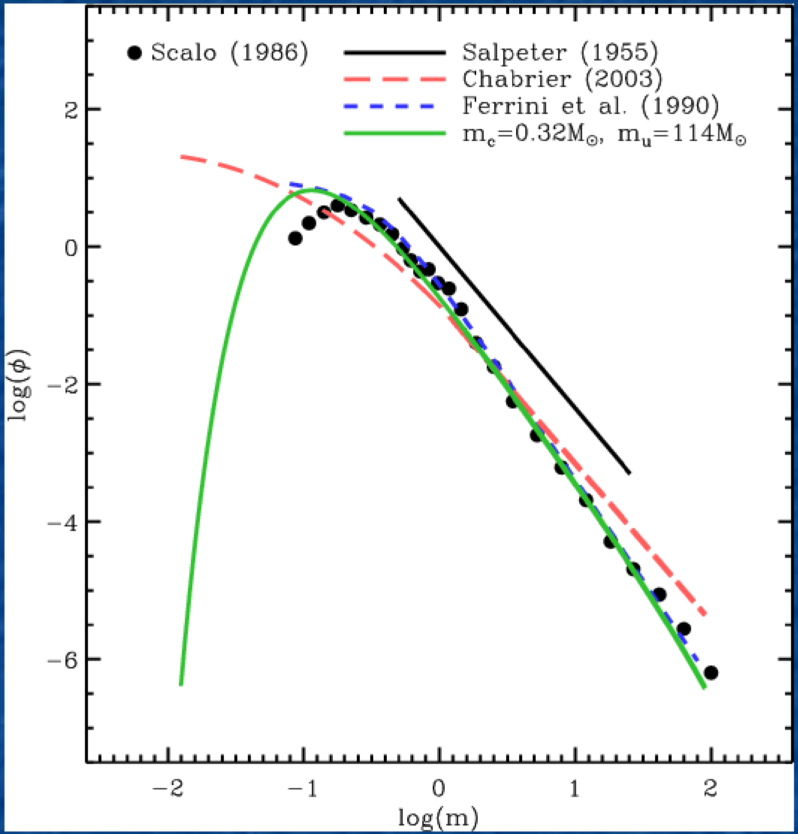
Formation and Evolution of Star Clusters

