The Observed Mass Function of Young Star Clusters

Søren S. Larsen
Astronomical Institute, Utrecht University

What is the ICMF?

Initial Cluster Mass Function (ICMF) = Distribution of cluster masses “at birth”.

What is the ICMF?

Initial Cluster Mass Function (ICMF) =
Distribution of cluster masses "at birth".

Not very practical: What does "at birth" mean?

What is the ICMF?

Better:
ICMF = *Mean birth rate* vs. cluster mass:

$$\psi(M) \hat{=} \frac{d^2 N}{dM\, d\tau}$$

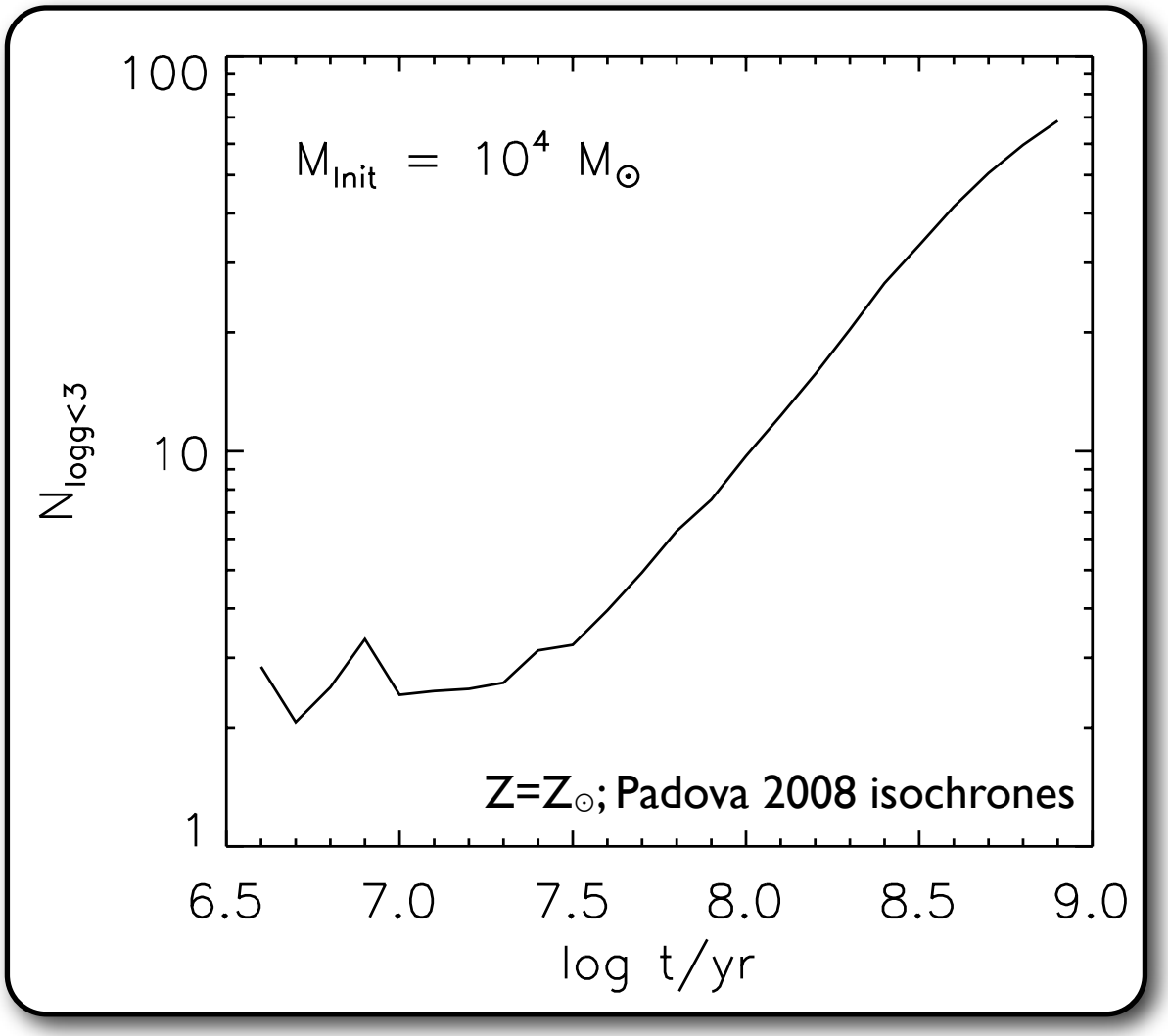
For large M (>10^5 - 10^6 $M_\odot$), birth rate is typically $\ll$1 Myr^{-1}, even in large galaxies.

Observational difficulties

- High masses:
  - Low birth rates → rare, *poor statistics*
- Low masses:
  - Clusters faint, short-lived
  - Integrated properties subject to *stochastic IMF sampling*
- Masses are observationally expensive to measure (virial masses prohibitive for large samples)

Stochastic IMF sampling

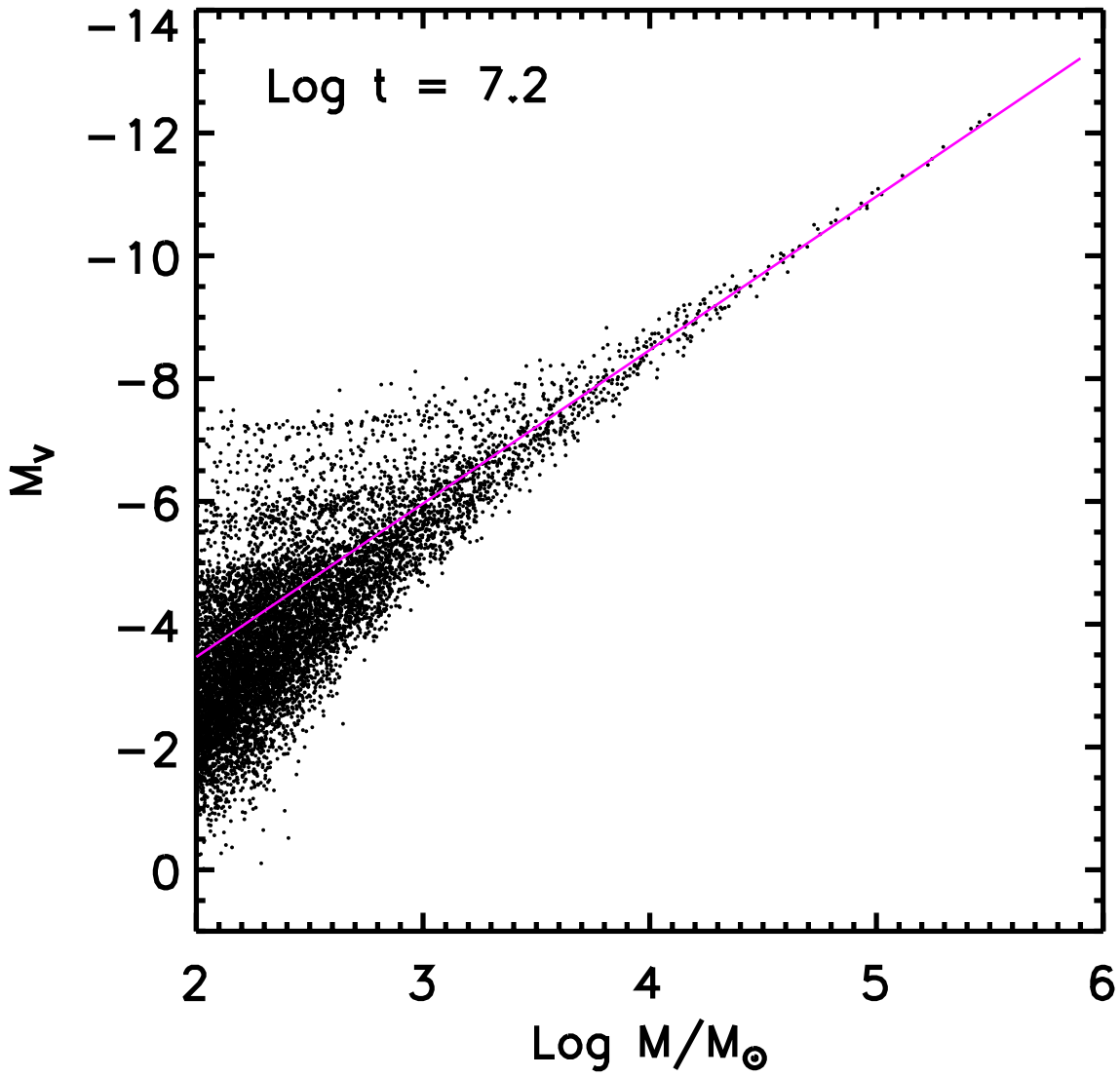
Mean number of supergiants vs age



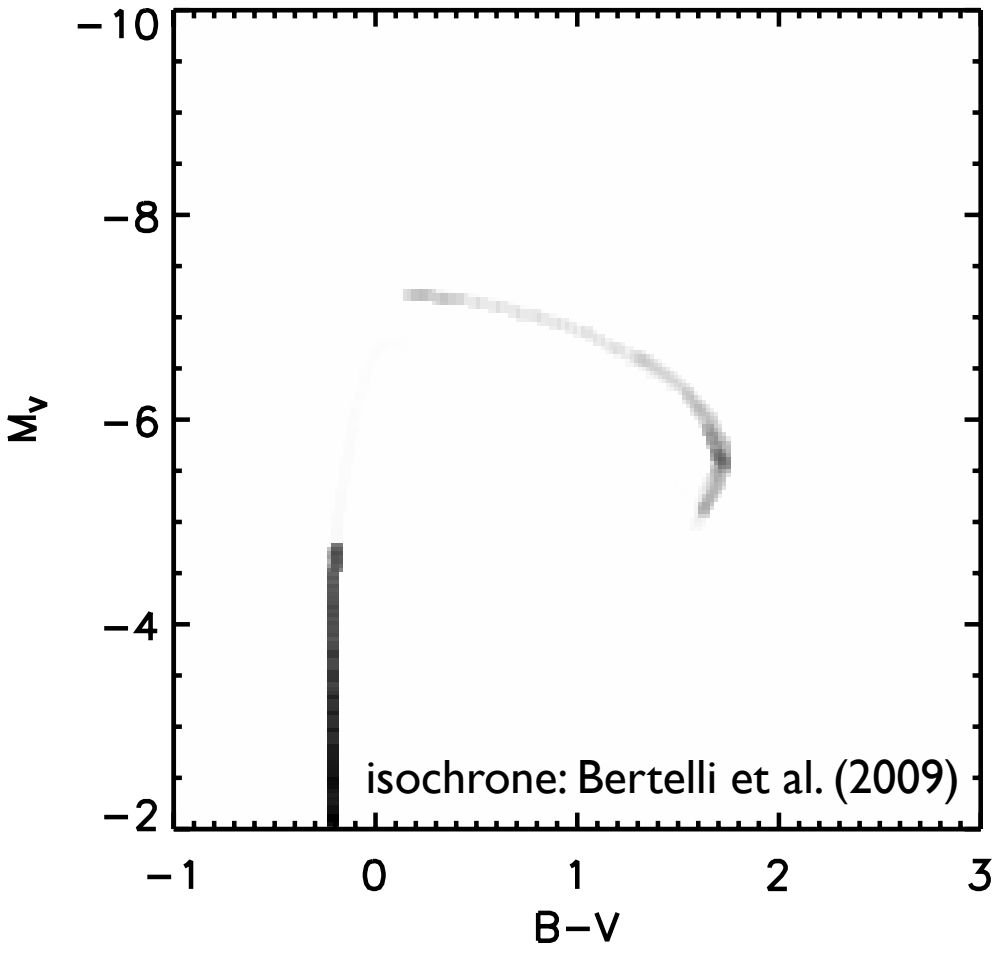
Stochastic IMF sampling becomes very important below $M \sim 10^4 M_\odot$.

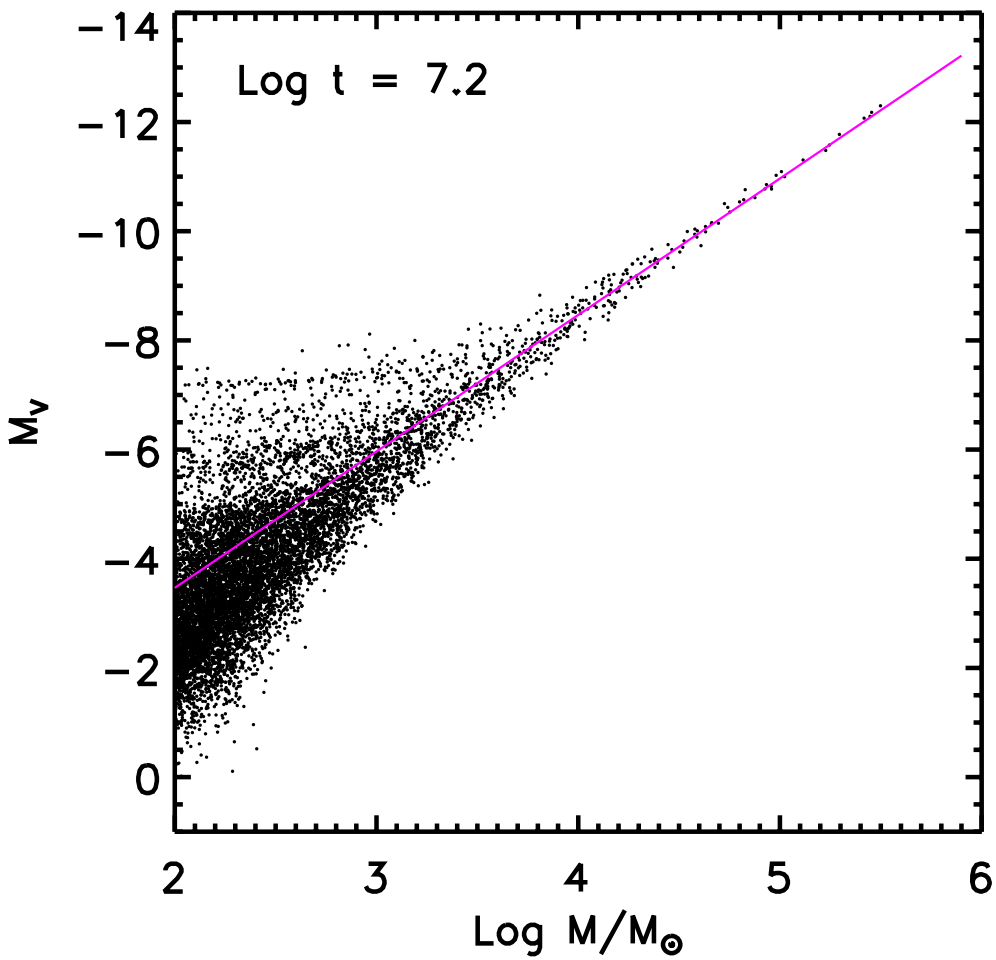
(Barbaro & Bertelli 1977;
Girardi et al. 1995;
Bruzual 2002;
Cerviño & Luridiana 2004,2006;
Maíz-Apellániz 2009;
Piskunov et al. 2009;
Fouesneau & Lançon 2010;
Popescu & Hanson 2010;
Silva-Villa & Larsen 2011)

