Globular Cluster Systems in Rich Galaxy Environments: New Issues in Formation and Evolution

Bill Harris, McMaster University
ESO June 29, 2011

Globular Cluster Systems in Rich Galaxy Environments: New Issues in Formation and Evolution

Globular
stellar
Clusters are laboratories for ~~galaxy~~ evolution
^

tracers of
Globular
Clusters are ~~laboratories for~~ galaxy evolution
^

Globular Cluster Systems in Rich Galaxy Environments:
New Issues in Formation and Evolution

The bottom line:

Globular cluster systems show what star formation in galaxies would have been like without feedback

(evidence for this will be given during the talk)

Studying the ensembles of globular clusters in galaxies is a hybrid field mixing stellar populations with galaxy structure and evolution

M104 ("Sombrero") has ~1900 of these

M87 (Virgo cD supergiant) has ~13,000

NGC 4874 (Coma cluster cD) has 23,000

Gemini-S + GMOS (E.H.Wehner & W.E.Harris)

NGC 3311/3309 d = 50 Mpc

Hydra I cluster

GCs are mostly starlike for

D > 15 Mpc (ground-based)

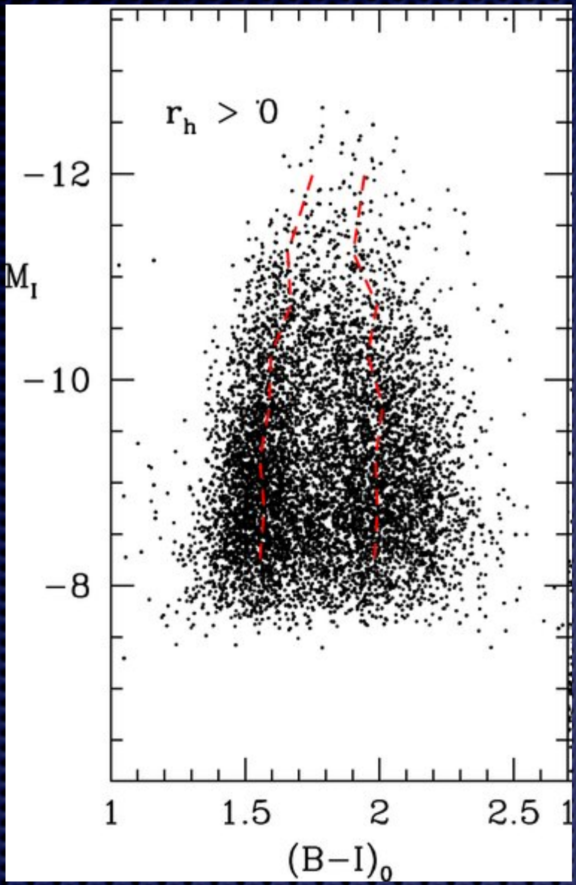
D > 80 Mpc (HST)

Visible as a statistical excess of point sources spatially concentrated around the host galaxy

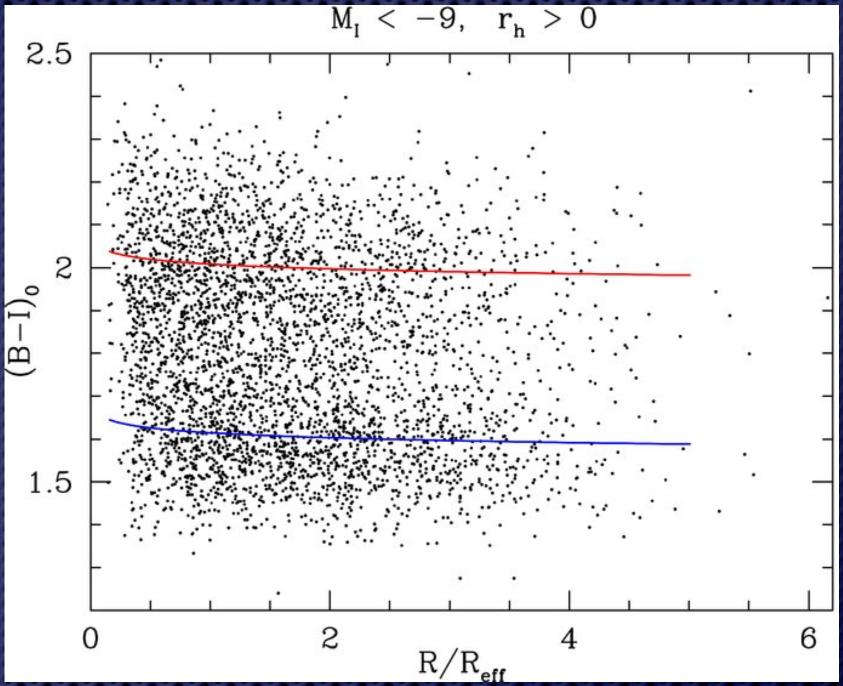
Present day: < 1% of total stellar mass

Initially: > 10% ? Due to substantial mass loss from protocluster to now

Bimodality: standard, near-universal "blue" and "red" sequences
mean [Fe/H] ~ -1.5 -0.5



Weak metallicity gradients $\langle Z\rangle \sim R^{-0.1}$

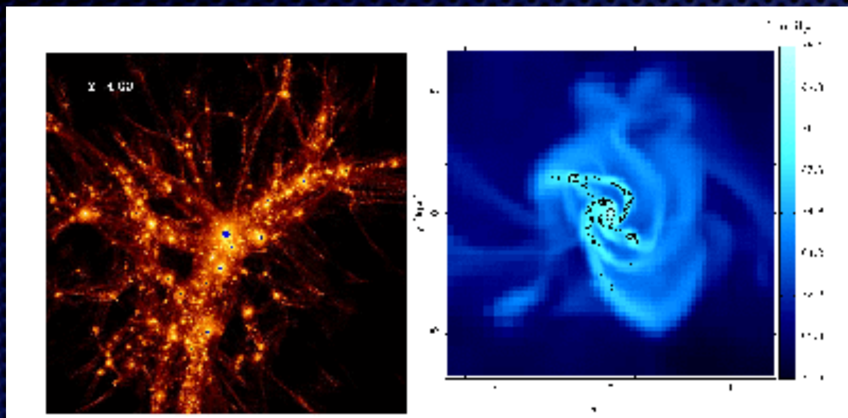


Composite data from 6 BCGs (Harris 2009, ApJ)

Thus, two distinct formation epochs? Doubtful !
the whole population must result from a *single, continuous hierarchical merging sequence*

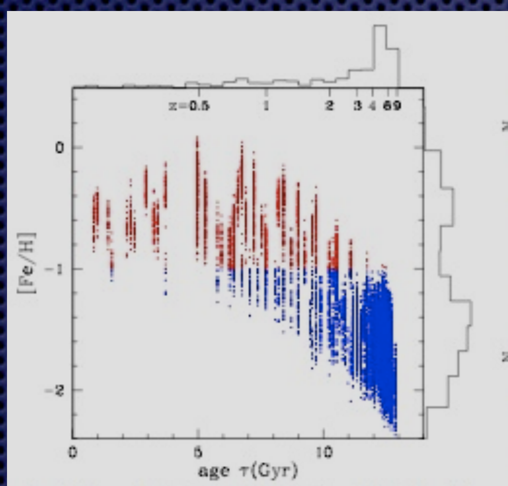
Formation redshifts
z = 10-5 (blue) *ages 12-13 Gyr*
5-2 (red) *ages 10-12 Gyr*

GC Formation: The Big Picture



Muratov & Gnedin 2010, ApJ 718, 1266

[Fe/H]



age

Later accretion may add to the low-[Fe/H] population of halo clusters

Host environments should be >~10^9 M_0 gas disks; all GCs assumed to form in mergers from beginning to end

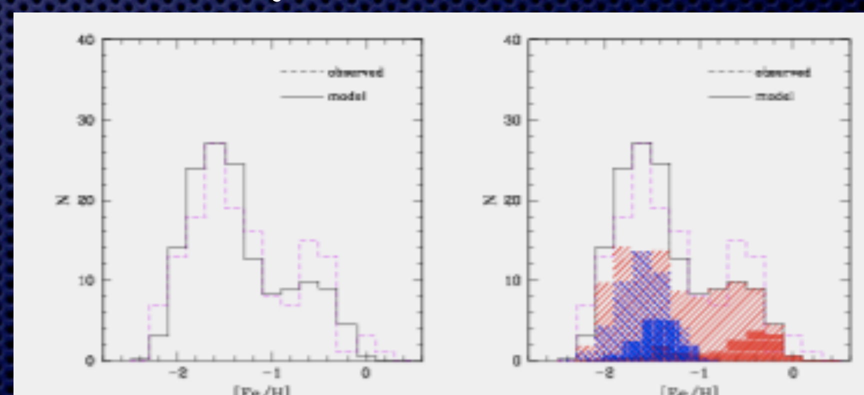
External reionization unimportant; massive host dwarfs self-shielded

