# *The Astrophysics of Massive Star Clusters:*

# *Formation and Evolution*

Seminar for McGill Graduate Student Workshop

August 27, 2009

47 Tucanae:  photo by L. K. Tan

## *Globular clusters are …*

Fundamental testbeds for evolution of low-mass 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 DM

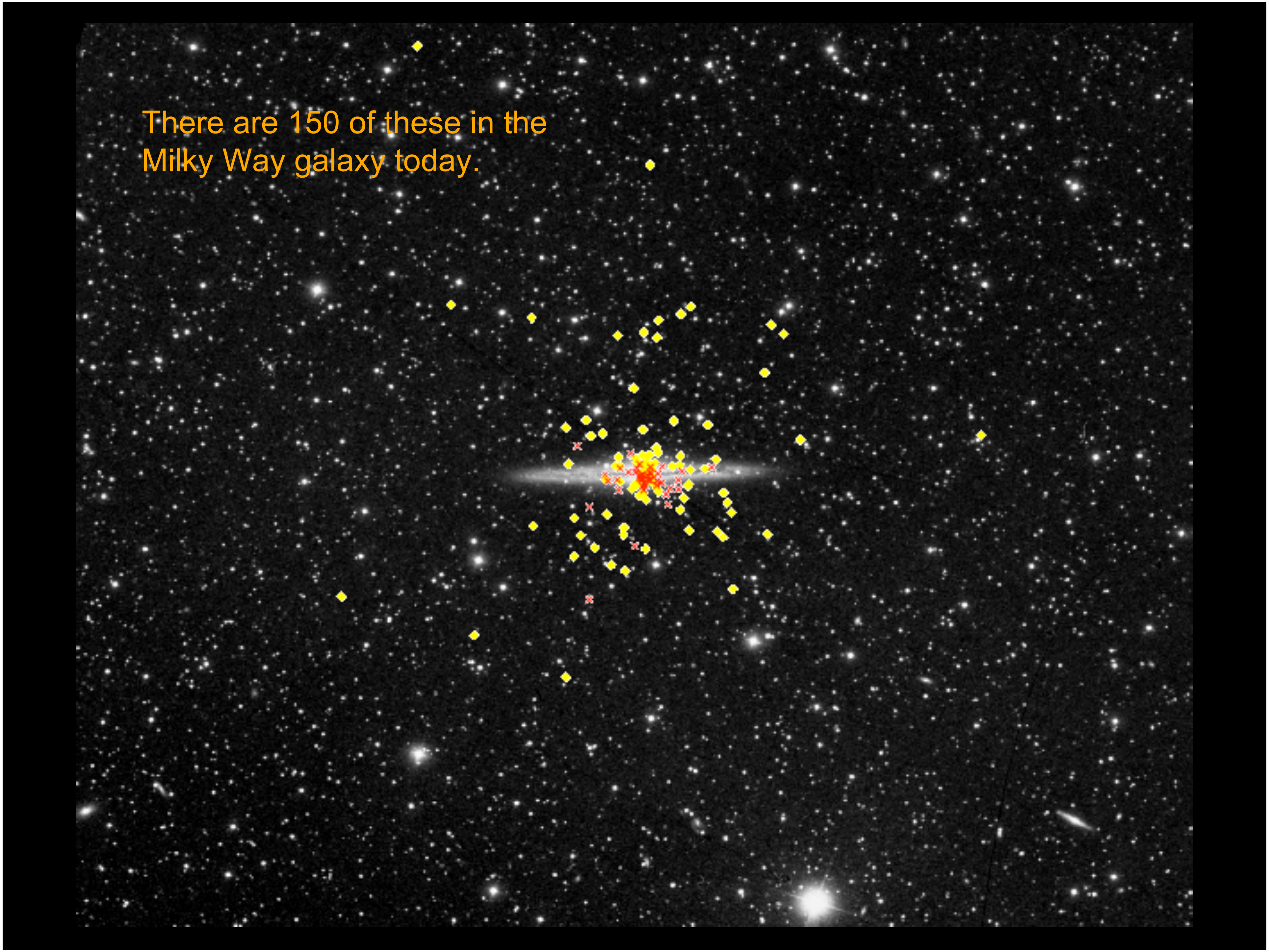
Oldest stellar structures in the universe: unique windows on earliest star formation in galaxies

What were the pregalactic clouds like at the beginning of hierarchical merging?

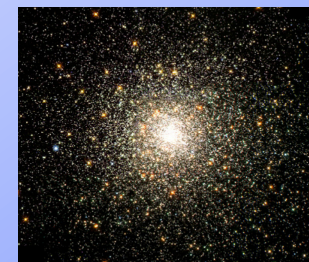
Starburst, merger, and chemical evolution histories of galaxies

Dynamics of high-density N-body systems (N--> $10^7$)

*They are everywhere!*


There are 150 of these in the
Milky Way galaxy today.

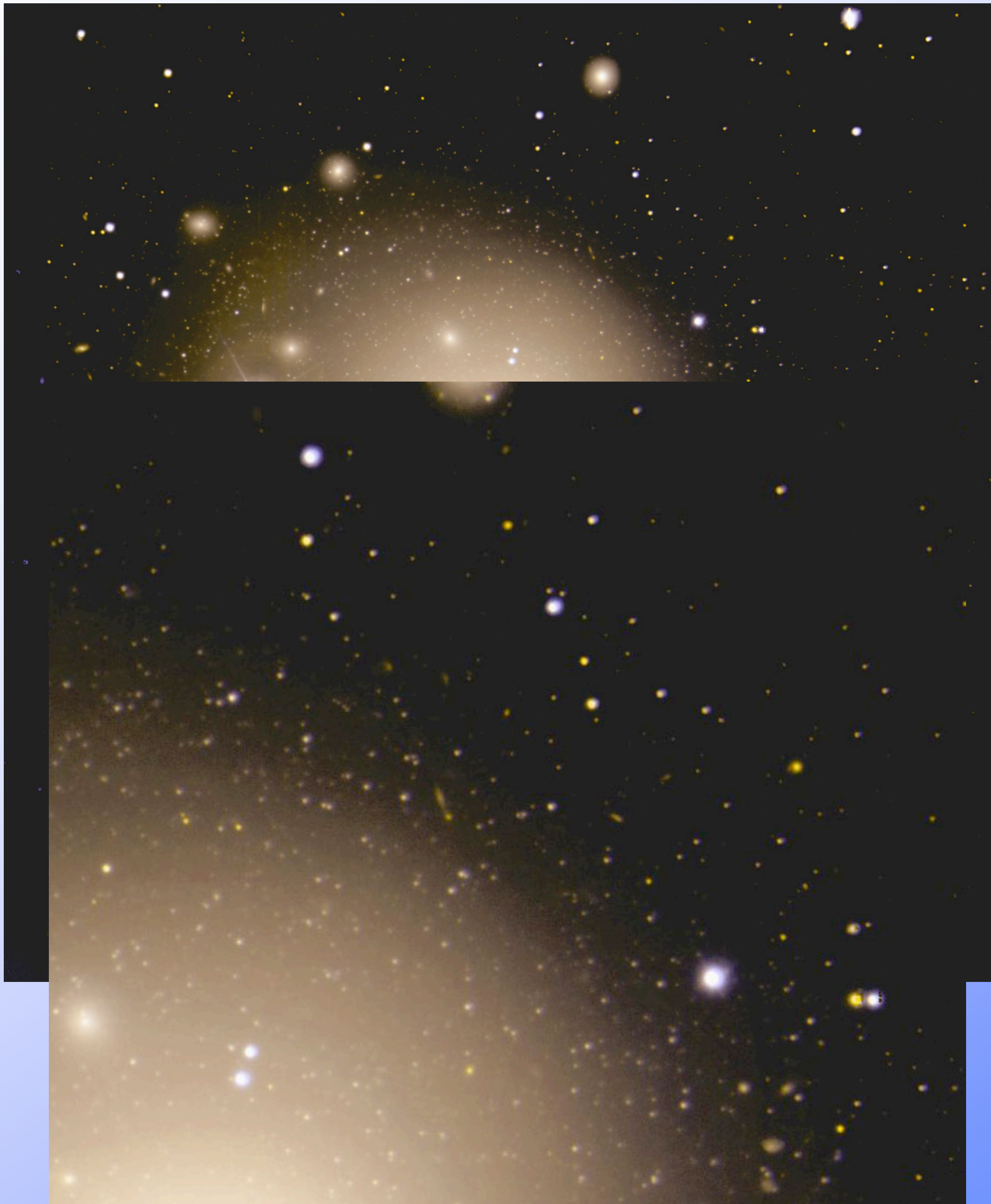
M31 (Andromeda) has ~400 of these



M104 (“Sombrero”) has ~1900

M87 (Virgo cD supergiant) has ~14,000

NGC 4874 (Coma cluster cD) has > 30,000



NGC 3311/3309 (A1060)

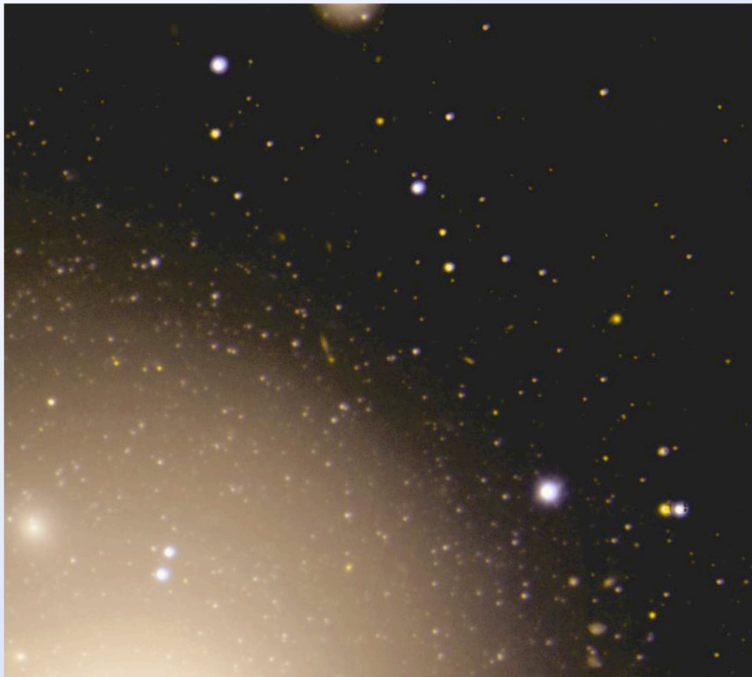
d = 50 Mpc

2 $r_h$ ~ 6 pc → 0.025”

fwhm(PSF) = 0.5”

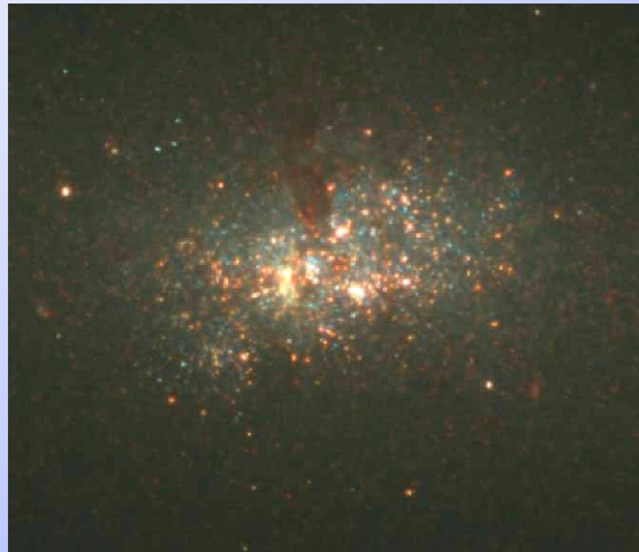
→ starlike! Even with HST resolution. In distant galaxies the GCs are visible as a *statistical excess of point sources* spatially concentrated around the host galaxy

