The Globular Cluster Luminosity Function

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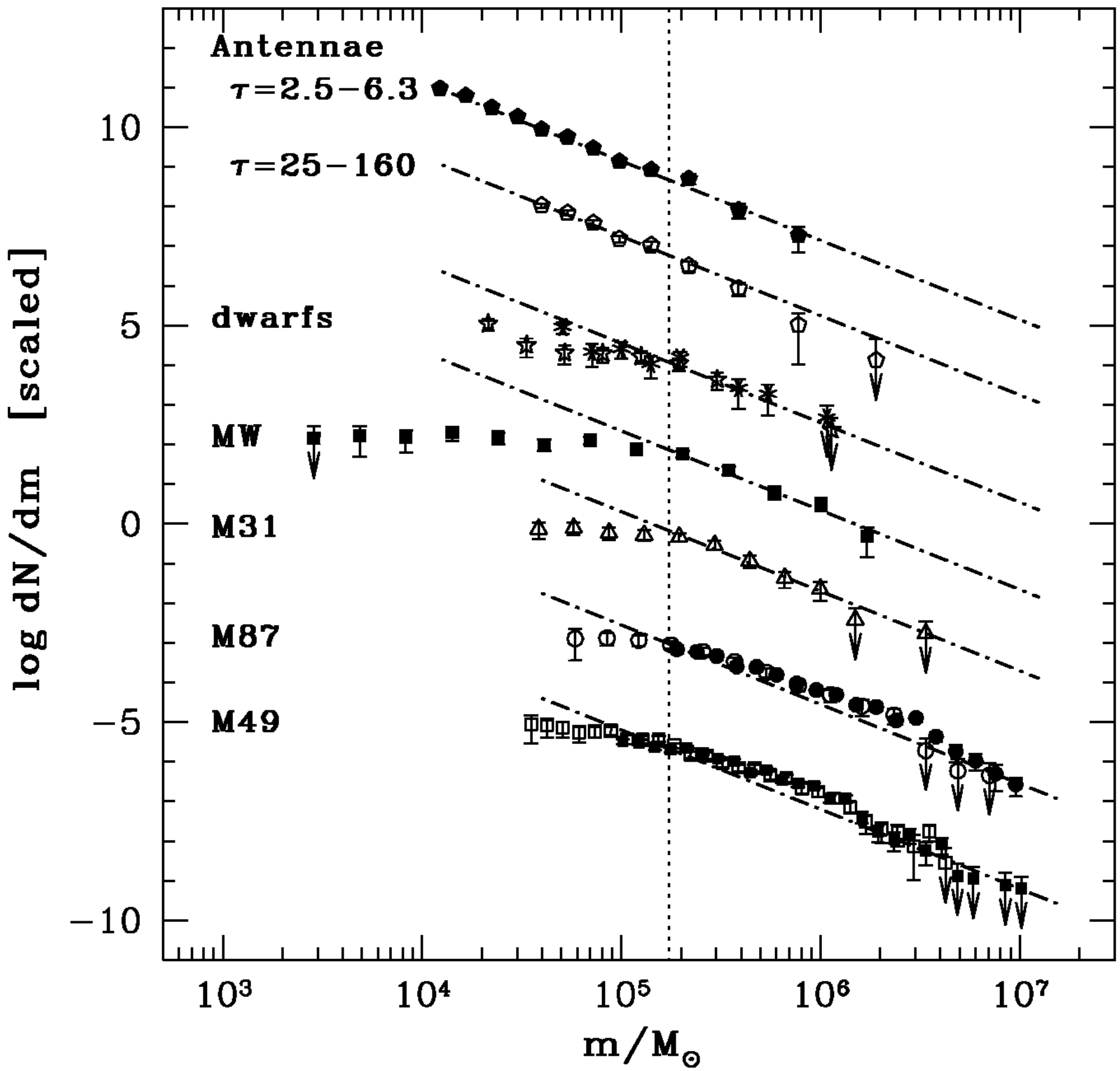
- dN/d(log M) = GC mass function (GCMF):
  not universal
- peak or turnover M_{TO} :
  increases with cluster half-mass density in the Milky Way
- width:
  decreases with increasing ρ_h
- must be accounted for in any theory of GCMF
- signature of cluster evaporation driven by internal two-body relaxation



