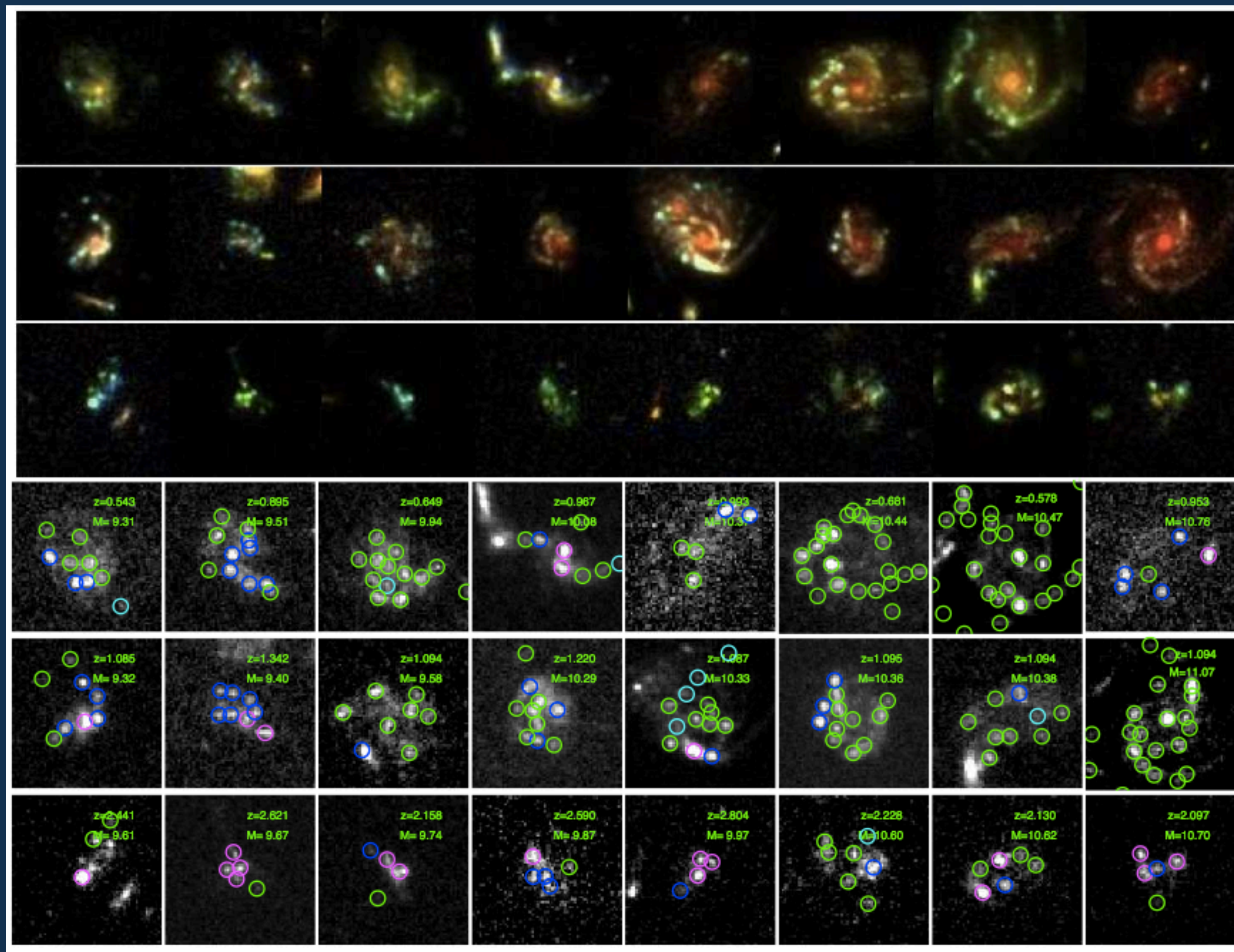




Massive star forming clumps in 0.5 < z < 3 galaxies. Strongly resemble the 'SGMCs' of Harris & Pudritz 1994, Kravtsov&Gnedin 2005 as sites of GC formation

Guo et al. 2015, ApJ (1410.7398)

HST BVI imaging (CANDELS)



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
1.6 +- 0.2	Eadie && 2015	satellite motions + Bayesian/MCMC

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)

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(halo)$^{0.96}$ and a plausible merger-tree model exists for reproducing it over its entire range

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

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

- We need more advanced theoretical models!