# *Formation? Necessary conditions?*



Wehner && 2008

Gemini/GMOS



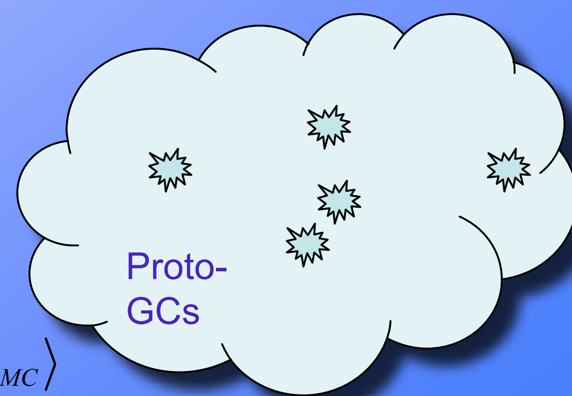
NGC 5253 HST

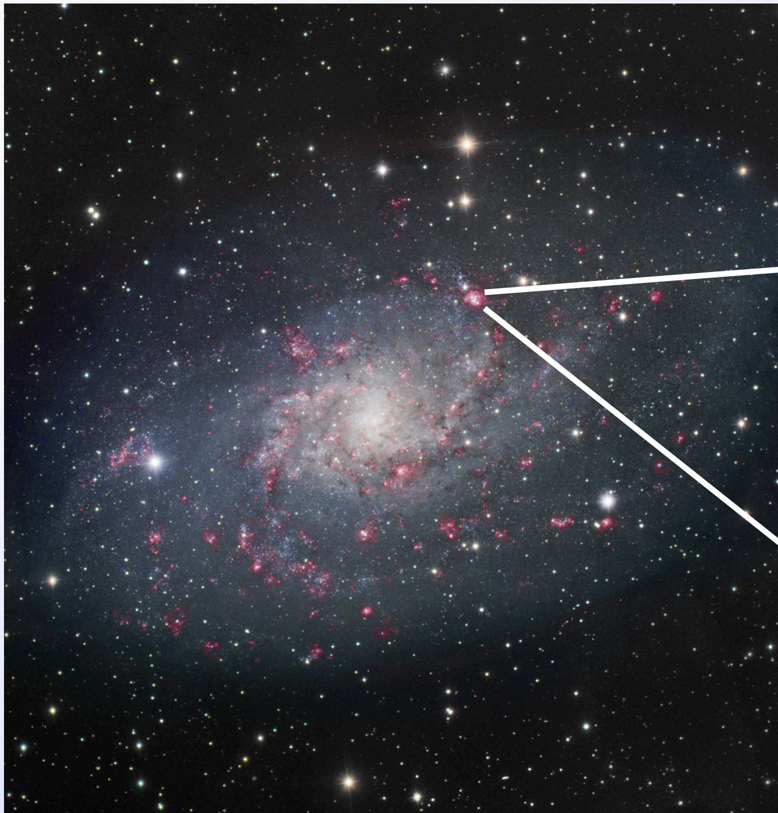
Young Massive Clusters (YMCs) forming in starburst dwarfs today

*A large reservoir of gas is needed to make one of these objects*

Pregalactic dwarf

$$\langle M_{GC} \rangle \leq 10^{-2} \langle M_{GMC} \rangle$$

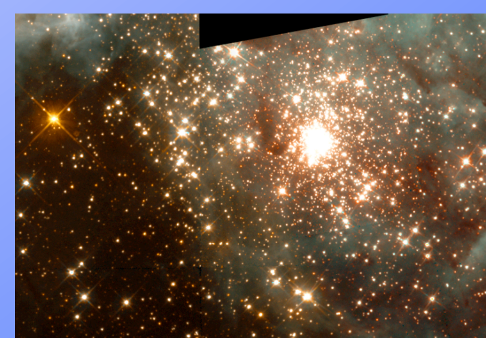




M33 (photo Rbt. Gendler)

NGC604 (M33)

30 Doradus
(LMC)



Cluster R136

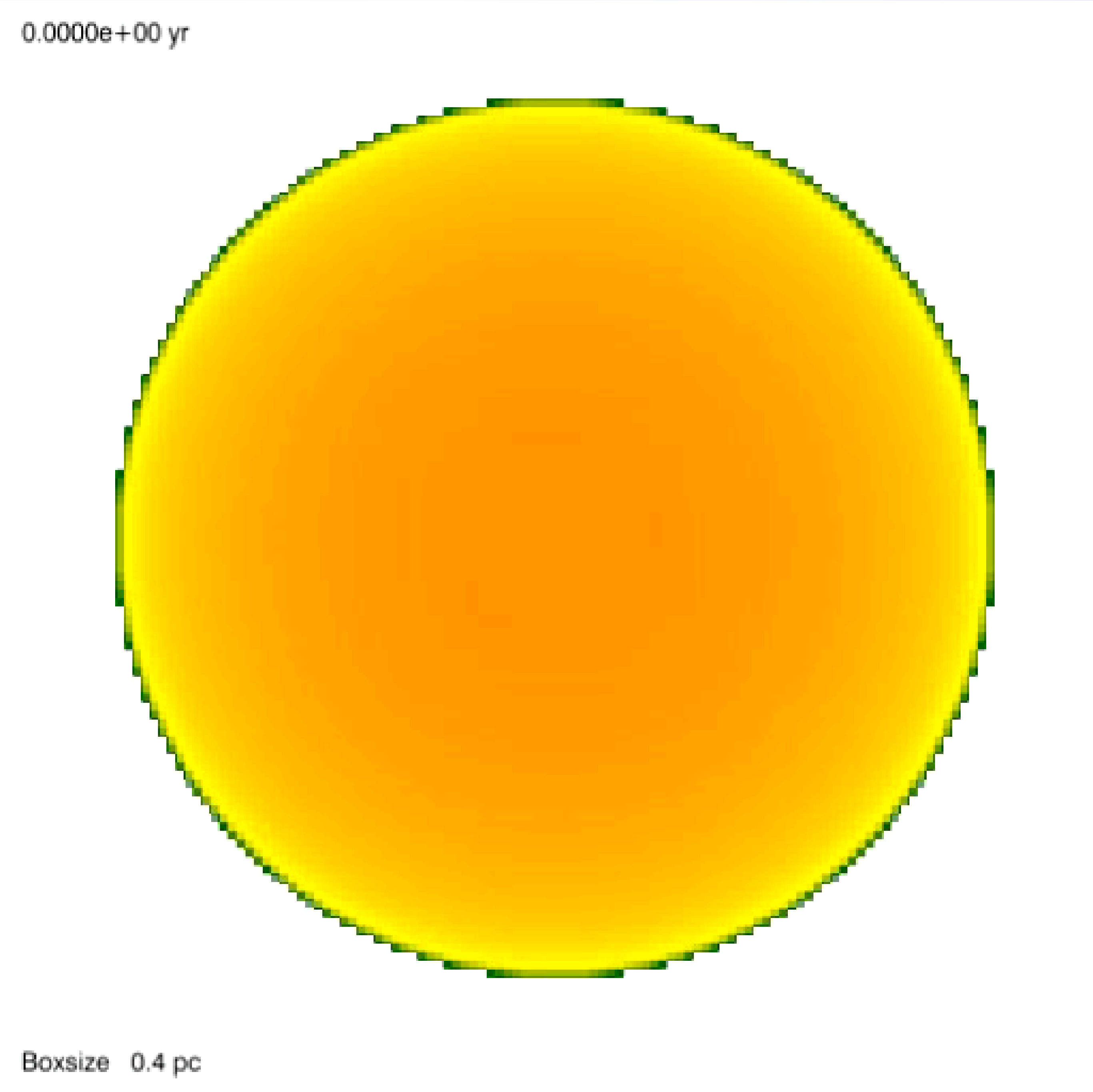
Age < 4 Myr

M = 60,000 $M_0$

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

Hubble Heritage image

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




Banerjee & Pudritz (2009)