$dN/dM \propto M^{-\beta} \Rightarrow$

$dN/d(\log M) \propto M^{1-\beta} \Rightarrow$

observable $dN/d(\log L)$

$\beta>1$: GCMF rises to low M

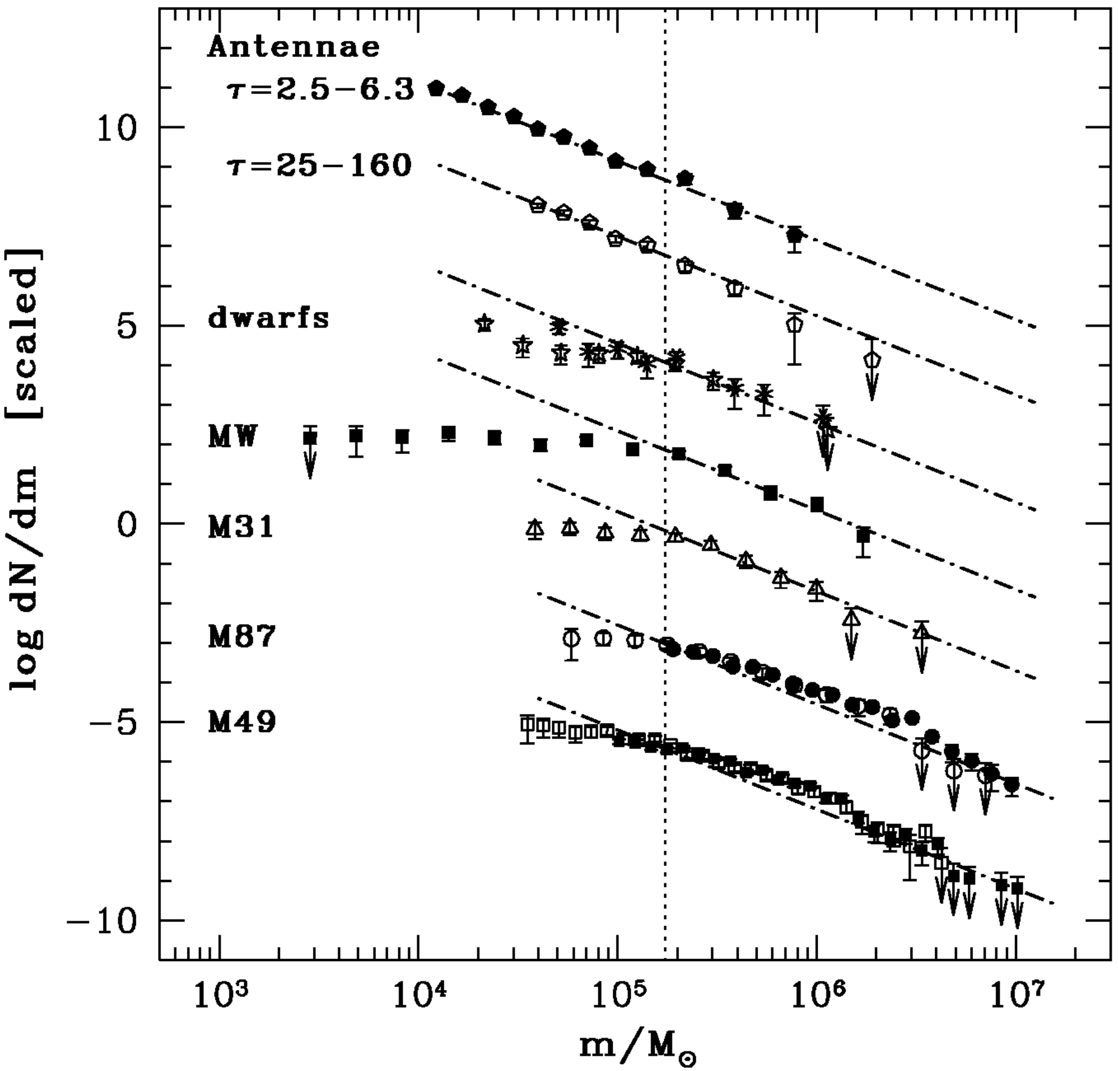
$\beta<1$: GCMF falls to low M

$\beta>1 \leftrightarrow \beta<1$: peak M_{TO}

young clusters: $\beta \simeq 2$ for 10^6–10^4 $M_\odot$

old GCs: $\beta \sim 2$ at $M>M_{TO}$ (with curvature!)