Luminosity vs. mass for stochastic IMF sampling

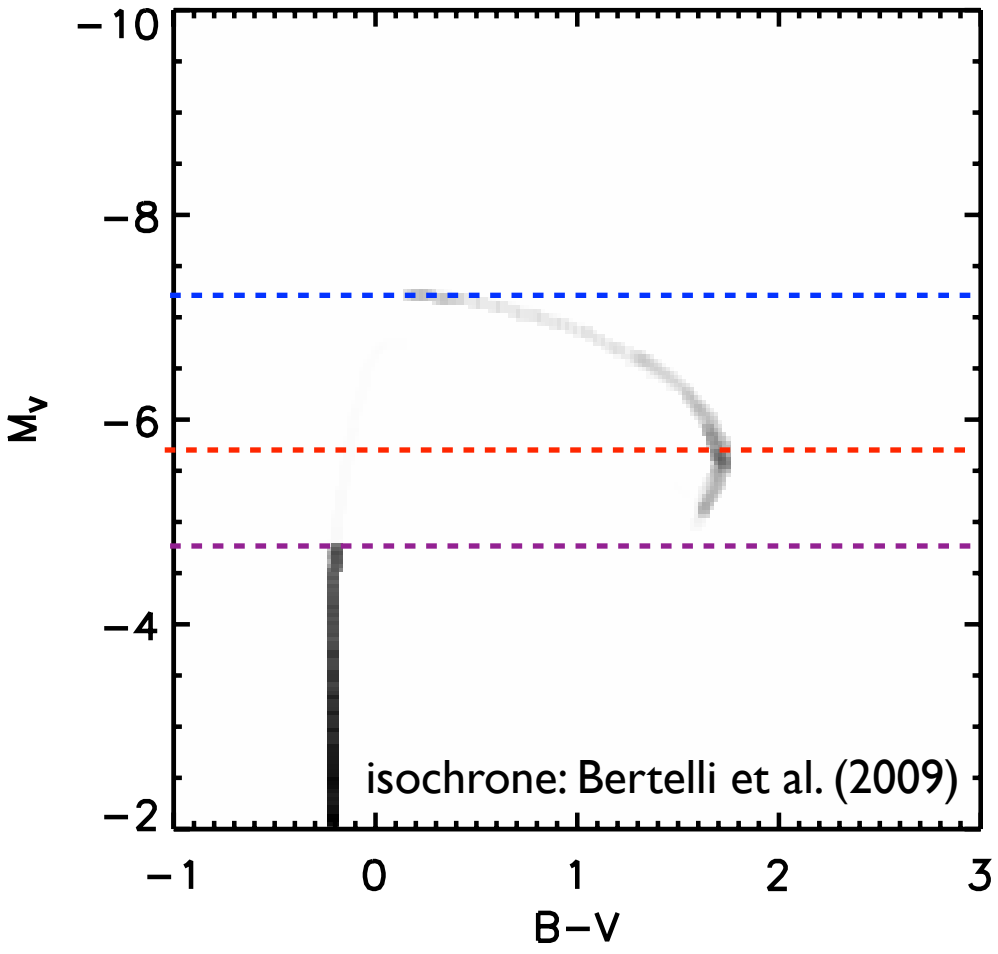


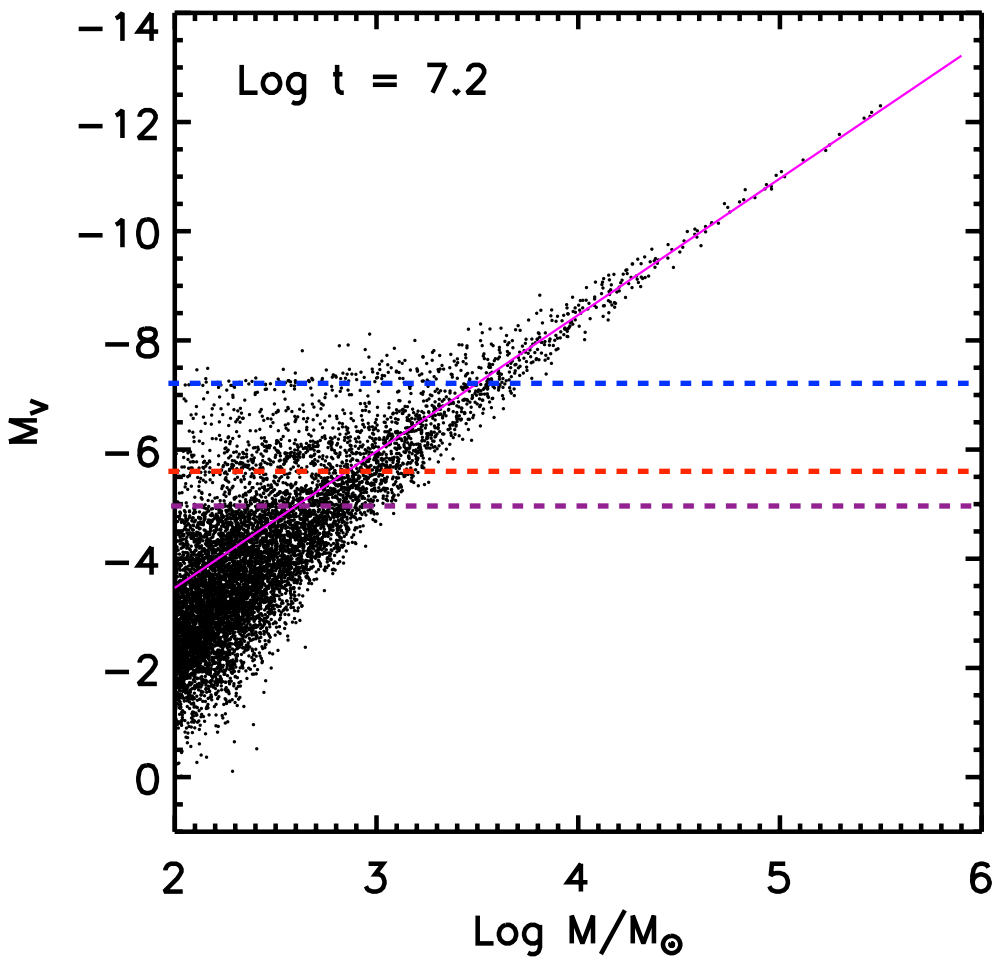
Luminosity vs. mass for stochastic IMF sampling



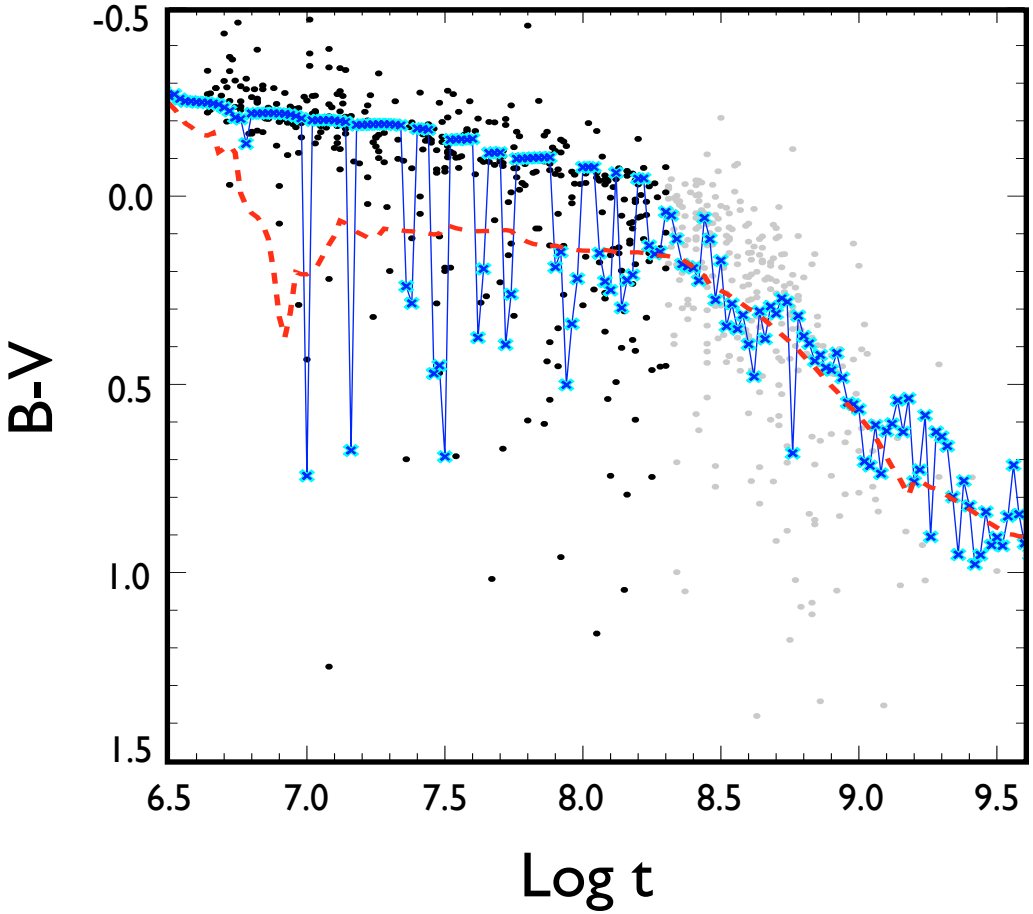


Luminosity vs. mass for stochastic IMF sampling





Colours of Galactic open clusters



Dots: observed colours

Blue curve: stochastically sampled models

Red curve: classical SSP model

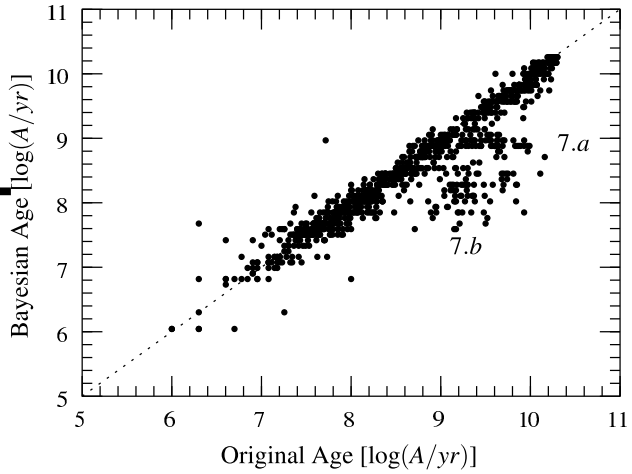
Piskunov et al. 2009

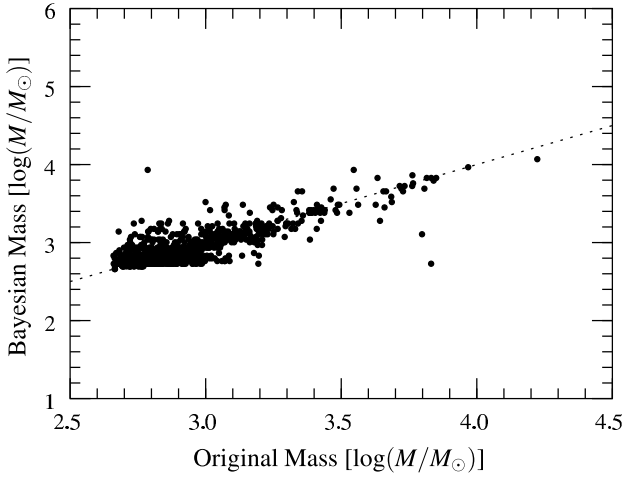
Ages and masses: stochastic effects

Ages

Masses

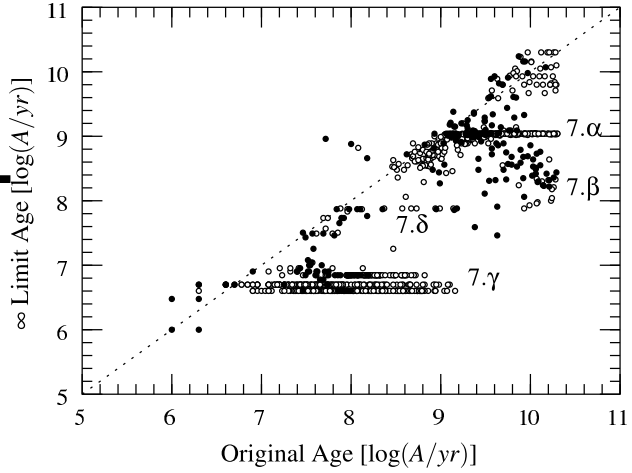
Output

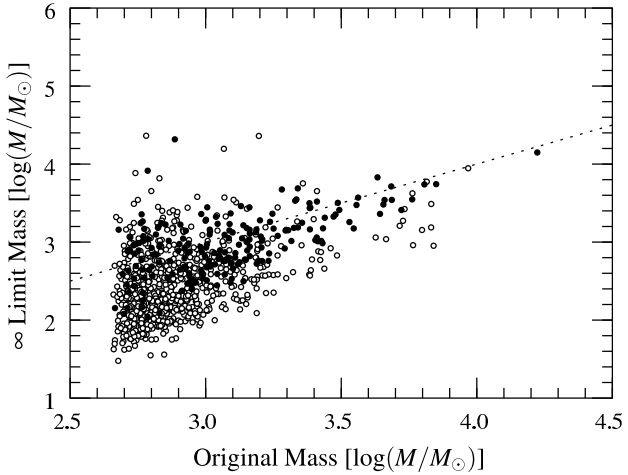




Bayesian approach

Output





Classical SSP models

Input

Input

Fouesneau & Lançon (2010)

