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

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Clusters are laboratories for galaxy evolution

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Globular

stellar

Clusters are laboratories for ~~galaxy~~ evolution

^

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Globular

tracers of

Clusters are ~~laboratories for~~ galaxy evolution

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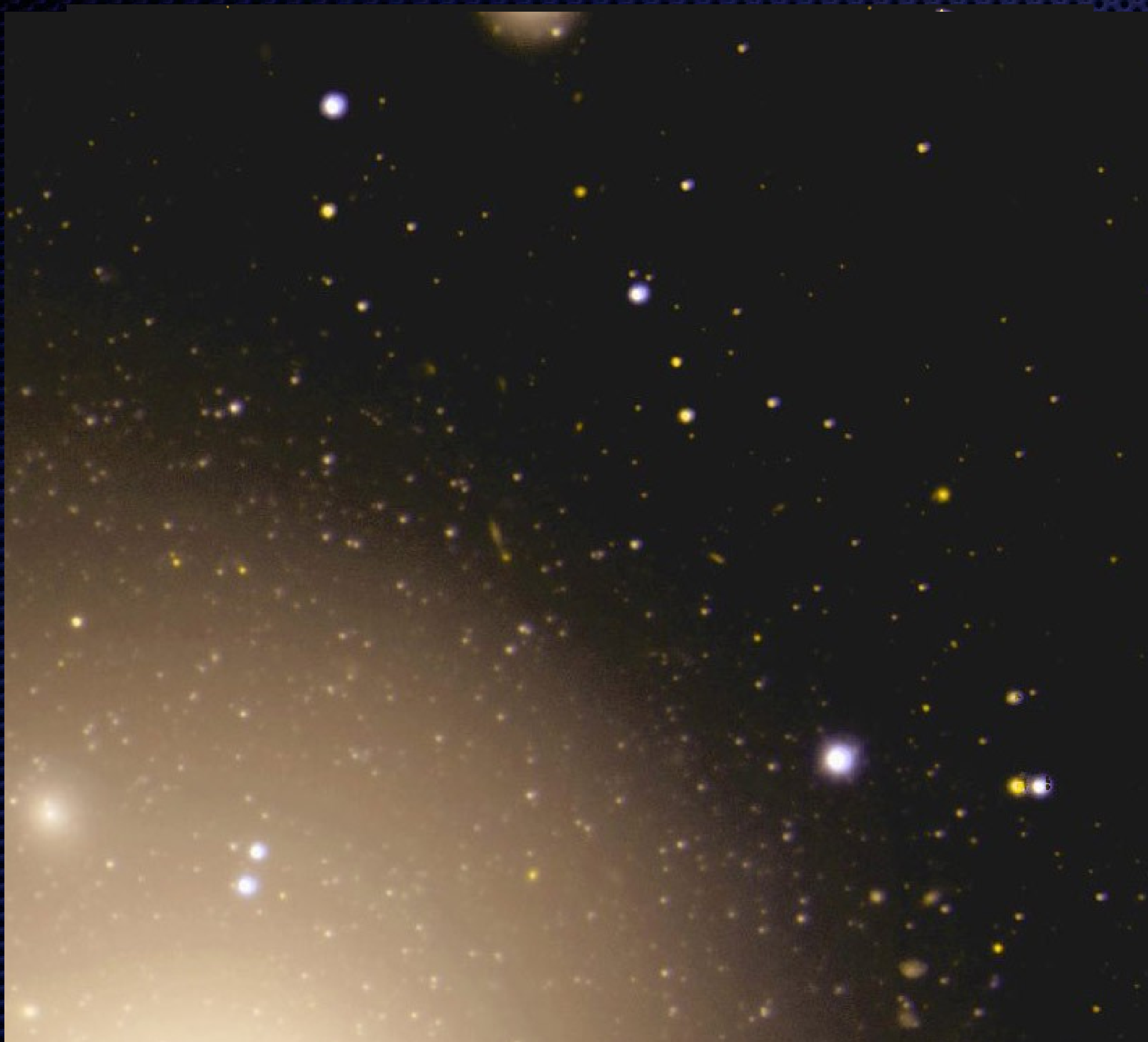
Studying the ensembles of globular clusters in galaxies is a hybrid field mixing stellar populations with galaxy structure and evolution

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)

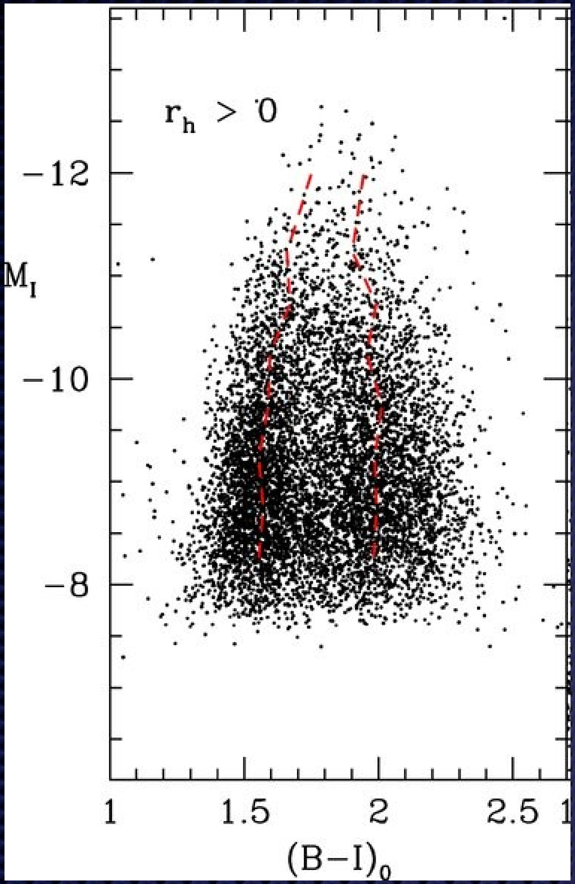
D > 80 Mpc (HST)

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

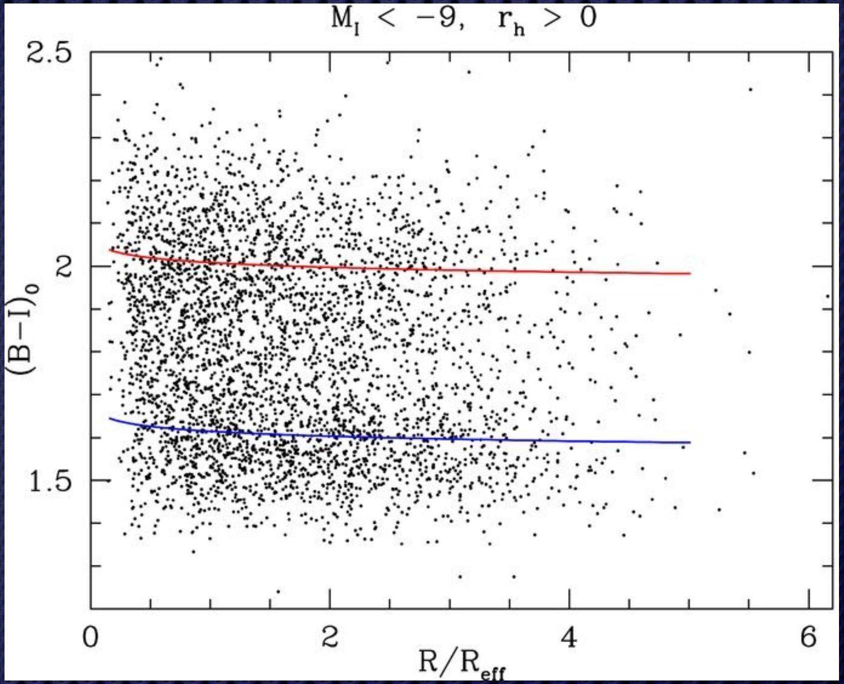
Present day: < 1% of total stellar mass

Initially: > 10% ?

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



Weak metallicity gradients <Fe/H> ~ $R^{-0.1}$

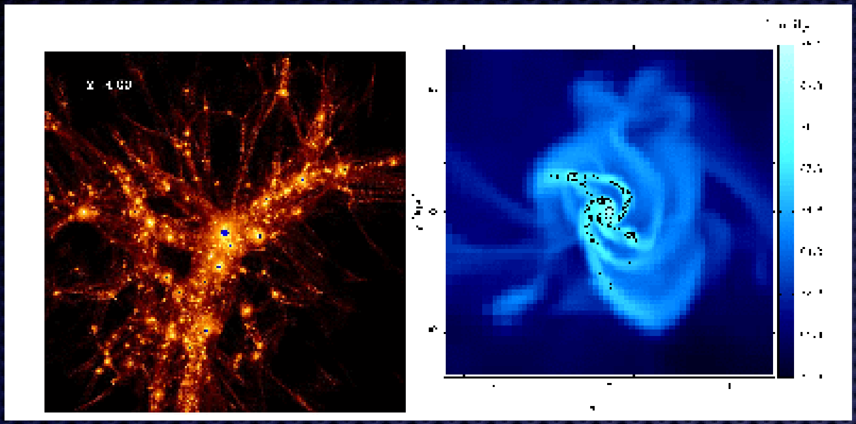


Composite data from 6 BCGs (Harris 2009, ApJ)

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

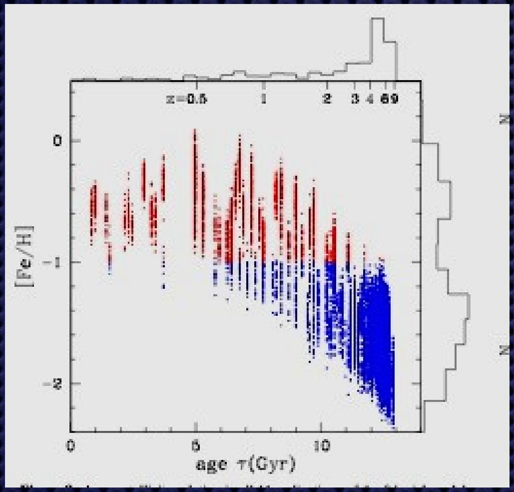
Two distinct formation epochs? Doubtful ...