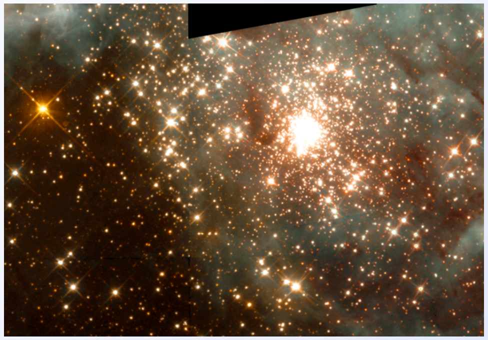
100-Solar-mass cloud

*Cluster formation is expected to be*

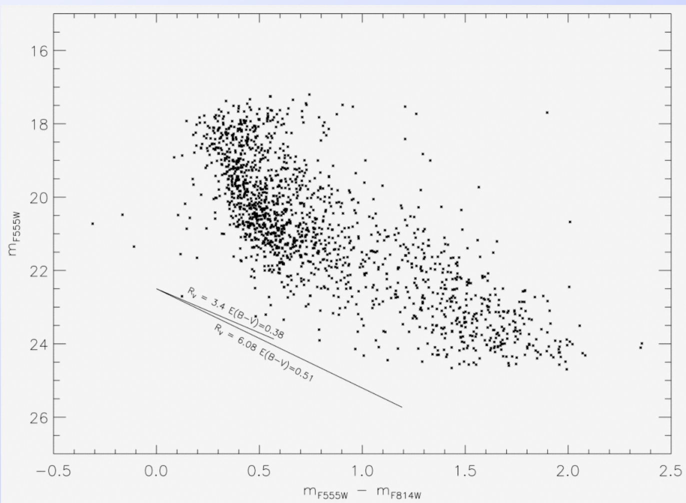
*- Clumpy*

*- Rapid*

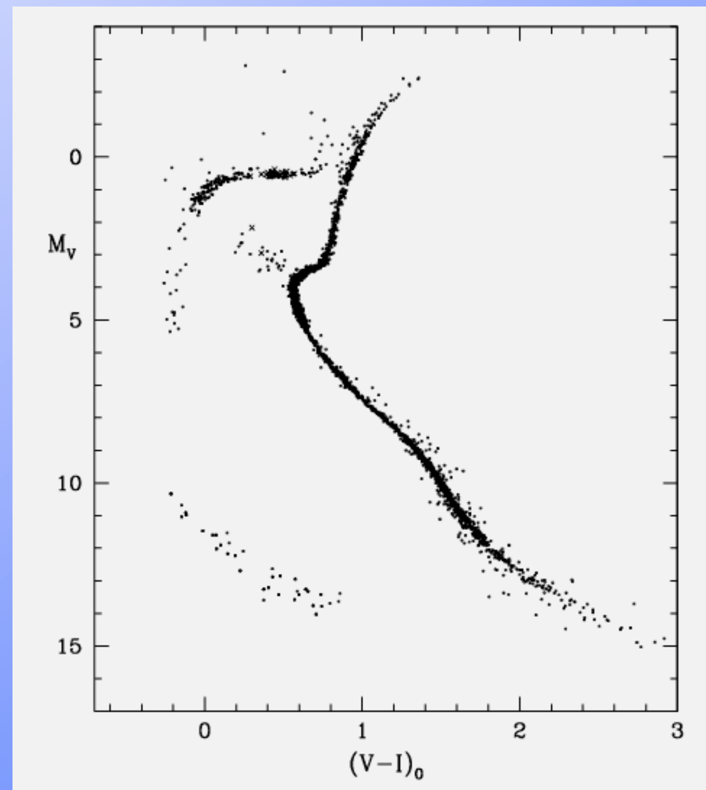
*- Asymmetric*



12 Gyr step.  What happens in between?




Sirianni && 2000

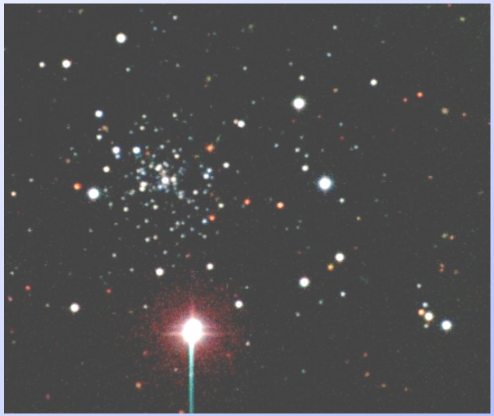


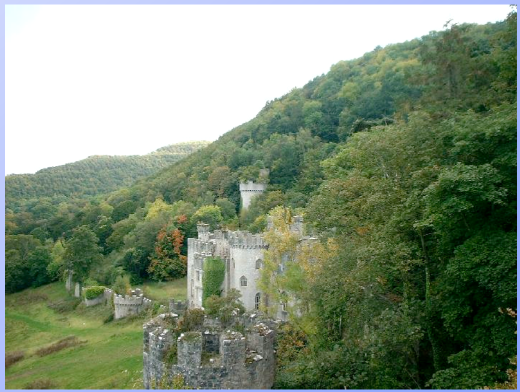

Harris 2003

M80 (Hubble Heritage image)

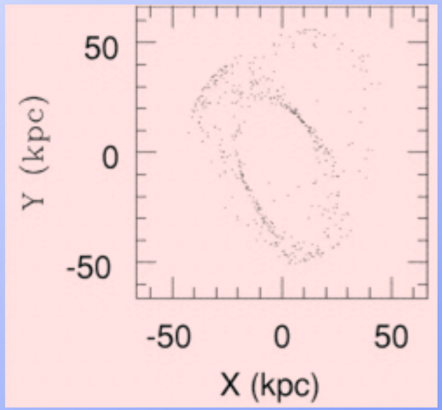
Dynamical age

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





Johnston et al. 2002




Why does a cluster evaporate with time?
(Why does it stay in near-equilibrium so long?)

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

Virial equilibrium:

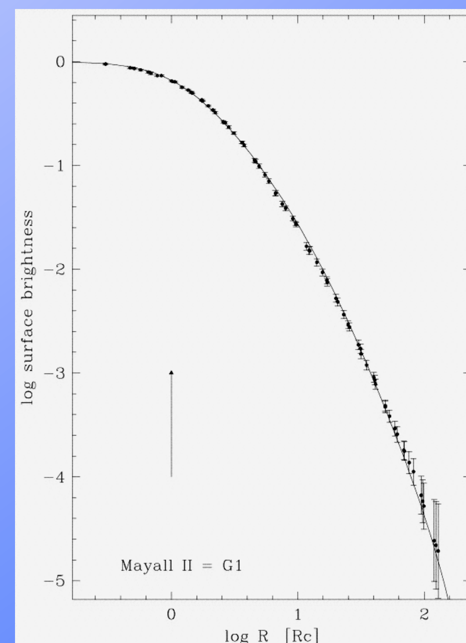
$$E = U + K \qquad \text{Where} \qquad K = -\frac{1}{2}U$$

*Infinite number of possible equilibrium velocity distributions, thus density profiles*

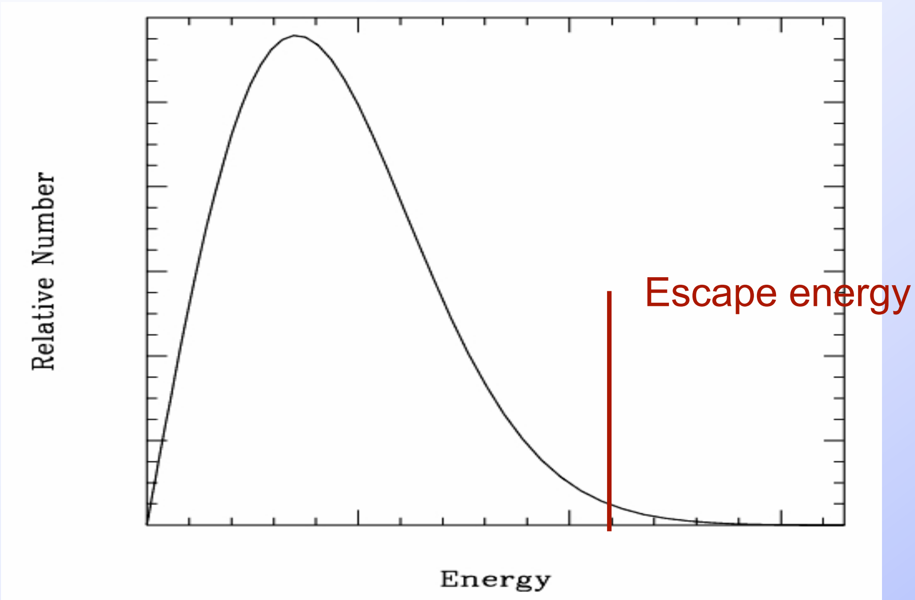
*BUT: 2-body interactions (large N!) gradually set up a nearly ideal Maxwellian distribution; relaxation time is ~$10^8$ years*

*Also include* *tidal escape boundary*

*-->>>  "King model"*

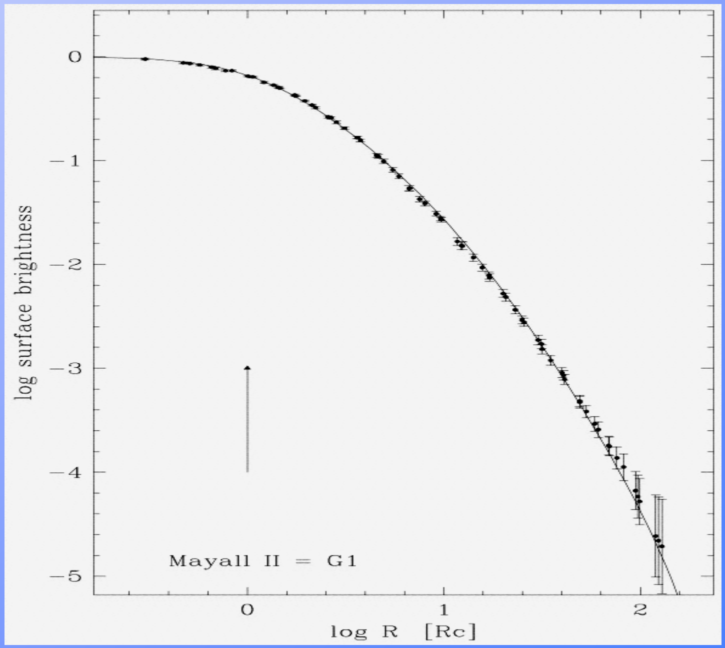


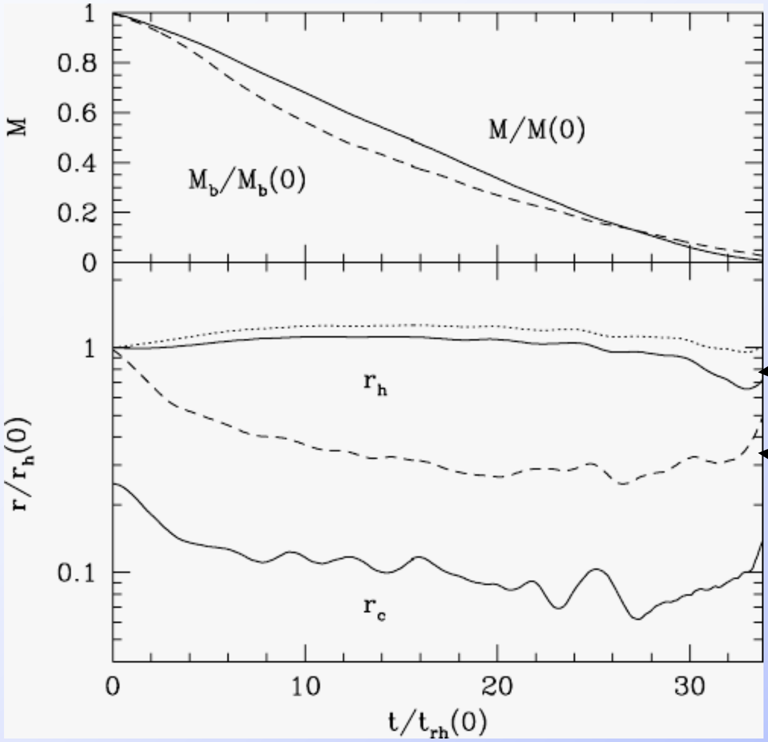

Meylan && 2001: M31-G1




Convert particle energy distribution to a density profile (2D projected)

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






Nearly linear mass loss with time. Stars continue to leak away … and the central concentration steadily increases

Single stars: $r_h$ is nearly constant!

Binaries!

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

Continual dynamical evolution will lead to *runaway core collapse*

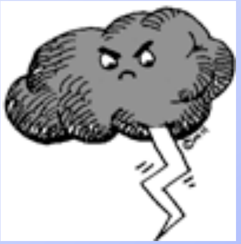
What will happen then?

Physical collisions between stars?

A single supermassive star at the center -- > hypernova?

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 $\rho_c \rightarrow \infty$ *in a finite time.*

Widely left as a puzzle for many years.

(A sociological detour …)

Classify scientific work by

***Innovation***

***Impact***

***Quality***

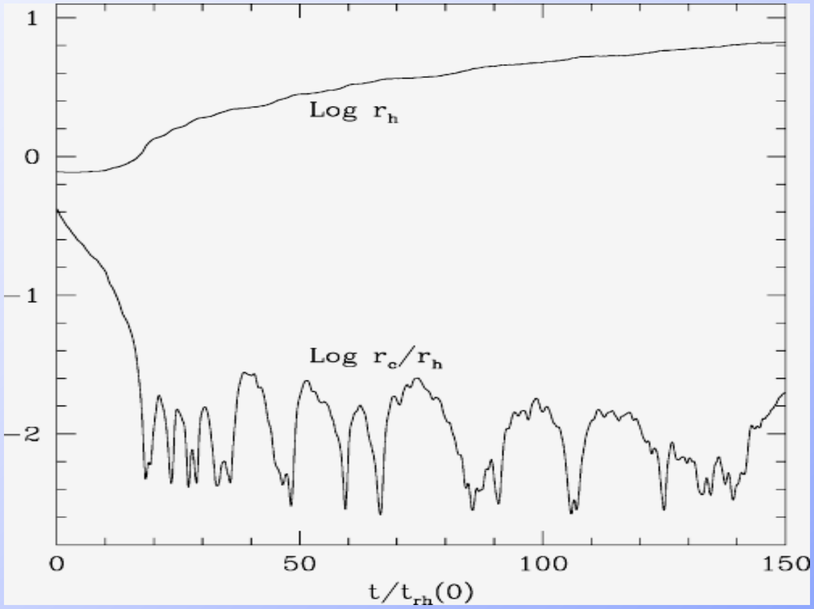
"It is notoriously difficult to select from among unmade discoveries those that will be the most useful." [John Polanyi, 1994]

"If we *knew* what we were doing, it wouldn't be research." [Anon.]

