# Formation and Dissolution of Star Clusters

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# Key Question:
# Is *recent* cluster formation a good guide to *ancient* cluster formation?

?

=>

# Similar vs Different Formation

*Similar:*

1. Observed similarities between coeval clusters in different galaxies (esp. mass functions)
2. Simplicity

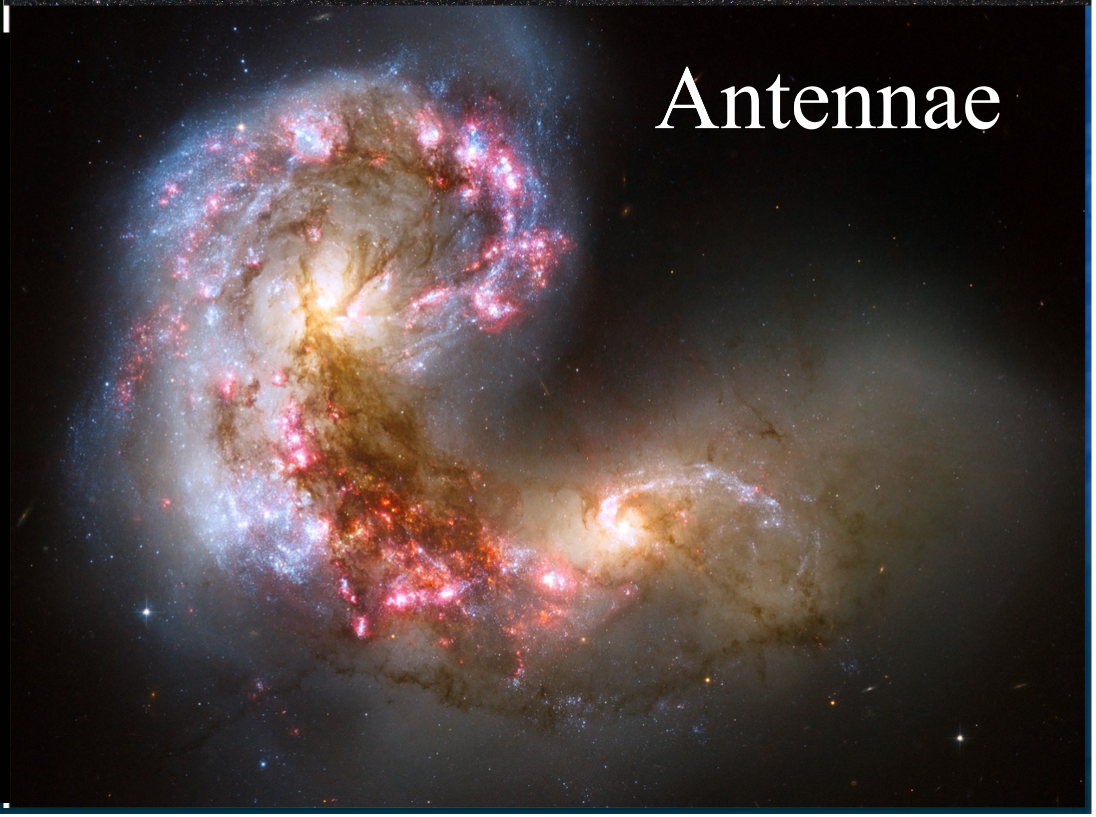
*Different:*

1. Observed differences between young and old clusters (esp. mass functions)
2. Lower metallicity and higher UV field in the past may have suppressed cooling below $10^4$ K, thus imprinting a high Jeans mass ~ $10^6\ M_{\mathrm{sun}}$