$N_{GC}(t)$ ~ Merger rate x cloud mass

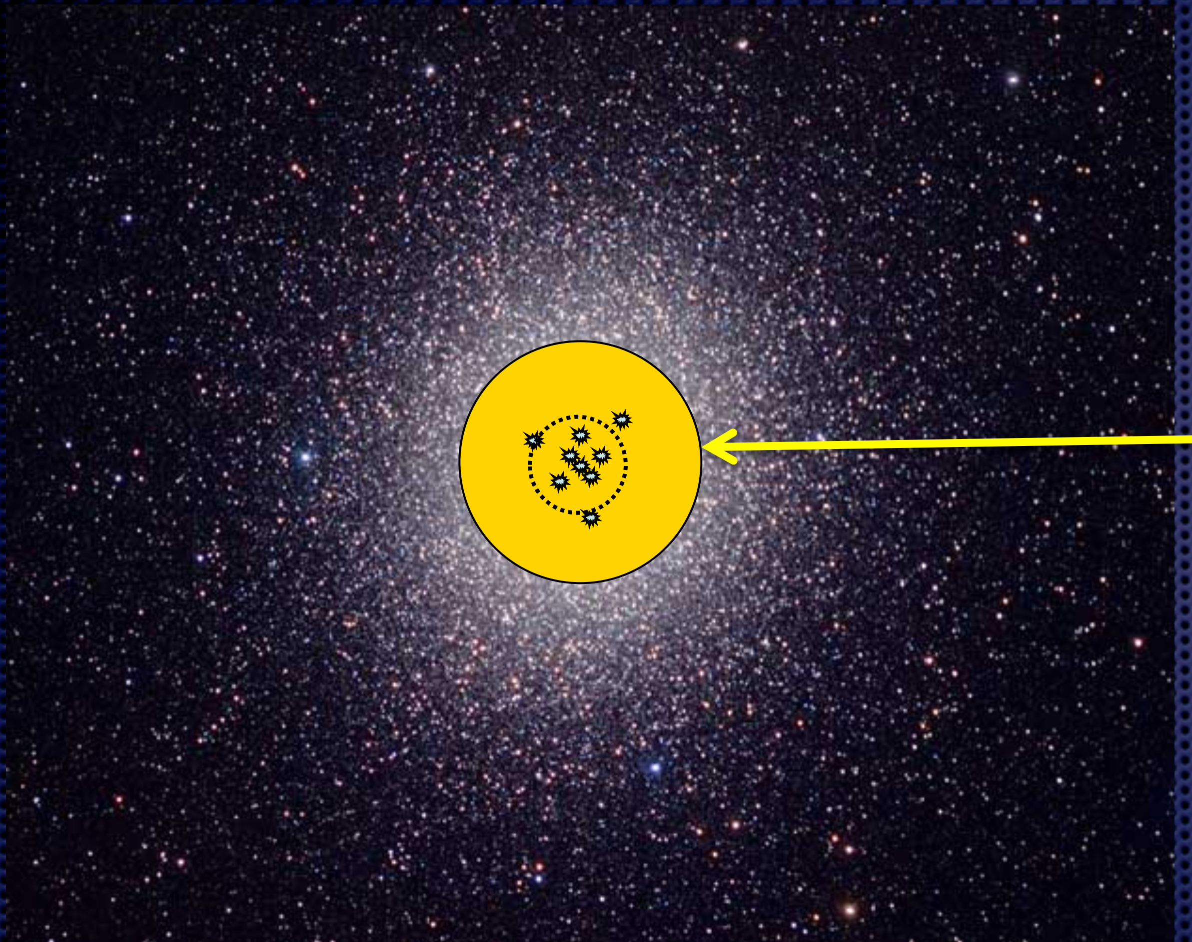
Semi-realistic bimodality emerges naturally though not every time.

Realistic mass distributions and spatial distributions

The final metallicity distribution *can* be matched by a bimodal Gaussian, as a numerical exercise. But it did NOT originate from "two major starbursts".



GC Formation: The Local Picture: Self-Enrichment?



Bailin & Harris 2009, ApJ 695, 1082 (model)

Internal self-enrichment possible, if initial SN ejecta can be retained in the protocluster during the first ~10 Myr (note that the dense cloud is mostly gaseous if SFE ~ 0.3)

Enriched gas will be retained if it lies inside an "escape radius" where total energy < potential energy at edge of cloud.

Heavy-element retention scales as

$$f_Z \sim \exp\left\{ -\frac{k\ f_* r_C^{eff}}{M_C} \right\}$$

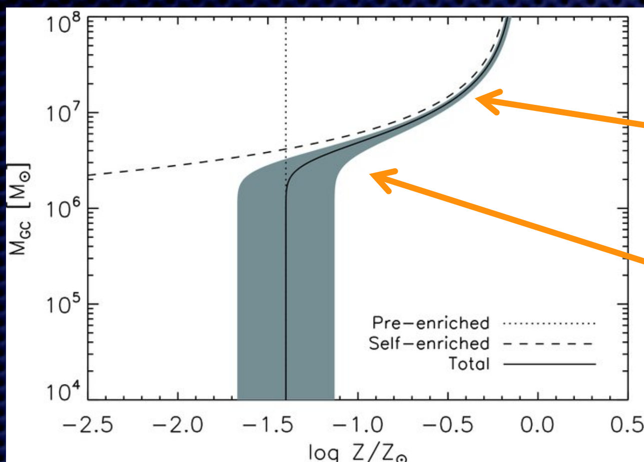
~ 1/e at $4\times10^7\ M_0$ (protocluster)

$4\times10^6\ M_0$ (today's GC)

Pre-enrichment = initial cloud metallicity

Self-enrichment = additional metallicity generated during formation

M

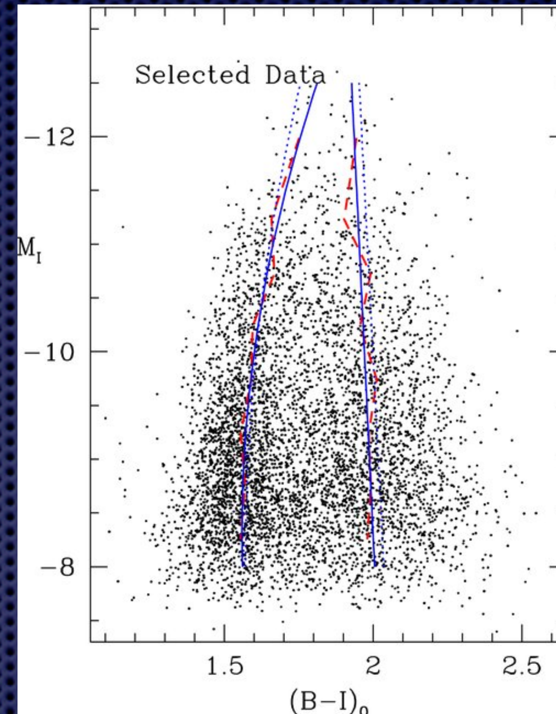


[Fe/H]

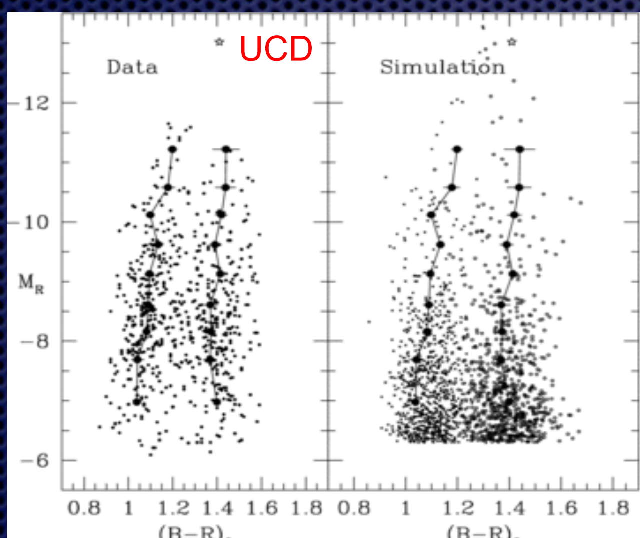
UCD and dE,N regime?

