Star Formation in Clusters

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Star Clusters: Near and Far

Very Near: ONC (400 pc)

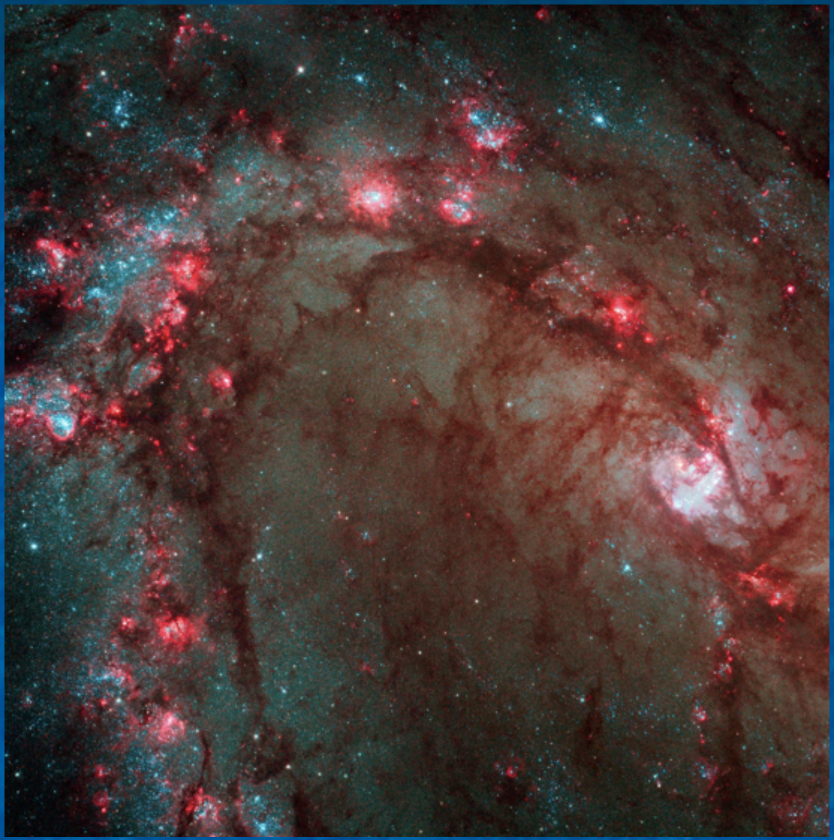
~10^3 Msun

Near: NGC 3603 (7 kpc)

~10^4 Msun

Star Clusters: Near and Far

Kinda Near: R136 (50 kpc)



Kinda Far: M83 (4.5 Mpc)

~10^5 Msun

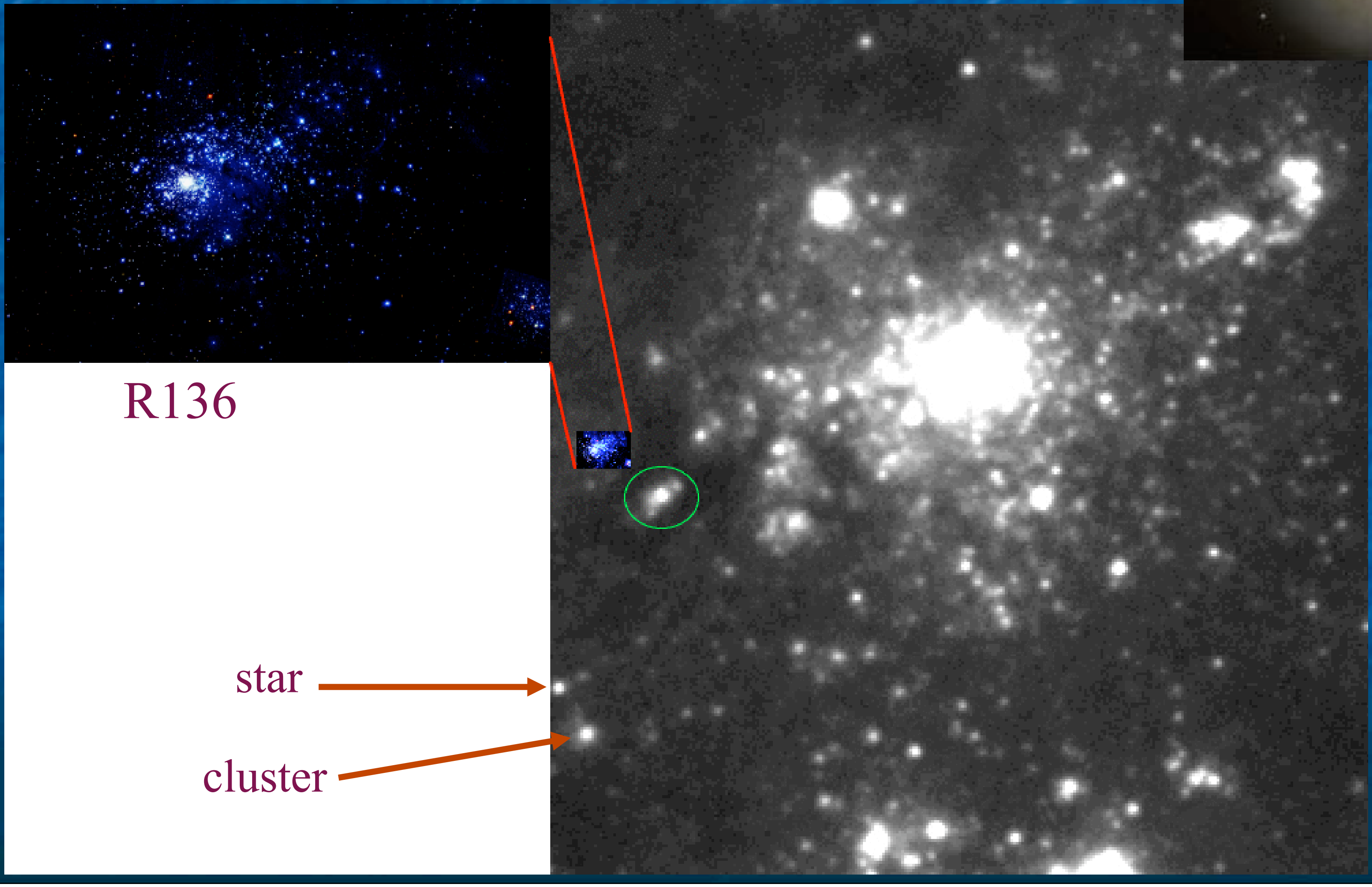
-- No longer resolve individual stars in compact clusters ~beyond the Magellanic Clouds; study integrated light of the clusters.

-- Allows us to study entire *systems* of star clusters at known distances

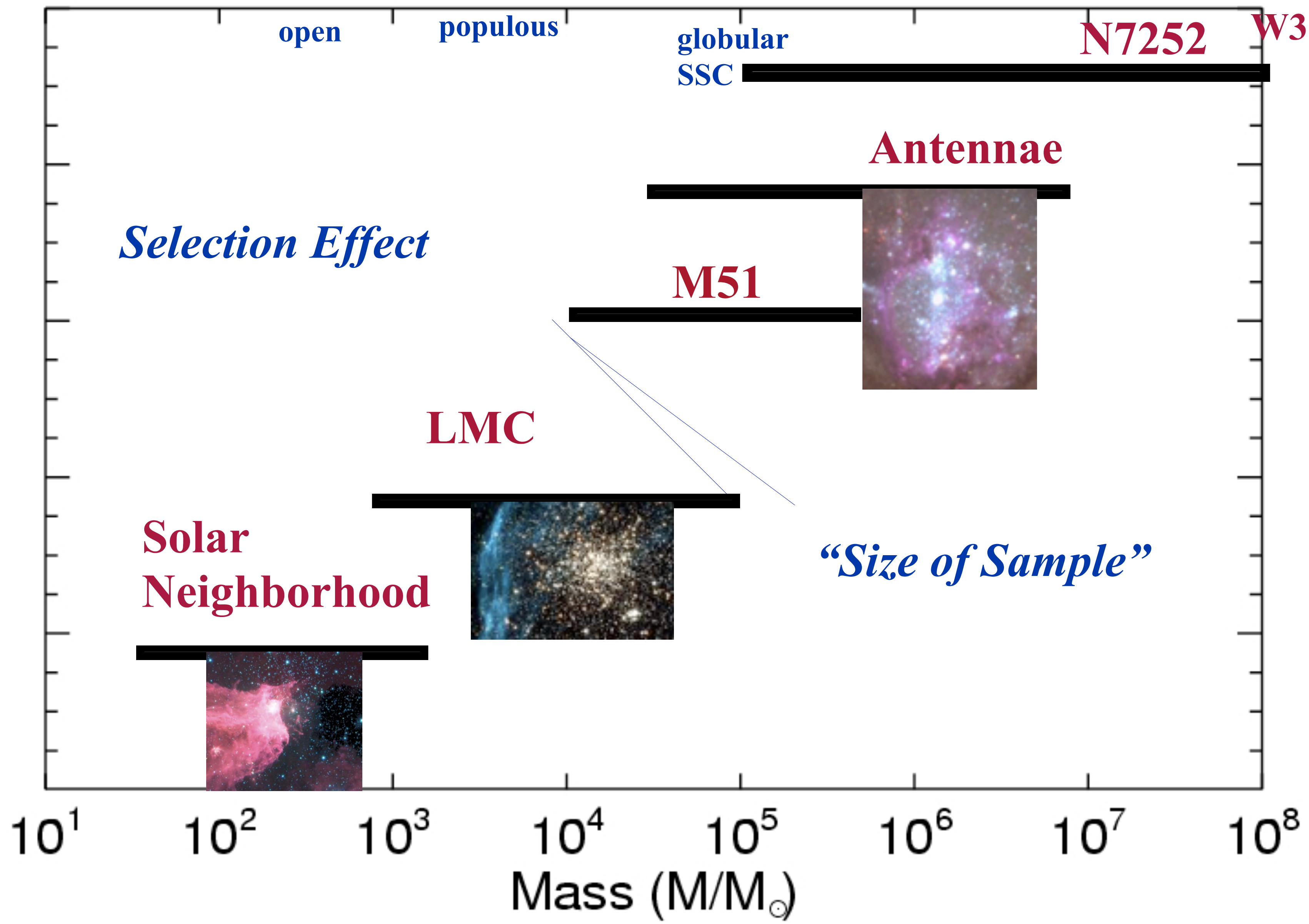
What Would R136 (~10^5 Msun) look like in the Antennae?

Far: Knot S (21 Mpc)

~10^7 Msun



Observable Mass Scales of Clusters in Different Galaxies



Motivation: Why Star Clusters are Important

The majority of local star formation occurs in embedded clusters. In the Antennae >20% of star formation occurs in compact clusters. This suggests that most stars in the universe formed in a star cluster.

