Origin and Evolution of the Globular Cluster Mass Function

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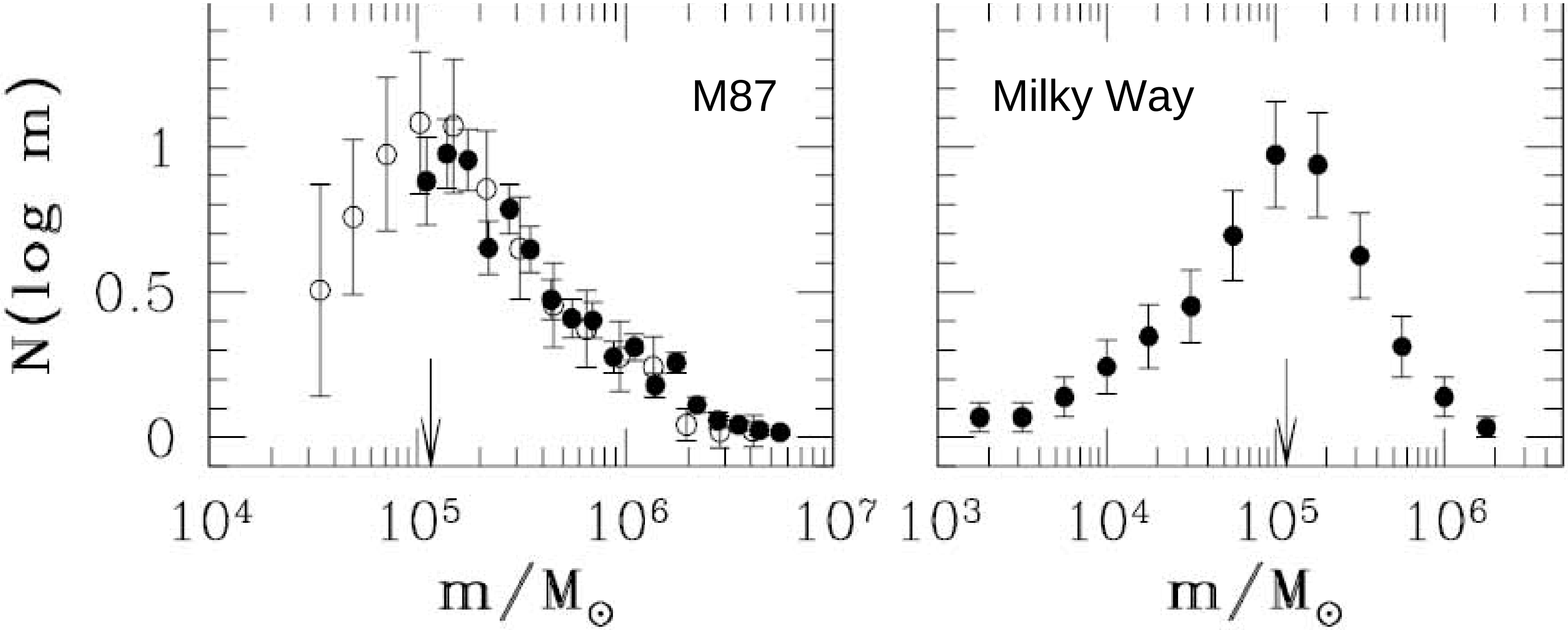
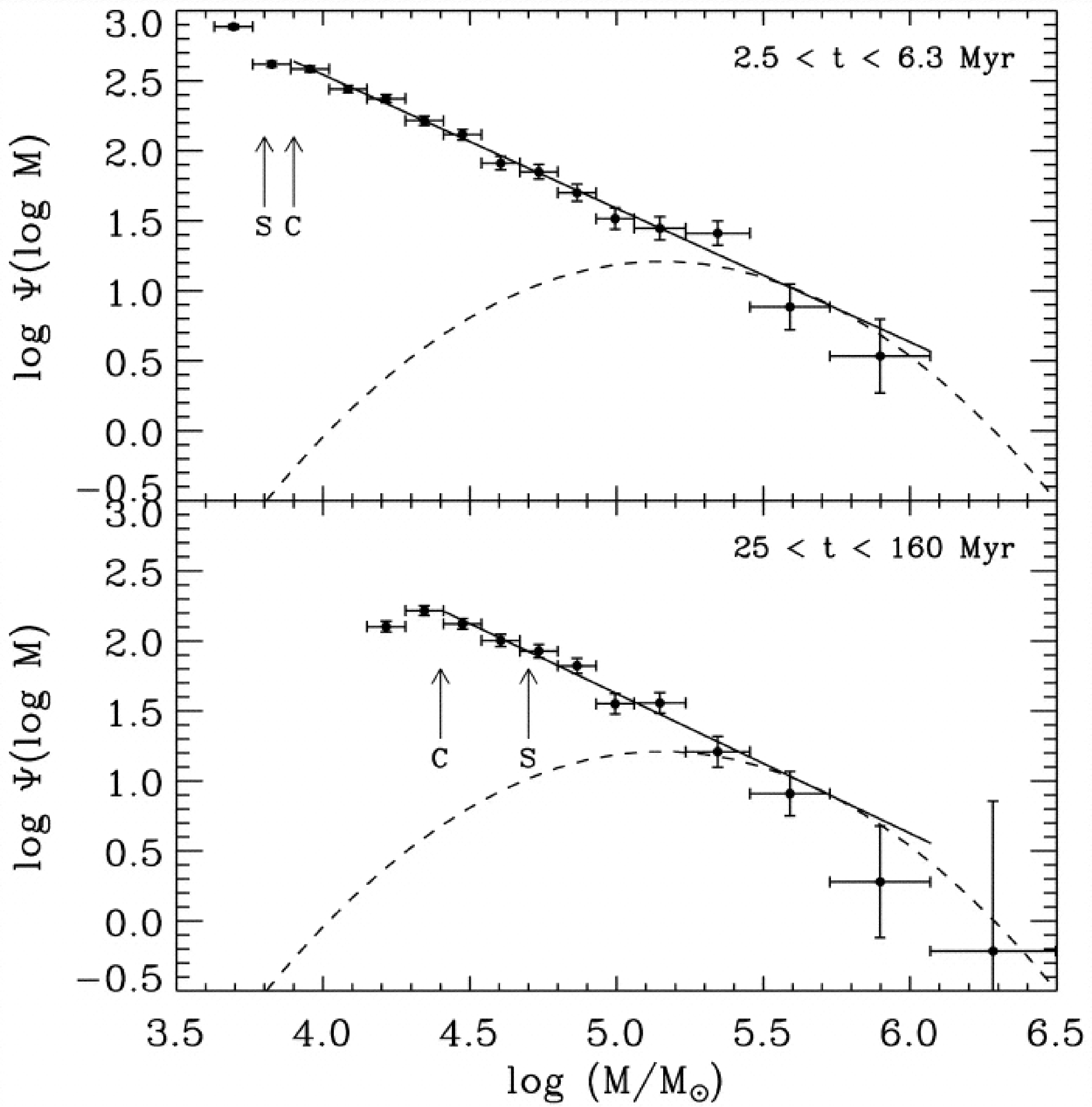
The MF for globular clusters is something like a log-normal



McLaughlin 2003

- Low mass part is more like a power law with slope 1
- Blue GCMF about the same as the red GCMF (Larsen +01; Wehner +08)

The MF for young clusters is a power law with a slope of about -2

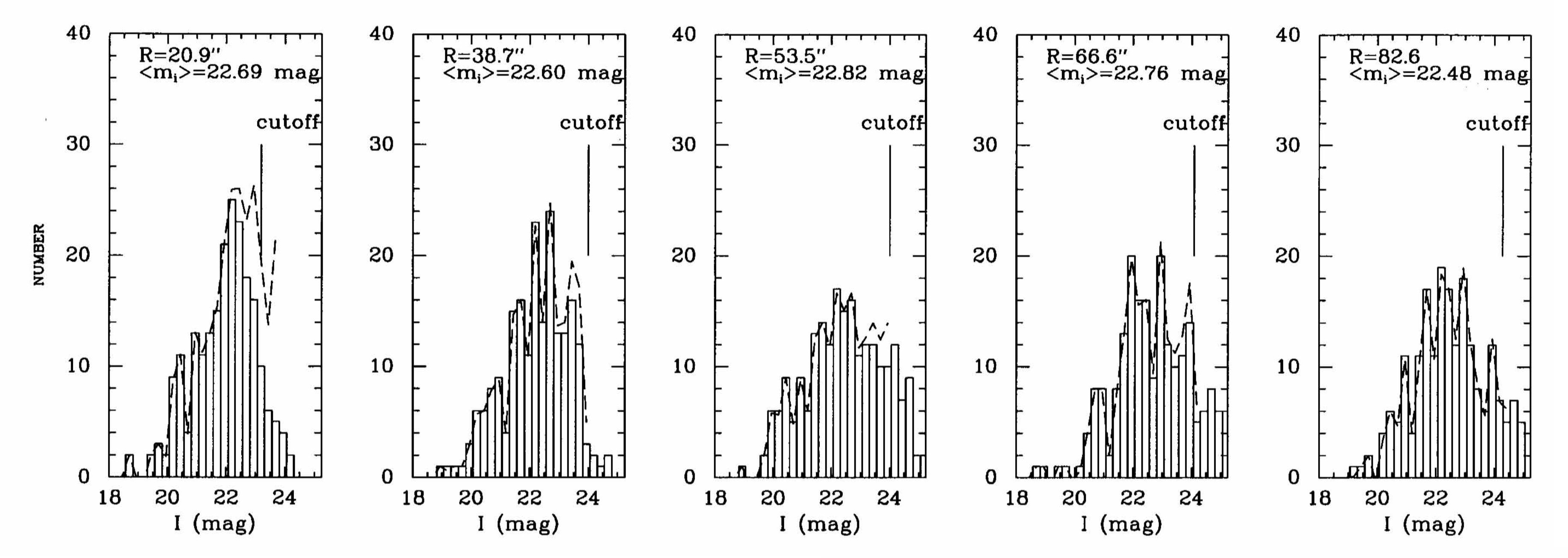


Antenna Galaxy:
Zhang & Fall 1999

The Problem

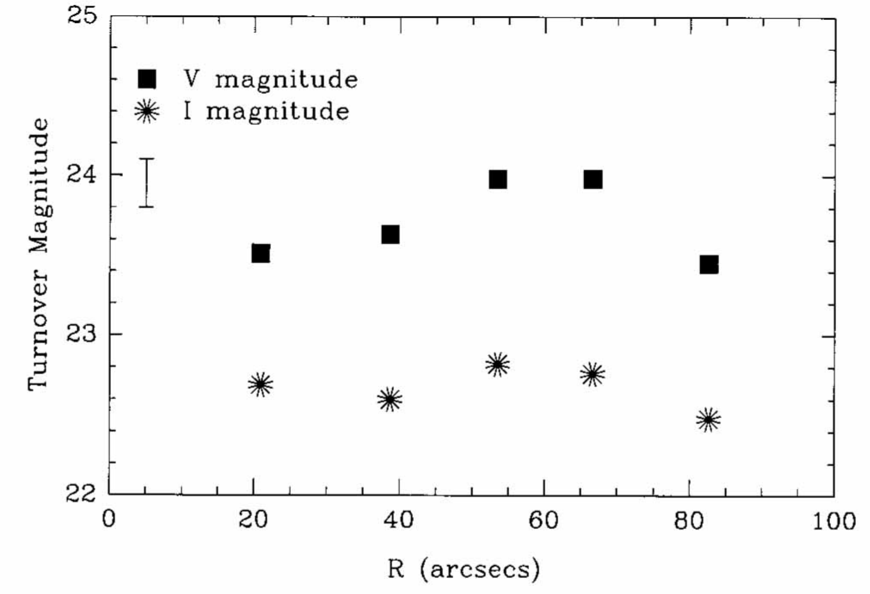
- GC MFs look like young-cluster MFs with the low-mass members gone
  - evaporation can cause the mass loss (McLaughlin & Fall 08)

- However, GC MFs are <u>independent of galactocentric radius</u> (Kundu +99, Tamura +06; Jordan +07) whereas the evaporation rate depends on the tidal density, which depends on Rgal
  - the outer regions of galaxies <u>should</u> have more low-mass GC remaining
    - Gieles & Baumgardt 08: small clusters should survive in low tidal densities
  - Radial GC orbits would help (Fall & Zhang 01), but they are not observed in M87 or the Milky Way (Vesperini +03), NGC 5128 (Woodley +10), NGC 1407 (Romanowsky +09)

