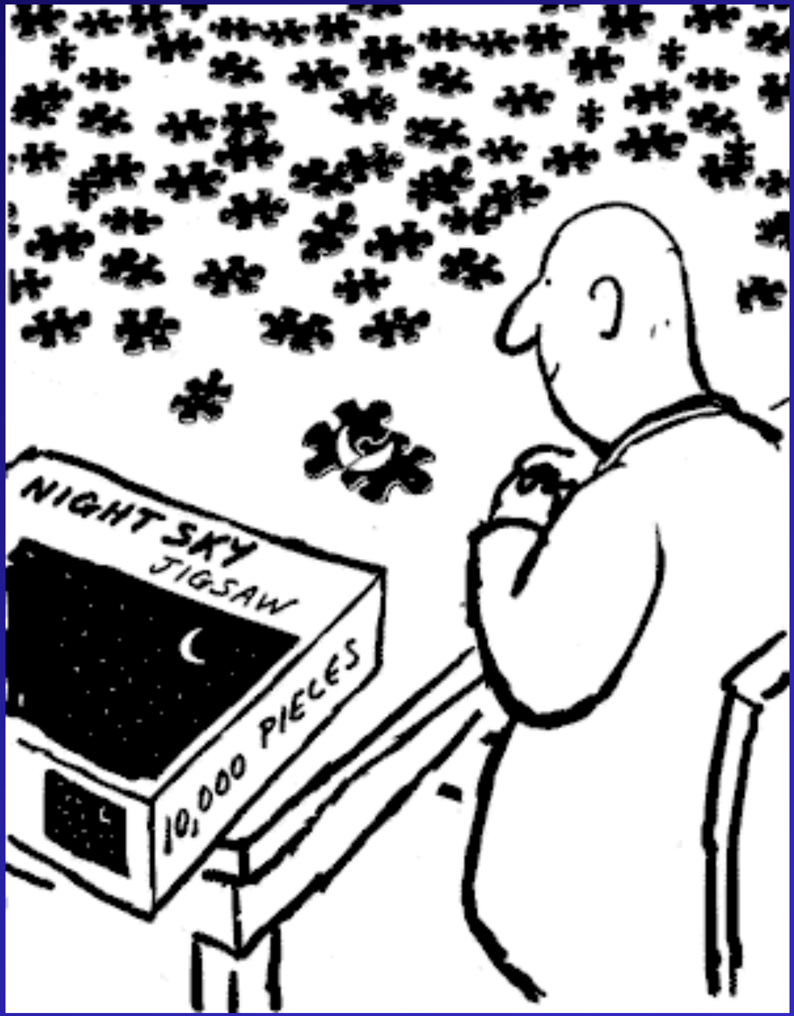
Between Galaxies and Stars



Bill Harris, McMaster University

For CASCA, May 2010

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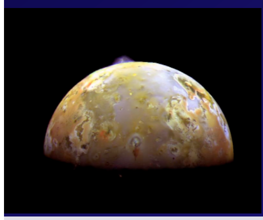

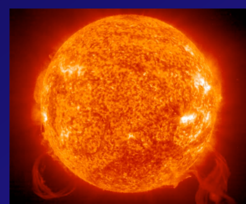

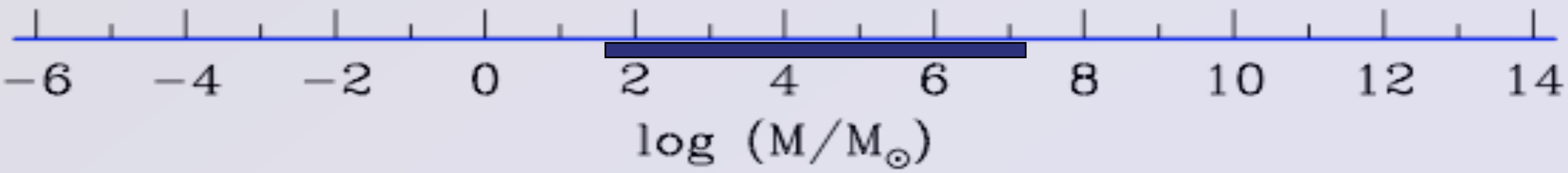

Bill Harris, McMaster University

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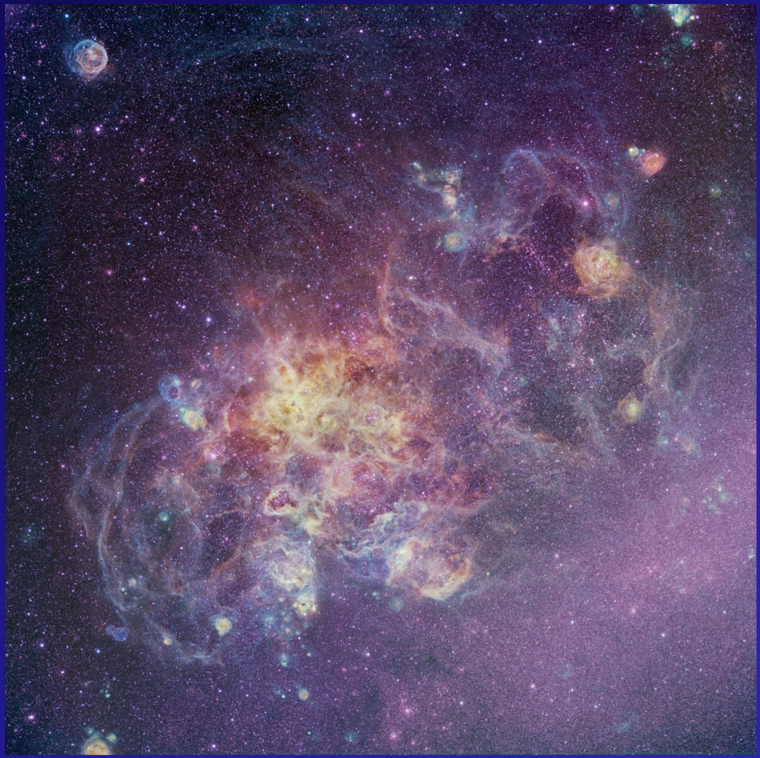
What did the progenitors of globular clusters look like?

NGC 602 (HST image) -- a few hundred solar masses and a few Megayears old; gas and dust

M31-G1 (HST) -- 5 million solar masses and 12 Gigayears old

This is not a fair comparison! This typical young SMC cluster falls at a very different mass scale.

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 it is still not a fair comparison because ……