Stochastic effects

Stochastic effects

- Very important for $M \lesssim 10^4\ M_\odot$

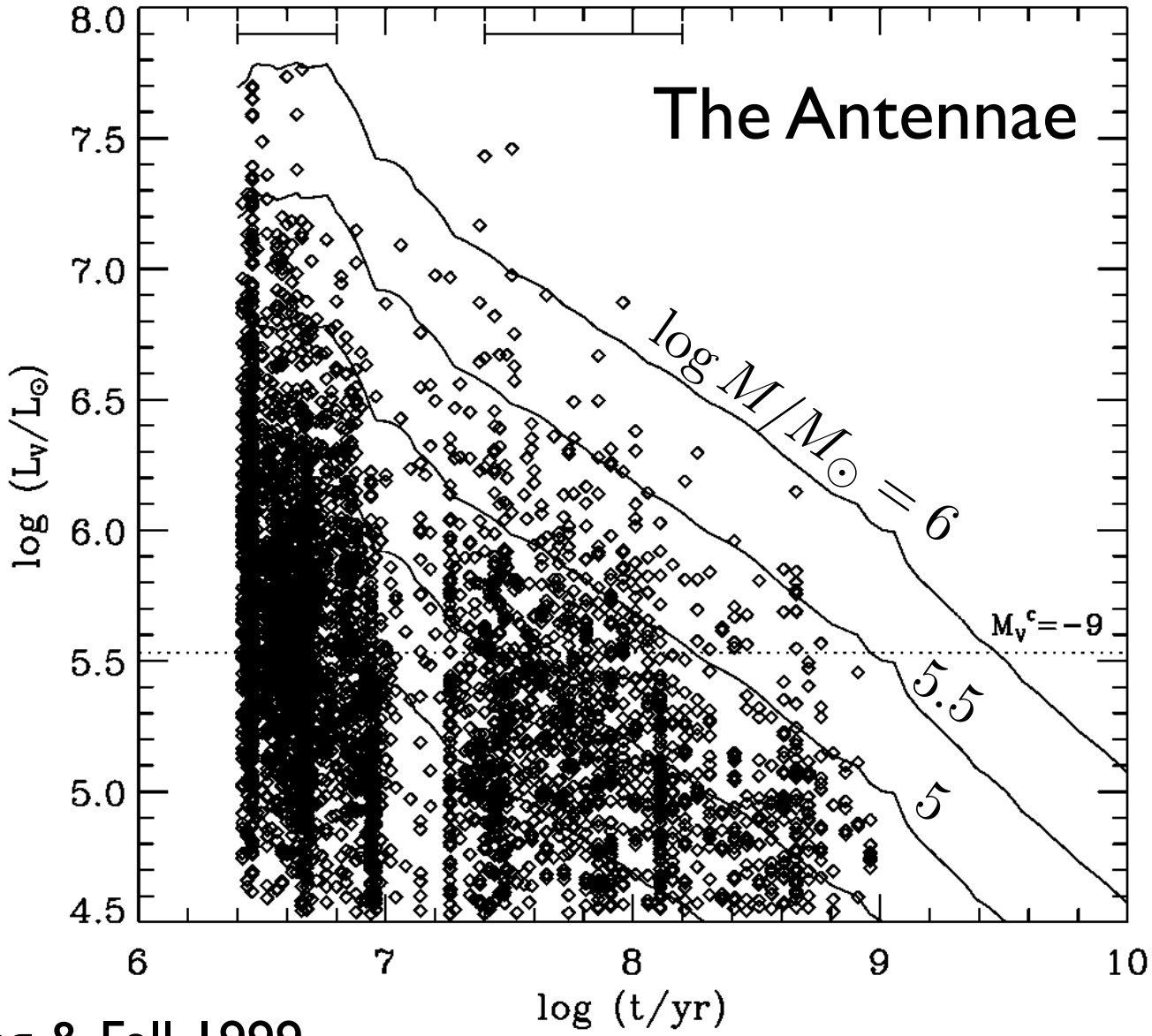
Stochastic effects

- Very important for $M \lesssim 10^4\ M_\odot$
- Possible ways to mitigate effects on photometry:
  - Use weights based on effect of stochasticity in different bands (Maíz-Apellaniz 2009)
  - Reject clusters with poor fits (Fouesneau & Lançon 2010)
  - Generate full model grid of stochastic clusters and search for best fit (Popescu & Hanson 2010; Fouesneau & Lançon 2010)

Stochastic effects

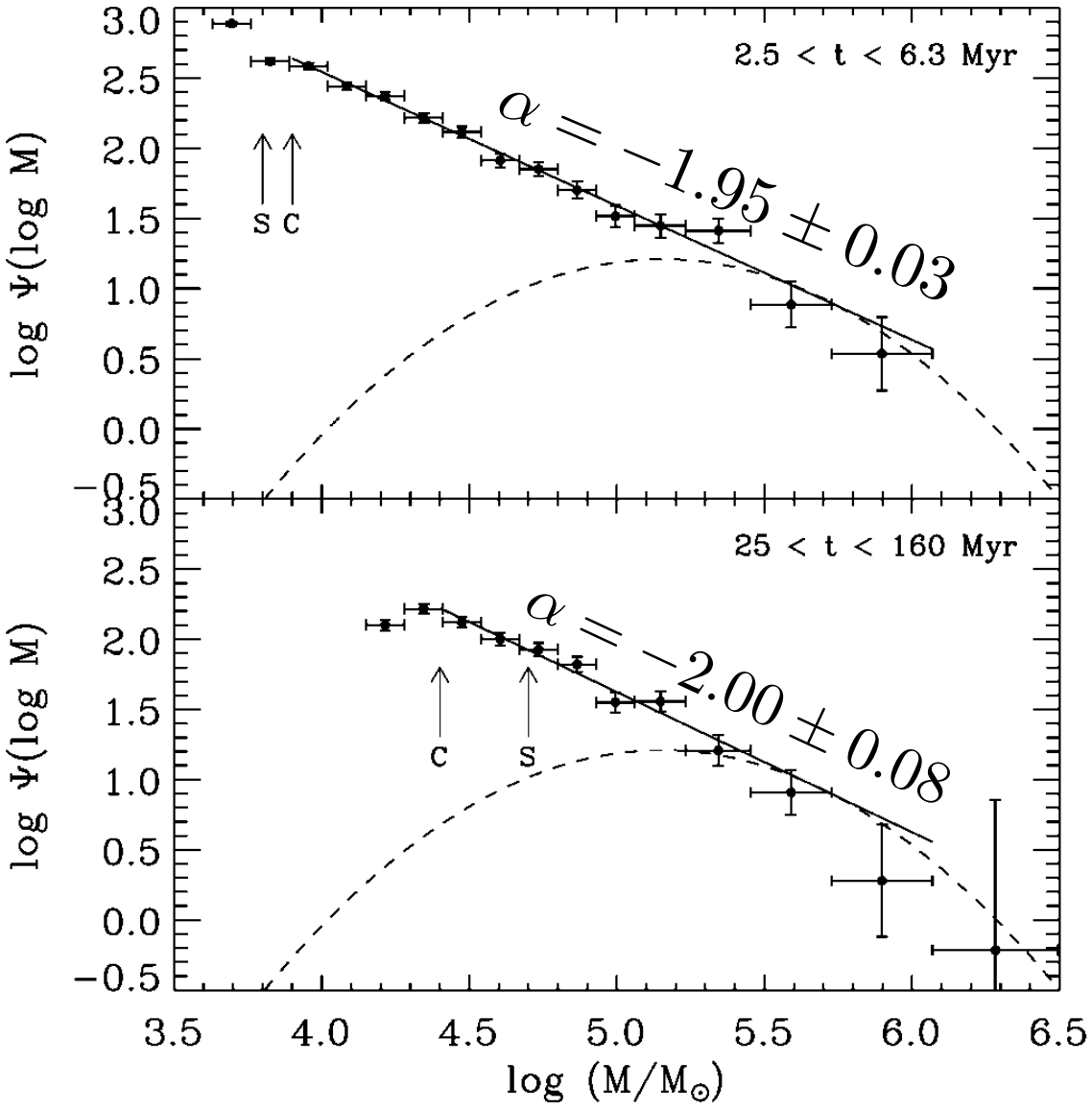
- Very important for $M \lesssim 10^4\ M_\odot$
- Possible ways to mitigate effects on photometry:
  - Use weights based on effect of stochasticity in different bands (Maíz-Apellaniz 2009)
  - Reject clusters with poor fits (Fouesneau & Lançon 2010)
  - Generate full model grid of stochastic clusters and search for best fit (Popescu & Hanson 2010; Fouesneau & Lançon 2010)
- Also affect cluster detection via biased size measurements (Silva Villa & Larsen 2011)

NGC 4038/4039, The Antennae



Zhang & Fall 1999

The CMF of clusters in The Antennae

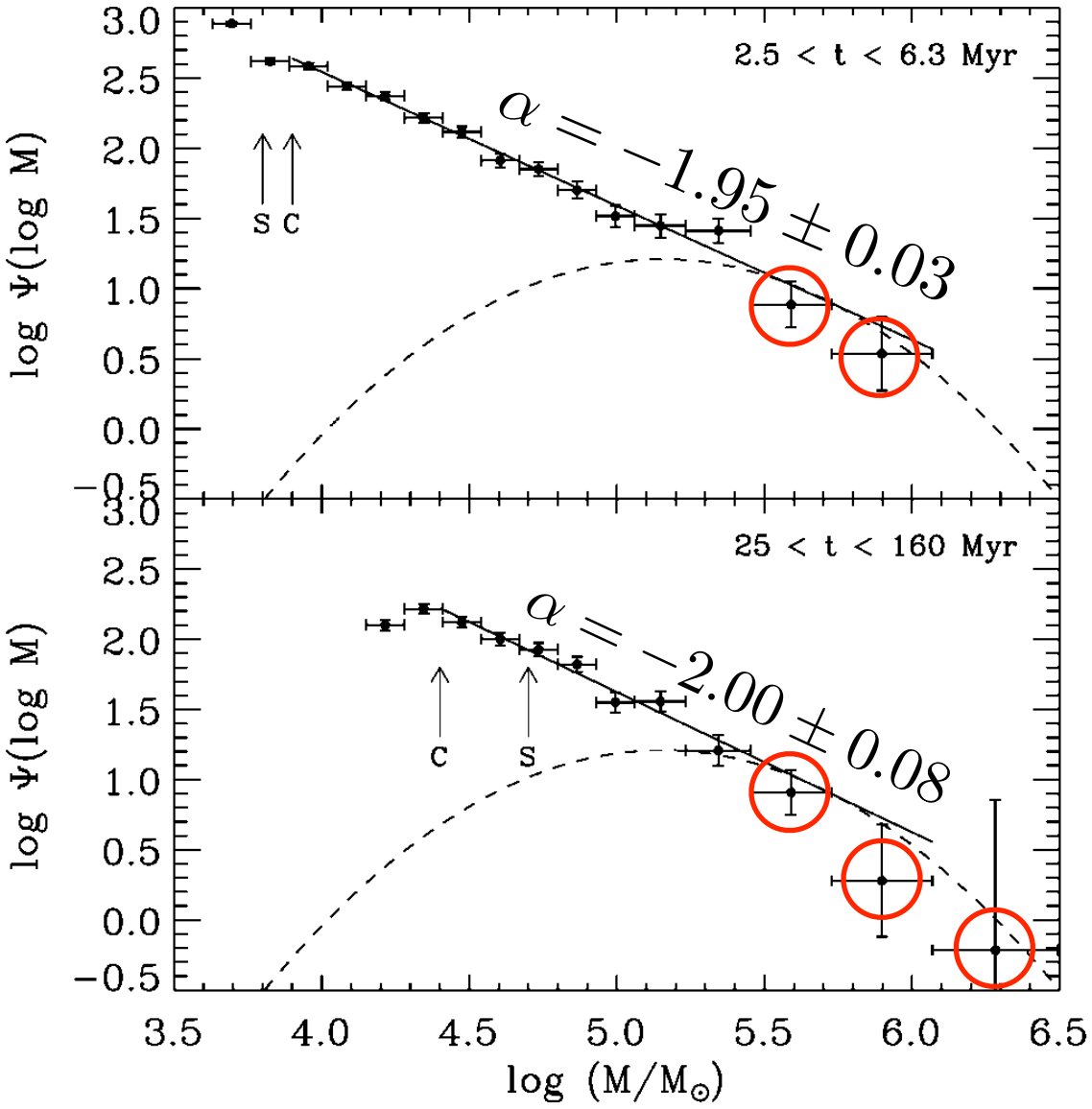


$$\frac{dN}{dM} \propto M^{-2}$$

$$; M > 10^4 M_\odot$$

Zhang & Fall 1999

The CMF of clusters in The Antennae



$$\frac{dN}{dM} \propto M^{-2}$$

$$; M > 10^4 M_\odot$$

(note: most massive bins all somewhat below fit)

Zhang & Fall 1999

Shape of the ICMF

*Cluster samples likely contaminated by complexes / associations

Shape of the ICMF

- Several studies: $dN/dM \sim M^{-2}$, *over some mass range*:
  - Milky Way open and embedded clusters (Elmegreen & Efremov 1997; Lada & Lada 2003; Selman & Melnick 2008); $\log M/M_\odot \lesssim 3$
  - Large Magellanic Cloud (Hunter et al. 2003; de Grijs & Anders 2006; Chandar et al. 2010); $3 \lesssim \log M/M_\odot \lesssim 5$
  - M51 (Bik et al. 2002; Chandar et al. 2011); $3 \lesssim \log M/M_\odot \lesssim 5$
  - Antennae (Zhang & Fall 2005; Fall et al.2009): $4 \lesssim \log M/M_\odot \lesssim 6$
  - Several spirals + irr (Dowell et al. 2008)*: $dN/dM \sim M^{-1.8}$ for $4 \lesssim \log M/M_\odot$
  - Starbursts: NGC 6745*/NGC 3310 (de Grijs et al. 2003): $5 \lesssim \log M/M_\odot$

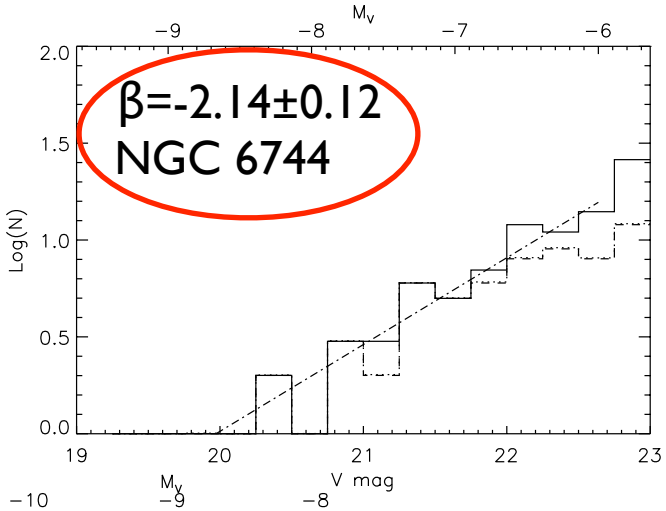
*Cluster samples likely contaminated by complexes / associations