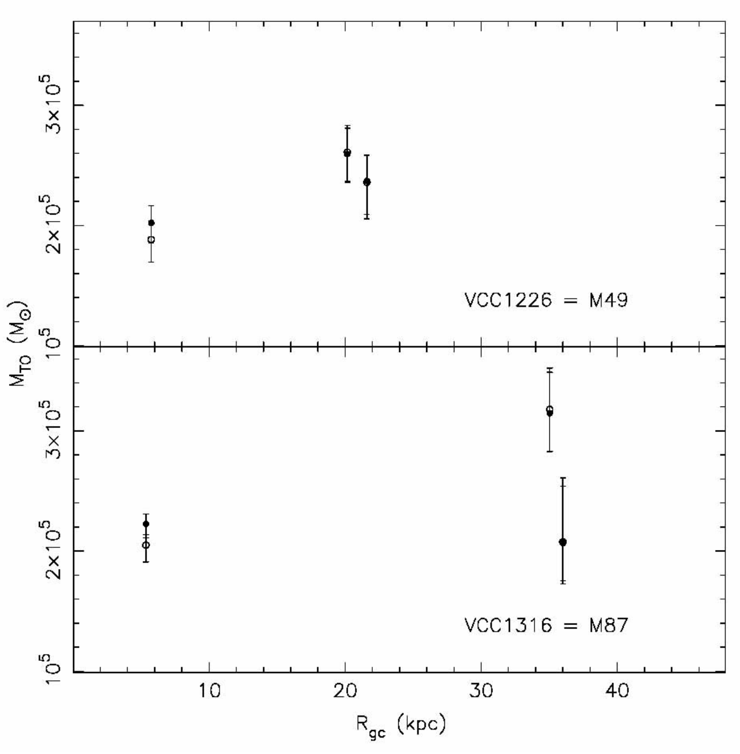


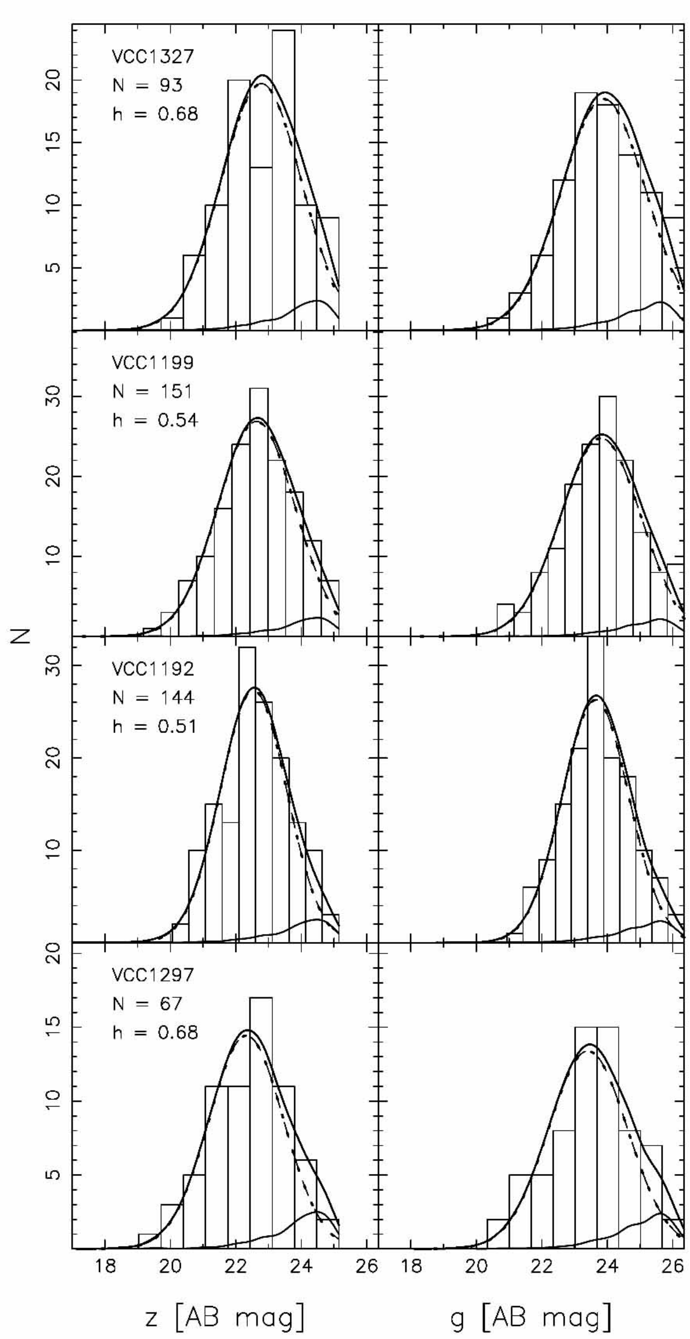
Kundu +99:

GC MF in M87 is independent of galactocentric radius.



Jordan +07 : GC MF for M87 and M49 using fields in nearby galaxies: no change with distance





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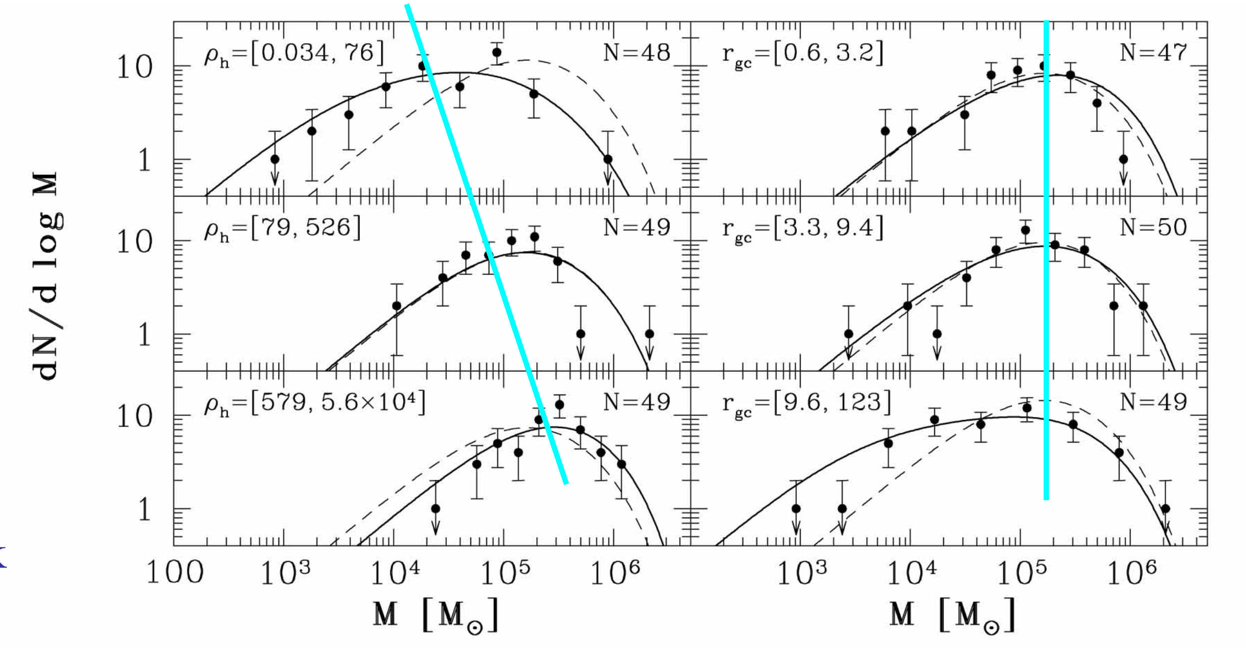
- Still, GCs with low half-mass densities have low MF peak masses, suggesting slower evaporation at low GC density (Chandar +07; McLaughlin & Fall 08).

McLaughlin & Fall 08:
Milky Way

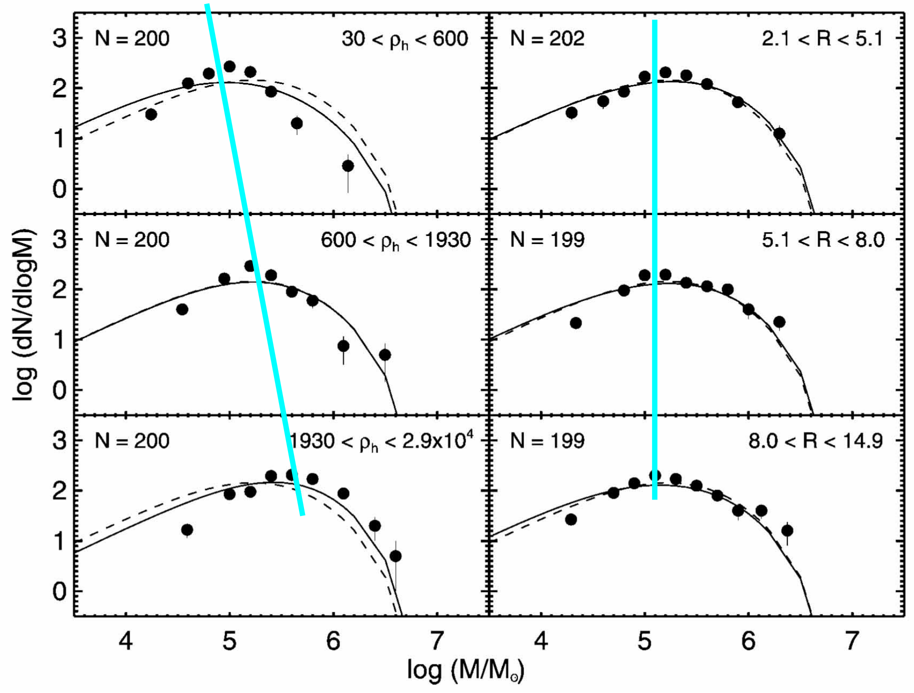


GCMFs separated into 3 groups according to density at half-light radius. The peak mass depends on density as expected for $dM/dt \sim \rho_h^{1/2}$.

The MFs are independent of position.

The fit is an evolved Schechter function.

Chandar +07: M104 (Sombrero)



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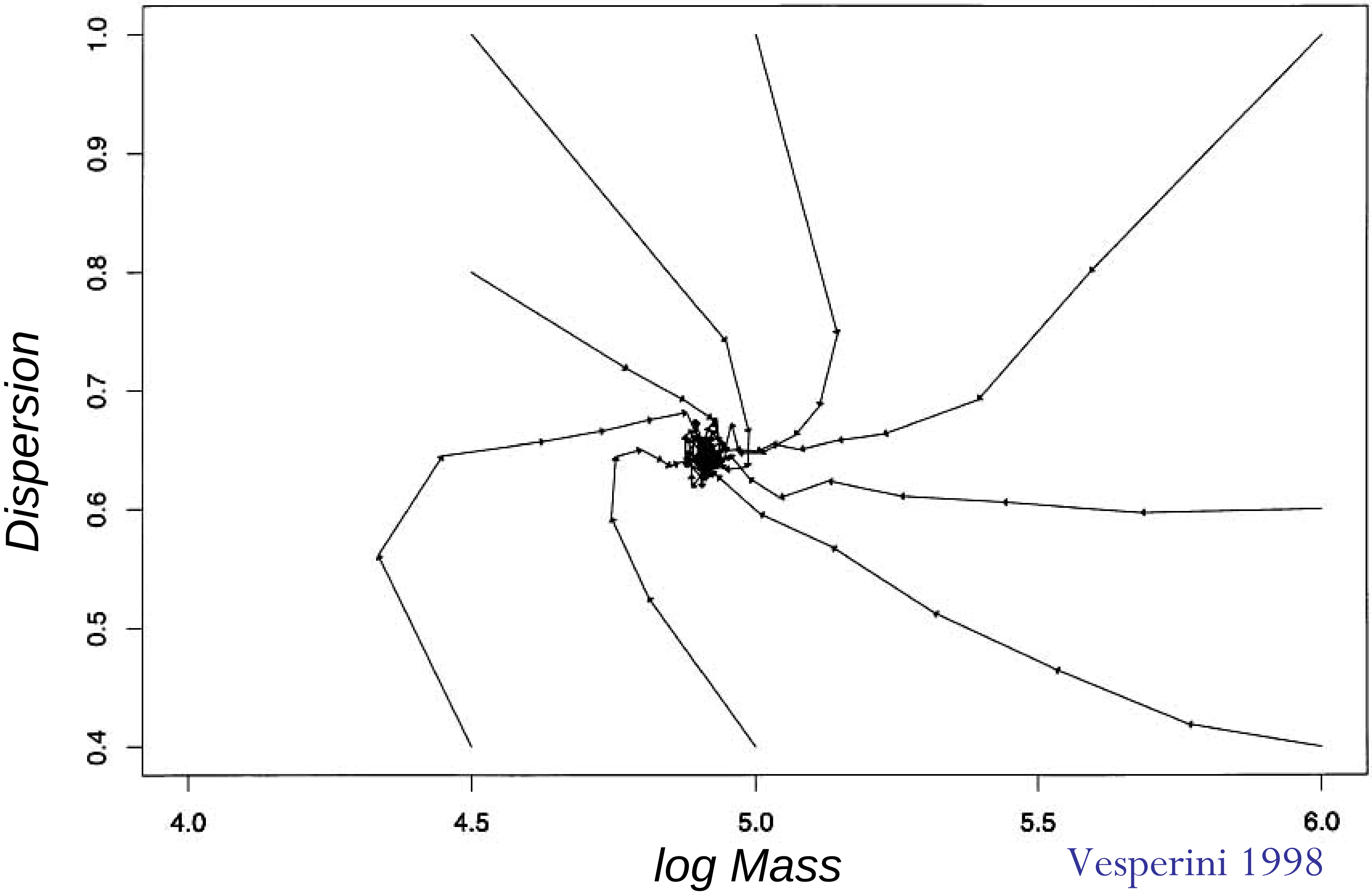
- Another solution: the GC MF was peaked from a young age and the peak was preserved during evaporation (Vesperini 00, de Grijs +05, Parmentier + 05-09).



