An Overview of Globular Clusters and Globular Cluster Systems in Galaxies

Messier 53
HST/STScI image
(NASA/ESA)

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Graduate lecture for P782*, March 2014

Massive (and supermassive) star clusters provide …

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

Fundamental testbeds for evolution of all stars

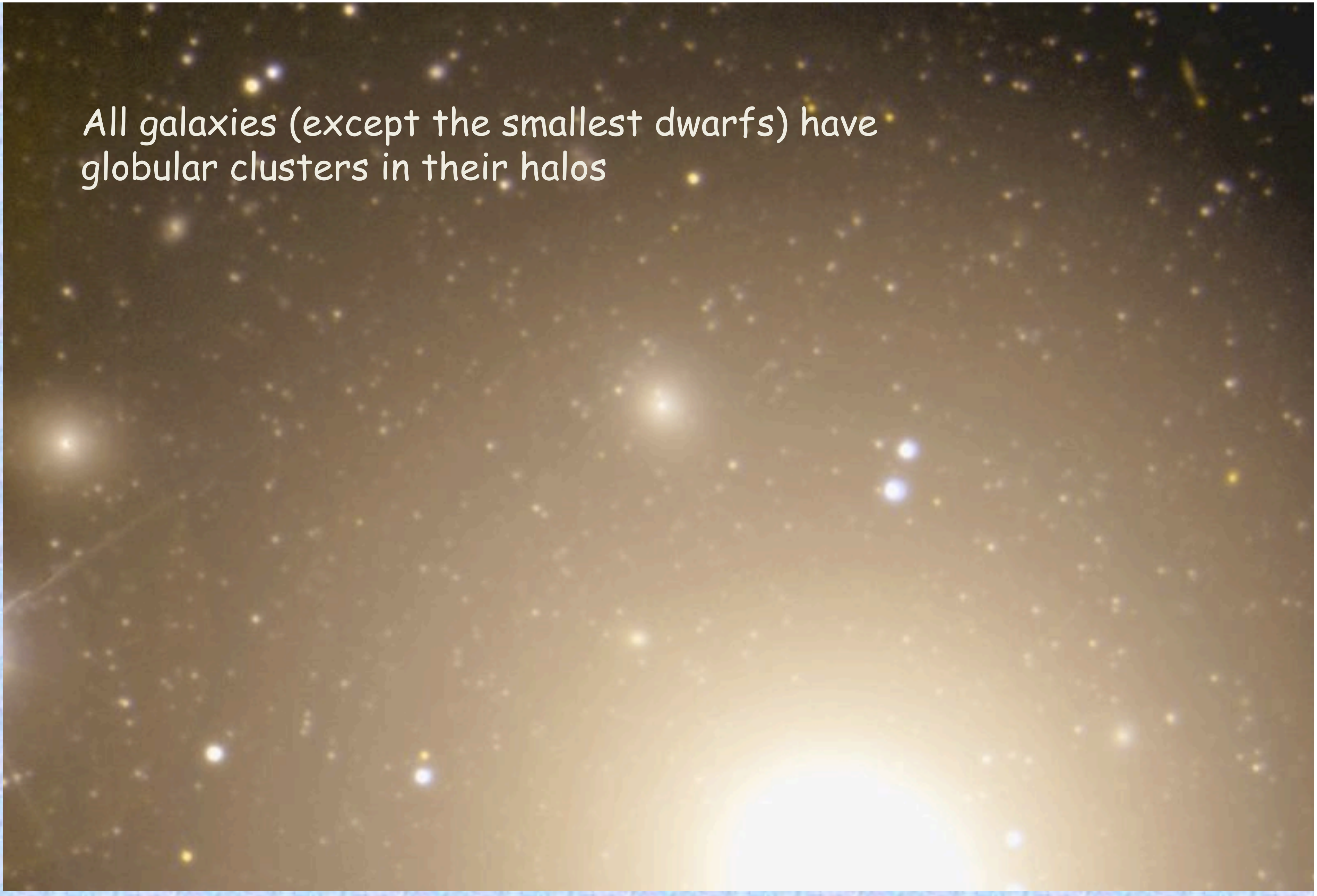
Internal dynamics and mass profile of galaxy's halo --> accurate assessment of dark matter

Unique windows on earliest star formation in galaxies

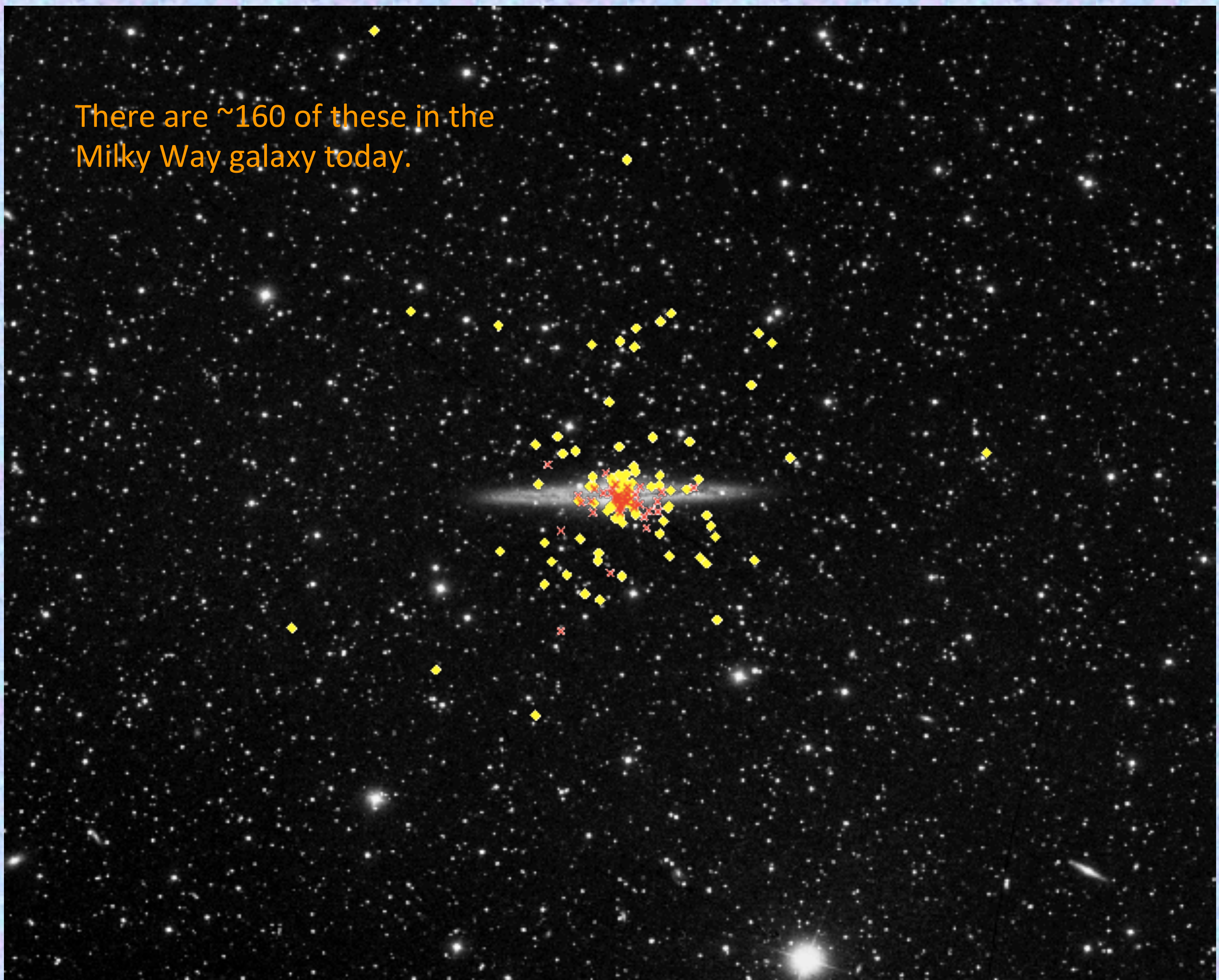
Testbeds for dynamics of high-density N-body systems (N--> 10^7)

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

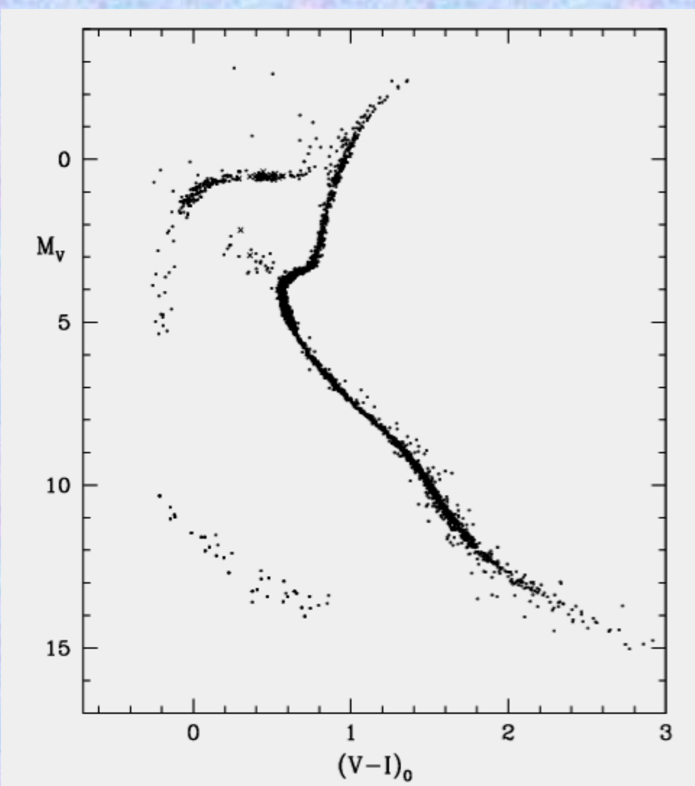
Tests of starburst, merger, and chemical evolution histories of galaxies



NGC 3311, central cD in A1060 (Wehner et al. 2008, ApJ 681, 1233)


There are ~160 of these in the
Milky Way galaxy today.

Ages and Age Distributions



Harris 2003, STScI Symposium Series 14, 78

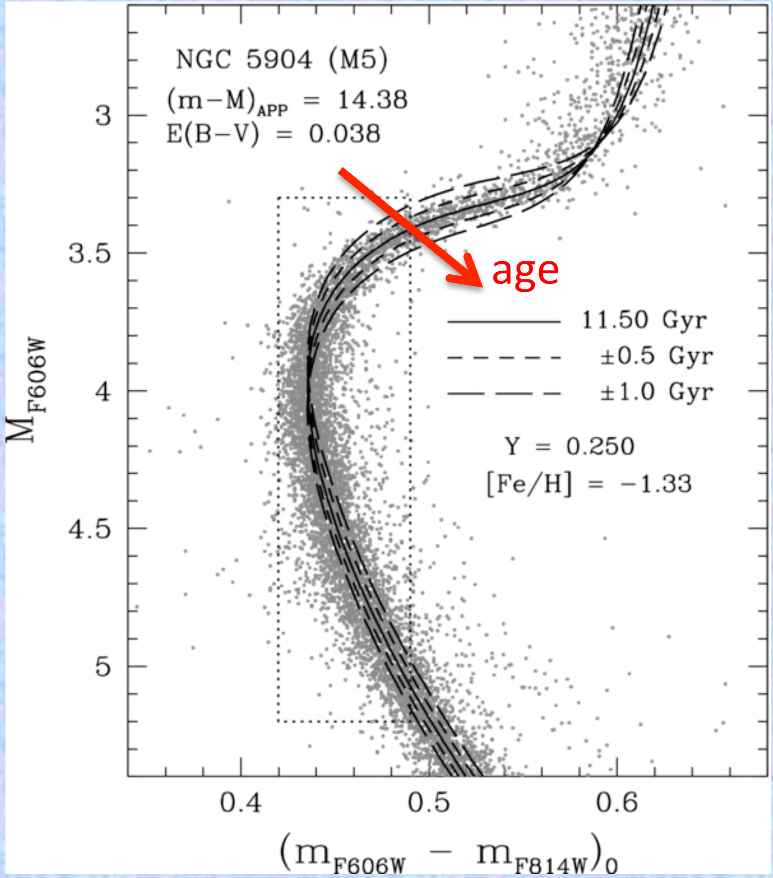
Color-magnitude diagrams are characteristically those of very old systems.

Obvious components present are

- Lower main sequence
- Well defined red-giant branch (shell H-burning)
- Horizontal branch (core He-burning)
- White dwarf cooling sequence
- Asymptotic giant branch AGB (shell He and shell H burning)

Plus trace populations of blue stragglers, neutron stars, possible central black hole

Ages: Isochrone fits in Milky Way GCs
VandenBerg et al. 2013, ApJ 775, 134
Leaman et al. 2013, MNRAS 436, 122

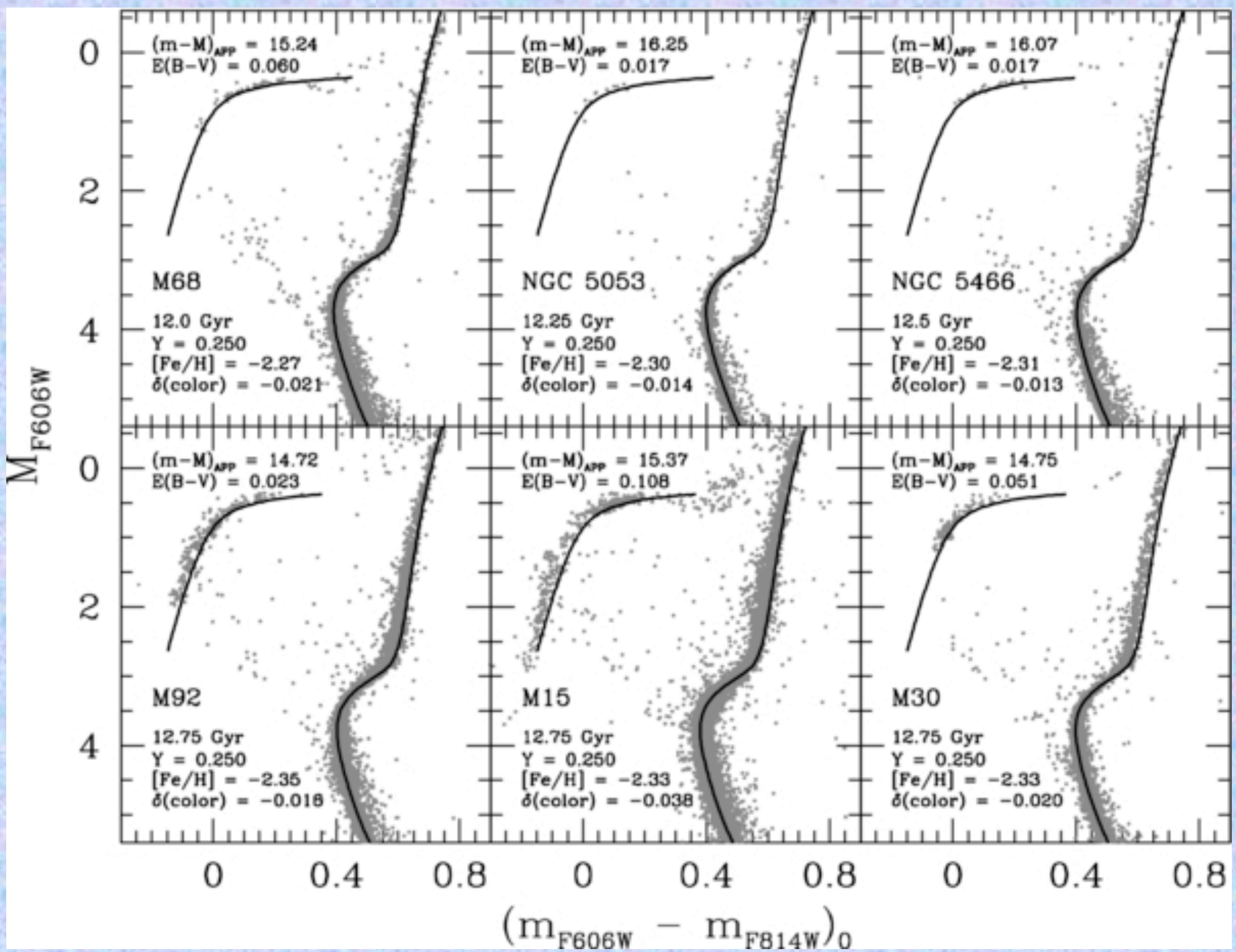


Main-sequence turnoff is main age calibrator but best-fit model should also match the HB and WD sequences for consistency