Massive-GC regime

Nonlinear mass-metallicity relation expected along both sequences, but easily visible only on blue sequence

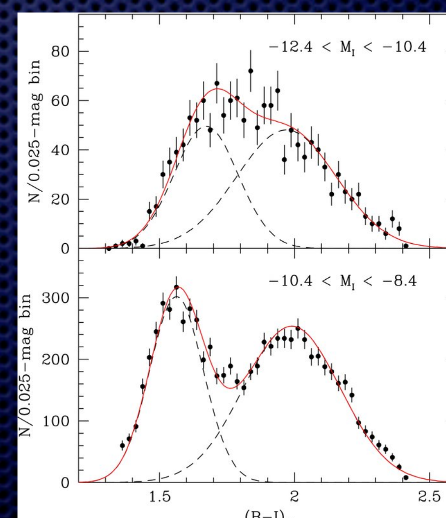


6 BCGs (Harris 2009)



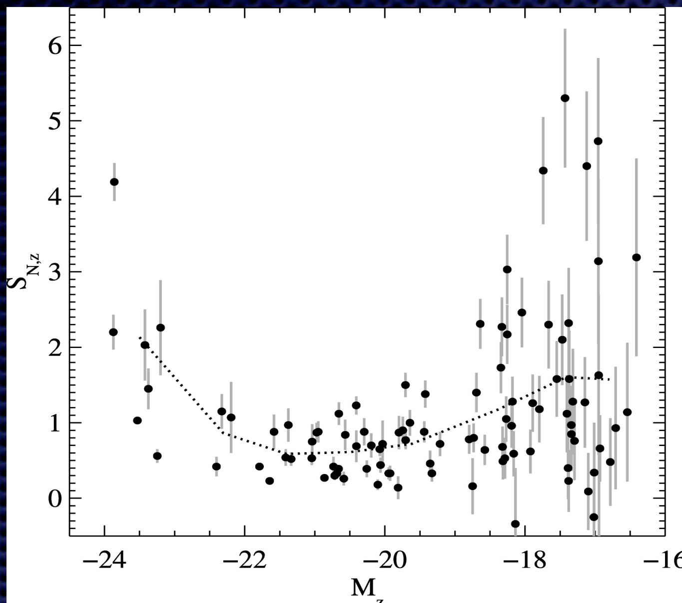
M104 data and simulation (Harris && 2010, MNRAS 401, 1965)

7 more cD's coming!

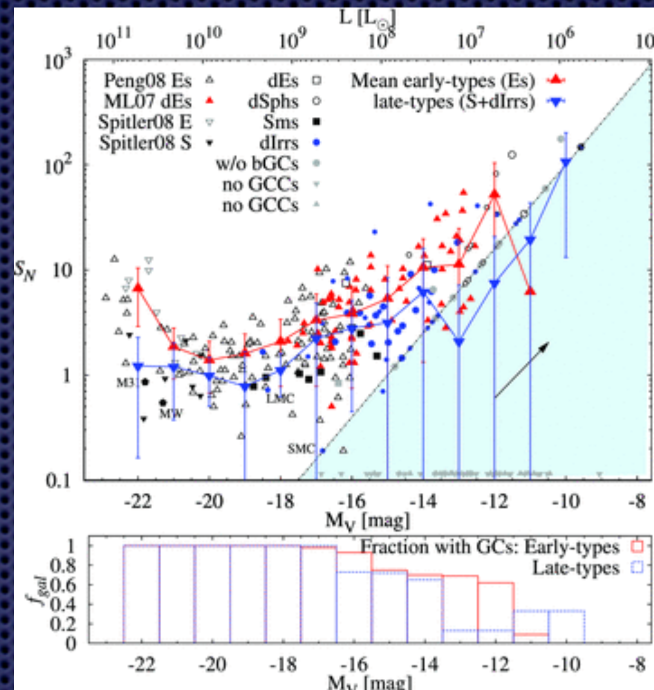


What determines the total population of GCs in a galaxy?

S_N



Peng && 2008, ApJ 681, 197



Georgiev && 2010 MNRAS 406, 1967

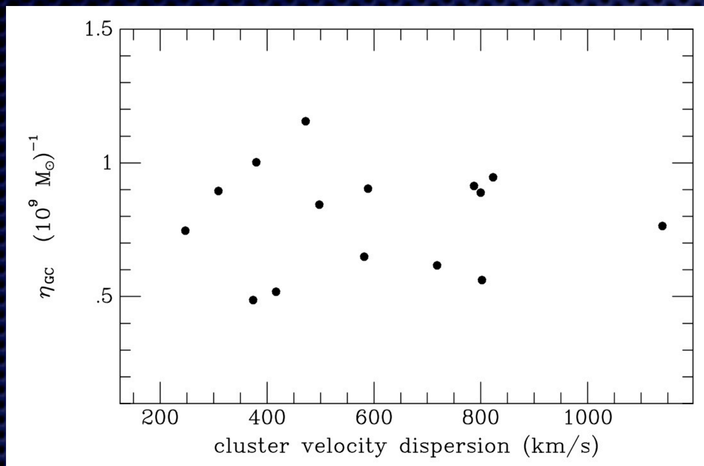
$$S_N = \alpha_1 \frac{N_{GC}}{L_*}$$

S_N measures cluster formation efficiency. Note the distinctive "valley" shape of the S_N trend versus galaxy luminosity. What causes this?

30th anniversary! (Harris & van den Bergh 1981)

Specific frequency and specific mass: Does N(GC) scale directly as total baryonic mass (stars+gas)? Or total mass (DM+bary)?

η

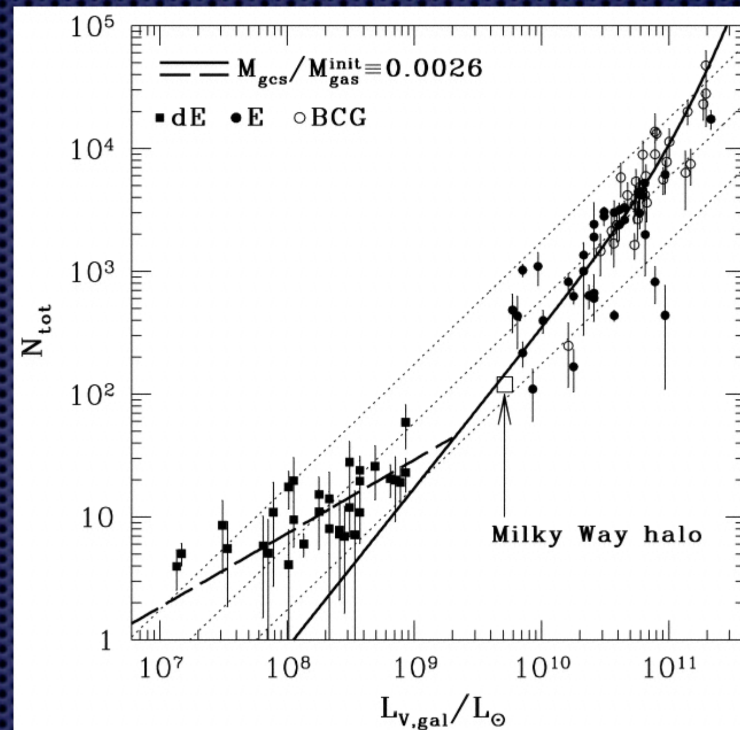


σ(cluster)

Blakeslee, Tonry, & Metzger 1997, AJ 114, 482

Blakeslee 1999, AJ 118, 1506

Kavelaars 1999, ASPC 182, 437



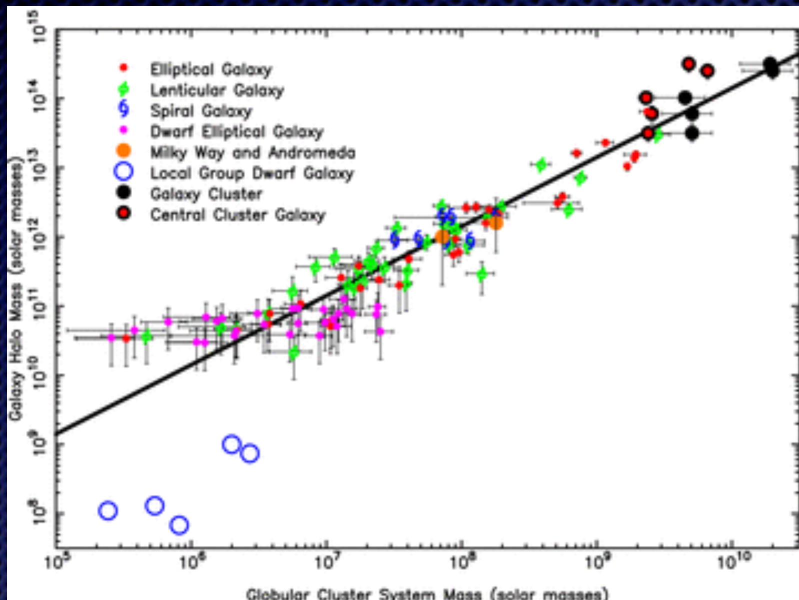
McLaughlin 1999, AJ 117, 2398

"The obvious generalization of these results is that most galaxies may have been subject to a single, common cluster formation efficiency." (McLaughlin 1999)

-- but efficiency relative to what?

