1

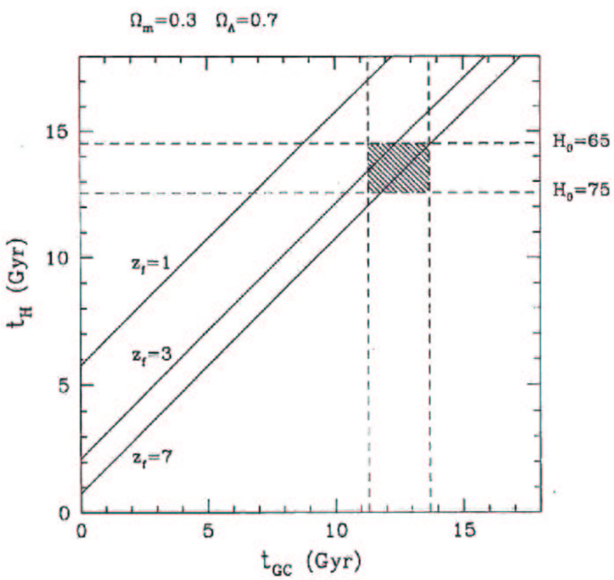
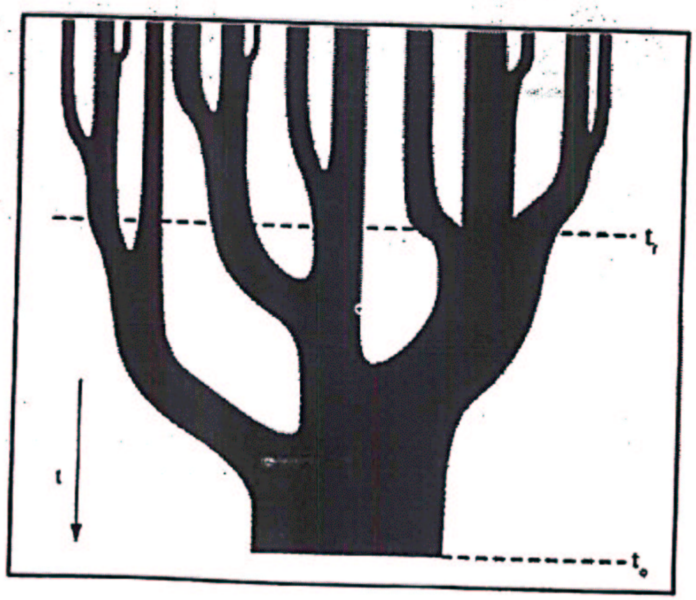


Figure 2: The age of expansion vs the age of globular clusters, as a function of the formation redshift z_f (eq. 3). Shaded box contains the current values of t_H and t_{GC} within the observational errors. In a flat Universe with $\Omega_\Lambda = 1 - \Omega_m = 0.7$, the age of expansion is $t_H = \frac{2}{3} H_0^{-1}\, \Omega_\Lambda{}^{-1/2} \ln[(1+\Omega_\Lambda{}^{1/2})(1-\Omega_\Lambda)^{-1/2}]$.

from Gratton et al astroph 0108034

2



dissipationless merger hypothesis supported by fact that many GC properties are blind to galaxy type

3

but GCs (probably) can't all form in dwarf galaxies:

- correlation between $\bar{Z}_{GC}$ and L_{host}

  [van den Bergh 1975, Brodie and Huchra 1991, Forbes et al 1997, Côté et al 1998, Larsen et al 2001]

- S_N higher in early type galaxies (e.g. Harris 1991, McLaughlin 1999)

- observations of massive cluster formation in mergers (Antennae etc: Schweizer 1998, Ashman and Zepf 1998, Whitmore et al 1999).