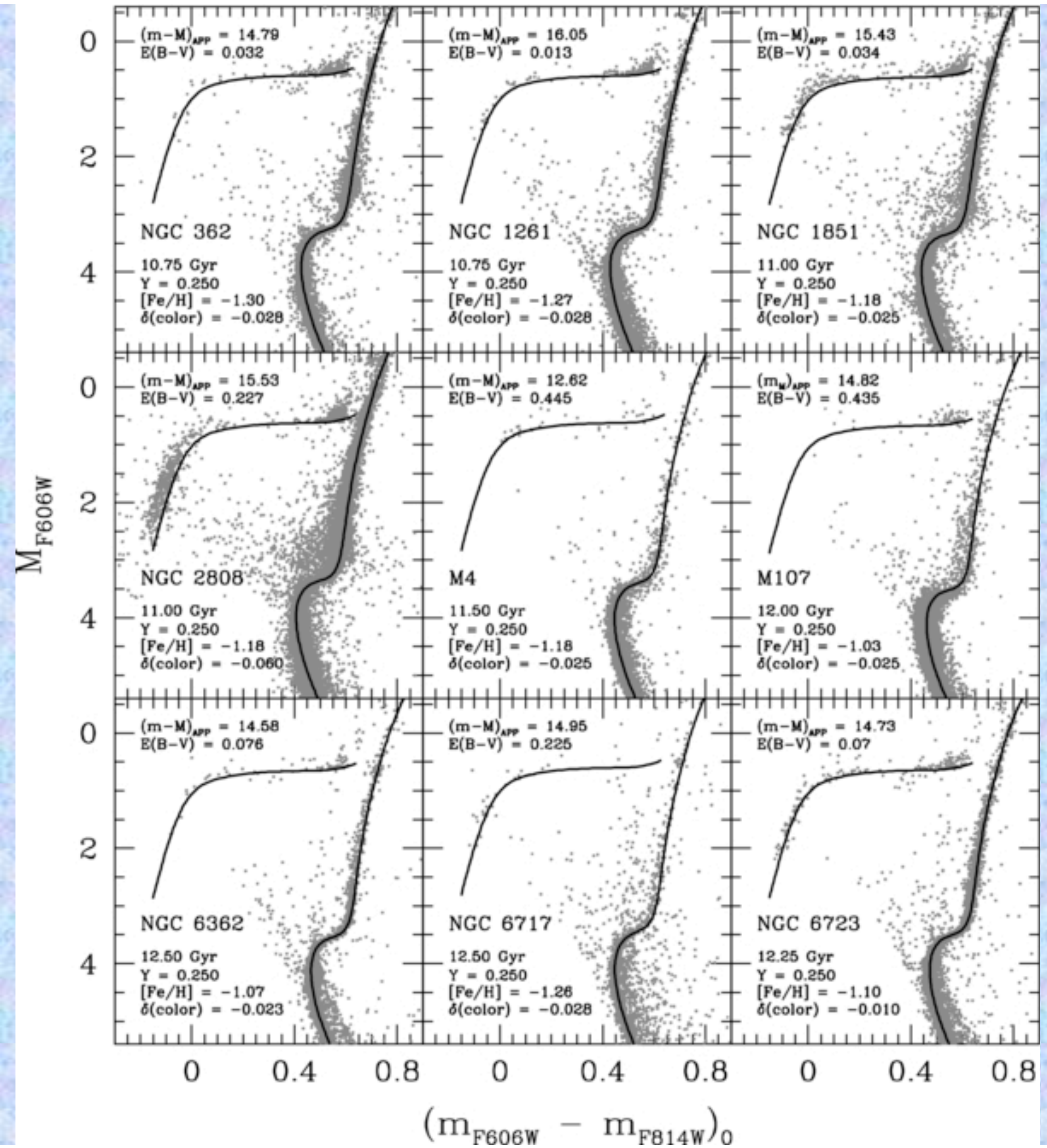
Free parameters for model fitting:

- Age τ
- Metallicity [Fe/H] (but fairly tight limits on this from direct spectroscopy data)
- Alpha-enrichment level [α/Fe] (should be around +0.3 for rapid early formation)
- Assumed distance modulus to cluster
- Plus subtle stellar-structure issues such as opacity, semiconvection, mixing length (and amounts of mass loss for late stages)

Example: fit to Messier 5: moderately low metallicity, age τ = (11.5 +- 0.5) Gy



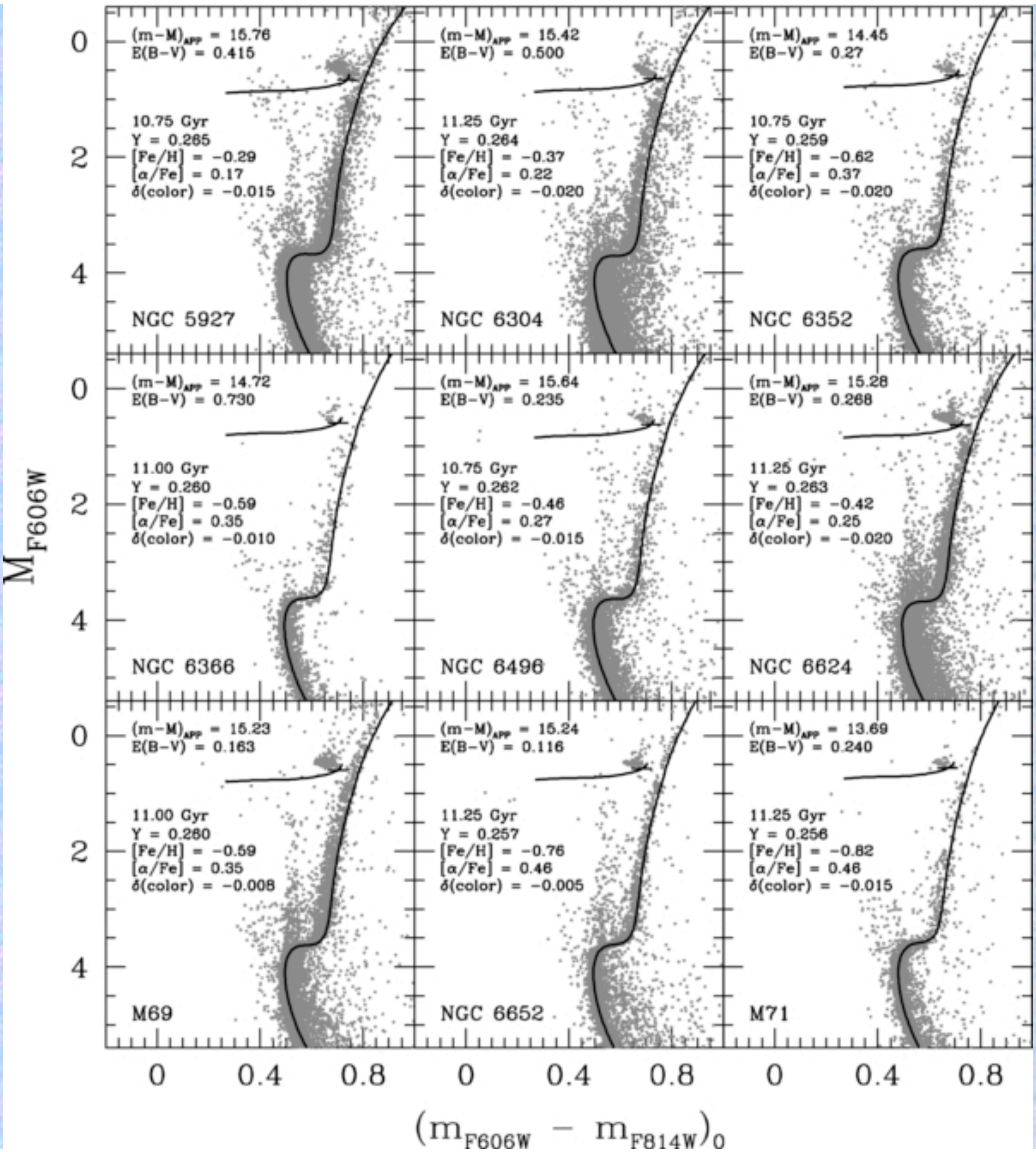
Fits to lowest-metallicity GCs: ages in range 12.0-12.75 Gy.
Note the HB with its blue extension (He-core-burning stars with very small H envelopes) (VandenBerg et al. 2013)



Moderately metal-rich clusters.
Ages in range 10.75 – 12.25 Gy

RGBs are redder because of higher envelope opacity

Note HB differences – can become a "red clump" as [Fe/H] gets progressively higher

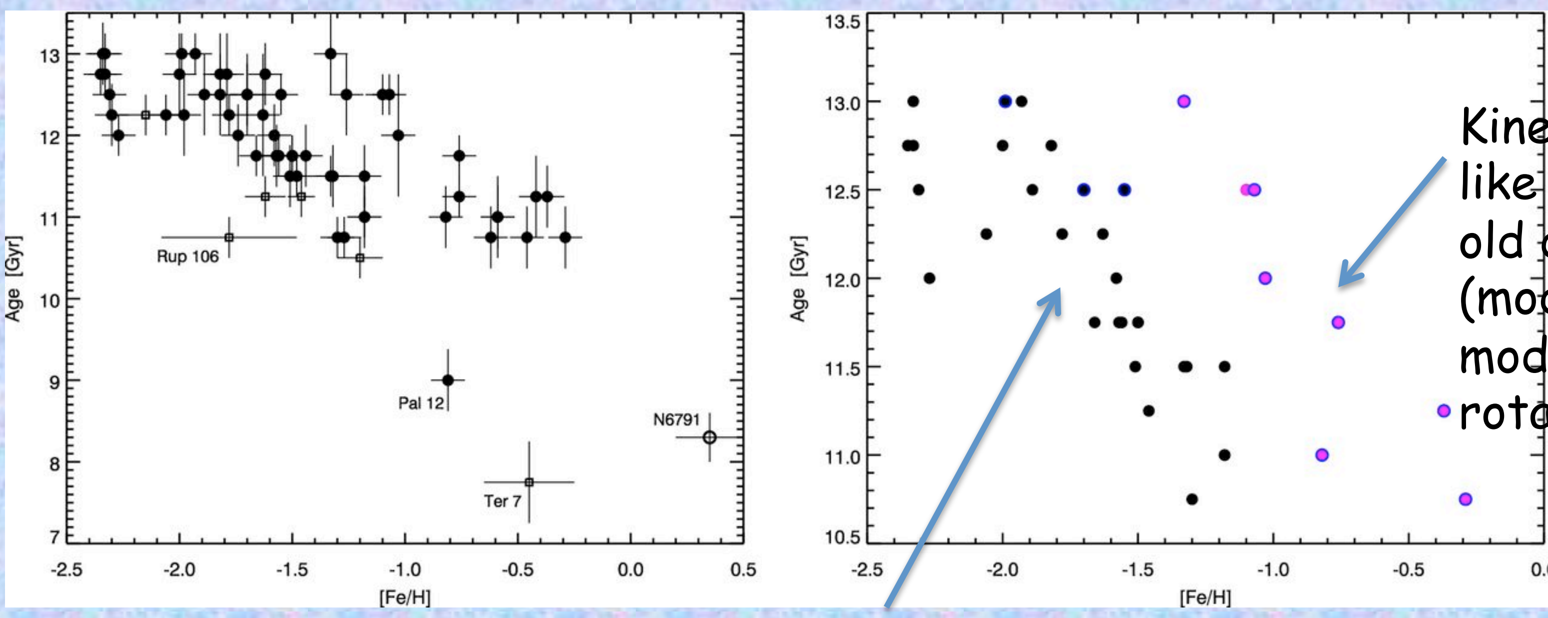


Highest-metallicity clusters.
Ages in range 10.75 – 11.25 Gy

RGBs are even redder

HBs are now all “red clumps”

The raw photometric data here look worse, because these clusters are in the Galactic bulge region – higher reddening, field contamination, and differential reddening



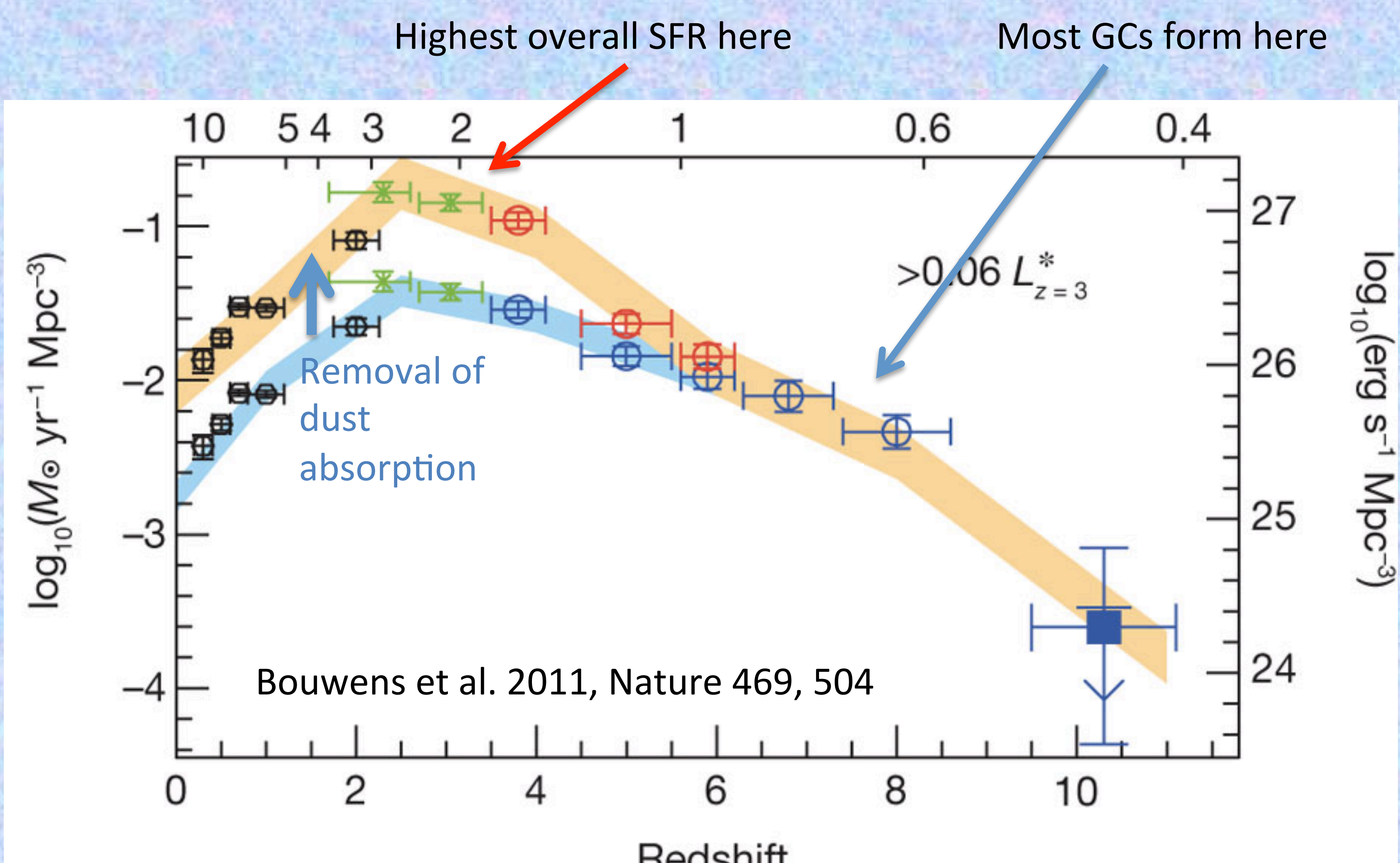
Kinematics ~ like bulge or old disk (moderate σ, moderate rotation)

Kinematics ~ like halo stars (high σ, low systemic rotation)

Age versus metallicity for Milky Way GCs (Leaman et al. 2013)

- Ages from 13.0 to 10.5 Gy → redshift epoch of formation z ~ 8 to 2
- "Bifurcated" age distribution: GCs with space motions similar to bulge or old-disk stars have similar age range as halo GCs, but higher metallicity
- A few younger clusters, ages 7-9 Gy. From accreted satellites?

Cosmic star formation history (Average SFR versus redshift)



Globular cluster formation is generally earlier than most star formation!