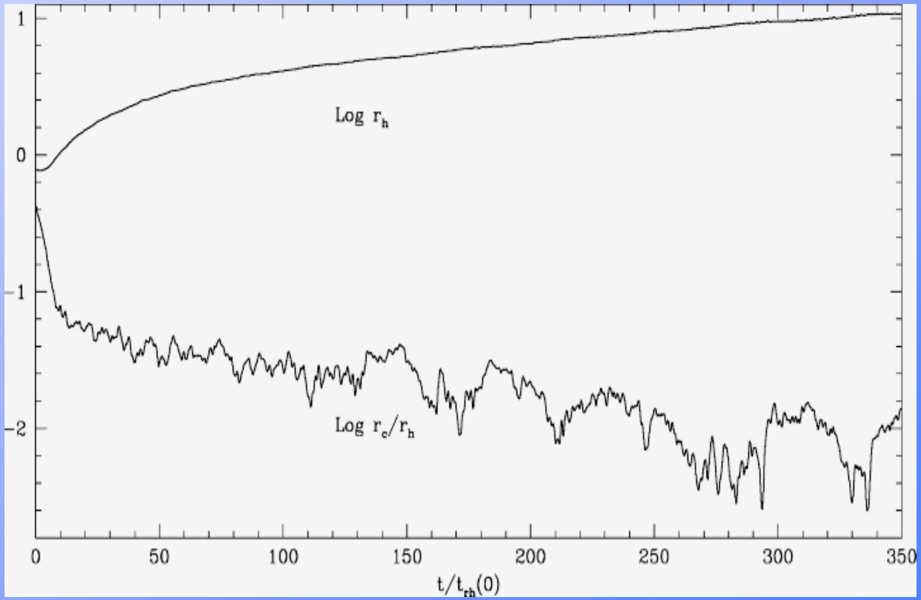
Binary stars will halt (and reverse!) the core collapse (Hills 1975; Heggie 1979), which would nominally happen after ~20 relaxation times $t_{rh}$

Core “bounces” and oscillates, or even avoids core collapse entirely

No primordial binaries



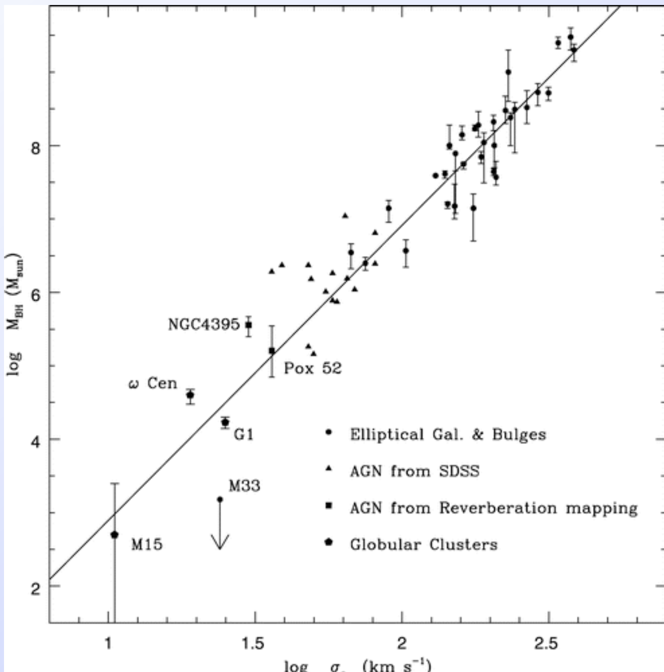

10% primordial binaries

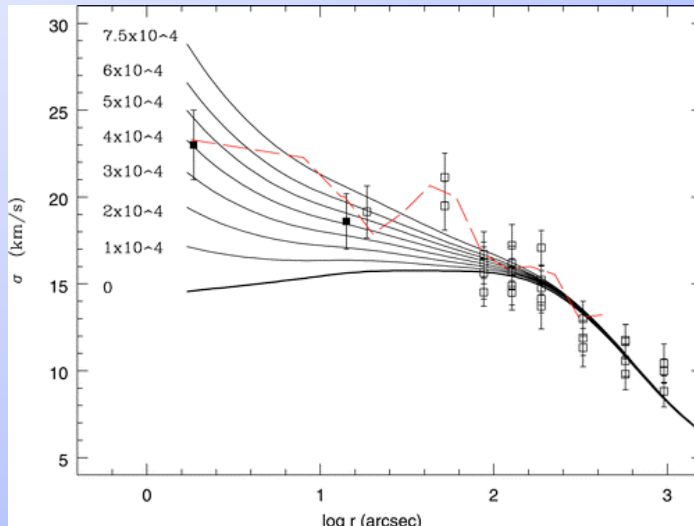



Heggie, Trenti, & Hut 2006

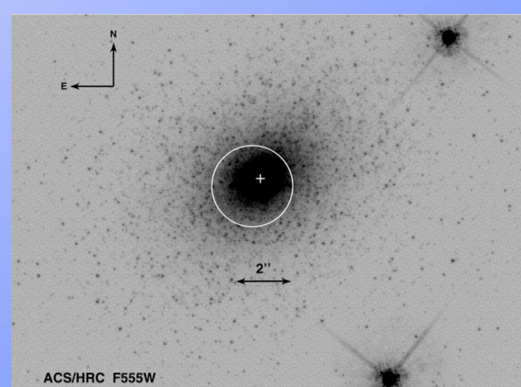
Nevertheless, black holes are still in the picture.

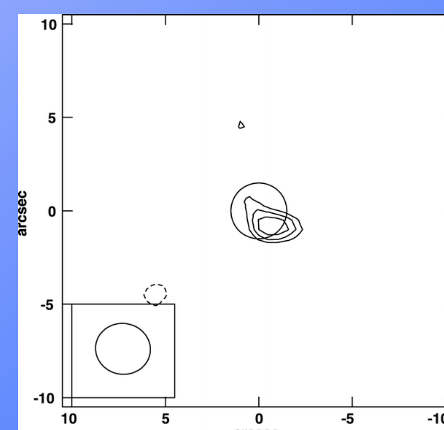
X-ray observations in the 1970's led to the discoveries of LMXB's instead, but IMBH's are expected for a different reason --




ω Centauri (Noyola & Gebhardt 2008)




M31-G1 (Gebhardt, Rich & Ho 2005; Ulvestad, Greene & Ho 2007); Kong 2007)

*Binding energy held by the cluster: KE + grav. PE, with constraint of Virial theorem*

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

*Distribution of mass inside the system ["central concentration" factor $c = \log(r_{tidal}/r_{core})$ ]*

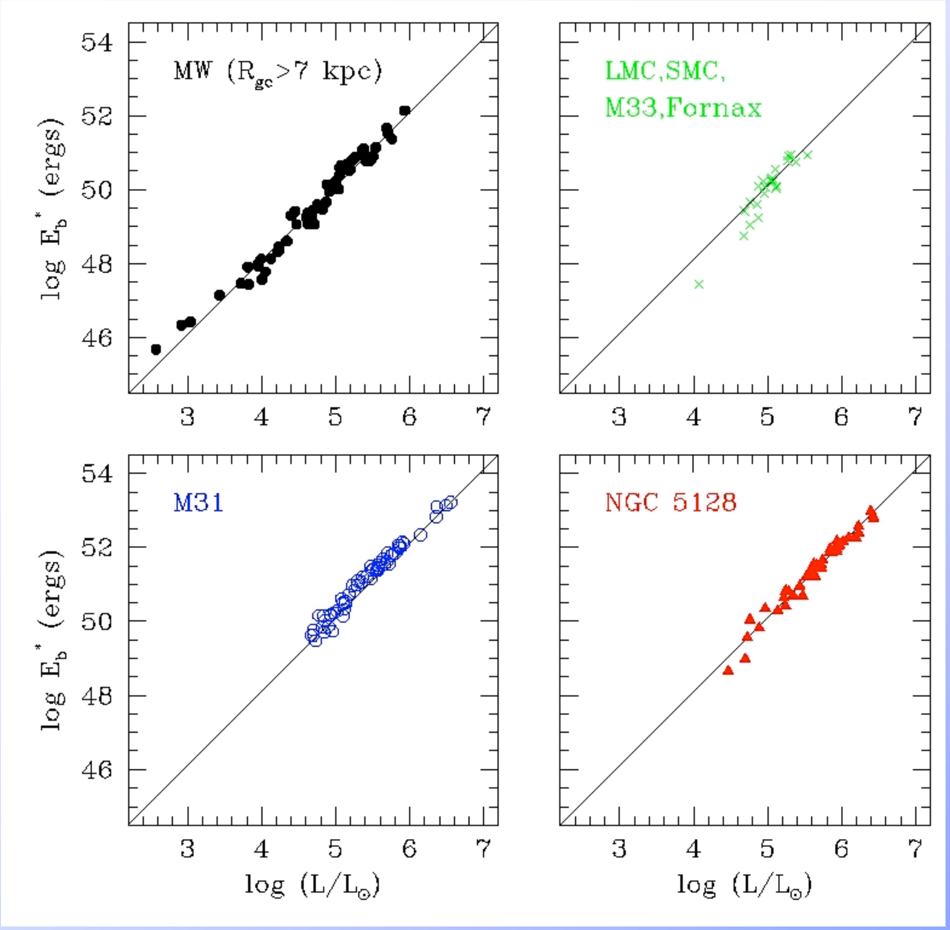
Uniform sphere + virial theorem

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

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-light" or effective radius $r_h$



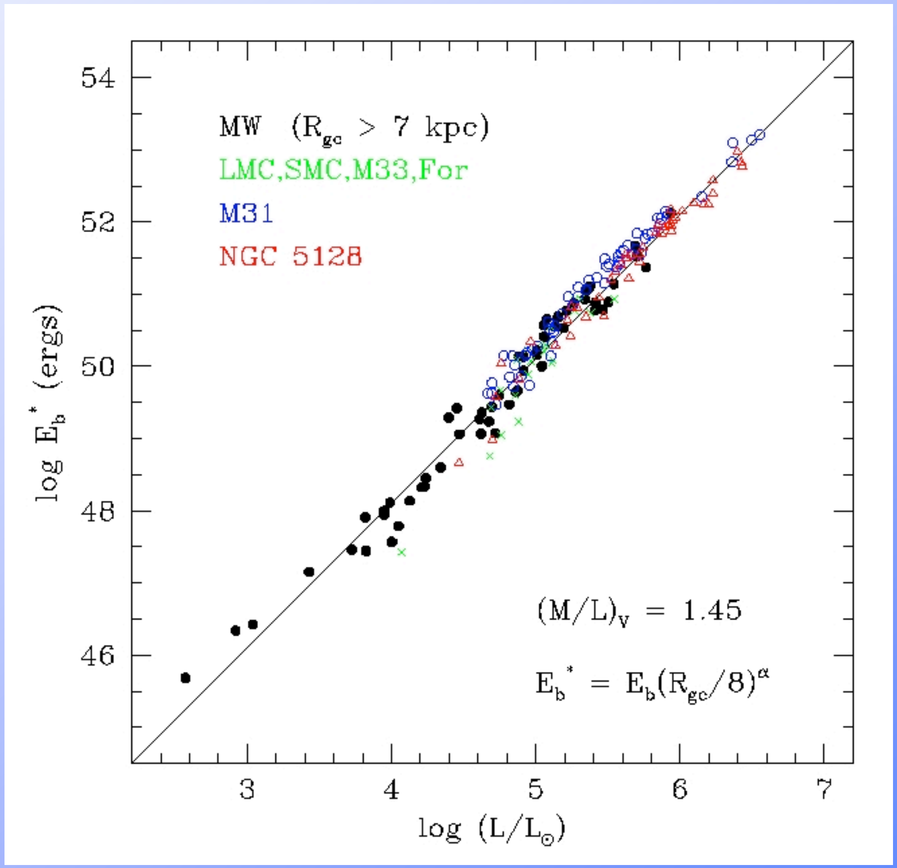

McLaughlin 2000;
McLaughlin et al. 2008;
Barmby et al. 2007

# *The binding energy plane*

$E_b(L)$ plane for all 7 galaxies

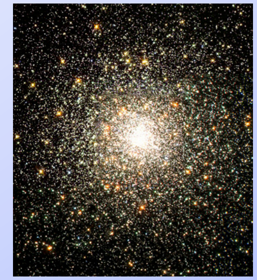
$E_b^* \sim L^2$ accurately over 4 orders of magnitude in L