4

CÔTÉ, WEST & MARZKE 19

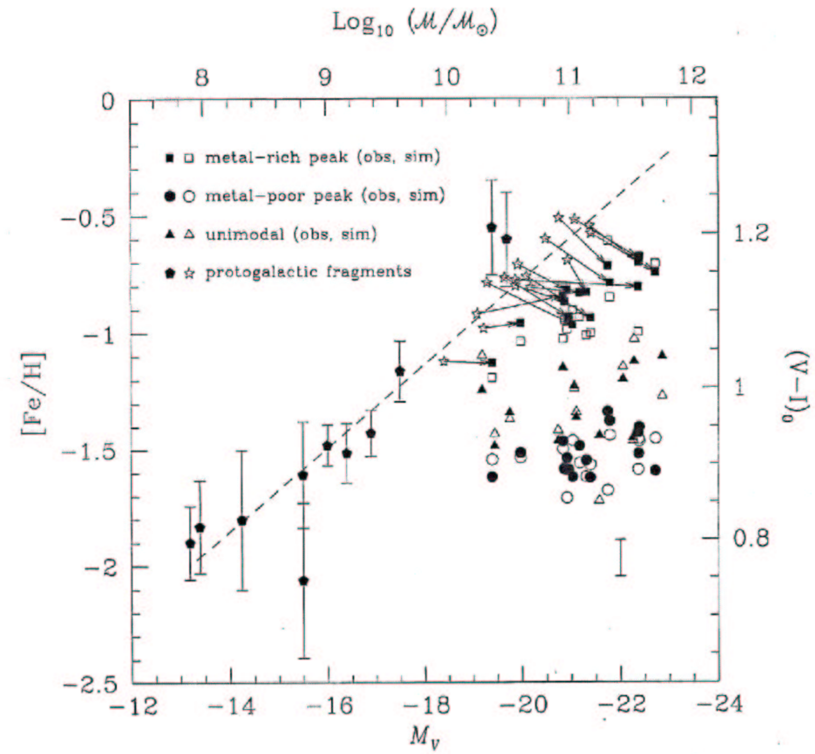
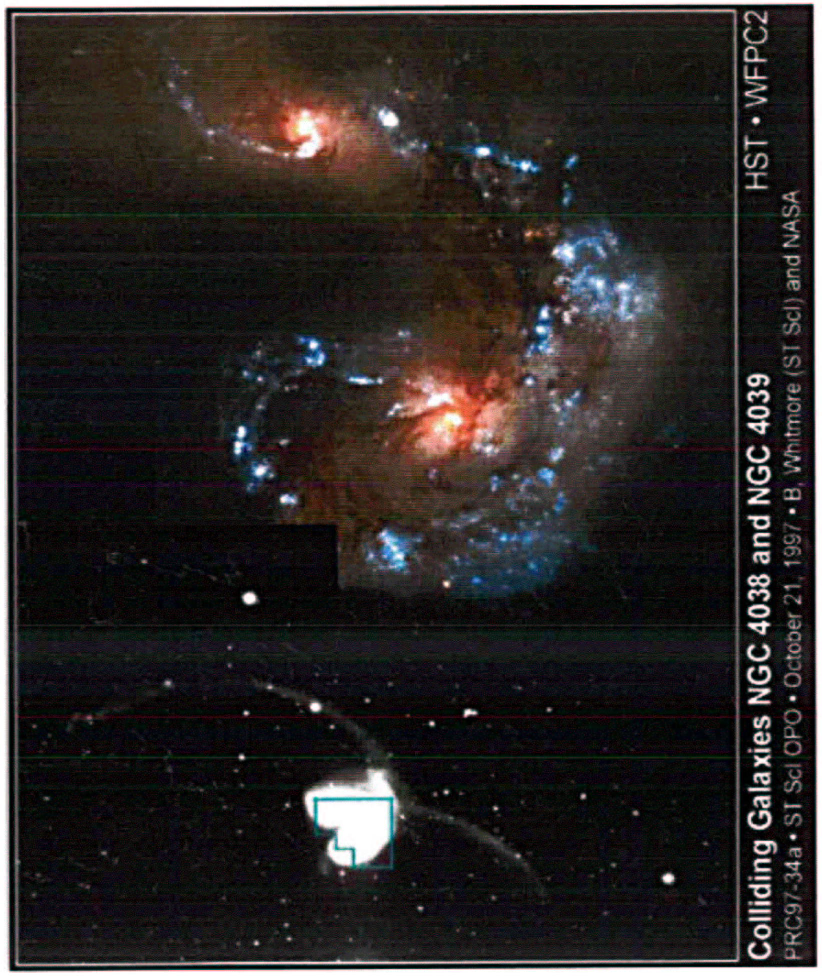