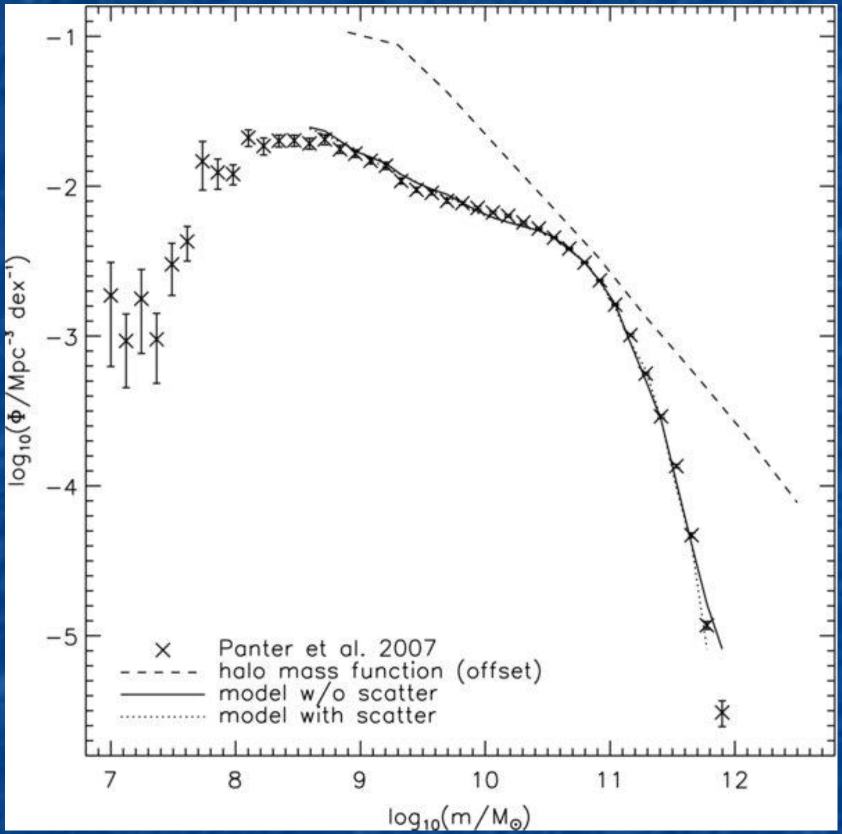
Michael Fall

KITP Conference

Mass Functions: Stars and Galaxies



Stars



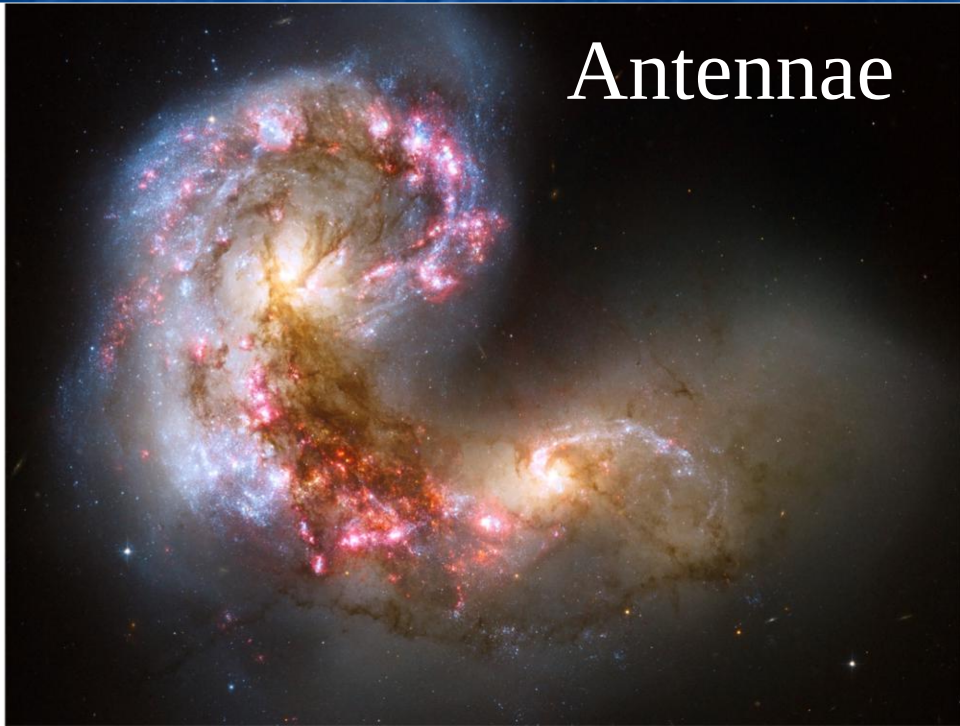
Galaxies

Young Cluster

Old Cluster


LMC & SMC

M51

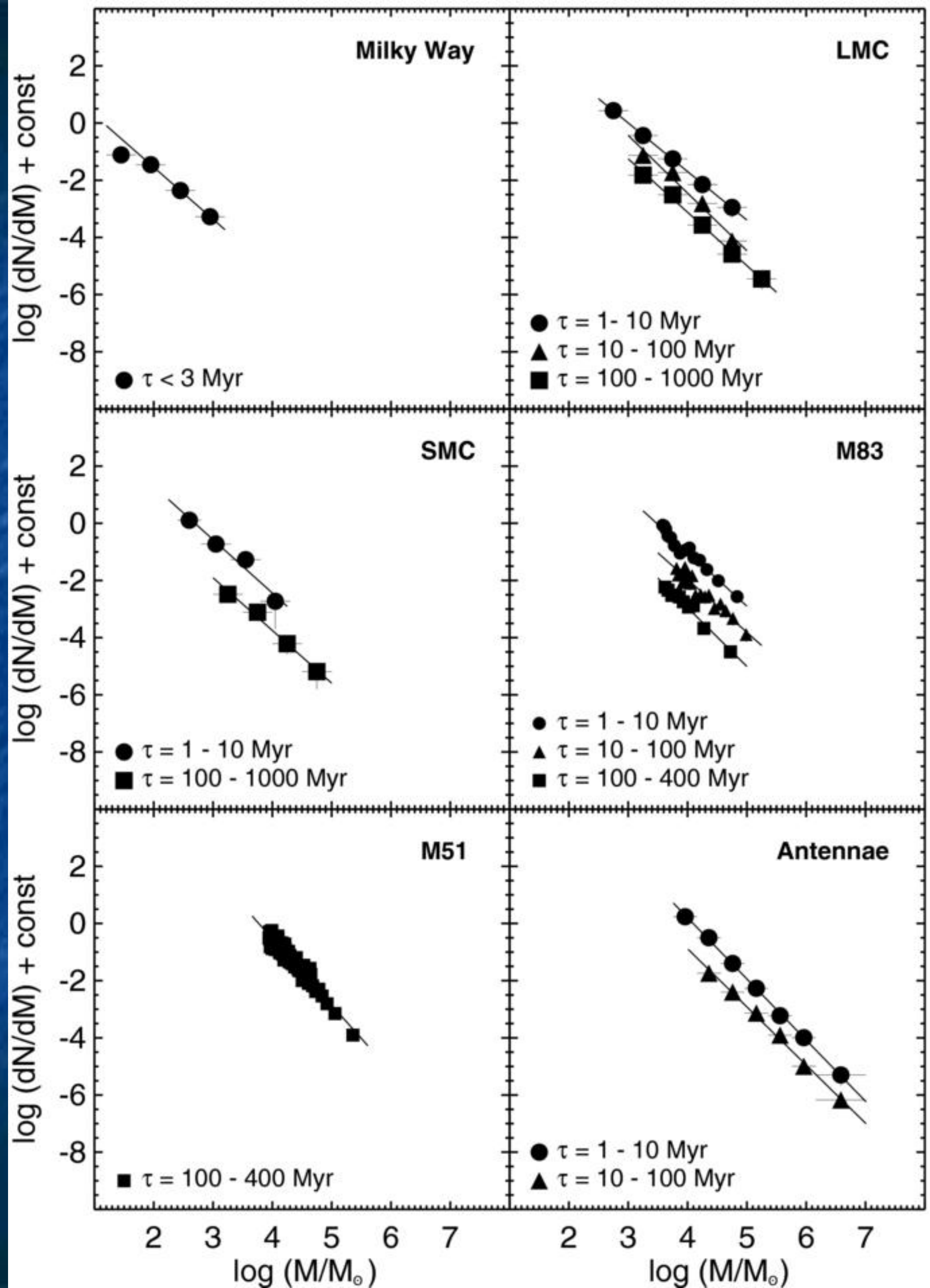
M83

Antennae

Mass Functions: Young Clusters

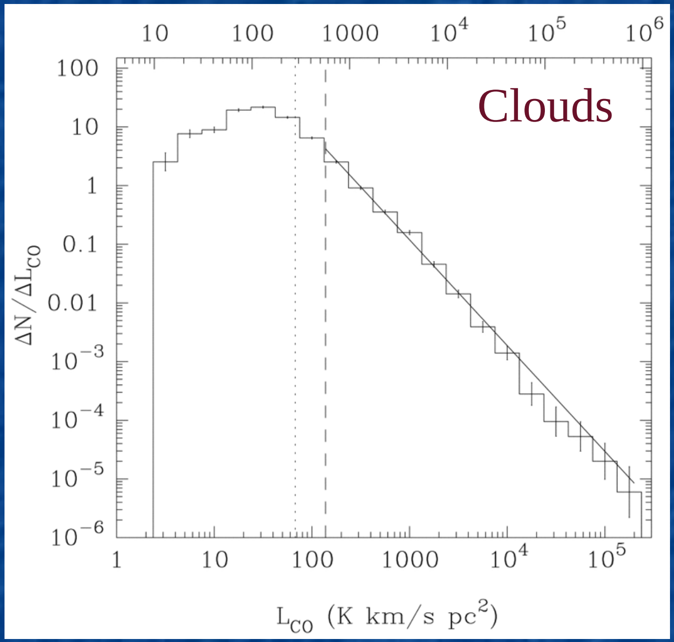
different ages
different galaxies

$dN/dM \sim M^{\beta}$

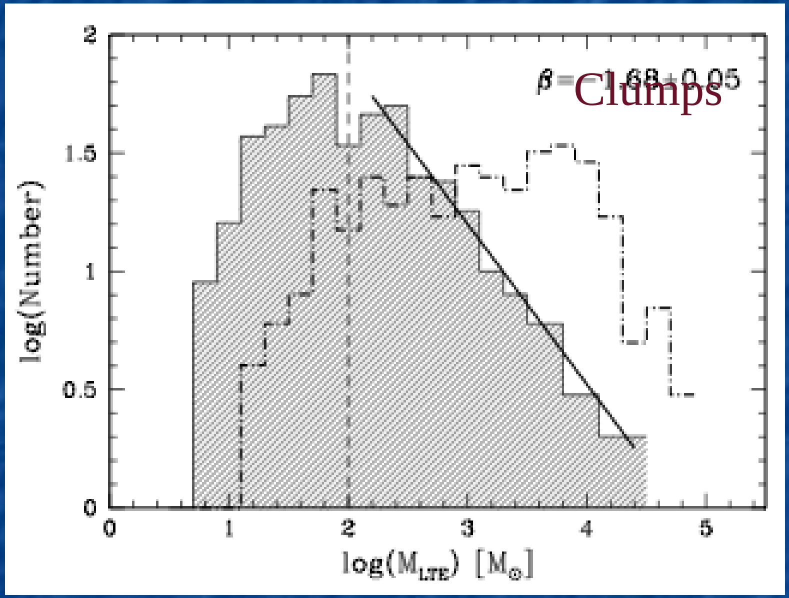
with $\beta \approx -2.0$