$M_{TO} \approx 1$–2×10^5 $M_\odot$



$\mathbf{M < M_{TO} : \beta \to 0}$

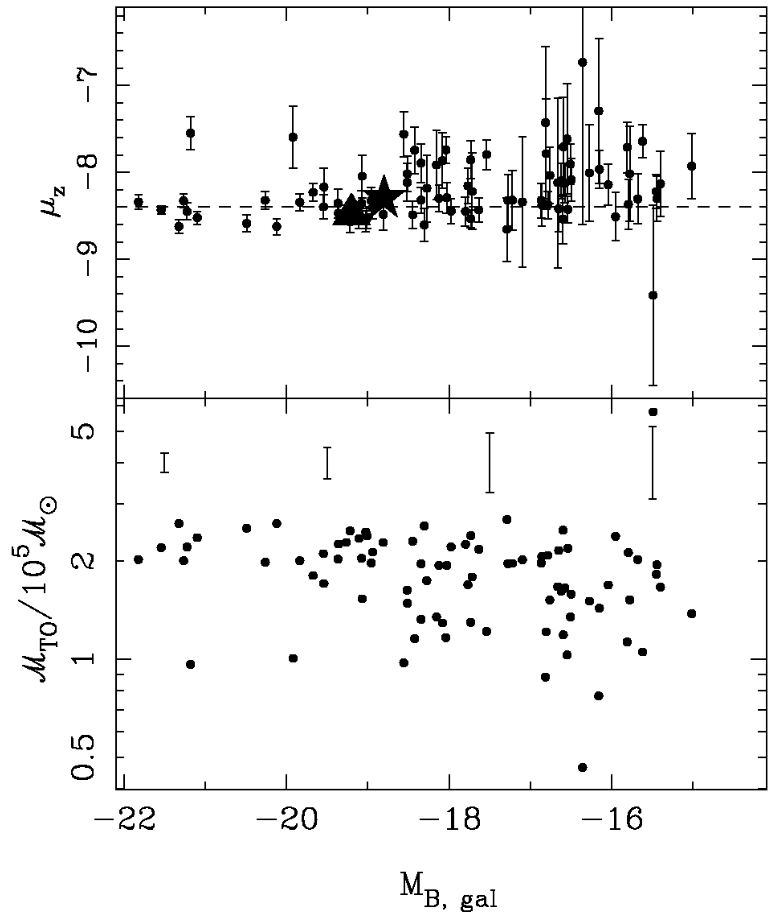
$dN/dM \to$ const.

$dN/d(\log M) \to M^{+1}$

generic?

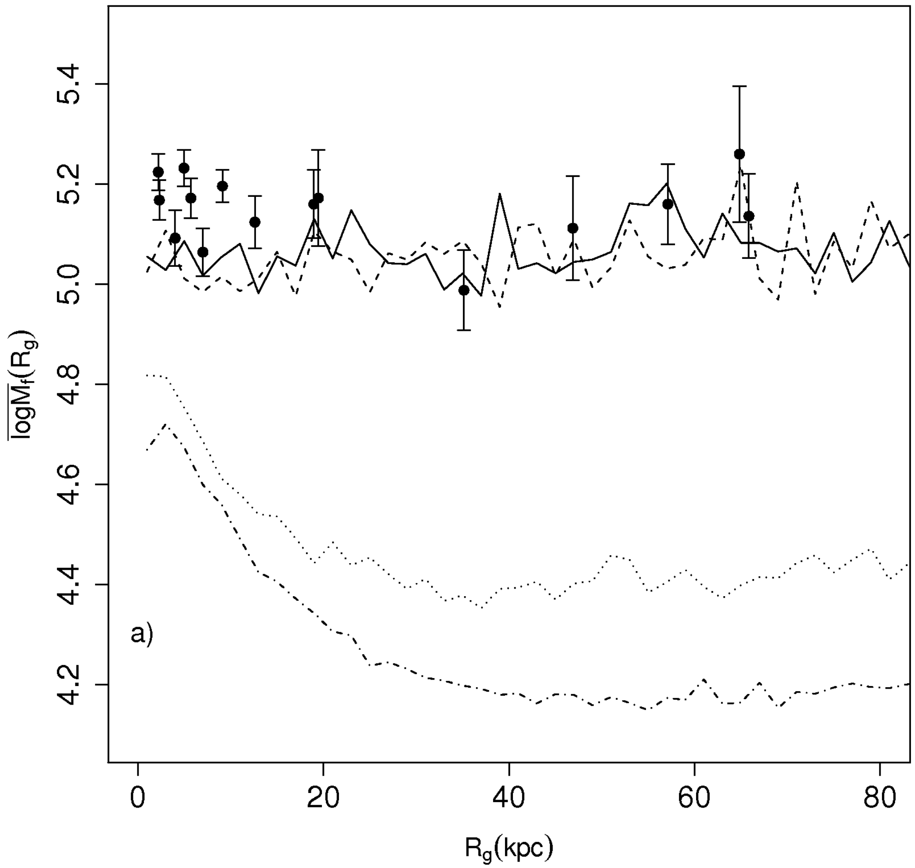
Milky Way	Fall & Zhang (2001)
M87	Waters et al. (2006)
Sombrero	Spitler et al. (2006)
89 Virgo galaxies	Jordán et al (2007)

GCMF turnover ≈ constant between and within galaxies



$M_{TO}/(10^5\ M_\odot)$ vs L_{gal}

(Jordán et al. 2006, 2007)



M_{TO} vs R_{gc} in M87

(Vesperini et al. 2003)

"universality" of $M_{TO} \approx 1\text{–}2 \times 10^5\ M_\odot$ *and* $\beta \rightarrow 0$ for $M < M_{TO}$

(near-)initial conditions?