-- Are the clusters formed in more violent star forming environments (e.g., mergers) physically similar to those formed in more normal galaxies (e.g., MW, LMC, spirals) ?

-- What is the initial cluster mass function? Is it similar to the mass function of progenitor GMCs and star forming clumps ?

-- How important is the destruction of star clusters? Are lower mass clusters destroyed earlier than higher mass clusters?

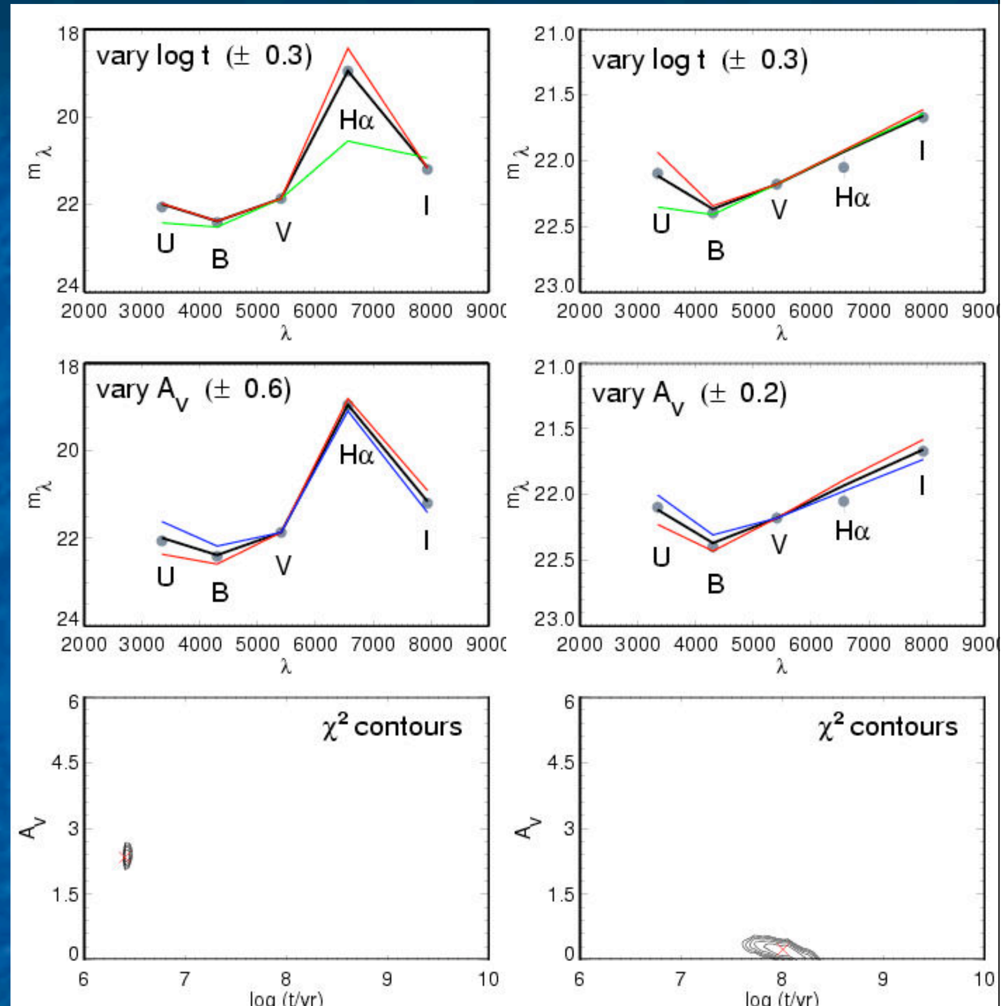
-- Could the young clusters observed today evolve to resemble old globular clusters after a Hubble time?

Antennae vs. LMC ('Weird' vs. 'Normal')

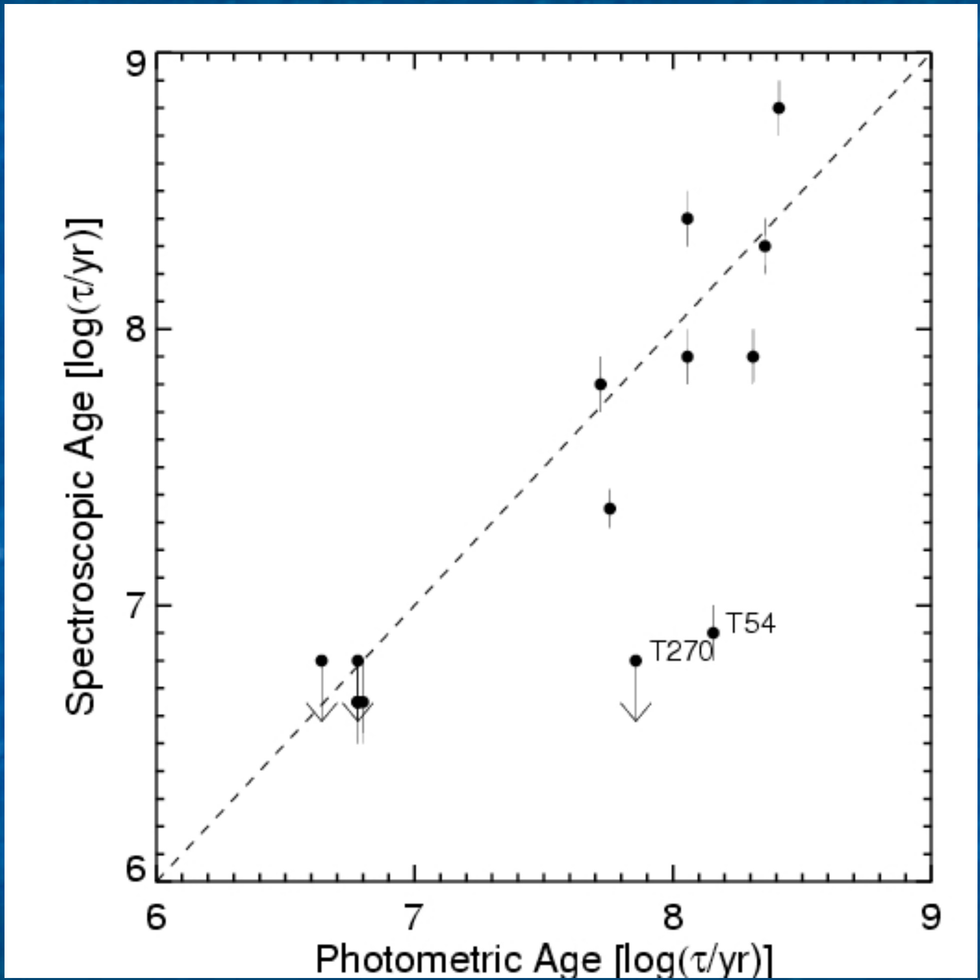
Antennae: *HST* UBVIHα imaging of several thousand clusters
LMC: ground-based UBVR imaging of ~850 clusters from Hunter et al. 2003

Estimating Ages and Masses for (*1000s*) of Distant Clusters

- Use 4-5 filters, including *U* band (more filters = better results); narrow-band filter (Hα) also improves age determinations (Fall et al. 2005)
    - Compare magnitudes with predicted luminosities from SSP models -> age, A_V, mass
    - typical uncertainties in log $\tau \approx$ logM ≈ 0.3-0.4

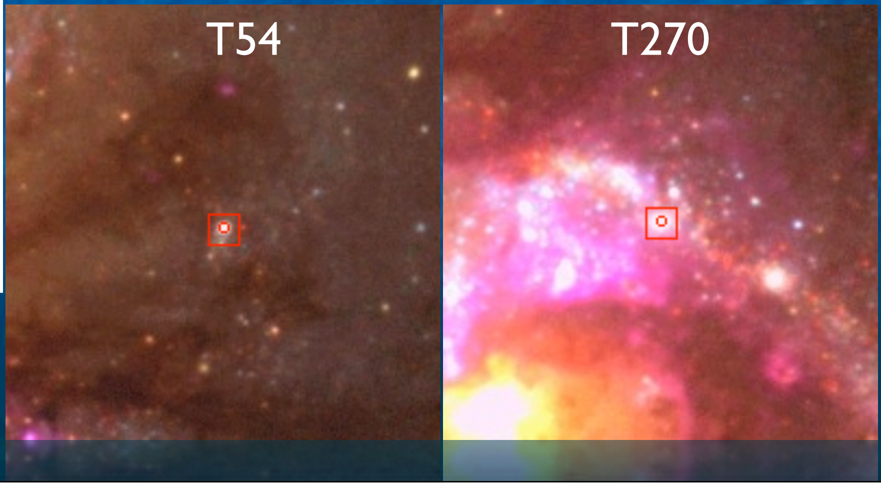


Photometric vs. Spectroscopic Ages for Antennae Clusters



Whitmore et al. 2009

- Spectroscopic ages from Bastian, Trancho et al. 2009 (ground-based: Gemini)
- Conclusion: Achieve good agreement with spectroscopic age determinations
- the 2 discrepant ages are likely due to differences in resolution