Dynamical Evolution

The GC is a thermodynamically "hot" system of N particles: maintains long-term stability against collapse or expansion [well, almost] *by random internal motions balancing gravity*

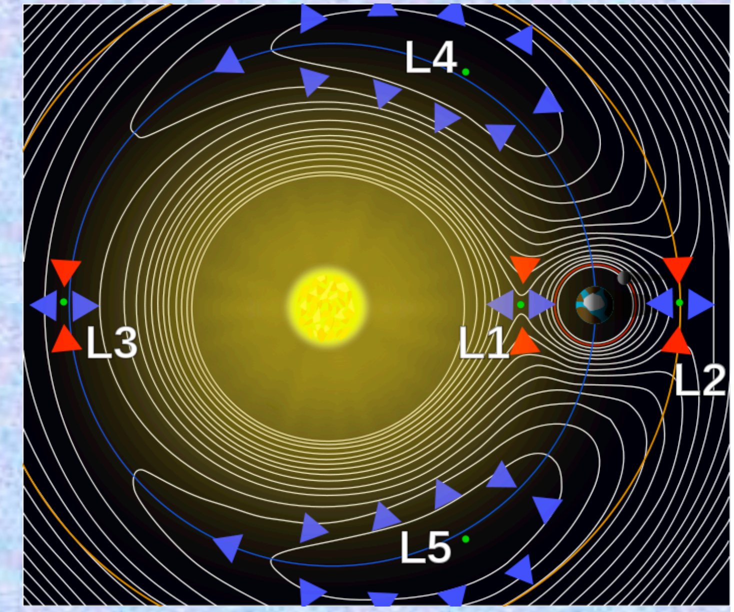
Nearly in virial equilibrium,

$E = U + K$ where $K = - U/2$

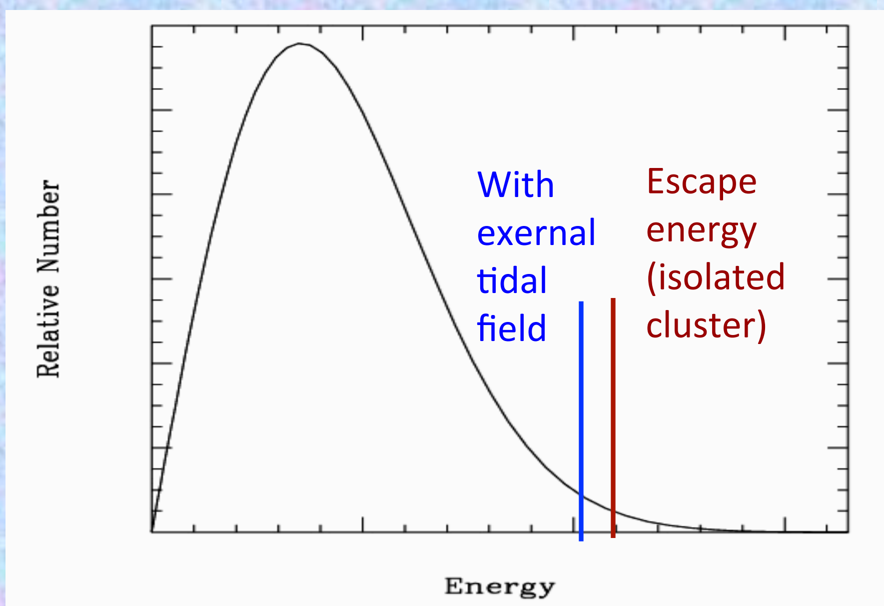
Infinite number of possible equilibrium velocity distributions, thus density profiles

BUT: 2-body interactions (large N!) gradually set up a nearly ideal Maxwellian distribution; relaxation time ~10^8 years

Cluster is also in orbit within a galaxy → must add in external potential of galaxy



Hill sphere (diagram from Wikipedia)

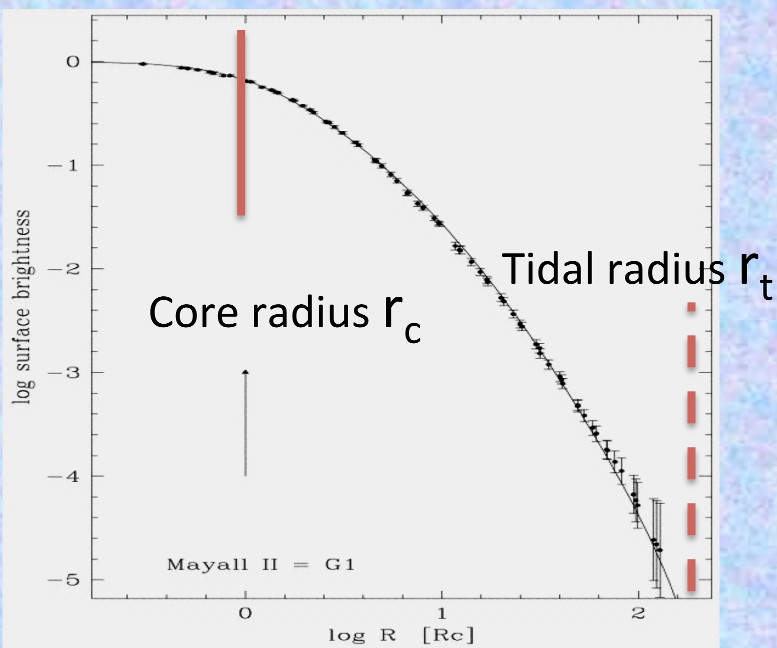


A cluster in isolation will have an escape energy = 6 times the Maxwell peak energy.

Addition of the surrounding galactic tidal field lowers the effective escape energy and speeds up dynamical evolution

$$\rho(r) = \int f(r,v) \cdot 4\pi v^2 \, dv$$

Convert particle energy distribution to a density profile (then project from 3D to 2D to match observations)



M31-G1: Meylan et al. 2001, AJ 122, 830

Binding energy held by the cluster: KE + grav. PE

$$E_b = f(c)\,\frac{GM^2}{R}$$

Distribution of mass inside the system ["central concentration" factor $c = \log(r_t/r_c)$]

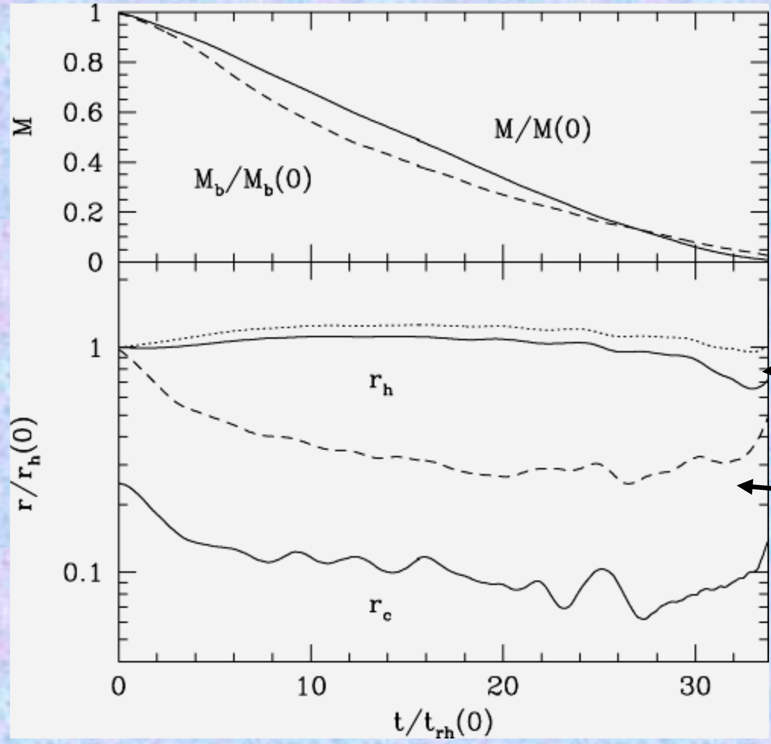
Uniform sphere + virial theorem

$$E_b = -(U+K) = \frac{3}{5}\frac{GM^2}{R} - \frac{1}{2}U = 0.3\frac{GM^2}{R}$$

Integration of King model profile leads to

$$E_b \cong 0.17\left(\frac{4\pi}{9}\right)\frac{GM^2}{r_h} = 0.24\,\frac{GM^2}{r_h}$$

'Half-mass" or effective radius r_h enclosing half the cluster mass



Nearly linear mass loss with time. Stars continue to leak away … and the central concentration steadily increases as massive stars drift inward (mass segregation)

Single stars: slow change in the "half-mass" radius r_h

Binaries!

Trenti, Heggie & Hut 2007, MNRAS 374, 344 (typical N-body integrations)

(Analogy: imagine a large city where people gradually move out to the country, but no one moves back in, and the remaining people move closer to city center)

Continual dynamical evolution will lead to *runaway core collapse*

What will happen then? Physical collisions between stars? Central cluster of neutron stars? Black hole formation?

LOOMING DISASTER?

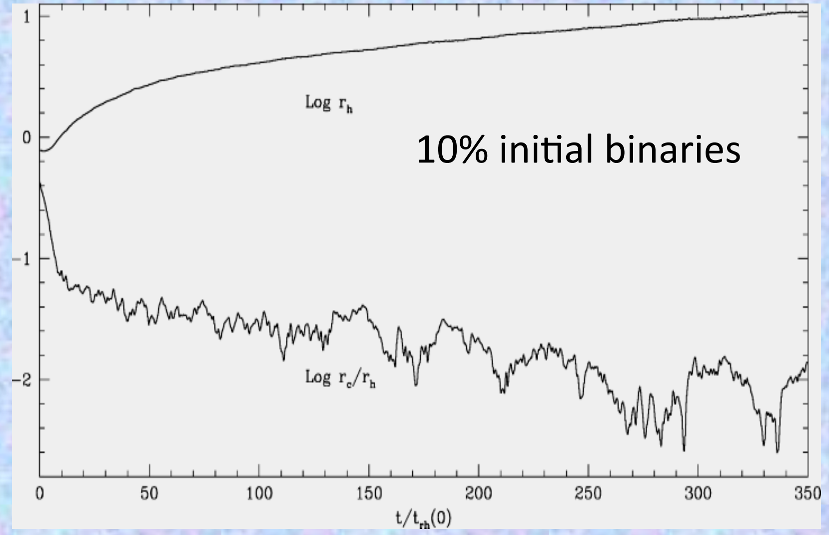
Hénon, M. 1961, *Sur L'Évolution Dynamique des Amas Globulaire* (Annales d' Astrophysique 24, 369)

Successfully predicts that the central density becomes infinite *in a finite time.*

Left as a puzzle for many years.

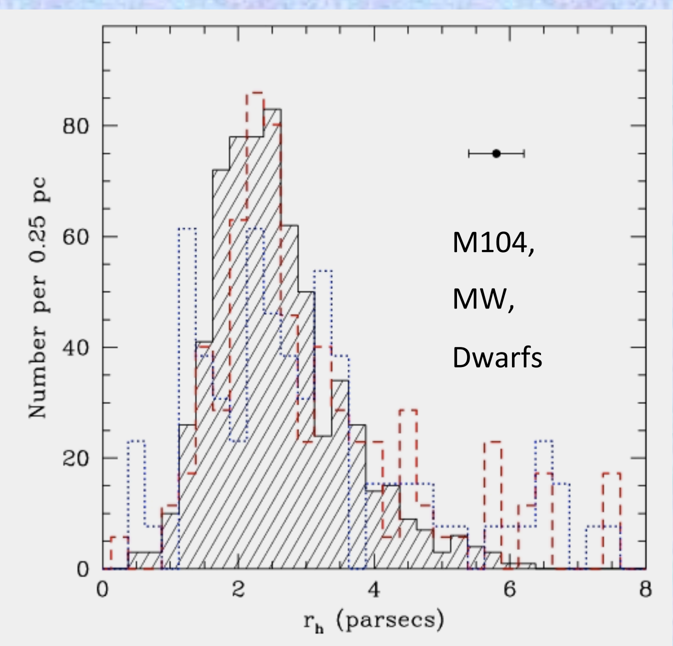
Binary stars will halt (and reverse!) the core collapse (Hills 1975; Heggie 1979), which would nominally happen after ~20 relaxation times t_{rh}. Binaries will be made during core collapse even if none are present initially

Core "bounces" and oscillates, or even avoids core collapse entirely



Heggie, Trenti, & Hut 2006, MNRAS 368, 677

The size distribution for GCs: how big, and why?



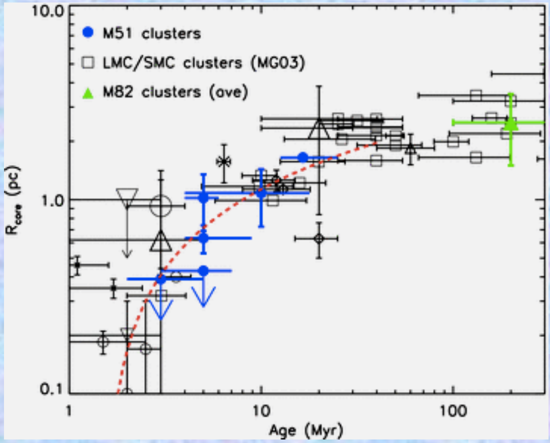
Harris et al. 2010, MNRAS 401, 1965

Remarkably similar in all galaxies --> *environment plays a minor role.* So then, what *local* conditions determine this distribution?

There are two phases of rapid structural evolution:

- *Core collapse*

- *Protocluster epoch* with star formation and rapid gaseous mass loss (~40 Myr)

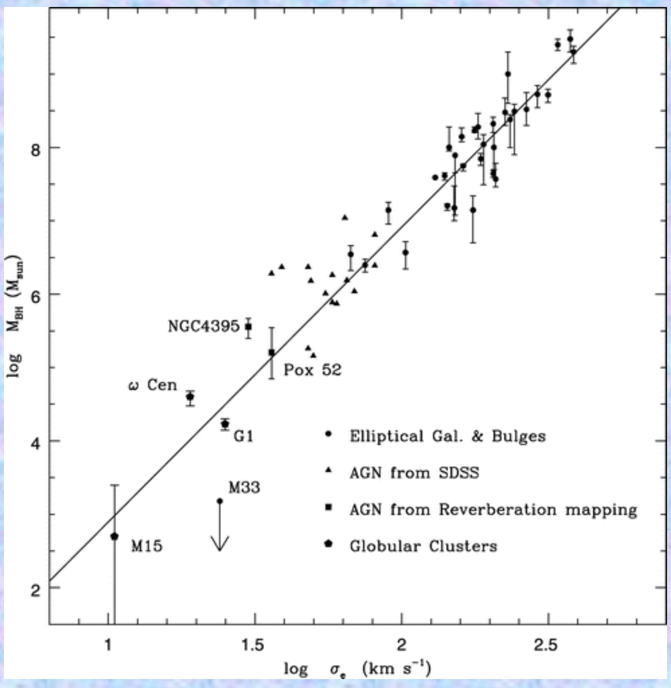


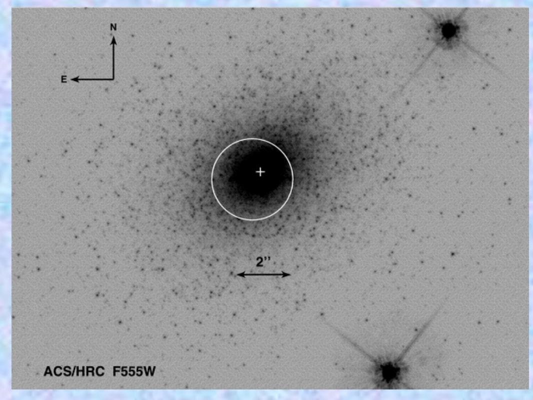
Protoclusters start with scale sizes < 1 pc and expand as they lose ~70% of their initial gas mass to winds and SNe

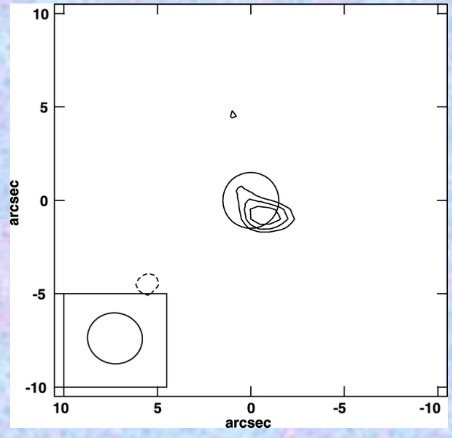
Bastian et al. 2008, MNRAS 389, 223

Black holes are still in the picture.

Extrapolation of central BH masses in galaxies down to a lower-mass regime (M_{BH} vs. σ) suggests GCs may have central black holes of ~10^3-10^4 M(Sun), called *intermediate-mass black holes* (IMBH). These may provide the seed black holes for buildup of SMBH at centers of large galaxies







M31-G1 is most massive GC in the Local Group galaxies. Evidence favoring an IMBH is presence of small radio and soft X-ray source at its center, consistent with a bit of gas flowing into a BH

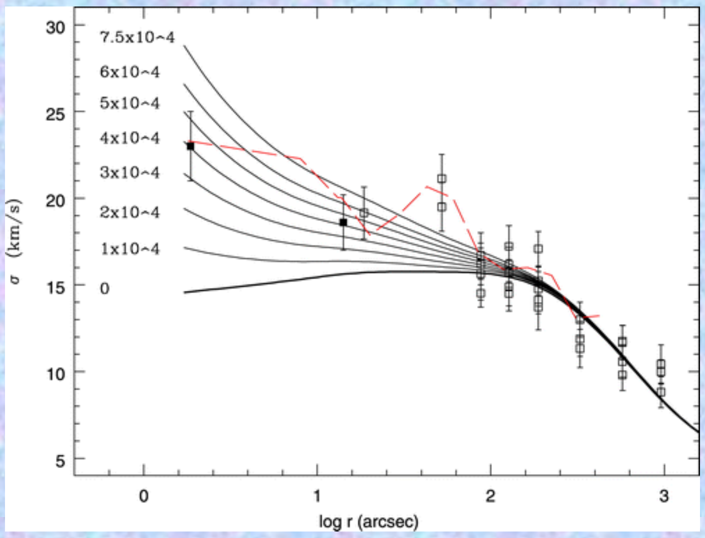
Gebhardt, Rich & Ho 2005, ApJ 634, 1093

Ulvestad, Greene & Ho 2007, ApJ 661, L151

Kong 2007, ApJ 661, 875

IMBH mass should be measurable by central rise in stellar velocity dispersion σ (due to King-model potential + central point mass).