3×10^6 M_0 at present day

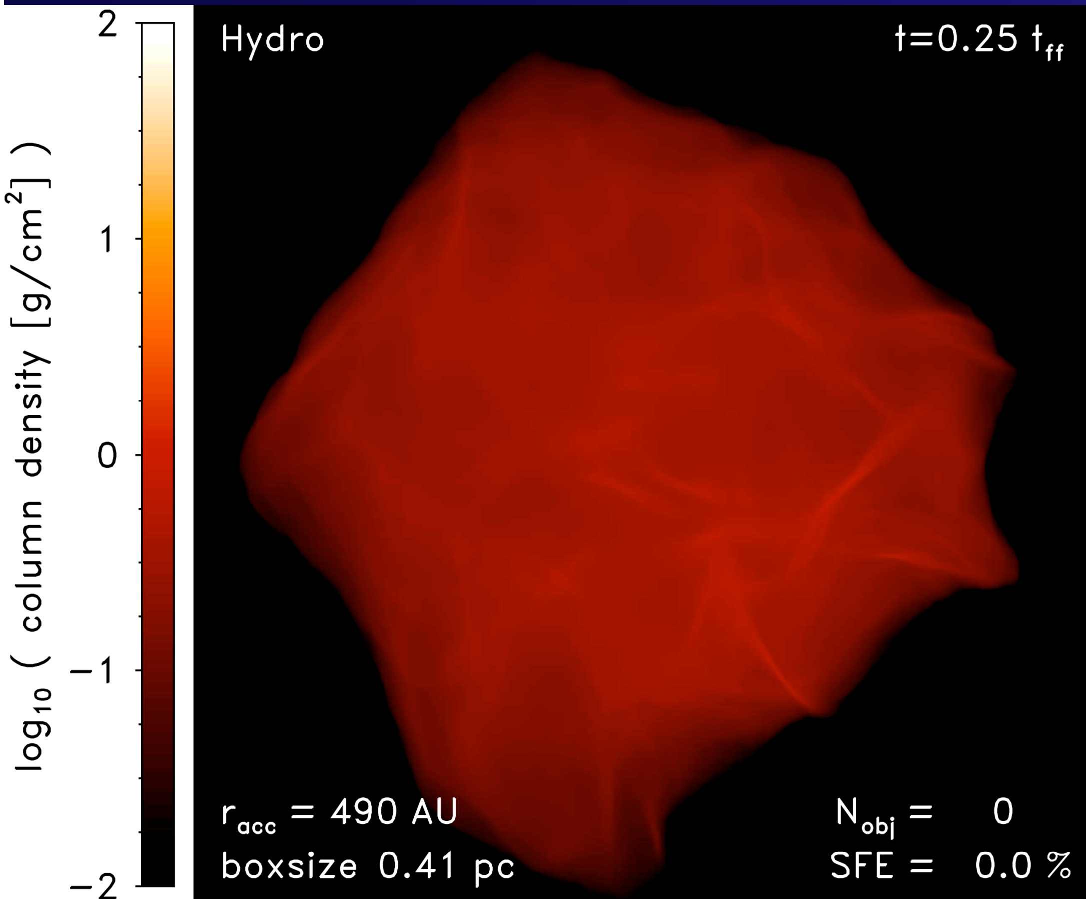
× 2-3 for "early rapid mass loss"

× 2-3 for slow dynamical mass loss over 10+ Gyr

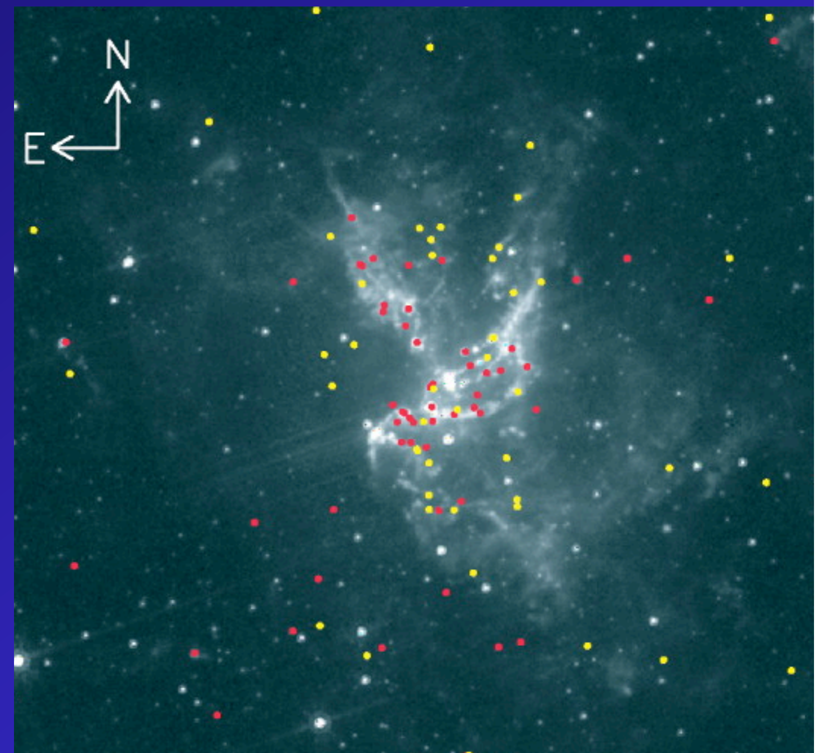
↓

Its protocluster needed to have $>10^7$ M_0 *within 1 pc radius*

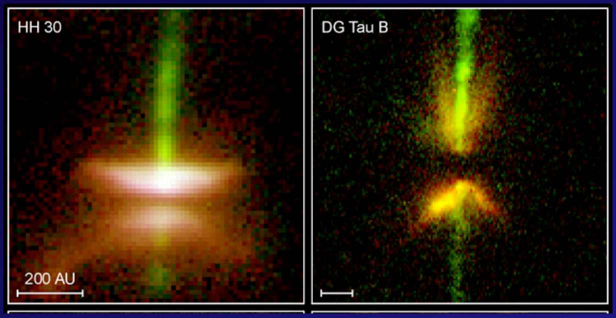
Thus -- a super version of 30 Doradus? Complex, highly turbulent, multiple subclumps with internal age spread?



Duffin, Federath, Pudritz, Banerjee, & Klessen 2010 -- high resolution simulation of 100 Solar mass protocluster cloud. Over two free-fall times, filamentary structure develops rapidly, followed by star formation in clumps, falling together into a single central cluster



NGC 346 (Simon et al. 2007) -- a structurally similar very young cluster



Cosmology and galaxy formation are important because they set the right context for understanding the formation of molecular clouds, stars, and star clusters.

?

A field should not be thought of as "important" only because of its support for some other field, and not on its own ground.

Gauge a field by the richness of its connections to other areas of astrophysics.

Massive and supermassive star clusters provide …

Fundamental testbeds for evolution of all stars

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

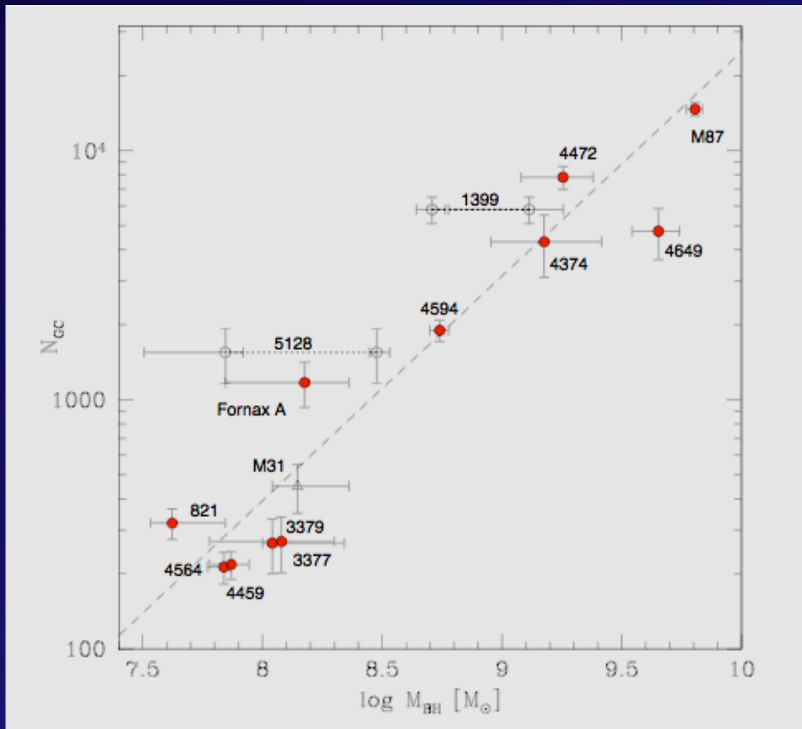
Internal dynamics and mass profile of galaxy's halo --> accurate assessment of dark matter