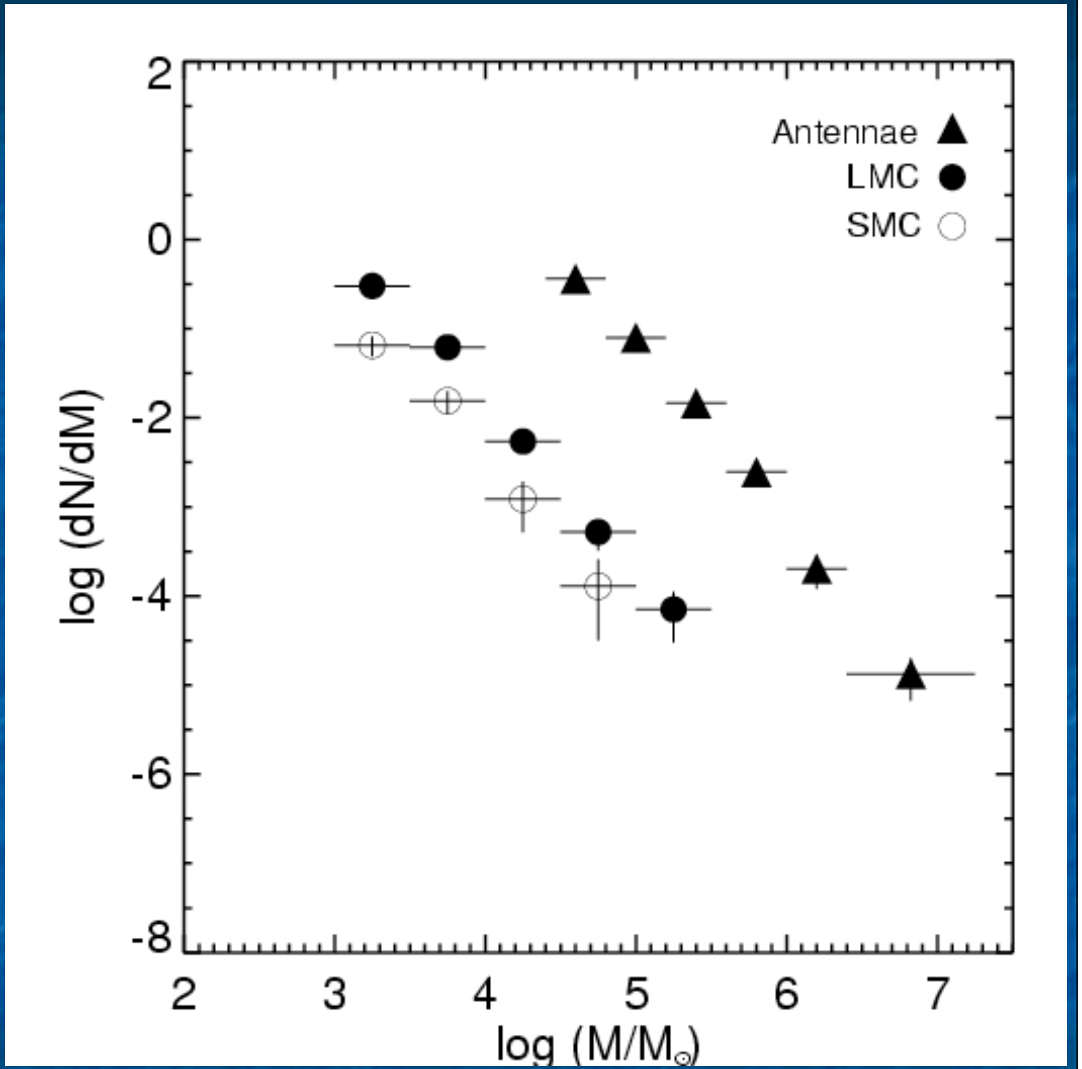
Cluster Mass Function

-- The "initial" mass function:

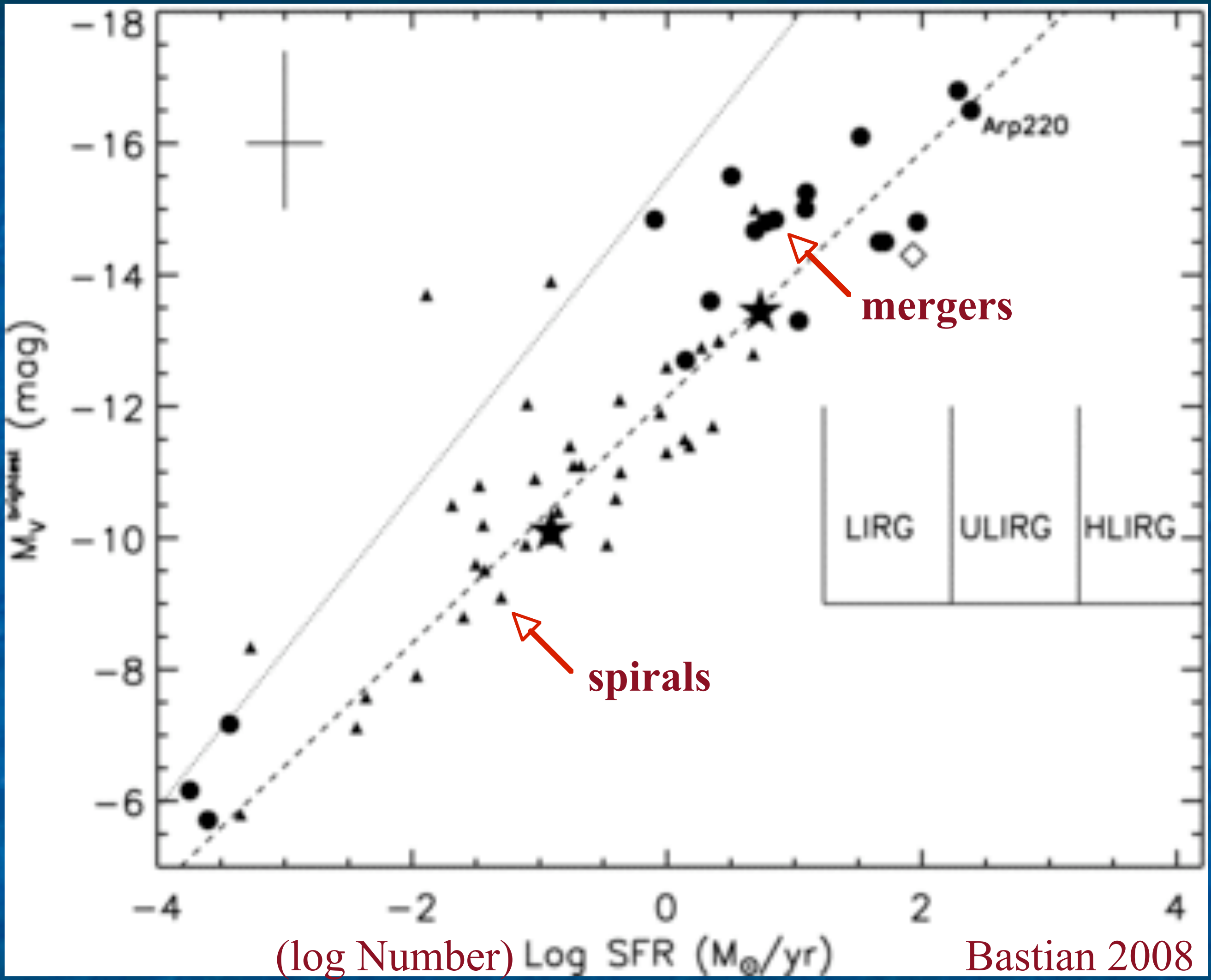
$dN/dM \approx M^{-\beta}$, with $\beta \approx -2$

-- N_{total} sets the normalization of the power-law (SMC has a few 100, LMC many 100, and Antennae 1000s of clusters)

Mergers may form the most massive (brightest) clusters because they form the most clusters



A “Universal” Scaling of Cluster Properties?

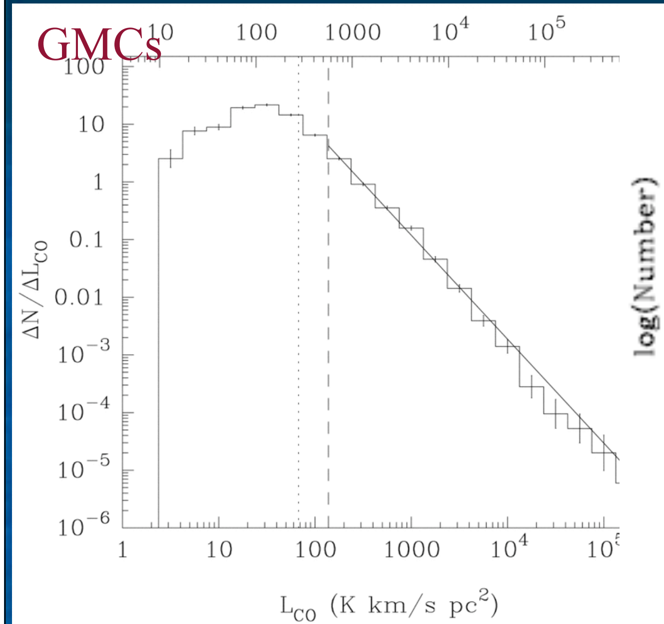


$M_{V,brightest}$ α SFR (e.g., Larsen 2004; Bastian 2008)

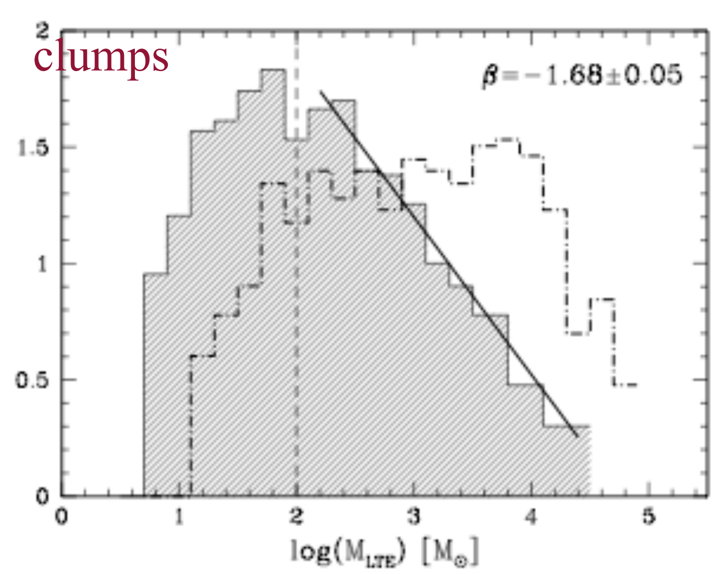
$M_{V,brightest}$ α $N_{cl,total}$ (Whitmore 2003)

Mergers form a natural extension of the spirals (“size of sample” effect)

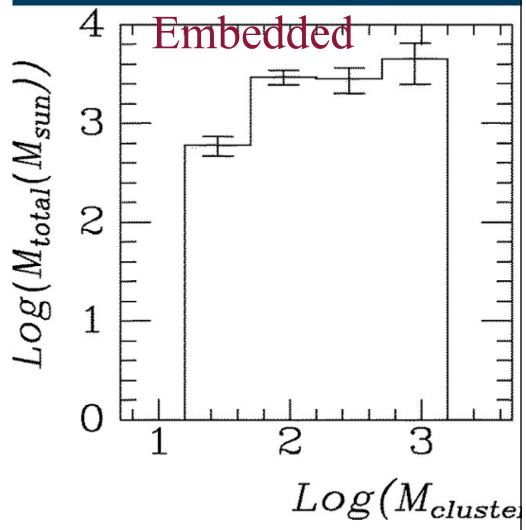
“Initial” Mass Function of Cluster Progenitors



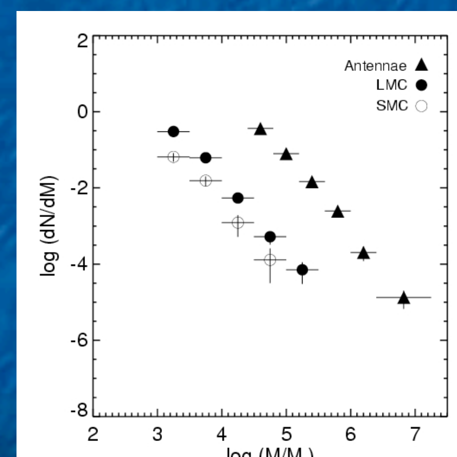
Heyer et al. 2001



Wong et al. 2008



Lada & Lada 2003



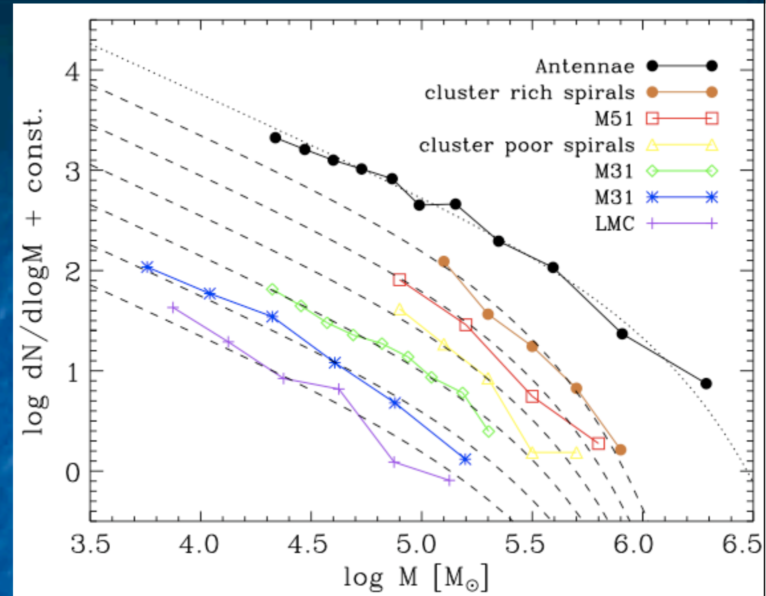
-- $dN/dM \approx M^\beta$, with $\beta \approx$ -1.6 to -2 for GMCs, clumps, and embedded clusters -- very similar to young clusters.