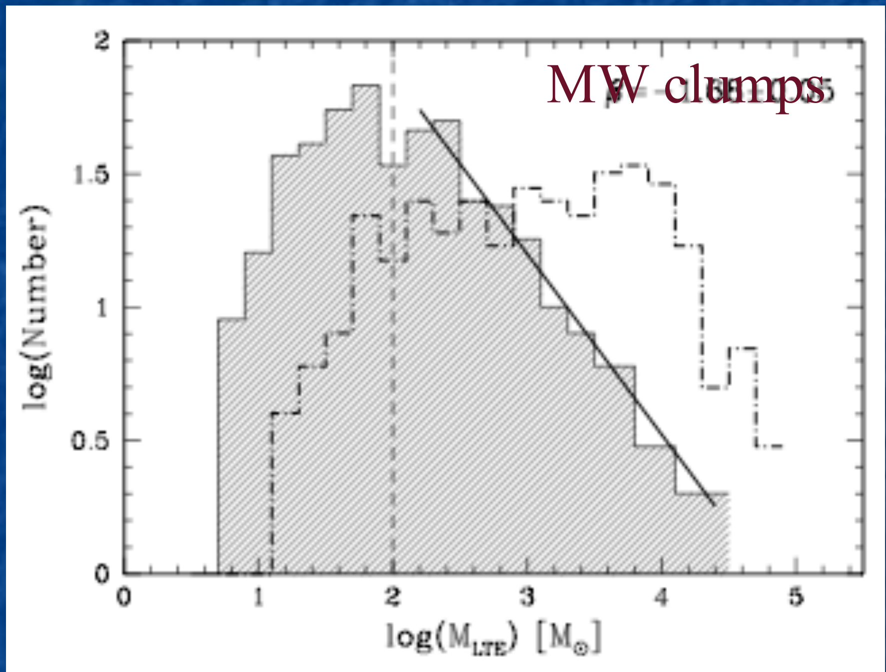

M83


LMC & SMC

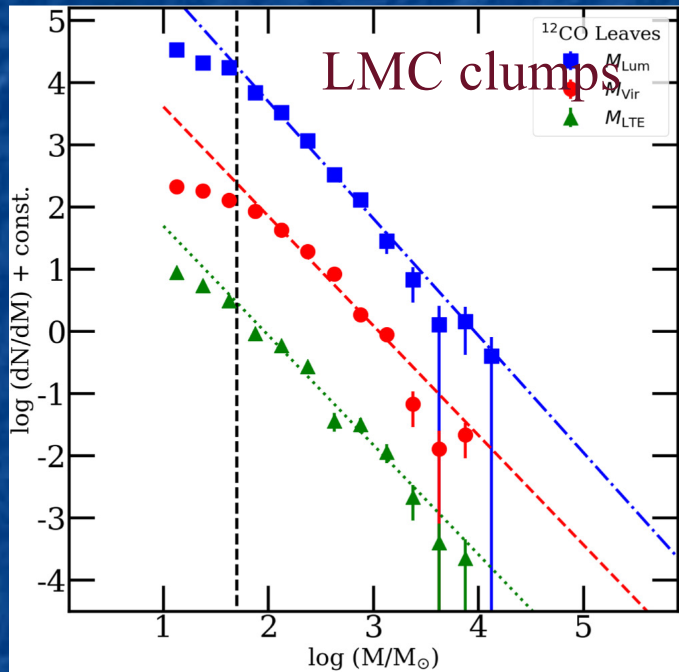

Sombrero
Hubble
Heritage
NASA and The Hubble Heritage Team (AURA/STScI) • Hubble Space Telescope ACS • STScI-PRC03-28