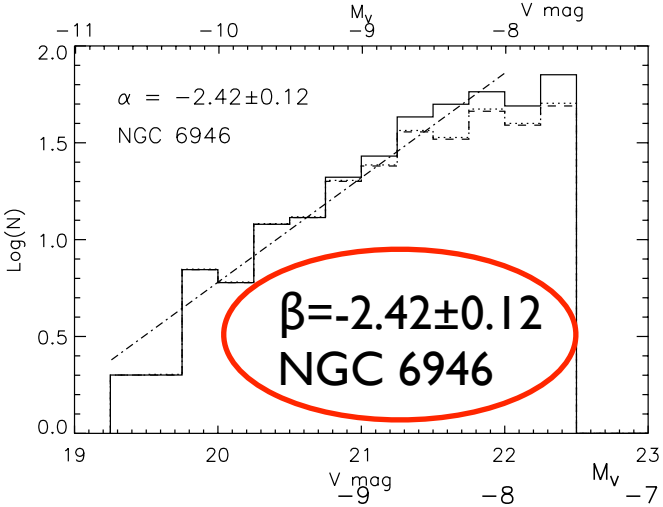
ICMF is universal: $\frac{dN}{dM} \propto M^{-2}$

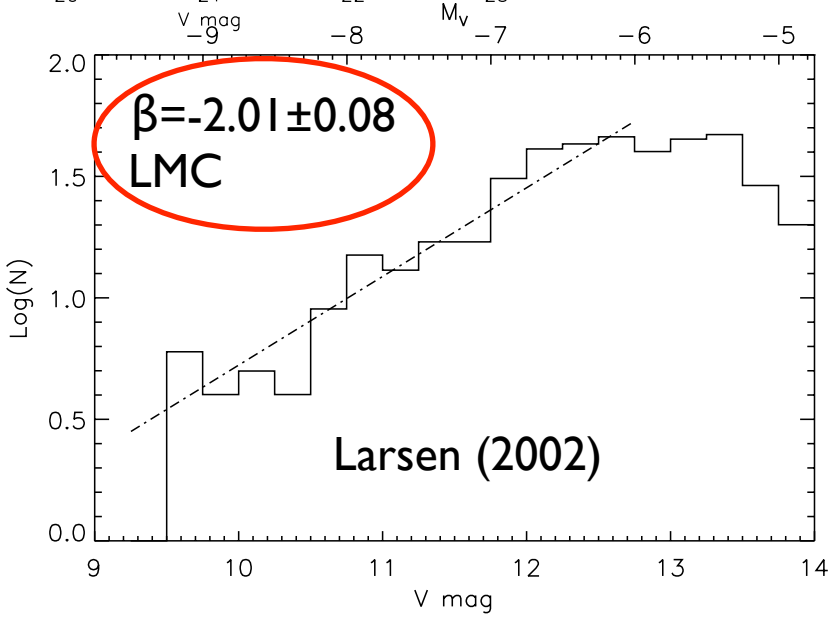
ICMF is universal: $\frac{dN}{dM} \propto M^{-2}$

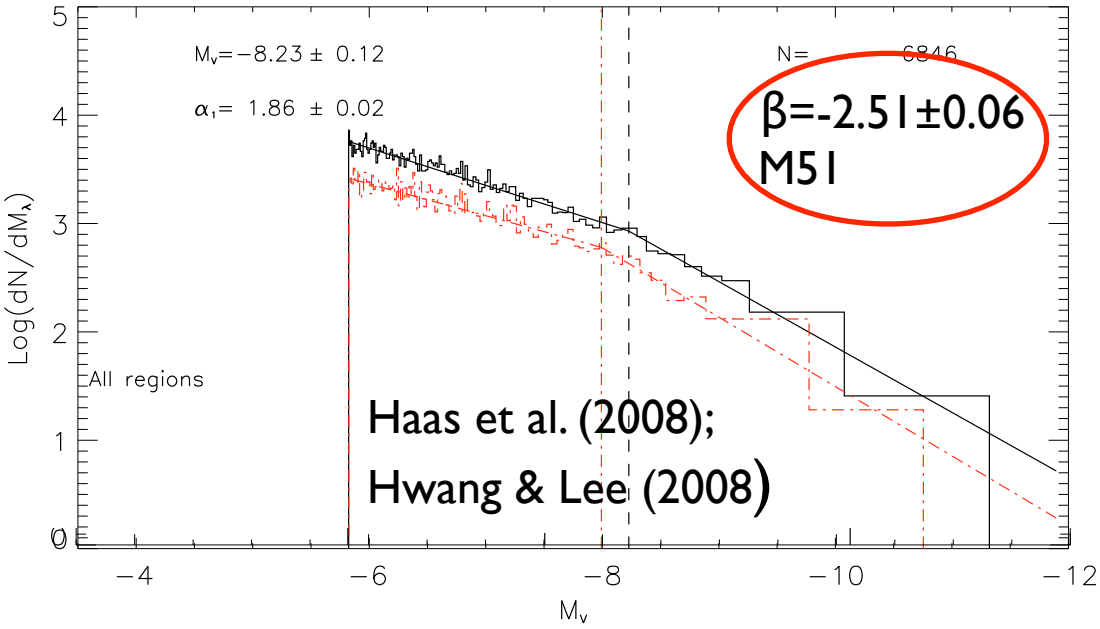
True or False?

Some observed LFs









NGC 3627: $dN/dL \sim L^{-2.43}$ for $M_V<-8$
(Dolpin & Kennicutt 2002)

Luminosity functions: slope vs. M_V

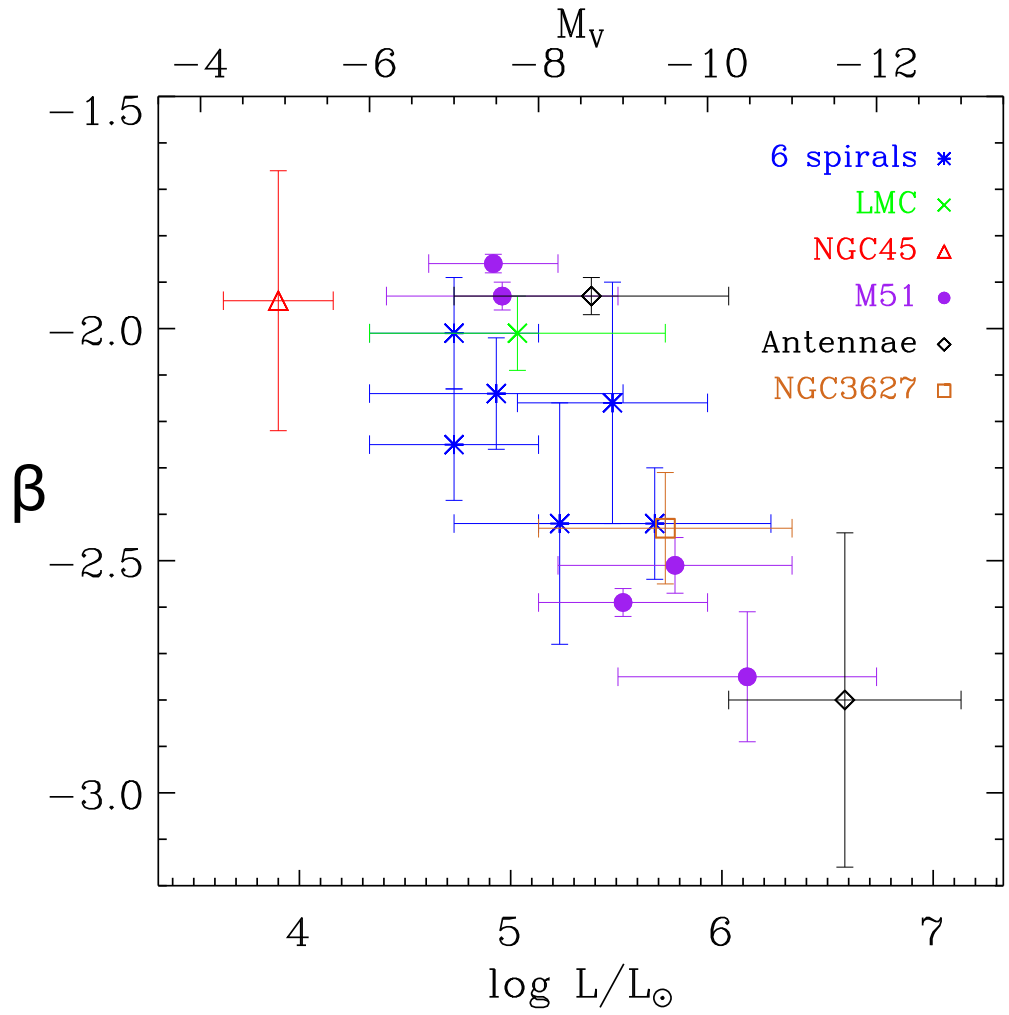


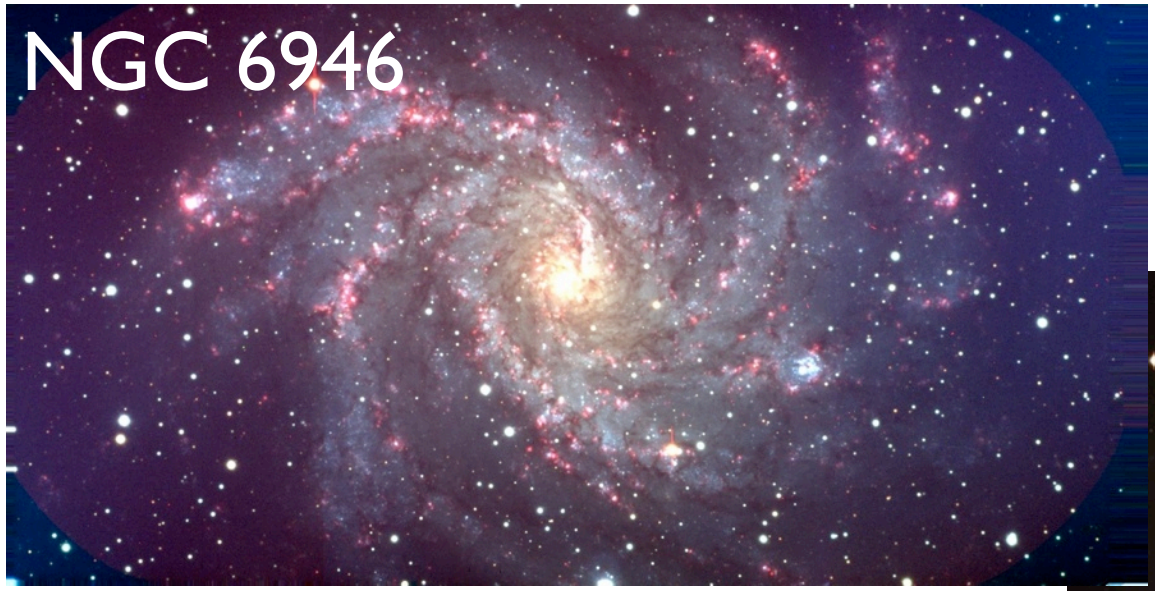
Figure 1. Sample of published indices of power law fit results to LFs of young star clusters as a function of the fit range. The results are taken from: Larsen (2002): six spirals and the LMC; Mora et al. (2007): NGC 45; Gieles et al. (2006b); Haas et al. (2008) and Hwang & Lee (2008): M51; Whitmore et al. (1999): Antennae; Dolphin & Kennicutt (2002): NGC 3627.

Gieles (2009)

Insight from LFs

- LFs invariably steeper than $dN/dL \sim L^{-2}$
- *Inconsistent* with $dN/dM \sim M^{-2}$ for all M
- Only way to get steep LFs is if ICMF is steeper, too and/or truncated
- MFs possibly truncated at several 10^5 $M_\odot$ (Gieles et al. 2006a,b)

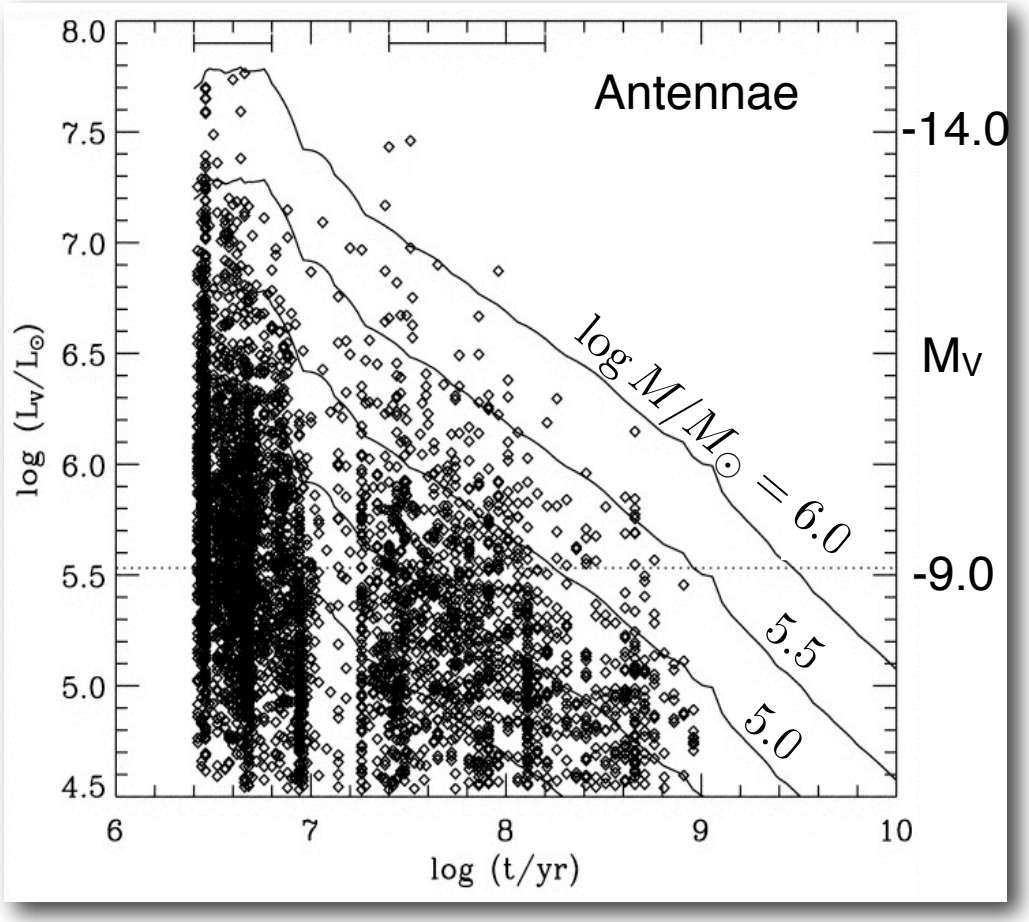
Two of the cluster-richest, nearby spirals