Vesperini 1998

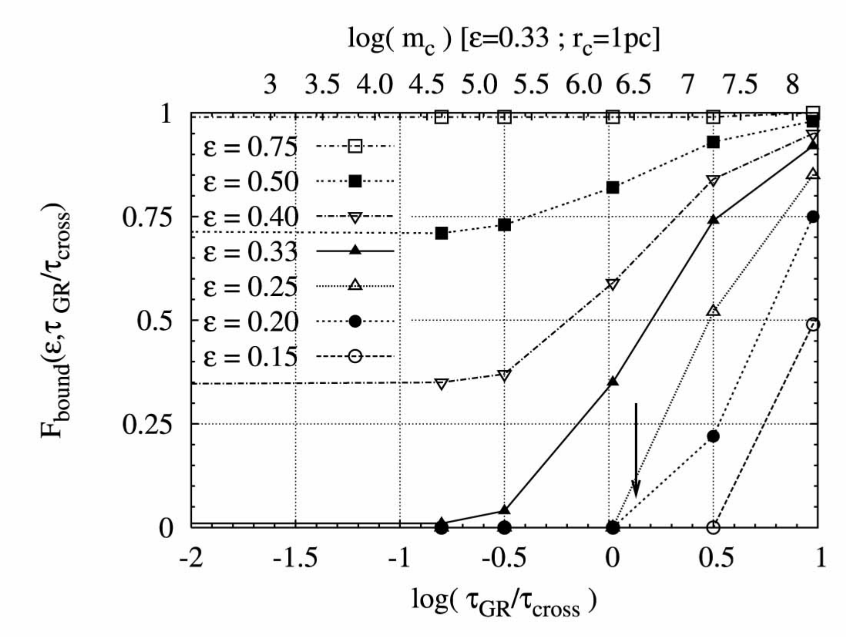
Initially peaked Mass Functions end up peaked after a Hubble time of evolution.

The equilibrium mass function is about the observed mass function.

Vesperini assumed an initial log-normal MF and an Rgal$^{-3.5}$ initial cluster distribution, and then followed cluster disruption for 15 Gyr. Arrows show initial to final evolution in Mass-dispersion plane.

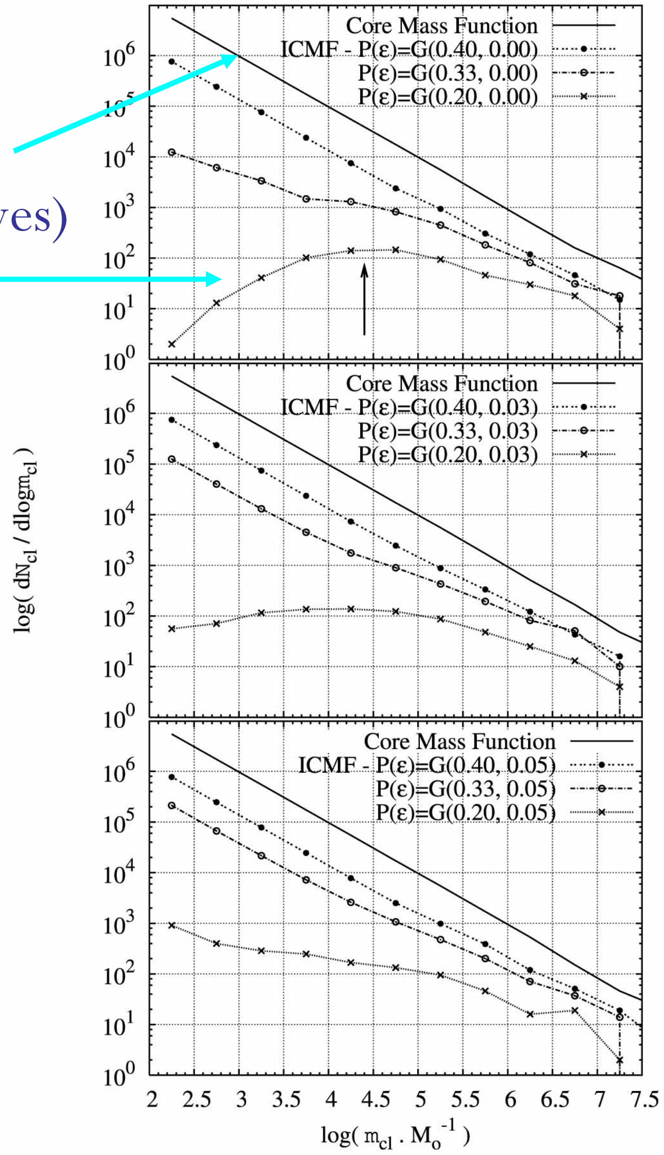
Models for Early Peaked MFs

- – No low-mass clouds to form low mass clusters (Parmentier & Gilmore 05, 07)
- – Low star formation efficiency for low mass clusters so low mass clusters disperse when the gas leaves (Parmentier + 08; Baumgardt + 08)
- – Low mass clusters are born with lower central concentration so they evaporate more quickly (Vesperini & Zepf 03)
- All of these require <u>peculiar star formation</u>



Remaining star fraction versus
log (gas removal time/cluster crossing time)

Before (solid)
and after (curves)
gas loss



Parmentier, Goodwin, Kroupa, Baumgardt +08 show that cluster disruption during initial gas removal can produce a log-normal MF at a very early stage.

Requires that halo GCs formed with lower ε (<25%) than disk clusters (ε ~ 40%)

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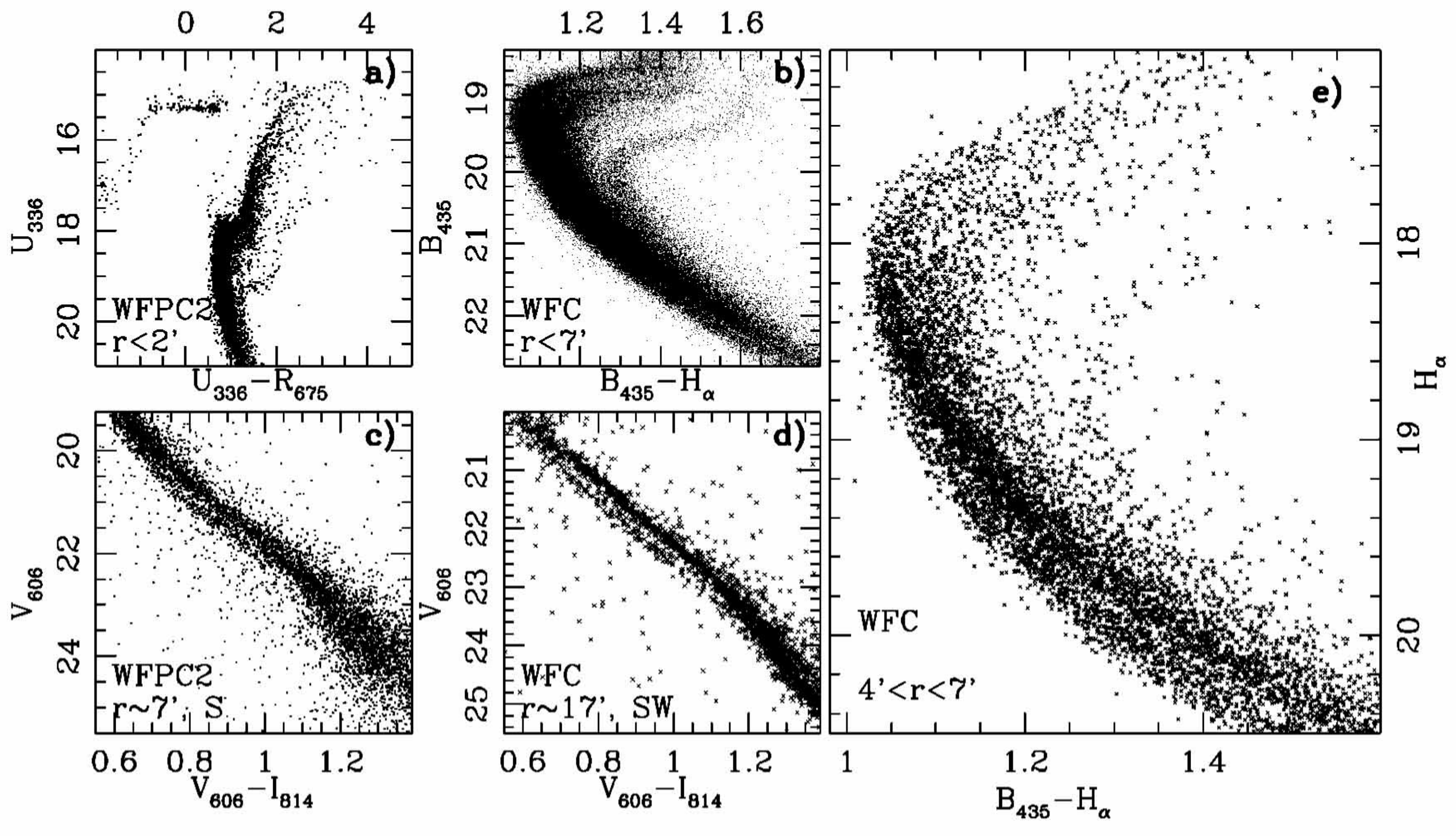
  - GC formed with an M^{-2} MF but in a <u>dense</u> environment, so evaporation and collisions with clouds <u>rapidly</u> eroded and destroyed them, producing a peaked MF early on (Elmegreen 2010)

- If initial conditions matter, then we have to know how GCs formed

GC are forming here:

HST

BUT old GCs have multiple populations
and often a clear connection to dwarf galaxies



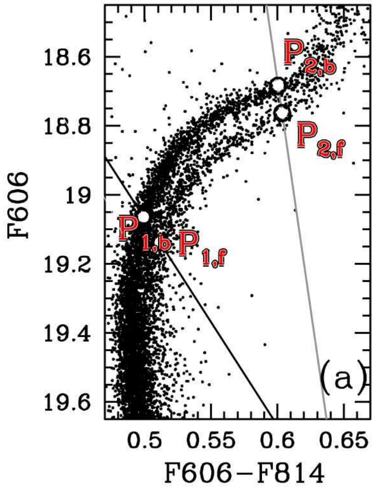
Self-enrichment in ω Cen: multiple main sequences & turnoffs (Bedin +04)

- Multiple MS means range of He abundance (D'Antona +02+08; Norris 04)
- Multiple subgiant branches means range of age (Milone et al. 2008) or CNO abundance (Cassisi +08)

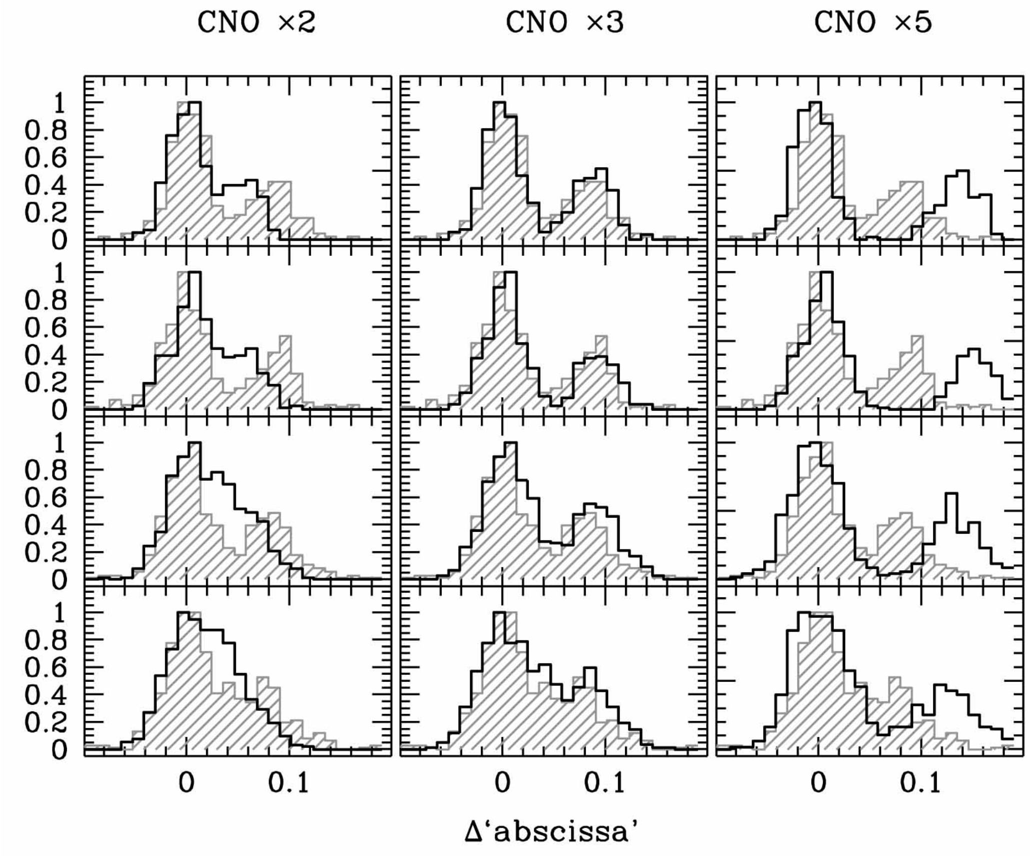
Ventura +09: the split subgiant branch in NGC 1851