GC Formation: The Big Picture



Muratov & Gnedin 2010, ApJ 718, 1266

[Fe/H]



age

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

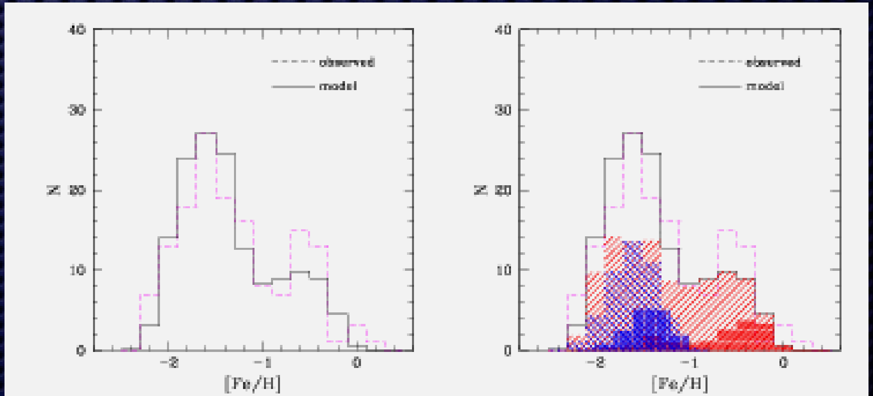
$N_{GC}(t)$ ~ Merger rate x cloud mass

Semi-realistic bimodality emerges naturally though not every time

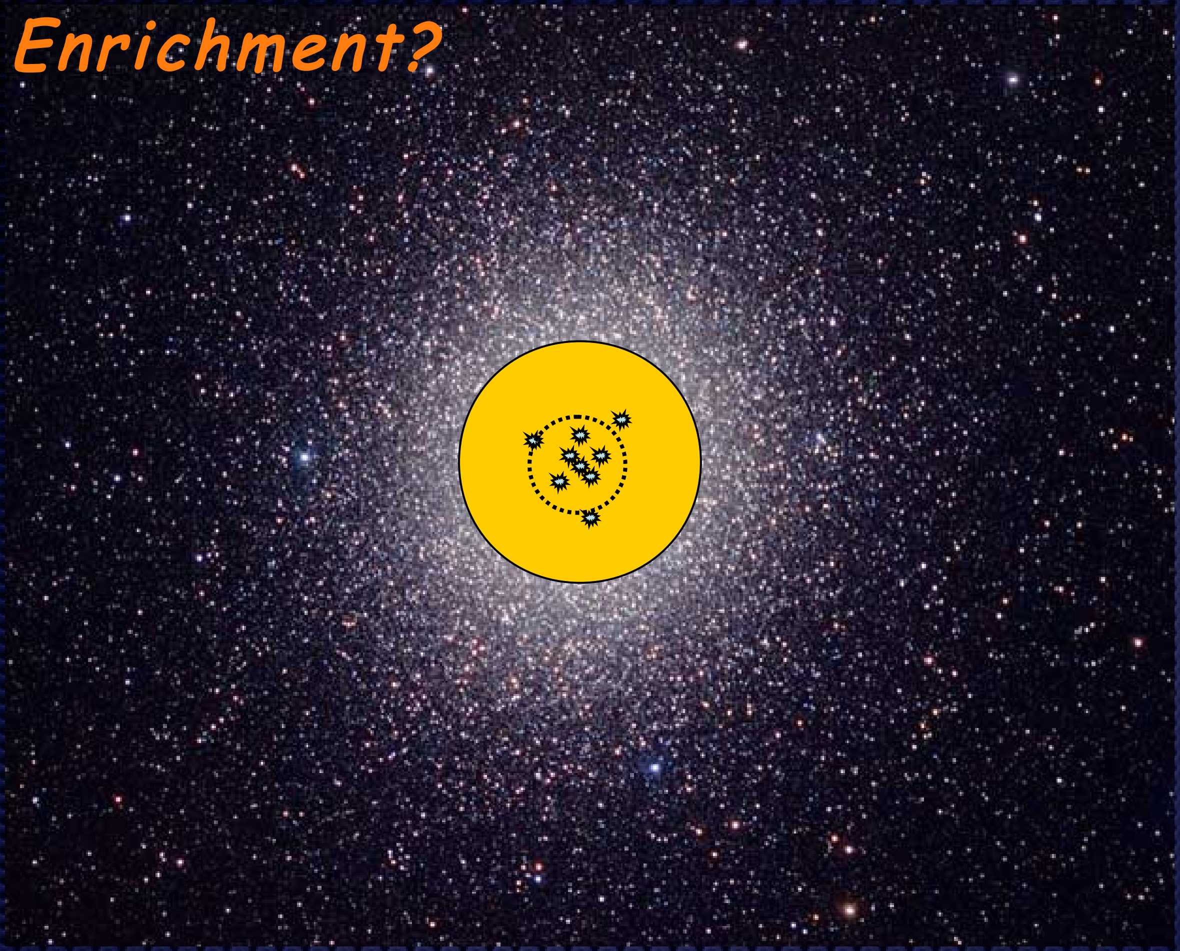
Realistic mass distributions and spatial distributions

Too many young, metal-rich GCs?

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



GC Formation: The Local Picture: Self-Enrichment?



Bailin & Harris 2009, ApJ 695, 1082

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

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

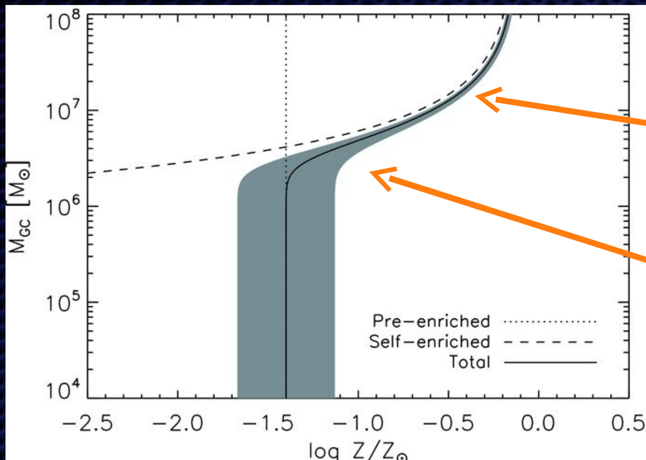
~ 1/e at $4 \times 10^7\ M_0$ (protocluster)

$4 \times 10^6\ M_0$ (today's GC)

Pre-enrichment = initial cloud metallicity

Self-enrichment = additional metallicity generated during formation

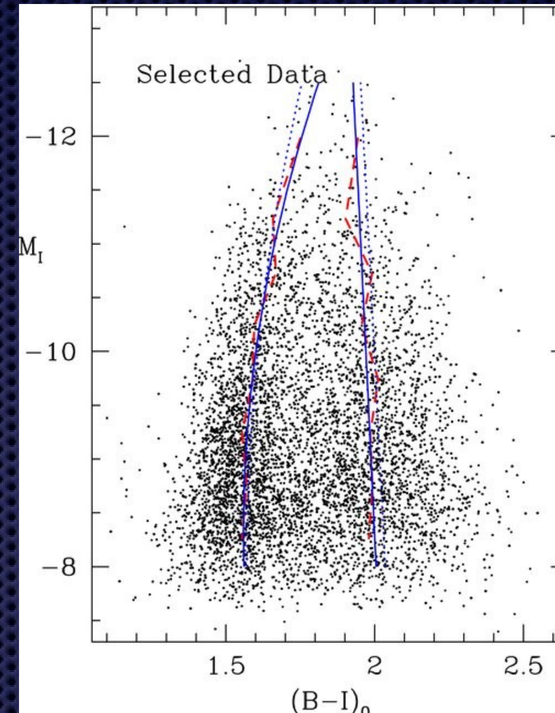
M



[Fe/H]

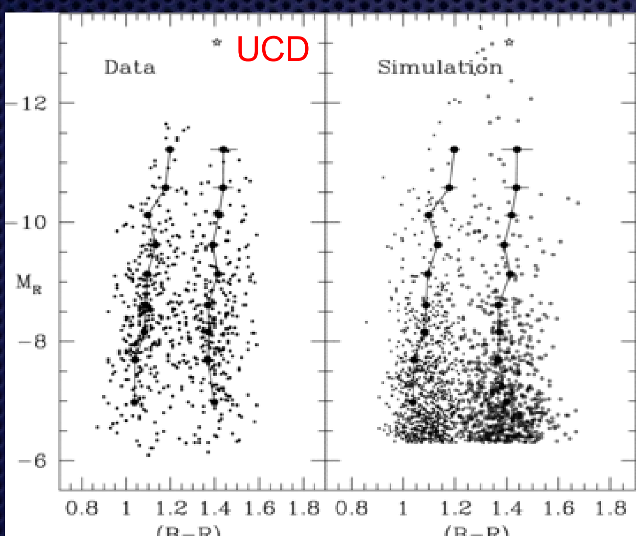
UCD and dE,N regime?