Antennae

# Mass Functions: Molecular Clumps




Wong et al. 2008



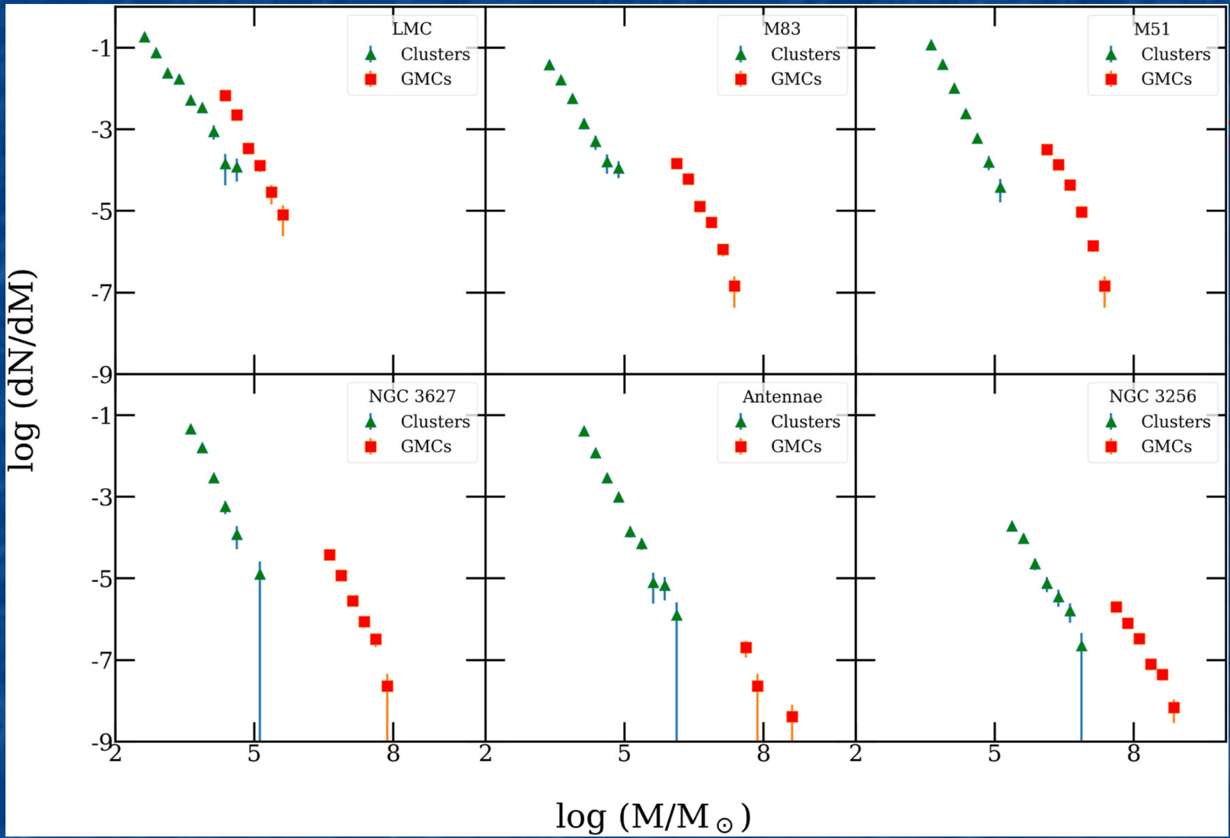

Mok et al. 2021

$$dN/dM \;\alpha\; M^{\beta} \quad \text{with} \quad \beta \approx -2$$

# Mass Functions: GMCs and Young Clusters

different galaxies

Mok et al. 2020



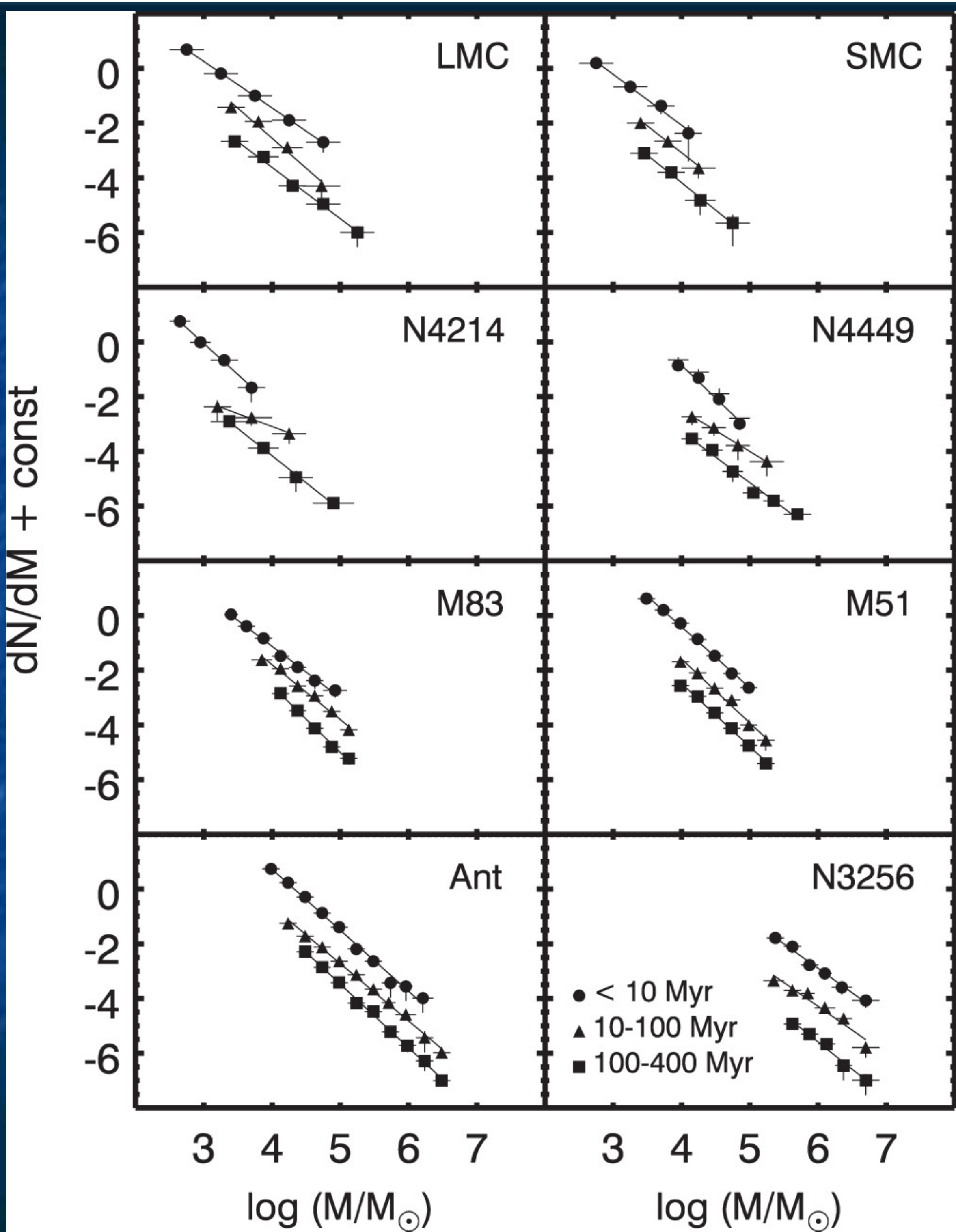

$$dN/dM \;\alpha\; M^{\beta} \quad \text{with} \quad \beta \approx -2$$