Unique windows on earliest star formation in galaxies

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

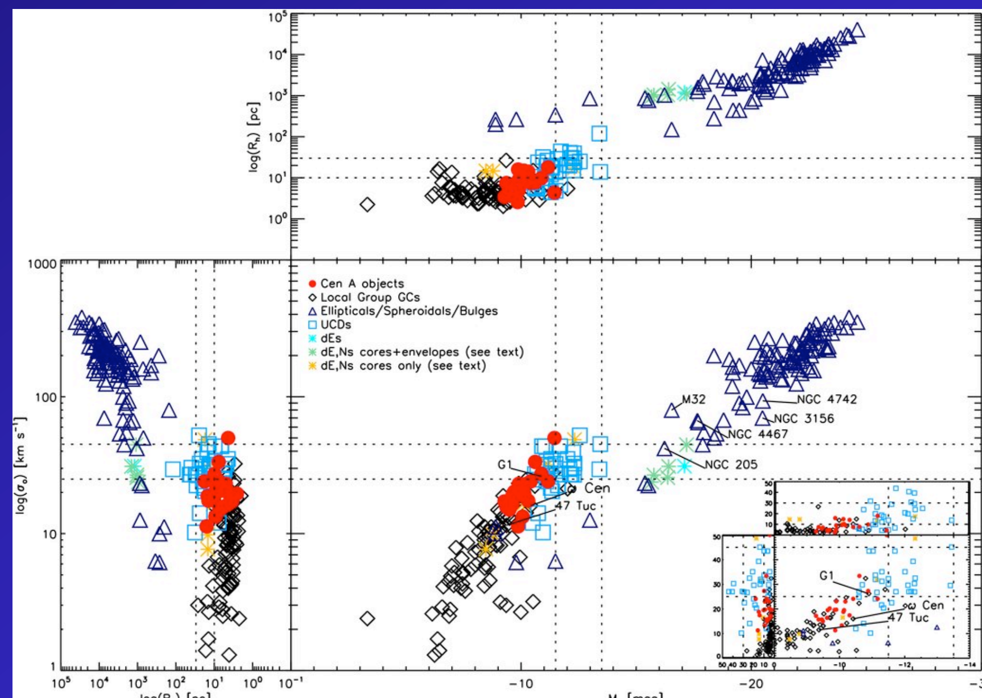
Testbeds for dynamics of high-density N-body systems (N--> 10^7)

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



New and surprising connections keep emerging

Structural bridges with UCDs, dE nuclei, dSph

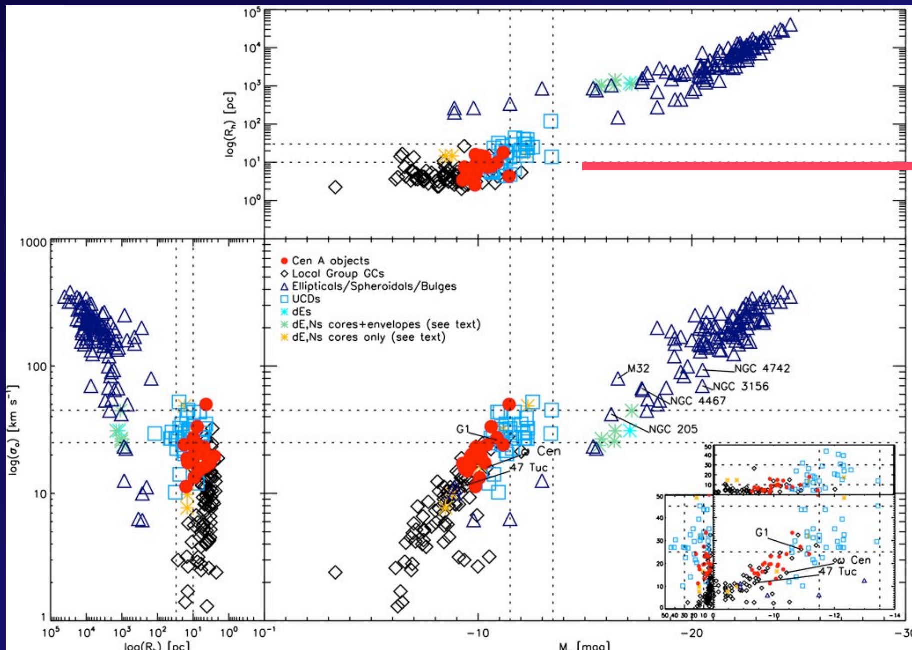


Burkert & Tremaine 2010

Total mass in the globular cluster system is closely related to the galaxy's central black hole mass

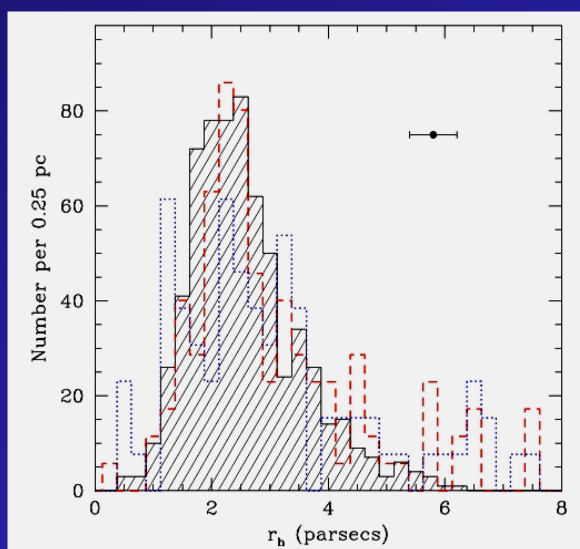
M(GCS) ~ M(SMBH) !