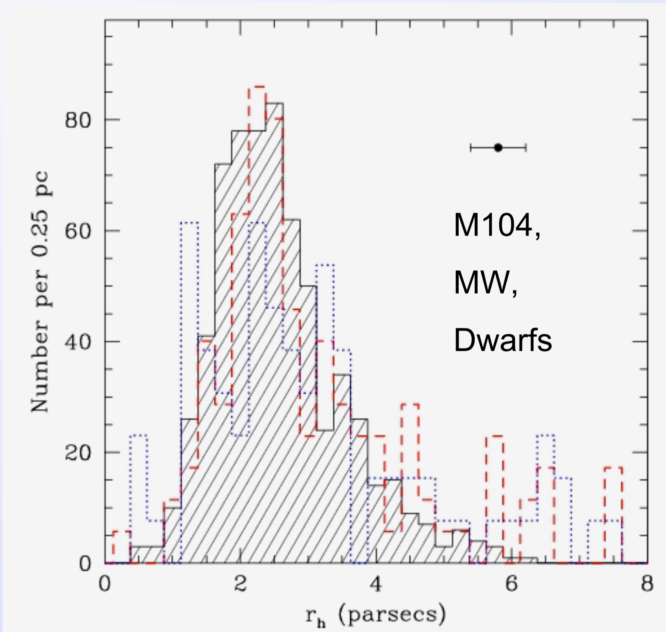
$$E_b = 0.24 \frac{GM^2}{r_h} = 0.24 \left(\frac{M}{L}\right)^2 \frac{GL^2}{r_h}$$




GCs have similar M/L and scale size independent of mass --> *very different from GMCs, E galaxies …*

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





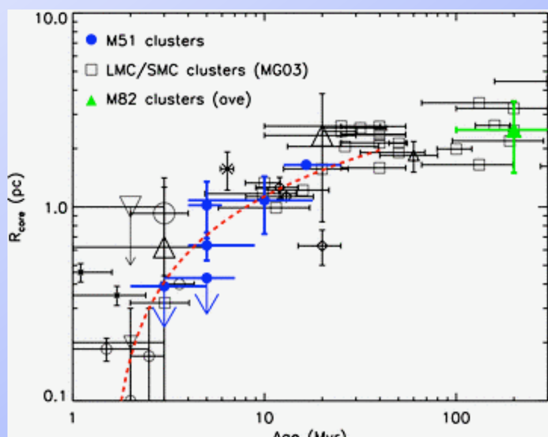

Remarkably similar in all galaxies  --> *environment plays a minor role.*  So then, what *local* conditions determine this distribution?

There are two phases of rapid structural evolution:

*- Core collapse*

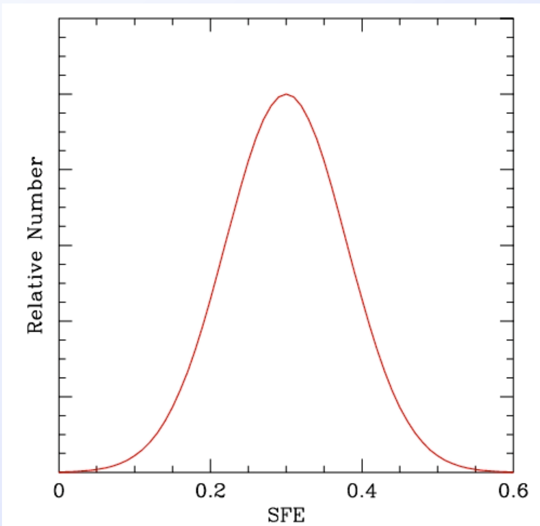
*- Protocluster epoch* with star formation and rapid gaseous mass loss (~40 Myr)

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




Bastian && 2008

After ~$10^8$ y, scale size $r_h$ ~ const [until core collapse].
The expansion ratio $R = r_h/r_h(0)$ depends on the star formation efficiency (SFE) and the gas "expulsion time"

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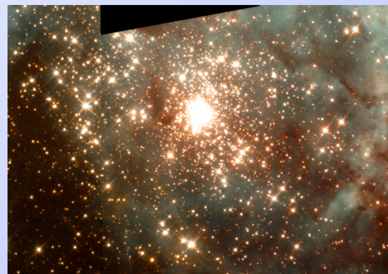
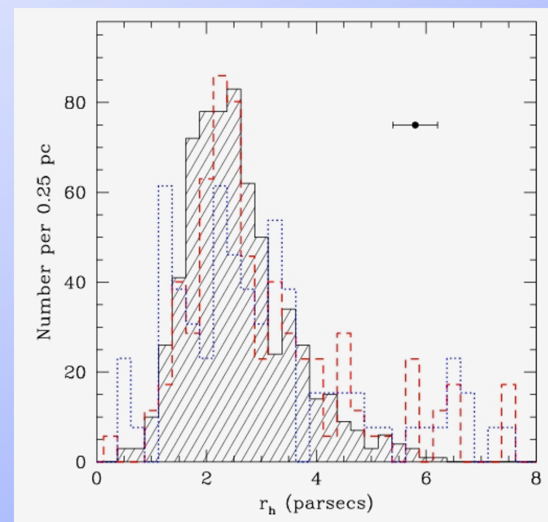
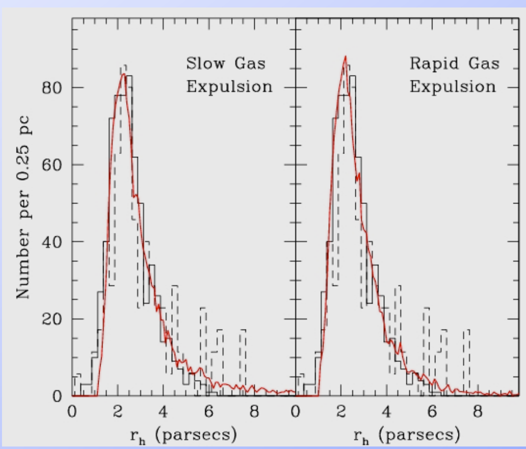
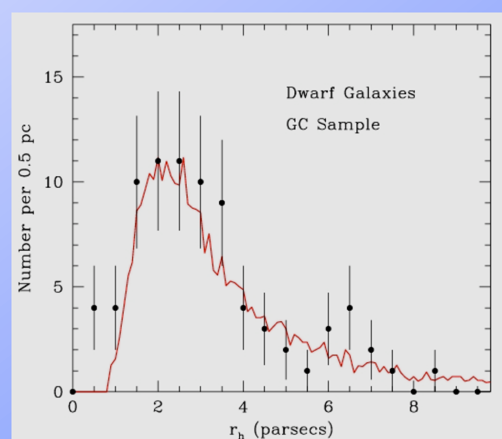





Harris, Spitler, Forbes & Bailin 2009

Mean SFE = 0.3 with

dispersion $\sigma$ ~ 0.08 ;

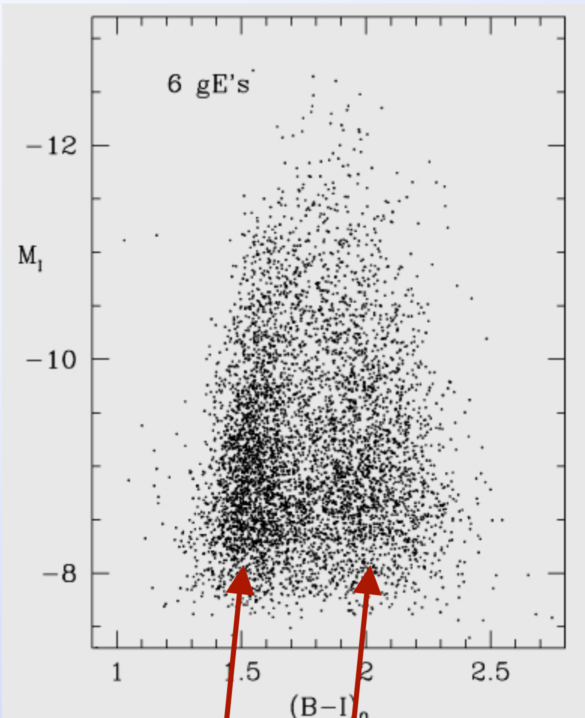
$r_h(0)$ ~ 0.8 pc

M87 (Virgo, d=16.5 Mpc)

Woodley et al. 2009

*Globular cluster populations in galaxies:
a hybrid field with much to tell*

supergiant E's

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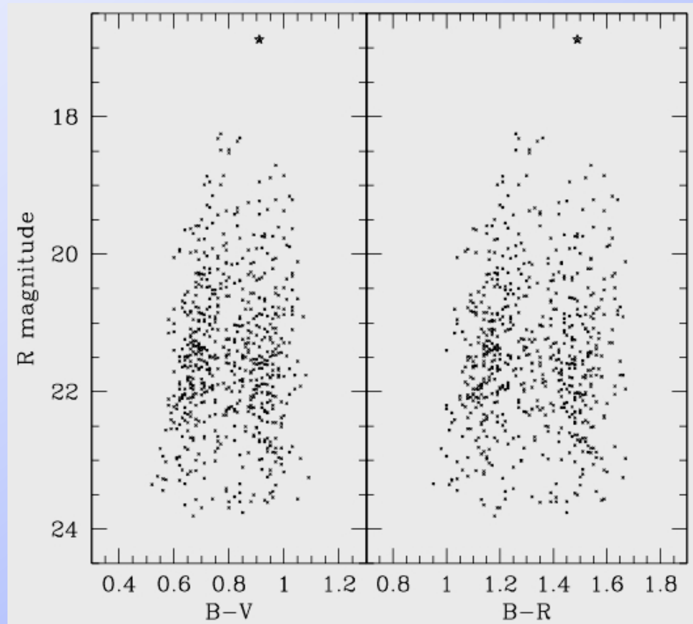
M104