# Mass Functions: Young Clusters

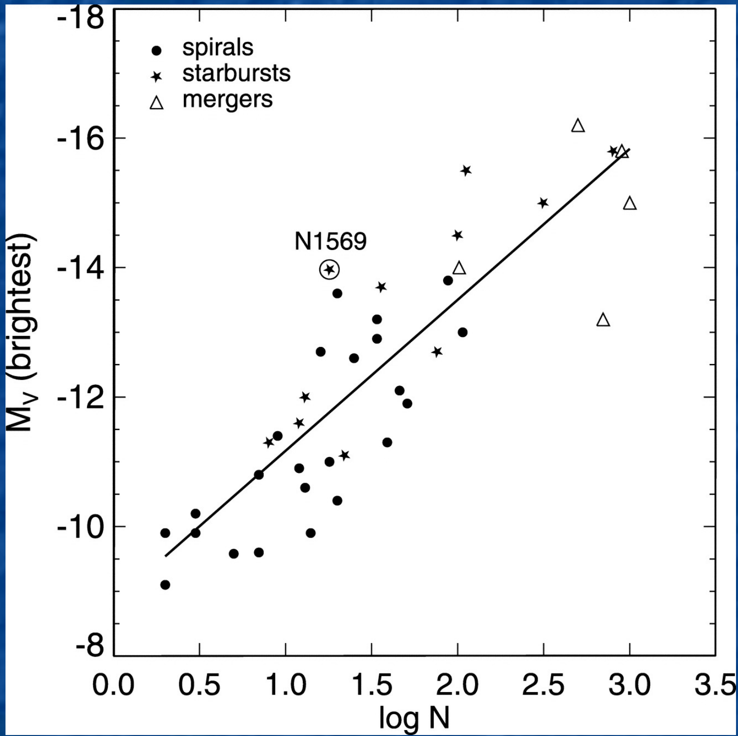
different ages
different galaxies

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

Chandar et al 2017



# Apparent Upper Cutoffs in MFs and LFs: Statistical (Size-of-Sample), Not Physical



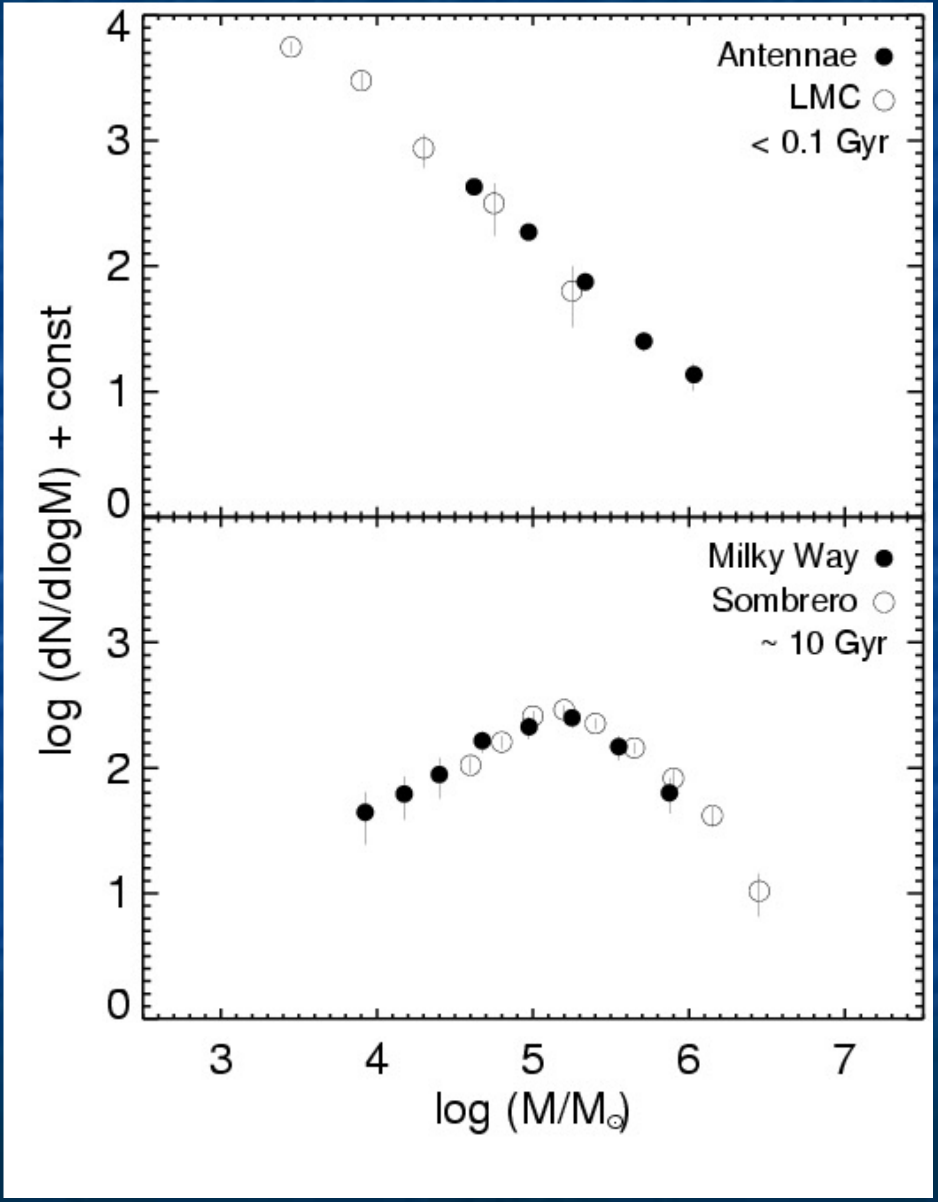

Line is expected scaling for $dN/dL \sim L^{-2}$

Whitmore et al 2007

See Mok et al 2019 for rigorous statistical tests.