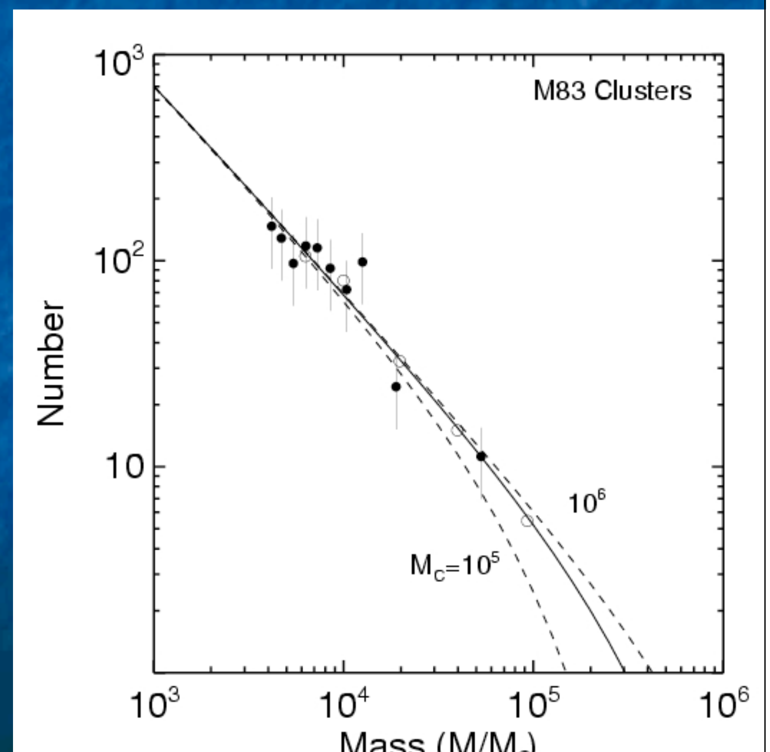
-- Lower SFE -> higher probability of disruption, therefore similarity in β implies that on average, low-mass protoclusters make stars as efficiently as high mass protoclusters.

Is There an Upper Mass Cutoff?

-- And if so, is M_c lower in spirals (~1-2x10^5 M_{sun}) than in mergers (>10^6 M_{sun}) ? (see review in Portegies Zwart et al. 2010)

Conclusion: There may be weak evidence for an upper mass cutoff in a handful of galaxies (at ~1-2 σ level; e.g., LMC). Don't see evidence for a cutoff in M83 or M51 (where it has been claimed previously), based on analysis of higher quality observations.





Chandar et al. *in prep*

What About Cluster Disruption?

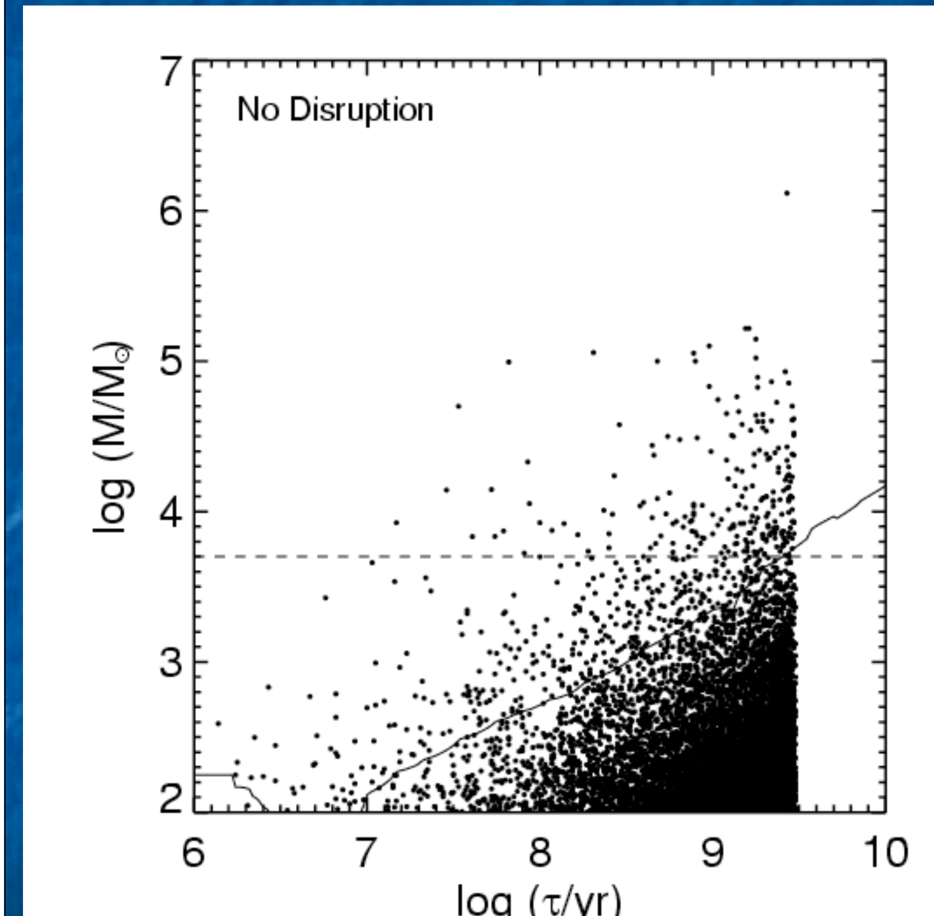
-- Lada & Lada (2003) suggested that fewer than 10% of embedded clusters will survive for ~100 Myr.

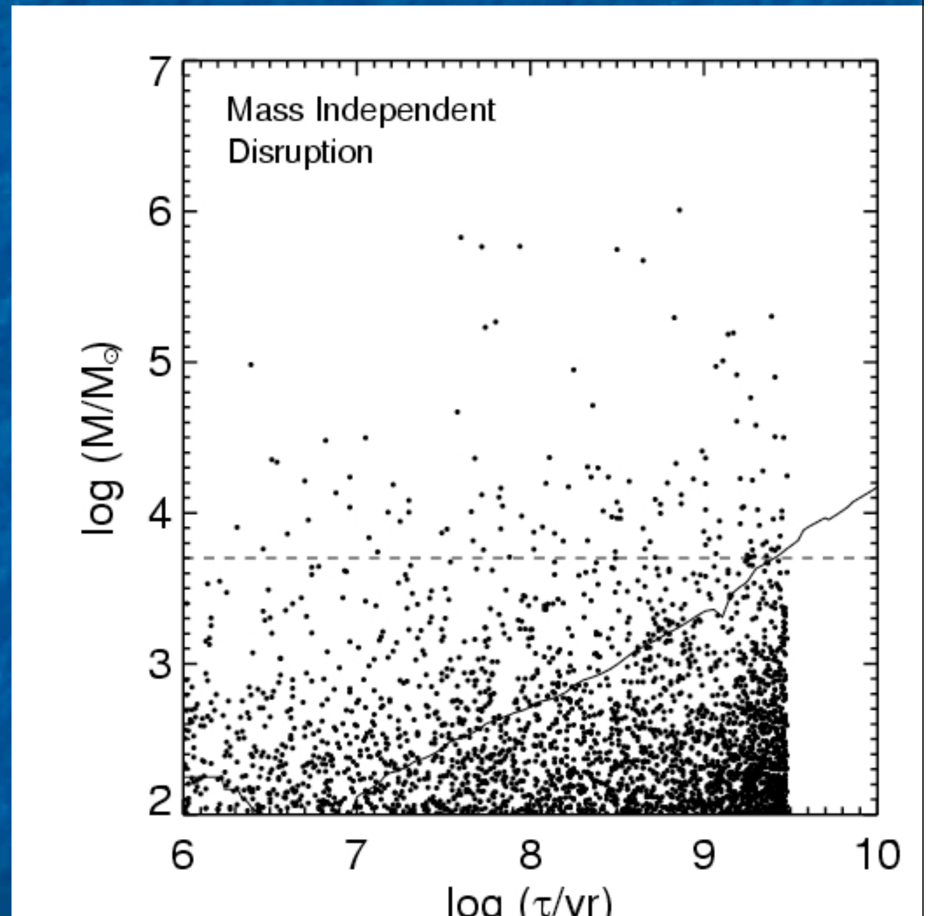
-- But many clusters that we observe in other galaxies are more compact and more massive than embedded clusters in the solar neighborhood. Will these 'globular-like' clusters also fall apart quickly?