Massive-GC regime

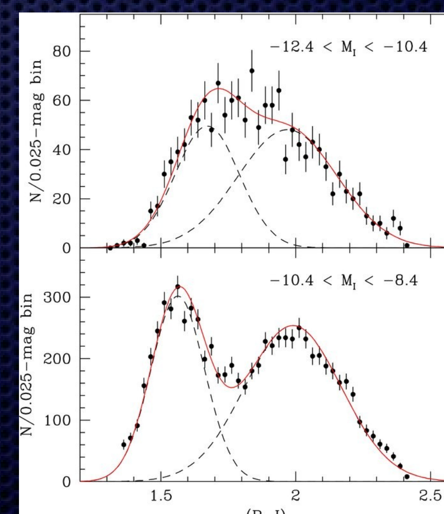


Nonlinear mass-metallicity relation expected along both sequences, but easily visible only on blue sequence

6 BCGs (Harris 2009)

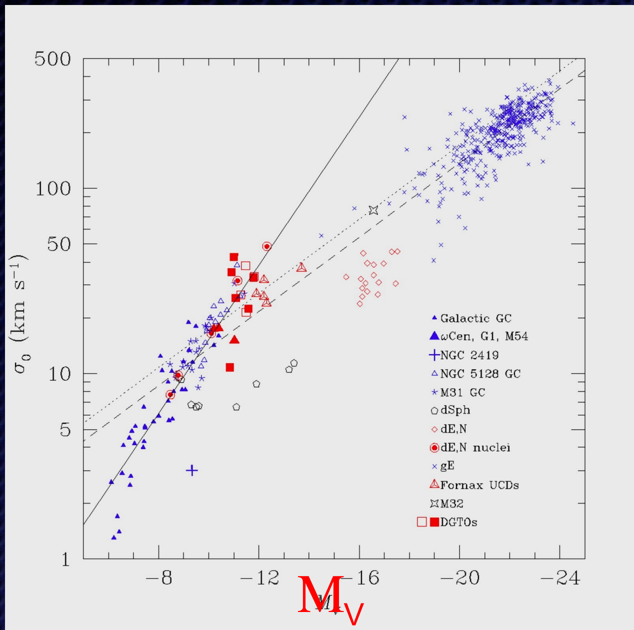


M104 data and simulation (Harris && 2010, MNRAS 401, 1965)



7 more cD's coming!

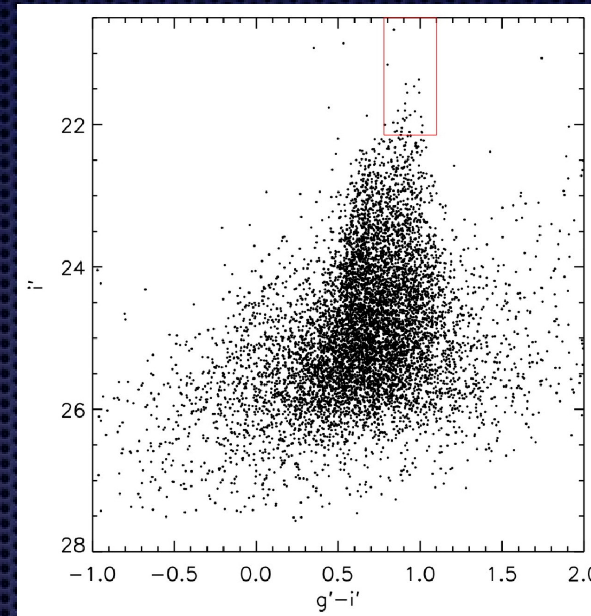
Links with UCD/dE regime



σ

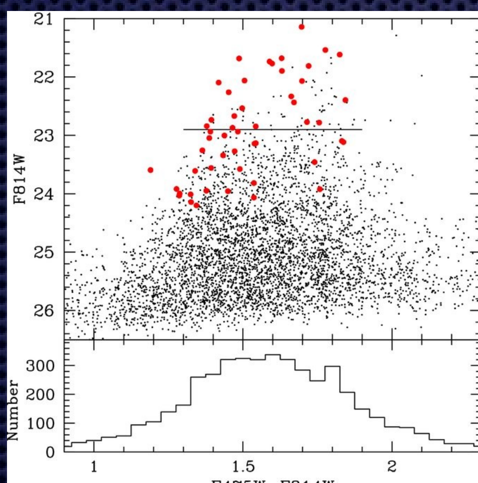
M_V

Hasegan && 2005,
ApJ 627, 203



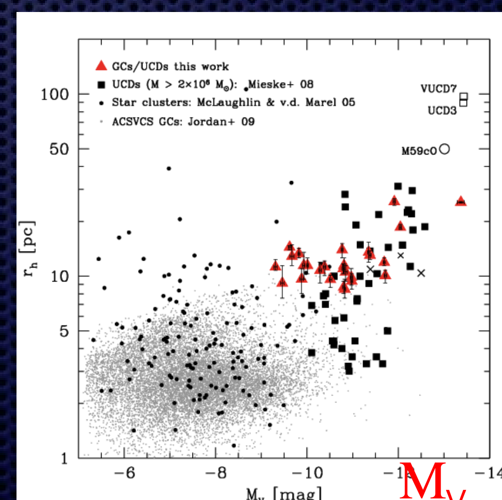
NGC 3311 (Hydra)
Wehner & Harris 2007, ApJ 668, L35, 1707
Misgeld && 2011, AA 531, A4

r_h > 10 pc



NGC 4874 (Coma)
Madrid && 2010, ApJ &22, 1707

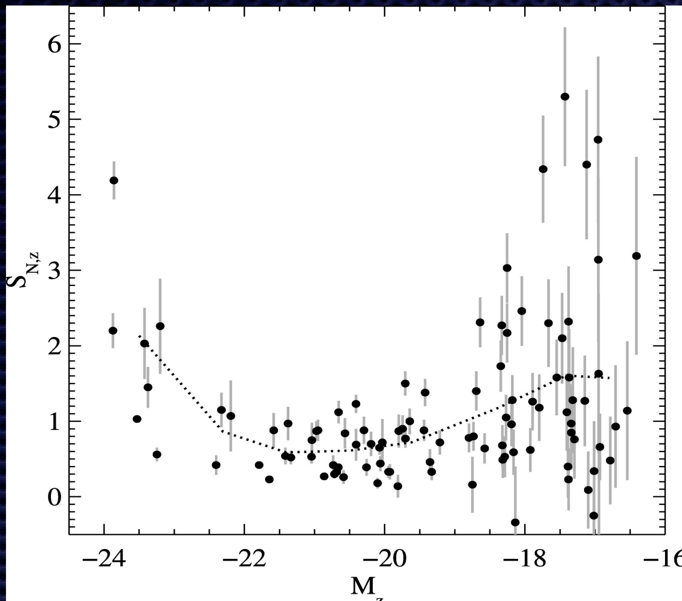
r_h



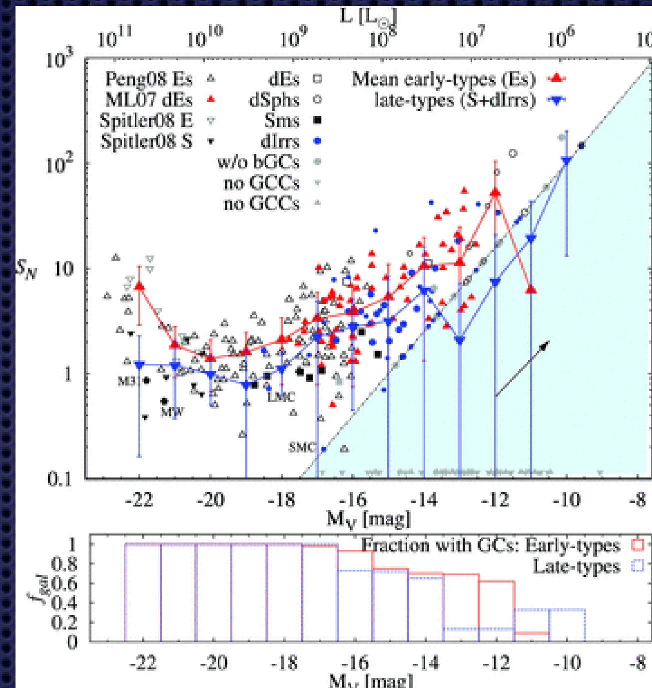
M_V

What determines the total population of GCs in a galaxy?