Heavy-element enrichment Z

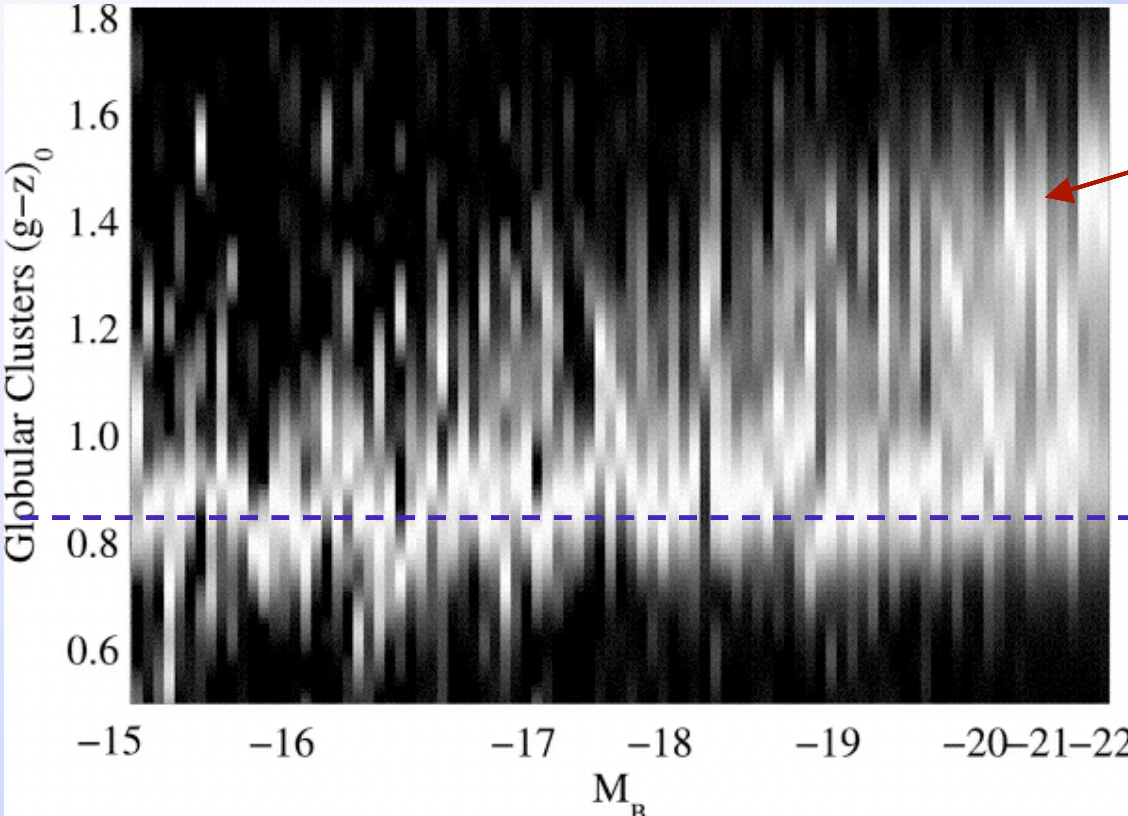
Two sequences: blue, red = low, high metallicity

*Bimodality*

The dispersions here represent real differences in Z

*Two major starbursts in the first few Gyr?*

Correlations with host galaxy luminosity
(Peng et al. 2006, Virgo Cluster Survey)

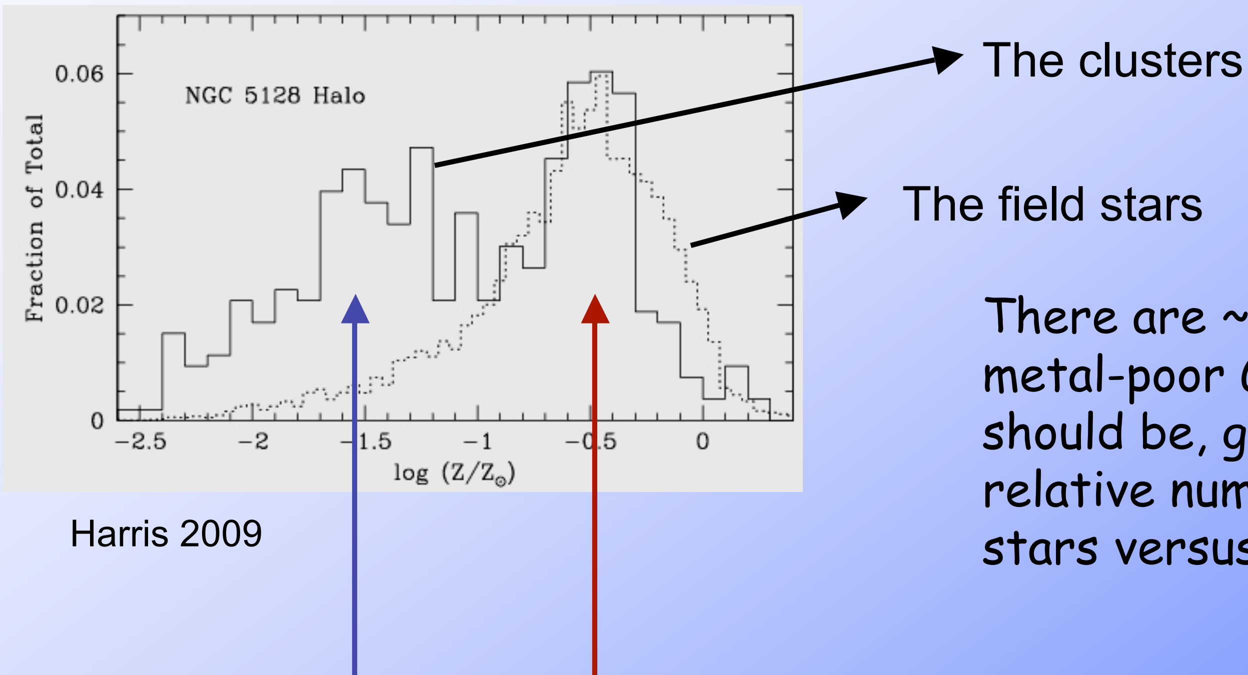



Red sequence more prominent in bigger galaxies

Blue sequence is always present and has nearly uniform metallicity

Higher enrichment levels are achievable with lots of gas in bigger, deeper potential wells

But there is a big, generic problem here: the *halo field stars* do not follow the same sort of metallicity distribution



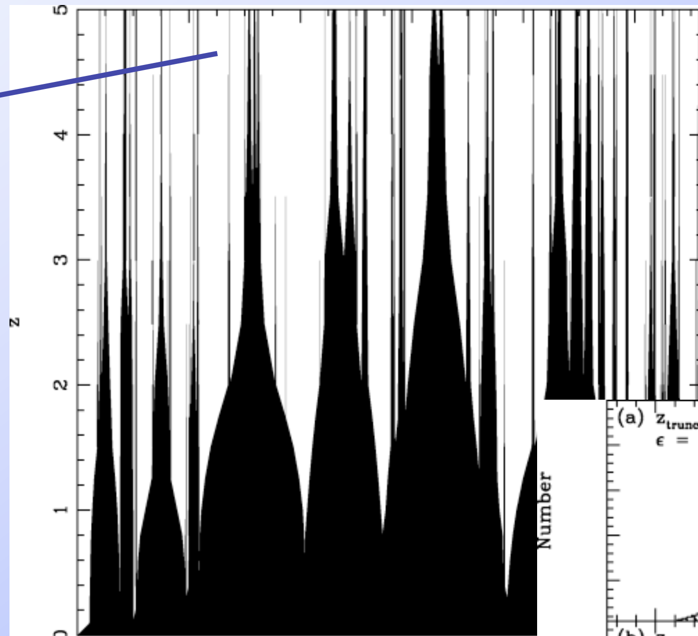

Harris 2009

There are ~5 times more metal-poor GCs than there should be, given the relative numbers of field stars versus metallicity.

Why are there so few metal-poor stars?

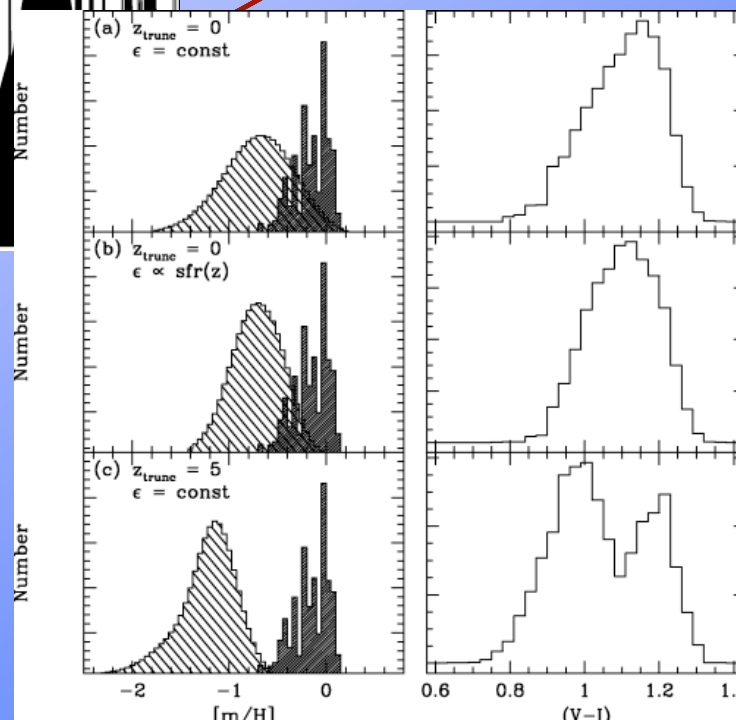
This mode is "normal". A giant galaxy is made up mostly of rather metal-rich stars (1/10 to 2x Solar). The metal-rich GCs formed as part of this step

"Merger tree" (example from Beasley et al. 2002)



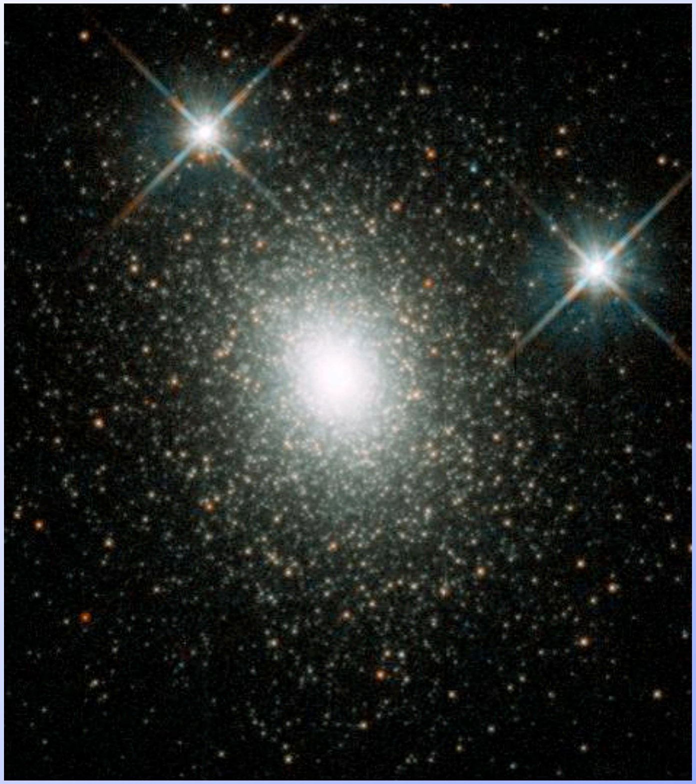

Low-Z "blue" clusters form up here, in the pregalactic dwarfs that are almost entirely gaseous and unenriched

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




Truncation of field-star formation at z(reionization)? (Beasley &&). High sensitivity of cluster formation to gas density? (Peng && 2008). Peculiar IMF or CMF?