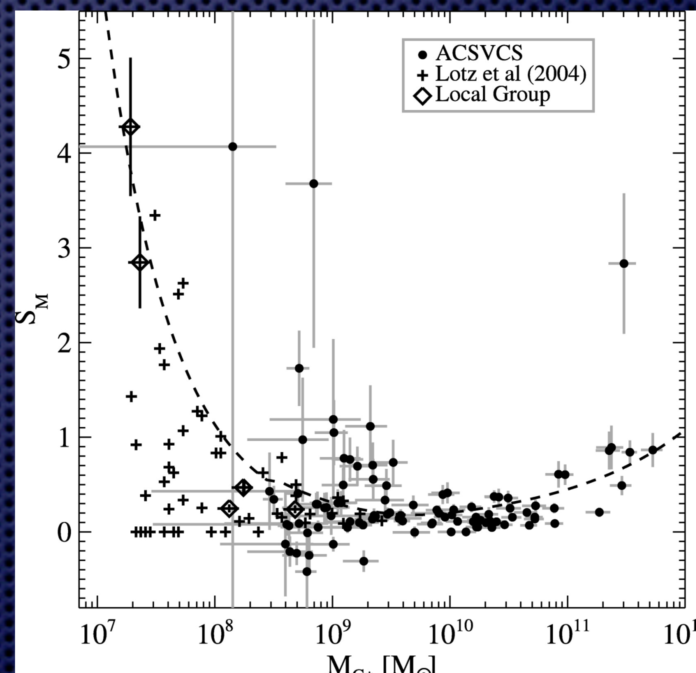
What if N(GC) ~ M(total) = dark+baryonic ?
Recent discussions following this line ...

M(tot)



M(GC)

Spitler & Forbes 2009, MNRAS 392, L1

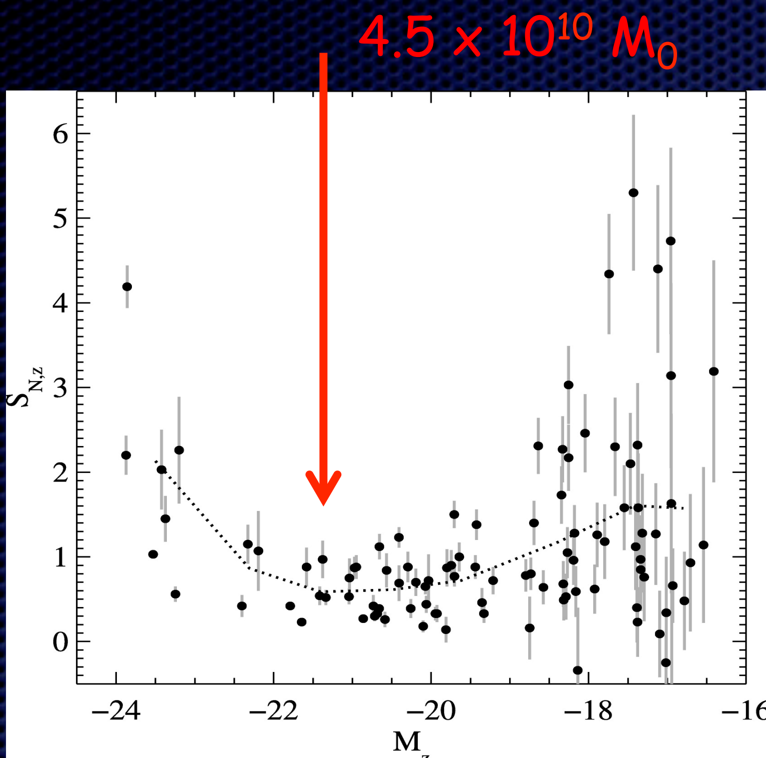


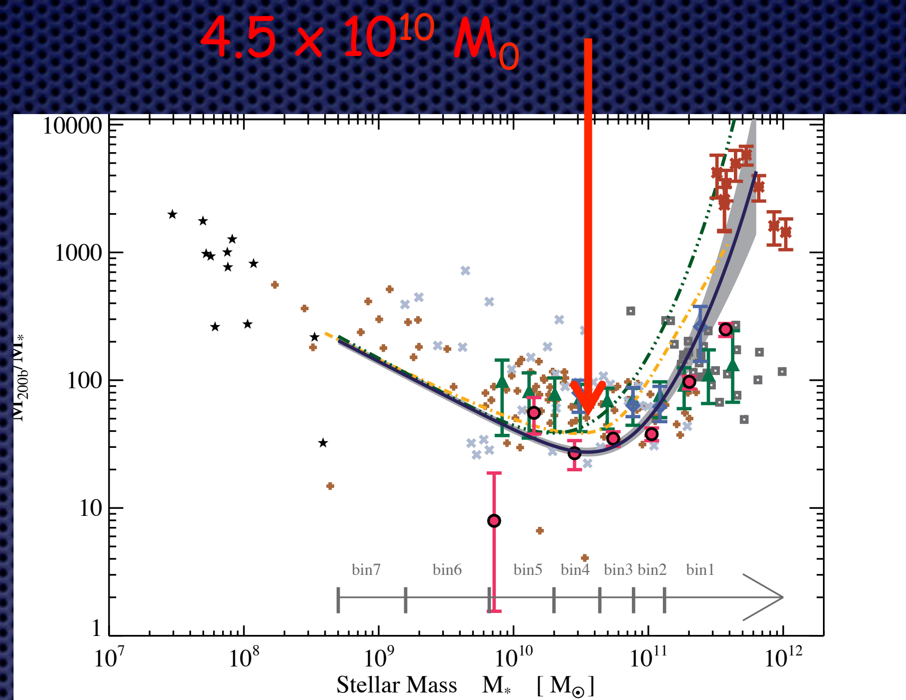
S_M = M(GC)/M(stellar)

Peng && 2008
Georgiev && 2010

M(stellar)

Curve assumes M(halo)/M(stellar) model from vandenBosch && 2007. The general trend of S_N versus luminosity is reproduced!





Peng && 2008

Leauthaud && 2011, ArXiv:1104.0928
COSMOS-z1 model + low-z data

Various information in the literature for the progressive change of M(tot)/M(stellar) with galaxy mass shows same shape as S_N curve, with a minimum (valley) at the same characteristic galaxy mass

$$\frac{M(halo)}{M(*)} = f(M(halo))$$

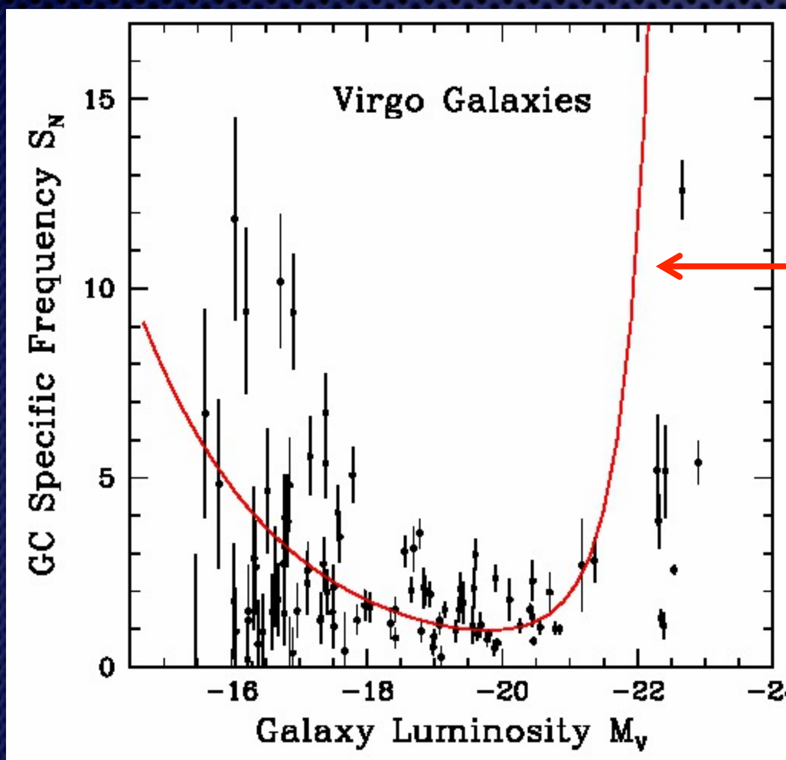
Maximally efficient conversion of infalling gas to stars near 10^{10} L_0.