S_N



Peng && 2008, ApJ 681, 197



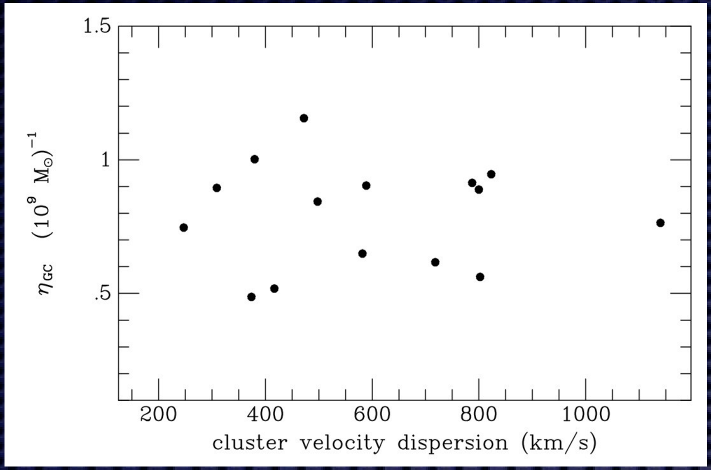
Georgiev && 2010 MNRAS 406, 1967

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

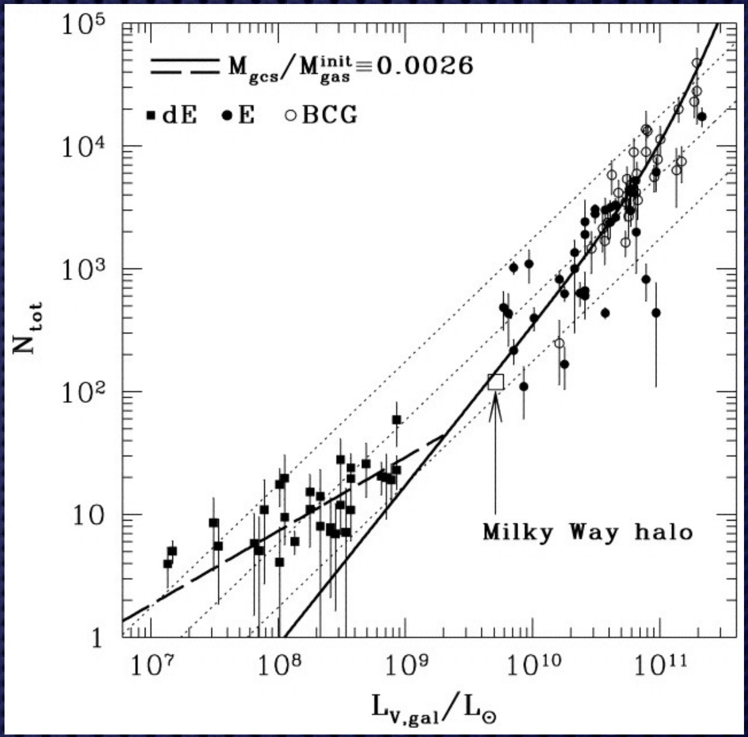
30th anniversary! (Harris & van den Bergh 1981)

Specific frequency and specific mass

η



σ(cluster)



Blakeslee, Tonry, & Metzger 1997, AJ 114, 482
Blakeslee 1999, AJ 118, 1506

Kavelaars 1999, ASPC 182, 437

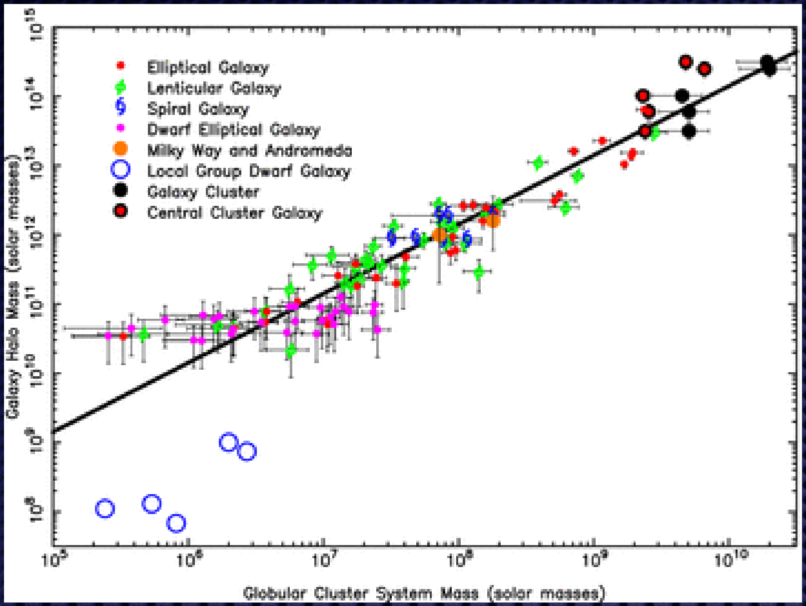
McLaughlin 1999, AJ 117, 2398

"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?

N(GC) ~ M(total) = dark+baryonic ?

M(tot)

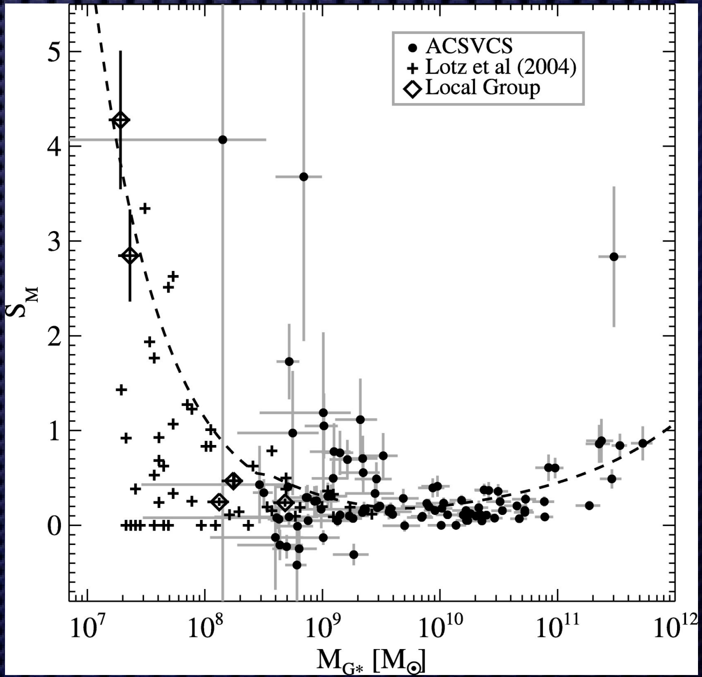


M(GC)

Spitler & Forbes 2009,
MNRAS 392, L1

S_M = M(GC)/M(stellar)

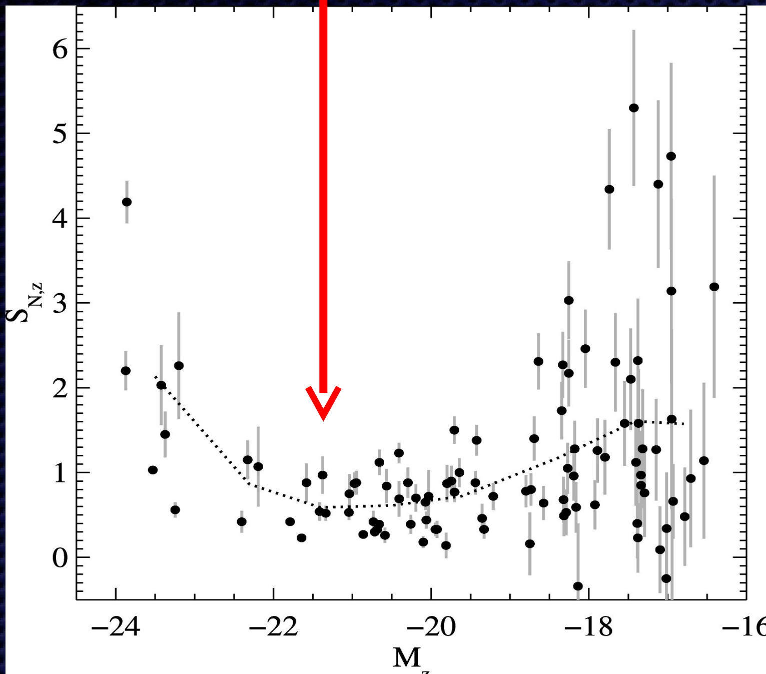
Peng && 2008
Georgiev && 2010



Curve assumes M(halo)/M(stellar) model
from vandenBosch && 2007

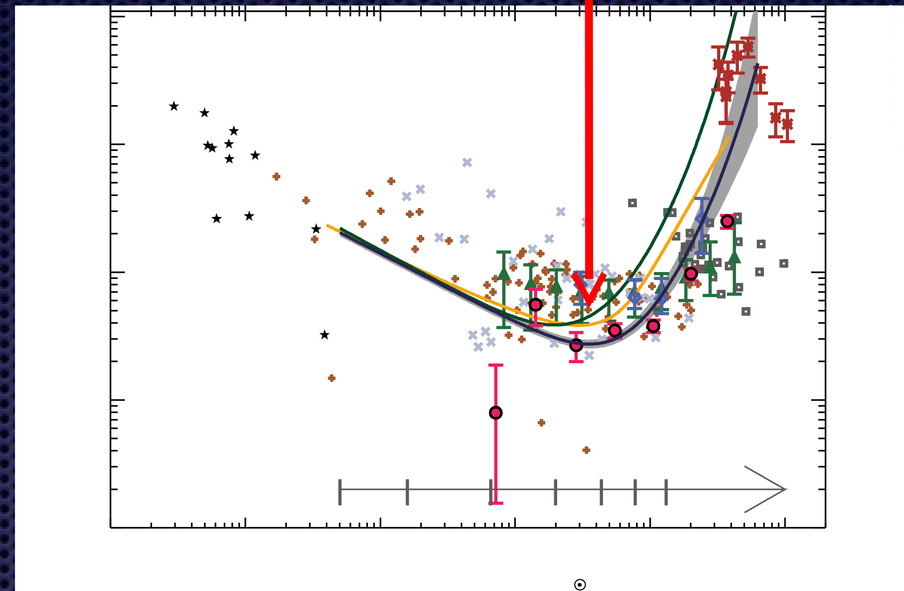
M(stellar)