-- The age and mass distributions of clusters provide a direct window into their formation and disruption

Predicted Mass-Age Distributions

$$g(M,\tau) \approx \psi(M)\,\chi(\tau) \sim M^{\beta}\,\tau^{\gamma}$$





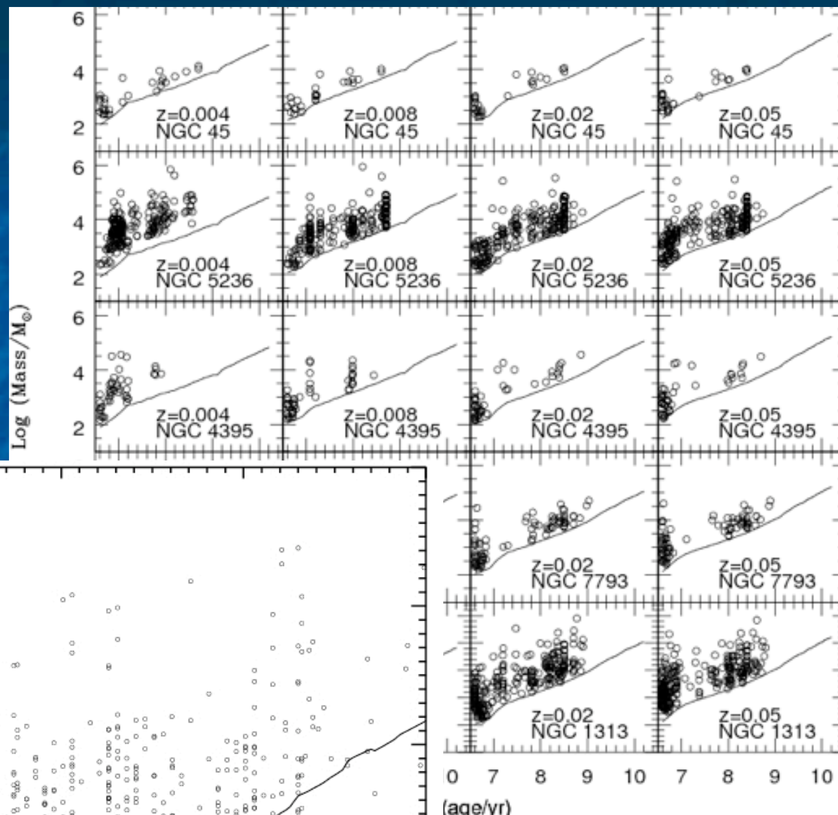
$g(M,\tau) \approx M^{-2}\,\tau^{0}$

$g(M,\tau) \approx M^{-2}\,\tau^{-1}$

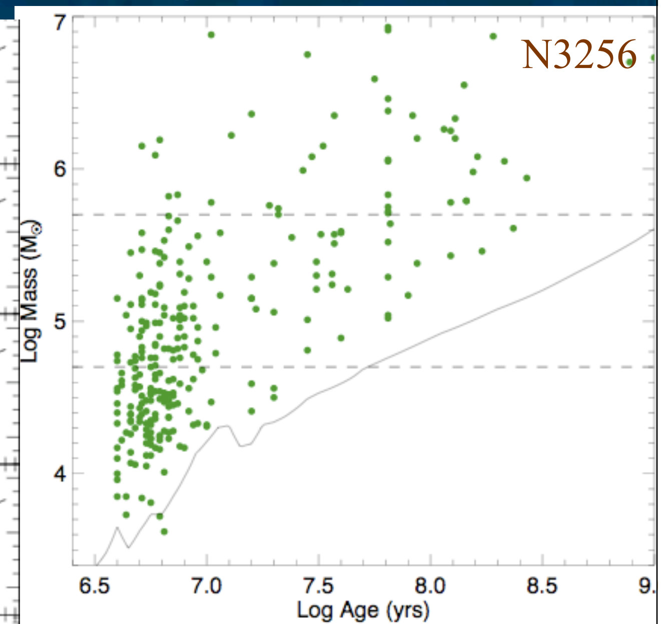
Observed M-t: Consistent with predictions of MID

See also:
Melena et al. 2009
Fall et al. 2009

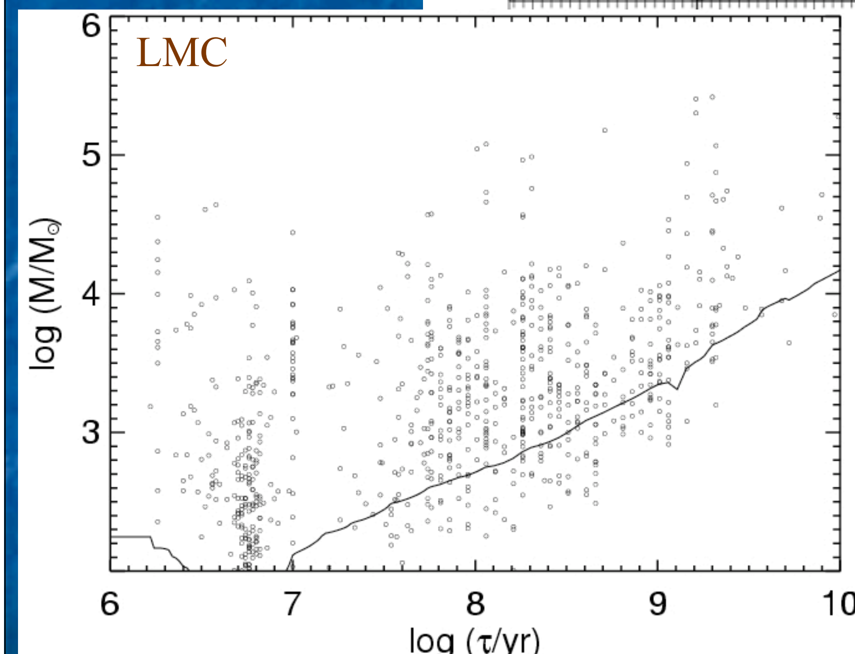
Mora et al. 2009

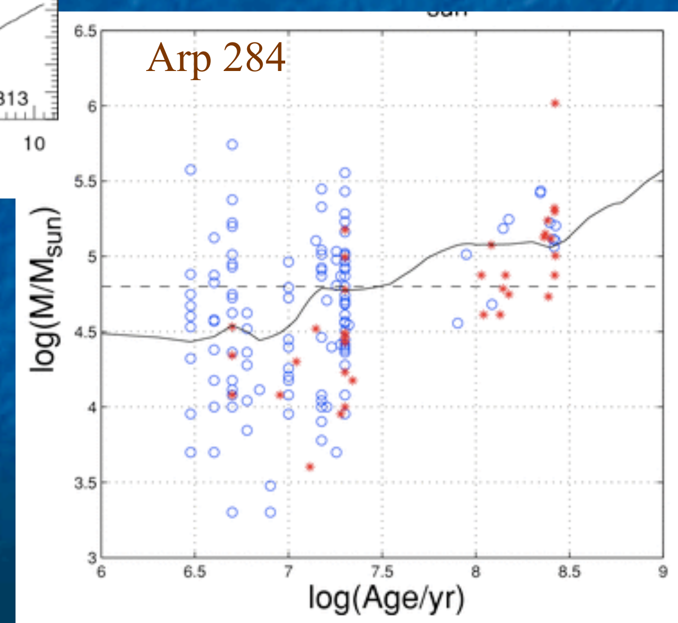


Goddard et al. 2010



Chandar et al. 2010





Peterson et al. 2009

M-t diagrams are similar in more than a dozen different galaxies of different type (dwarf, massive, spiral, irregular, quiescent, merging) !

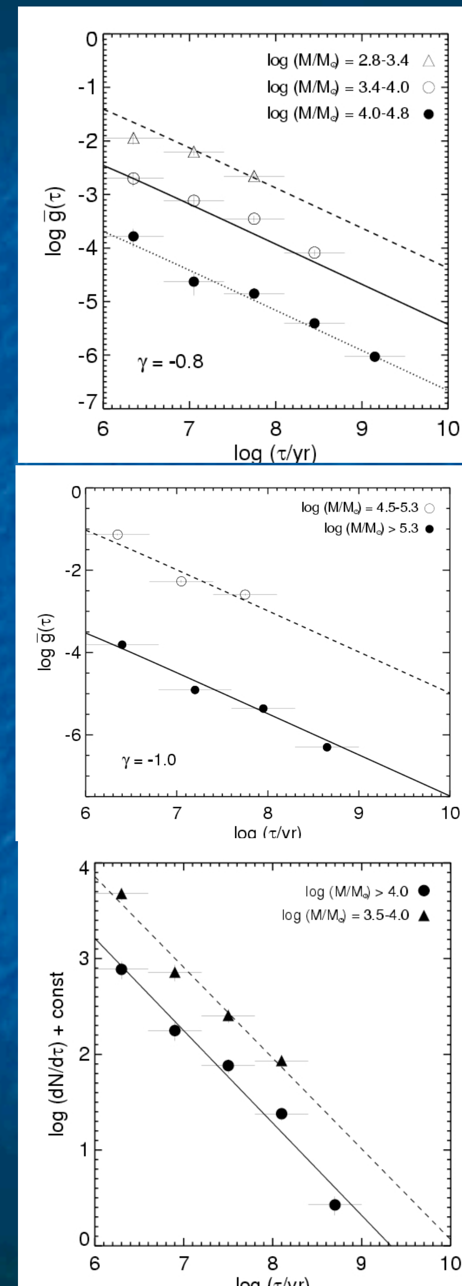
M-τ Distributions: Empirical Results and Implications

1. Declining $dN/d\tau$ (for mass-limited samples) in galaxies of different type, mass, environment
$\chi(\tau) \sim \tau^{\gamma}$, with $\gamma \sim -0.7$ to -1.0 (~"universal")

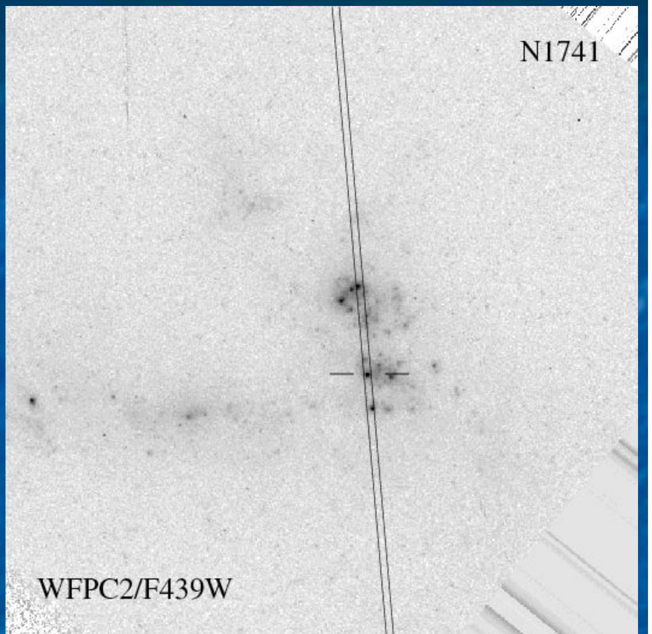
2. $\gamma_{obs} = \gamma_{form} - \gamma_{disrupt}$ -> similarity in γ for different galaxies implies that $\gamma_{disrupt}$ dominates γ_{obs} for $\tau < 10^9$ yr