FIG. 10.— Mean color (metallicity) of globular cluster systems, plotted against galaxy magnitude (mass). The dashed line shows the "zero-age" relation between galaxy mass and globular cluster metallicity shown in Figure 1 for unmerged protogalactic fragments: i.e., isolated galaxies of low and intermediate mass, and the bulge components of spiral galaxies (filled pentagons). The filled squares and circles show the observed colors for the metal-rich and metal-poor globular clusters in the 16 galaxies classified as bimodal by Kundu & Whitmore (2001). Open squares and circles indicate the median color of these components based on 100 simulations of the globular cluster metallicity distributions using the (α, ζ) values reported in Table 1. The filled and open triangles show the observed and simulated colors of globular clusters belonging to the 12 galaxies classified by Kundu & Whitmore (2001) as unimodal. The errorbar in the lower right corner shows the 1σ scatter about these median values. For each galaxy with a bimodal metallicity distribution, a thin arrow connects the original position of the most massive protogalactic fragment (open stars) to the measured position of the metal-rich peak.



- 2 mass scales

$M_{clus} >>> M_*$

$M_{Jeans}(P, T)$? → M_{clus}: Peebles and Dicke 1968; Fall and Rees 1985

$M_{Jeans}(P, T)$? → M_*: Harris and Pudritz 1994; McLaughlin and Pudritz 1996; Padoan et al 1997; Elmegreen and Efremov 1997

pre-requisites for fragmentation:

$t_{cool} < t_{ff}$ Rees and Ostriker 1977

AND

non-linear density structure at onset of cooling Larson 1978; Klessen et al 1998; Bate et al 2001

↑ compatible with pressure supported progenitor?

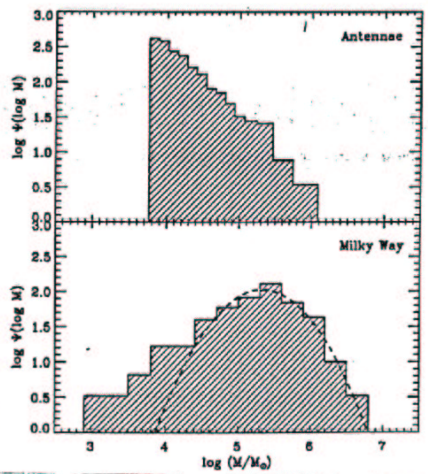
like local star formation in GMCs

M_{clus} set by "dynamic potentials" ....

- mass function of young globular clusters in mergers has ≃ same slope as mass functions of GMCs. [e.g. Elmegreen + Efremov 1997]

$\psi(M) \propto M^{-2}$ →

2 Fall & Zhang



mass function of MW GCs shaped by survival against disruption, but

- need initial mass function of MW GCs to steepen at $M_{clus} = 10^6 - 10^7 M_\odot$ (e.g. Fall and Zhang 2001).

9

- proto-GCs versus GMCs (see Ashman & Zepf 2001)

masses similar

$r_{\frac{1}{2}} \sim 3$ pc	$r_{\frac{1}{2}} \sim 20$ pc
$\epsilon = \frac{M_*}{M_{tot}} \gtrsim 25\%$ (to be bound)	$\epsilon \sim 0.2\%$