e.g., Kroupa & Boily (2002); Vesperini & Zepf (2003); Parmentier & Gilmore (2007)

long-term evolution from initial $\beta \simeq 2$ power law at low M?

low-mass clusters preferentially destroyed over $\simeq$ 13 Gyr of evolution in galaxy tidal fields (gravitational shocks, two-body relaxation) "universality" of $M_{TO} \approx 1-2\times10^5\ M_\odot$ *and* $\beta \rightarrow 0$ for $M < M_{TO}$

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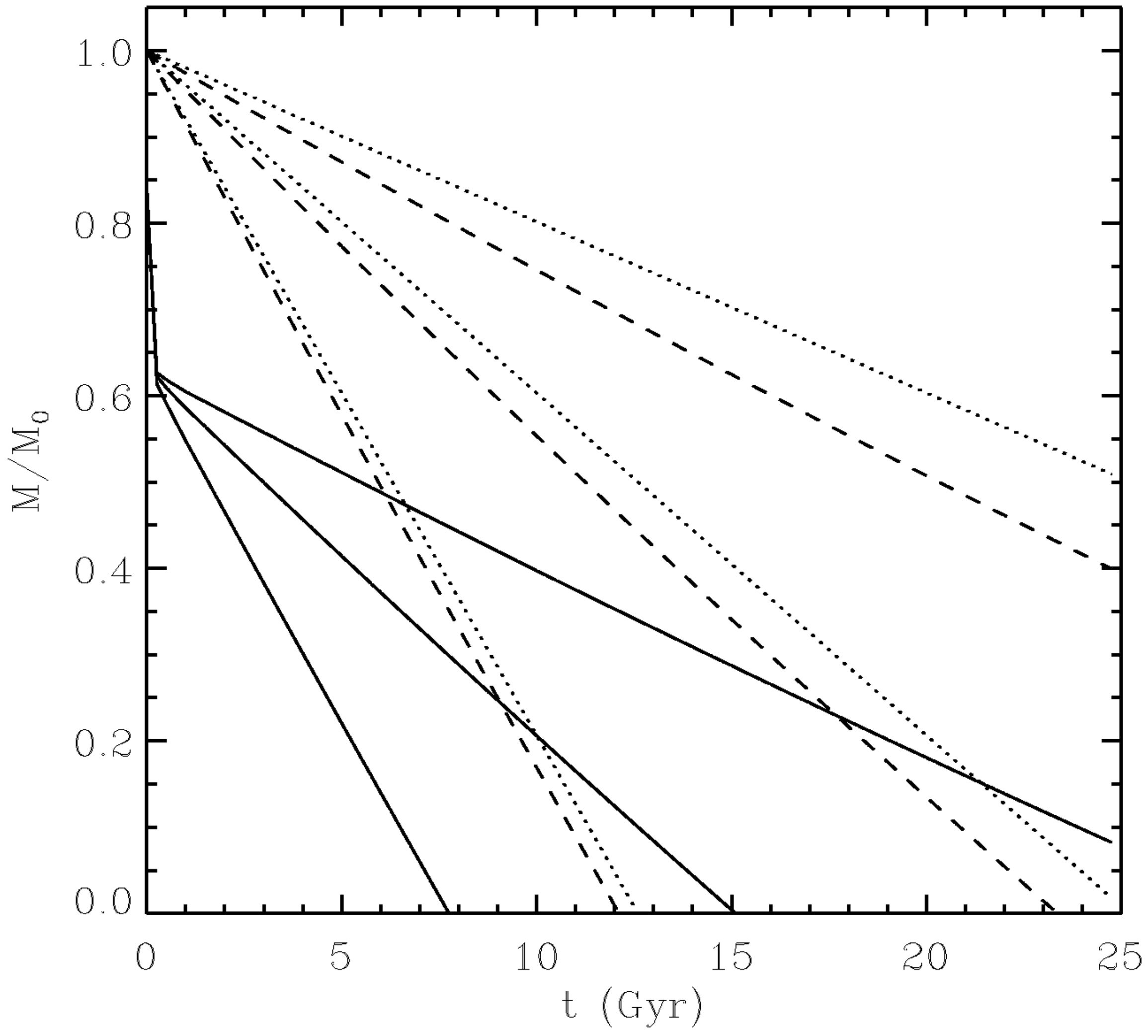
star formation and "infant mortality" inevitably affect the "initial" GCMF at $\sim10^8-10^9$ yr

subsequent dynamical evolution inevitably affects the mass distribution of old clusters as observed

what is ***necessary*** vs. what is ***possible***?

Cluster mass-loss rates (Fall & Zhang 2001, ApJ)



Two-body relaxation:
most important

Gravitational Shocks:
secondary
(Gnedin et al. 1999 ;
Prieto & Gnedin 2006)

Stellar evolution:
no effect on MF

NOTE! relaxation-dominated evolution ⇒ **M linear in time**
(also: Vesperini & Heggie 1997; Gnedin et al. 1999; Giersz 2001; Baumgardt & Makino 2003; Trenti et al. 2007; ...)