Modeled the second generation with 3xCNO abundance of first generation.

suggest massive AGB stars in 1st generation have ejecta with 5xCNO abundance of the stars themselves and this ejecta is diluted by 50% with pristine gas to keep the He abundance low



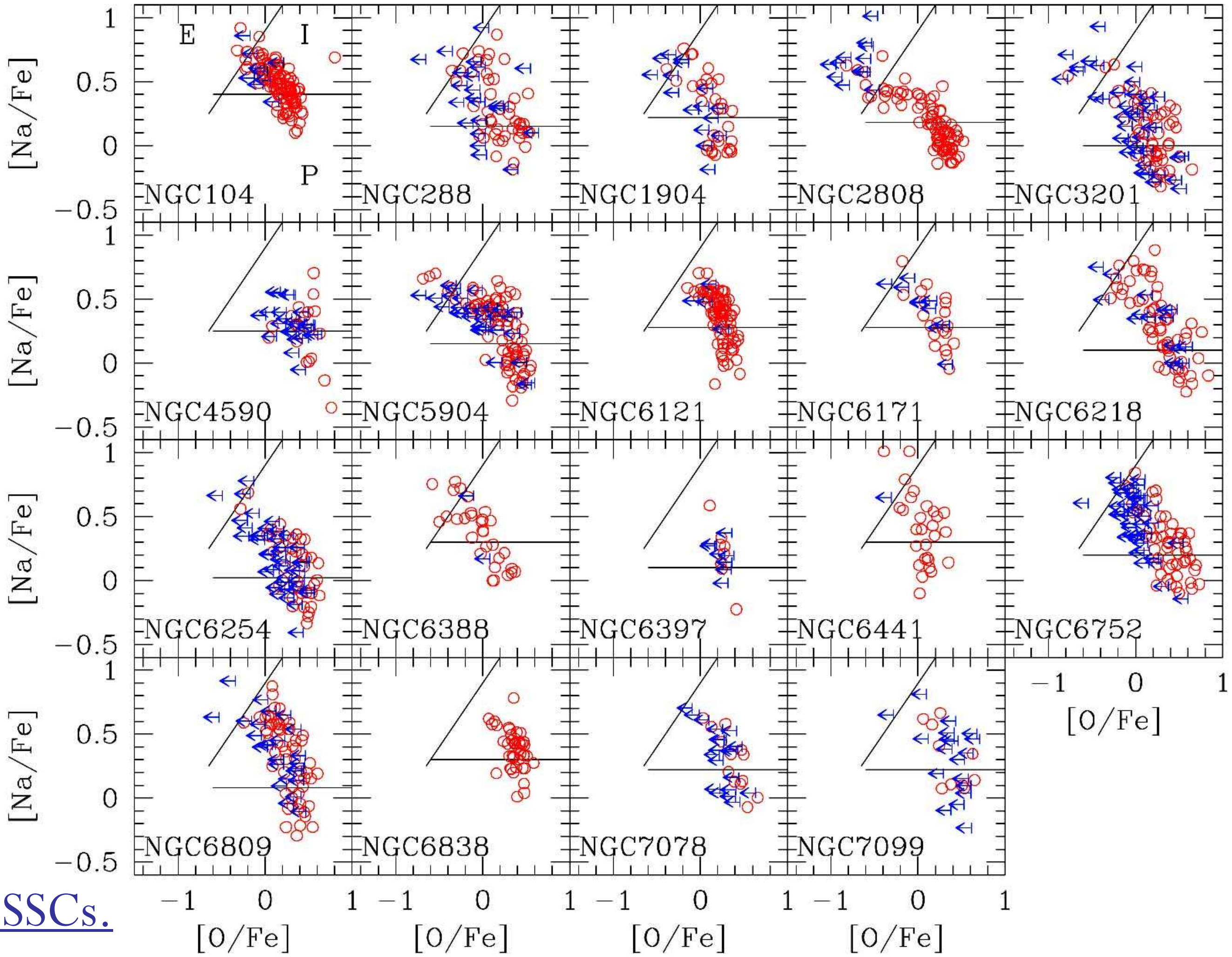
grey = observed
line = model



CNO enrichment

- CNO enrichment is usually so large that the progenitor stars originally had to outnumber the cluster stars
  - either the former cluster was much more massive (D'Ercole et al. 2008)
  - or the GC was the core of a dark matter halo (e.g., dwarf galaxy) which collected ejecta from many other clusters (Bekki & Norris 2006).

Na-O anticorrelation



Carretta et al 2010:

All observed GCs show an anticorrelation between Na and O.

Suggest this is the *defining characteristic* of GCs.

Old disk GCs differ from SSCs.

P = primordial (30% of stars in all GCs), same high O and low Na as halo field stars,
I = intermediate (50-70% of stars in GCs); E = extreme (not present in all GCs).

Position, kinematics and abundance allow GC classification into thick disk/bulge, inner halo, and outer halo. The MF is independent of class: early peak is required.

D'Ercole + 08 model

- First generation cluster assumed
- Second generation forms from AGB ejecta plus pristine infall
  - 2nd gen cluster more centrally concentrated
  - Two He abundances (ejecta and pristine)
- 1st gen stars lost from outer layer by evaporation and stellar evolution, leaving a high proportion of 2nd gen stars
- Thermal motions eventually mix populations

Carretta+10 model: several steps to enrichment

- $10^9 M_O$ DM+gas fragment hits the early MW and forms $10^5 M_O$ of “precursor” stars
  - DM halo stripped away
  - SNe trigger $10^6\ M_O$ of “primordial” (1st gen) stars and enrich them to GC metallicities.
    - before intermediate mass stars produce Aluminum
  - Winds and SNe from primordial (1st gen) stars disperse the SF region
  - Most primordial stars drift off

- Winds from 1st gen AGB stars (D’Antona +04; Karakas +06) or fast-rotator stars (Prantzos +06; Decressin +07) make a cooling flow and 2nd generation cluster
  - 60% of the GC mass today
  - SNe in the 2nd generation terminate SF

- More massive clusters terminate earlier and enriched by only the most massive stars, producing a 2nd generation cluster with higher He enrichment.

- Clusters forming in the disk are smaller and pre-enriched. They cannot self-enrich much.

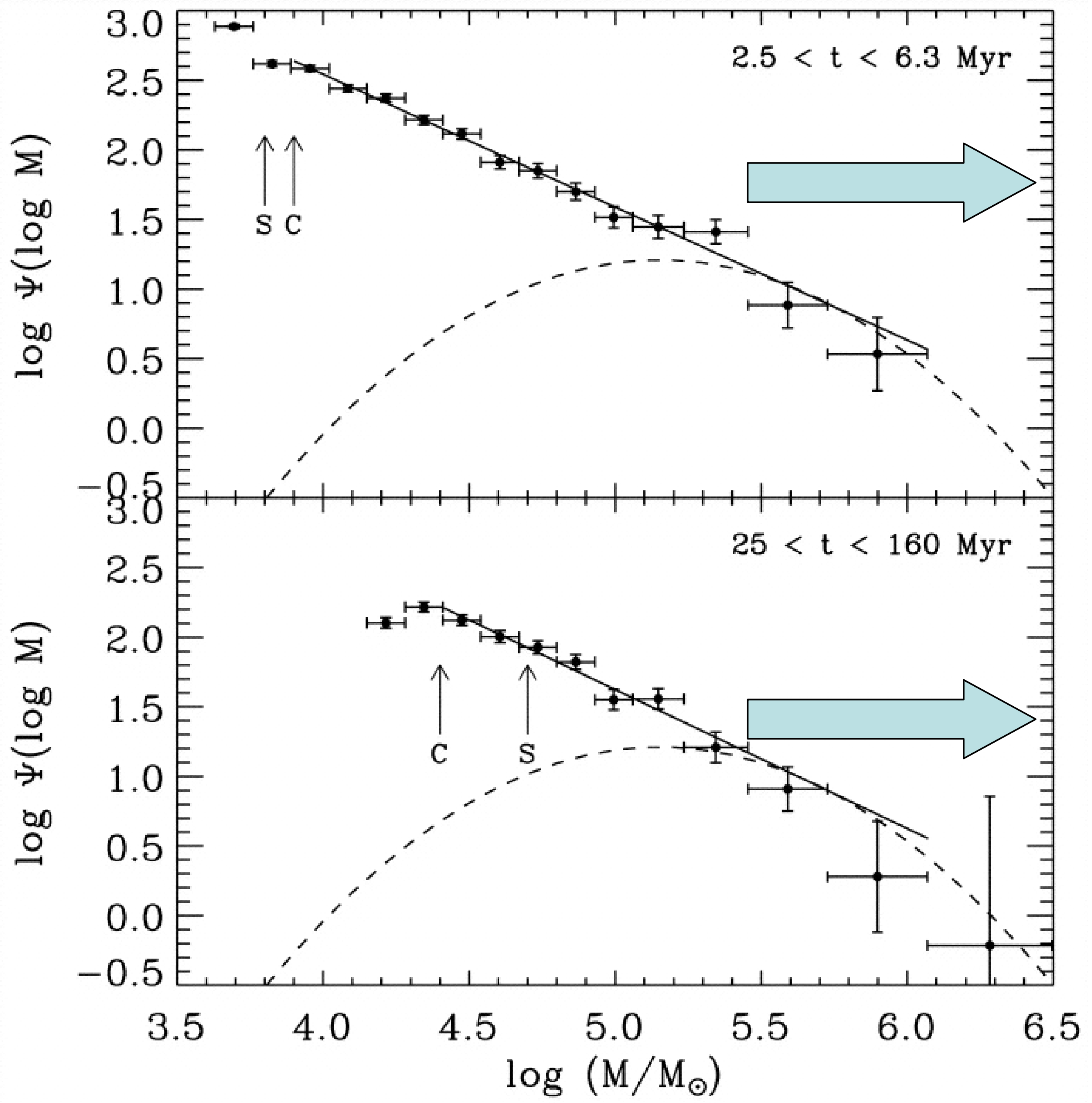
- Dwarf Sph galaxies are the same types of cosmological fragments, but further from the MW and do not collide with it or trigger early star formation

Schaerer & Charbonnel 2011

- Halo stars with anomalous abundances compared to dissolved GCs
  - If all GCs had multiple generations
  - and the initial GC masses were x10 higher to account for the high pollution
  - then an initial power law GC mass function would put far too many anomalous stars into the MW halo compared to an initial log-normal GCMF.
    - (the observed anomalous star fraction in the halo is only a few %)
- Suggest that the initial GCMF was log-normal

  - Although, low mass GCs might not have had multiple generations (Bekki +11)

GCs 10x larger would have 10x more dissolved stars



Antenna Galaxy:
Zhang & Fall 1999

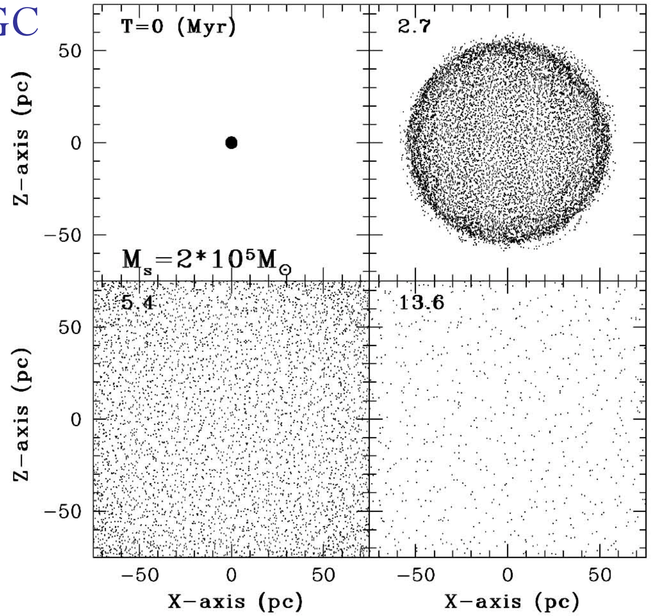
Bekki +11 models AGB wind in cluster of different masses.

