Globular Cluster Sub-populations and Galaxy Assembly

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Study of Astrophysics of Globular clusters in Extragalactic Systems

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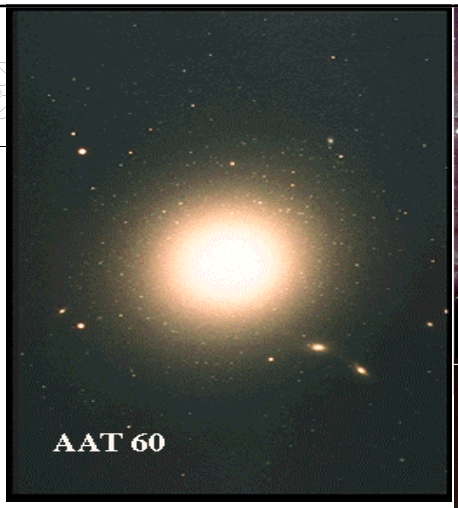
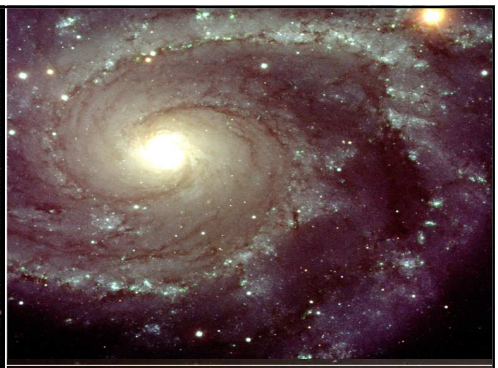
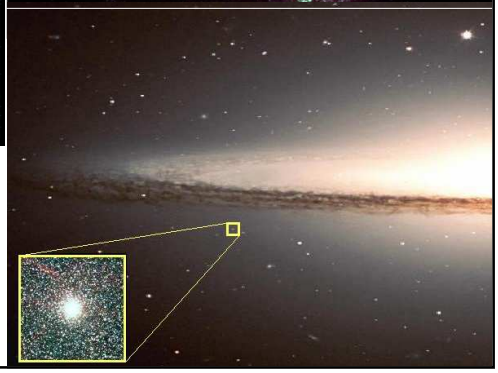


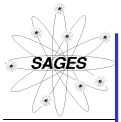




Associated with galaxies of all morphological types
~150 in MW
~400 in M31
> 10,000 in some ellipticals

Good tracers of star formation histories of galaxies

- Massive star clusters form during all major star formation events
  (Schweizer 2001)
- #of young clusters scales with amount of gas involved in interaction
  (Kissler-Patig, Forbes & Minniti 1998)
- Cluster formation efficiency depends on SFR in spirals (Larsen & Richtler 2000)



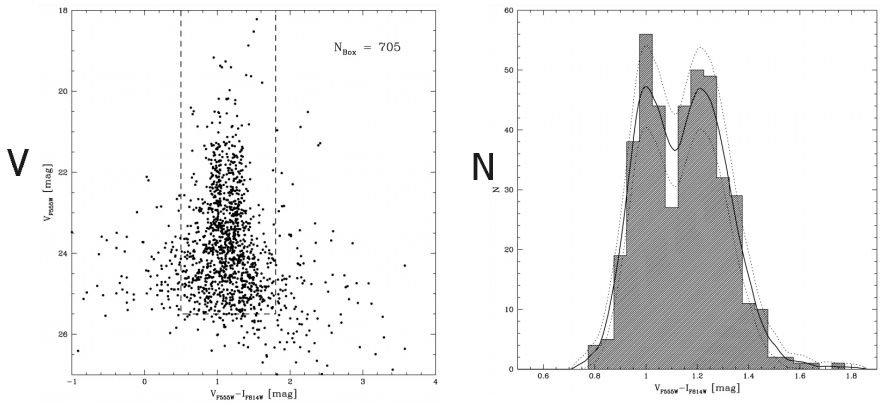
Advantages over galaxy starlight

- GCs are simple stellar populations
  — single age and metallicity
- GCs can be studied out to several R_{eff}
  — probe DM halos/galaxy cluster potential
- Galaxy starlight usually only sampled in center [1 R_{eff}
  — difficult to disentangle different stellar populations
  — recent but unimportant (in mass) star formation episode can dominate

Bimodal Color Distributions

NGC 4472 (M49)