Does efficient feedback in GMCs inflate them? X

does compactness of proto GCs → short t_{dyn} → inefficient feedback? maybe

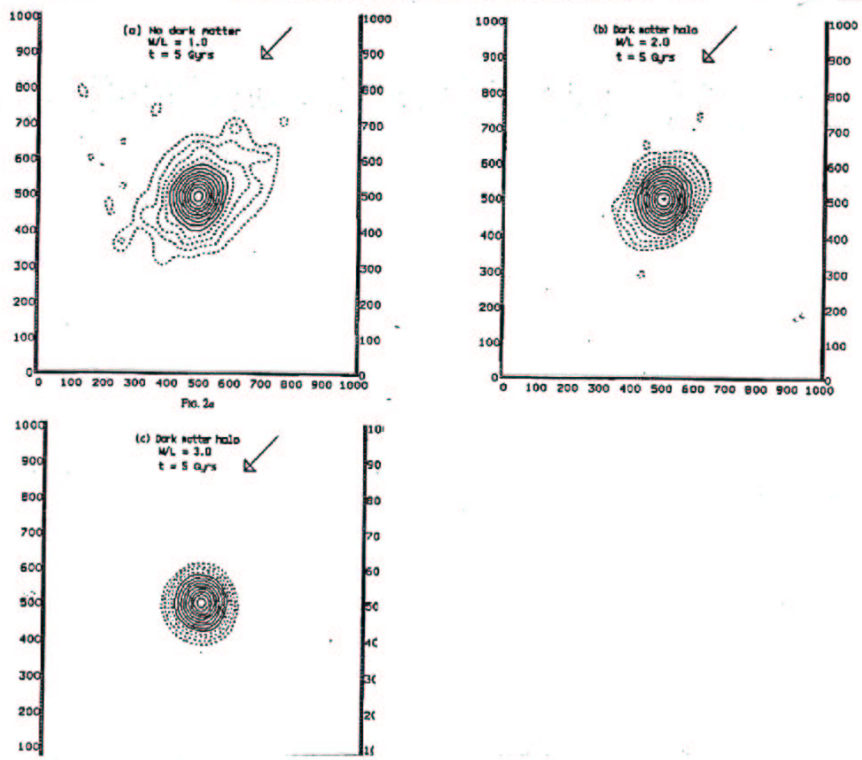
does compactness of proto GCs result from high P environment? maybe

(10)

• GCs don't have significant DM halos

1996ApJ...461L..13M

No. 1, 1996 CONSTRAINTS ON GLOBAL MASS-TO-LIGHT RATIOS (Moore 1996). L15



.... or significant DM within optical radius.

(Pryor et al 1989).

(11)

• GCs are not Pop. III ($Z \gtrsim 10^{-2} Z_\odot$)

but

• narrow width of giant branch

Freeman and Norris 1981
Fahlman et al 1985.
Murray + Lin 1990

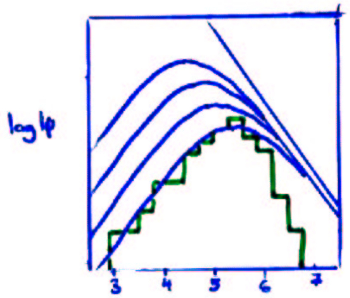
⇒ not self-enriched

(8)

Evolution of mass function of GCs

— = 0, 1.5, 3, 6 & 12 Gyr

— = observed mass function in MW



from Fall & Zhang 2001
astro-ph 0109298.

(12)