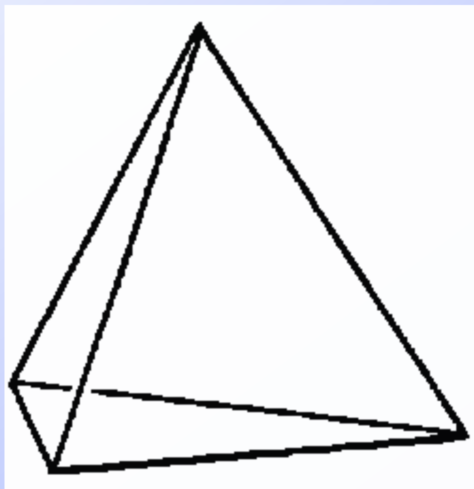
The origin of bimodality is not known.



*A lot depends on the events within the progenitor GMCs!*
*We need better questions -*

Where do ideas come from?

## *The Eigenfunctions of a Scientist*

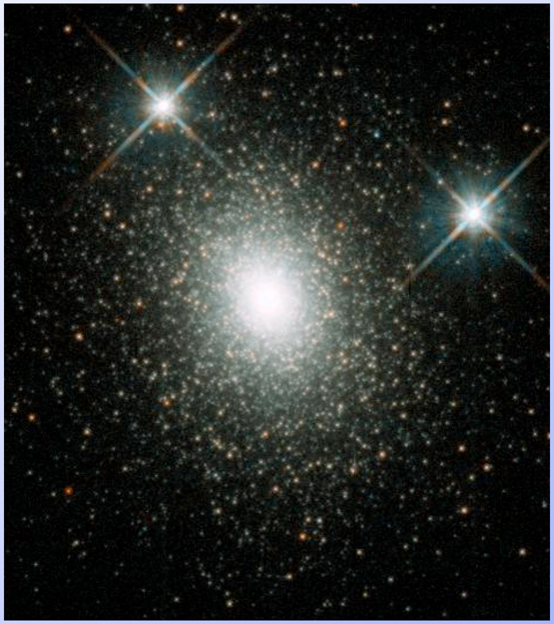



*How to be creative?*

- Study all you can about your subject, and related subjects
- Think about it all the time
- Wait for inspiration to happen.

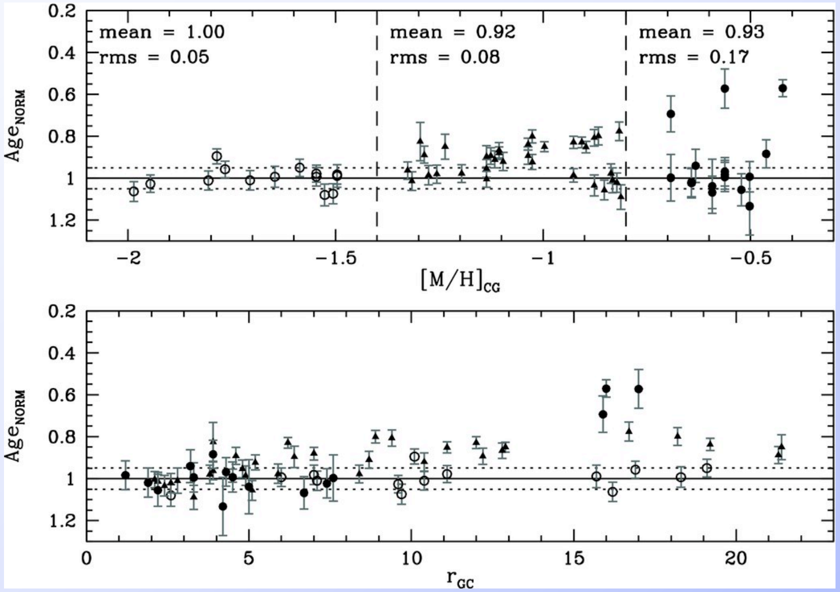
*Balance is essential ….*

# *Lots to do!*



McMaster University

# Enrichment Histories: Trends and Puzzles




Marin-Franch et al. 2009

Baseline data from the Milky Way show that chemical composition ramped up from 1/100 Solar to 1/2 Solar in the first 3 Gyr or less.

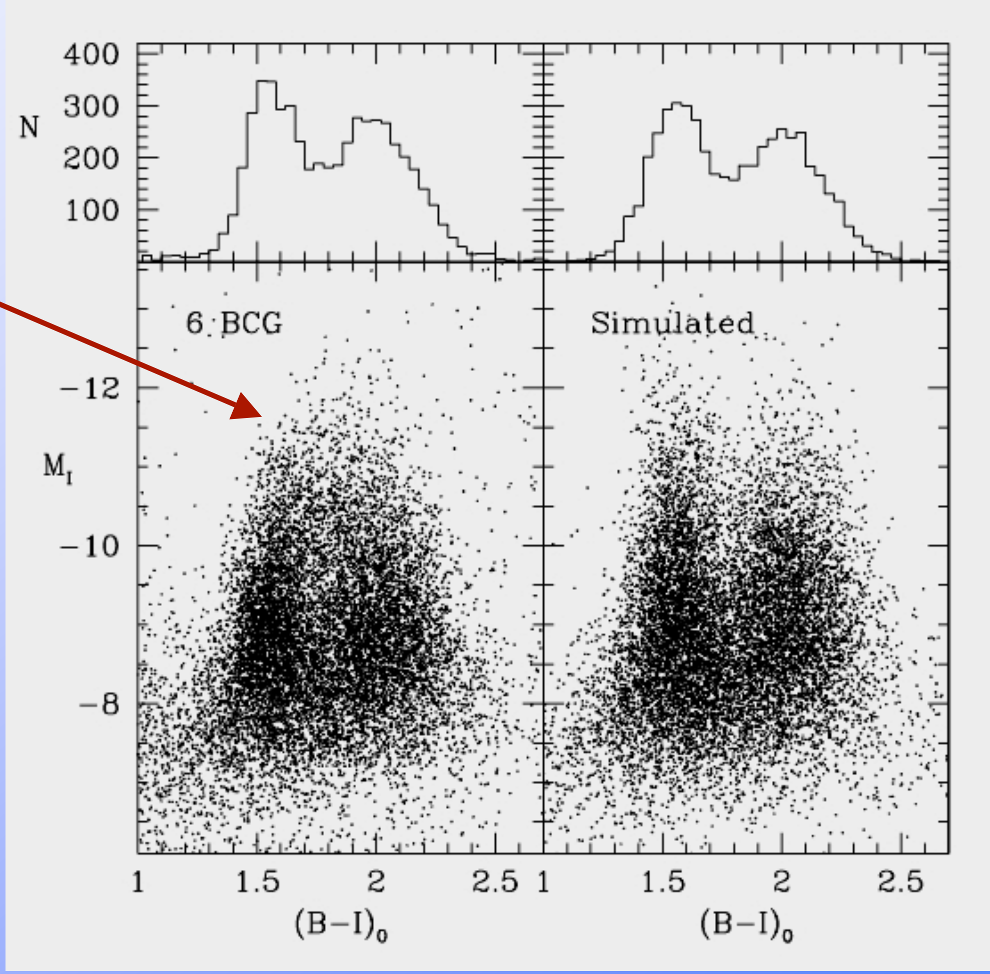
The low-metallicity clusters have the same age to within +-0.5 Gyr!

Later accretions from dwarf satellites may be important.

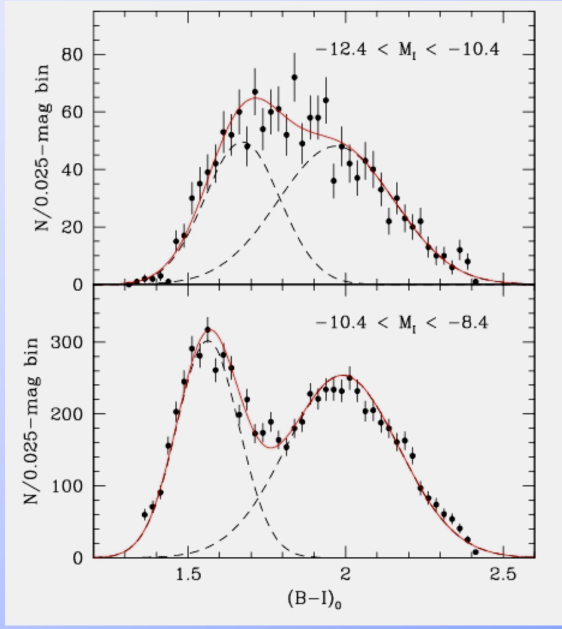
The high-luminosity, high-mass end seems to have some surprises.

What is going on here? The two sequences start to overlap. Why?

These are *supermassive* GCs (> $10^6$ Solar masses)

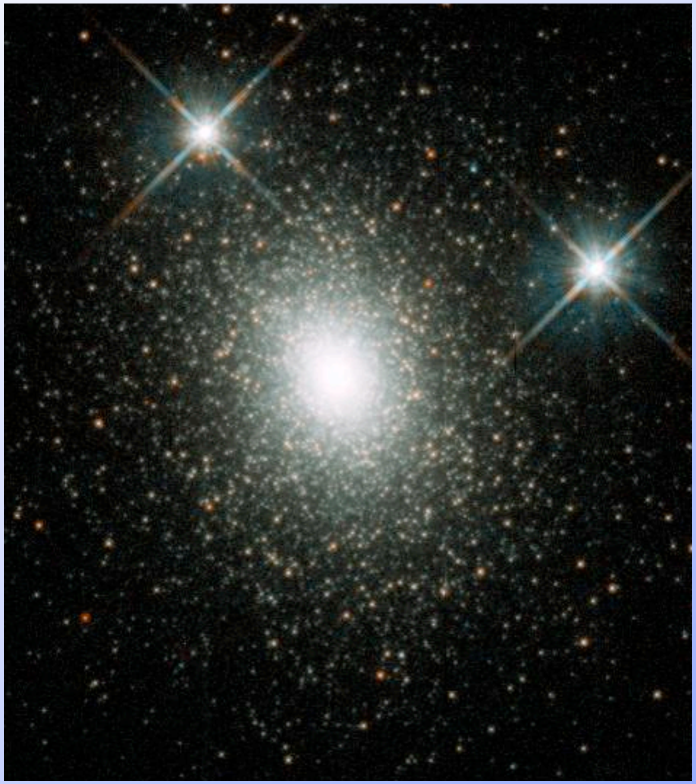



Harris 2009



McMaster University

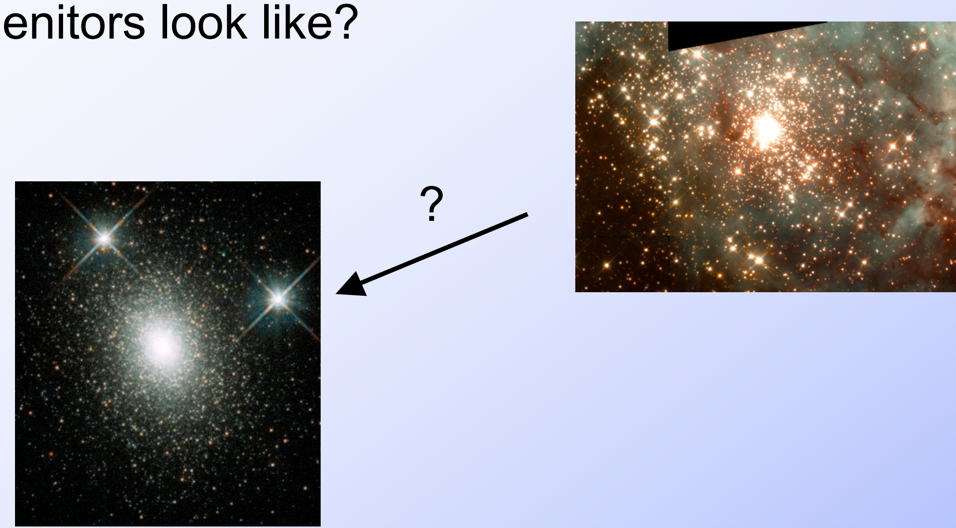
What do these supermassive GCs look like?