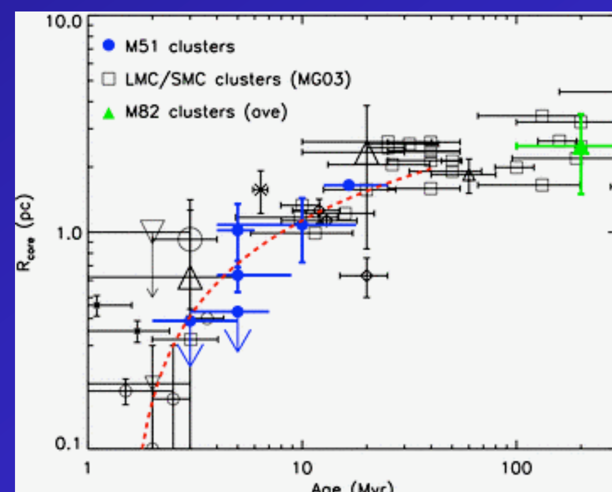
Taylor et al. 2010, ApJ 712, 1191



Present-day clusters have effective radii 2 - 3 pc

Gaseous protocluster must be ~1 pc and undergo virial expansion during gas loss

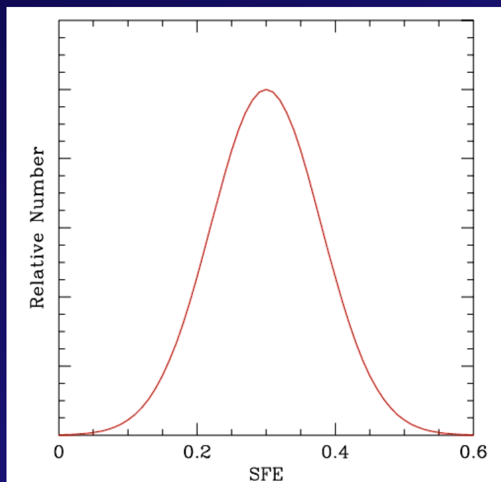


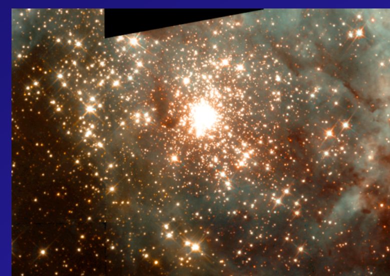


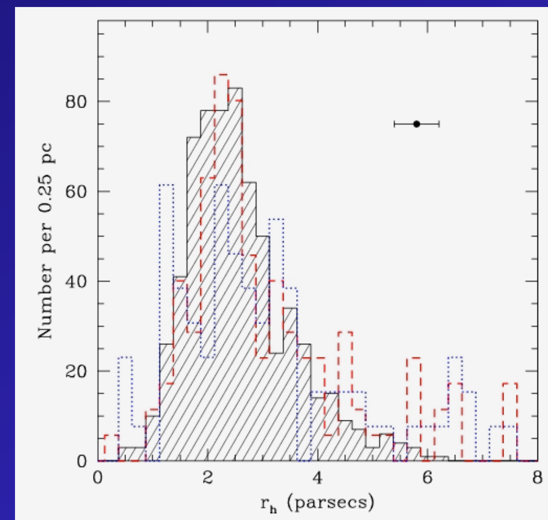
Harris, Spitler, Forbes & Bailin 2010, MNRAS 401, 1965

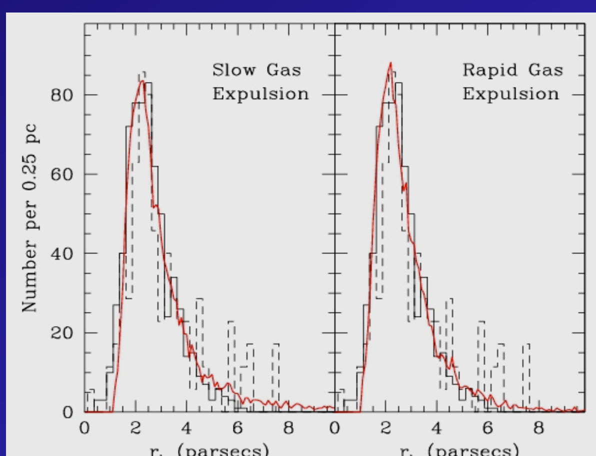
Bastian && 2008, MNRAS 389, 223

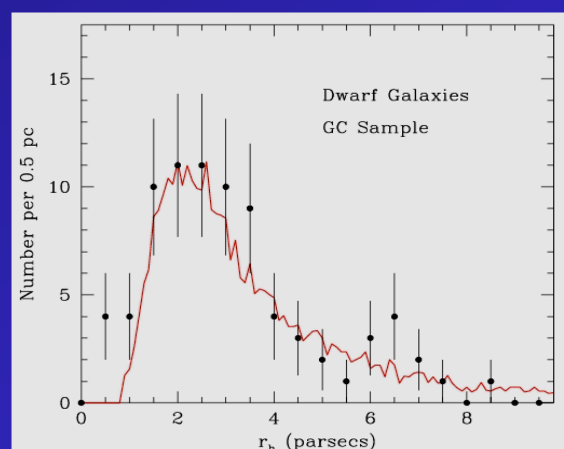
The expansion ratio $R = r_h/r_h(0)$ depends on the star formation efficiency (SFE) and the gas expulsion time











Monte Carlo simulation with initial Gaussian distribution of SFE = 0.3 +- 0.08

And initial size of protocloud $r_h(0)$ ~ 0.8 pc

Harris, Spitler, Forbes & Bailin 2010

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 > 30,000

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

NGC 3311/3309
d = 50 Mpc

GCs are 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

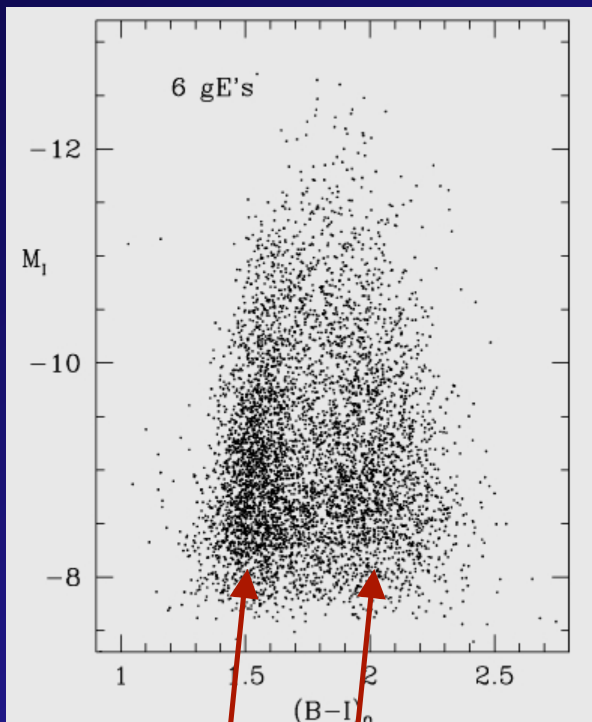
Present day: < 1% of total stellar mass

Initially: > 10% ?