# Mass Functions: Young and Old Clusters

Note very different forms




Young

Old

# Questions

1. Why do the mass functions of young clusters and molecular clouds and clumps have similar (power-law) shapes?

2. Why do the mass functions of young clusters of different ages have similar (power-law) shapes?

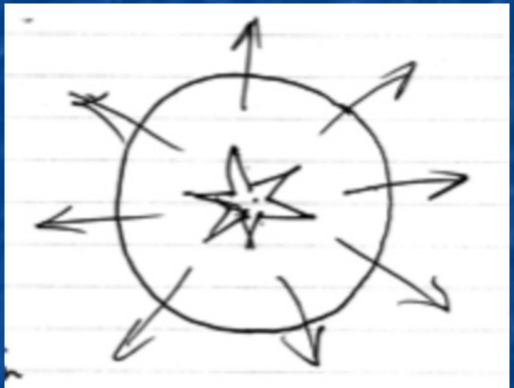
3. Why do the mass functions of old (globular) clusters have such different (non-power-law) shapes from those of young clusters?

# Dominant Mass-Loss Processes

1. *Protoclusters* (aka star-forming clumps):
   Gas expulsion driven by stellar feedback
   ($t < 10^6/10^7$ yr)
2. *Disk clusters* (aka open clusters, YMCs):
   Stellar escape driven by tidal interactions with passing molecular clouds ($10^6$ yr $< t < 10^9$ yr)
3. *Halo clusters* (aka globular clusters):
   Stellar escape driven by internal two-body relaxation ($t > 10^9$ yr)

# Gas Expulsion by Stellar Feedback

(1) protostellar outflows,
(2) photoionization heating,
(3) radiation pressure on dust,
(4) stellar winds



SFE($\varepsilon$) is set by the mass of stars $M_s$ needed to expel the remaining mass of gas $M_g$ at the escape speed $V_e$.

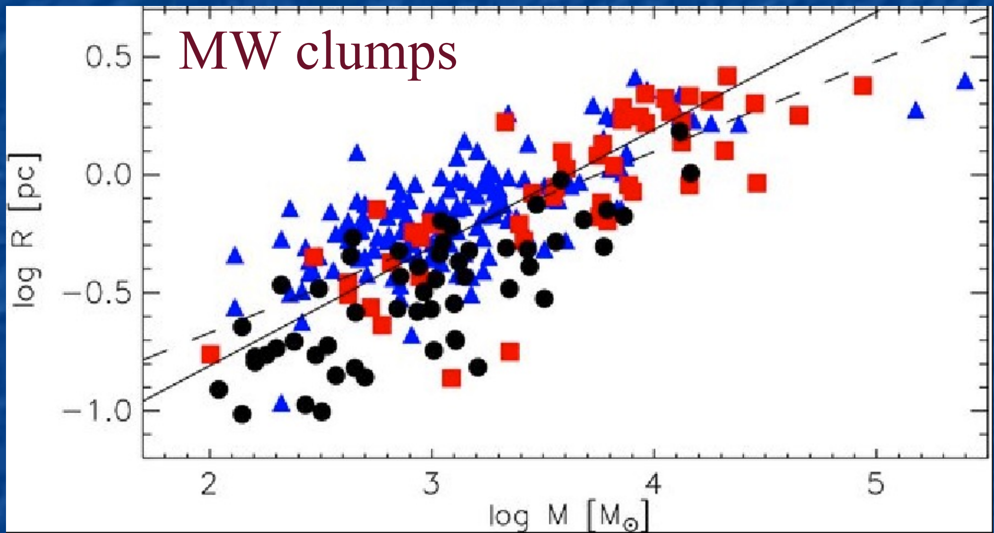
=> scaling relns for
$\varepsilon = M_s / (M_s + M_g)$

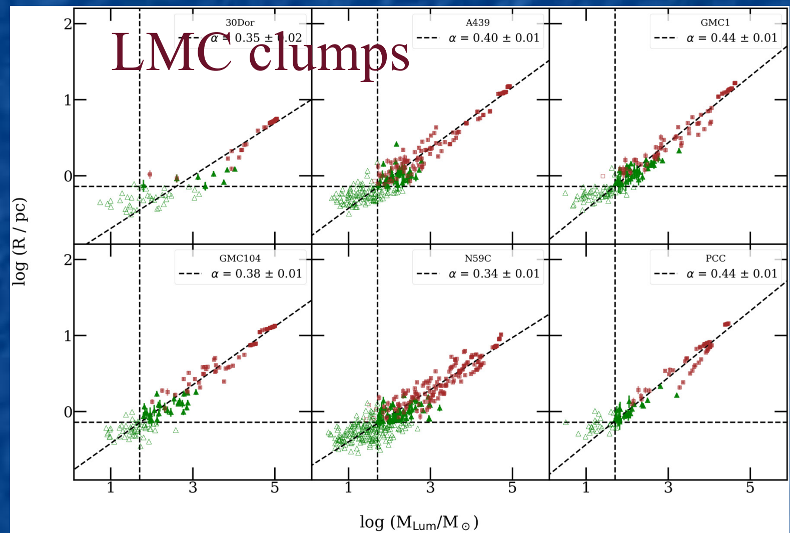
Fall et al 2010

$$\mathcal{E} \propto V_e^3 / R_h \propto M^{(3-5\alpha)/2} \text{ (energy driven)},$$

$$\mathcal{E} \propto V_e^2 / R_h \propto M^{1-2\alpha} \text{ (momentum driven)}.$$