Mass Functions: Molecular Clouds and Clumps



Heyer et al. 2001



Wong et al. 2008

$$dN/dM \sim M^{\beta} \quad \text{with} \quad \beta \approx -1.7$$

Antennae

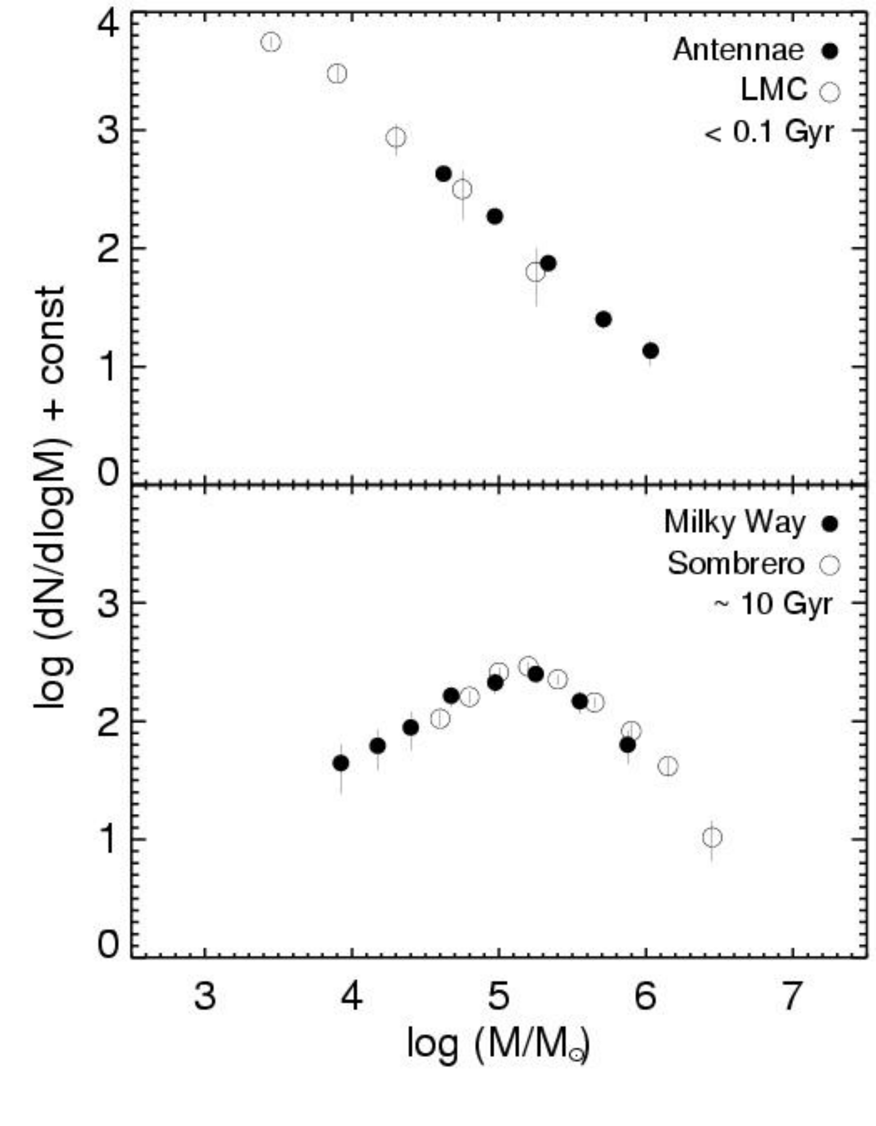

Hubble Heritage
NASA, ESA, and The Hubble Heritage (STScI/AURA)-ESA/Hubble Collaboration • HST/ACS • STScI-PRC06-46

Sombero


M104
Hubble Heritage
NASA and The Hubble Heritage Team (AURA/STScI) • Hubble Space Telescope ACS • STScI-PRC03-28

Mass Functions: Young and Old Clusters