Assume GC formation is proportional to M(halo) instead of stellar mass

$$\frac{M(halo)}{M(*)} = f(M(halo))$$

$N_{GC} = \alpha_2 M(halo)$

$$S_N = \alpha_1 \frac{N_{GC}}{L_*} = \alpha_1 \alpha_2 (M/L)_* \frac{M(halo)}{M(*)}$$

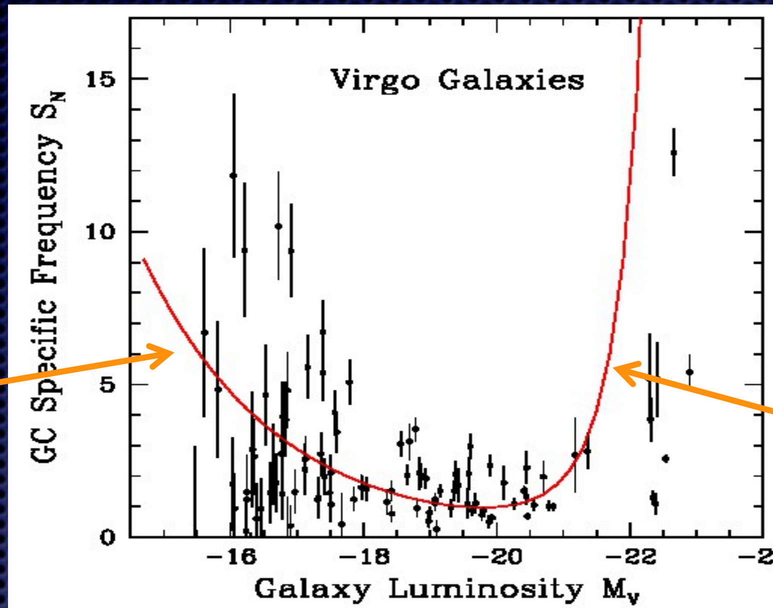


f(M(halo)) from COSMOS-z1 model

NB: Transition from nuclear star cluster to central supermassive black hole occurs near 2 x 10^9 L_0 (M_V ~ -18.5) – not relevant to the location of the minimum

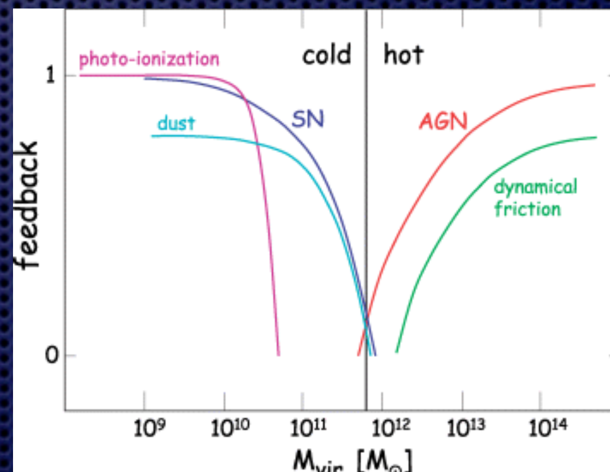
Interpretation: the field-star population is affected by feedback at either extreme, while proto-GCs are not

SNe + starburst winds + photoionization feedback



The GCs can successfully form as if there were no feedback! They react only to the total initial mass of gas or DM

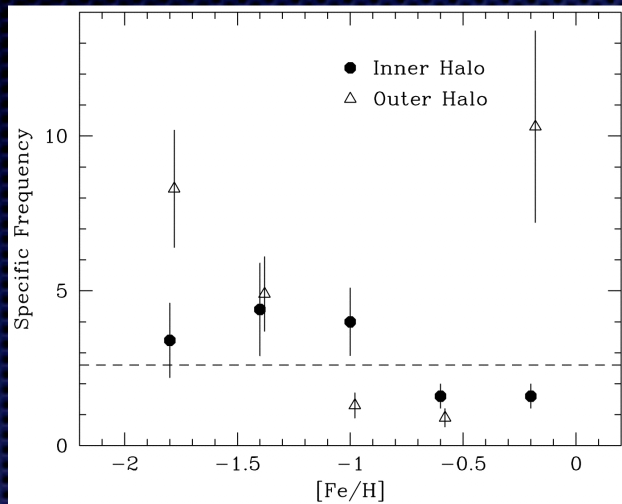
Shock heating + AGN feedback



Dekel & Birnboim 2006, MNRAS 368, 2

Are the most massive protoglobular clusters (densities → $10^6\ M_0/pc^3$, scale sizes ~ 1 pc) self-shielded from either extreme? Result is that the N(GC) numbers more accurately reflect the initial amount of gas mass (or DM) present

$M(halo) \sim= 2.5 \times 10^9\ N_{GC} \sim= 1.7 \times 10^4\ M_{GC}(now)$

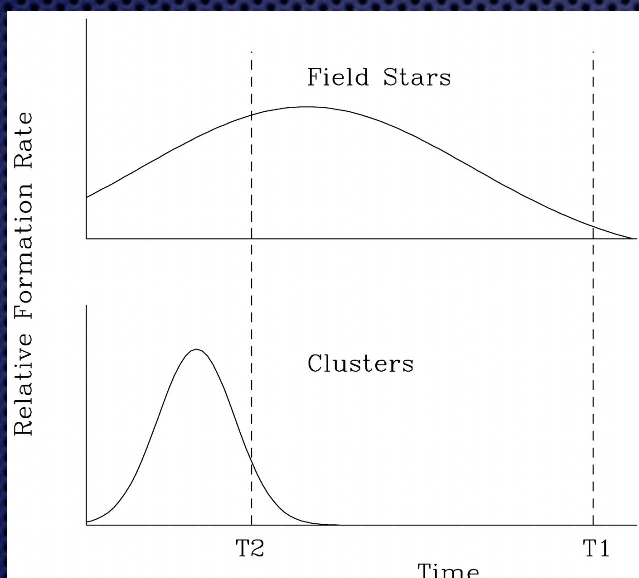


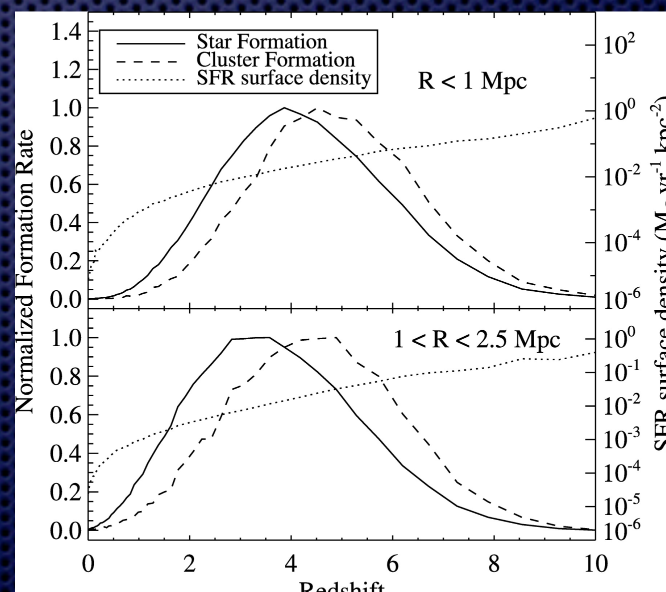
Protocluster formation peaks earlier than lower-density field-star formation