Magnitude versus color = luminosity vs. mean temperature

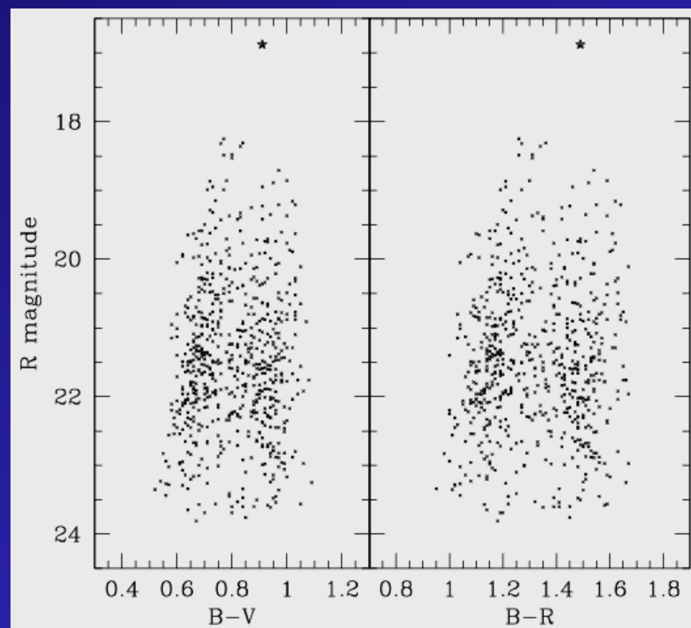
= mass vs. heavy-element enrichment

supergiant E's



M104 = giant Sa

L



Heavy-element enrichment Z

Two sequences: blue, red = low, high metallicity

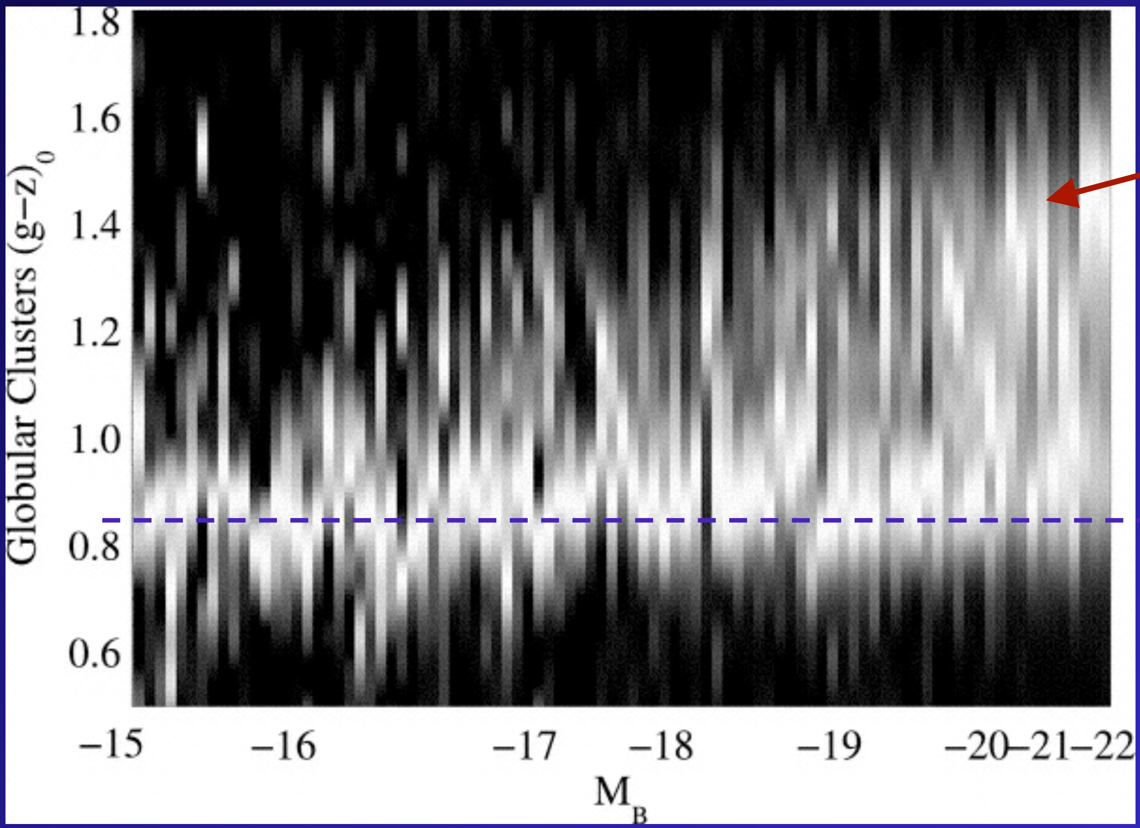
Bimodality

The dispersions of color here represent intrinsic cluster-to-cluster differences in Z

Two major starbursts in the first few Gyr? Or a continuous sequence?

Correlations with host galaxy size

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

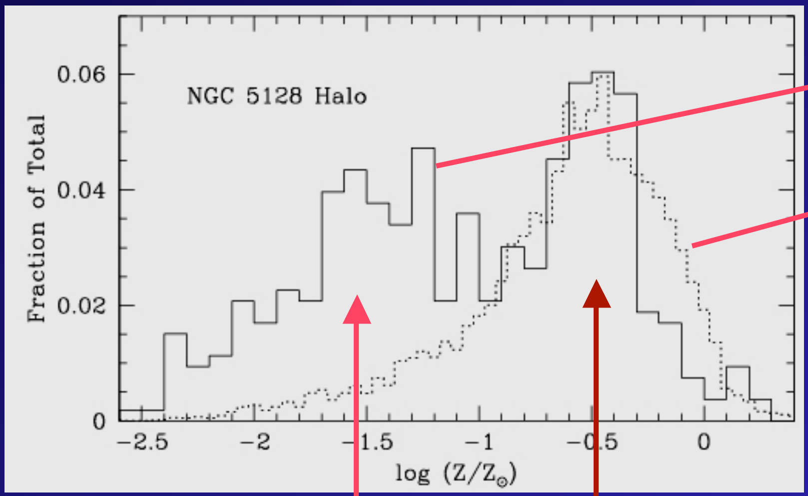


Red sequence (metal richer) more prominent in bigger galaxies

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

Higher enrichment levels are achievable with lots of gas in bigger, deeper potential wells. But why the smaller numbers at intermediate Z?

The big, generic problem is that the *halo field stars* and *globular clusters* do not follow the same metallicity distribution



The clusters

The field stars

Harris 2009

There are ~5 times more metal-poor GCs than there should be

This mode is "normal". A giant galaxy is made up mostly of rather metal-rich stars (1/10 to 2x Solar). The metal-rich GCs formed during this major phase

What extra astrophysics affects the (massive) clusters particularly, and what happened in the low-Z formation regime?

Additional ideas -

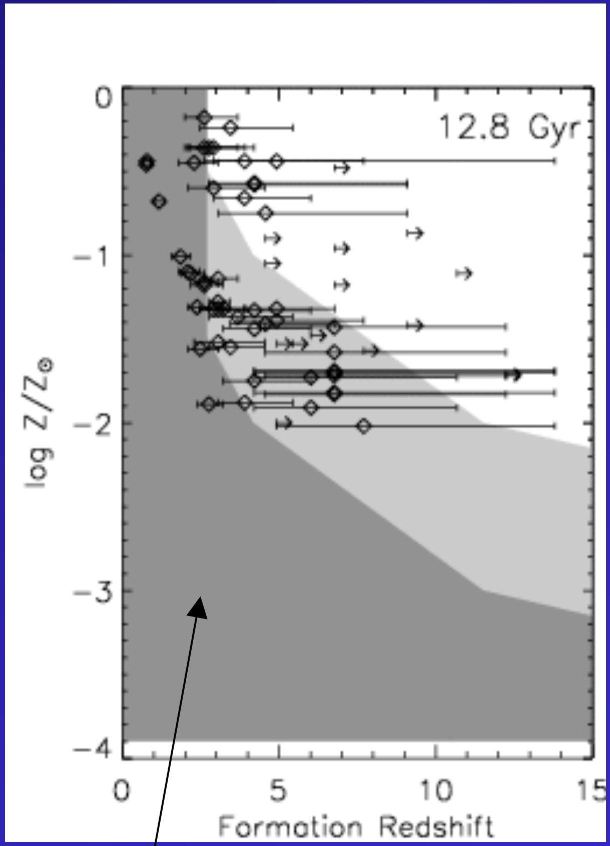
At very early times, T_{CMB} may regulate star formation if $T_{CMB} > T_{min}$ along cooling curve

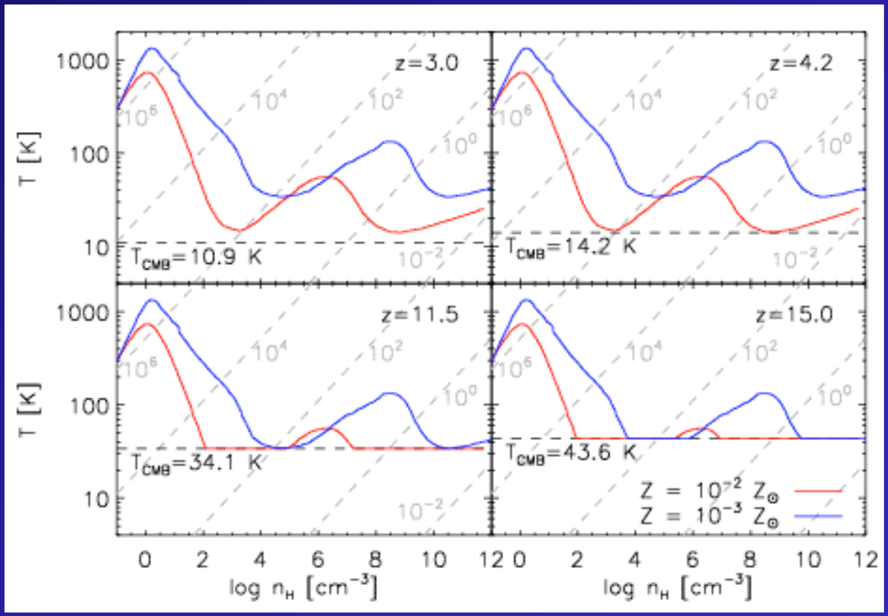
→ get top-heavy IMF because fragmentation does not finish

→ affected clusters do not survive

Can this have prevented the first round of clusters with [Fe/H] > -1 from surviving?