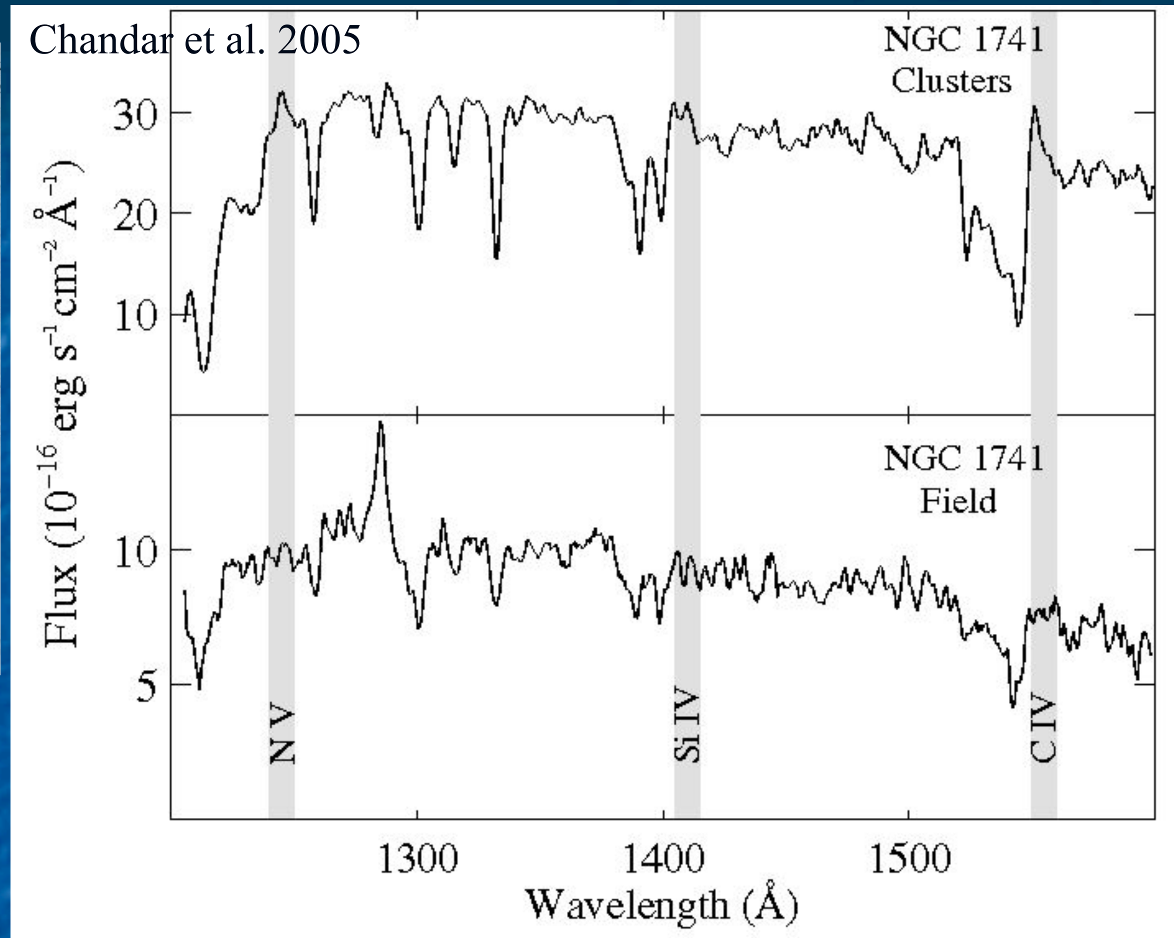
3. A good statistical description of young cluster systems:
$g(M,\tau) \approx M^{\beta} \tau^{\gamma}$ with $\beta \approx -2$ & $\gamma \approx -1$, for $\tau < 10^9$ yr

4. The stars from disrupted clusters -> field star population



Field Stars As Disrupted Clusters

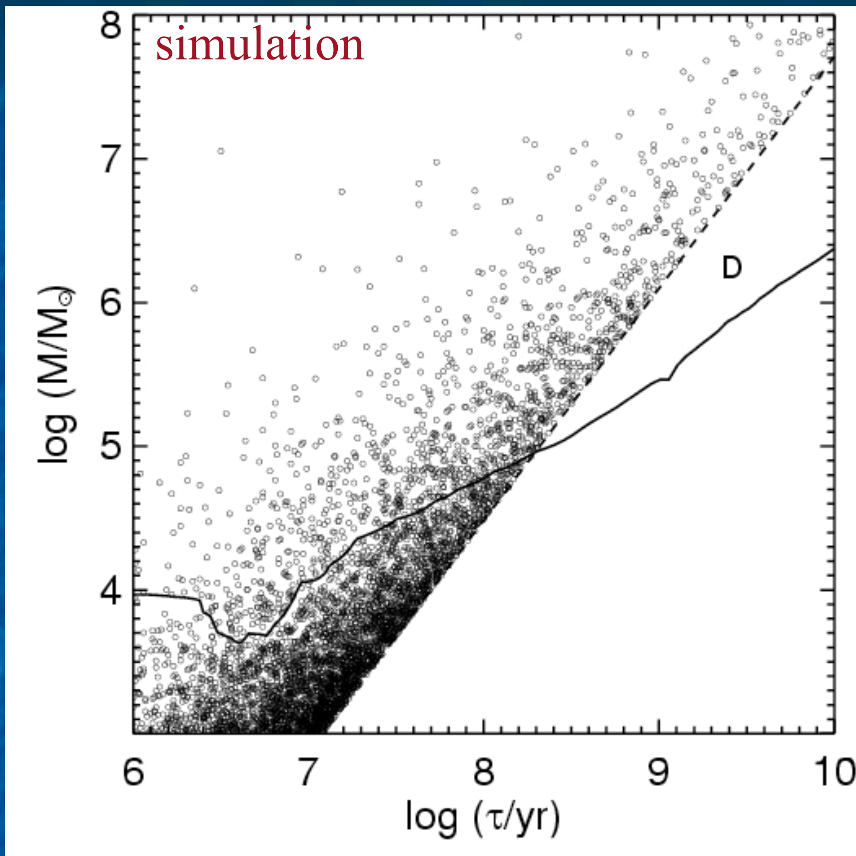




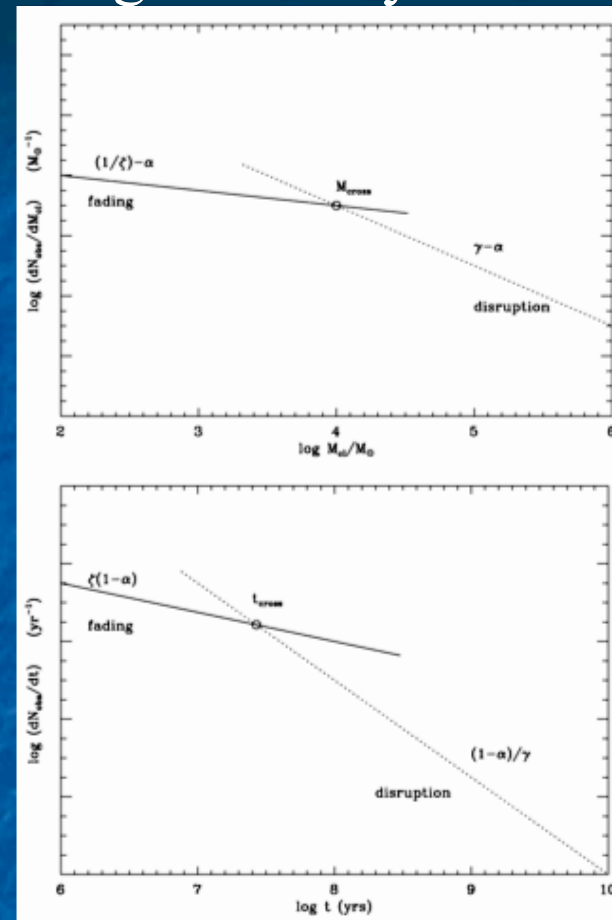
-- Don't see massive O stars in the (UV-bright) field regions of 11 starburst galaxies. Suggests that massive stars don't form here.

-- This "age sequence" between stars in clusters and in the field is a natural consequence of early cluster disruption -- implies disruption timescales of ~7-10 Myr (don't need a "cluster" and "field" mode of star formation)

Is mass-dependent disruption important for young cluster systems ?



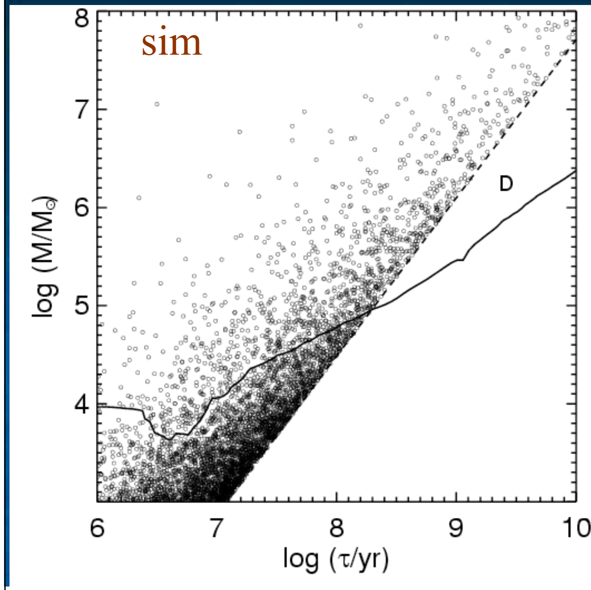
Fall et al. 2009



$\tau_{\mathrm{dis}} = \tau_* (M/10^4)^k$ Boutloukos & Lamers 2003

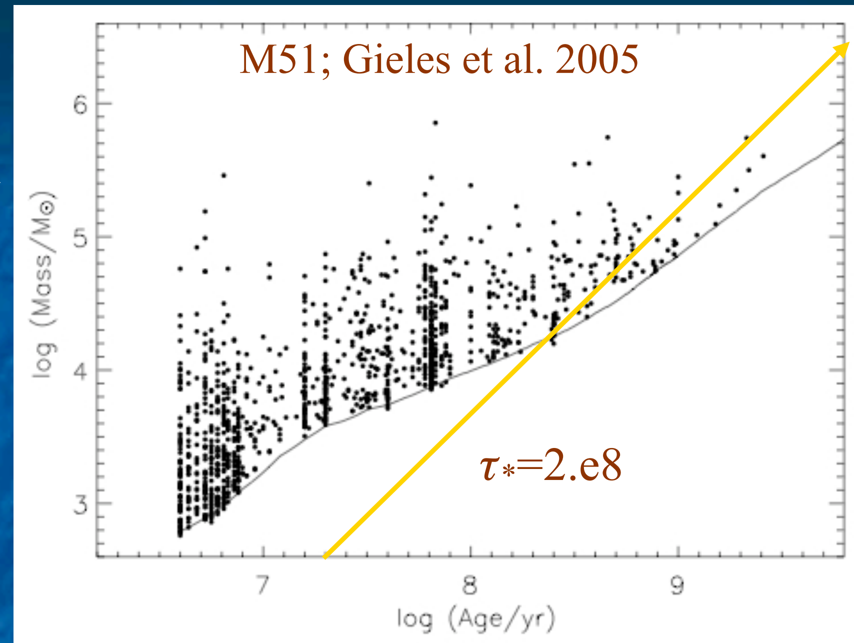
Many disruption processes (e.g., removal of ISM from young clusters; tidal disturbances by GMCs; relaxation-driven evaporation) are believed to disrupt low mass clusters earlier than high mass clusters. Its been suggested that the *rate* of mass-dependent disruption varies strongly from galaxy to galaxy (e.g., Boutloukos & Lamers 2003)