$M = 2x10^5\ M_O$ cluster cannot hold in wind

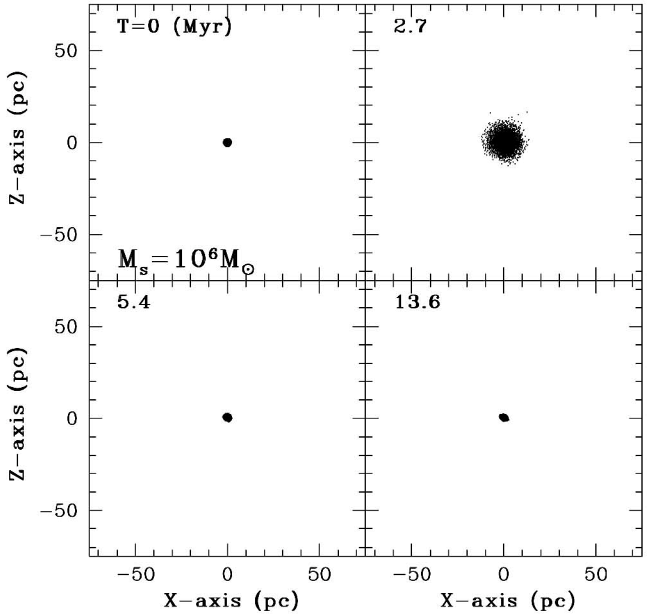
$M = 10^6\ M_O$ cluster holds in wind and can make 2nd generation stars

<u>Key to multiple generations is the much larger masses of old GCs</u>

$2x10^5 M_O$ GC disperses AGB wind



$10^6 M_O$ GC keeps AGB wind



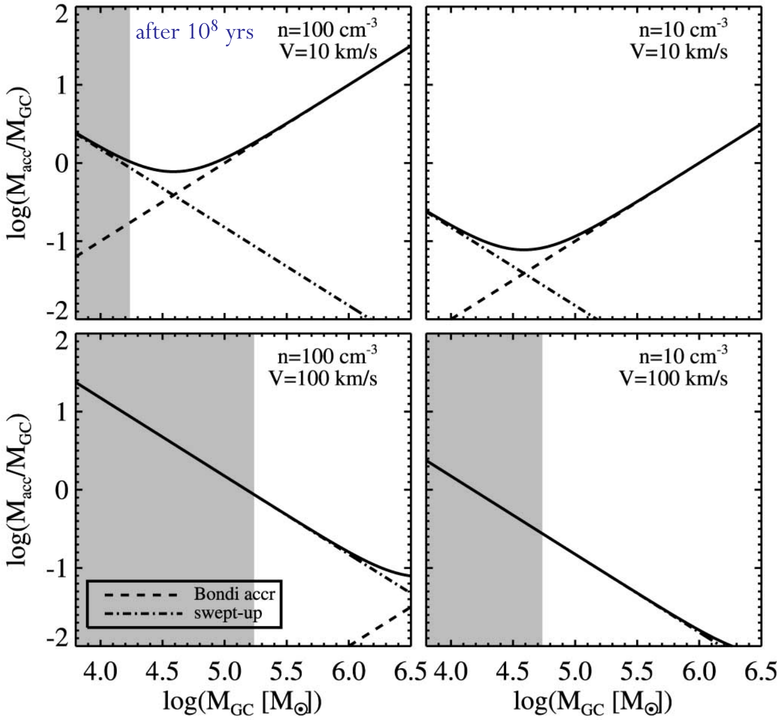
Conroy & Spergel 2011:

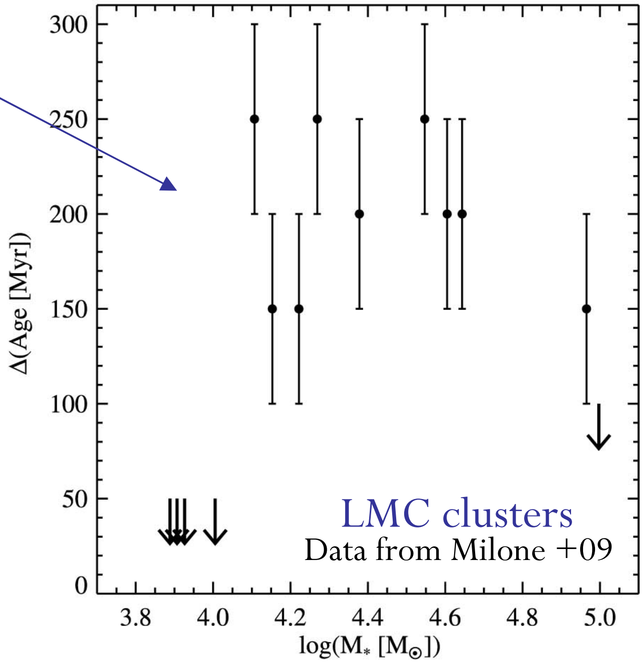
- Assume 2nd gen stars form from a mixture of AGB winds and accreted gas with <u>most from accretion</u>
  - Does not require 1st gen M >> 2nd gen M
  - High 1st gen M produces too many remnants

- Model accretion to see when accreted M = 1st gen M and whether ram pressure from disk impacts removes gas from cluster

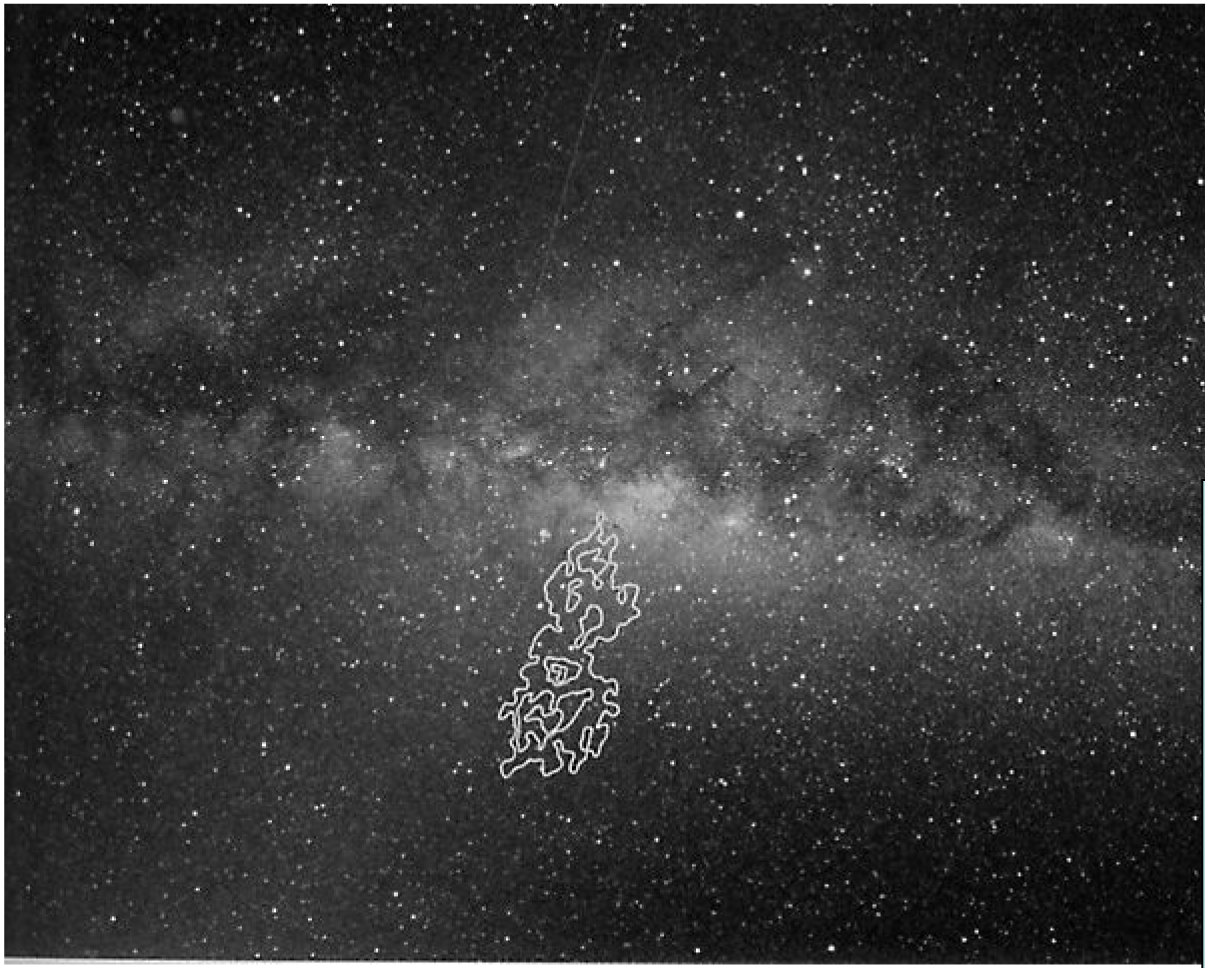
- Suggest all $M>10^4$ clusters form multiple pops, depending on environment (ram pressure stripping)
  - Rubele +11: there are prolonged SF or multiple populations in Gyr-old LMC/SMC clusters

- Suggest the most massive GCs (ωCen, NGC 2808, M22, M54) with multiple CMD sequences, formed in dwarf galaxies
  - Georgiev +09: all GCs with extended (hot) horizontal branches may have originated in dwarf galaxy nuclei