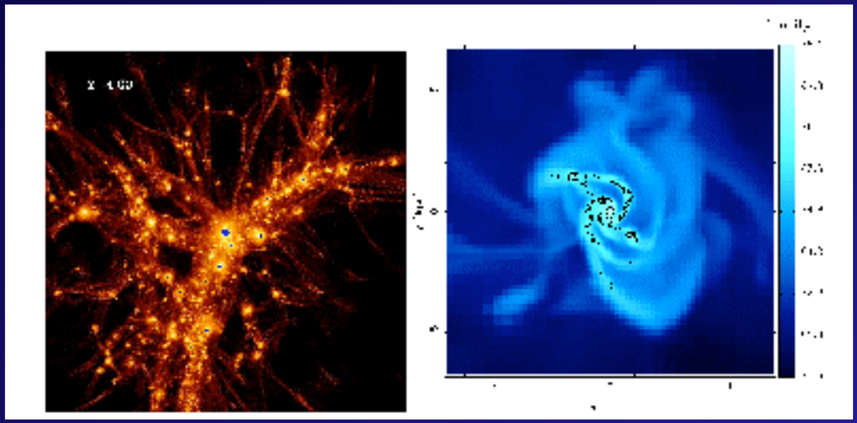
Bailin et al. 2010, ApJ 715, 194





Normal IMF in shaded region where fragmentation slow but not too slow

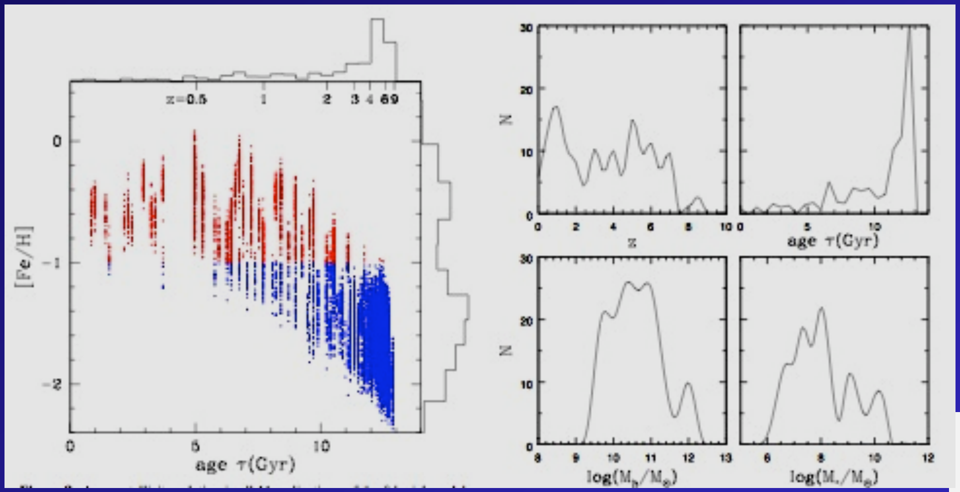
Muratov & Gnedin 2010, arXiv:1002.1325



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

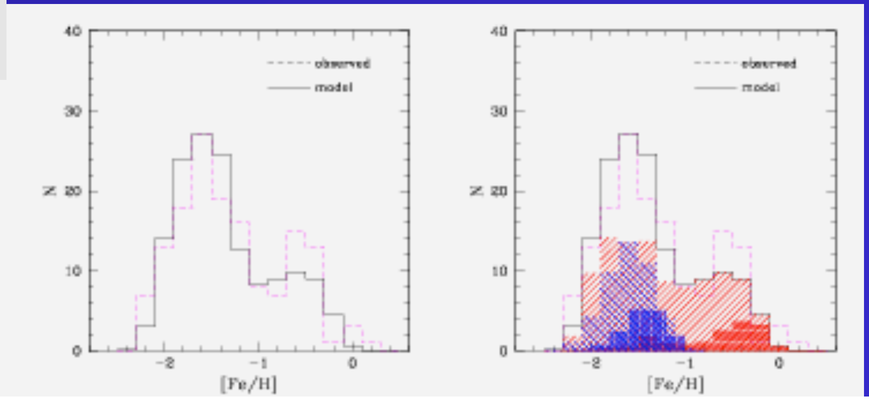
Merger rate x cloud mass ~ const



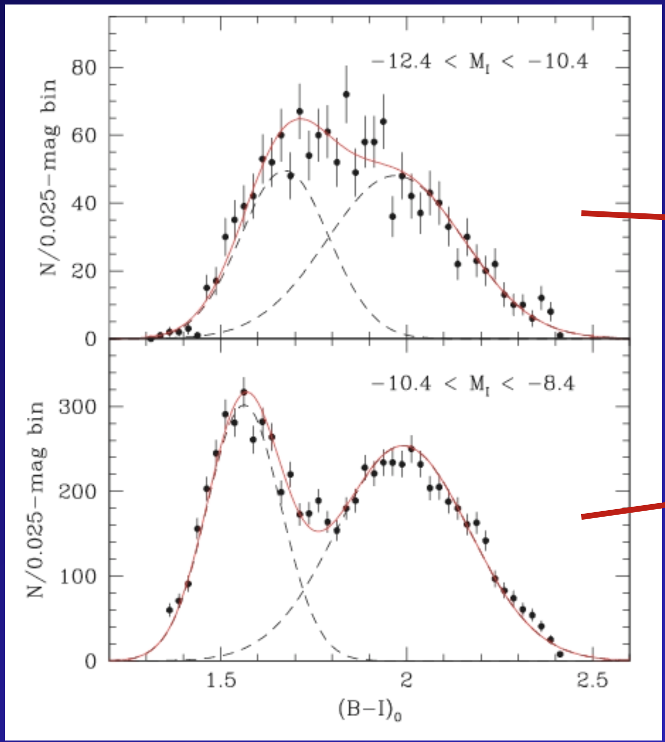
Semi-realistic bimodality emerges naturally though not every time

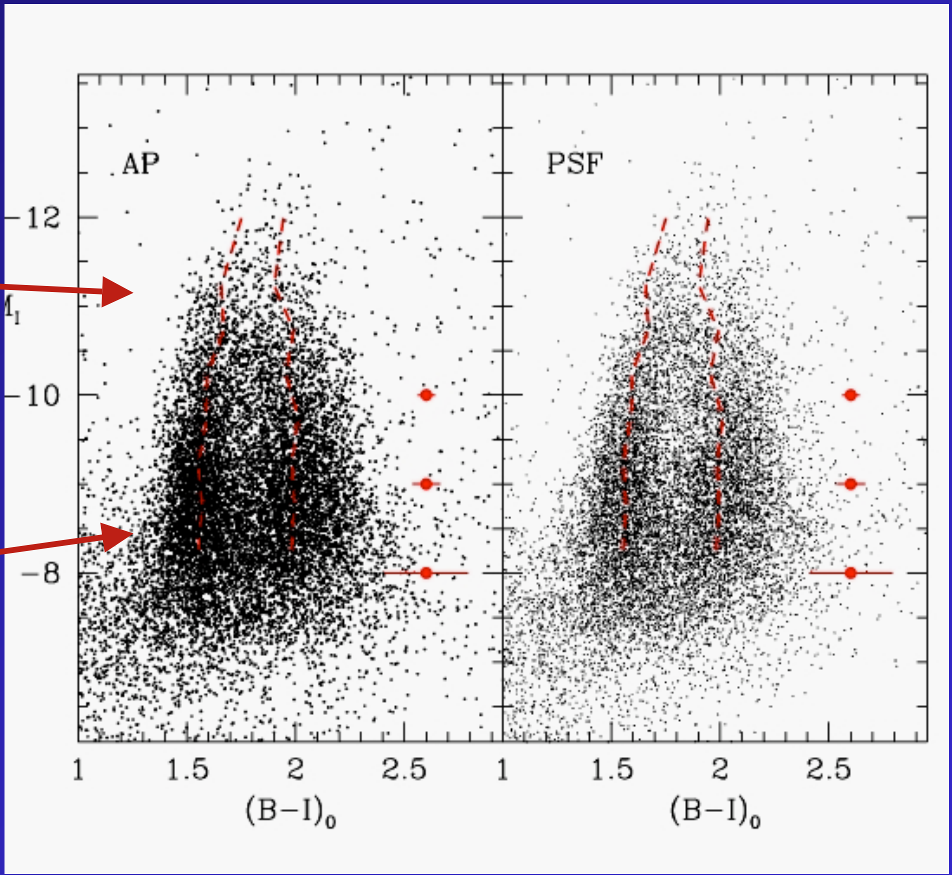
Realistic mass distributions and spatial distributions