Linear decrease $dM/dt \simeq$ constant is crucial (Fall & Zhang 2001)

$\mathbf{M(t) = M_0 - \mu_{ev} t}$ $\Rightarrow$ if initial $dN/d(\log M_0)$ rose to low masses, peak develops at

$\mathbf{M_{TO} \sim \mu_{ev} t}$ (roughly speaking)

more generally:

current masses $M \ll \mu_{ev} t$ are remnants of initial $M_0 \approx \mu_{ev} t$

number at all $M \ll \mu_{ev} t$ is $\approx$ initial number at $M_0 \approx \mu_{ev} t$

i.e., low-mass $\beta \rightarrow \mathbf{0 : dN/d(\log M)} \rightarrow \mathbf{M^{+1}}$ *always*

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N-body: $t_{dis} \propto t_{rh,0}^{3/4}\, t_{cross,0}^{1/4} \Rightarrow \boldsymbol{\mu_{ev} \propto \Sigma_{h,0}^{3/4}}$

(Baumgardt & Makino)

Relaxation-driven mass-loss rate increases with cluster half-mass density

Fall & Zhang: $\mu_{ev} \propto \rho_h^{1/2}$ and ρ_h=constant (Hénon 1961)

plausibly explains *global* M_{TO} in Milky Way GC system from initial Schechter function with low-mass power law β=2

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then infer strong radial-orbit bias for GC system: to reproduce near-constant $M_{TO} \sim \rho_h^{1/2} \sim r_p^{-1}$ vs. current r_{gc}

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- abandon long-term dynamical evolution for peak and low-mass shape of GCMF?
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secondary assumptions about geometry and time-dependence of Galactic halo ⇒
GC ρ_h vs. r_p and r_{gc} that may be ***unrealistic***

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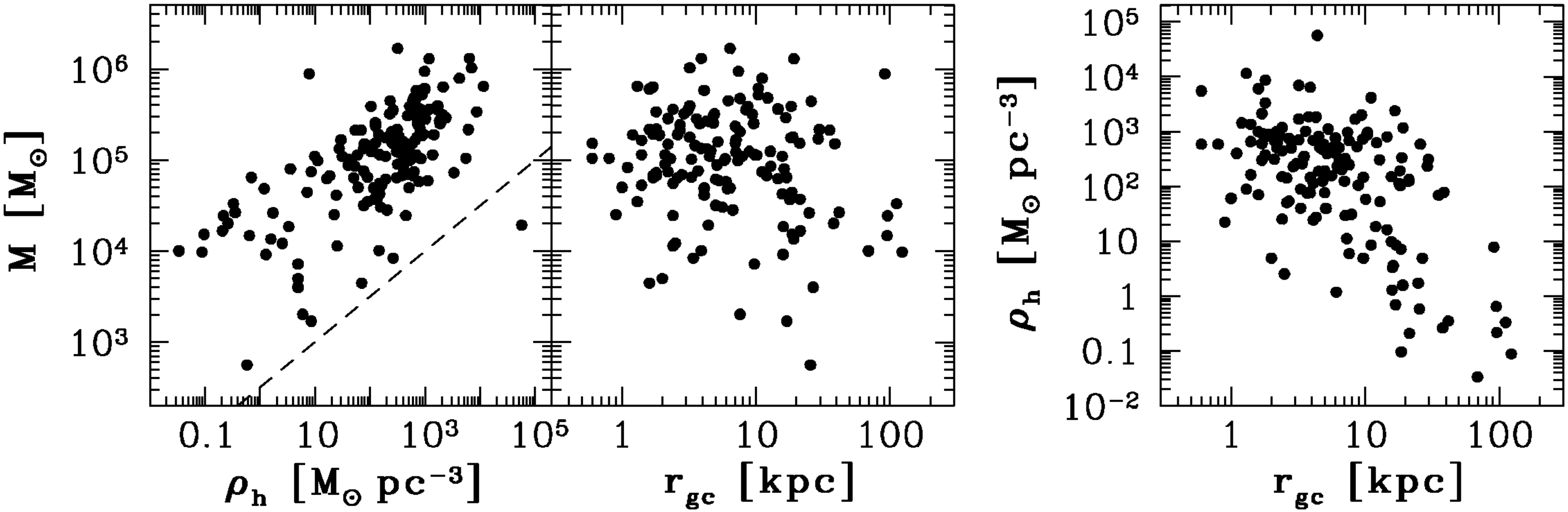
relaxation-dominated cluster mass loss ⇒
prediction of GC dN/d(log M) dependence on cluster density ρ_h (or Σ_h) : ***check!***

McLaughlin & Fall (2007)