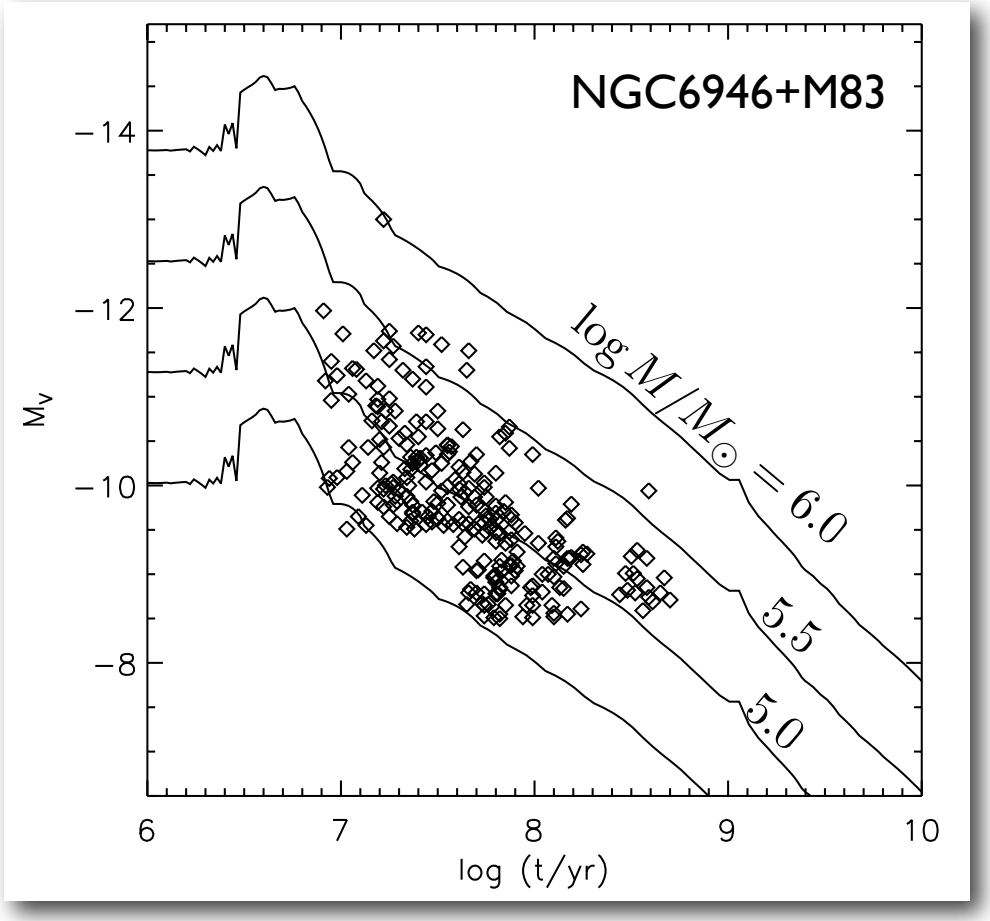


Ground-based data → relatively shallow, but allows to cover whole galaxies

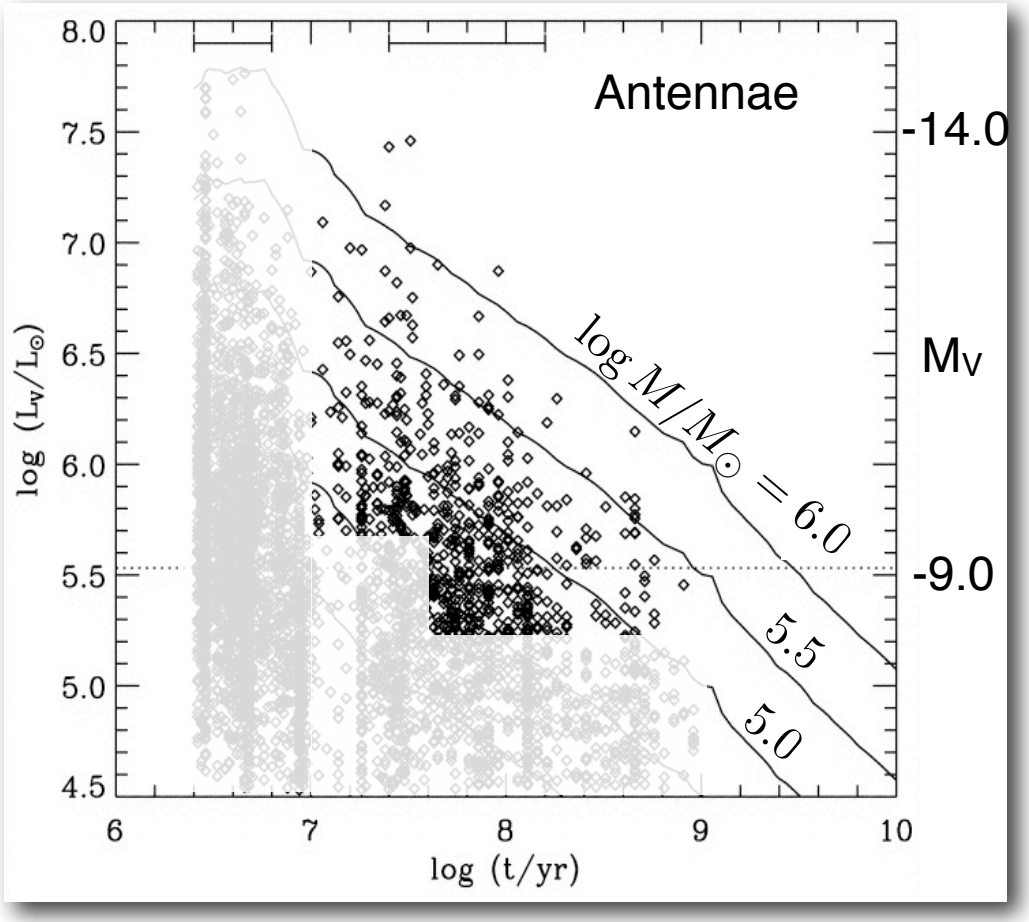
Larsen & Richtler (1999; 2000)

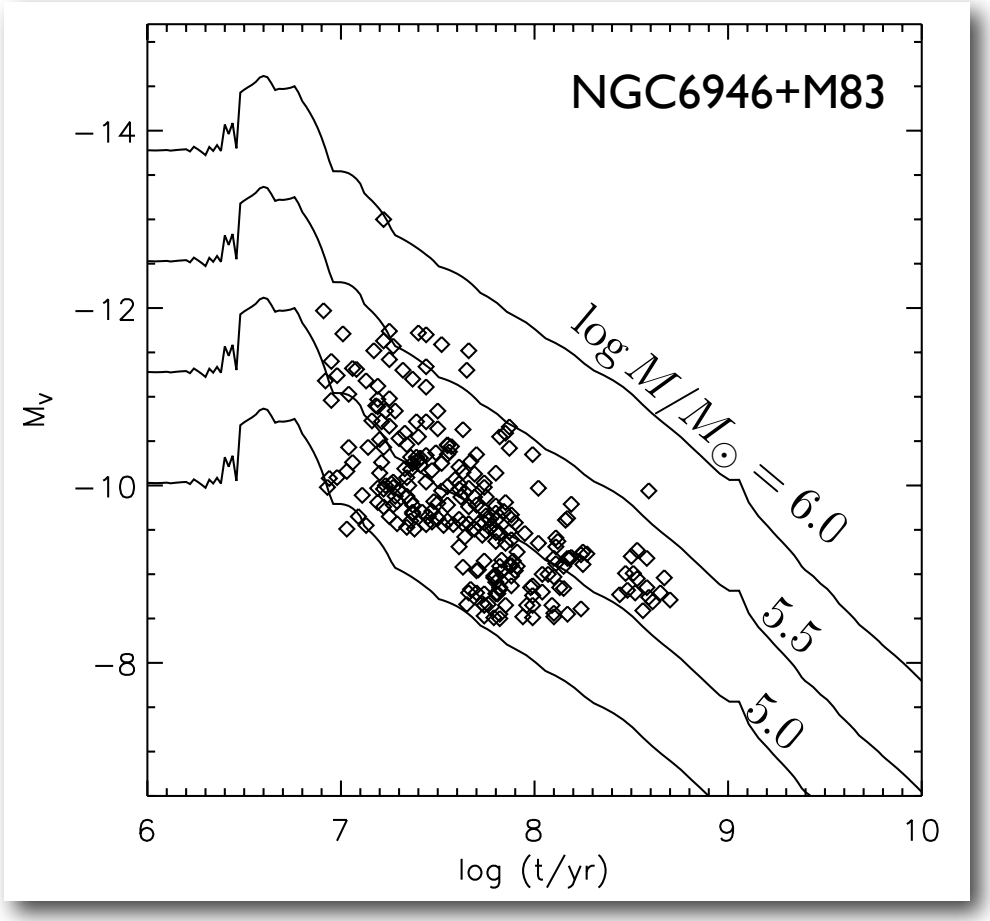
Clusters in the Antennae and NGC6946+M83



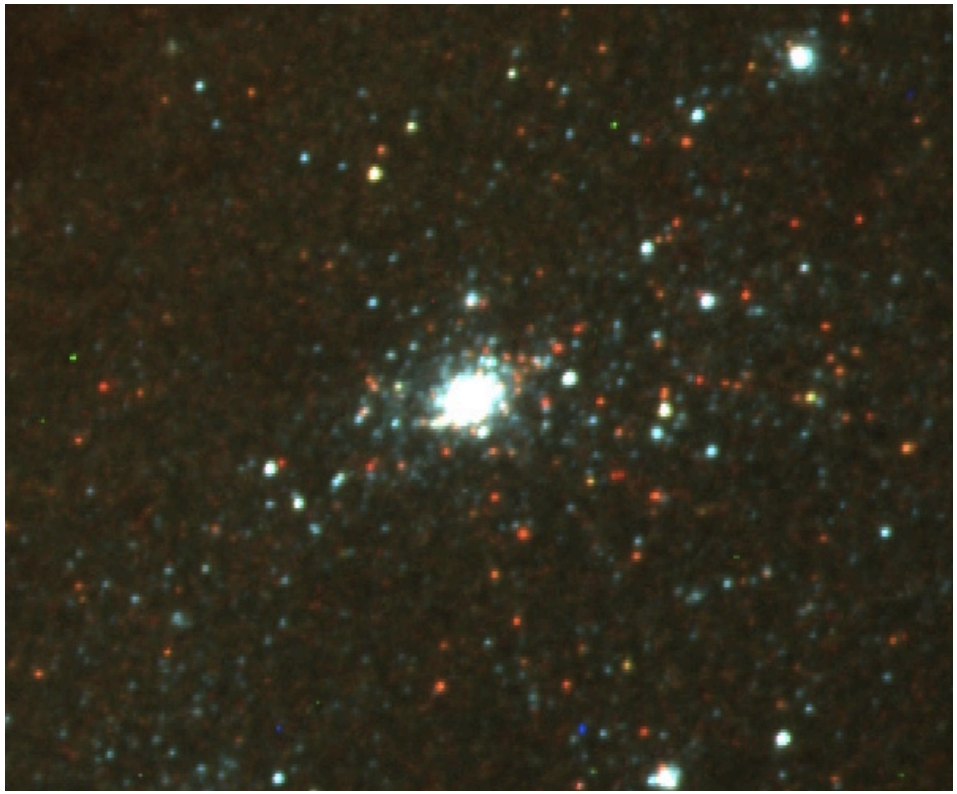


Clusters in the Antennae and NGC6946+M83





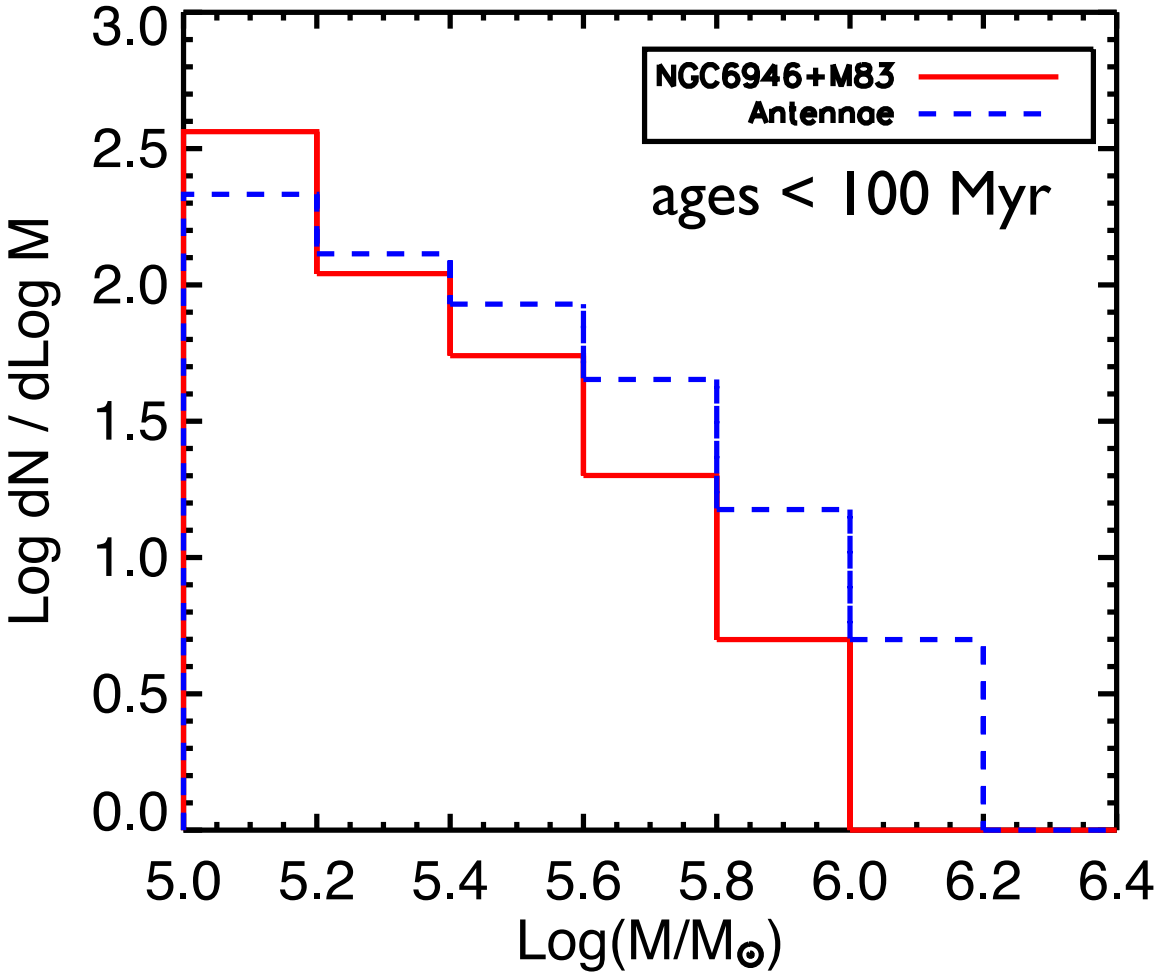
N5236-F1-1: 1.7×10^5 $M_\odot$



N1313-F3-1: 2.8×10^5 $M_\odot$

HST/ACS images - note resolution into individual stars!