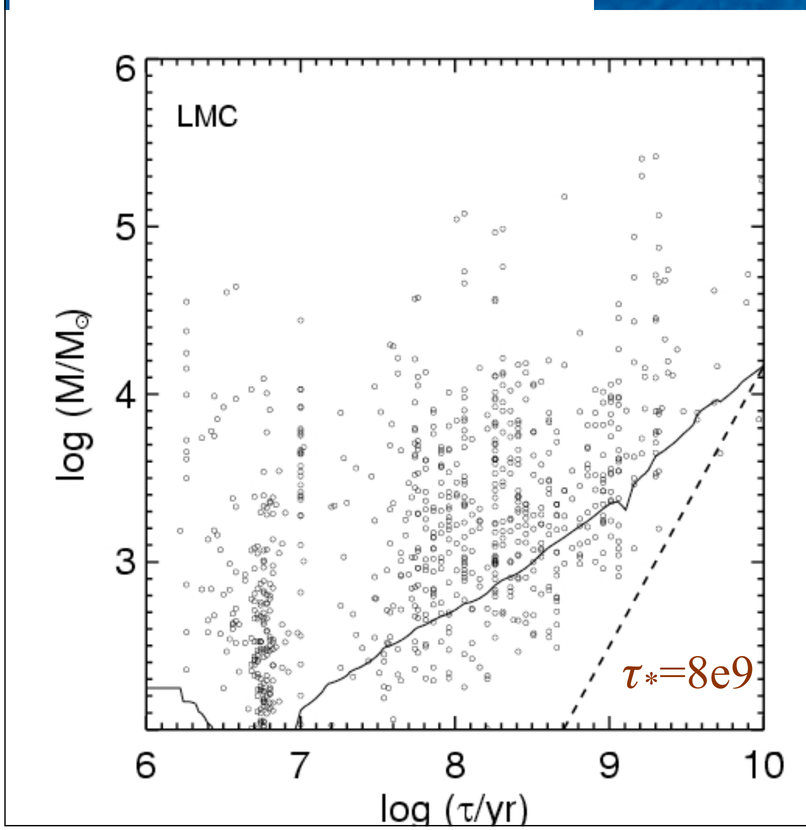
Little evidence for MDD for $t < 10^9$ yr

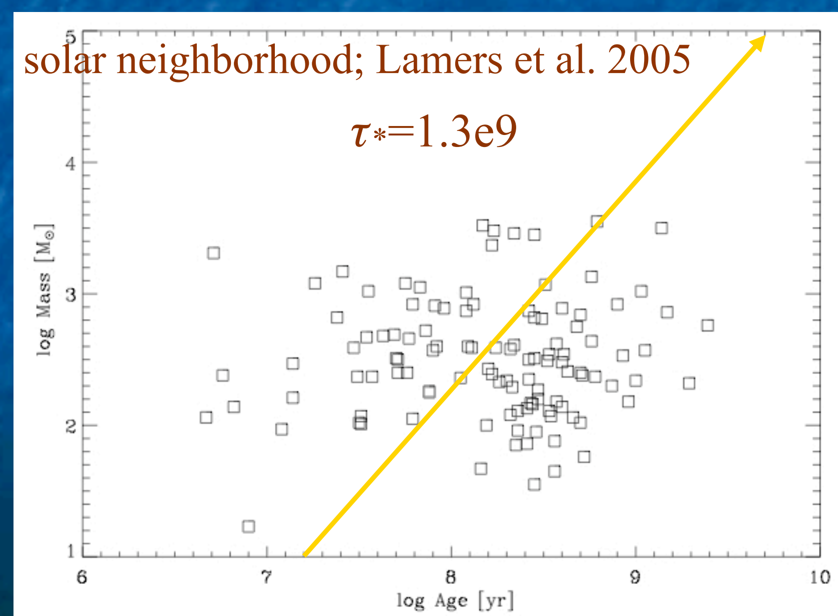


$$\tau_{dis} = \tau_* \,(M/10^4)^k$$

k=0.6; BL03



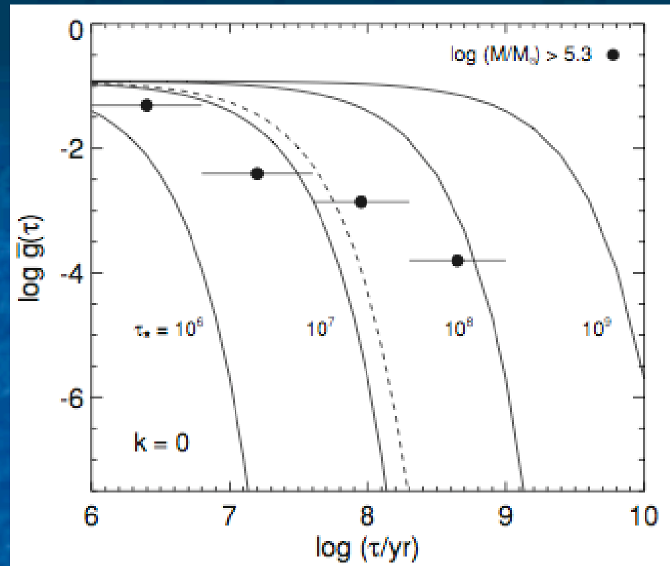


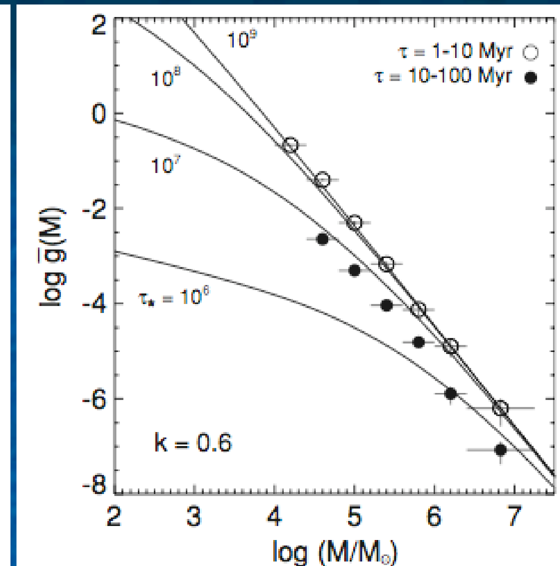


Age Distribution

Mass Function

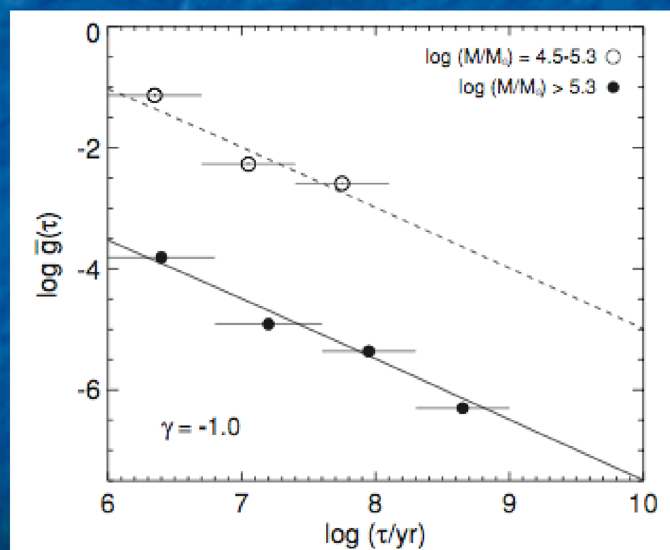
Mass-dependent
Disruption

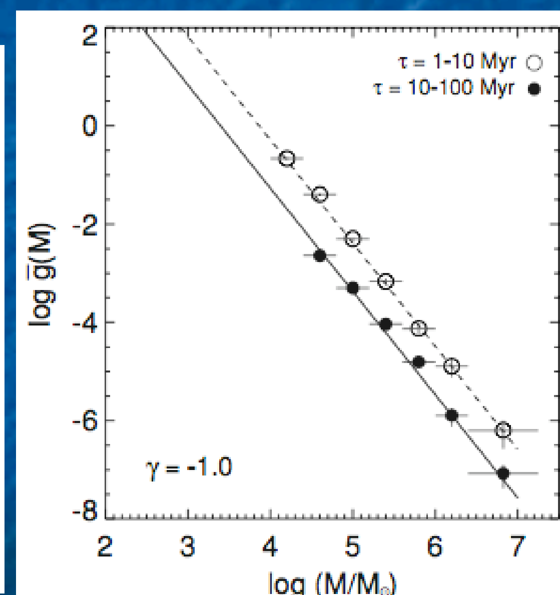




-- Mass-dependent disruption -> curvature in dN/d*τ* and dN/dM.