# Radius-Mass Relation for Molecular Clumps




Fall et al 2010

Mok et al 2021

Observed relation: $R \;\alpha\; M^{\alpha}$ with $\alpha \approx$ 0.4-0.5

=> $\Sigma(M) \;\alpha\; M/R^2 \approx$ const => $\varepsilon(M) \approx$ const

=> cluster & clump MFs with similar indices $\beta$

# Dissolution Timescales

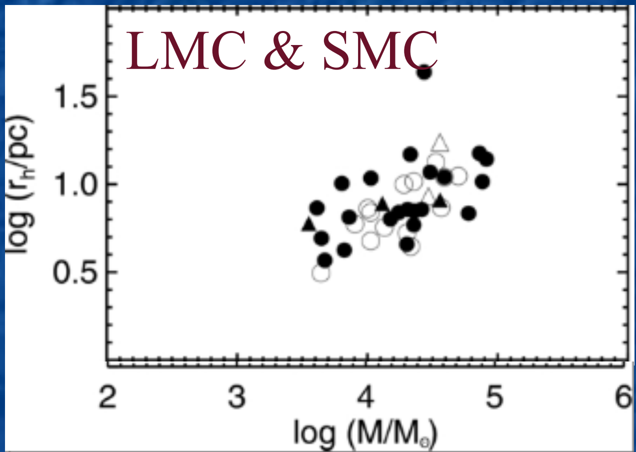
1. Tidal interactions, dominant for young (disk) clusters, is mass-*in*dependent for $\rho_h \approx$ constant:

$$t_d \;\alpha\; \rho_h^{\nu} \quad \text{with } \nu = ½ \text{ (catastrophic regime)}$$
$$\nu = 1 \text{ (diffusive regime)}$$

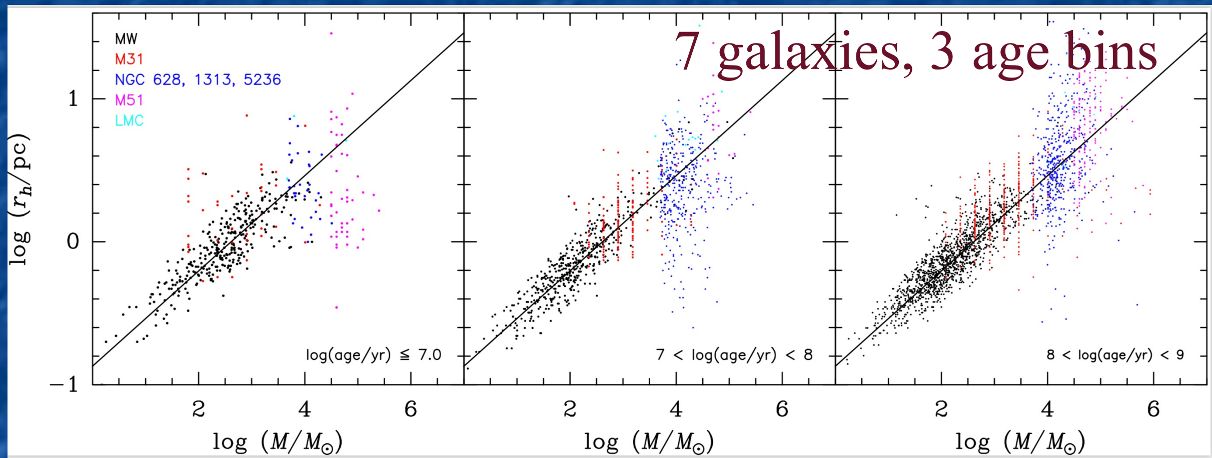
2. Two-body relaxation, dominant for old (halo) clusters, is mass-*de*pendent for $\rho_h \approx$ constant:

$$t_d \approx 20\, t_{rh} \;\alpha\; M\rho_h^{-½}$$

# Radius-Mass Relation for Young Clusters




Fall & Chandar 2012



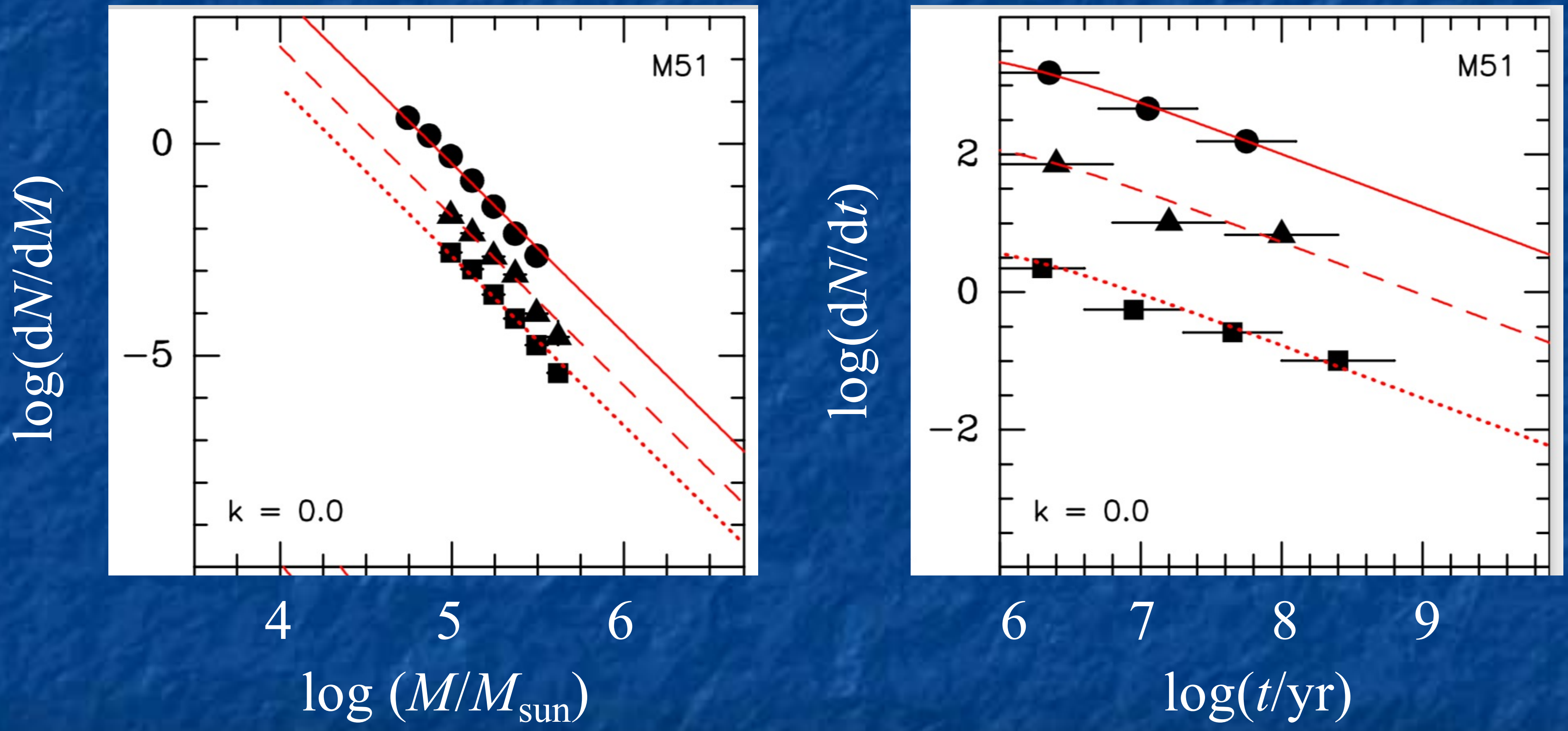

Krumholz et al 2019

Observed relation: $r_{\mathrm{h}}\ \alpha\ M^{\alpha}$ with $\alpha \approx 0.3$