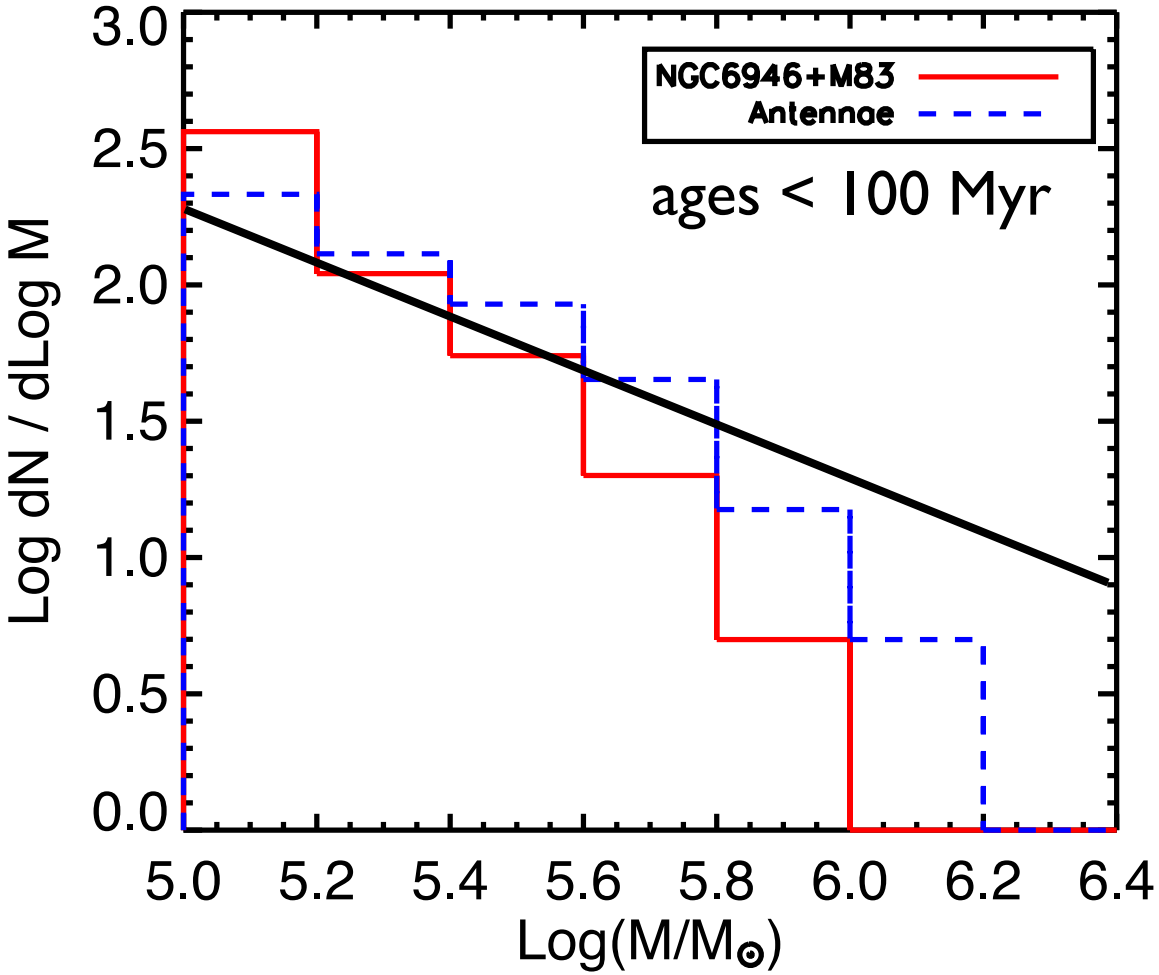
CMFs in the Antennae and NGC6946+M83



$dN/dM \sim M^{-2}$?

Larsen (2009)

CMFs in the Antennae and NGC6946+M83



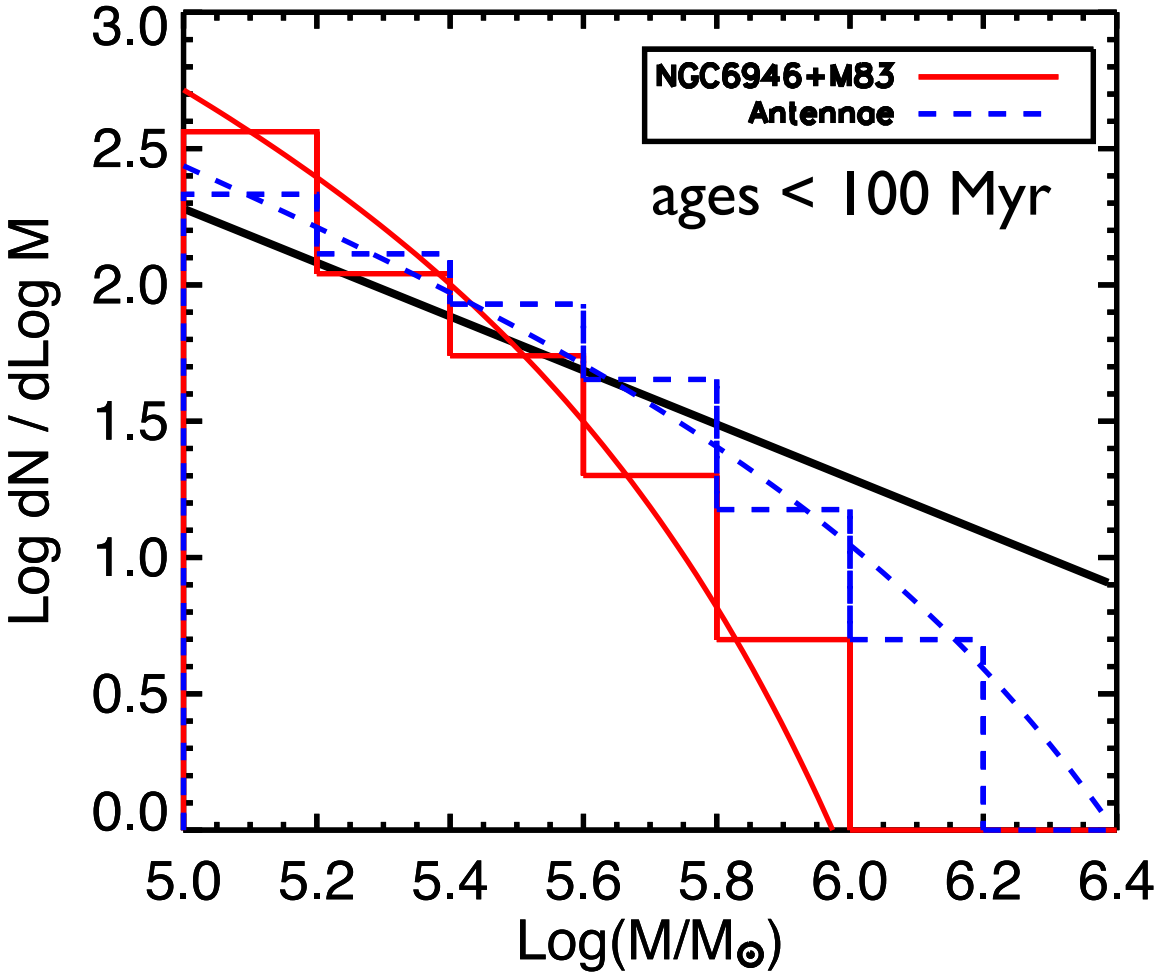
$dN/dM \sim M^{-2}$?

Antennae - OK

Spirals - NO ($P = 10^{-7}$)

Larsen (2009)

CMFs in the Antennae and NGC6946+M83



Larsen (2009)

dN/dM ~ M^{-2}?

Antennae - OK

Spirals - NO ($P = 10^{-7}$)

Best fits:

$$\frac{dN}{dM} \propto M^{-2} \exp\left(-\frac{M}{M^{\star}}\right)$$

$M^* = 2 \times 10^5\ M_\odot$ (spirals)

$M^* \sim 2 \times 10^6\ M_\odot$ (Antennae; Jordán et al. 2007)

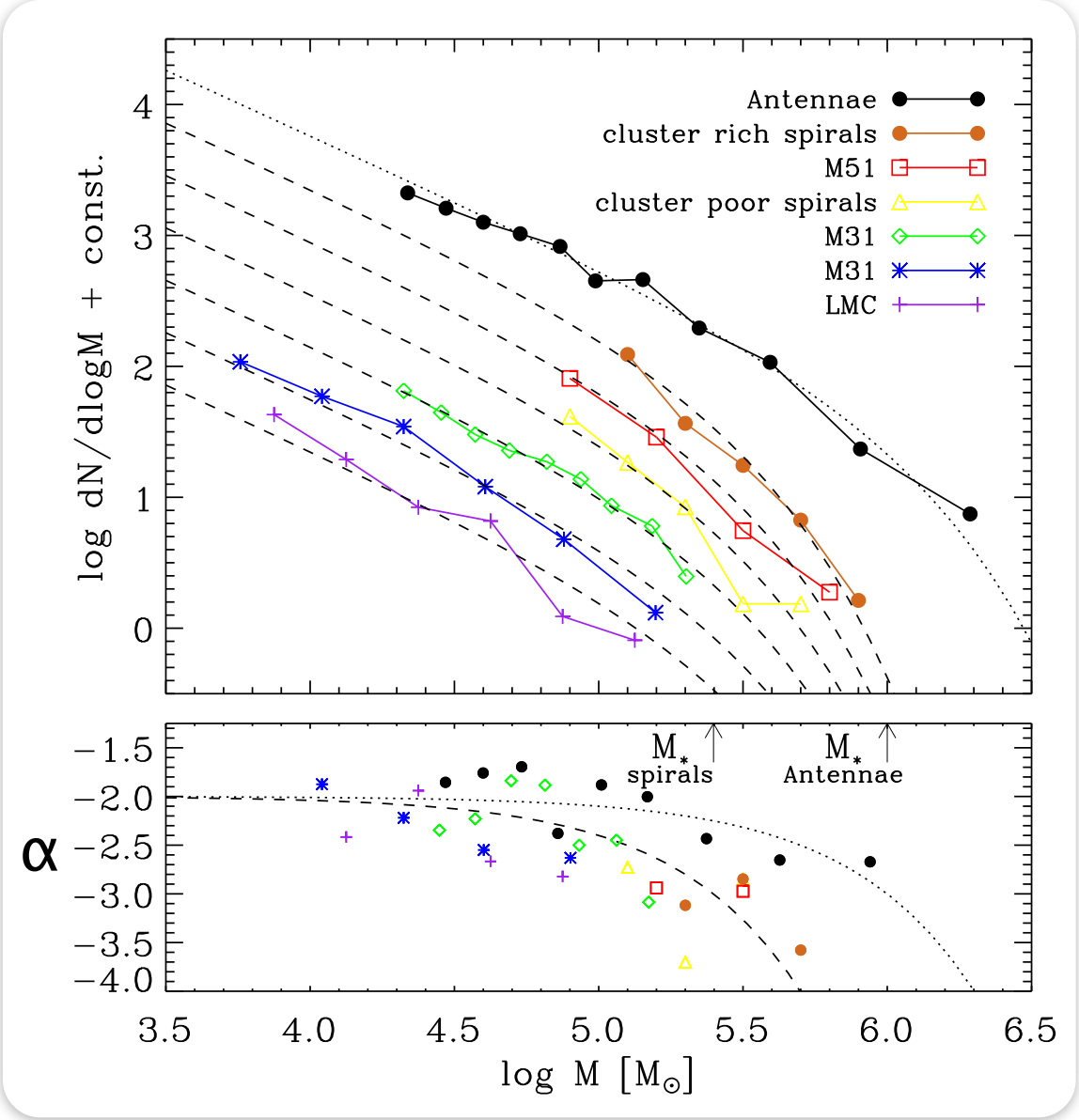
More MFs

Spirals:

Generally consistent with
$M^* = 2 \times 10^5\ M_\odot$ Schechter fct.