In practice, the problem is the small IMBH *sphere of influence* R_0. Outside R_0, the orbital speed around the BH is less than the random velocity dispersion σ of the surrounding stars



ω Centauri (Noyola et al. 2008, ApJ 686, 1008)

$$\text{Orbital speed} \quad v = \sqrt{\frac{G\,M_{IMBH}}{R}}$$

$$\Rightarrow \quad R_0 = \frac{G\,M_{IMBH}}{\sigma^2}$$

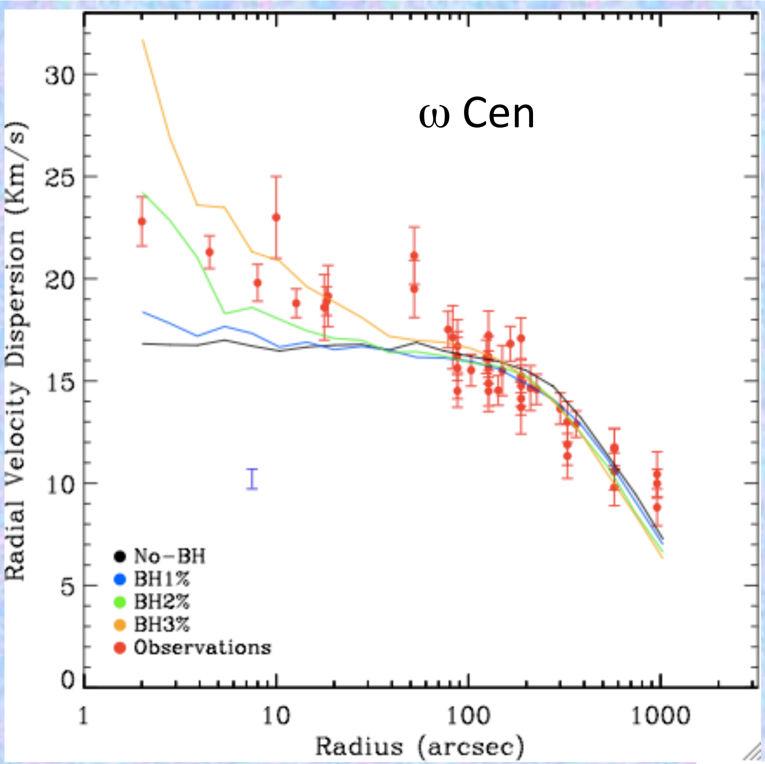
If M(IMBH) ~ 10^4 M(Sun)

And σ ~ 15 km/s

→ R_0 = 0.19 parsec = 39,000 AU

~ 4 arcsec if d=10 kpc

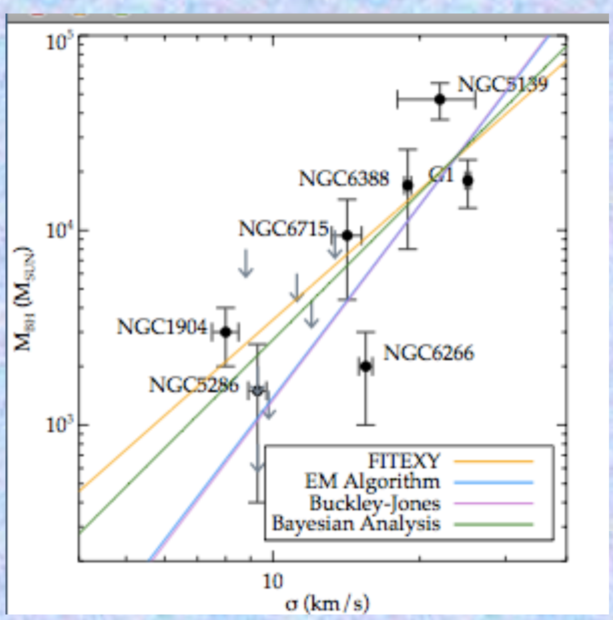
Very difficult to find unambiguously.
Requires careful modelling of $\sigma(r)$

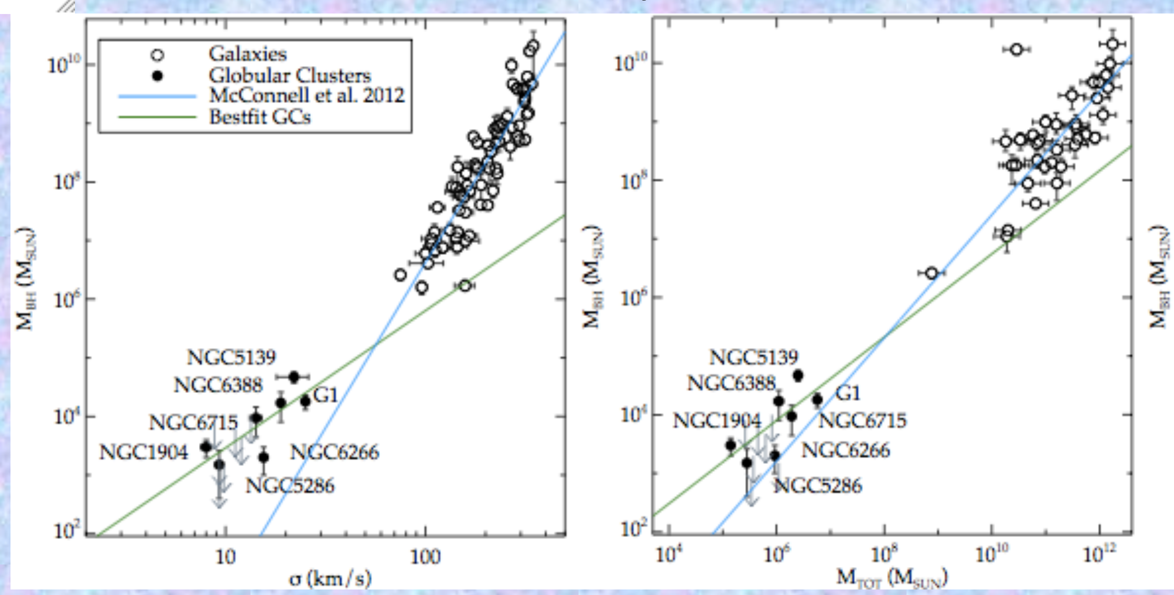


Jalali et al. 2012, AAp 538, A19

M(BH) = 50,000 M(Sun) for ω Centauri
(the biggest IMBH known among GCs)

Lutzgendorf et al. 2013, AAp 555, A26
Combined results for 14 clusters: scaling relation M(BH) ~ M(sys) OK?



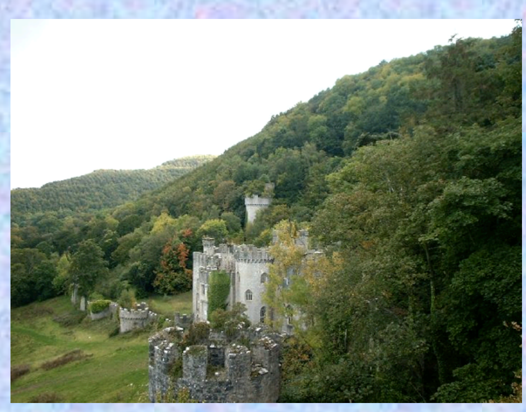


GC Dynamical evolution?

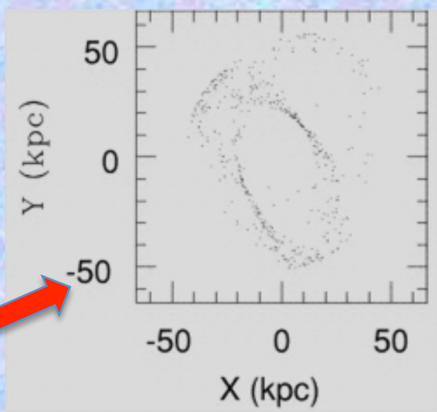
M80 (NASA Hubble Heritage image)

Dynamical age

Palomar 13 (Siegel et al. 2002, Las Campanas)



Johnston et al. 2002, ApJ 570, 656

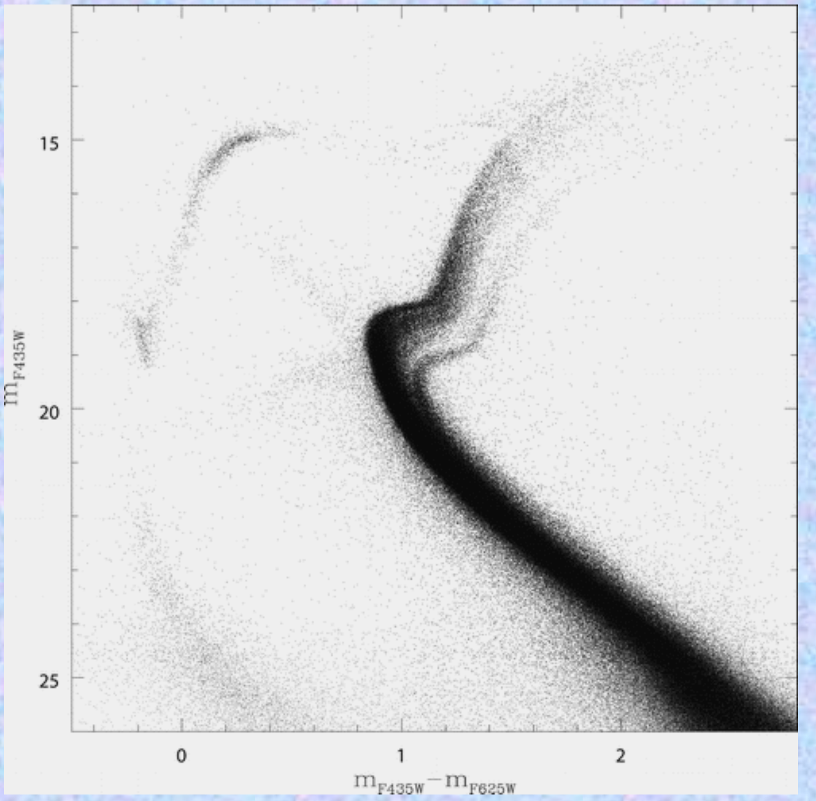


Is much of the halo assembled this way by satellite accretion?

Multiple sub-populations of stars inside GCs:

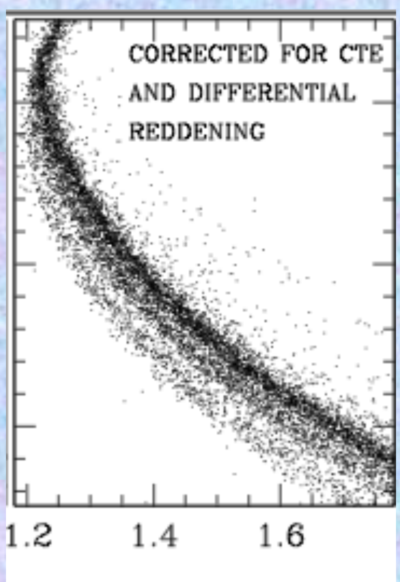
Traditionally thought that all stars in a cluster were the same age and metallicity (though must be an approximation at some level)

New precise CMD photometry reveals at least some have multiple sequences → differing age or metallicity (or both?)



Villanova et al. 2007, ApJ 663, 296
Bedin et al. 2004, ApJ 605, L125

ω Centauri: 4 subgiant and giant branches and split main sequence: both Z and Helium differences?



Milone et al. 2012, AAp 537, A77
Triple main sequence in NGC 2808

Now let's look at GCs in other galaxies.

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

NGC 3311, d = 50 Mpc

GCs are unresolved (starlike) for

D > 15 Mpc (ground-based)

D > 60 Mpc (HST)

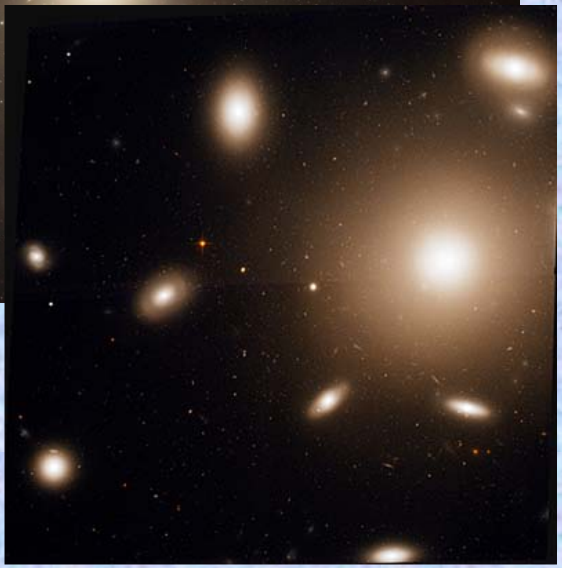
Visible as a statistical excess of point sources spatially concentrated around the host galaxy.

Gemini-S + GMOS imager (Wehner et al. 2008, ApJ 681, 1233)

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

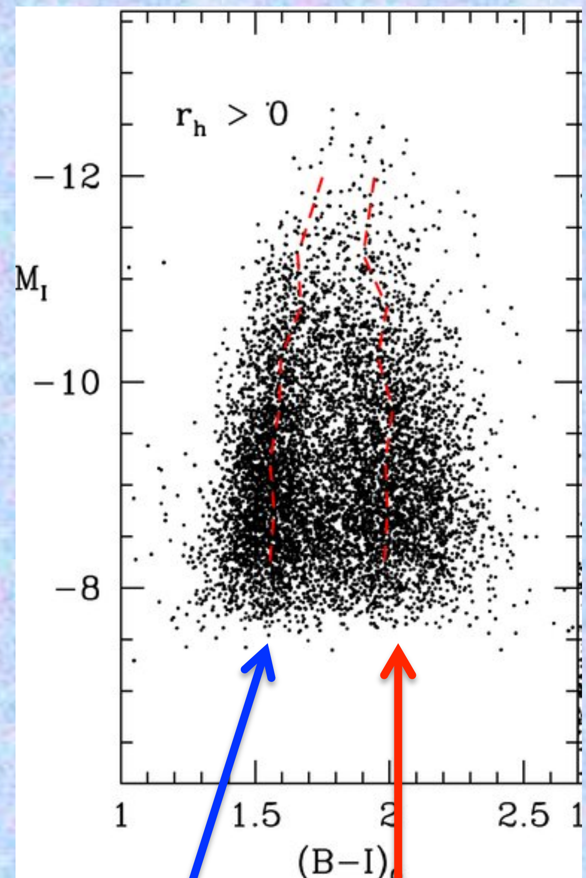
M87 (Virgo cD supergiant, d=16 Mpc) has ~13,000



NGC 4874 (Coma cluster cD, d=100 Mpc) has > 30,000

What is measurable?