Puzia et al. (1999) AJ

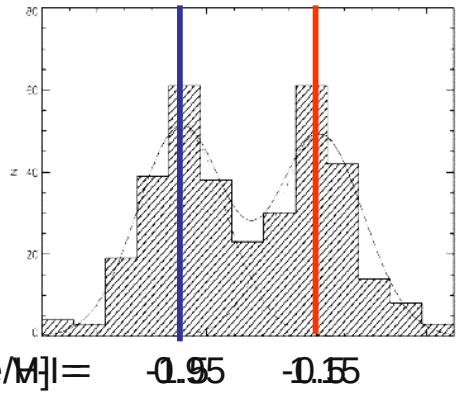


Bimodality: Implications

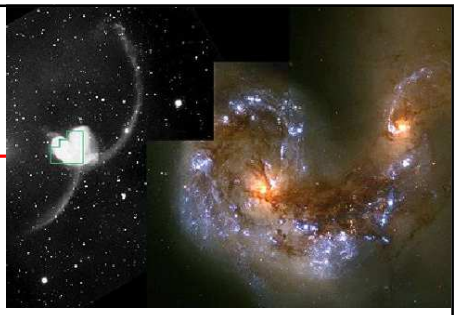
Bimodal color distributions υ
globular cluster sub-populations

Color differences are due to
age differences
and /or
metallicity differences

υ Multiple epochs and/or mechanisms of formation

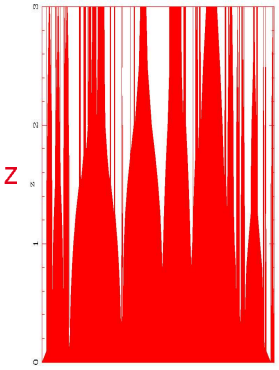


GC/Galaxy Formation Models



1. Formation of ellipticals/GCs in mergers (Schweizer 1987, Ashman & Zepf 1992)
2. In situ/multi-phase collapse (Forbes, Brodie & Grillmair 1997)
3. Accretion/stripping (Cote' et al. 1998)
4. Hierarchical merging (Beasley et al. 2002)

2 & 4 require (temporary) truncation of GC formation at high redshift



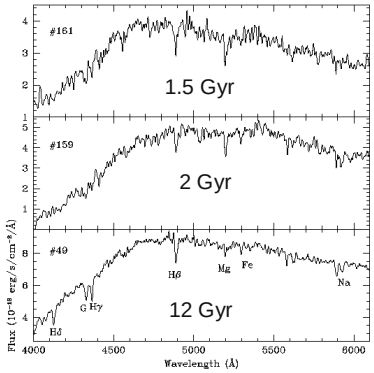
Model Predictions

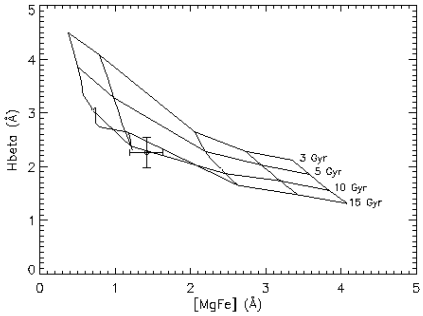
Key properties:

Ages, metallicities, abundance ratios, kinematics, luminosity functions of red and blue sub-pops

- Merger model — τ old population (~age of universe less ~1 Gyr) + young population with age of merger
- Multi-phase collapse — τ 2 old populations one slightly (~2–4 Gyr) younger than other
- Accretion — τ blue and red clusters about the same age
- Hierarchical merging — τ age substructure in red sub-pop + red globulars in low-luminosity field/group ellipticals ~ 2 Gyr younger than in bright cluster ellipticals

How well can we estimate ages?





At distance of Virgo 6 hrs with Keck
- H_β errors: +/- 0.15 – 0.3 Å
- 2 – 4 Gyr at 12 Gyr

Model-dependent absolute ages
Relative ages ~OK

- Models are highly degenerate at low metallicities and old ages
- Cannot distinguish relative ages > 10 Gyr in low metallicty ([Fe/H] – 1) systems
- Caveats BHBs, AGB luminosity function

Examples of Recent Work

- 17 relatively nearby "early-type" (ellipticals, lenticulars) galaxies observed with HST
- Homogeneous deep data set
- Data reach well below GCLF turnover (Is GCLF really universal?)