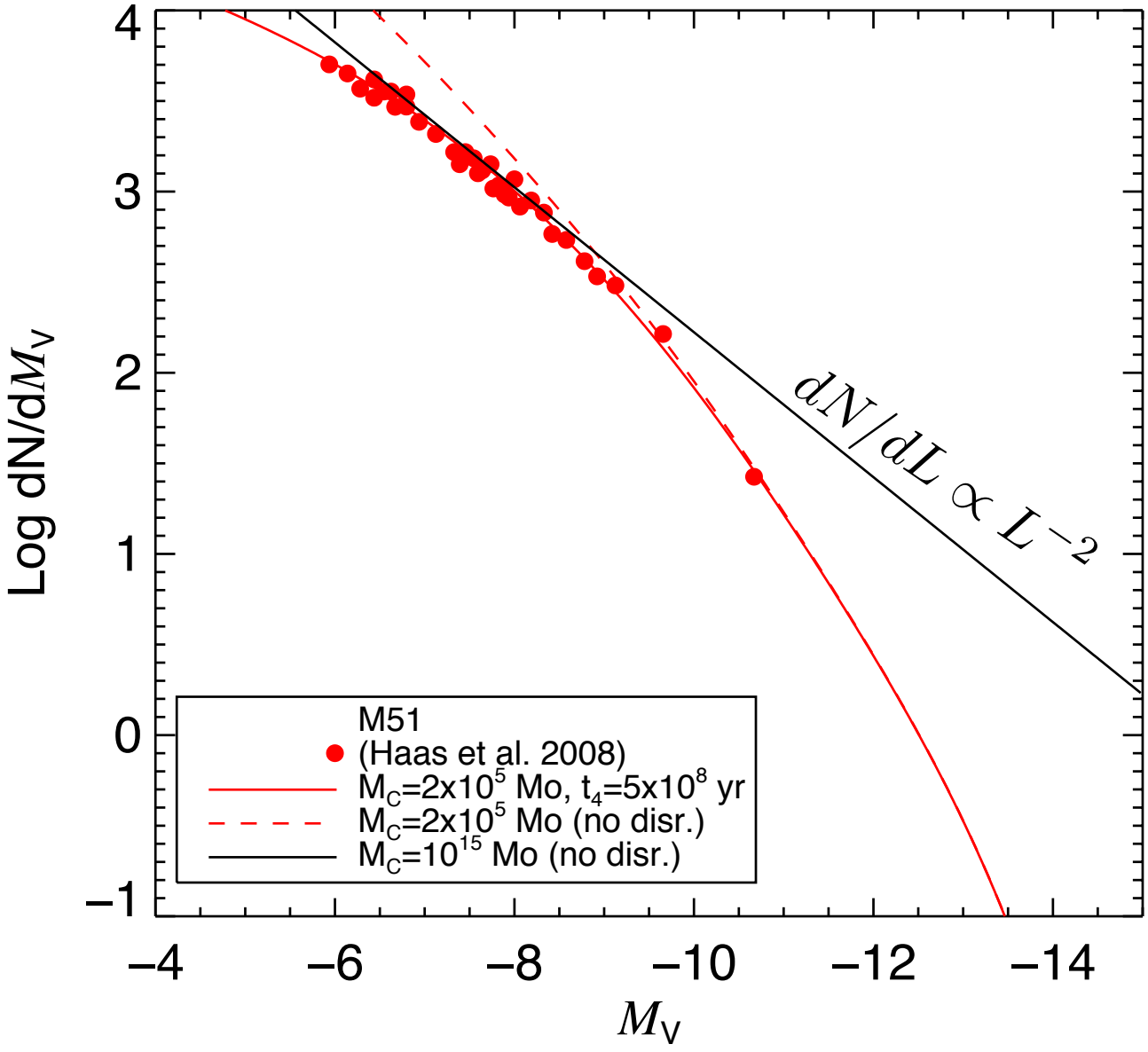
Antennae:

Cut-off at higher mass ($>10^6\ M_\odot$)



Portegies Zwart, McMillan, Gieles 2010, ARA&A

LF of young clusters in M51



dN/dL ~ L^{-2}? Poor fit

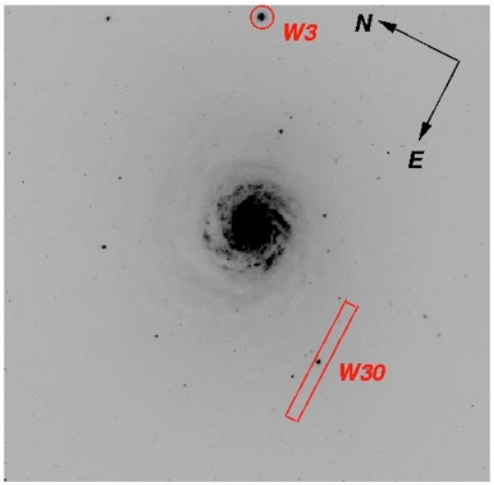
LF based on Schechter MF with M* = 2x10^5 $M_\odot$?

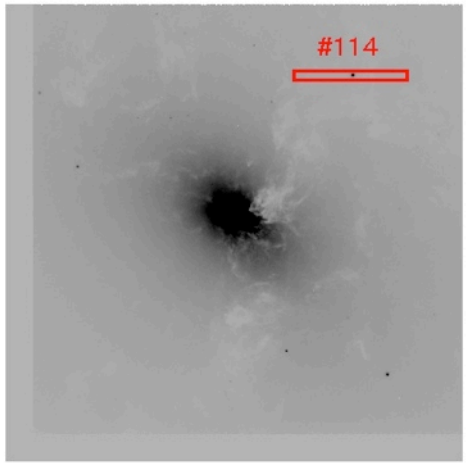
OK fit, if there is some disruption.

The Most Massive YMCs

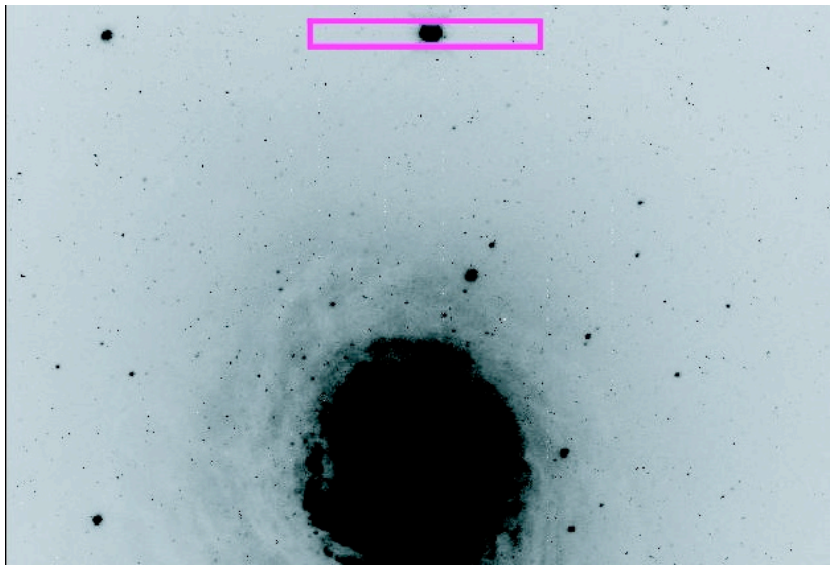
Clusters with M~10^7 $M_\odot$ in starbursts → ICMF more top-heavy than in spiral discs

NGC 7252 - W30: M_{Vir} = (1.6±0.3)x10^7 $M_\odot$, R_{eff} ~ 9 pc
NGC 1316 - G114: M_{Vir} = (1.6±0.1)x10^7 $M_\odot$, R_{eff} ~ 4 pc
(Bastian et al. 2006)





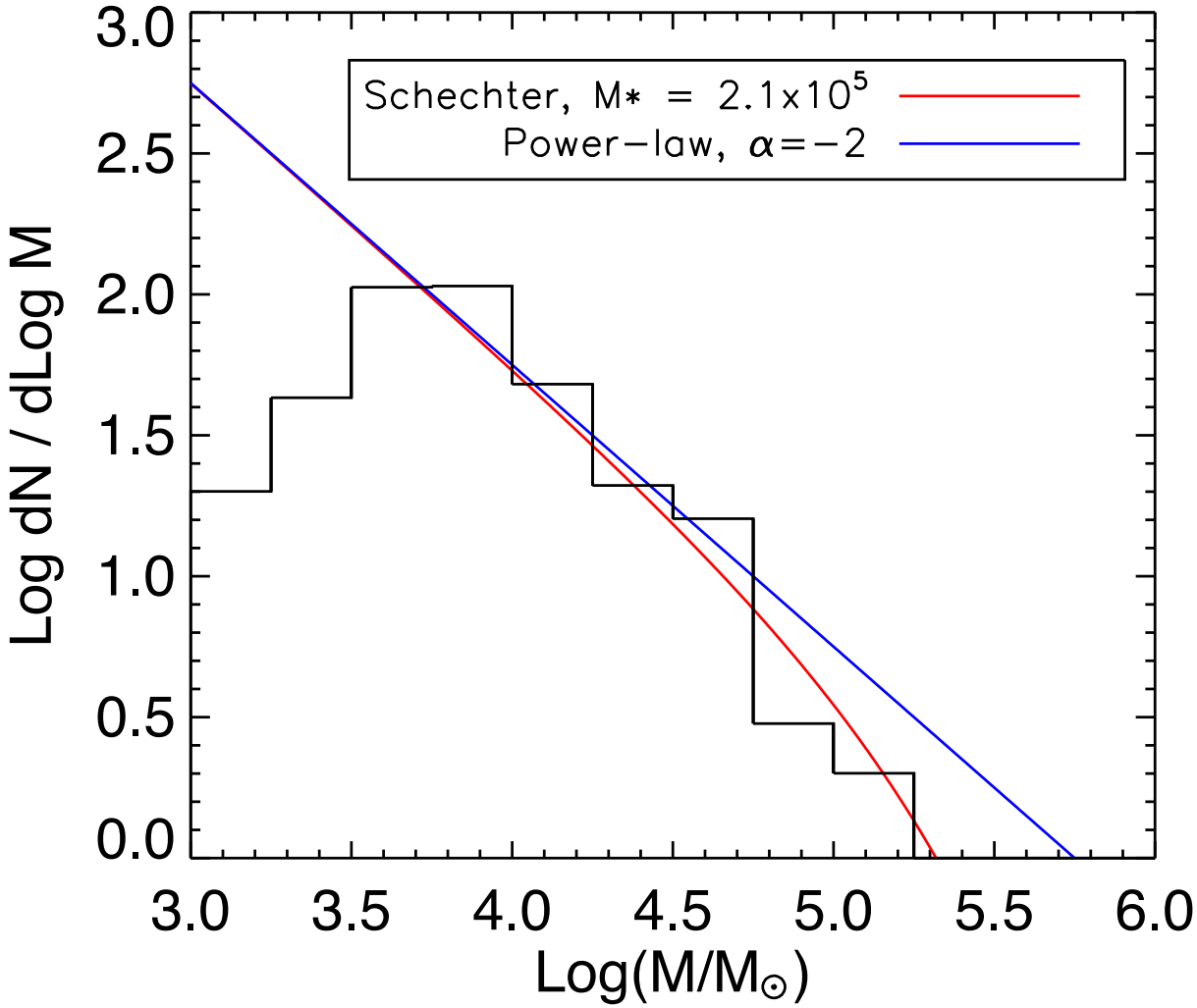
Arp 220 - most massive clusters ~10^7 $M_\odot$,
R_{eff} ~ 10 pc (Wilson et al. 2006).



NGC 7252 - W3: M_{Vir} = (8±2)x10^7 $M_\odot$,
R_{eff} ~ 18 pc (Maraston et al. 2004)

Small samples: hard to tell the difference

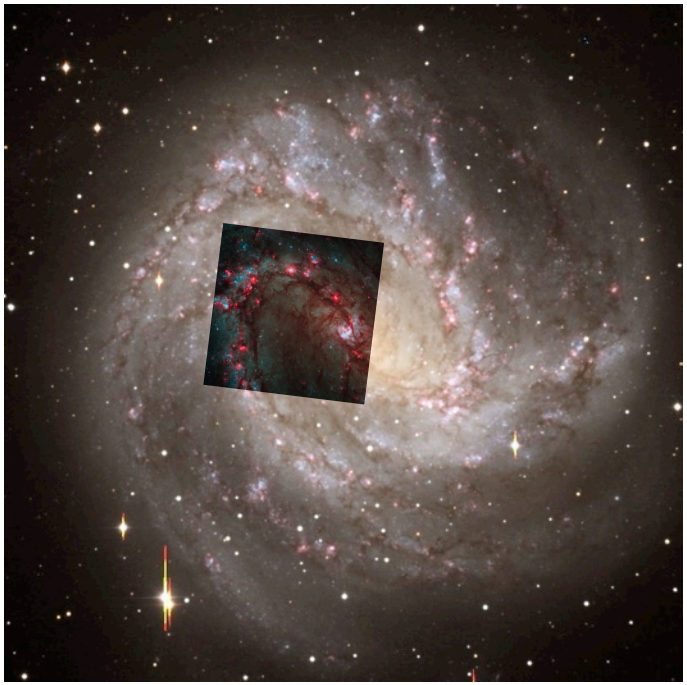
Large Magellanic Cloud:



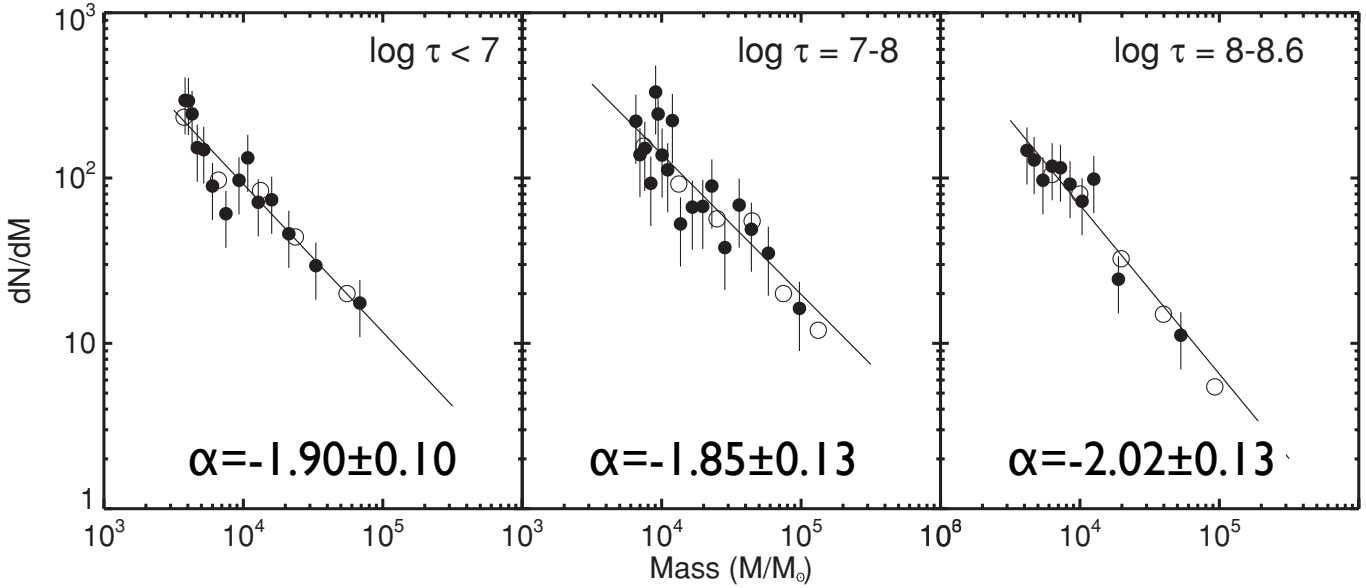
Consistent with α=-2 power-law?
YES (P=0.56)

Consistent with $M^*=2\times10^5$ $M_\odot$ Schechter fct?
YES (P=0.94)

M83 (WFC3 early release)