M vs ρ_h : M ↑ and "scatter" ↓ as ρ_h ↑

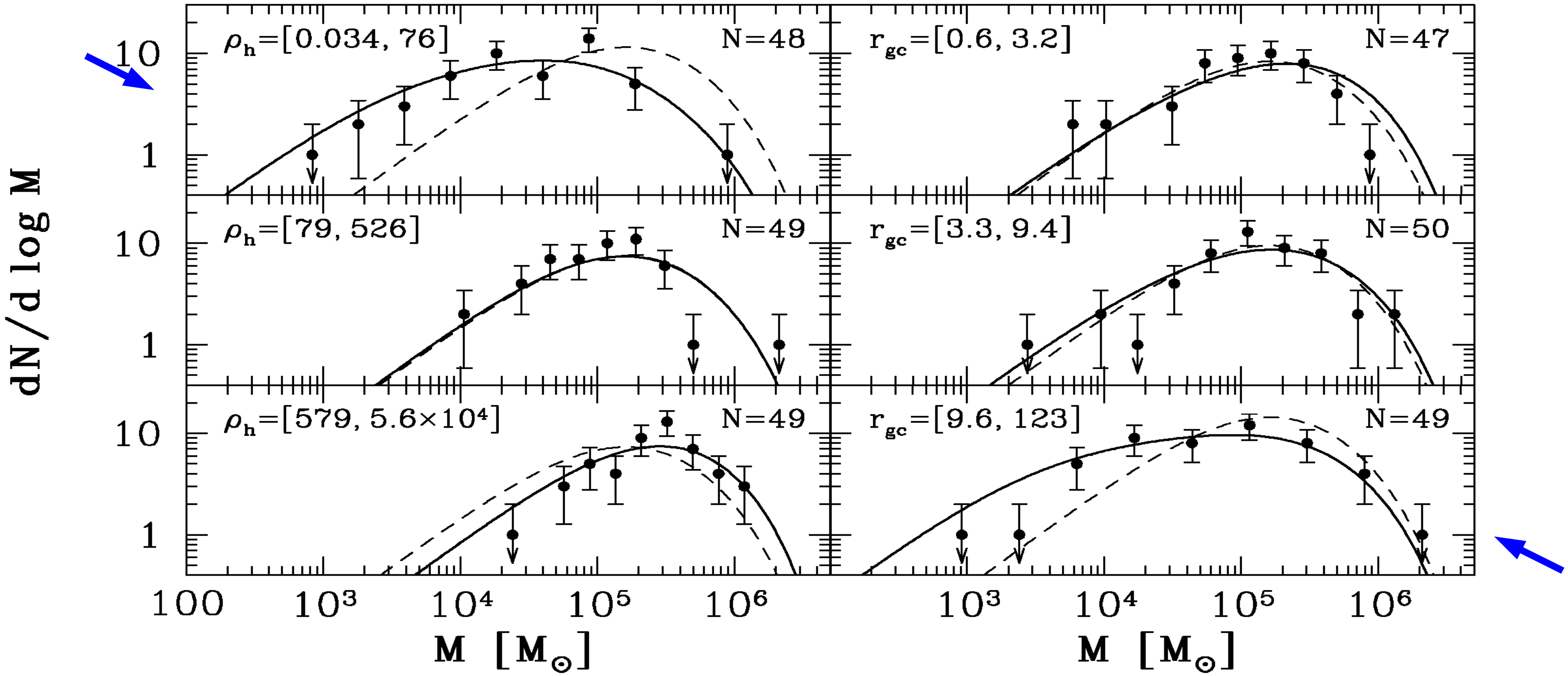
lower envelope $M \propto \rho_h^{1/2}$ (constant t_{dis})

M vs r_{gc} : no strong trend (broader at large r_{gc})

ρ_h vs r_{gc} : large scatter, no *unique* fit like $\rho_h \propto r_{gc}^{-2}$

convolving with $M(\rho_h)$ *erases* GCMF variations

McLaughlin & Fall (2007)