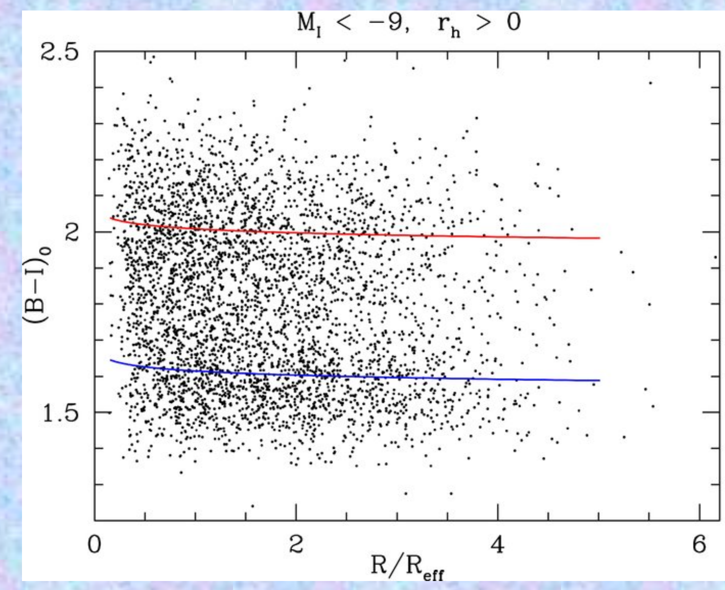
- **Luminosities** (absolute magnitudes – treat each GC as one object and measure its total brightness)
- **Color indices** – ratio of luminosities in different filters
- If D <~ 15 Mpc: can do spectroscopy → get **velocities and mean metallicities**
- **Spatial distributions** (thus, structure of halo)
- **Total numbers** of GCs



"Blue" and "Red" sequences
(would be more accurate to call them "yellow" and "orange")

Bimodality in cluster color distribution
Immediate impression from color/magnitude diagram; *universal, major feature*

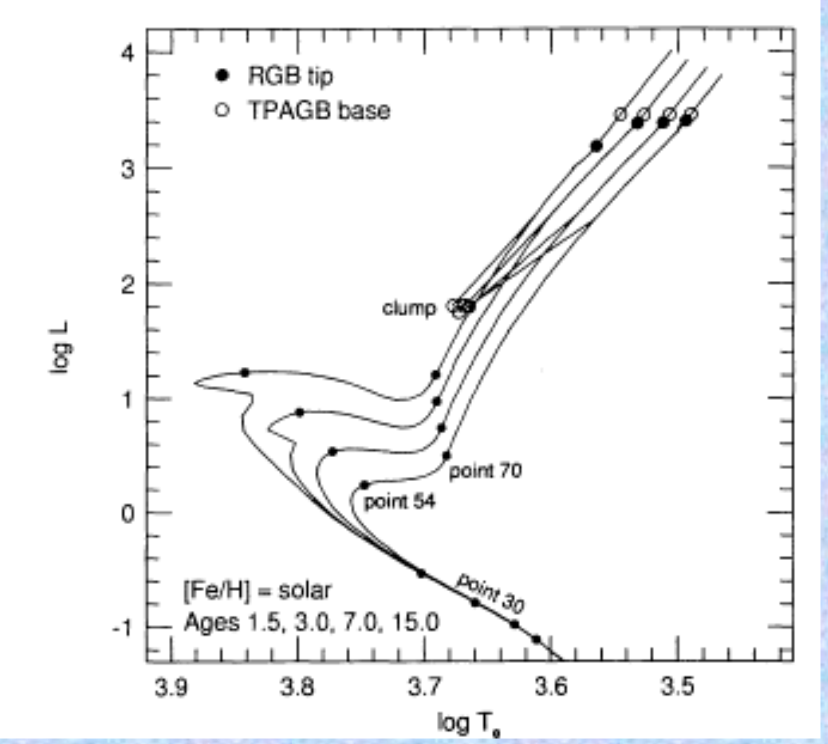
Weak metallicity gradients with galactocentric distance, $\langle Fe/H \rangle \sim R^{-0.1}$



Sequences correspond to mean $\langle Fe/H \rangle \sim -1.5$ (blue), -0.5 (red)
(weak functions of galaxy luminosity)

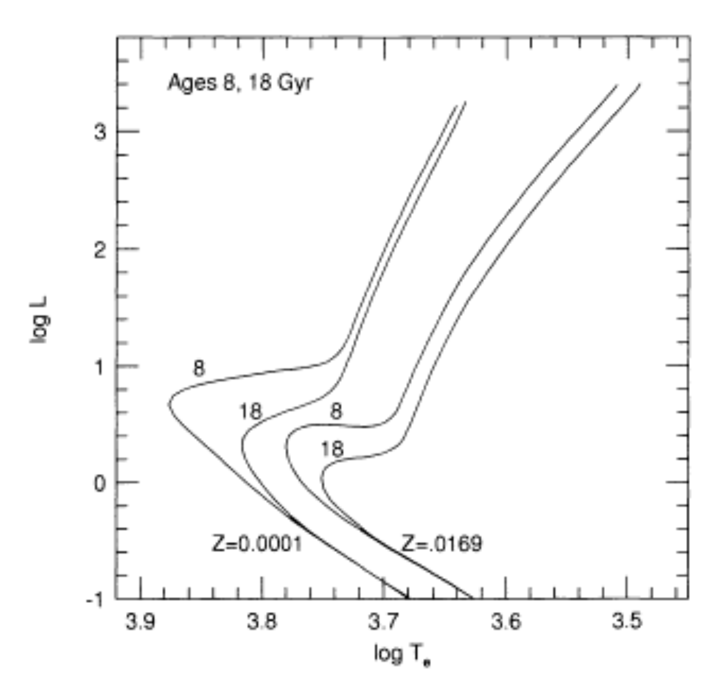
Composite data from 6 BCGs (Harris 2009, ApJ 699, 254)

Cluster luminosity obviously represents cluster mass
Why does color represent metallicity?



Integrated color is the luminosity-weighted average color of all the stars in the cluster. Most of the light comes from the giant and subgiant stars, so their color is what counts.

Increased age makes the RGB redder, but as long as τ > 2 Gy it's a small effect

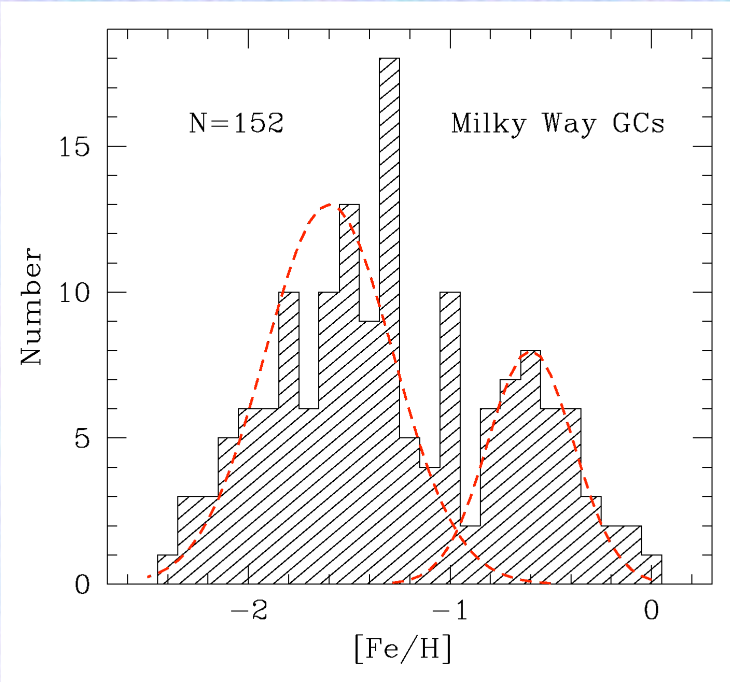


Worthey 1994, ApJS 95, 107 isochrones

However, increased metallicity has a big effect on the isochrone color. (Due to higher envelope opacity in the RGB stars.)

Does bimodality in color imply bimodality in metallicity (heavy-element abundance)? Important question.

Depends on transformation of color index ←→ metallicity



Data from Milky Way GC catalog (2010 edition of Harris 1996, AJ 112, 1487)

Milky Way: [Fe/H] values from high-dispersion spectroscopy of individual cluster stars (i.e., as good as it gets) → bimodality emerges (within statistical scatter)

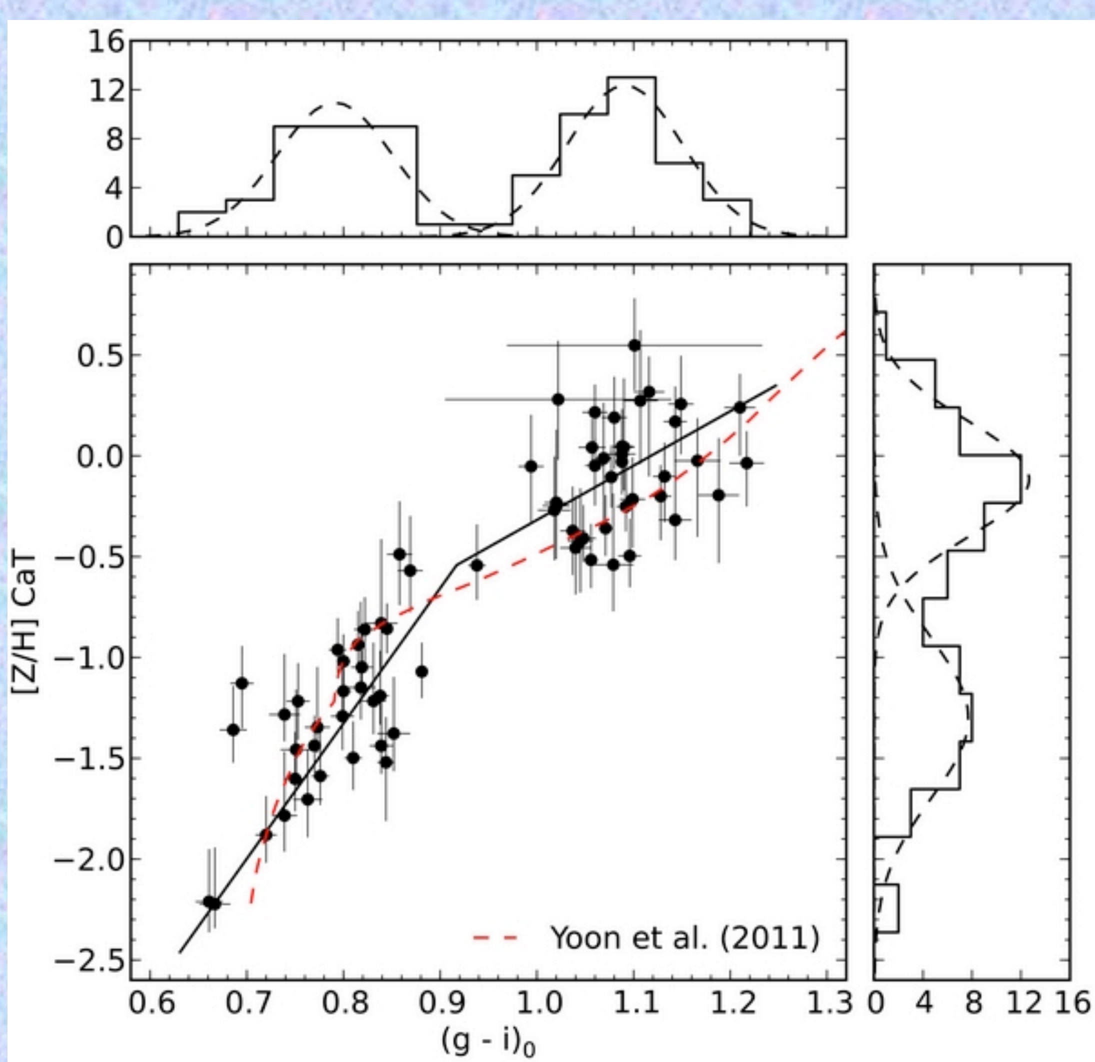
For more remote galaxies, spectroscopy is harder, but [Fe/H] measures based on integrated-light spectral features are available for several systems including M31, NGC 5128, M104, M49: bimodality is common

NB: no actual "gap"; two modes overlap

Usher et al. 2012, MNRAS 426, 1475
Woodley et al. 2010, ApJ 708, 1335

Brodie et al. 2012, ApJ 759, L33
Caldwell et al. 2011, AJ 141, 61

An example for NGC 3115 (large S0 at d ~ 10 Mpc)



Calcium-triplet (CaT) line strengths transform linearly to [Fe/H].

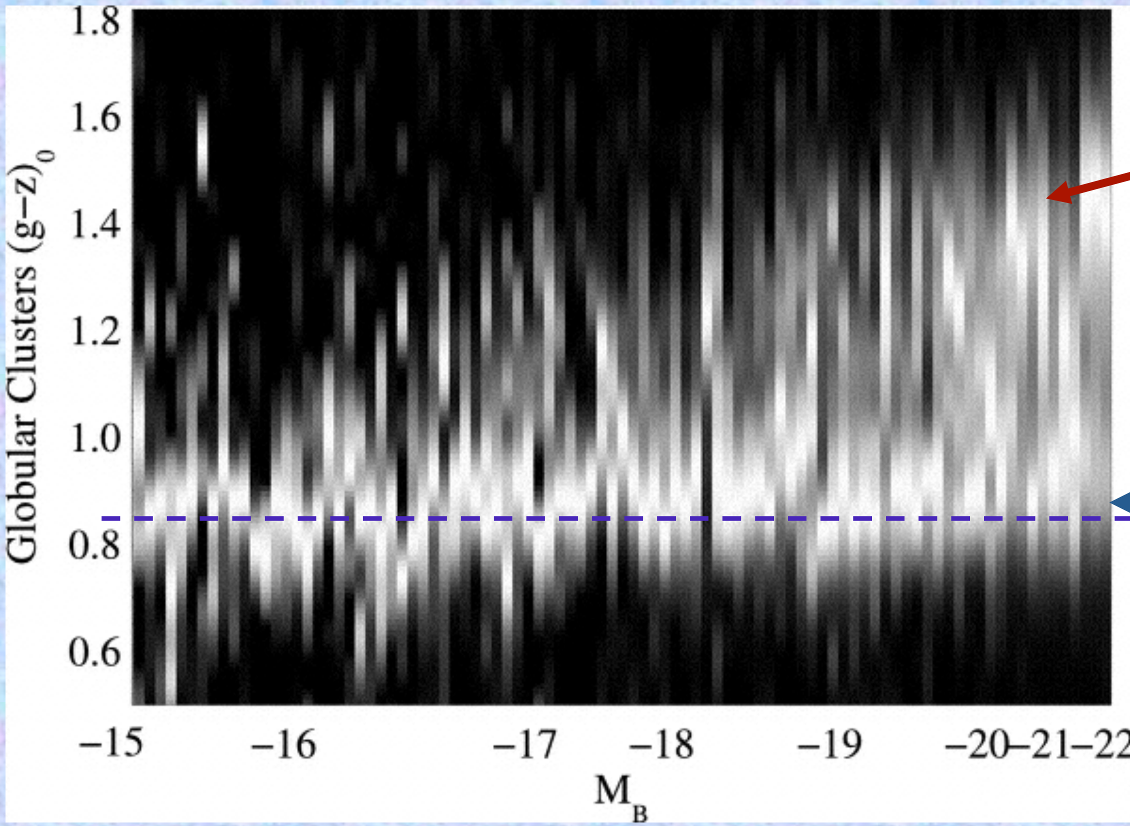
Transformation of color index (here, (g-i)) may be nonlinear, but distribution is still bimodal in both color and metallicity

(NB: *all* color indices increase *monotonically* with metallicity)

Brodie et al. 2012, ApJ 759, L33

Correlations with host galaxy size

(Peng et al. 2006, ApJ 639, 95 from Virgo Cluster Survey)



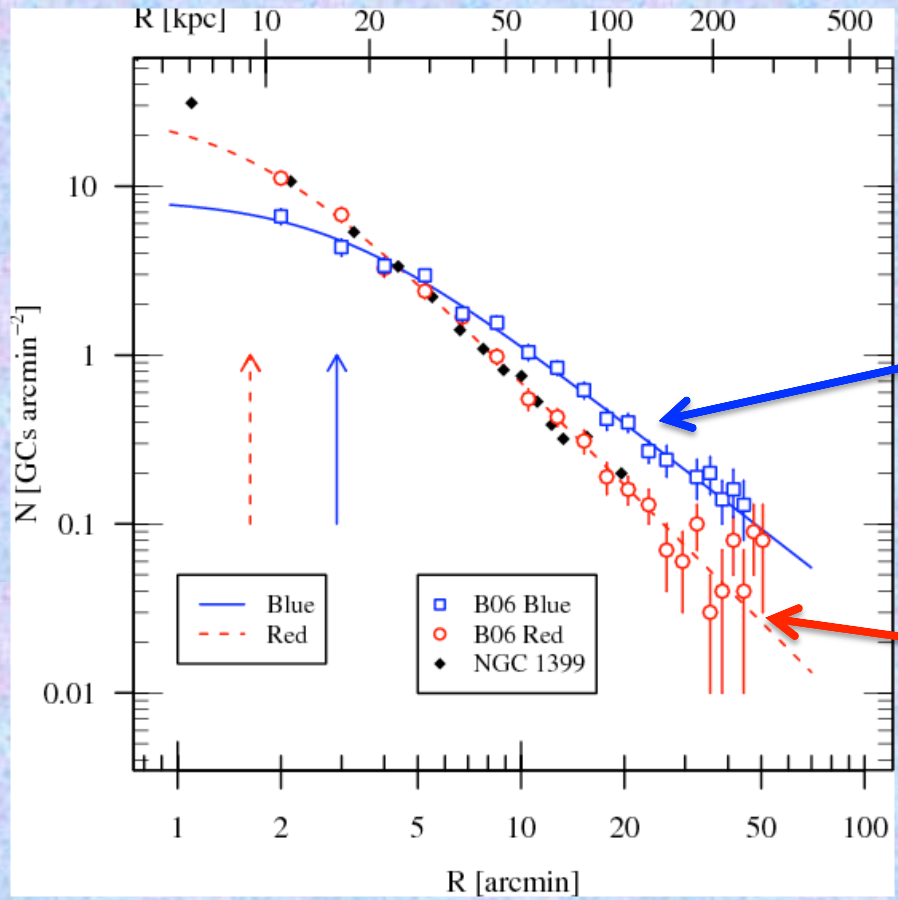
Redder clusters (metal richer) more frequent in bigger galaxies