Earliest epochs less subject to external disruption

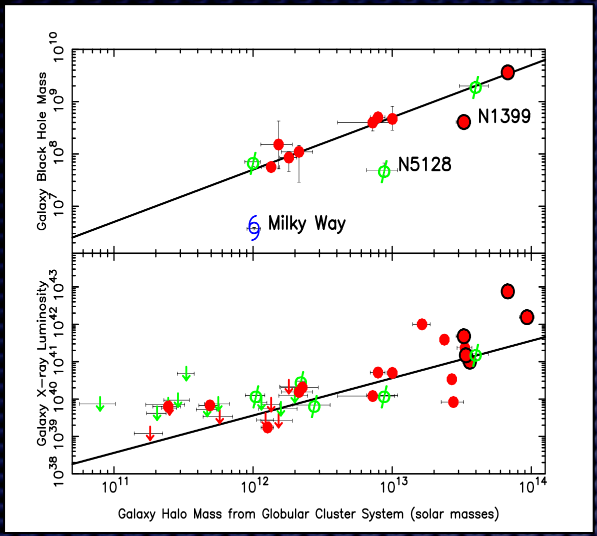
Harris & Harris 2002

Peng && 2008



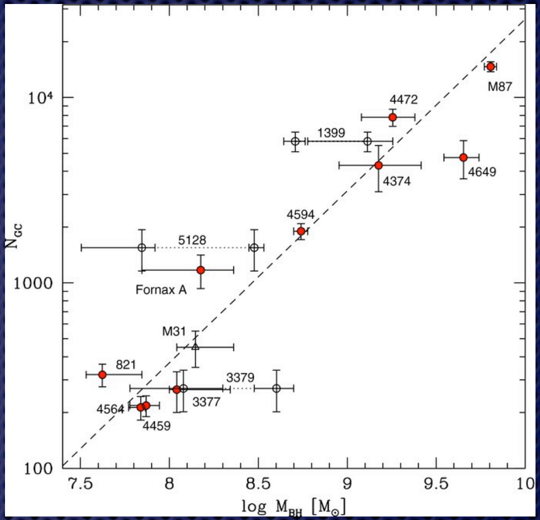


Links with other Galaxy Features: Central Black Holes and Dynamical Masses



Spitler & Forbes
2009, MN 392, L1

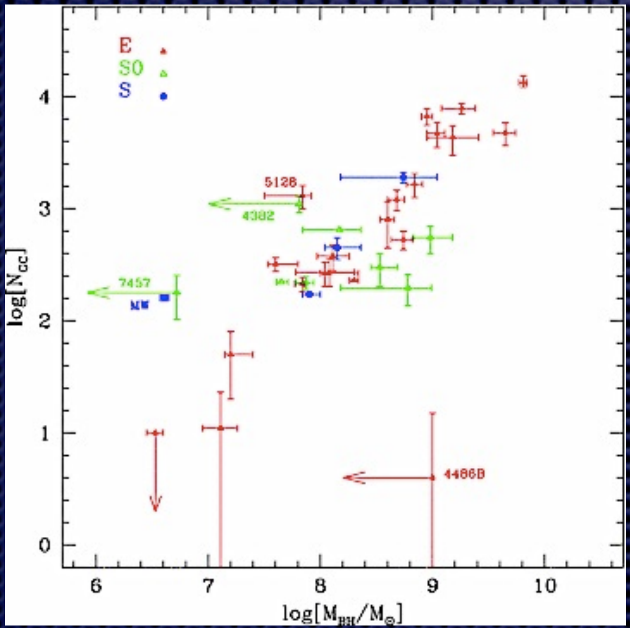
N_{GC}



M_{SMBH}

Burkert & Tremaine
2010, ApJ 720, 516

N_{GC}



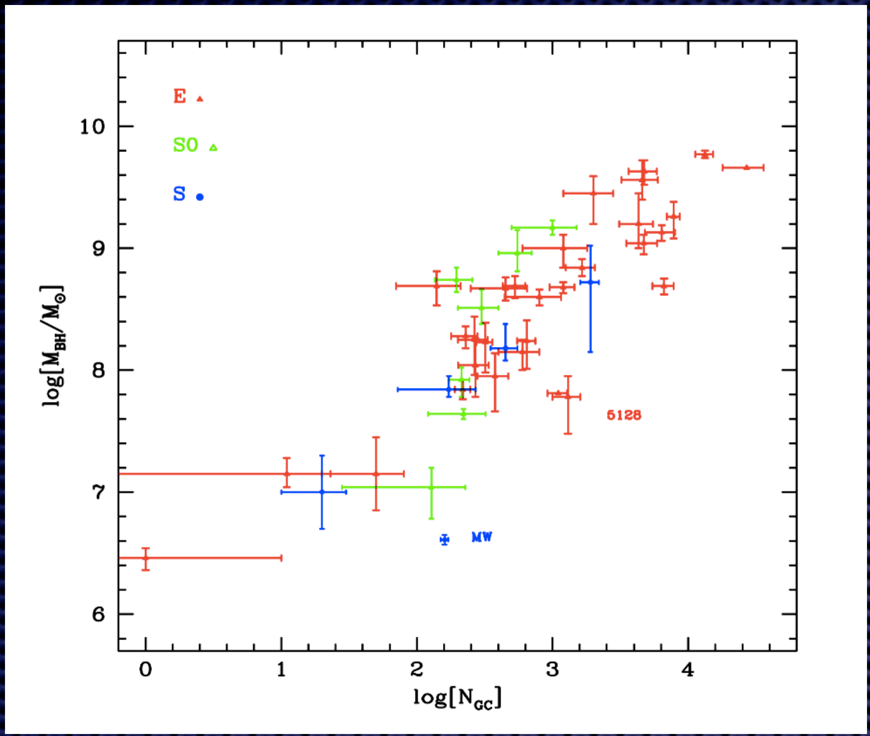
M_{SMBH}

G.Harris & W.Harris 2011,
MNRAS 410, 2347

Low-SMBH outliers = pseudobulges?
(e.g. Milky Way; Kormendy && 2006)

The fact that $N_{GC} \sim M_{BH}$ is not surprising (bigger galaxies on the average have more GCs and bigger SMBHs). But this zeroth-order statement does not explain the actual slope or the small scatter. Can there be any kind of causal link?

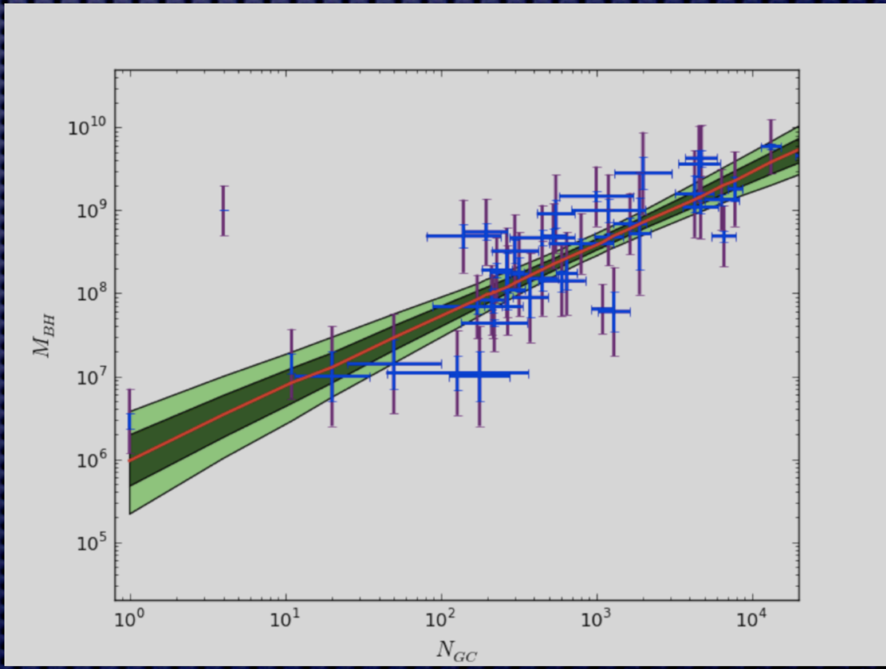
45 galaxies with *all* of N(GC), R_e, σ_e, M(SMBH)