A successful GC formation scenario

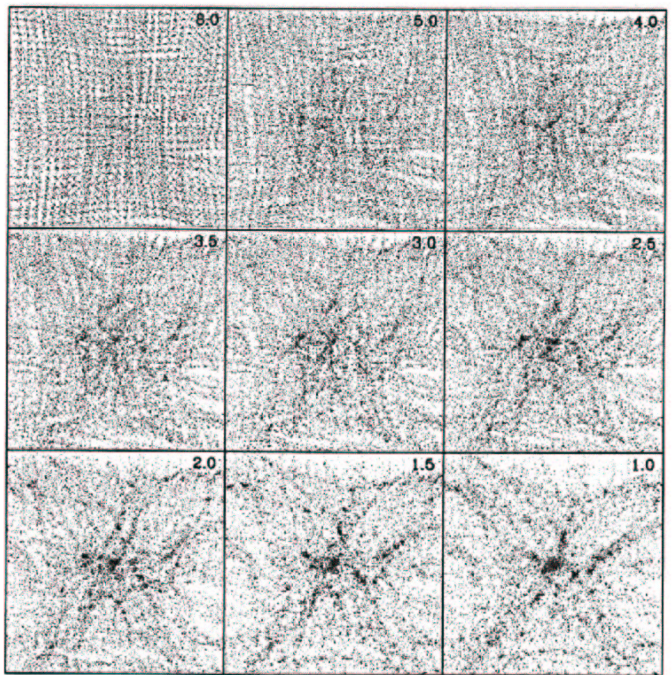
must → clusters which are

- populous ($N \gtrsim 10^7$)
- compact
- chemically homogeneous ($Z \gtrsim 10^{-2} Z_\odot$)

with • $\bar{m}_* \lesssim 1 M_\odot$

- and no detectable DM component

GC Formation in Cosmological Simulations (13)



← 2Mpc comoving →

FIG. 2b

- $M_{DM} \sim 5 \times 10^{11} M_\odot$

  $M_{gas} \sim 10^{11} M_\odot$

- identify bound gas clouds as Super Giant Molecular Clouds (SGMCs) in which GCs may form

- resolution limits: $r_{res} \simeq 1$ kpc

  $M \simeq$ few $\times 10^{8} M_\odot$

(14)

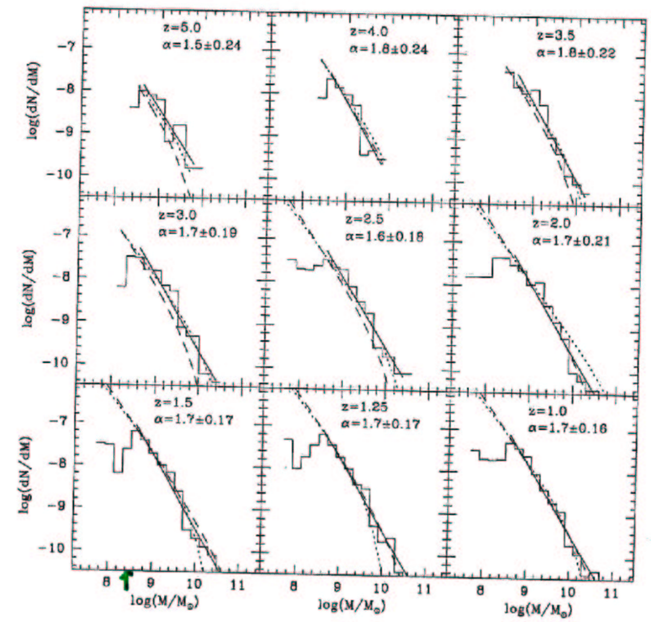


FIG. 6.—Mass spectrum of combined dark matter clumps for all seven runs shown at nine redshifts. The solid lines show power-law fits, as described in the previous figure caption. The dotted and dashed lines are fits of the Press-Schechter multiplicity function of eq. (1) with $n = 1$ and $n = 0$, respectively.

mass spectra of DM clumps

– like GCs!

(see also Cen 2001, Gnedin et al 2001, Bromm & Clarke 2002)

if this is relevant to GC formation, then similarity with GMC mass spectrum is fortuitous.

15.

GC formation in low mass haloes?