-- No curvature observed (for *young* clusters)

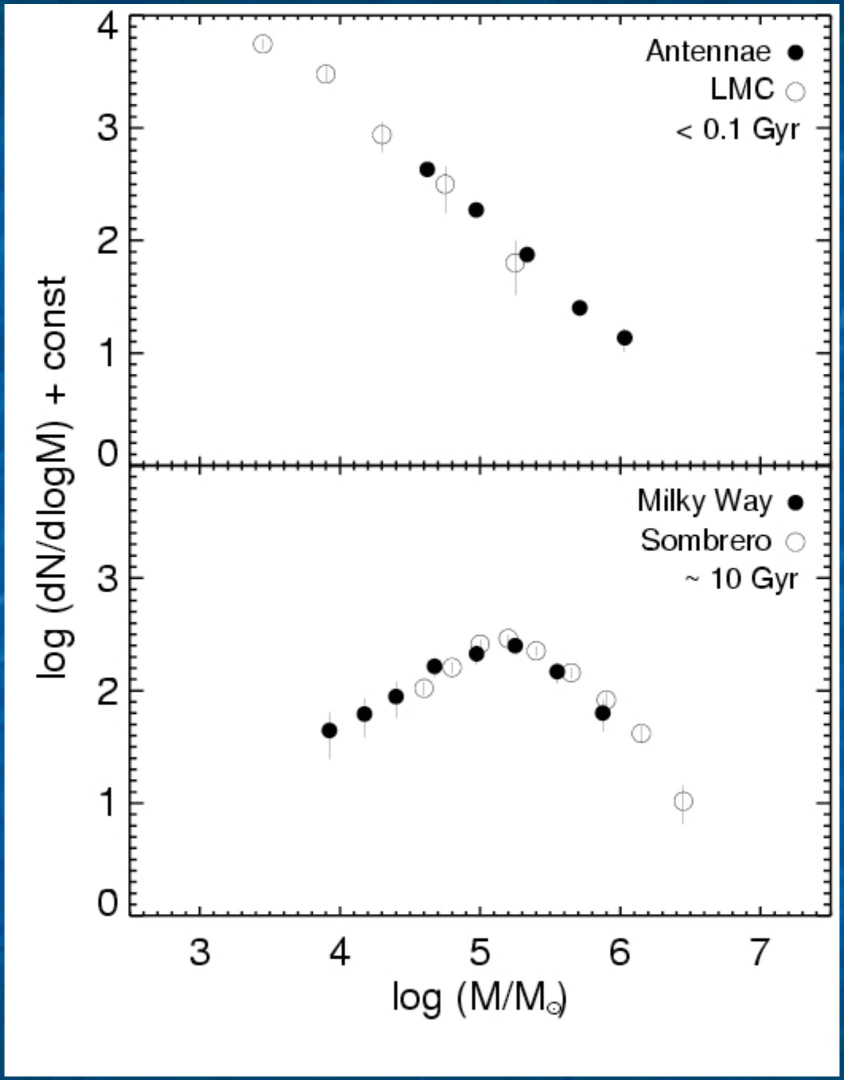




Mass-*in*dependent
Disruption

Longer Term Evolution *is* Mass-Dependent: See curvature in dN/dM for old clusters

Note very different forms



Young

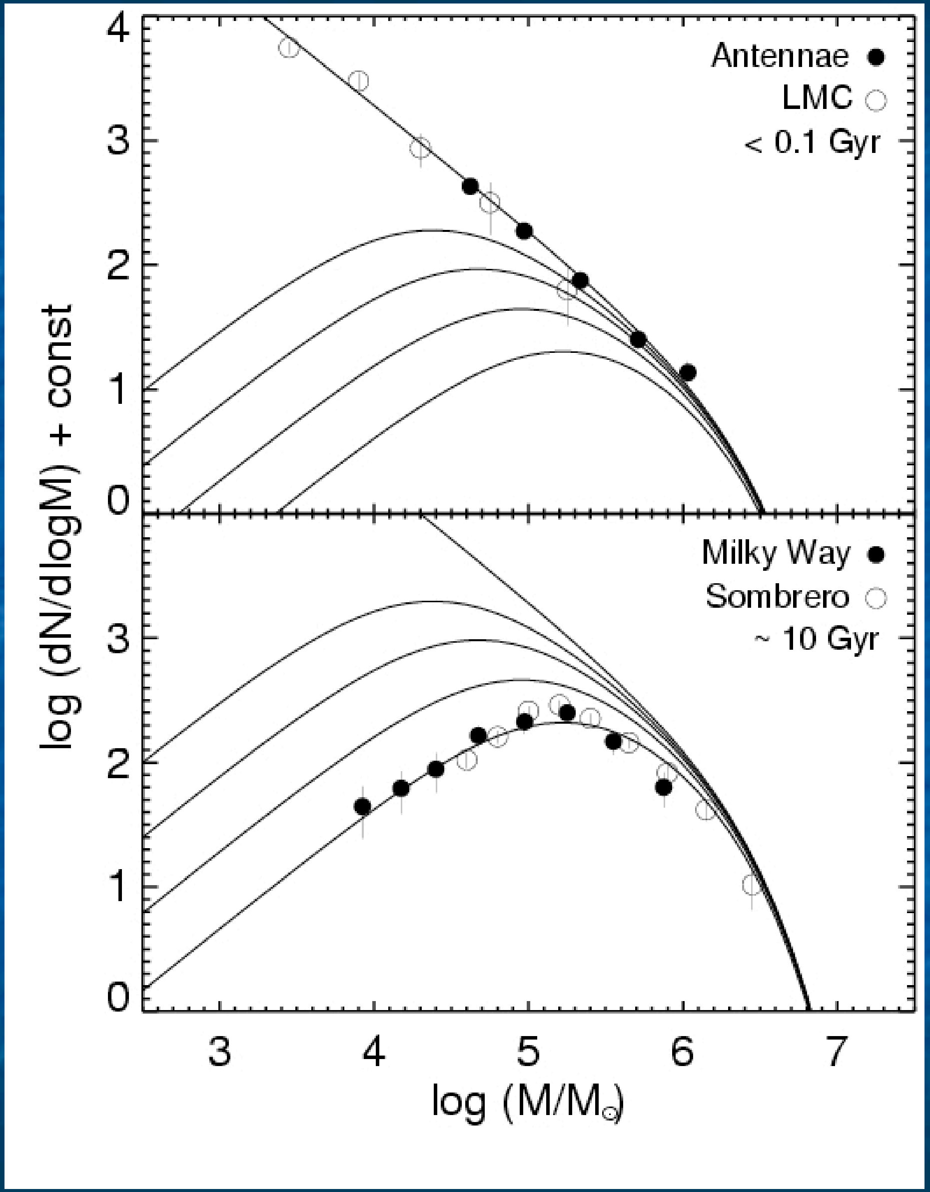
Old

Question: Could the old ones have formed with a power-law form like the young ones?

Predictions from Simple Evaporation Model

Mass of a cluster decreases (approximately) linearly with time,
$M = M_0 - \mu t$
where $\mu \sim \rho^{1/2}$

This causes a peak in the mass function (starting from an initial power-law like distribution):
$M_p \sim \rho^{1/2}$ t (McLaughlin & Fall 2008)

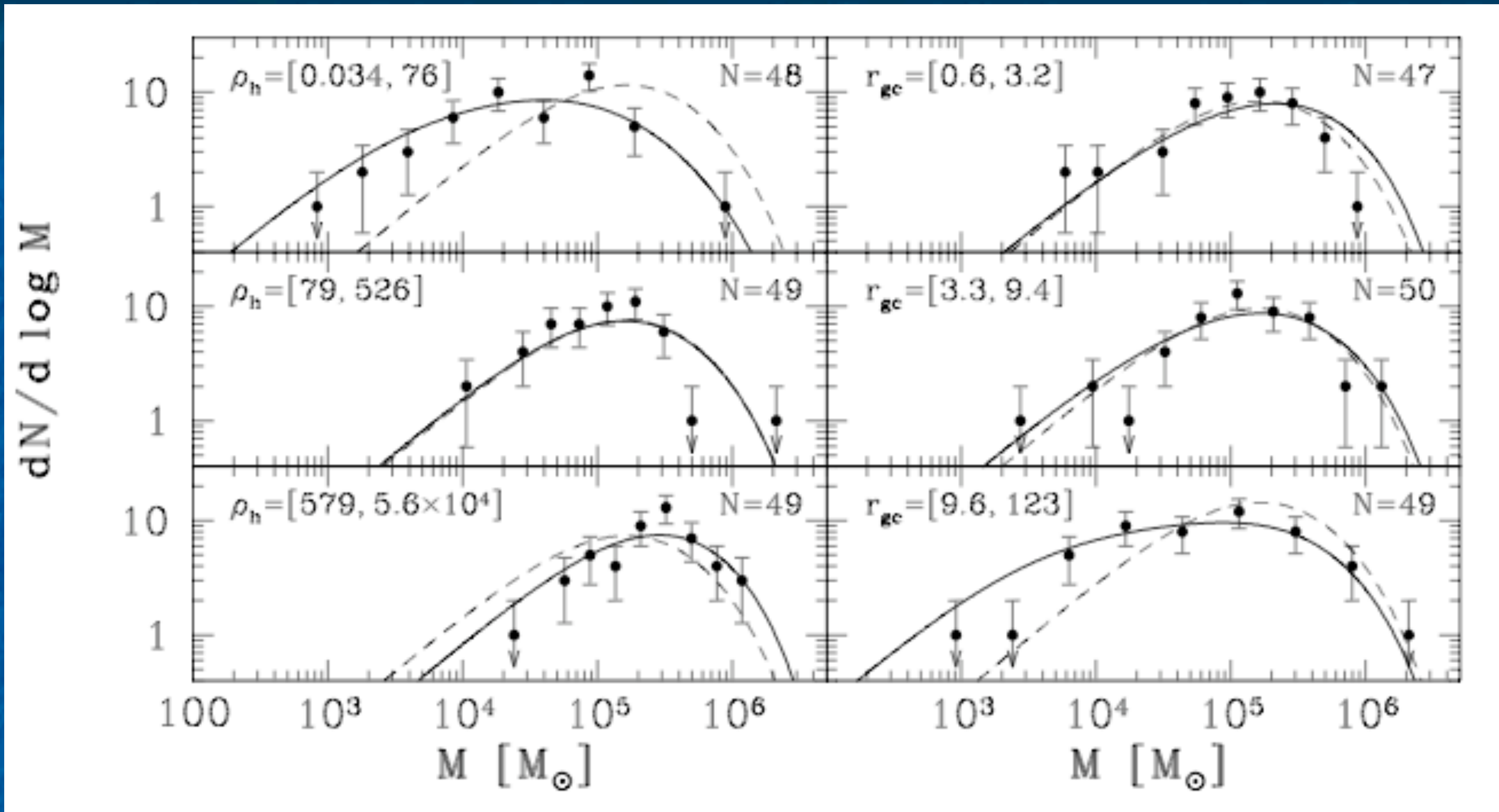


Young

Old

Fall et al. 2009

Comparison Between Observed and Predicted GCMF



Milky Way; McLaughlin & Fall 2008

Predictions from the simple evaporation model of MF08 nicely match the shape of the globular cluster mass function in the Milky Way (MF08) and the Sombrero (Chandar et al. 2007).

(Answer: yes)

Conclusions

1. The shape of the mass function is preserved when going from molecular clouds (& massive, self-gravitating clumps) to young clusters (β is invariant for $\tau < 10^9$ yr) --> the average star formation efficiency is ~independent of the masses of proto-clusters

2. After formation, rapid, ~mass-independent disruption drives the overall demographics of young cluster systems. This is why the joint distribution of ages and masses can be approximated as:
$g(M,\tau) \approx \sim M^{-2}\, \tau^{-1}$

3. If this form for g(M,t) is 'universal', the main difference between populations of young clusters in different galaxies is simply in their normalization (amplitude), and hence in the # of clusters formed

Conclusions

4. Mass-Dependent disruption is unimportant for shaping cluster systems for the first ~Gyr (at least for the observed ranges of masses and ages)

5. Relaxation-driven stellar mass loss, which depends on the internal density of clusters, is the dominant disruption process after this time, and can evolve an initial power law-like mass distribution (observed for young clusters) to peaked ones (observed for old clusters), with $M_p \sim \rho^{1/2}\, t$