Significant fraction of young, metal-rich GCs formed



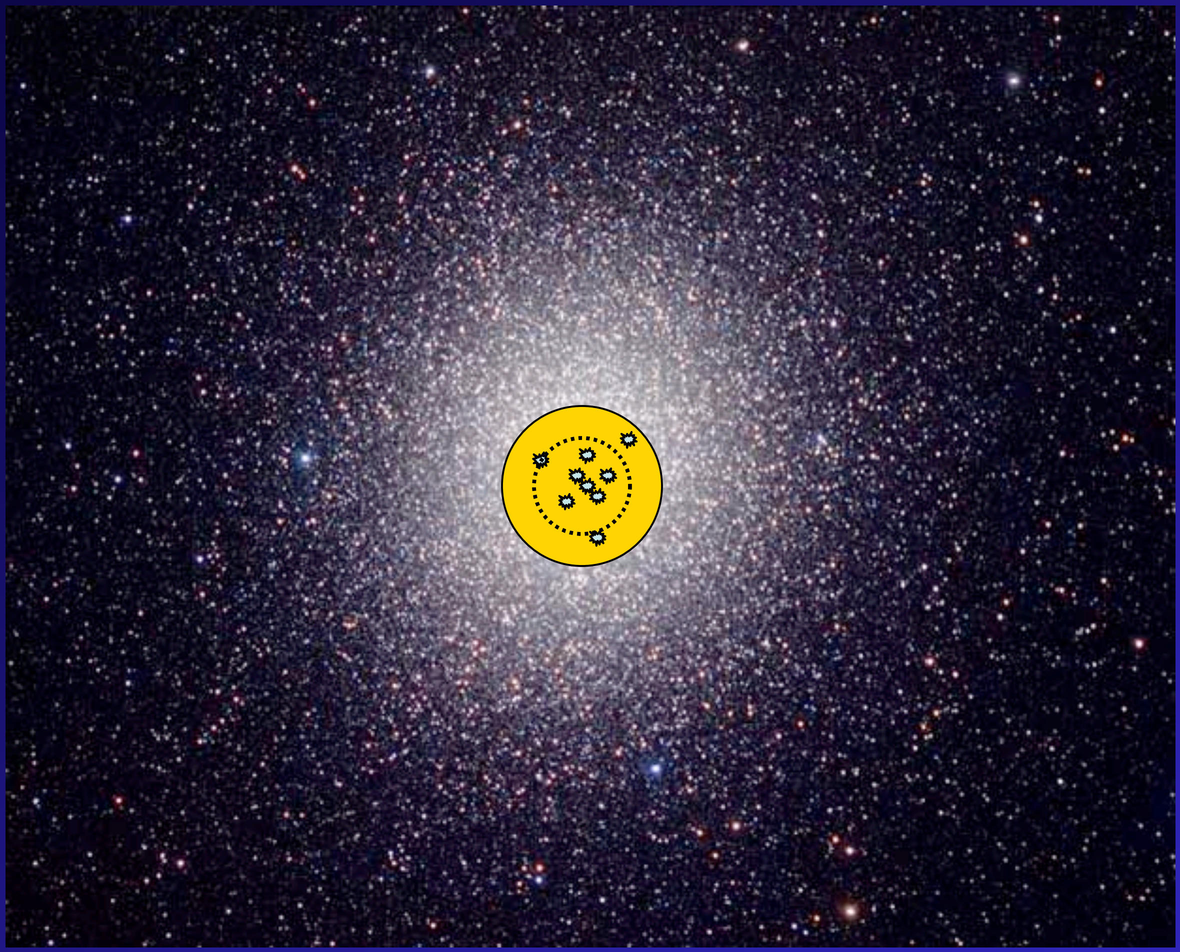
When does massive become supermassive? Above 10^6 Solar masses, GCs show traces of new correlations including a mass/metallicity relation -- bimodality still present but blue sequence moves closer to red





New photometric sample of 12000 clusters above 10^5 M_0 in 6 giant ellipticals. Largest GC sample in existence!

Harris et al. 2006, ApJ 636, 90
Harris 2009, ApJ 699, 254



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 still mostly gaseous at this point)