Larsen, Brodie, Huchra, Forbes & Grillmair (AJ 2001)

Color Histograms

Nearby early-type galaxies

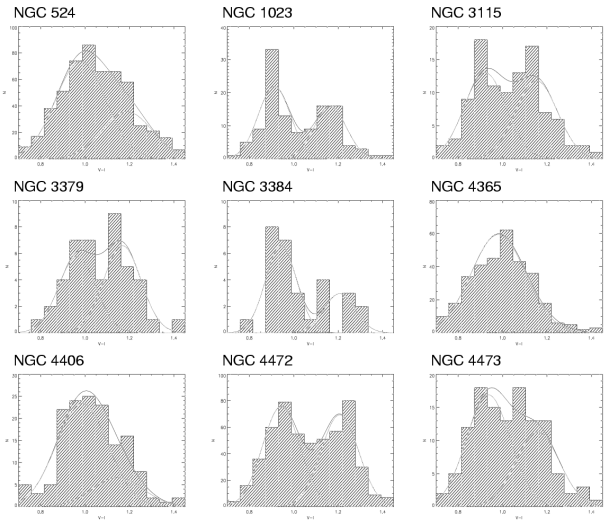
Larsen, Brodie, Huchra, et al (2001)

Kundu & Whitmore (2001)

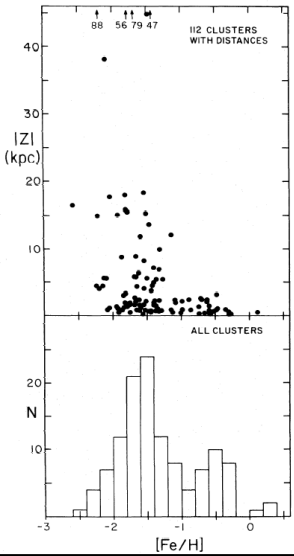
- Average blue peak color $(V-I)_o = 0.95 \pm 0.02$
- Average red peak color $(V-I)_o = 1.18 \pm 0.04$

[Fe/H] = – 1.4, –0.6

(Kissler-Patig, Brodie, Schroder et al. 1998 AJ)



Milky Way



Peaks at

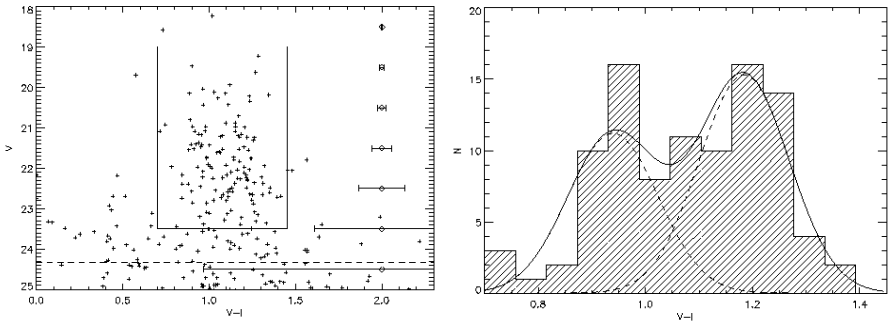
[Fe/H] ~ – 1.5 and – 0.6

(Zinn 1985)

Sombrero

Peaks at $(V-I)_0=0.96$ and 1.21

Larsen, Forbes & Brodie (MNRAS 2001)



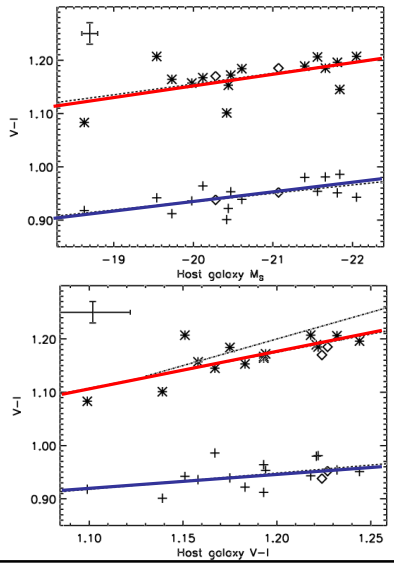
Follow-up spectroscopy at Keck indicates vast majority of GCs (both red and blue) are old (~13 Gyr)

Larsen, Brodie, Forbes (2002)