$4.5 \times 10^{10}\ M_0$



Peng && 2008

$4.5 \times 10^{10}\ M_0$



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

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

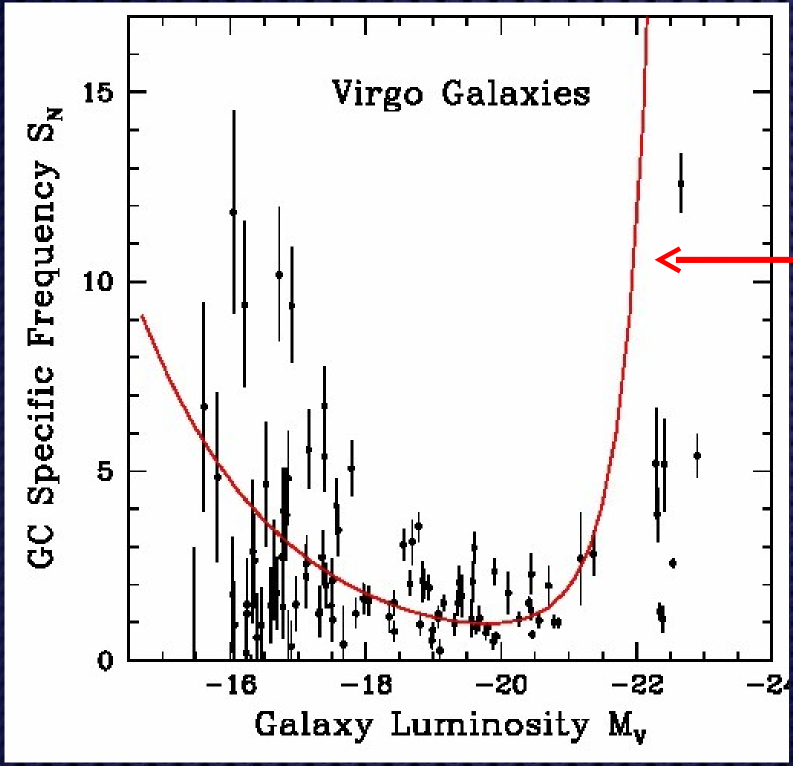
Maximally efficient conversion of infalling gas to stars near $10^{10}\ L_0$.

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

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

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

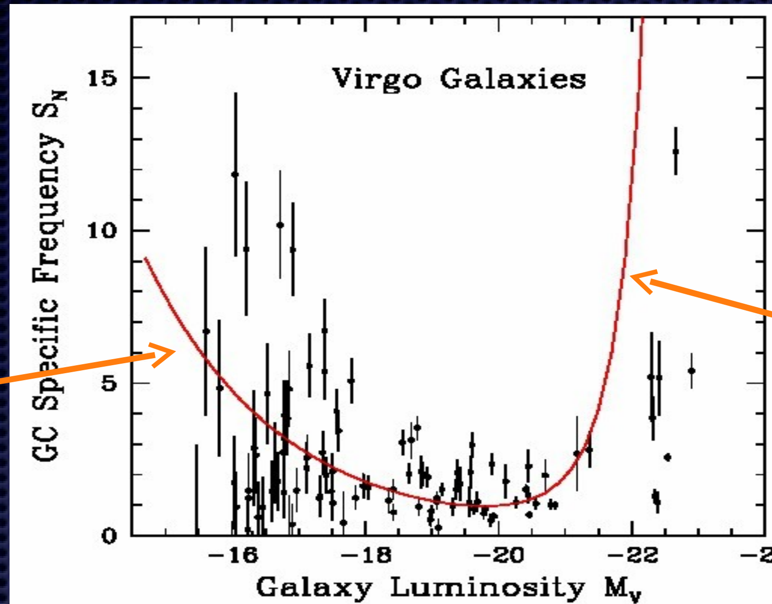
$$S_N = \alpha_1 \frac{N_{GC}}{L_*} = \alpha_1 \alpha_2 (M/L)_* \frac{M(halo)}{M(*)}$$



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

NB: Transition from nuclear star cluster to central supermassive black hole occurs near $2 \times 10^9 L_0$ ($M_V \sim -18.5$)

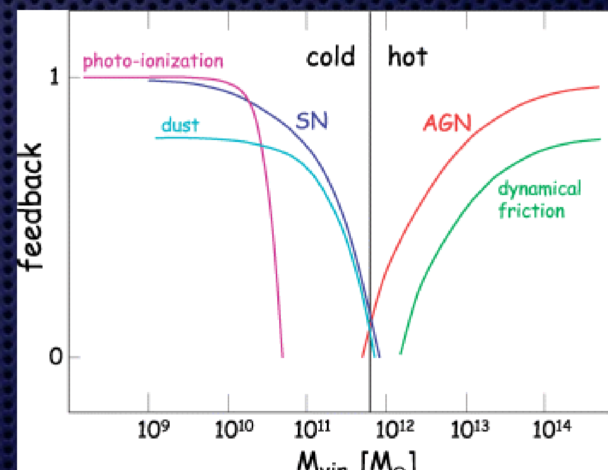
SNe + starburst winds + photoionization feedback



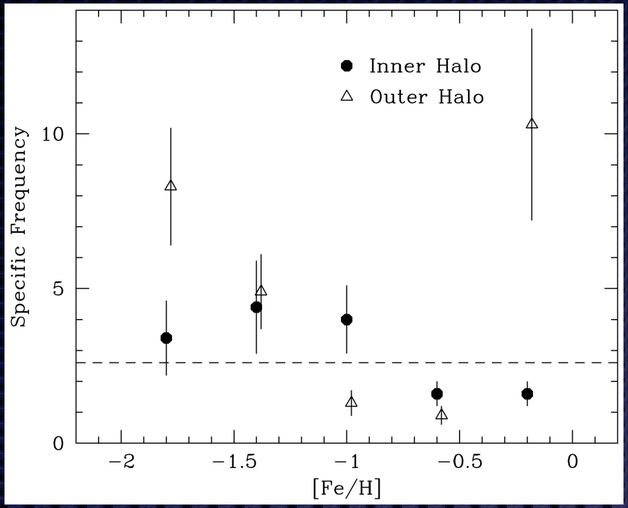
Shock heating + AGN feedback

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?



M(halo) ~= 2.5 x 10^9 N_{GC} ~= 1.7 x 10^4 M_{GC}(now)

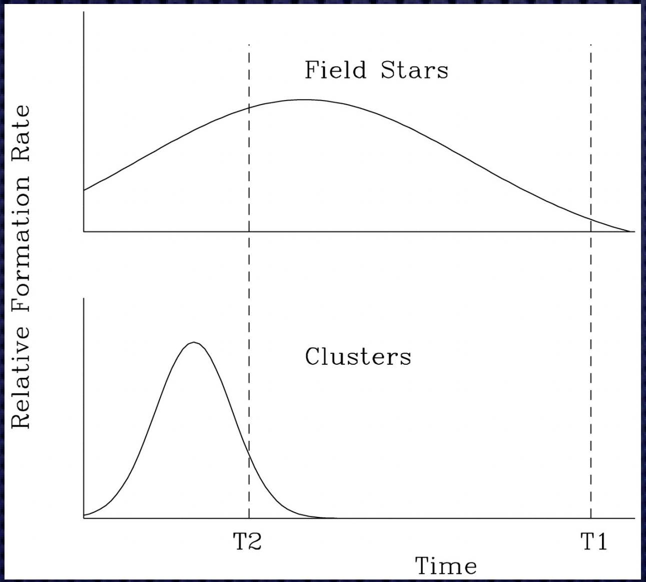


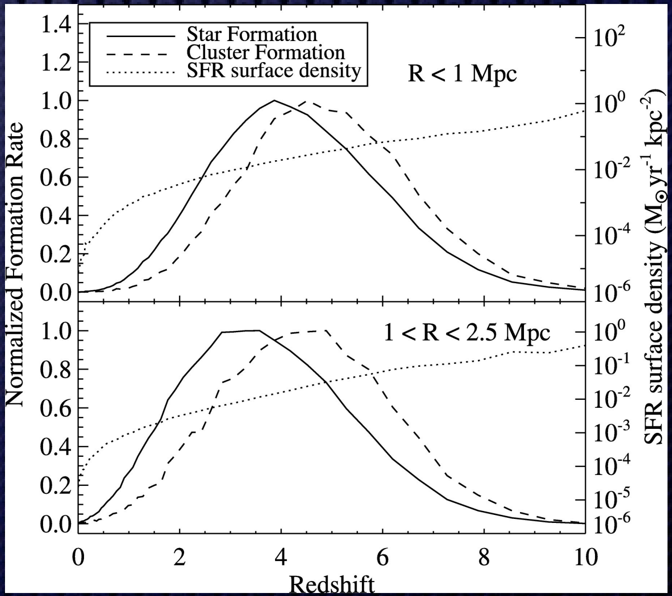
Protocluster formation peaks earlier than lower-density field-star formation