G.Harris, W.Harris, G.Poole 2011

M(SMBH) vs. N(GC), with errorbars from literature:
Slope = 0.82 +- 0.06

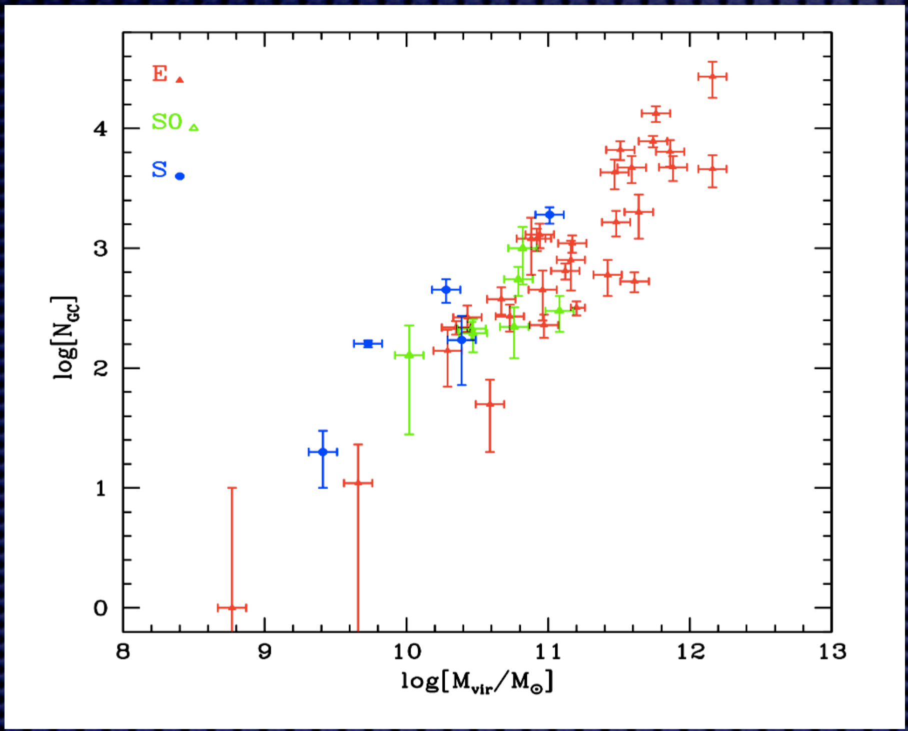
MCMC formalism: additional cosmic scatter required (or quoted uncertainties too small)



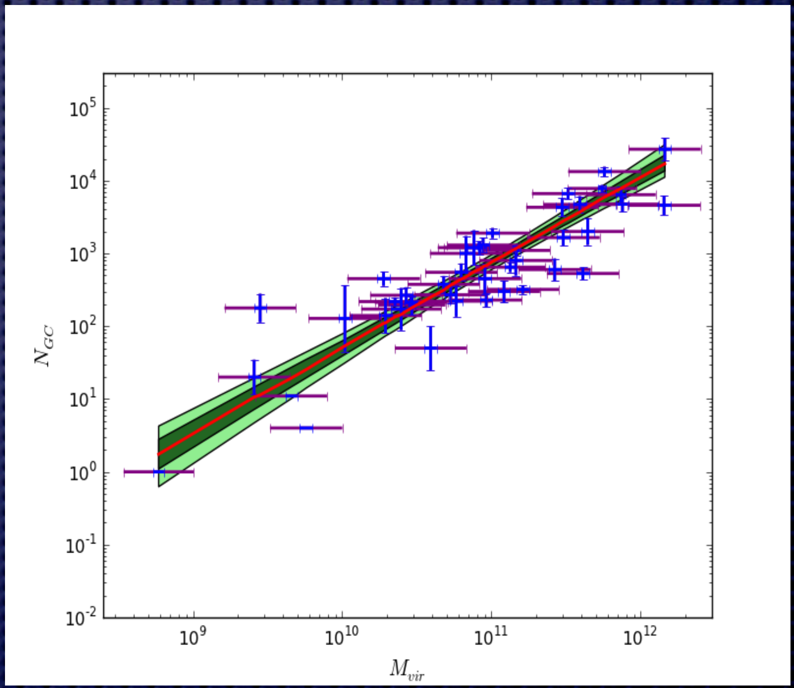
GCs and early SMBH's have similar ages. Is it possible that the AGN jet transmits enough energy into the halo to influence star/cluster formation?

The best correlation emerging from these comparisons is the one between N(GC) and the bulge/spheroid dynamical mass

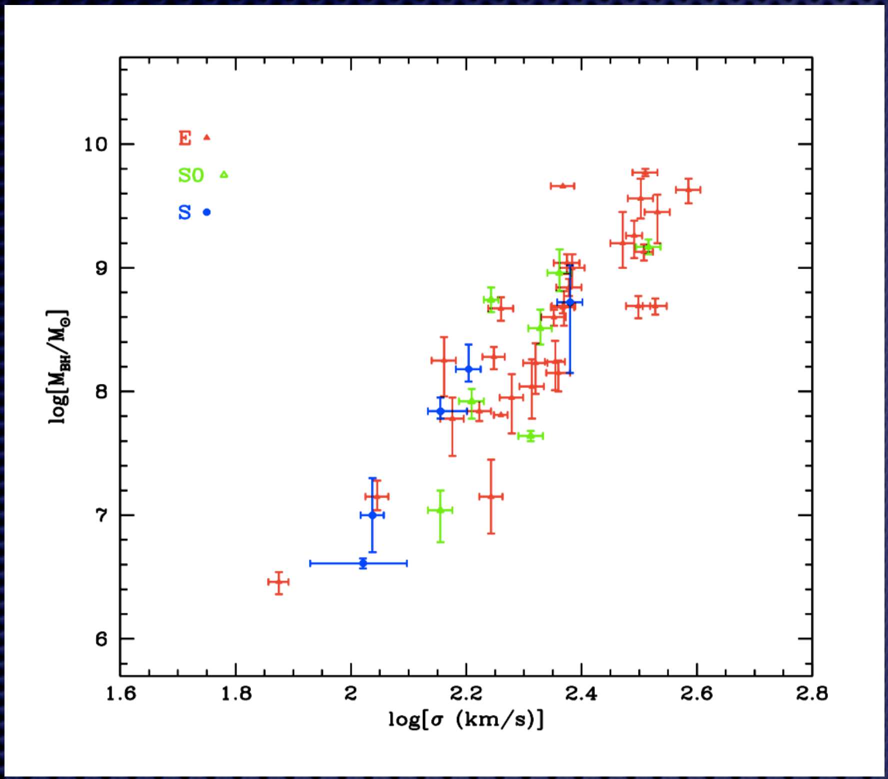
Slope = 1.02 +- 0.08 for same sample of 45 galaxies