Note very different forms



Young

Old

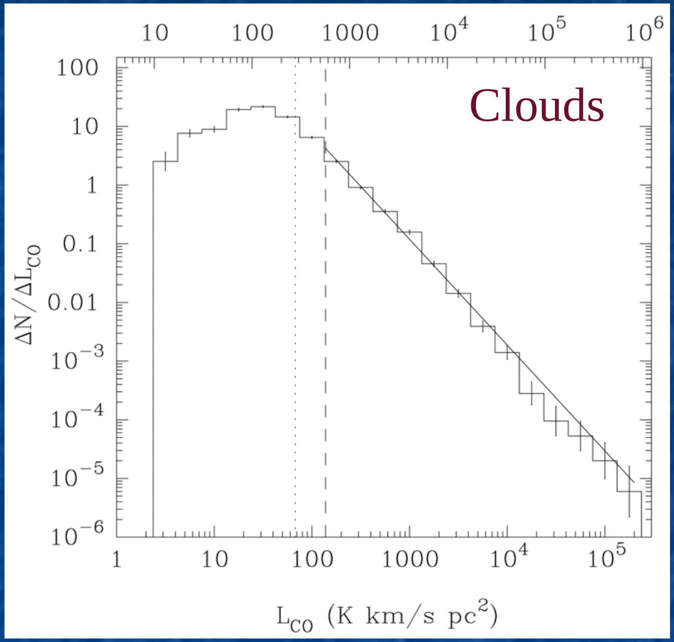
Questions

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

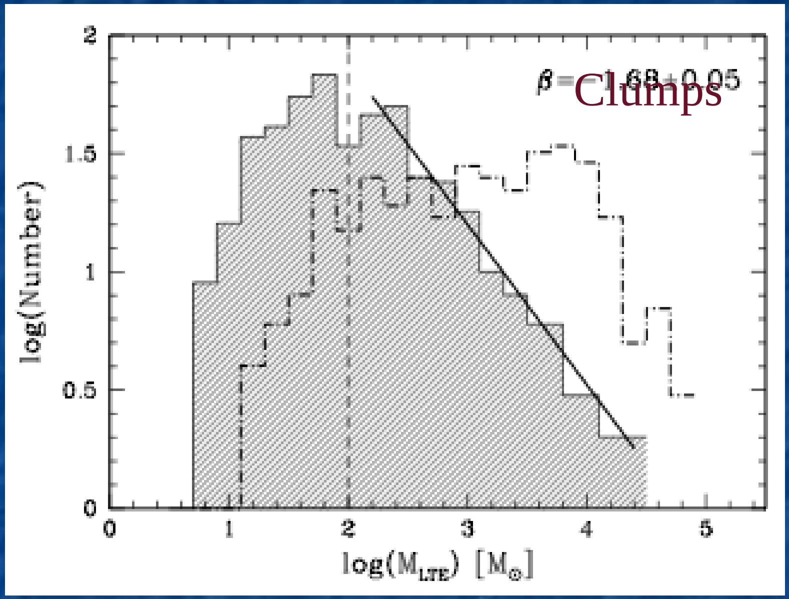
2. Why do the mass functions of young clusters of different ages have nearly the same (power-law) shape?

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

Mass Functions: Molecular Clouds and Clumps



Heyer et al. 2001



Wong et al. 2008

Correction for mass-dependent lifetimes (CIMF):