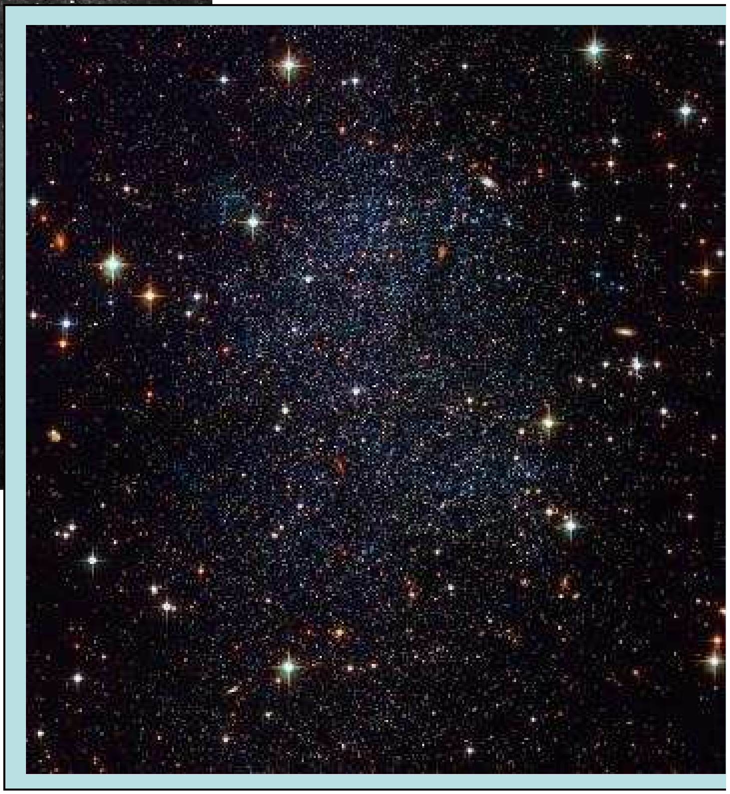


LMC clusters
Data from Milone +09



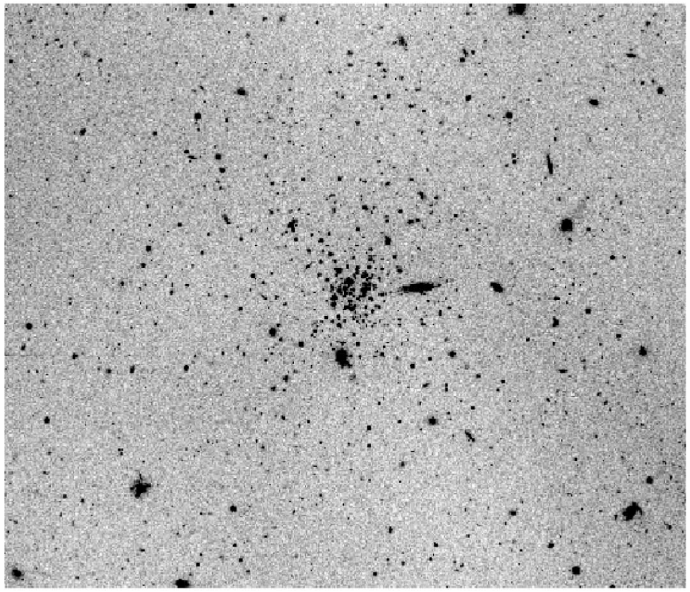
Ibata, Gilmore, Irwin 94

NASA, ESA



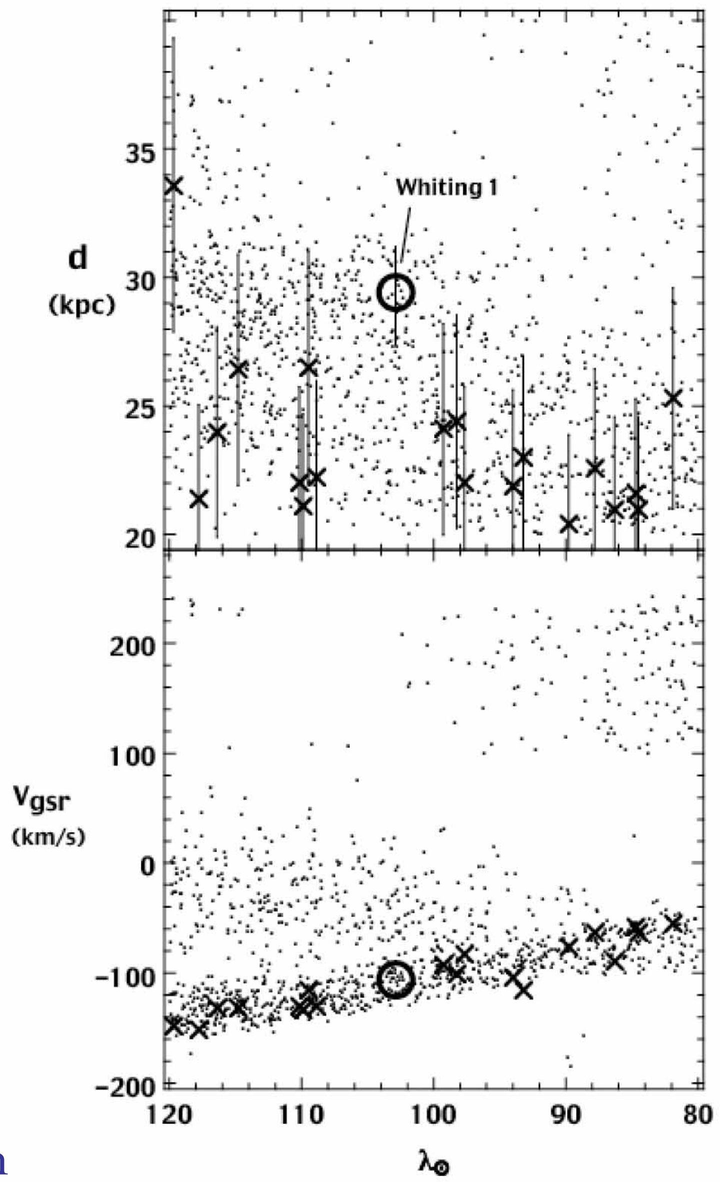
Sagittarius Dwarf Galaxy

Possible associated GCs: Terzan 7, Terzan 8, Arp 2, M54, …



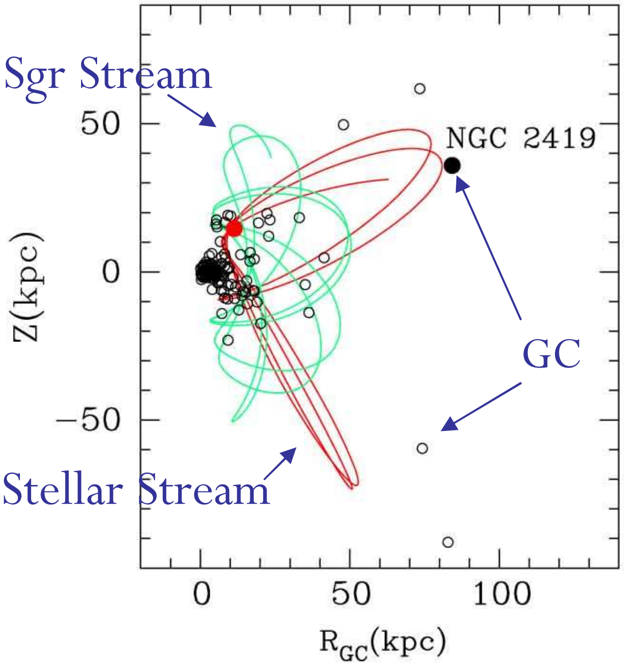
Carraro +09: Whiting 1 GC likely associated
with Sgr dwarf (now, 6 total GC with Sgr dw):

- 6.5+-.7 Gyr old, Fe/H= -0.4 to -1.1 (consistent with age-Z of Sgr dwarf)
- extended luminosity profile (tidal tail)
- position, distance, velocity in Sgr stream



x = M giants from Majewski +03,04
dots = N-body model from Law +05

Casetti-Dinescu +09: Virgo Stellar Stream may contain GC NGC 2419



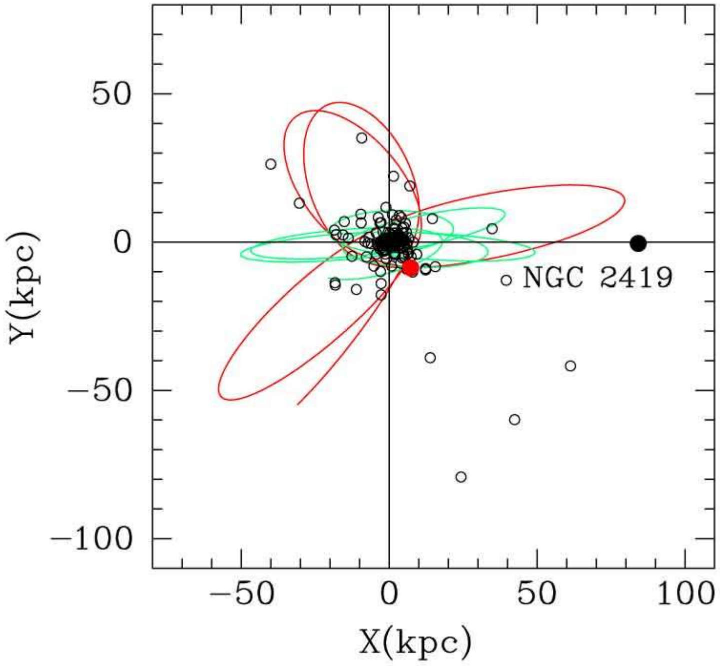
Green = Sgr Stream

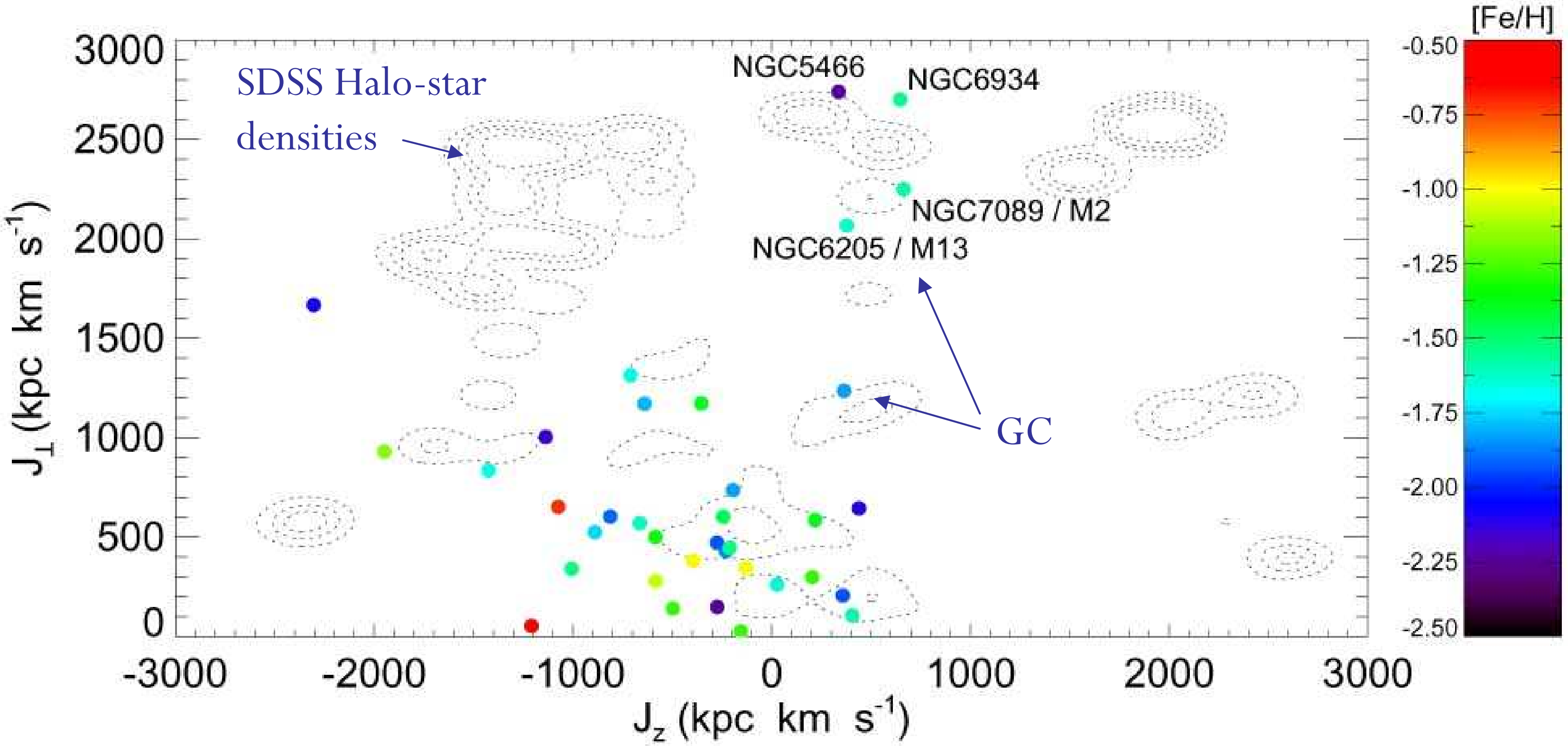
GC

red = Virgo Stellar Stream

Stellar orbits integrated back for 5 Gyr

GC NGC 2419 could be in this stream





SDSS Halo-star densities

GC

Ang. mom. perp and par to the MW plane

$J_{perp} = [(yv_z - zv_y)^2 + (zv_x - xv_z)^2]^{1/2}$

$J_z = xv_y - yv_x$

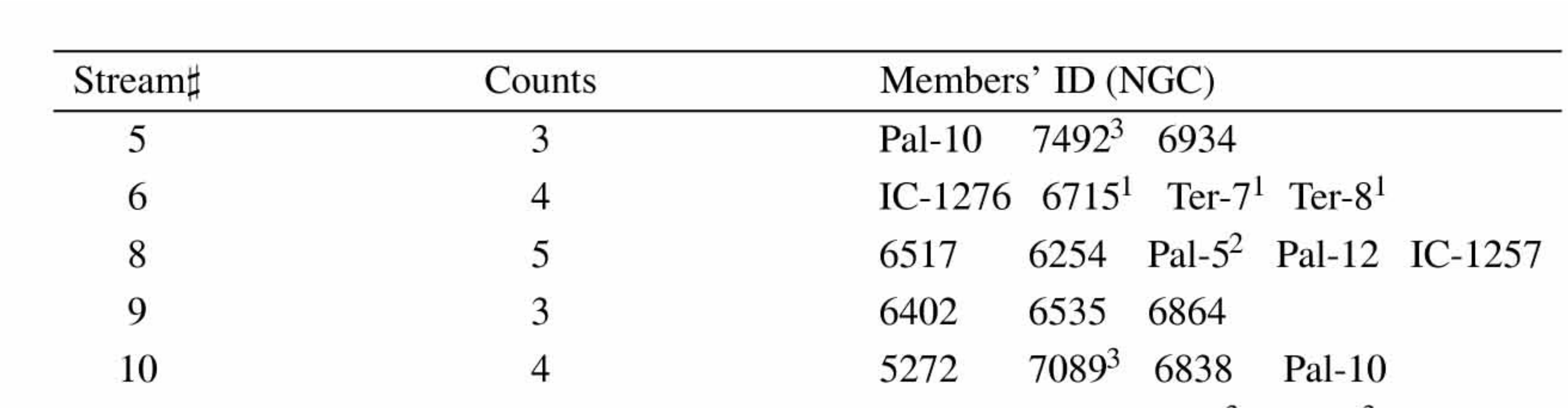
Smith +09: Four GCs lie in a halo star kinematic overdensity

metallicities: -2.22, -1.54, -1.58 and -1.65

NGC5466 is disrupting (Odenkirchen & Grebel 2004; Belokurov et al. 2006)

(see also Dinescu +99; Palma +02; Mackey & Gilmore 04)

Gao+07 find common streams for MW globular clusters, based on common energy, angular momentum and orbit poles.