Earliest epochs less subject to external disruption

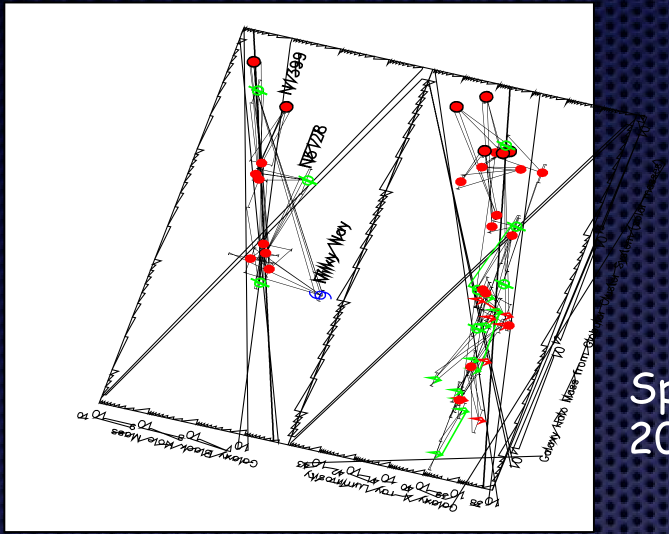
Harris & Harris 2002

Peng && 2008



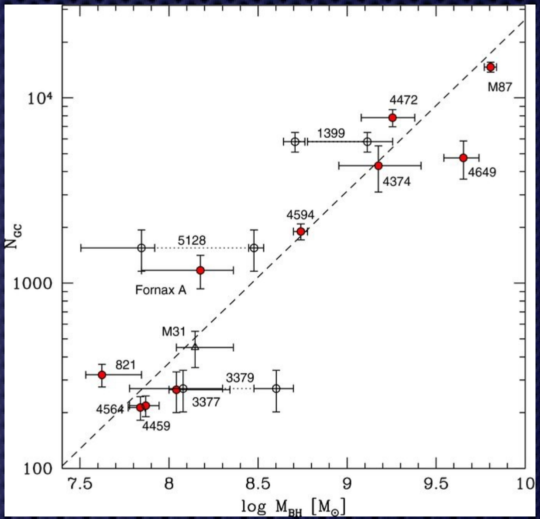


Links with other Galaxy Features



Spitler & Forbes 2009, MN 392, L1

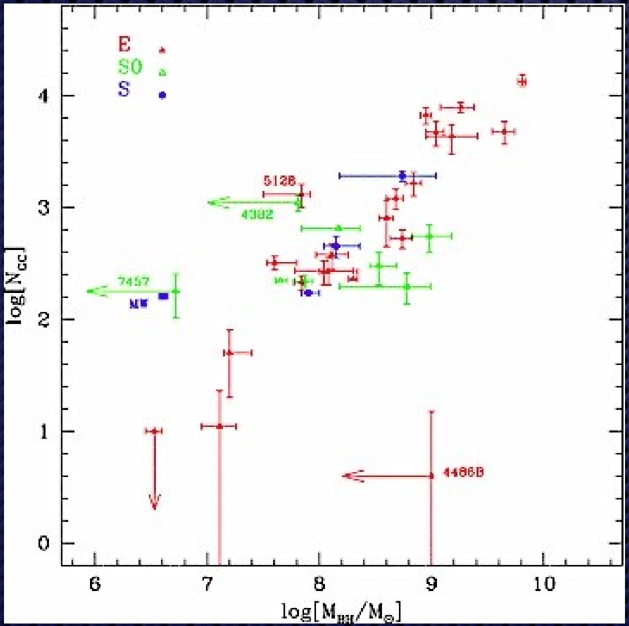
N_{GC}



M_{SMBH}

Burkert & Tremaine 2010, ApJ 720, 516

N_{GC}

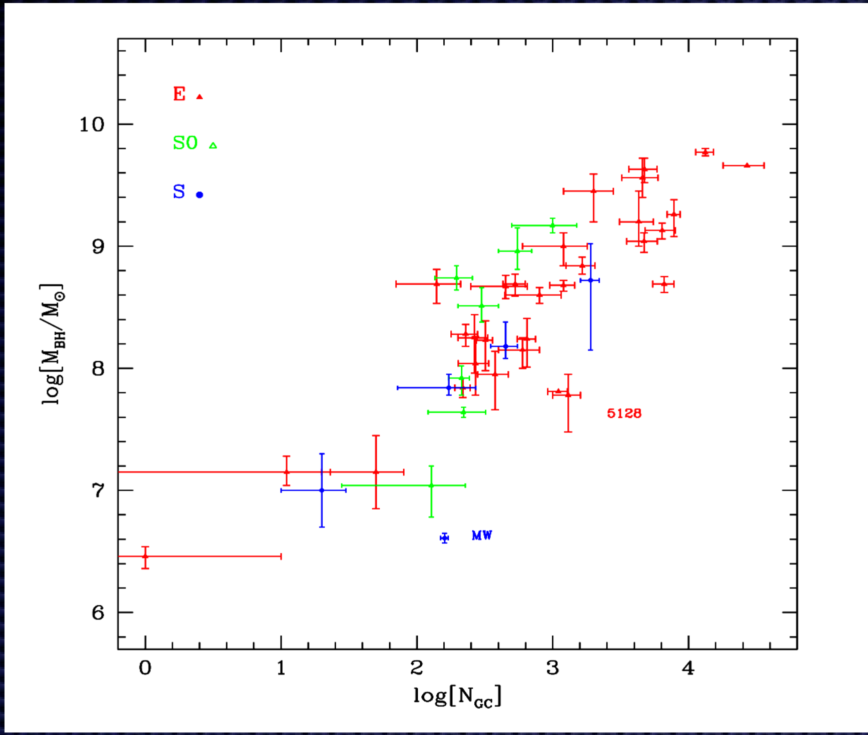


M_{SMBH}

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

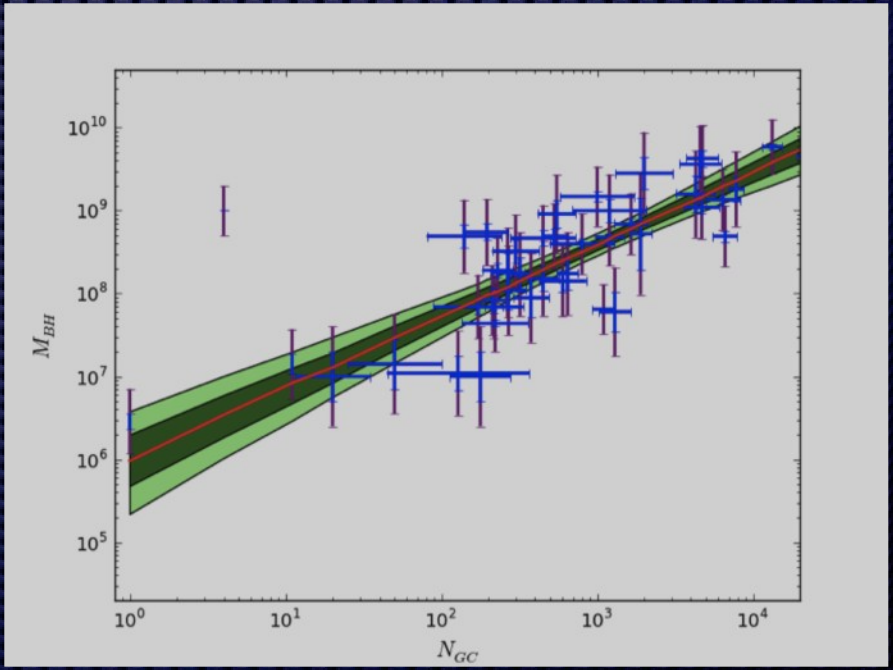
Low-SMBH outliers = pseudobulges?
(e.g. Milky Way; Kormendy && 2006)

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



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)