Blue sequence (metal poor) is always present and has nearly uniform metallicity

Dwarfs: N(red) ~ 0 Giants: N(red) ~ N(blue)

Higher enrichment levels are achievable with lots of gas in bigger, deeper potential wells. → suggestion: redder clusters form later, after initial enrichment has happened

The blue/red modes also show different
- Spatial profiles
- Kinematics and dynamics

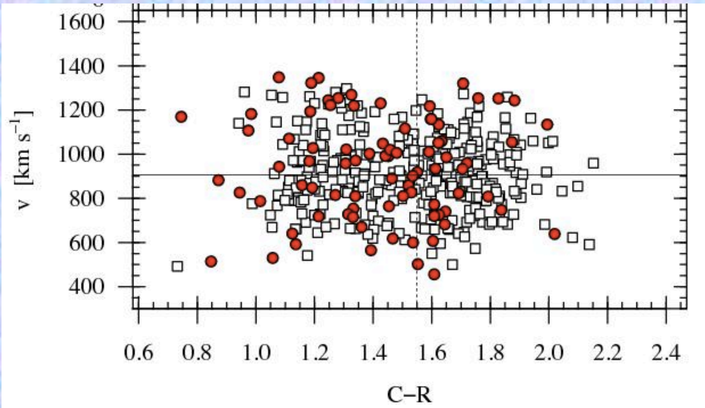


Projected density profile for GCS in NGC 1399 (cD in Fornax)

Blue GCs have shallow radial profile more closely resembling dark-matter halo

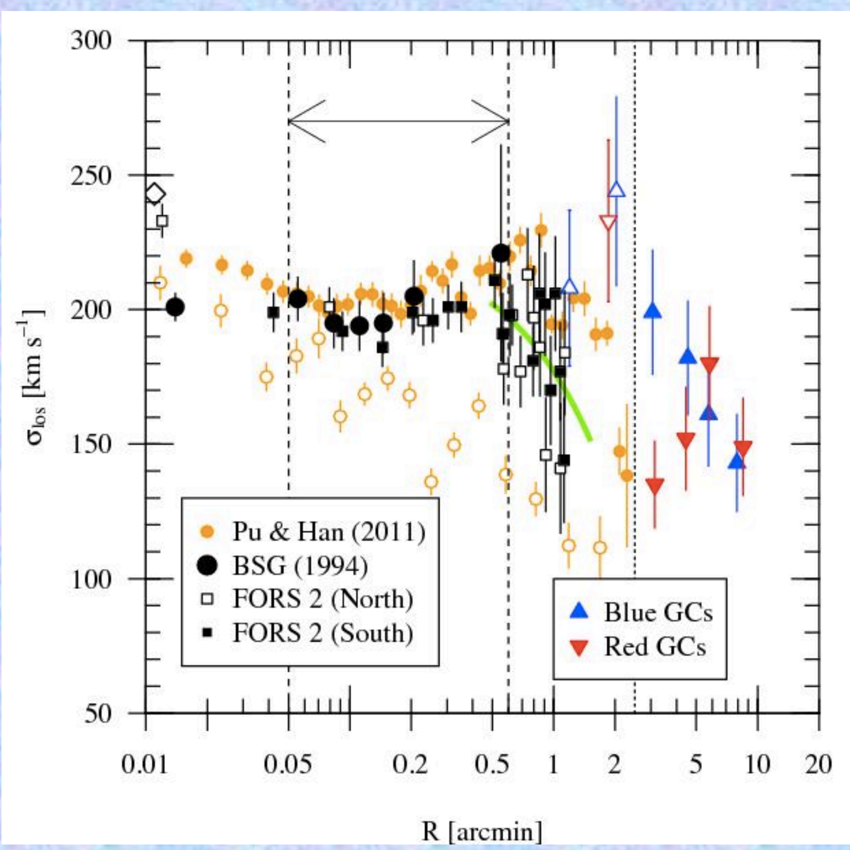
Red GCs have steeper profile closely resembling visible halo light (i.e. the field stars defining the visible galaxy)

Schuberth et al. 2010, AAp 513, A52



Virgo gE, NGC 4636
(Schuberth et al. 2012, AAp 544, A115)

High velocity dispersion indicates large random motions through the halo (pressure-supported system)

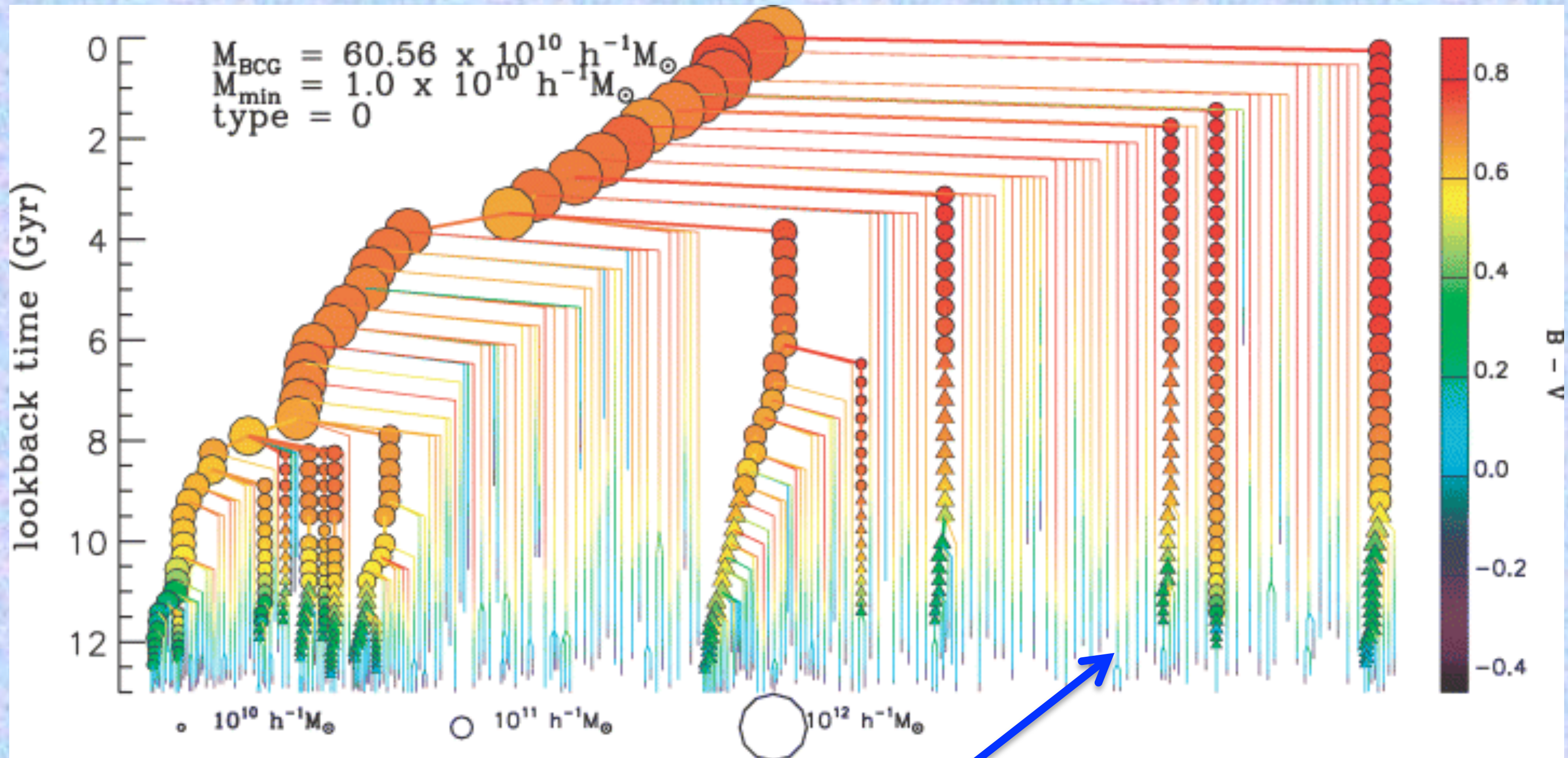


Velocity dispersion profile + Jeans equation → mass profile M(r)

$$\frac{\mathrm{d}\left(n(r)\,\sigma_r^2(r)\right)}{\mathrm{d}r} + 2\,\frac{\beta(r)}{r}\,n(r)\,\sigma_r^2(r) = -n(r)\,\frac{G\cdot M(r)}{r^2},$$

Fit into standard hierarchical-merging picture of galaxy formation.

Typical "Merger tree" for supergiant (De Lucia & Blaizot 2007, MNRAS 375, 2)

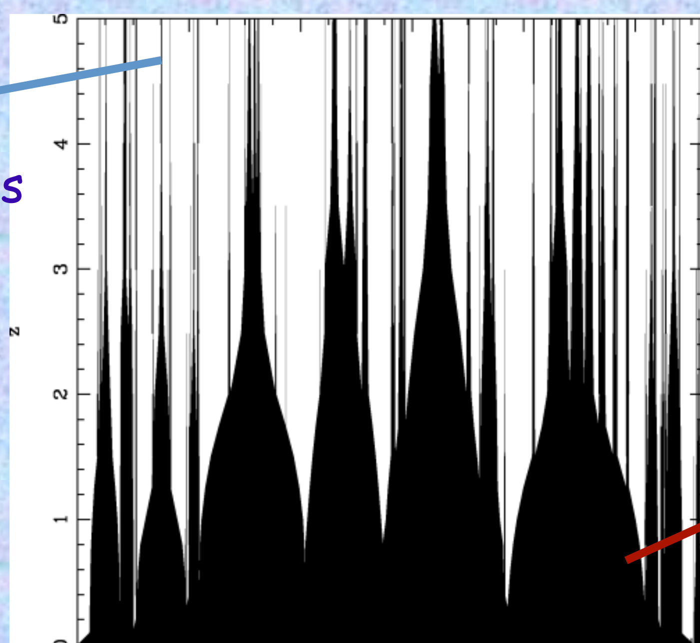


t, z

Initial population of dwarfs –- low-mass, low-metallicity, high gas content, and spatially more dispersed

Note: *most mergers are minor* (big pieces absorbing small ones)

Another "merger tree" example (Beasley et al. 2002)



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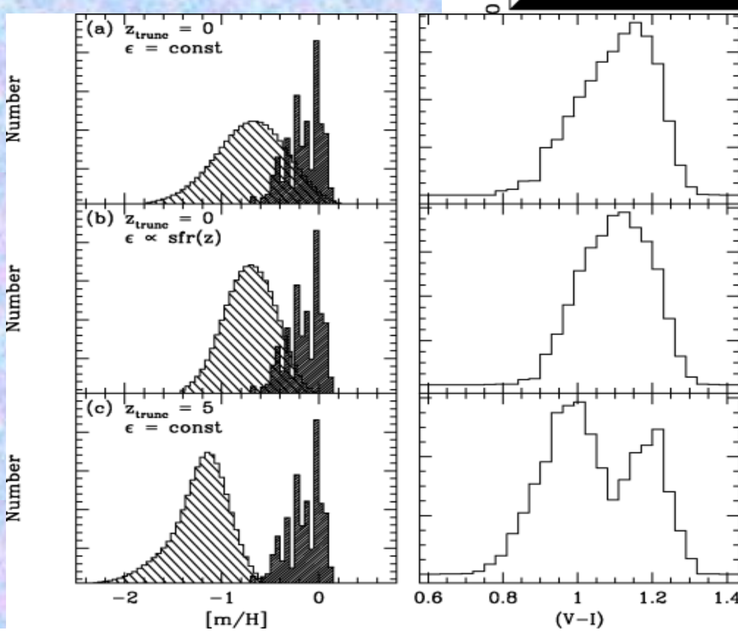
Low-Z "blue" clusters form up here, in the pregalactic dwarfs that are almost entirely gaseous and unenriched

High-Z "red" clusters form in the last few major mergers and starbursts at lower z

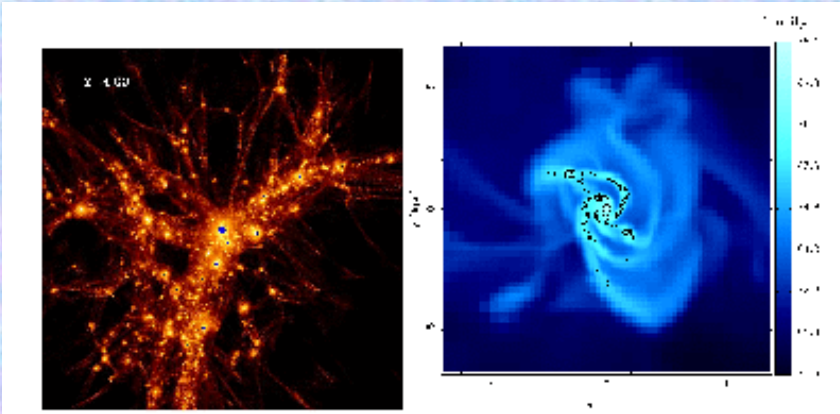


Final metallicity distributions for 3 example simulations. Note:

- Overlap between blue and red modes
- Bimodality only emerges if blue cluster mode is "truncated" around z~5

Not satisfactory --

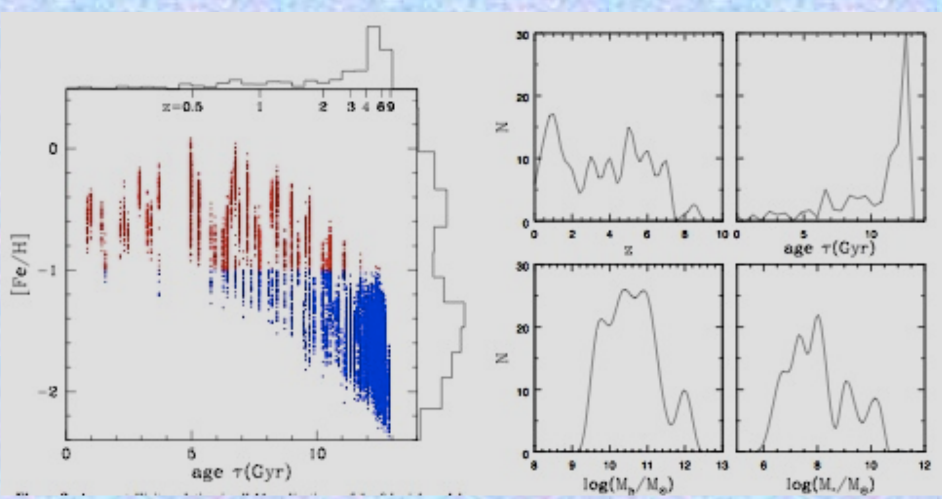
Muratov & Gnedin 2010, Astrophys.J. 718, 1266: N-body models for Milky-Way-type galaxies



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

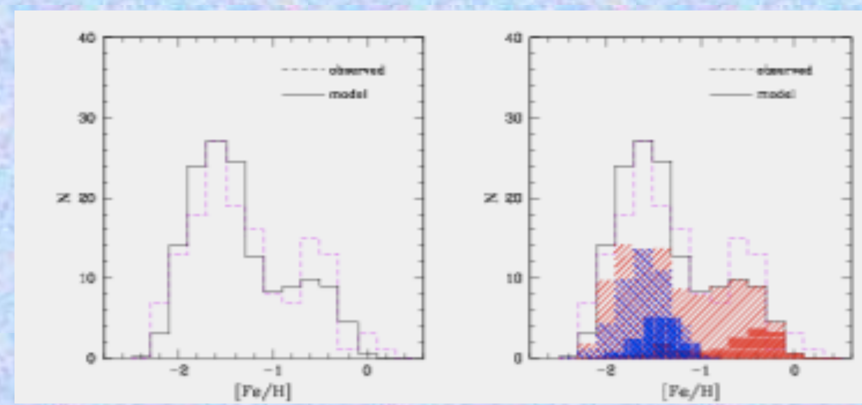
Merger rate × cloud mass ~ const



Semi-realistic metallicity range emerges naturally

Realistic mass distributions and spatial distributions

Key point: bimodality is so universal that it needs to emerge automatically in a formation model



An example of a late merger between two spirals. Lots of gas brought together and compressed along shock fronts

NGC 4038/39, “Antennae” (D.Verschatse)

Hubble Heritage image (HST/STScI/NASA)

“This galaxy is having a really bad Gigayear.” [APOD]

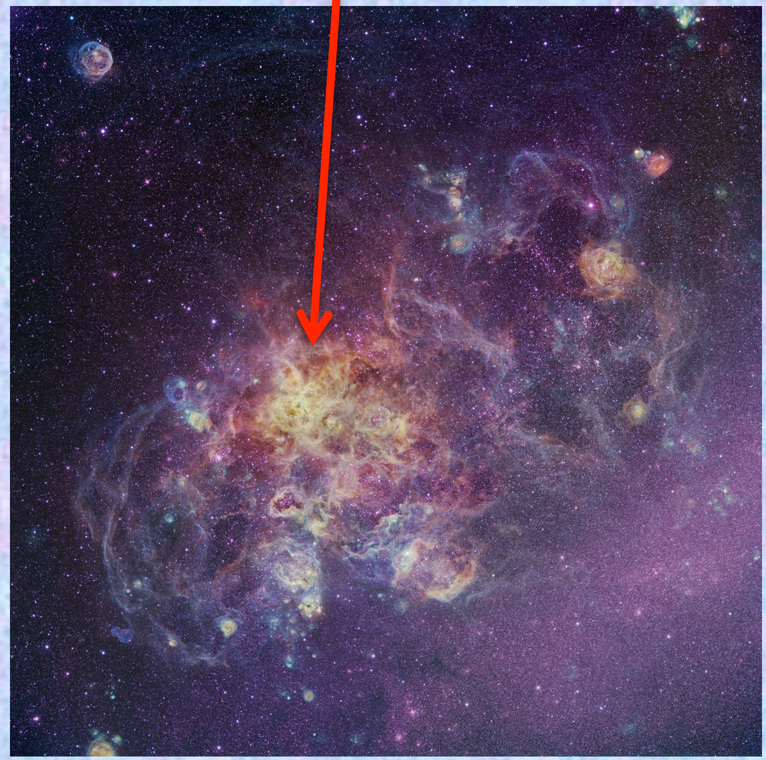
At a more local level, what did the progenitors of globular clusters look like?