=> $\rho_{\mathrm{h}}(M) \approx$ const => $t_{\mathrm{d}}(M) \approx$ const

=> shape of MF is preserved by tidal interactions

# Mass-Age Distributions of Young Clusters

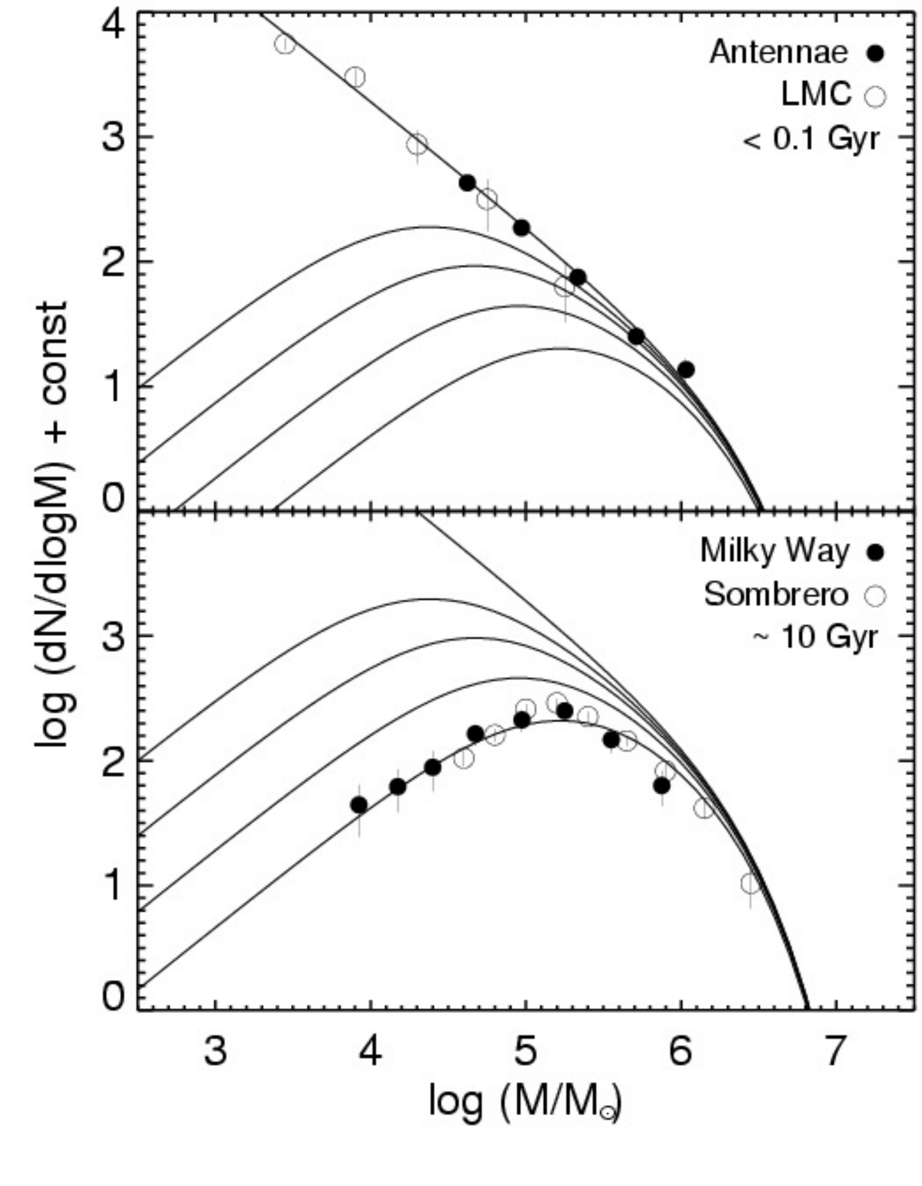



Fall & Goudfrooij 2022

# Evolving Mass Function of Old Clusters

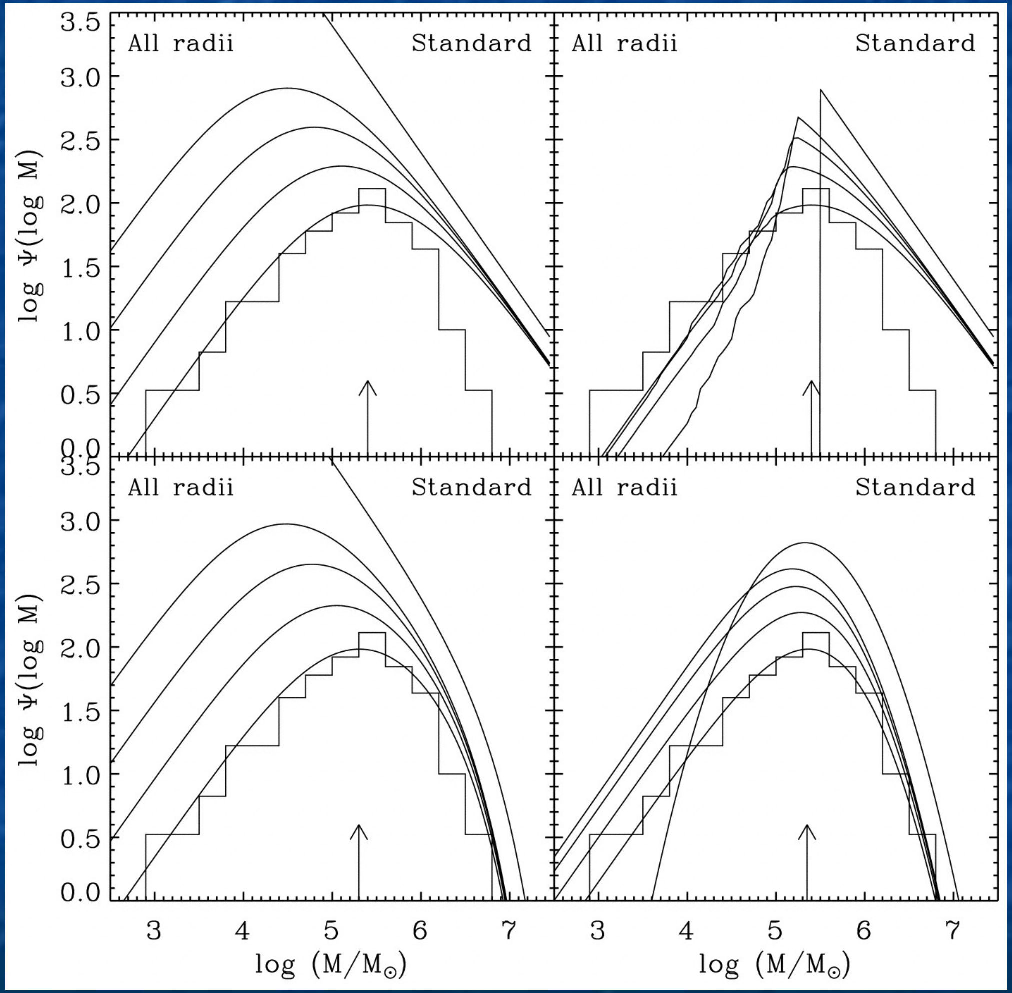
Young
(initial)

Old
(evolved)




Fall & Zhang
2001

# Evolution from Different Initial Conditions




Note: the late, low-mass form of *dN/dM* is independent of initial conditions

Fall & Zhang 2001

# Conclusions

1. Populations of young and old (globular) clusters are remarkably similar from one galaxy to another.

2. Clusters lose mass mainly by (1) stellar feedback, (2) tidal interactions, (3) two- body relaxation.

3. Simple models of these processes account well for the observed properties of cluster populations.

# Thanks to my collaborators!

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