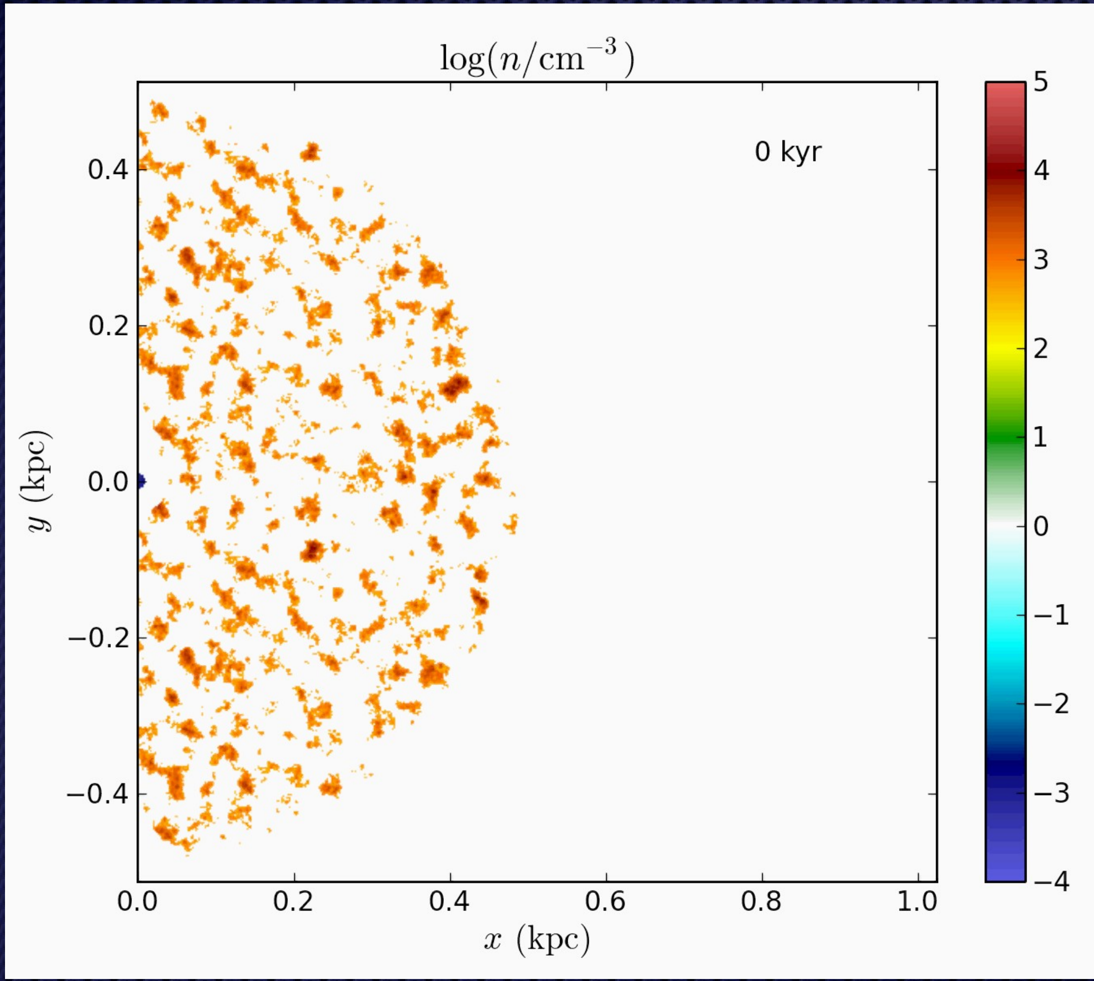


G.Harris, W.Harris, G.Poole 2011

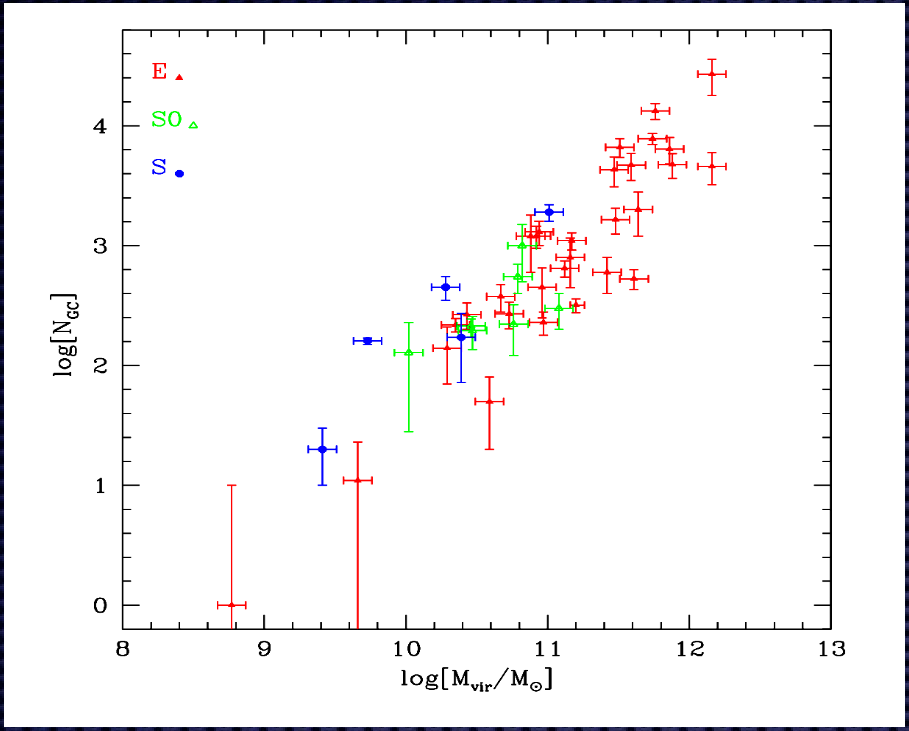
GCs and early SMBH's have similar ages. How far out into the protogalactic halo can the AGN influence cluster formation?