Correlations with Host Galaxy Properties

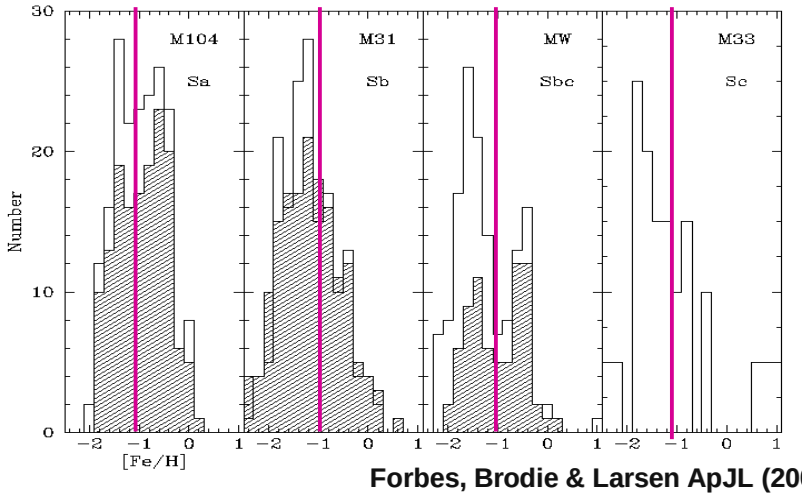
- Colors of *both* reds and blues correlate with galaxy mass (M_B and ρ_o) at the 2–3 ρ level
- 4 ρ correlation between red GC colors and galaxy colors (2 ρ for blues)
- Slope steeper for reds

Larsen et al AJ 2001



Bulge GCs

Number of metal-rich GCs scales with the bulge



Forbes, Brodie & Larsen ApJL (2001)

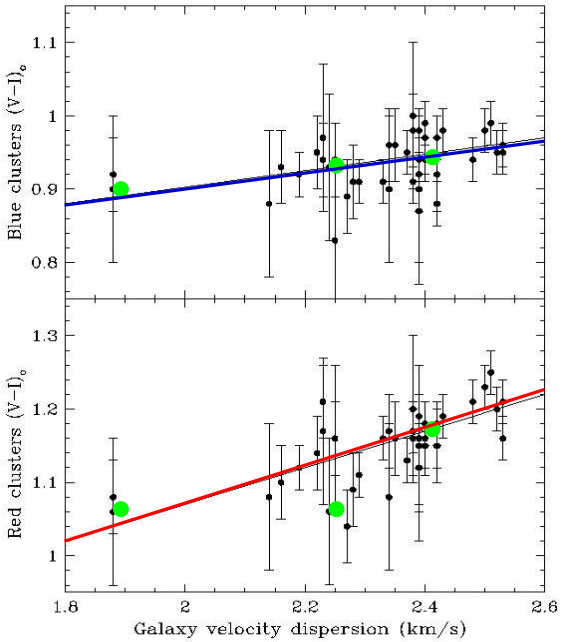
Numbers/Specific Frequency

- Metal-rich GCs in spirals are associated with the bulge not the disk
- The number of bulge GCs scales with bulge luminosity (bulge S_N ~1)
- The total S_N for field ellipticals is 1-3 (Harris 1991)
- The fraction of red GCs in ellipticals is about 0.5
- The bulge S_N for field ellipticals is ~1
- Spirals and field ellipticals have a similar number of metal-rich GCs per unit starlight

Spirals fit the trend

Red GC relation has similar slope to galaxy color relation
Red GCs and galaxy stars formed in the same star formation event

Metal-rich GCs in spirals and ellipticals have the same origin —
they formed along with the bulge stars



Brodie & Huchra 1991; Forbes, Brodie & Grillmair 1997;
Forbes, Larsen & Brodie 2001

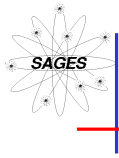
GC Ages

- Increasing evidence that both red and blue globular clusters are very old (>10 Gyr)
- Small percentage of red globular clusters may be young
- Ellipticals/Lenticulars

  NGC 1399 (Kissler-Patig, Brodie, Schroder et al. 1998; Forbes et al 2001)
  M87 (Cohen, Blakeslee & Ryzhov 1998)
  NGC 4472 (Puzia et al 1998; Beasley et al. 2000)
  NGC 1023 (Larsen & Brodie 2002)
  NGC 524 (Beasley et al. 2002)
  NGC 3610 (Strader, Brodie et al. 2003)
  NGC 4365 (Larsen, Brodie et al.2003)