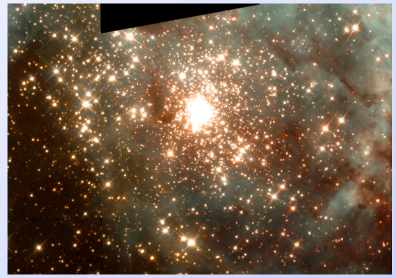
M31-G1

Omega Centauri

What did their progenitors look like?



*Need to draw from a gas-mass reservoir of > $10^9\ M_0$*



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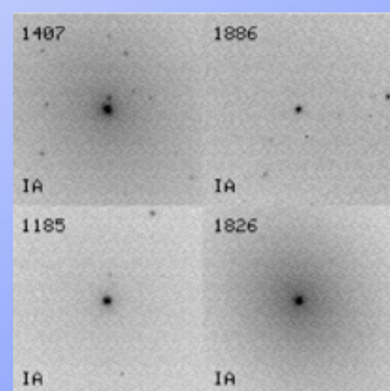
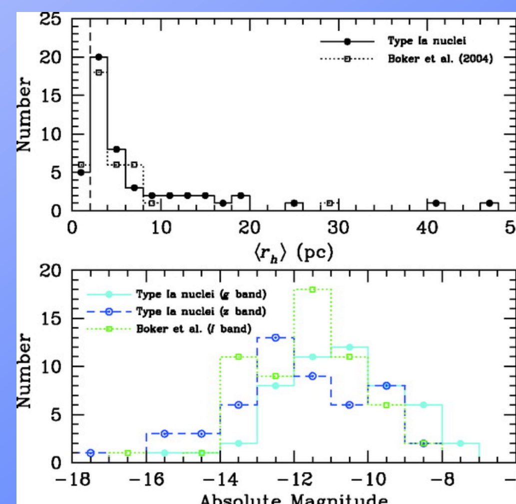
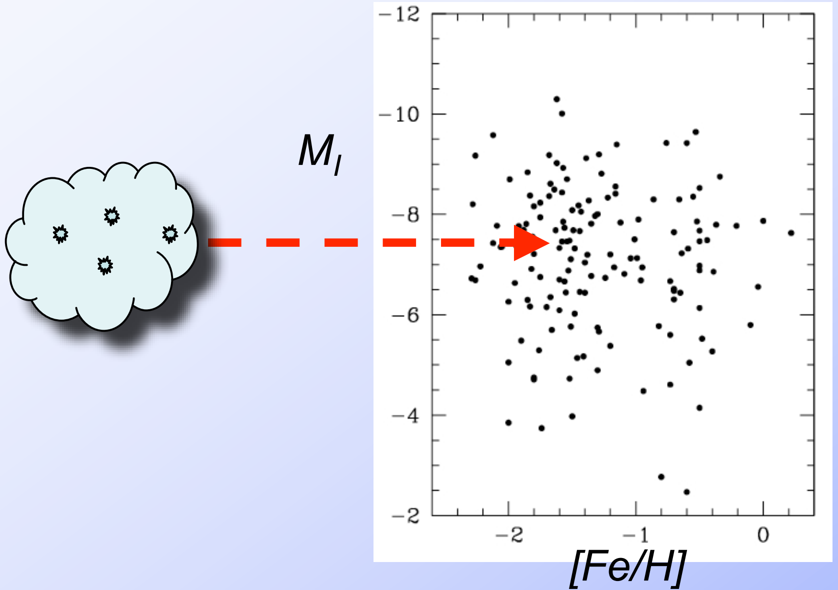



Cote et al. 2006

## What is responsible for the metallicity distribution function (MDF)?

*Bailin & Harris 2009*




Is a proto-GC:

- PRE-enriched from the surrounding GMC gas?

- internally SELF-enriched by its own SNe within the first few Myr?

- stochastic? (can self-enrichment be responsible for the internal *dispersion* of the MDF?)

Input assumptions to self-enrichment model:

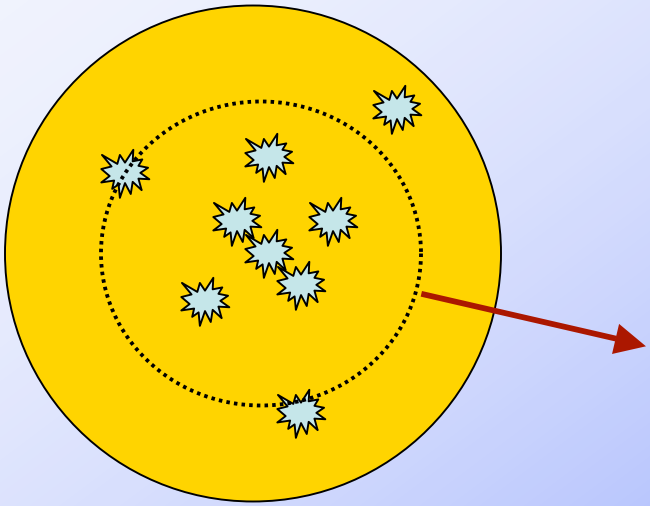
SNe from >8 $M_0$ stars enrich lower-mass stars *while still in formation*

Salpeter IMF 0.3 → 100 $M_0$ and SF efficiency $f_* \sim 0.3$

Woosley/Weaver SN yields, and fraction $f_Z$ of heavy elements retained in proto-GC

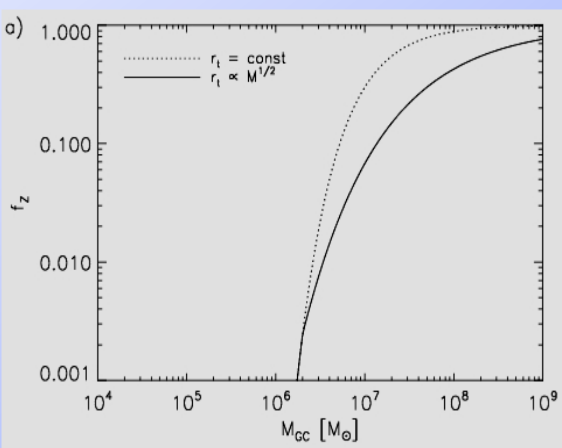
$$\Rightarrow Z_{cluster} = \frac{f_Z M_Z}{M_{cluster}}$$ and thus $$[Z/H] = 0.38 + \log(f_{SF} f_Z)$$

*The physically important key is that $f_Z$ is a strong function of M(init) -- deeper potential well can hold back more gas, and $10^7$ Solar masses within 1 pc is effective!*



Proto-GC = truncated isothermal sphere with logarithmic potential F(R). All SNe go off while PGC is still mostly gaseous; all ejected energy absorbed and thermalized.

Gas will leave if it lies outside an "escape radius" defined by total energy > potential energy at edge of cloud.




Ejecta become efficiently retained at a characteristic mass (after star formation)

$$M_c(retain) = \frac{E_{SN} f_{SF}^2 r_{eff}}{100 G M_0}$$

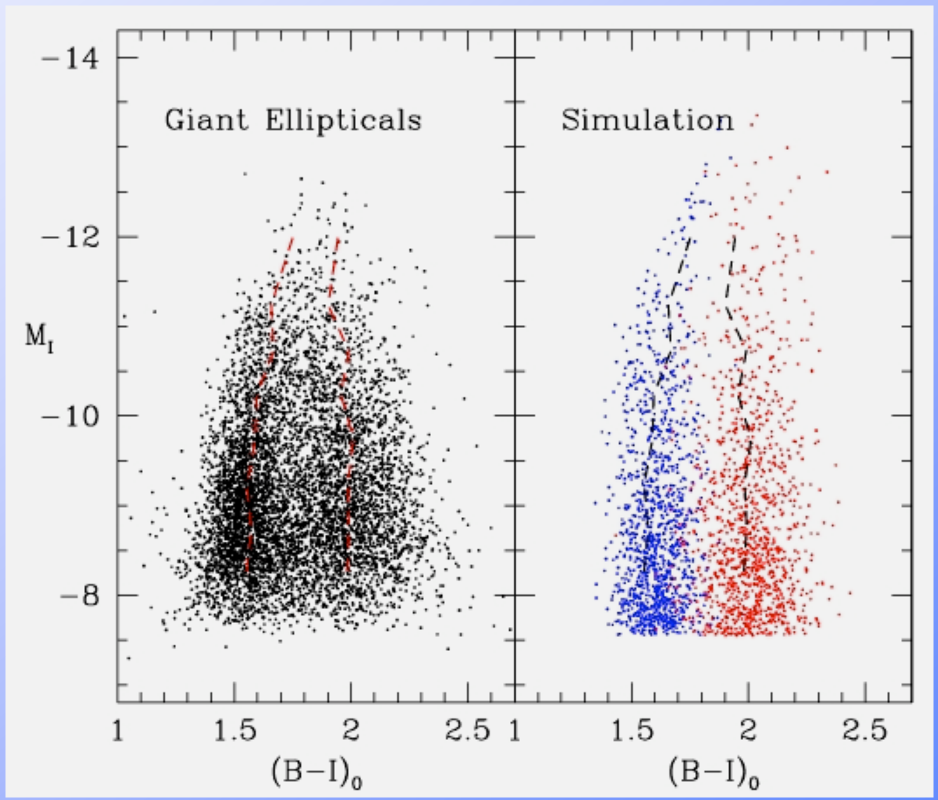
Key features of the model:

- Progressive increase of cluster Z depends on protocluster mass (nonlinear MMR). For M < ~$10^6$ $M_0$, sequences expected to be nearly vertical).

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

- Similar red-sequence MMR should exist at top end, but smaller amplitude (*but:* red sequence could also have a "population-based MMR" if it is a composite of several sub-components formed at different times)

-Validity of model depends crucially on an extended star formation period within a massive protocluster lasting ~20 Myr or more



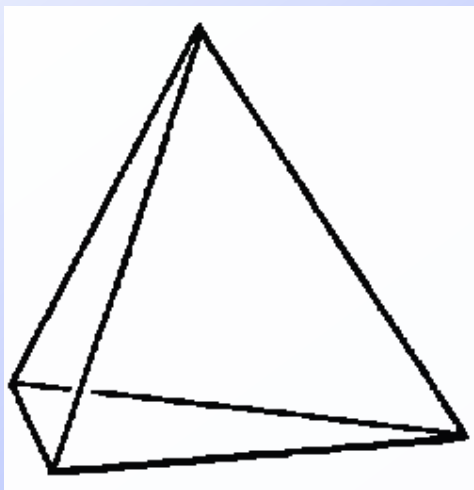

Harris 2009

***A lot depends on the events within the progenitor GMCs! We need better questions -***

McMaster University

Where do ideas come from?

## *The Eigenfunctions of a Scientist*




*How to be creative?*

- Study all you can about your subject, and related subjects
- Think about it all the time
- Wait for inspiration to happen.

*Balance is essential ….*