Wagner & Bicknell 2011, ApJ 728, 29

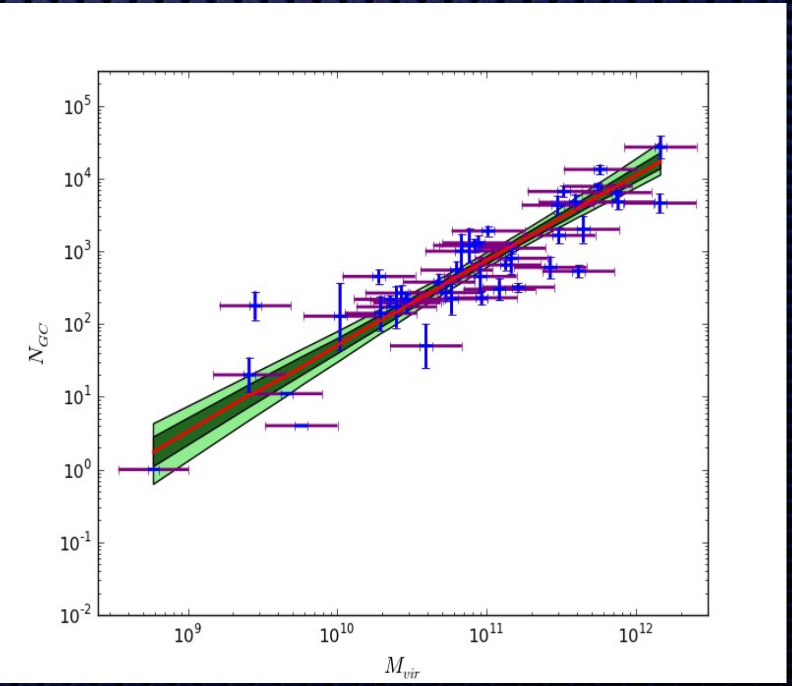
Relativistic AGN jet + fractal-like ISM



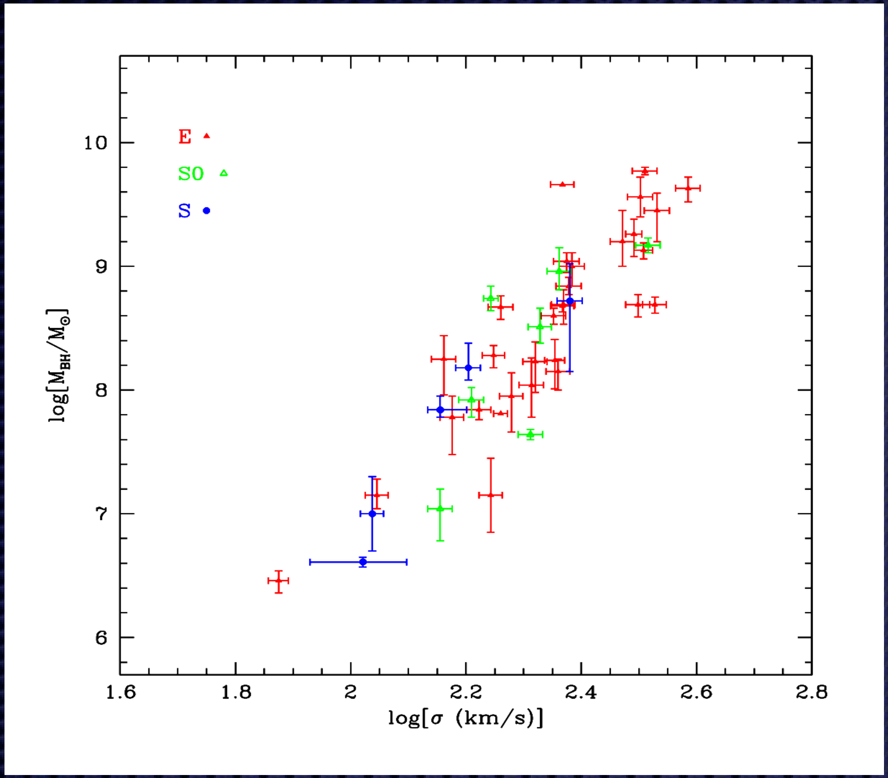
N(GC) vs. M(dyn): Slope = 1.02 +- 0.08

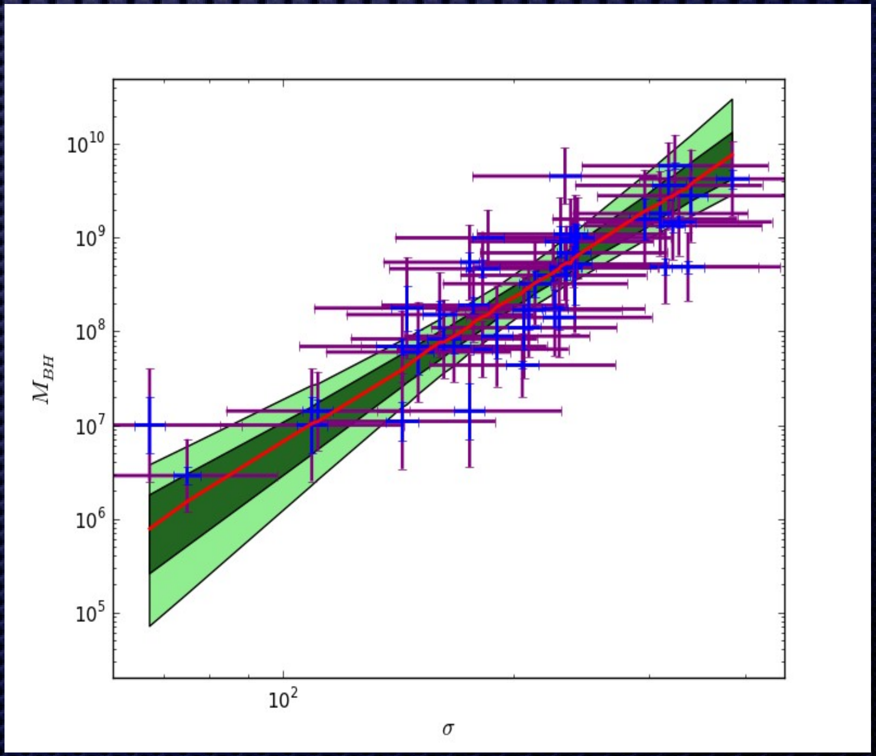


$M_{dyn} = 3\, R_e\, \sigma_e^2 / G$

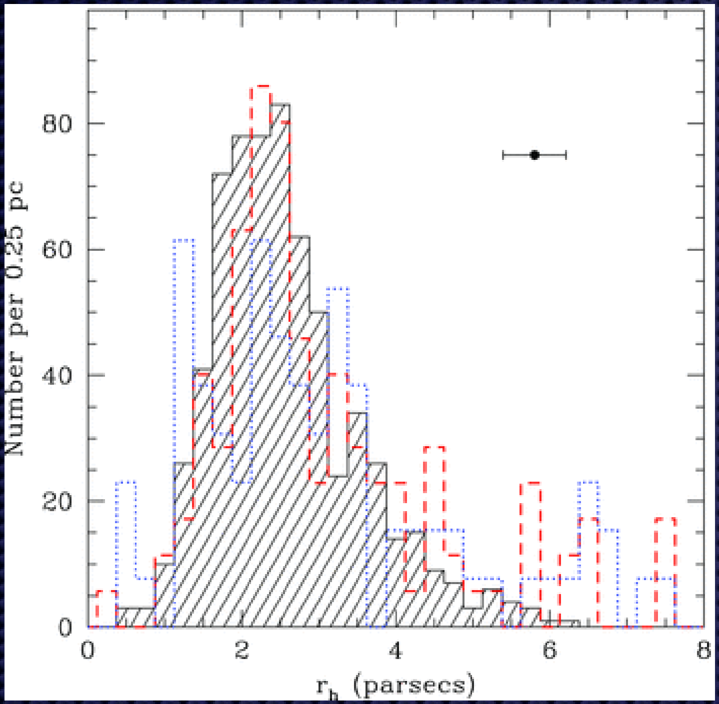


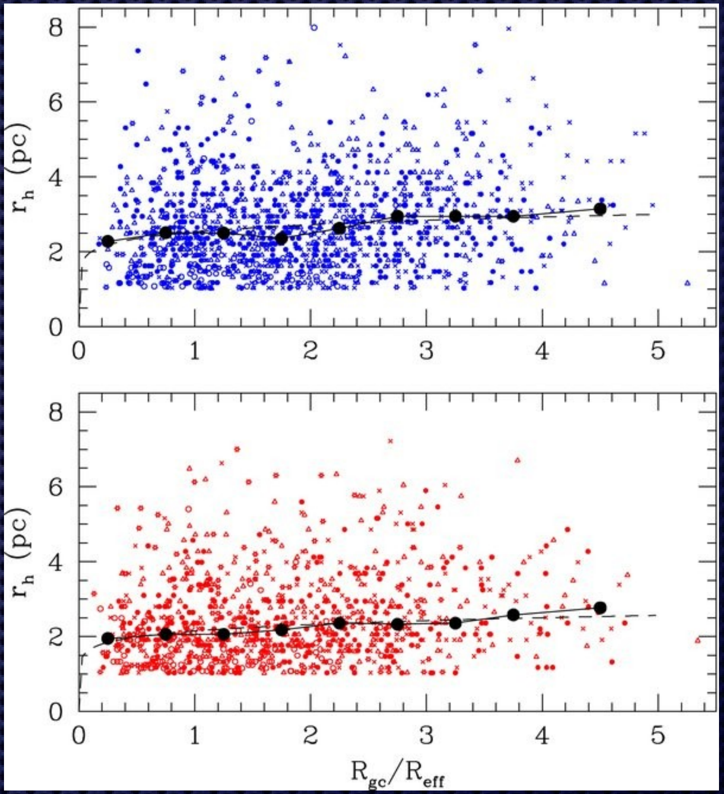
M(SMBH) vs. velocity dispersion σ_e:
Slope = 4.79 +- 0.33





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





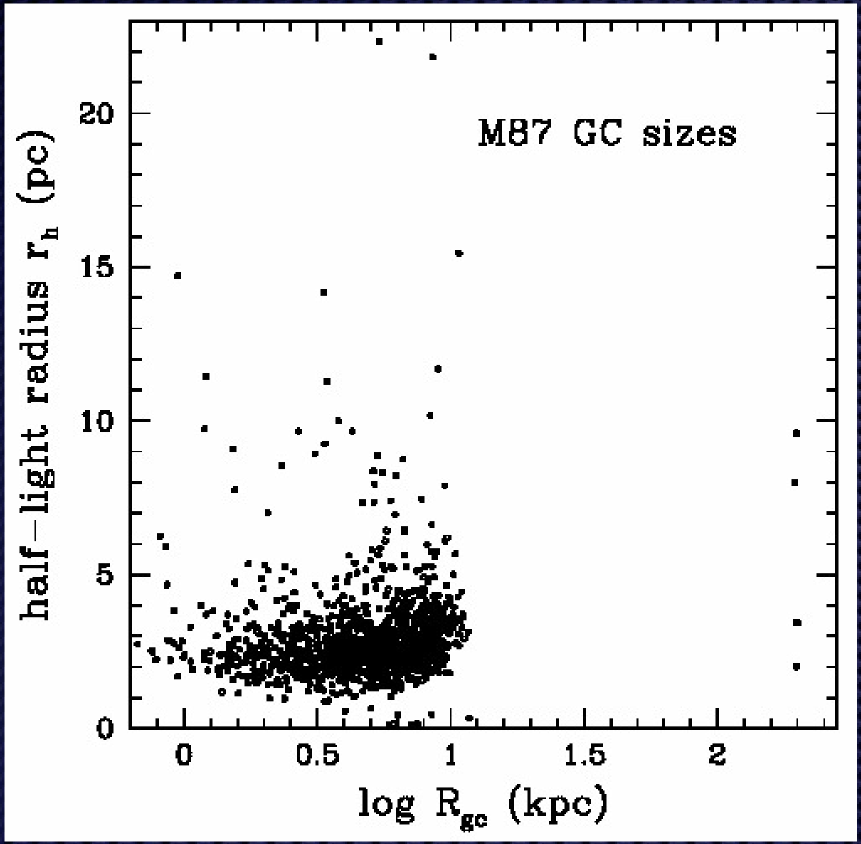
$r_h \sim R_{gc}^{-0.2}$ out to 5 R_e

$\langle r_h \rangle \sim$ 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.



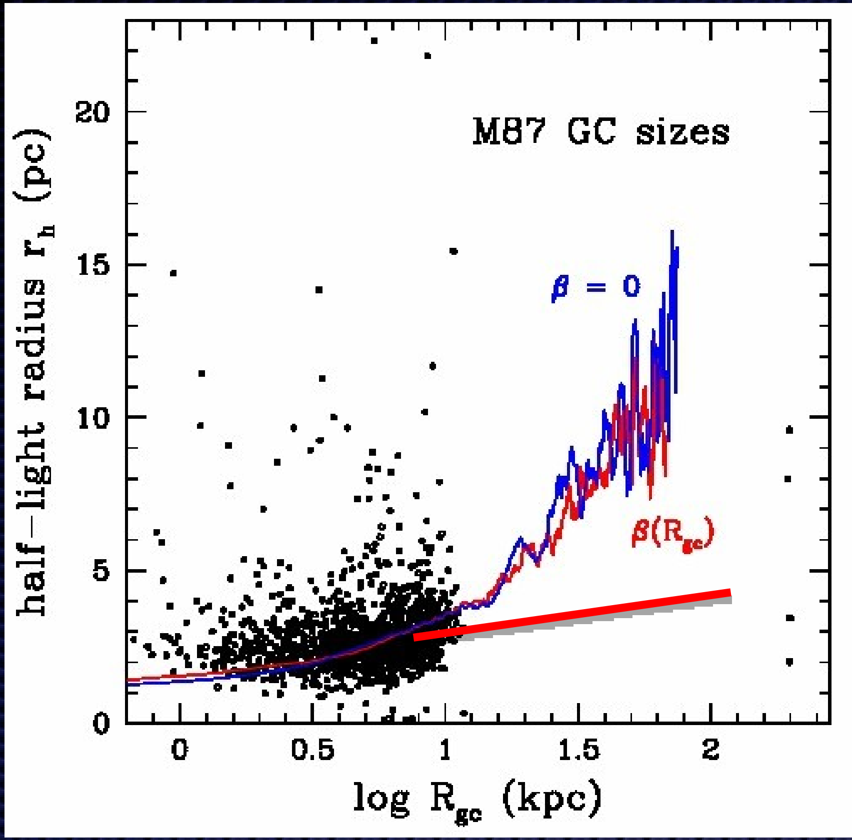
$$r_t \propto \left(\frac{m_{GC}}{M_{gal}} \right)^{1/3} r_{gal} \quad \text{and} \quad M_{gal} \propto r_{gal}$$

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

Projection to 2D →

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

Observations: $r \sim R_{gc}^{0.2}$



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

M87 system model 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*

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