$dN/dM \sim M^{\beta}$ with $\beta \approx -2.0$

=> Star-formation efficiency approx independent of mass

Feedback Processes

1. Protostellar outflows (momentum driven)

2. Photoionization heating (momentum driven)

3. Radiation pressure (momentum driven)

4. Stellar winds (momentum or energy driven)

5. Supernovae (momentum or energy driven)

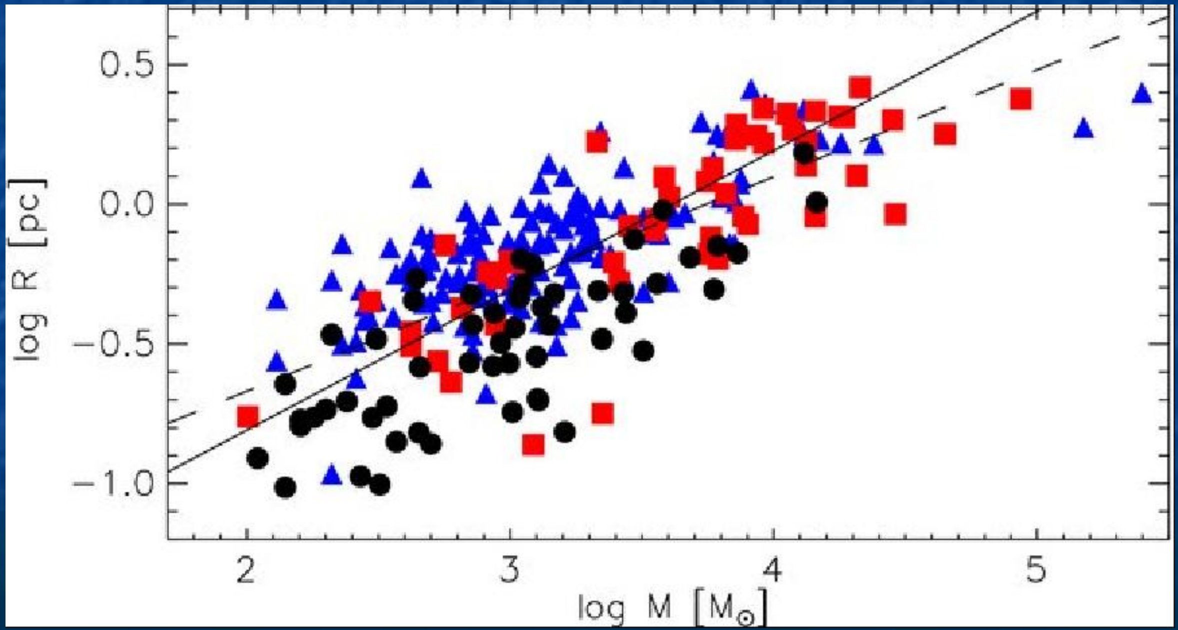
Gas Expulsion by Stellar Feedback

Star Formation Efficiency

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

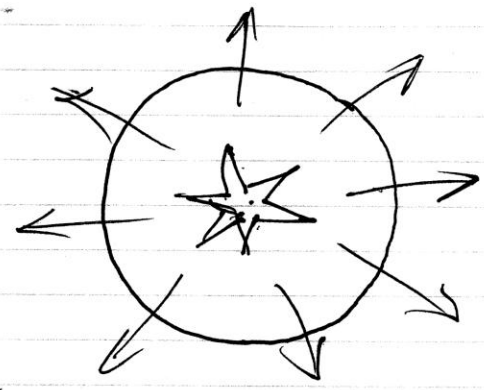
$$\mathcal{E} \propto V_e^2 / R_h \propto M^{1-2\alpha} \text{ (momentum driven)}.$$

Observed radius vs mass for MW clumps $R \sim M^{\alpha}$ with $\alpha \approx 0.5$



STAR FORMATION EFFICIENCY ε

Feedback in protocluster:
mass M, radius R
velocity dispersion
$V_{rms} \propto (GM/R)^{1/2}$
input energy E_{in}
input momentum P_{in}



Escape Conditions:

$$E_{in} \approx \dot{E}\Delta t \approx E_{crit} \approx \frac{1}{2} M V_{esc}^2$$

(energy-driven)

$$P_{in} \approx \dot{P}\Delta t \approx P_{crit} \approx M V_{esc}$$

(momentum-driven)

$$\dot{E} \propto \dot{P} \propto M_* \propto \varepsilon M \quad (\text{for } \Delta t \lesssim 2\times10^6 \text{ yr})$$

$$\Delta t \propto \tau_{dyn} \propto R/V_{rms}$$

$$V_{esc} \approx \sqrt{2}\, V_{rms} \propto (M/R)^{1/2}$$

$$\Rightarrow \begin{cases} \varepsilon \propto M^{3/2} R^{-5/2} \propto M^{(3-5\alpha)/2} & \text{(energy)} \\ \varepsilon \propto M R^{-2} \propto M^{1-2\alpha} & \text{(momentum)} \end{cases}$$