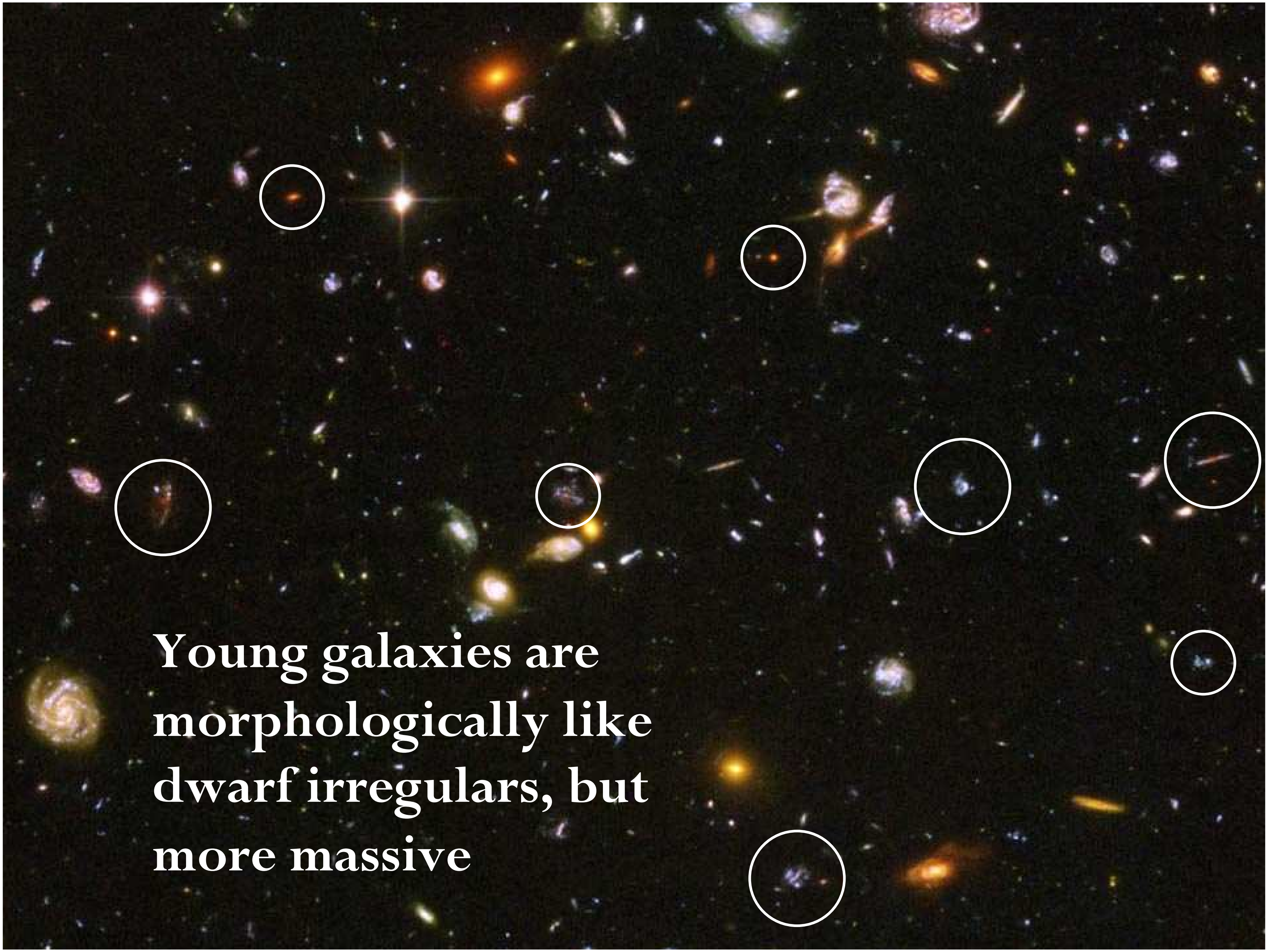
Stream♯	Counts	Members' ID (NGC)				
5	3	Pal-10	7492[3]	6934		
6	4	IC-1276	6715[1]	Ter-7[1]	Ter-8[1]	
8	5	6517	6254	Pal-5[2]	Pal-12	IC-1257
9	3	6402	6535	6864		
10	4	5272	7089[3]	6838	Pal-10	

e.g., stream 6 part of the Sgr dwarf stream

Suggest 20% of GCs are in common streams.

Is something like this the birthsite for the oldest GCs?

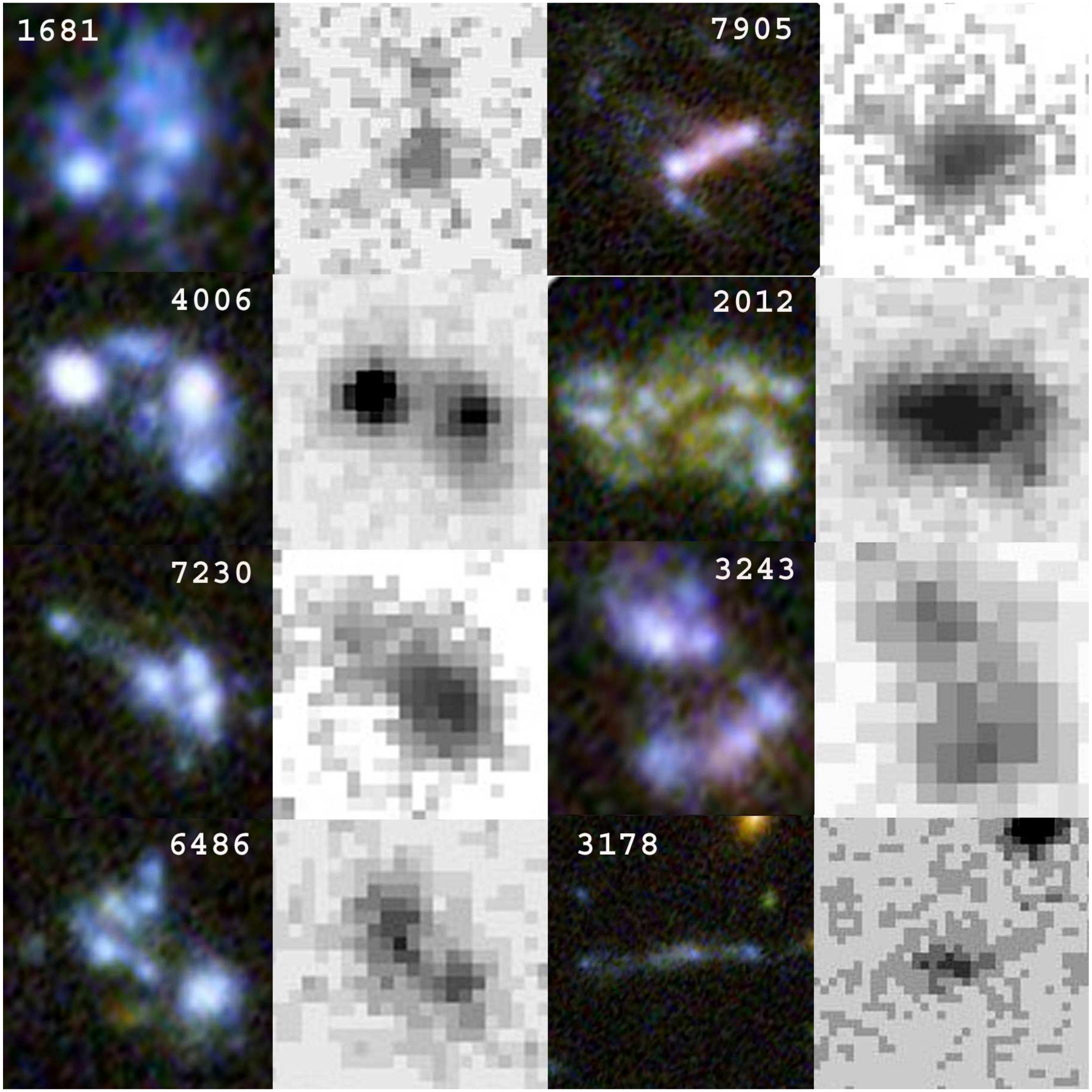
NGC 1569 – a Dwarf Irregular Galaxy



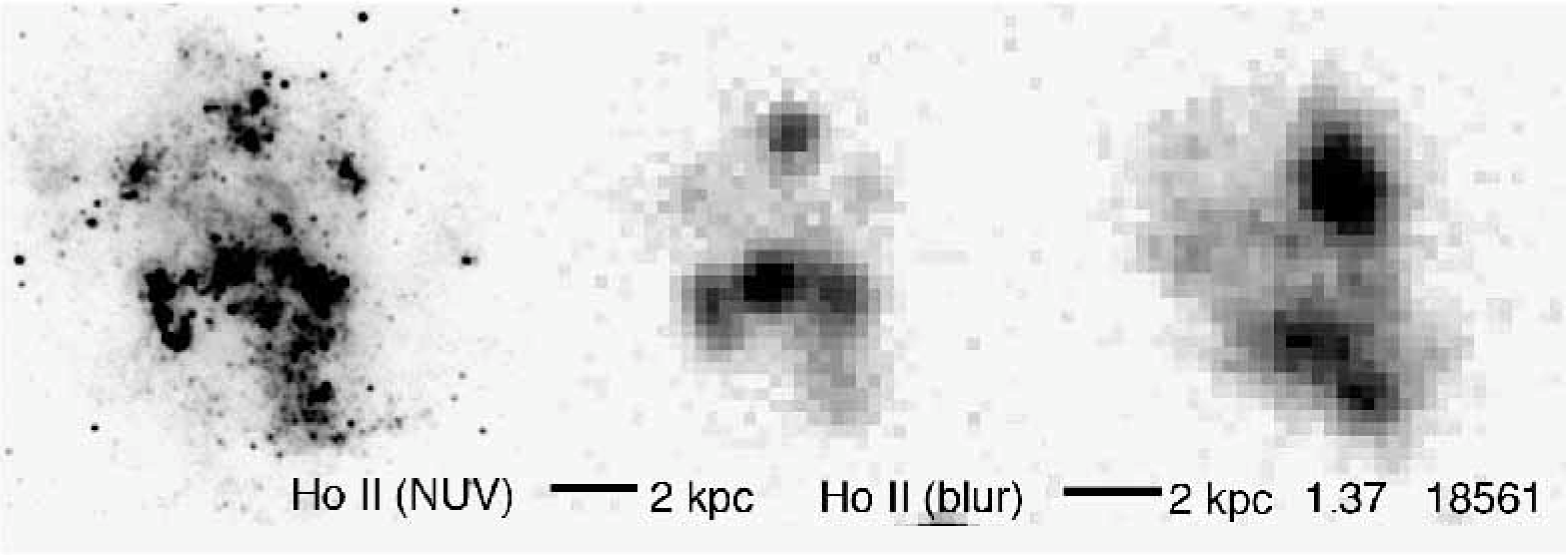
Young galaxies are morphologically like dwarf irregulars, but more massive

UDF Clumpy galaxies without “bulges”

ACS / NICMOS - H



Elmegreen +09



A local dwarf irregular galaxy is a good match to a clumpy young galaxy.

Local Dwarf Irregulars vs Clumpy Young Galaxies

- Clumpy young galaxies resemble local dwarf irregulars because:
  - both have high gas fractions (e.g., Tacconi, Daddi, …)
  - both have high velocity dispersions relative to the rotation speed
  - and …. L_{Jeans}/Galaxy Size ~ H_{disk}/Galaxy Size ~ $(\sigma/V)^2$
    - both have big complexes relative to the galaxy size
    - both have relatively thick disks
  - both are irregular
    - because of the relatively high gas mass and high σ/V
  - both are relatively young!

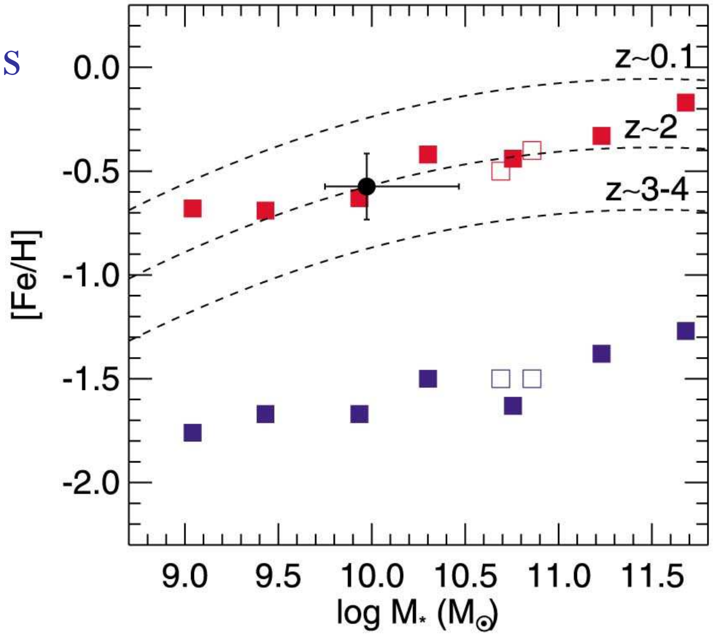
- Bekki +08 model GC formation in small galaxies at z~5 (on GC per galaxy) and follow the galaxy SF histories, metallicities, and mergings to reproduce today's GC systems (no mass functions).
  - Metal poor GCs form in low-mass galaxies z>6, metal rich GCs form slightly later in mergers and isolated gas-rich galaxies.

Shapiro +10 suggested that thick-disk/bulge GCs formed in clumpy young galaxy disks (z~2)

Star formation in these systems is intense, short-lived & high pressure.