NGC 602 (HST image) – SMC cluster a few hundred solar masses and a few Megayears old; plus gas and dust

M31-G1 (HST) – ~10^7 Solar masses and 12 Gigayears old

This is not a fair comparison! Completely different regimes of mass and mass density. Need to find much more massive extremely young star clusters

30 Doradus + R136 (J.P.Gleason)



M72 (Hubble Space Telescope)

This is closer: both R136 and M72 are presently about 50,000 solar masses (R136 is 3 My old)

BUT still not quite a fair comparison because the progenitor of M72 (its protocluster) must have been ~10x more massive to allow for 12-13 Gy of mass loss and dynamical evolution

ω Centauri: 2 x 10^6 Solar masses at present day

Rolf Olsen

x 2-3 for initial SF efficiency 0.3-0.5

x 2-3 for dynamical mass loss over 12 Gyr

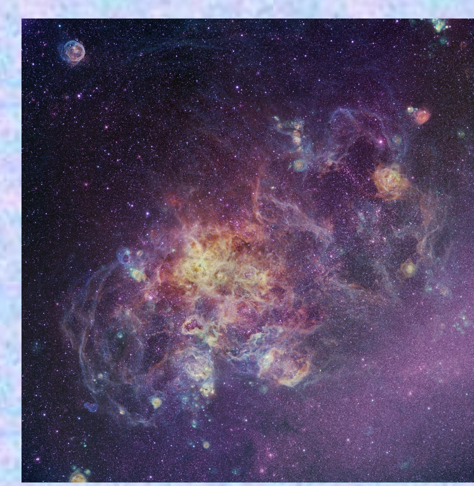
Its protocluster must have had ~10^7 M(Sun) of gas within r ~ 1 pc.

Extremely high mass, high density conditions

Orion Nebula Giant Molecular Cloud

Central star cluster "Trapezium" ~10^3 M(Sun)

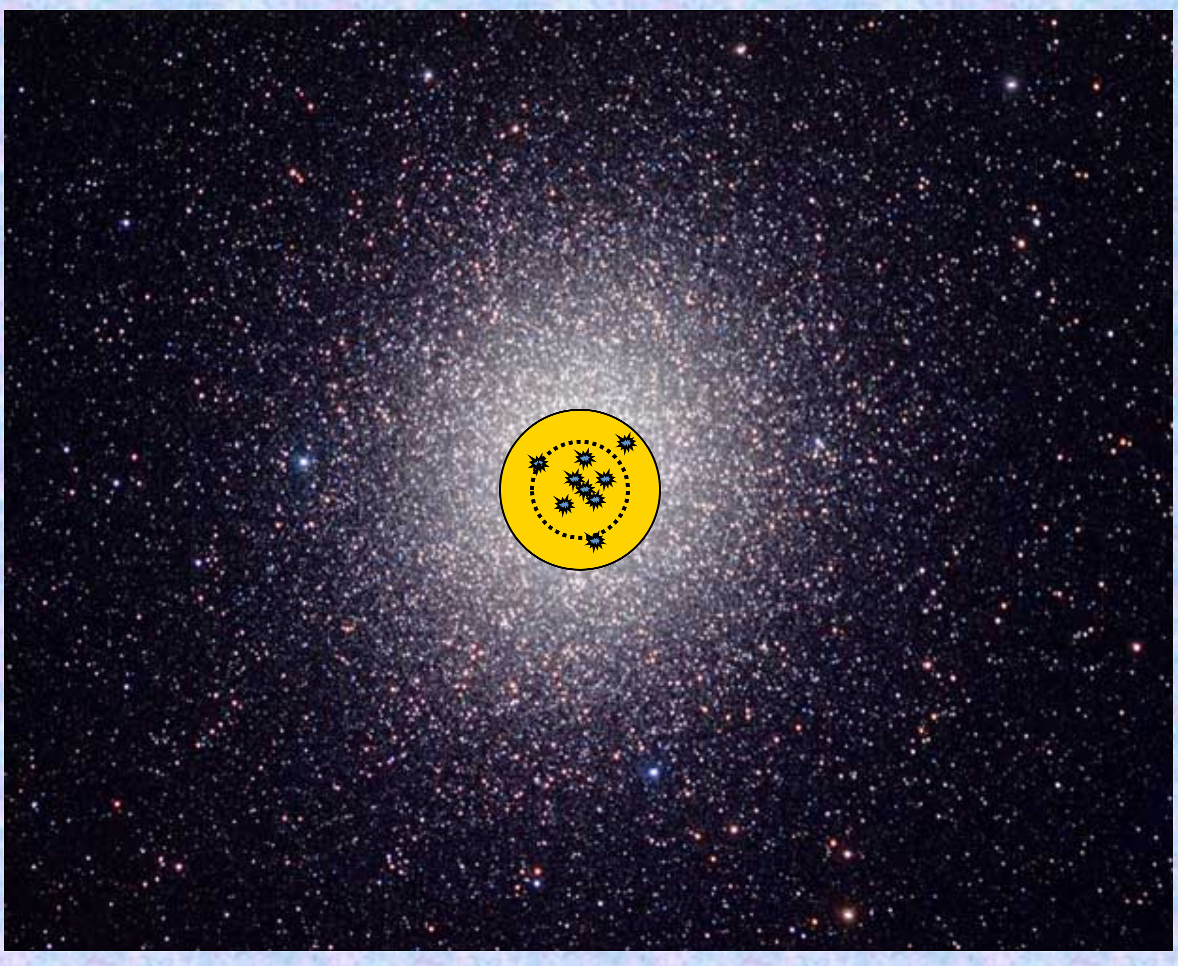
Entire GMC has 100x larger gas mass



30 Doradus

If similar scaling applies to GC progenitors, their host GMCs needed to be ~10^8 M(Sun) to produce a 10^5 M(Sun) cluster seen today (Harris & Pudritz 1994, ApJ 429, 177). Large enough to resemble the pregalactic dwarfs

In general, should be able to form GCs wherever lots of gas has been brought together and compressed



If proto-GC is massive enough:

Internal self-enrichment? Possible, if initial SN ejecta can be retained in the protocluster during the first 10 Myr (the dense cloud is still mostly gaseous)

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

Z-retention scales as

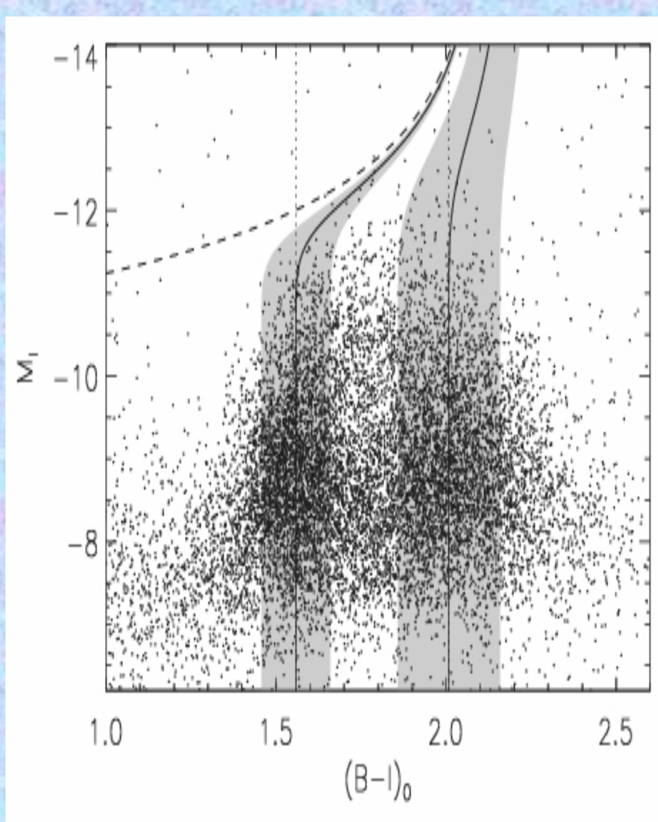
$$f_Z \sim \exp\left\{-\frac{E_{SN} f_* r_{eff}}{100 M_0 G M_C}\right\}$$

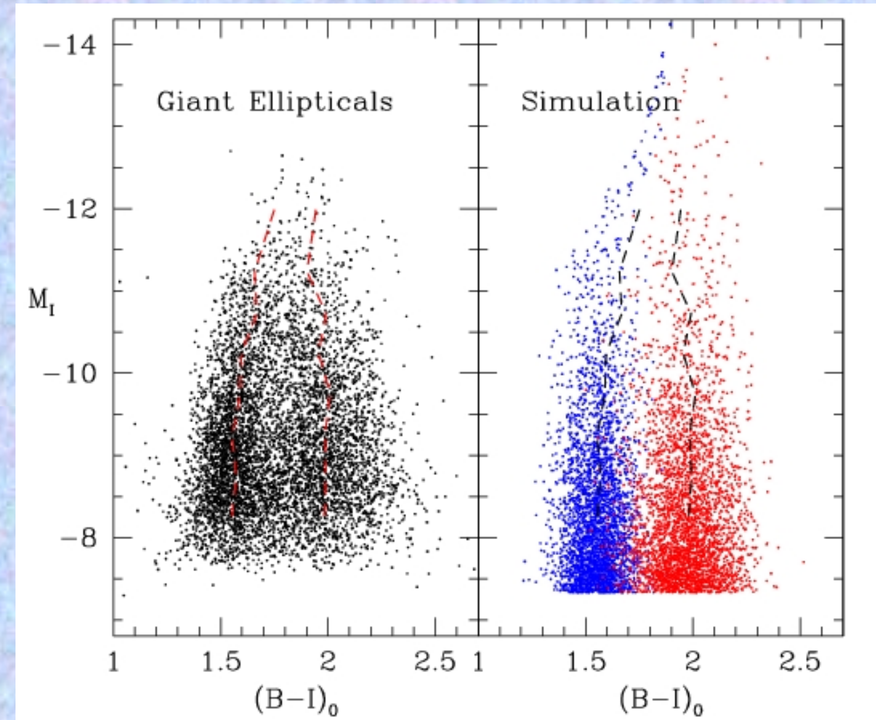
Bailin & Harris 2009, ApJ 695, 1082

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

Self-enrichment for $M>10^7$ M(Sun) causes blue, red sequences to "swing" over to higher metallicity.

But for $M<10^6$ M(Sun), both sequences should be vertical (metallicity independent of mass)



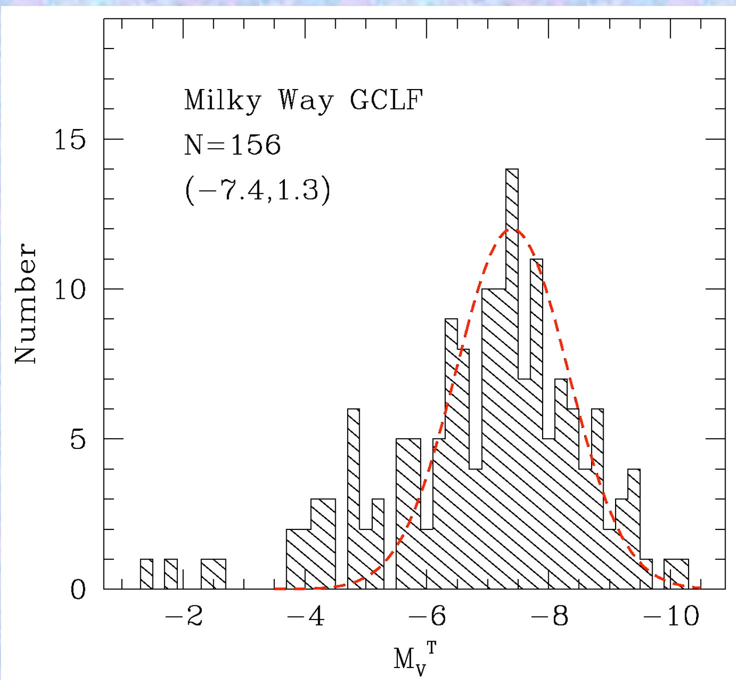


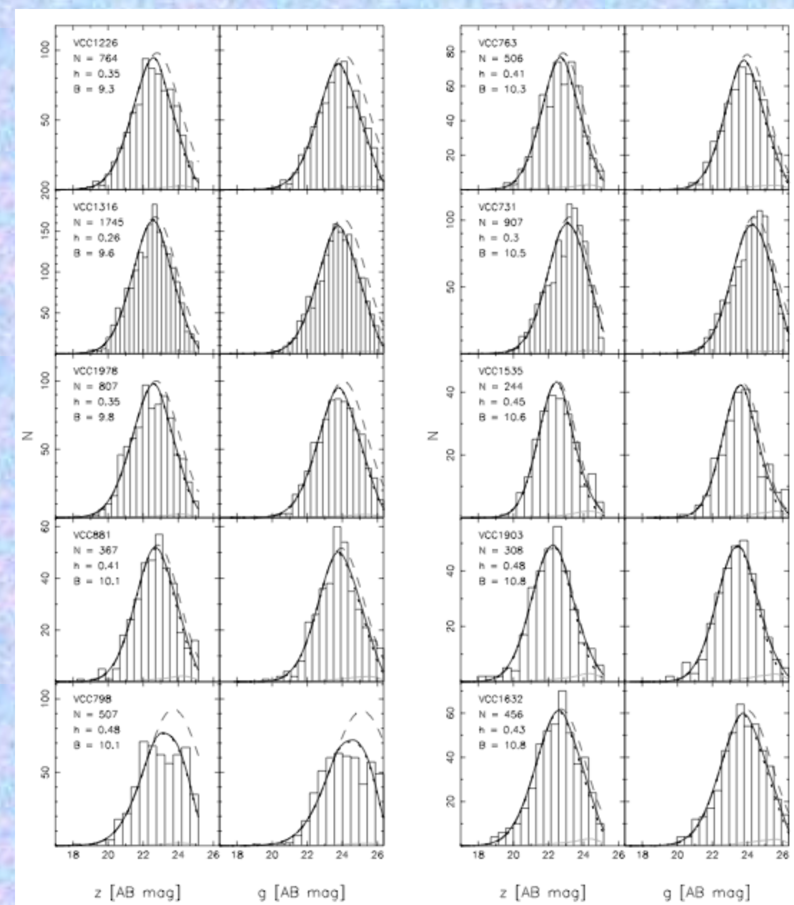
Very metal-poor, *very* massive GCs should be rare (anywhere).