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

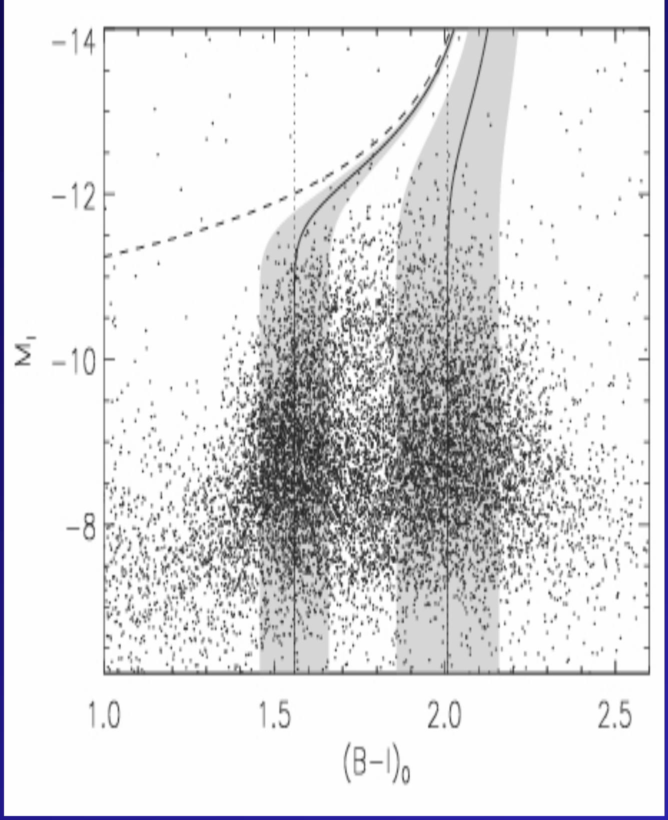
Z-retention scales as

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

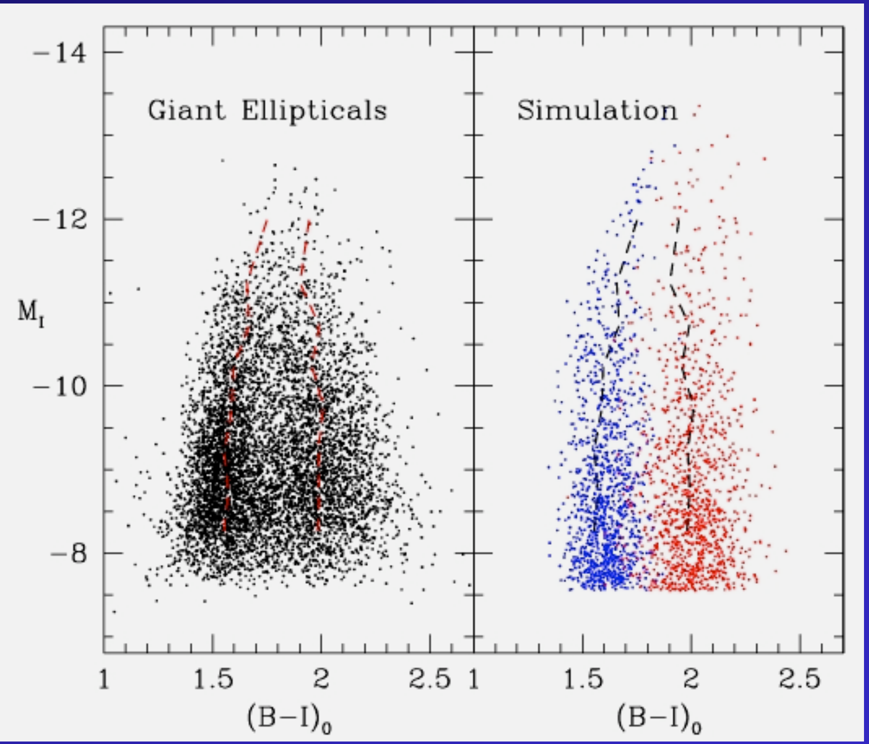
Bailin & Harris 2009, ApJ 695, 1082

~ 1/e at 4×10^7 M_0 (protocluster mass)

Combined effects of pre-enrichment & self-enrichment



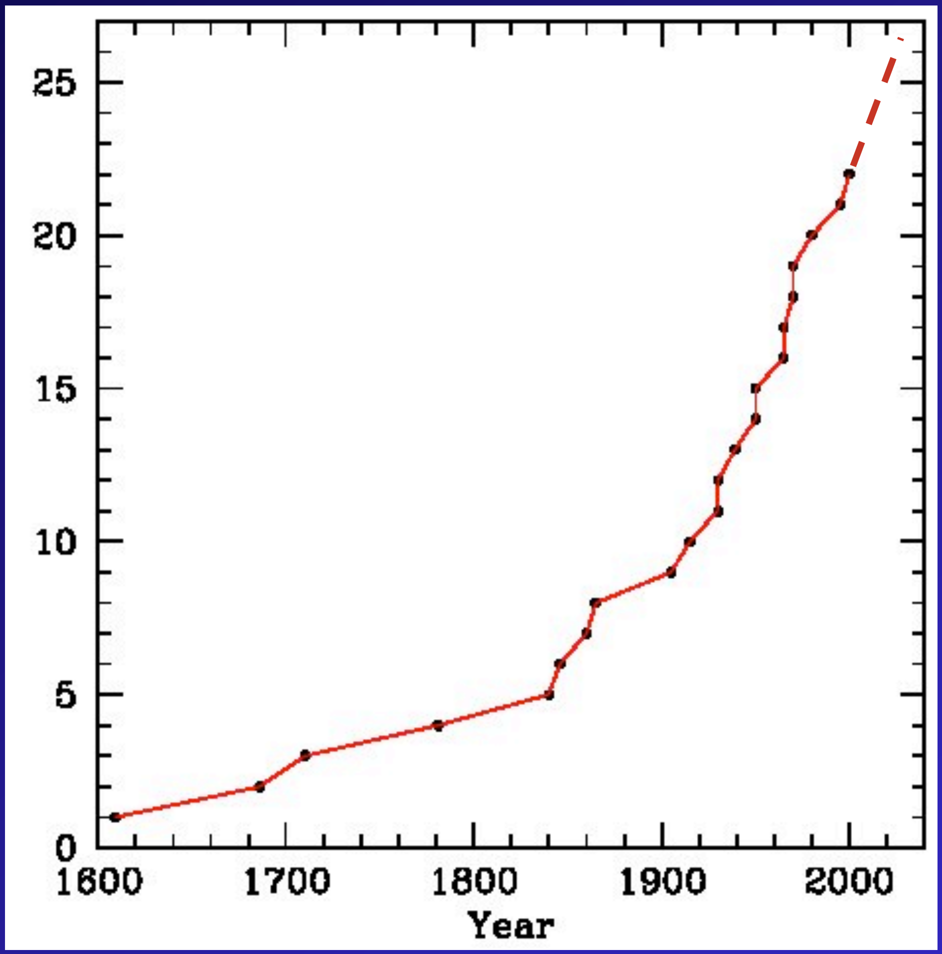
The mass/metallicity correlation should be nonlinear. For $M < \sim 10^6\ M_0$, sequences nearly vertical.



Very metal-poor, *very* massive GCs should be rare (anywhere). Are UCDs just these top-end, self-enriched objects?

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

Lots of new discoveries to be expected! on both the observational and computational fronts.



How long before the next big thing?
Empirical discovery rates --> every 7-10 years or so

Prediction is difficult, especially about the future.
Neils Bohr

Discovery vs. Understanding

The discoveries

The science

The guaranteed recipe for making discoveries:

(1) Study everything you can about the subject, including what others have said.

(2) Think about it night and day.

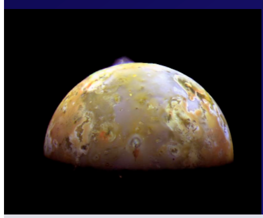
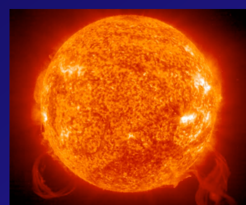
(3) Wait for inspiration to strike.

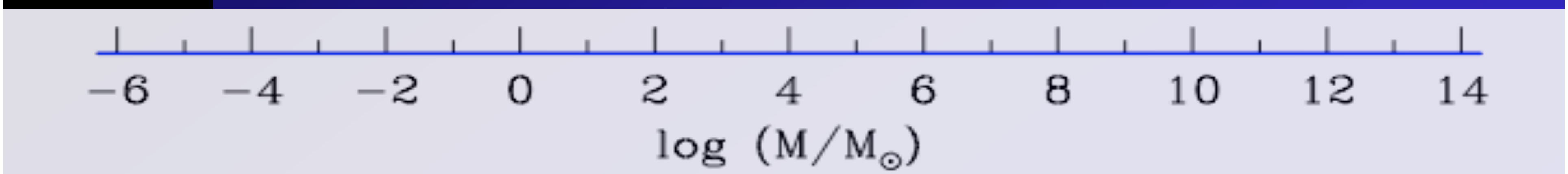
A discovery is an accident meeting a prepared mind. (Albert Szent-Gyorgi)

Look and you will find it -- what is unsought will go undetected. (Sophocles)

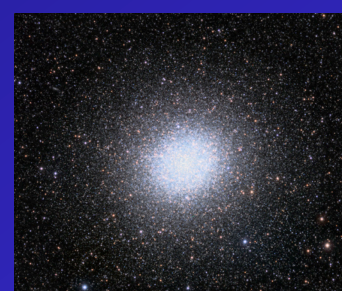
When you seek it, you cannot find it. (Zen proverb)

A philosopher once said, “It is necessary for the very existence of science that the same conditions always produce the same results." Well, they do not. (Richard Feynman)






From so simple a beginning, endless forms most beautiful and wonderful are being evolved. (Charles Darwin)