The short timescale gives α-enhancement, as also observed in z=2 survey galaxies and at higher redshifts (Pettini +02; Halliday +08; Quider +09)

The ages of red GCs are 9–12 Gyr in the Milky Way (De Angeli +05, Mendel +07) and 10 ± 2 Gyr in other galaxies (Puzia +06). Comparable to the look-back time at z = 1.5–4



Fe/H versus host galaxy mass for red GC (red) and blue GC (blue) in Virgo

black circle: z2SFG mean

open squares: MW and M31

dash lines: mass-metal relation for different redshifts

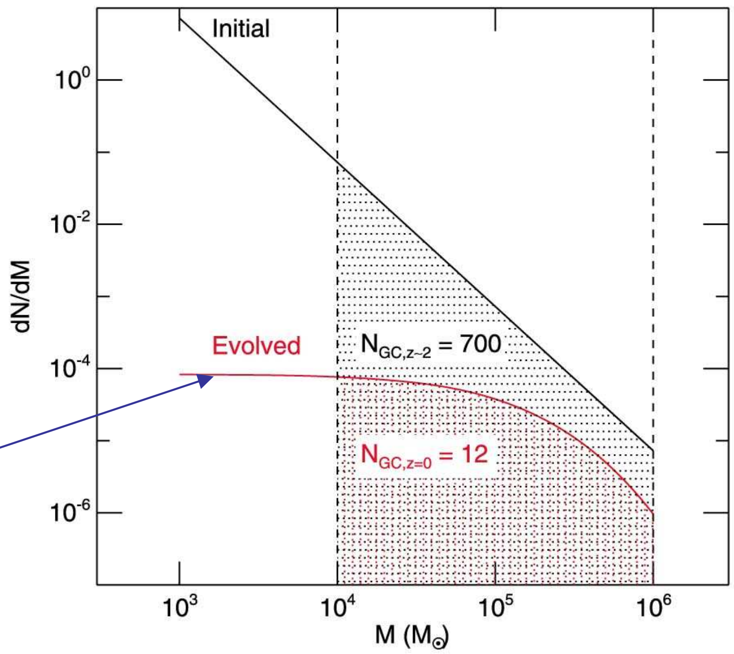
Zinn '85 also suggested MW disk GC formed in "thick-disk" phase

Shapiro +10:

Assume the GC mass is limited to 10^{-3} to 10^{-6} times the cloud mass,

Assume the initial M^{-2} mass function evolves by evaporation with a constant mass loss per cluster (Jordan +07).

Total remaining ~12 per clump, or ~100 per MW galaxy.



An Initial log-normal GCMF from Early Dispersal

- Clusters can be born with the usual M^{-2} mass function up to the sample-size limit (perhaps with an upper cut-off) and down to "zero" mass, and constant efficiency

- but the <u>environment</u> at redshift ~2 to 10 had higher turbulent gas speeds, higher gas fractions, and higher gas densities.

- Then low mass clusters are destroyed <u>rapidly</u> by cloud collisions and mutual cluster collisions
  - Peak in the GCMF can form after 100-500 Myr of SF

Details

- For disruption from collisions with cloud debris and other clusters:

  $dM/dt = -M/t_{dis}$ where $t_{dis} \sim \rho_{cl}/(\Sigma_n \rho_n) = \xi_{env} M^{\gamma}$ (Spitzer '58)

  - ρ_{cl} = internal cluster density; Σ_n is the column density of collision partners, ρ_n is the space density of collision partners
  - Gieles +06 assumed $\gamma=0.6$; if all cluster radii are about the same, then $\gamma=1$

  – Locally, ξ_{env} makes $t_{dis} \sim 8$ Gyr for $M=10^5\ M_O$ (Gieles +06), but for high z galaxies, Σ_n and ρ_n were higher, making $t_{dis} \sim 0.5$ Gyr or less at $10^5\ M_O$.

- RESULT: Low mass clusters dispersed quickly in dense environment

Slower

Monte Carlo result with <u>continuous formation</u>

4 destruction rate parameters ξ (top to bottom)

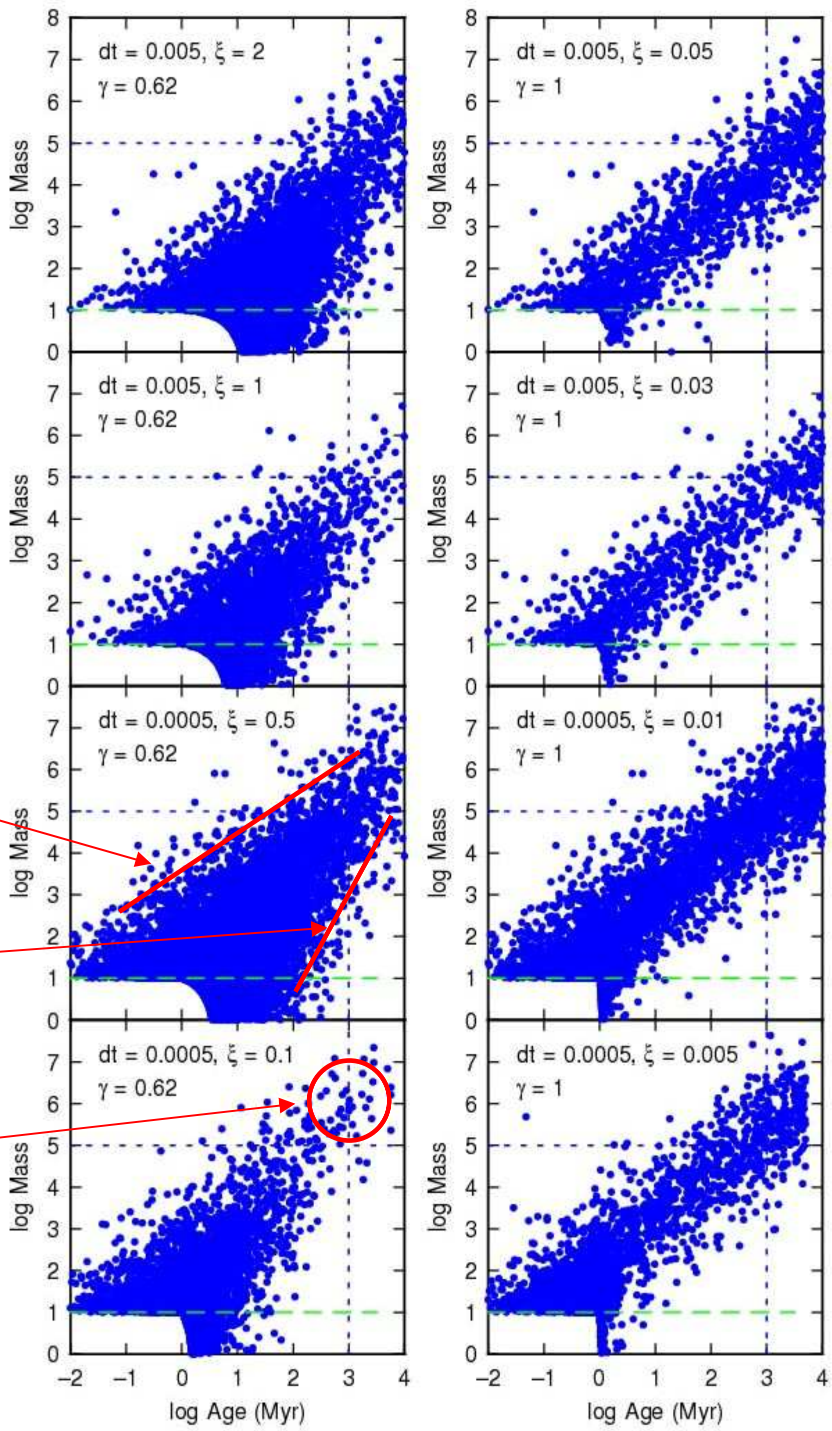
γ=0.62 (left) and γ=1 (right)

Plots show log M versus log age after
10 Gyr of evolution in a steady state.

Upper limit increases by the size of sample effect.

Lower limit increases by cluster destruction: $M_{min} = (age/\xi)^{1/\gamma}$

Faster disruption (smaller ξ) produces a larger M_p after 1 Gyr.



Faster

Elmegreen 2010

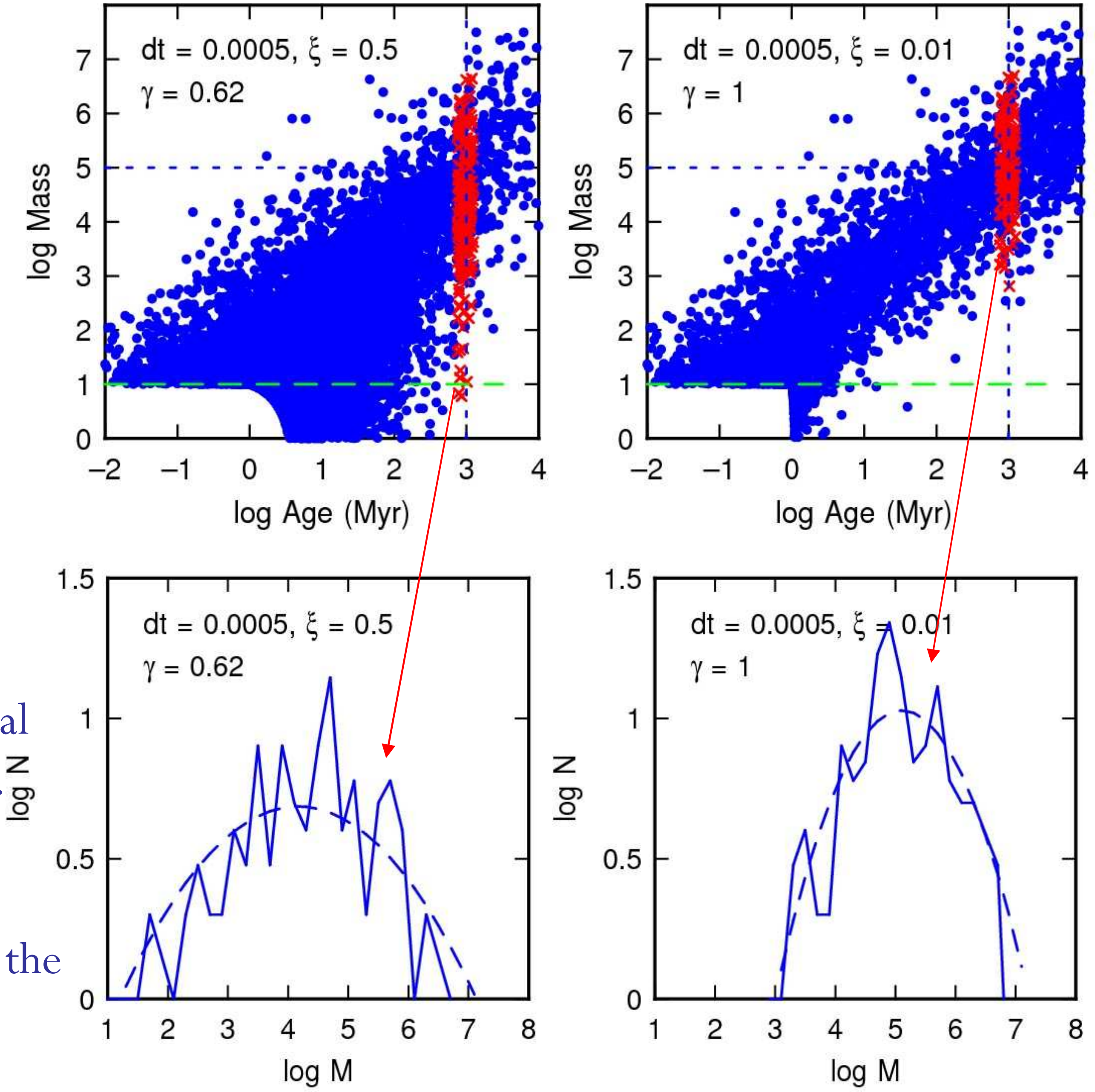
For a <u>short burst</u> of SF:

Red crosses are for a burst of SF lasting 0.5 Gyr and viewed after 1 Gyr.

There would be no blue dots then.

Mass functions are log normal with a reasonable peak mass.

Vesperini 1998 evolution of the GCMF then takes over



Summary

- Origin of the GCMF is still not understood
  - A Hubble time of evaporation changes the GCMF, but does this account for the whole GCMF or was the early MF also deficient in low-M clusters?
  - Favoring the slow evaporation models:
    - it happens anyway
    - peak mass observed to depend on GC density
  - Favoring early peak:
    - universality
      - with respect to position, metallicity, 1st gen/2nd gen ratio
    - too high total mass for MW (x10) if self-enrichment gas comes from AGB stars
- Models of the GCMF (GCs form in mergers, clumpy disks and dwarfs)
  - Evaporation of an initial M^{-2} power law or Schechter function from normal SF
  - Early peak from abnormal star formation
    - lower initial cutoff in mass for GCs than for today's clusters
    - lower efficiency for low mass clusters at high z than today
  - Early peak from cluster disruption in abnormal environment
    - high density & velocity dispersion of z>2 galaxies destroys low-M clusters quickly

The End