Stellar Dynamical Disruption Processes

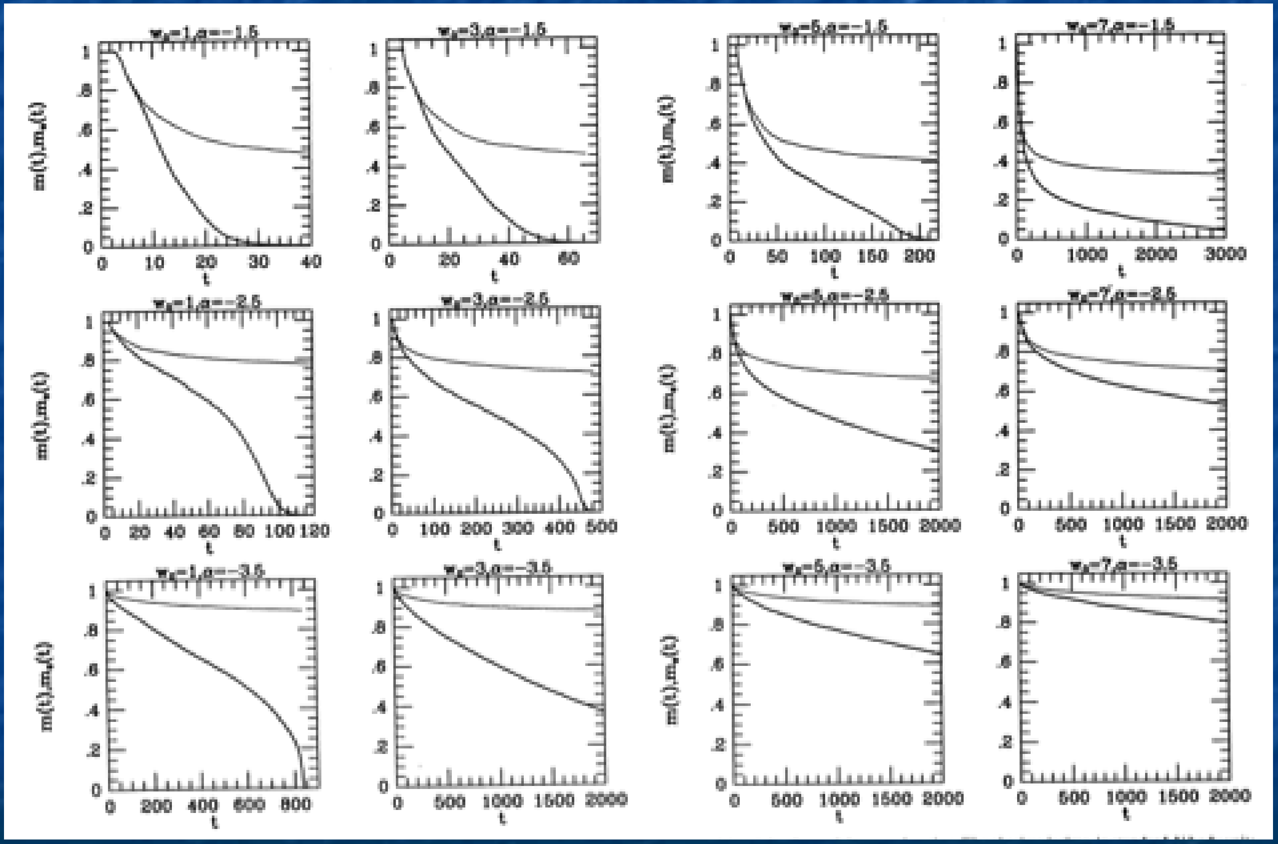
1. Stellar mass loss with tidal limitation (10^7 yr < t < 10^8 yr)

2. Tidal disturbances by molecular clouds ($t > 10^8$ yr)

3. Stellar dynamical "evaporation" ($t > 10^9$ yr)

Stellar Mass Loss with Tidal Limitation

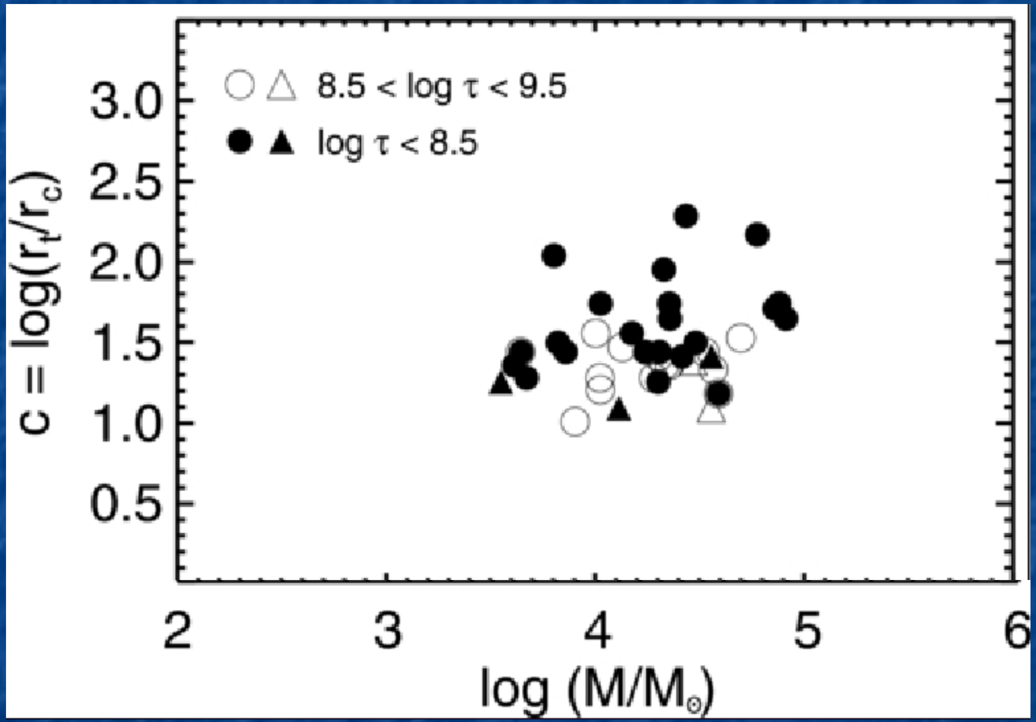
M vs *t* for different *c* (W_0) and IMF



Fukushige & Heggie 1995

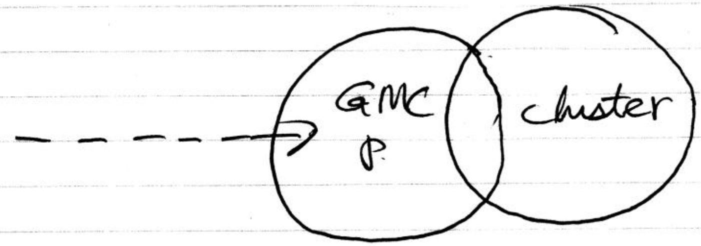
Disruption by Stellar Mass Loss with Tidal Limitation Depends on Concentration (dimensionless binding energy)