- Spirals

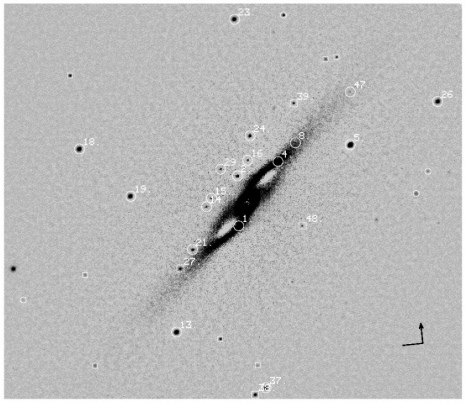
  M 31 (Barmby, Huchra, Brodie et al. 2000)
  M 81 (Schroder, Brodie, Huchra et al. 2001)
  M 104 (Larsen, Brodie, Beasley et al. 2002)

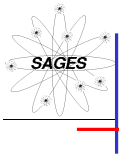


NGC 3610

- Intermediate age (4 Gyr) merger remnant
- Keck spectra of 6 candidate young clusters (+ 2 with bluer colors)
- $3 < R_g < 13$ kpc
  $R_{eff3610} = 2.3$ kpc

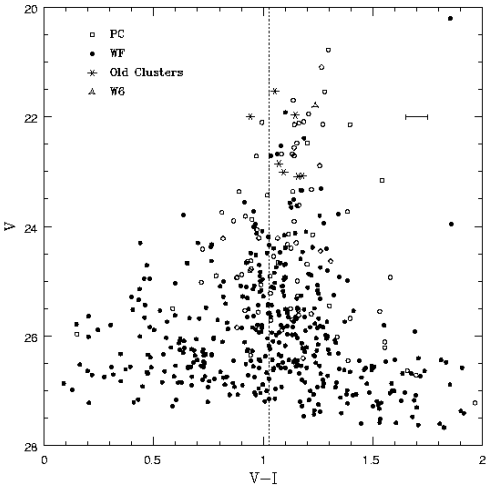
Strader, Brodie, Schweizer et al (2003)





Candidate Selection

Candidate young clusters are brighter and redder than majority of blue objects

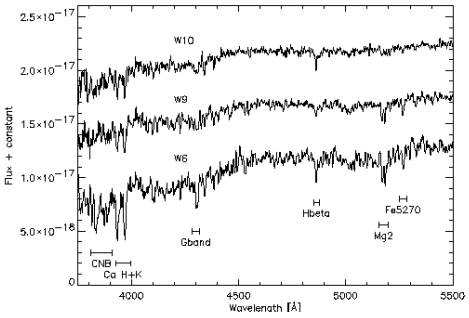


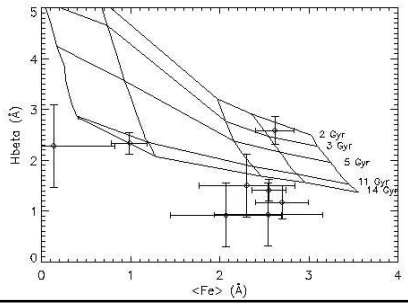
NGC 3610
Spectra + Models

3 distinct sub-groups:

- old and metal-poor
- old and metal-rich
- single metal-rich young (~ 2 – 4 Gyr) cluster!

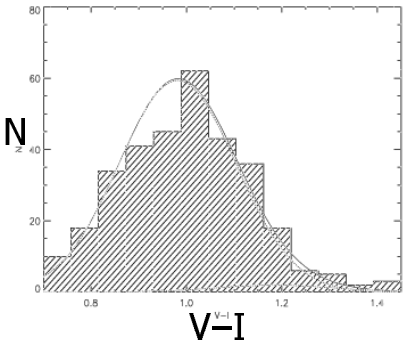
Within errors, all 7 old clusters are coeval