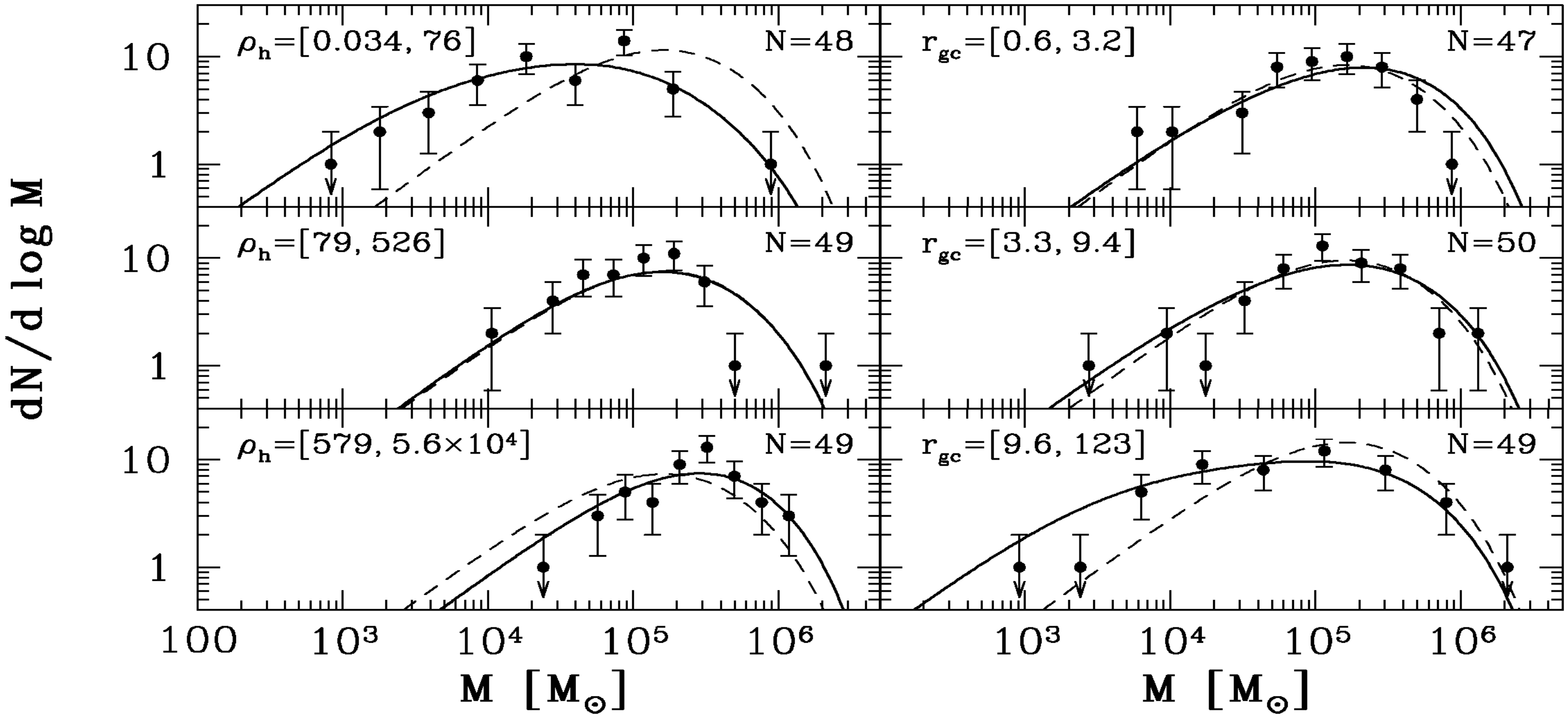


M_{TO} increases with ρ_h : not universal

expected for μ_{ev} ↑ as ρ_h ↑

broader distribution at low ρ_h : less evolved

broad GCMF at large r_{gc} : very broad range of ρ_h



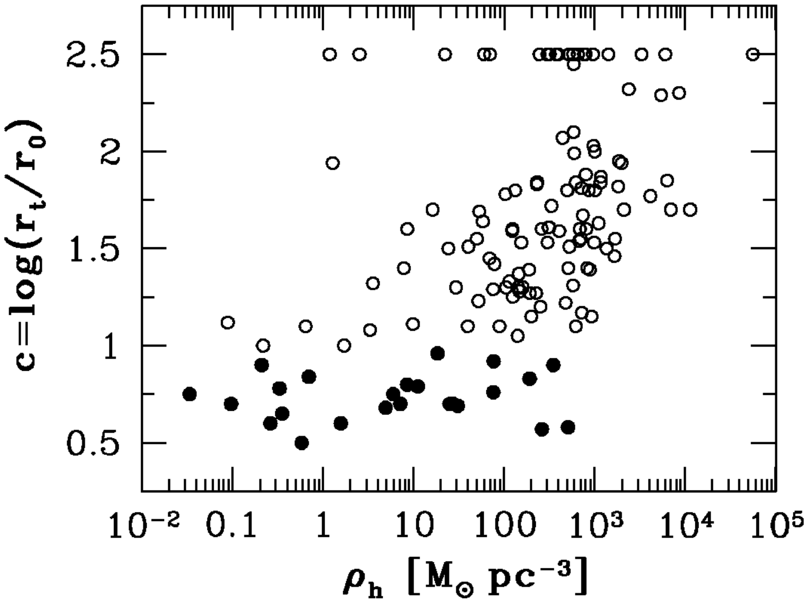
initial GCMF: $dN/d(\log M_0) \propto M_0^{-1} \exp(-M_0/M_c)$ [β=2 at low M]