Observed concentration vs mass for MC clusters: No correlation



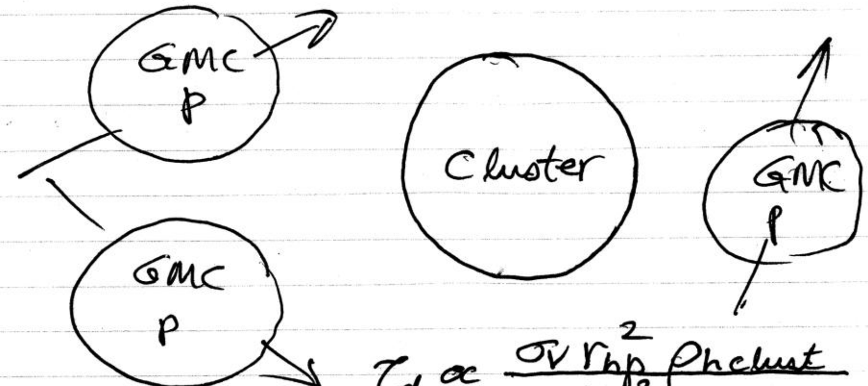
TIDAL DISRUPTION

Catastrophic Regime —
disruption by a single strong encounter



$$\tau_d \propto \frac{\rho_{hclust}^{1/2}}{M_p n_p}$$

Diffusive Regime —
disruption by a series of weak encounters



$$\tau_d \propto \frac{\sigma_V r_{hp}^2 \rho_{hclust}}{M_p^2 n_p}$$

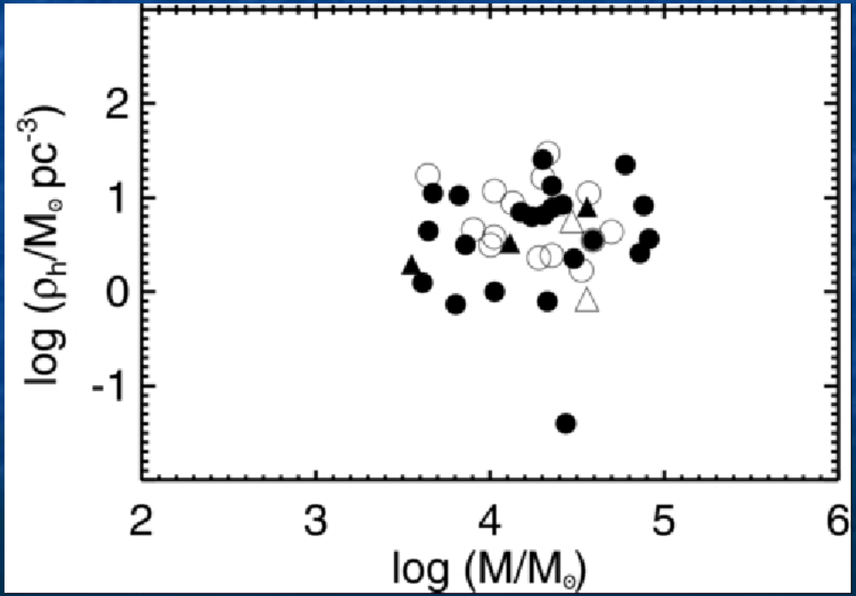
Tidal Disturbances by Molecular Clouds

Disruption Timescale

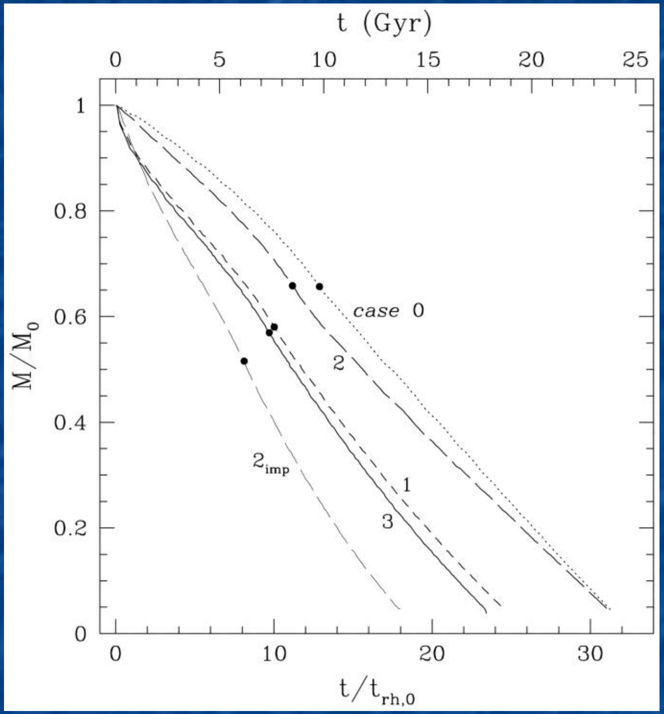
$$\tau_d \propto \frac{\rho_h^{1/2}}{M_p n_p} \qquad \text{(catastrophic regime)},$$

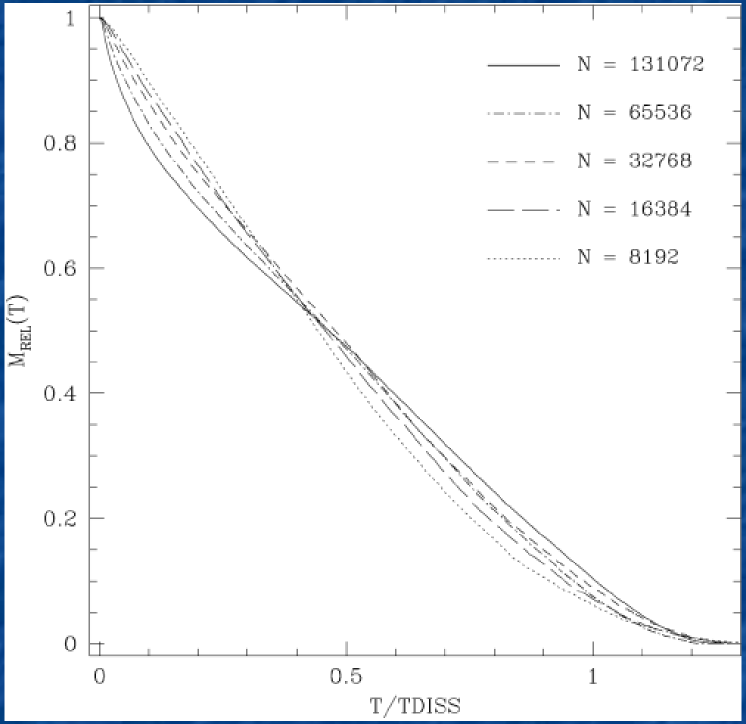
$$\tau_d \propto \frac{\sigma_v r_{hp}^2 \rho_h}{M_p^2 n_p} \qquad \text{(diffusive regime)}.$$