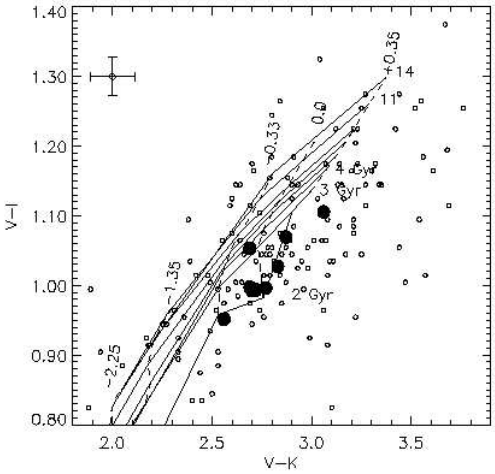


Unimodal color distributions

NGC 4365



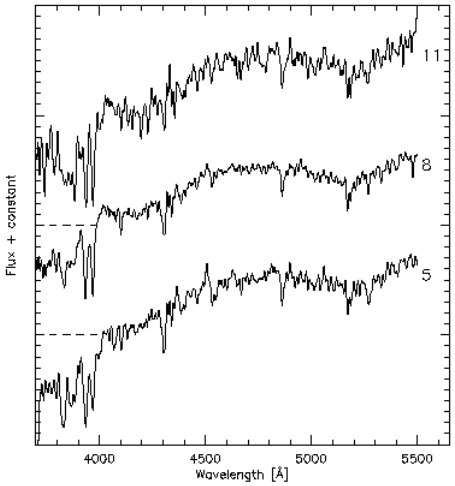
Larsen et al (2001)



Puzia et al (2002)

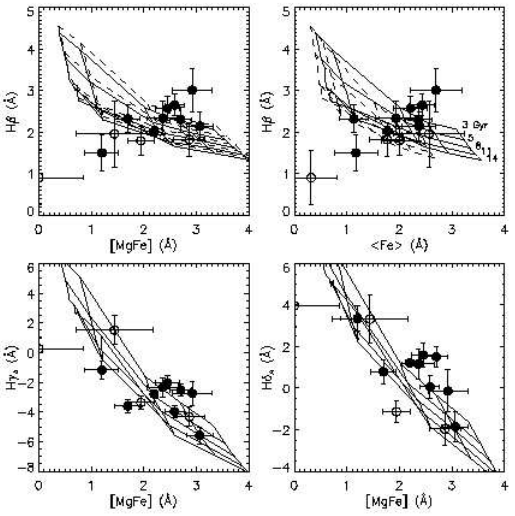
NGC 4365 Spectra

- 14 clusters
- 6.5 hrs with Keck



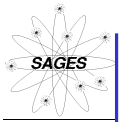
Spectroscopic Ages

- Some, but not all, IR selected clusters are young (2–5 Gyr) and metal-rich (–0.4 [Z/H] 0) rather than old (~10–15 Gyr) and metal-poor
- Ages and metallicities conspire to produce a single broad distribution in the optical



Where are the field stars?

- No signatures of recent mergers
- Luminosity-weighted age of ~ 14 Gyr for stellar population (Davies et al 2001)
- At most 1–5% of mass could be hidden in a 2–5 Gyr field star population
- Estimate (from IR) ~ 25% GCs in inner regions are of intermediate age
- Where is the intermediate age stellar component?



Summary I

Color, luminosity distributions of globular clusters in "nearby" galaxies

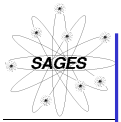
- Two Gaussians almost always preferred over a single Gaussian – peaks always consistent

Multiple epochs/mechanisms of formation universal

Summary II

Correlations with parent galaxy properties

- Correlation between globular cluster colors and host galaxy luminosity (mass) and color for *both* reds and blues
  Both populations "knew" about the size of the final galaxy to which they would belong
  – fragments in which GCs formed at early times were already embedded in dark halos of final galaxy
  – one of few observational constraints on properties of pre-galactic clouds that combined to build galaxies we see today
- Similarities between peak colors in spirals and ellipticals
  Hints at universal GC formation processes



Summary III

- Slope of red GC color vs. galaxy mass relation same as galaxy color vs. galaxy mass relation
  Common chemical enrichment history for metal-rich GCs (in spirals and ellipticals) and the host
- Old ages of both sub-populations
  Inconsistent with late merger picture
  Galaxy assembly happened at high z – rest is just "frosting"
- GCs can form with little associated field star formation (Blue GCs, NGC 4365?)
  Biasing of cluster mass function, connection to SFR?

Conclusions

Our data are best explained by a formation scenario in which the bulk of both globular cluster sub-populations formed at early epochs within the potential well of the protogalaxy in multiple episodes of star formation