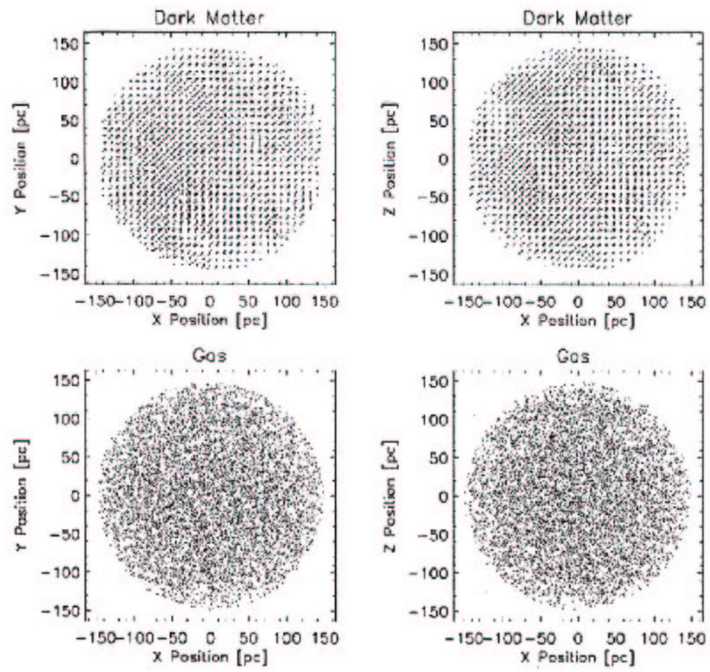
Cen (2001) envisaged gas 'sitting idly' in low mass haloes

re-ionization (z ~ 7). → shock compression
collapse
fragmentation

.... but would it sit idly?

16.

fig7.h.gif (GIF Image, 1333x1269 pixels) http://www.journals.uchicago.edu/ApJ/journal/issues/ApJ/v564n1/5...

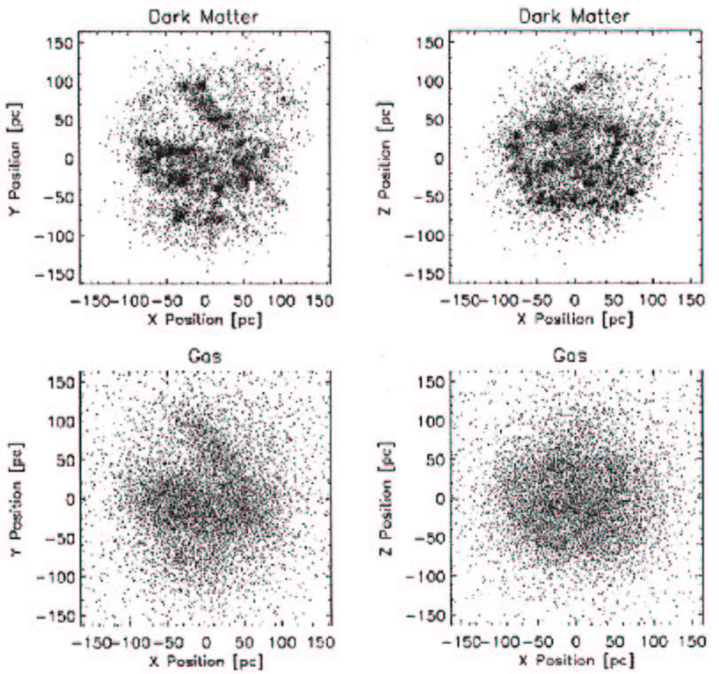


from Bromm et al 2002

1 of 1 01/22/03 11:21

17.

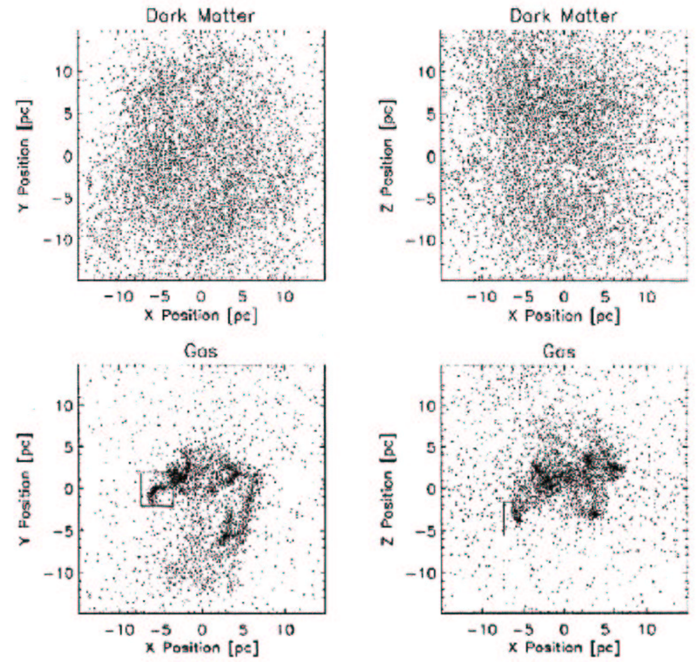
fig8.h.gif (GIF Image, 1333x1269 pixels) http://www.journals.uchicago.edu/ApJ/journal/issues/ApJ/v564n1/5...