$$\frac{dN}{d\log M} = \sum_{i=1}^{N} A_i \frac{M}{(M+\Delta_i)^2} \exp\left(-\frac{M+\Delta_i}{M_c}\right) \qquad (M_c \simeq 10^6\, M_\odot)$$

$$\Delta_i = 1.45 \times 10^4\ M_\odot\ (\rho_{h,i} / M_\odot\ pc^{-3})^{1/2}$$

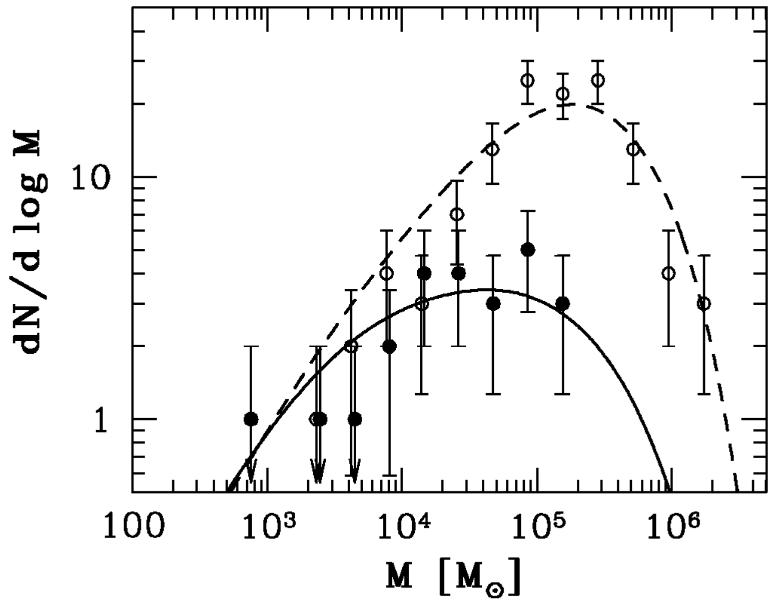
$$\mu_{ev,i} = \Delta_i / 13\ Gyr = 1.1 \times 10^3\ M_\odot\ Gyr^{-1}\ (\rho_{h,i} / M_\odot\ pc^{-3})^{1/2}$$

McLaughlin & Fall (2007)



Galactic GCMF vs cluster concentration

Smith & Burkert (2002):
difference between $c < 0.99$
and $c \geq 0.99$



result of different ρ_h distributions in different c ranges

same $\Delta \propto \rho_h^{1/2}$ as before

Single $\mu_{ev} \propto \rho_h^{1/2}$ as in relaxation-dominated evaporation explains GCMF as function of ρ_h

as (non-)function of r_{gc}

in different concentration ranges

etc....

weak/null radial variation of GCMF inside galaxy not an argument against long-term dynamical evolution

strong radial orbit bias results from too-simple attempt to connect ρ_h to r_{gc} : Galaxy is not spherical and static over a Hubble time

derive $\rho_h(r_{gc})$ distribution from detailed simulations in hierarchical cosmology (e.g., Prieto & Gnedin 2006) from "fitted" mass-loss rate $\mu_{ev} \propto \rho_h^{1/2}$:

GCMF $t_{dis} = M_0/\mu_{ev} \approx 10\ t_{rh,0}$

standard relaxation theory: $t_{dis} \sim 20–30\ t_{rh,0}$

GC lifetimes estimated from GCMF within factor of ~2 of independent theory

various possible resolutions: shocks? stellar IMF?
initial low-mass power law $\beta<2$?
current $\rho_h \neq \rho_{h,0}$

or relaxation theory itself: $t_{dis} \sim 6–7\ t_{rh,0}$ at $10^5\ M_\odot$
in Baumgardt & Makino (2003)

Baumgardt & Makino (2003):

$$t_{dis} \propto t_{rh,0}^{3/4}\, t_{cross,0}^{1/4} \Rightarrow \mu_{ev} \propto \Sigma_{h,0}^{3/4}$$

replacing $\rho_h^{1/2}$ with $\Sigma_h^{3/4}$ in preceding:

no change to basic results

key point: near-linear M(t) and μ_{ev} increasing with *some* measure of half-mass density

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$$mass \quad loss \quad rate \qquad -\mu_{ev} \propto \sqrt{\rho} = constant \qquad \Rightarrow$$

$$M(t) = M_0 - \mu_{ev} t = M_0 - \Delta$$

$$\frac{dN}{dM}(t) = \frac{dN}{dM_0}\left|\frac{\partial M_0}{\partial M}\right| = \frac{dN}{dM_0}$$

$$\frac{dN}{dM_0} = M_0^{-2} \exp(-M_0 / M_c) \qquad \Rightarrow$$

$$\frac{dN}{dM} = \frac{1}{(M+\Delta)^2} \exp\left(\frac{-M+\Delta}{M_c}\right)$$

Evolved Schechter Function

M_c sets scale $\quad\quad$ Δ / M_c fixes shape