Observed density vs mass for MC clusters: No correlation



Stellar Dynamical Evaporation (*M* vs *t*)





Fokker-Planck Models

Gnedin et al 1999

N-Body Models

Baumgardt & Makino 2003

Evolution of Mass Function $\psi(M,t)$

Defn: $\psi(M,t)dM$ is the number of clusters with masses in $(M, M+dM)$ at time t

Continuity equation for a coeval population of clusters:

$$\psi(M,t) = \psi_0(M_0)|\partial M_0/\partial M|$$

Procedure:

Step 1. Mass-removal processes => $M(M_0,t)$

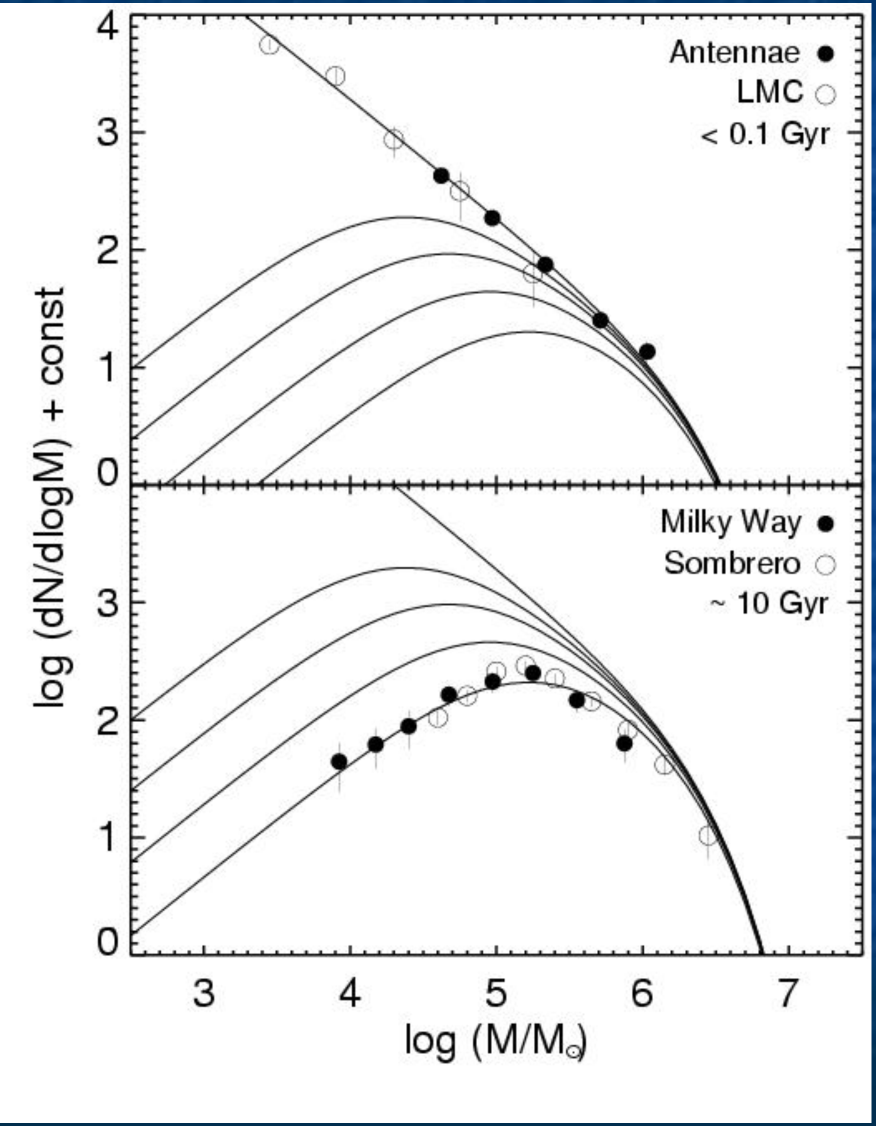
Step 2. Invert => $M_0(M,t)$

Step 3. Specify initial mass function $\psi_0(M_0)$

Step 4. Solve for evolved mass function $\psi(M,t)$

Mass Functions: Late Evolution

Note very different forms



Young

Old

Conclusions

1. Young clusters are disrupted by stellar feedback, stellar mass loss, and tidal disturbances

2. The young cluster mass function depends on the protocluster radius-mass relation and the cluster concentration-mass and density-mass relations

3. Old clusters are disrupted mainly by stellar dynamical evaporation

4. The old cluster mass function is very similar to that of globular clusters, irrespective of initial conditions

References

1. Fall & Zhang (2001) ApJ
2. McLaughlin & Fall (2008) ApJ
3. Fall, Krumholz, & Matzner (2010) ApJ
4. Fall & Chandar (2012) ApJ

End