1 of 1 01/22/03 11:24

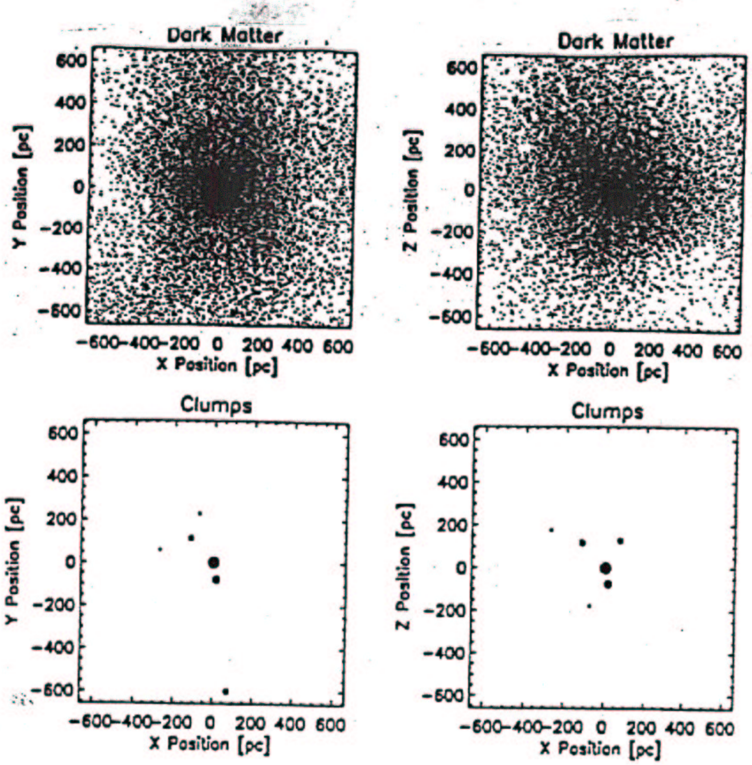
18.

fig9.h.gif (GIF Image, 1311x1269 pixels) http://www.journals.uchicago.edu/ApJ/journal/issues/ApJ/v564n1/5...



1 of 1 01/22/03 11:26

(19)