Validity of this idea depends crucially on the star formation period within a massive protocluster lasting ~10-20 Myr

Luminosity function (GCLF) = number of GCs per unit magnitude

Convert to mass function with $M = (M/L) \times L$; $(M/L)_V = 2$

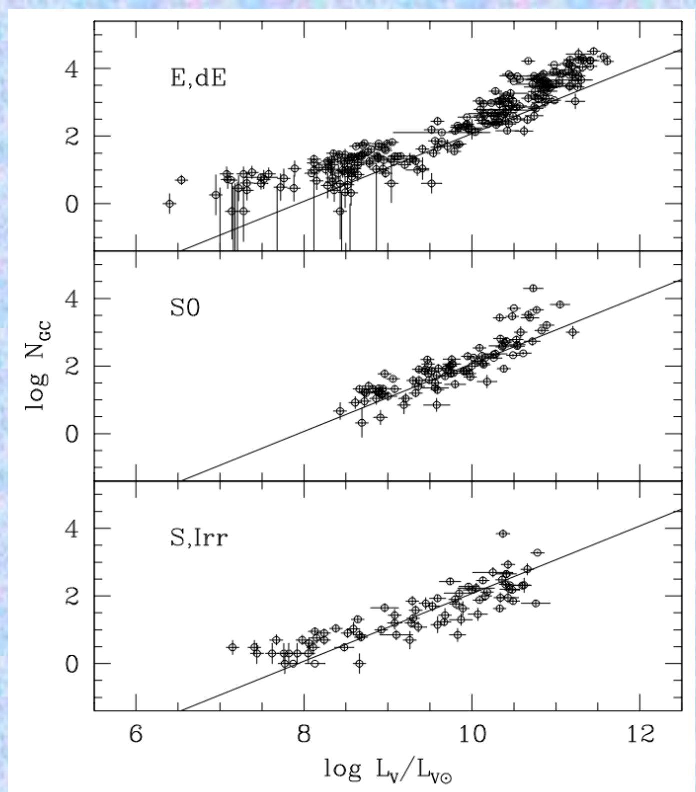




Characteristic Gaussian-like shape; with tail to lower L
M_V(peak) ~ -7.4 and dispersion $\sigma = 1.3$
Empirically, very similar in all galaxies.

Jordan et al. 2007, ApJS 171, 101
Sample GCLFs for Virgo galaxies

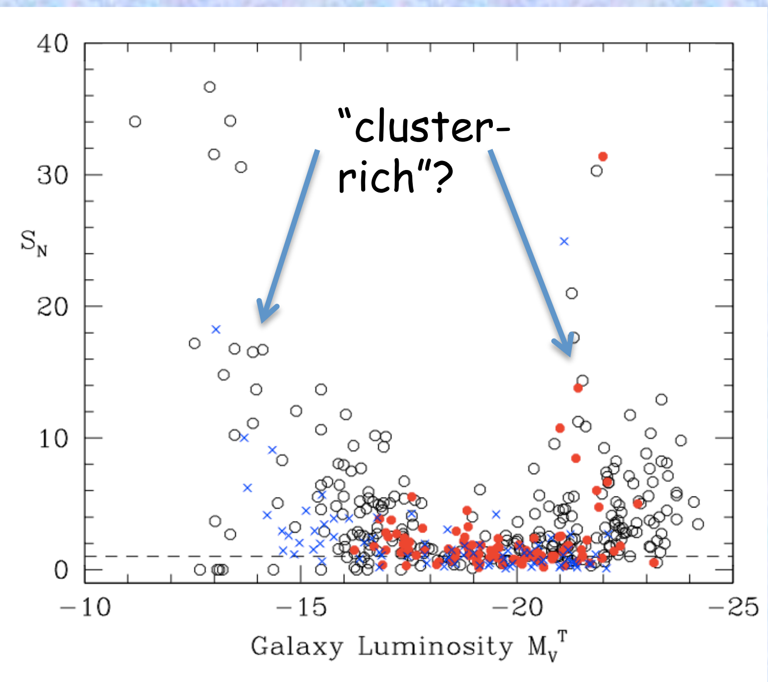
Total numbers: N(GC) goes up with galaxy luminosity, but not linearly. More complex behavior



Harris, Harris & Alessi 2013, ApJ 772, 82

Define "Specific Frequency"

$$S_N = const \frac{N_{GC}}{L_V(galaxy)}$$



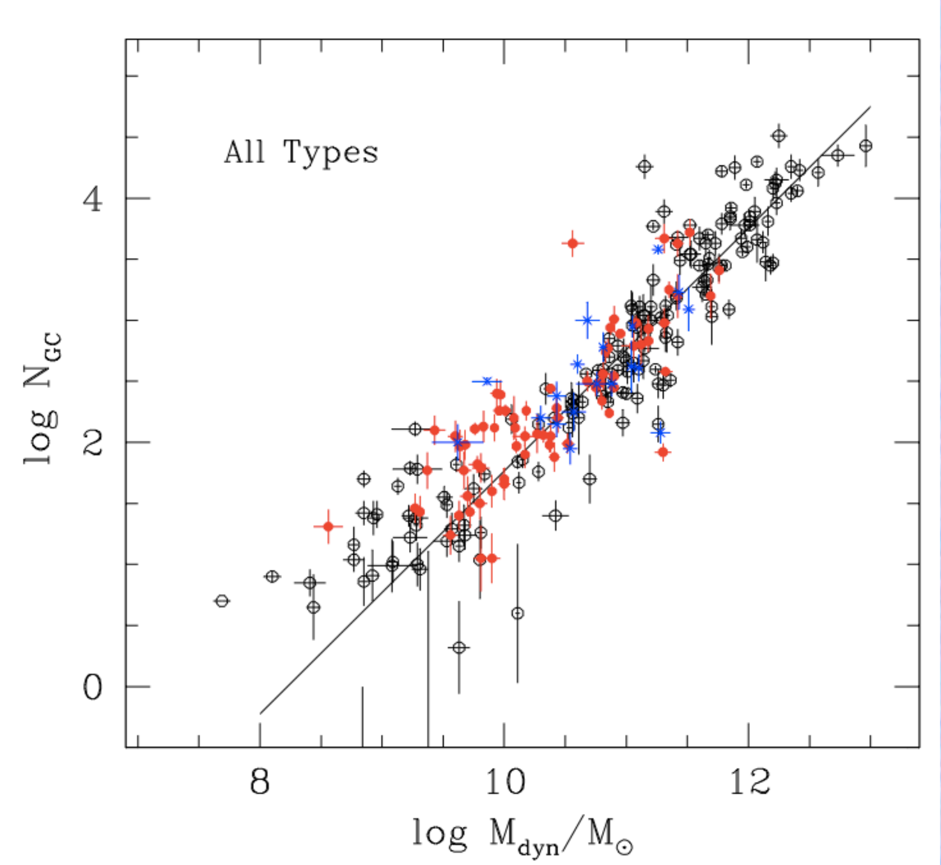
U-shaped trend, big variations. ??
Another approach needed ---

Try looking at a mass ratio instead. Perhaps the GC numbers respond to either

(a) The total baryonic mass in the galaxy [which would be the total initial gas mass before any star formation], or

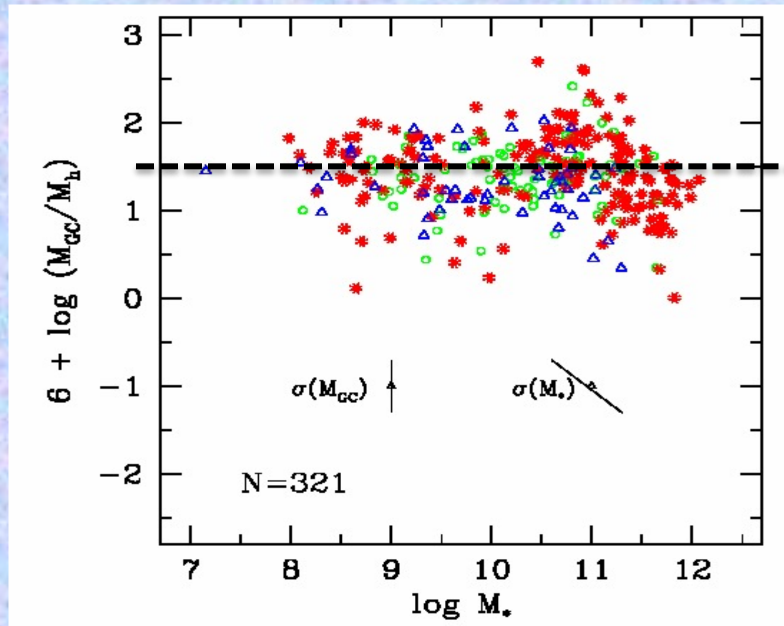
(b) The total mass in the galaxy's potential well, including dark matter.

N_{GC} vs. baryonic mass: Scatter, plus systematic issues at low-mass end



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

where M_{GC} = total mass in globular clusters
M_h = "halo mass" (dark matter + all else)
η is then an "absolute" efficiency of GC formation



Elliptical S0 S/Irr

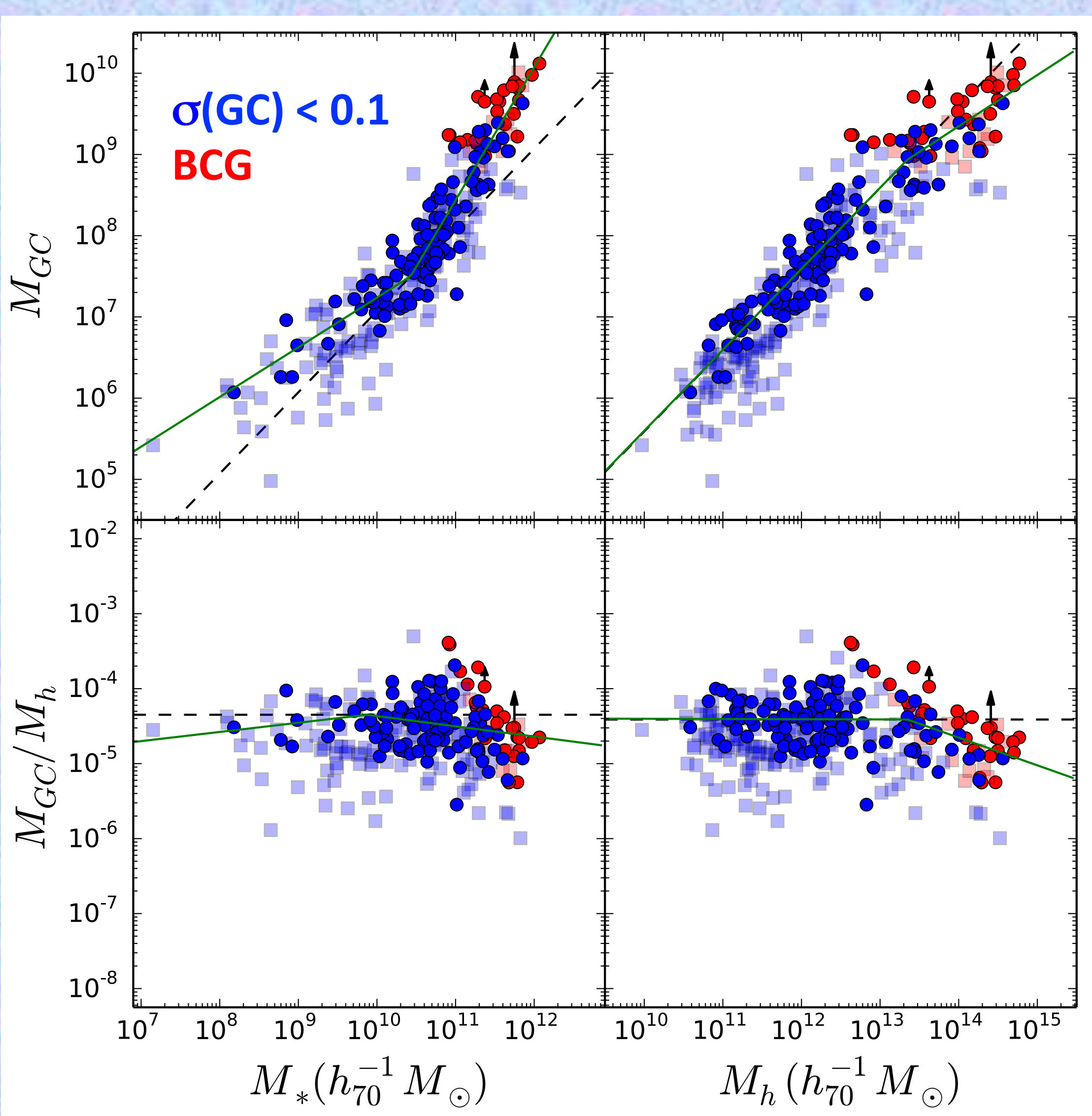
$\langle\eta\rangle = 4 \times 10^{-5}$

All GCS catalog galaxies with K-band luminosities: L_K used to calculate M_*

Hudson, Harris, & Harris 2014, ApJ

Globular clusters form in proportion to galaxy halo mass, regardless of galaxy size or type

Hudson, Harris, & Harris 2014, ApJL submitted



Work in progress:

- Add 100 more galaxies with L_V but not L_K self consistently
- Mass fractions of GCs subdivided by metallicity (blue, red)
- Is there a systematic effect due to environment?

M_{GC} ~ const. M_h suggests 3 conditions needed:

- *Initial* gas mass present in pregalactic potential well is proportional to halo mass
- GC formation rate is proportional to available gas mass
- GCs formed earliest, before feedback effects dominate

Dwarfs: stellar winds (photoionization), SNe
Giants: AGN activity and infall heating

Intermediate-mass galaxies (like Milky Way or L_* galaxies) are least affected and make field stars most efficiently. But the GC's don't seem to care about feedback

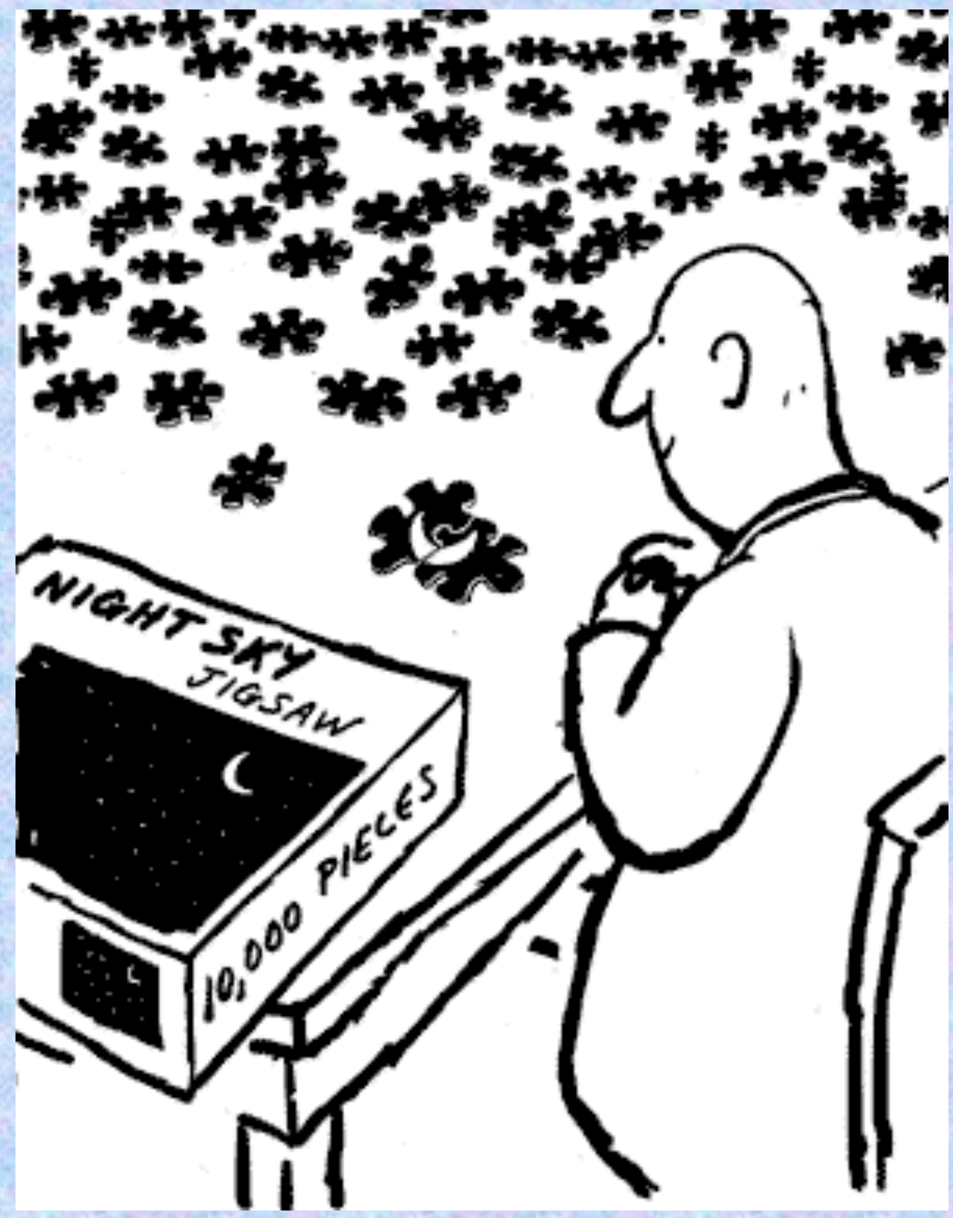
Review papers on globular cluster systems:

Harris 1991, ARAA 29, 543

Harris 2001, in Saas-Fee Advanced Course 28, Swiss Society for Astronomy and Astrophysics, ed.L.Labhardt and B.Bingelli (Springer-Verlag)

Brodie & Strader 2006, ARAA 44, 193

Harris 2010, PhilTransRoySoc 368, 889


NIGHT SKY
JIGSAW
10,000 PIECES