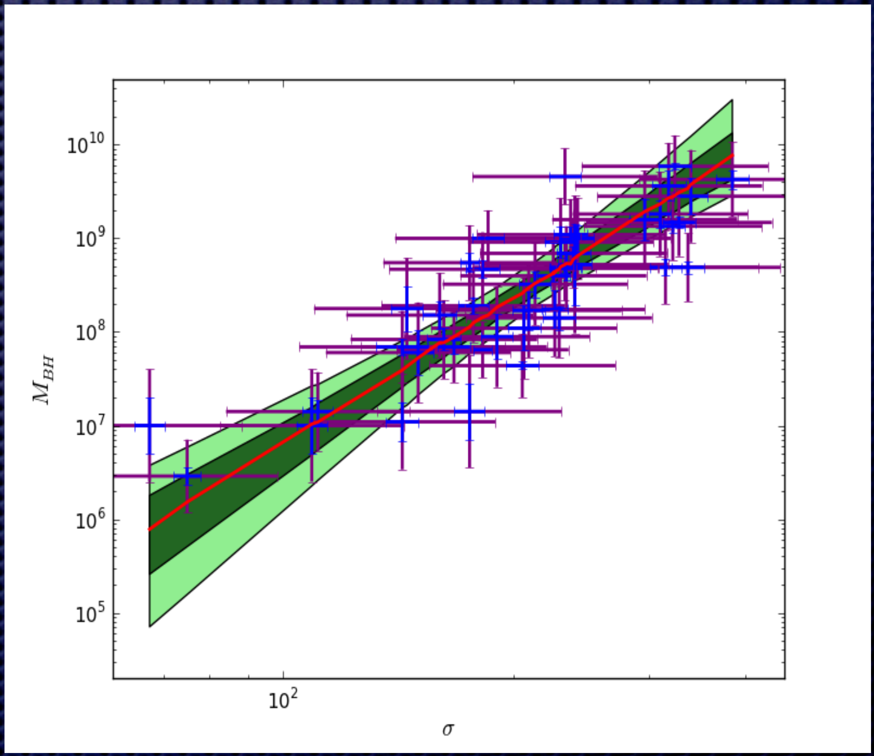


$M_{dyn} = 3 R_e \sigma_e^2 / G$



M(SMBH) vs. velocity dispersion σ_e:
Slope = 4.79 +- 0.33

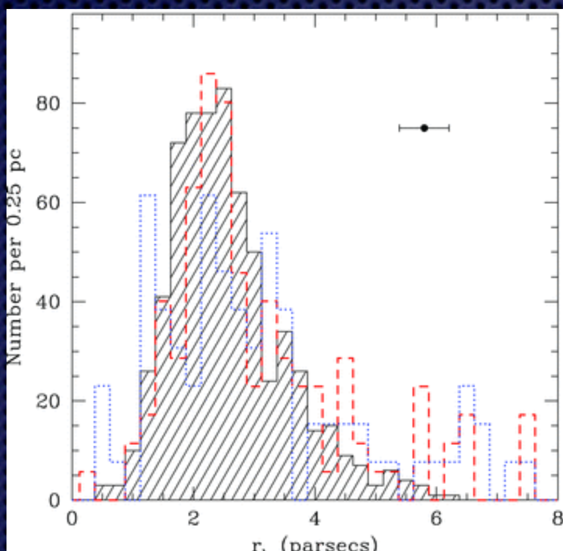


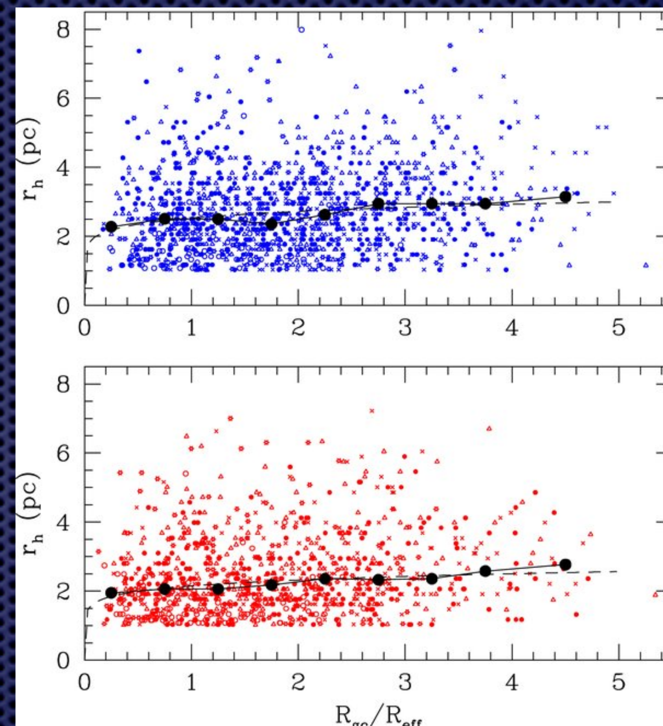


GC Scale Sizes and Tidal Limits: an impending confrontation with tidal-limit theory?

Harris 2009

Harris et al. 2010





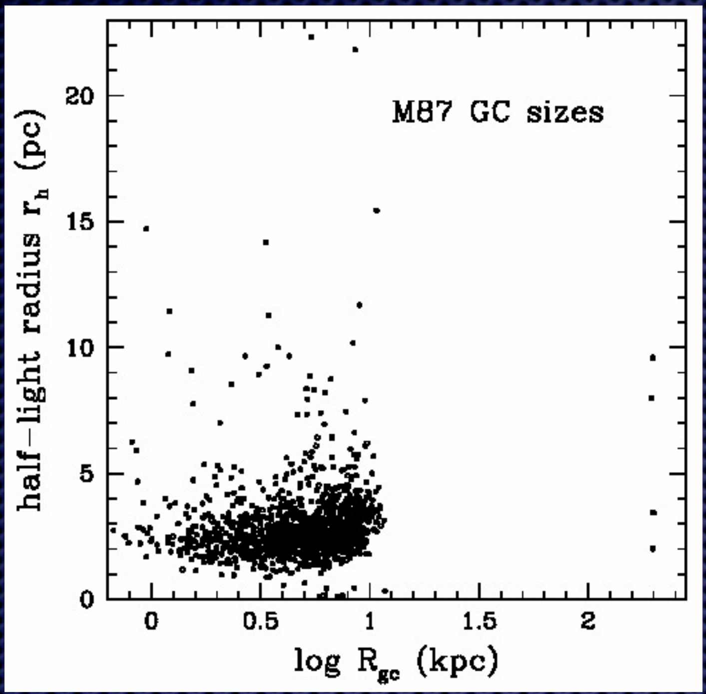
$r_h \sim R_{gc}^{0.2}$ out to 5 R_e -- very shallow increase in cluster size with galactocentric distance

$\langle r_h \rangle \sim$ 2.5 pc with large-r "tail"; somewhat larger in dwarfs

+ Puzia et al. N1399 data

M87 GC size measurements from extremely deep M87 HST/ACS images in (V,I) → r_h measurable to +-0.5 pc

Webb, Sills, & Harris 2011 in prep.



Standard tidal-limit theory: cluster sized is determined by cluster mass, distance from galactic center, and galaxy mass lying within the perigalactic point of its orbit:

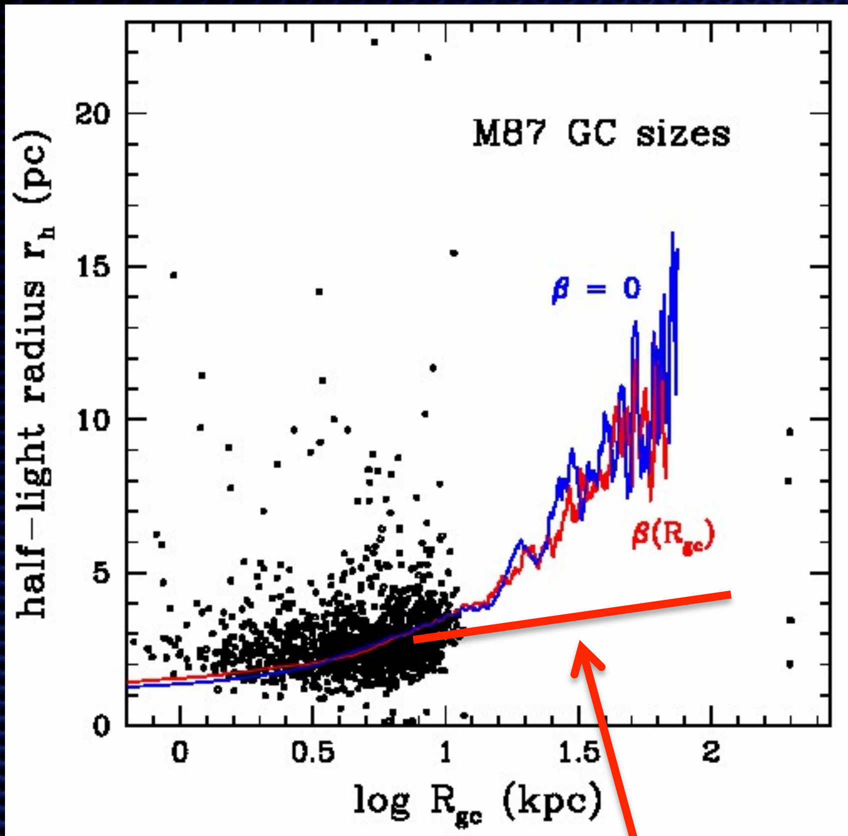
$$r_t \propto \left(\frac{m_{GC}}{M_{gal}}\right)^{1/3} r_{gal} \quad \text{and} \quad M_{gal} \propto r_{gal}$$

$$\Rightarrow r_t \propto m_{GC}^{1/3}\, r_{gal}^{2/3}$$

Projection to 2D →

r_t , $r_h \sim m^{1/3} R_{gc}^{0.5}$

Observations: $r \sim R_{gc}^{0.2}$, much shallower than is expected from standard tidal theory



Trend of data

M87 system simulation assuming:

- Observed GC spatial dist'n (spherical symmetry)
- Standard GC mass distribution function
- King-model cluster profiles, standard c-distribution
- Isotropic (or anisotropic) velocity distribution with measured σ(R) profile
- Tidal radius is set at or near perigalacticon
- *Assume King r_t same as tidal-theory r_t*

$$\beta = 1 - \frac{\sigma_\phi^2 + \sigma_\theta^2}{2\sigma_r^2}$$

Radially anisotropic orbits (β > 0) in outer halo can force agreement with data, but requires β ~ 0.8 (very high)

In progress:
- HST Cycle 19 imaging of outer halo clusters
- N-body integrations

Questions

- Does bimodality in color / metallicity result naturally from a *single* formation sequence during hierarchical merging?
- Does self-enrichment really work in dense, massive protoclusters? (does star formation last for 10 Myr or more in such systems?)
- How much (and how far out into the halo) can SMBH/AGN feedback influence GC formation?
- Is the GC population size a good tracer of total galaxy mass (including DM)?

What we need from theory:

- Full SPH models of GC formation for 10^5-10^7 M_0 protoclusters sufficient to resolve star formation
- … and coupled to galaxy-scale hierarchical merging including AGN feedback.
- N-body integrations of tidally limited GCs covering range of halo locations