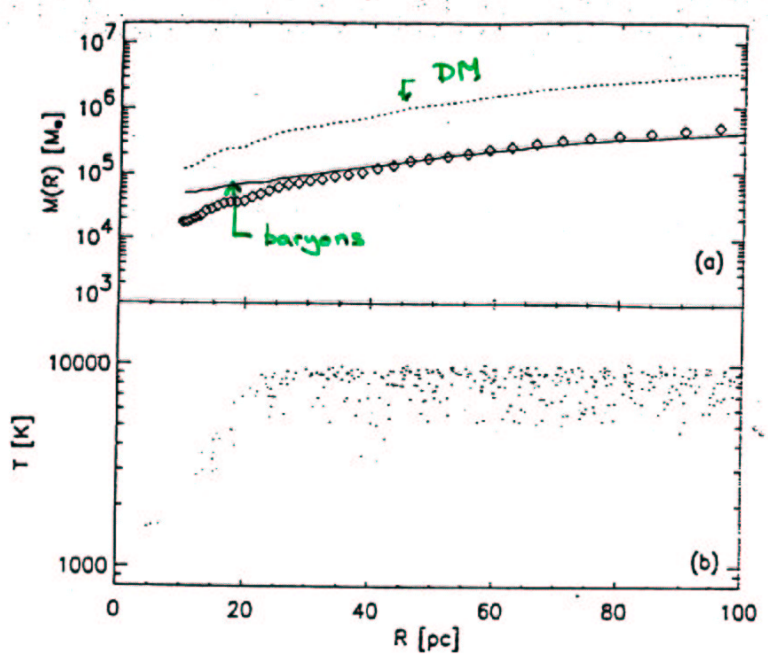
z=15

$M_{DM} = 2\times10^{8} M_\odot$, $Z = 10^{-2} Z_\odot$

clump masses: $4\times10^4 M_\odot$, $5\times10^4 M_\odot$, $2\times10^3 M_\odot$, $3\times10^5 M_\odot$, $1.3\times10^6 M_\odot$, $2.2\times10^7 M_\odot$

- are these GCs, if not, what are they?

(20)



The first clump @ z=24.

How does model perform?

- fragmentation? can't say yet
- sizes? $r \lesssim 10$ pc, $t_{ff} \lesssim 10^6$ years.
- mass distribution?

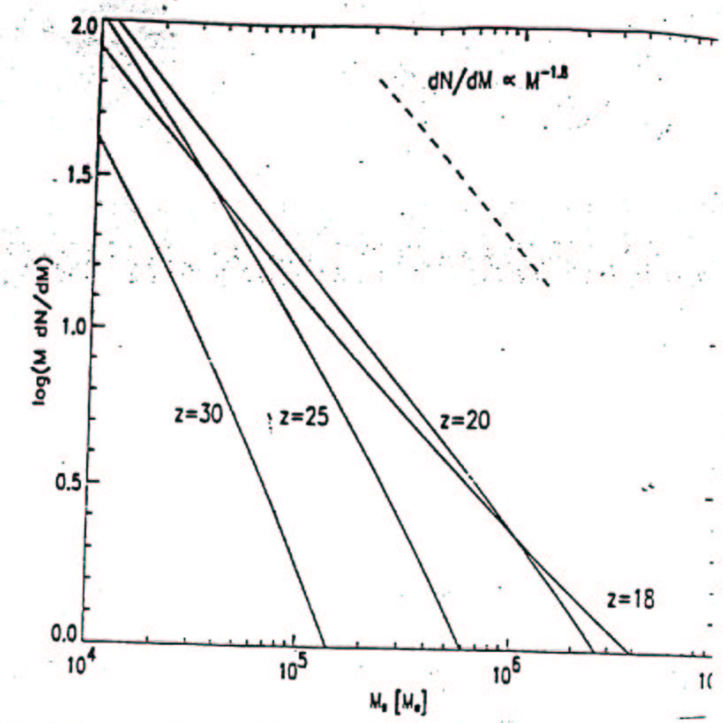
  power law from DM clustering statistics

  $M_{min} = M_{res}$

  M_{max} = good fraction of total baryon mass

  (most massive clump is not GC-like.... nucleus of dwarf.....)

- association with DM? haloes erased ✔



EPS calc. of mass spectrum of haloes which at $z = 15$ will have merged into a dwarf galaxy mass $M = 2 \times 10^8 M_\odot$

(23)

Unsolved Problems I

What sets M_{max} ?

- invoke change in DM power spectrum?

  if $P(k) \propto k^n$, mass variance = $\int_0^{1/L} P(k)\, k^2\, dk$

  and $M \sim L^3$ $\Rightarrow$ variance $\propto M^{-\left(\frac{n+3}{3}\right)}$

  $\Rightarrow$ n close to 3, variance ~ flat

  small scale régime $\Rightarrow$ efficient erasure of DM substructure

- stop process at $z \sim 7$

  (re-ionisation prevents gas collapsing in small haloes)

- not 'globular like' at lower z

  (longer t_{ff} $\Rightarrow$ efficient feedback).

(25)

Future tasks:

- higher resolution simulations
- incorporation in hierarchical merging scenarios