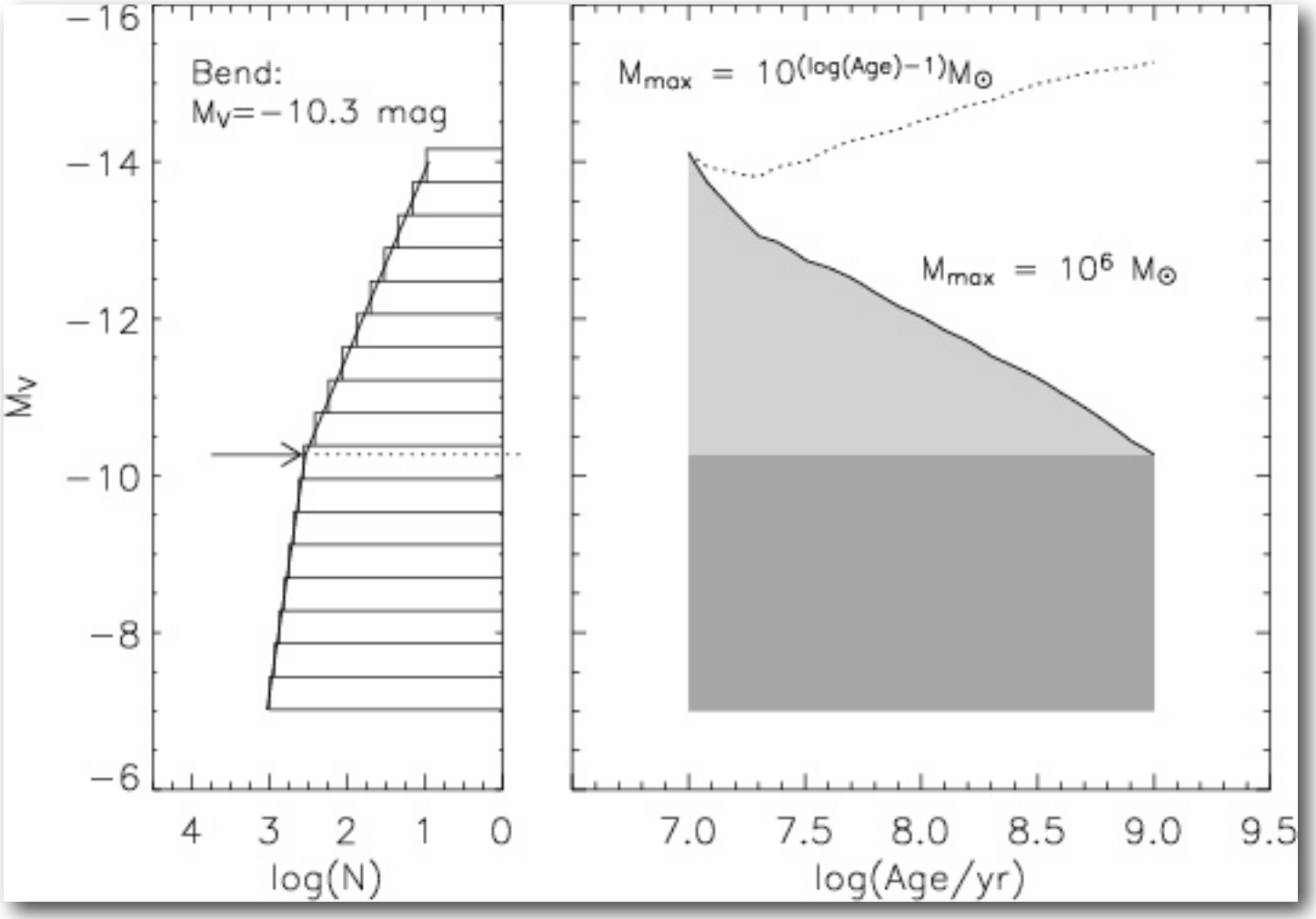


Data consistent with any
$M^* > 10^5\ M_\odot$
(Chandar et al. 2010)



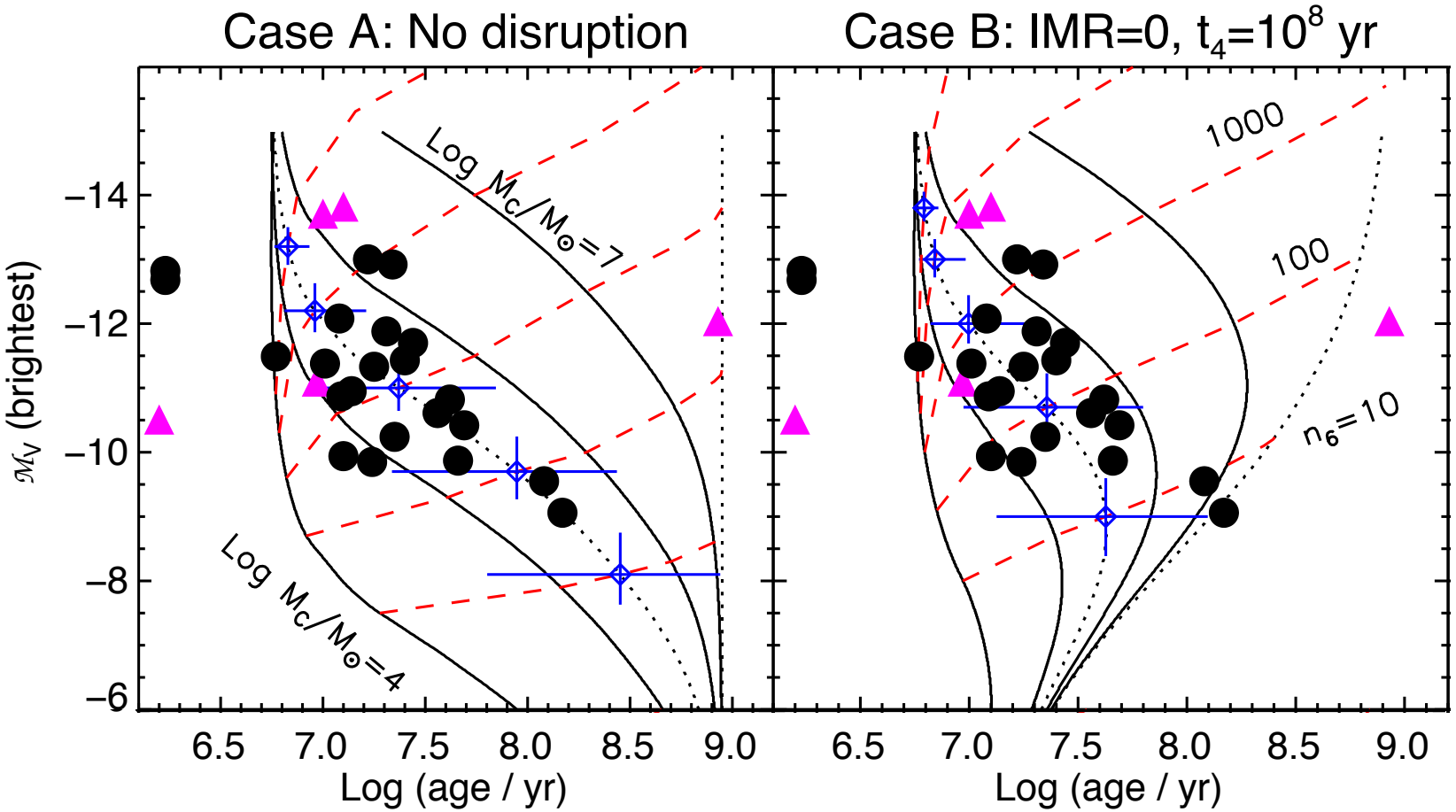
ICMF upper cut-off consistent with other constraints?

Upper ICMF limit → Brighter Clusters Should be Younger



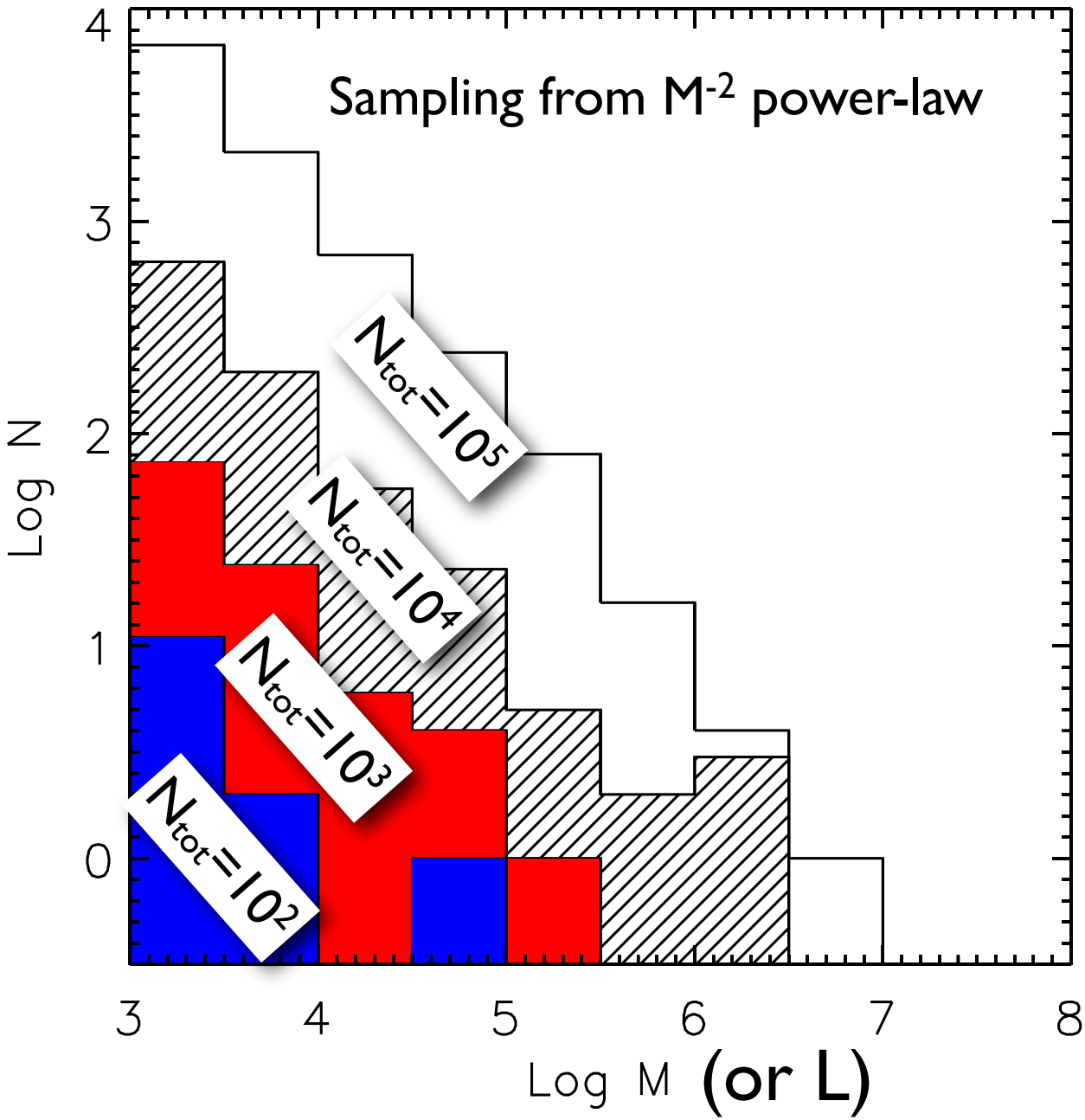
Gieles et al. (2006)

Brighter clusters *are* younger



Larsen (2009)

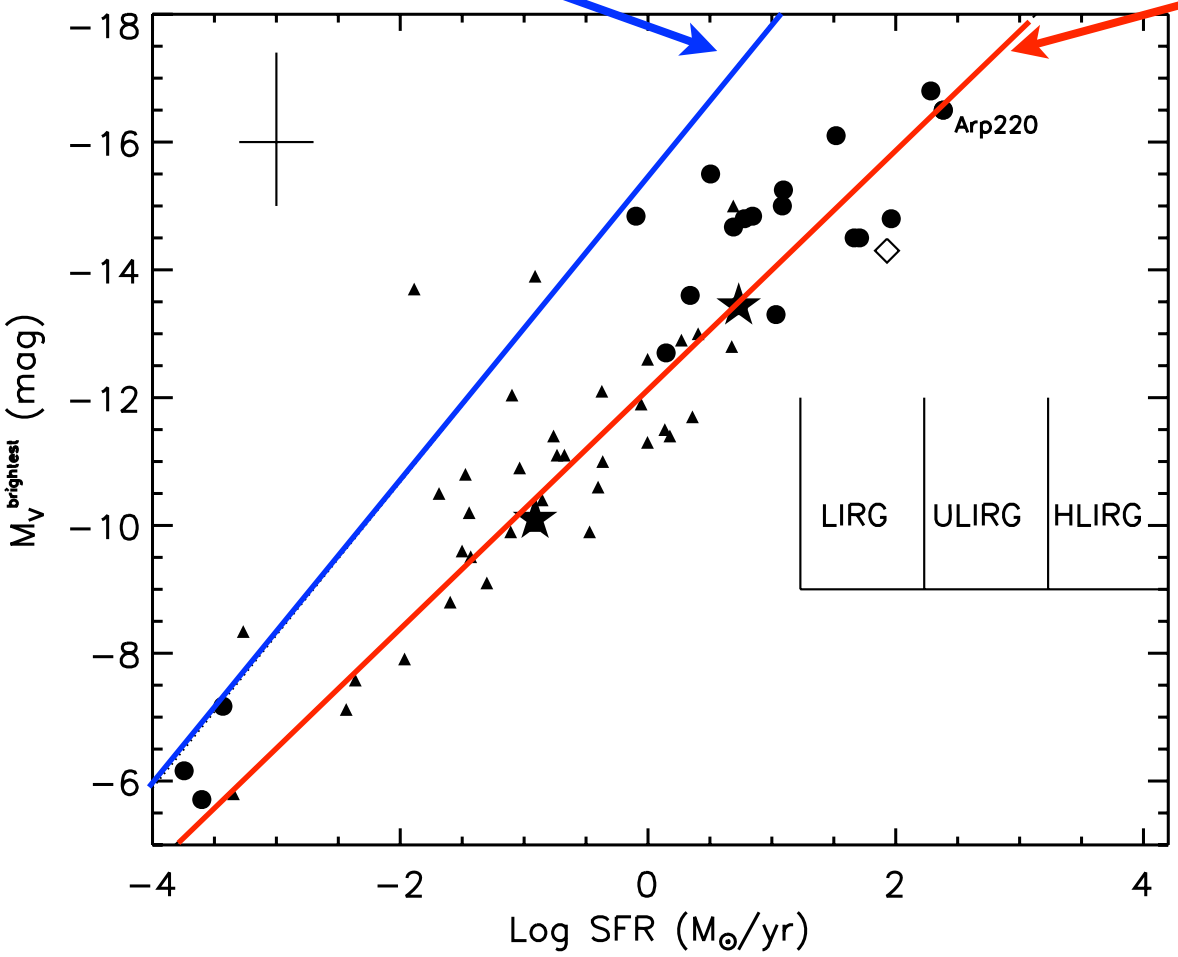
Size-of-sample effects



Brightest clusters: size-of-sample effects

$L_{\max} \propto \mathrm{SFR}\ (\beta = -2.0)$ $L_{\max} \propto \mathrm{SFR}^{0.748} \Rightarrow \beta = -2.3$

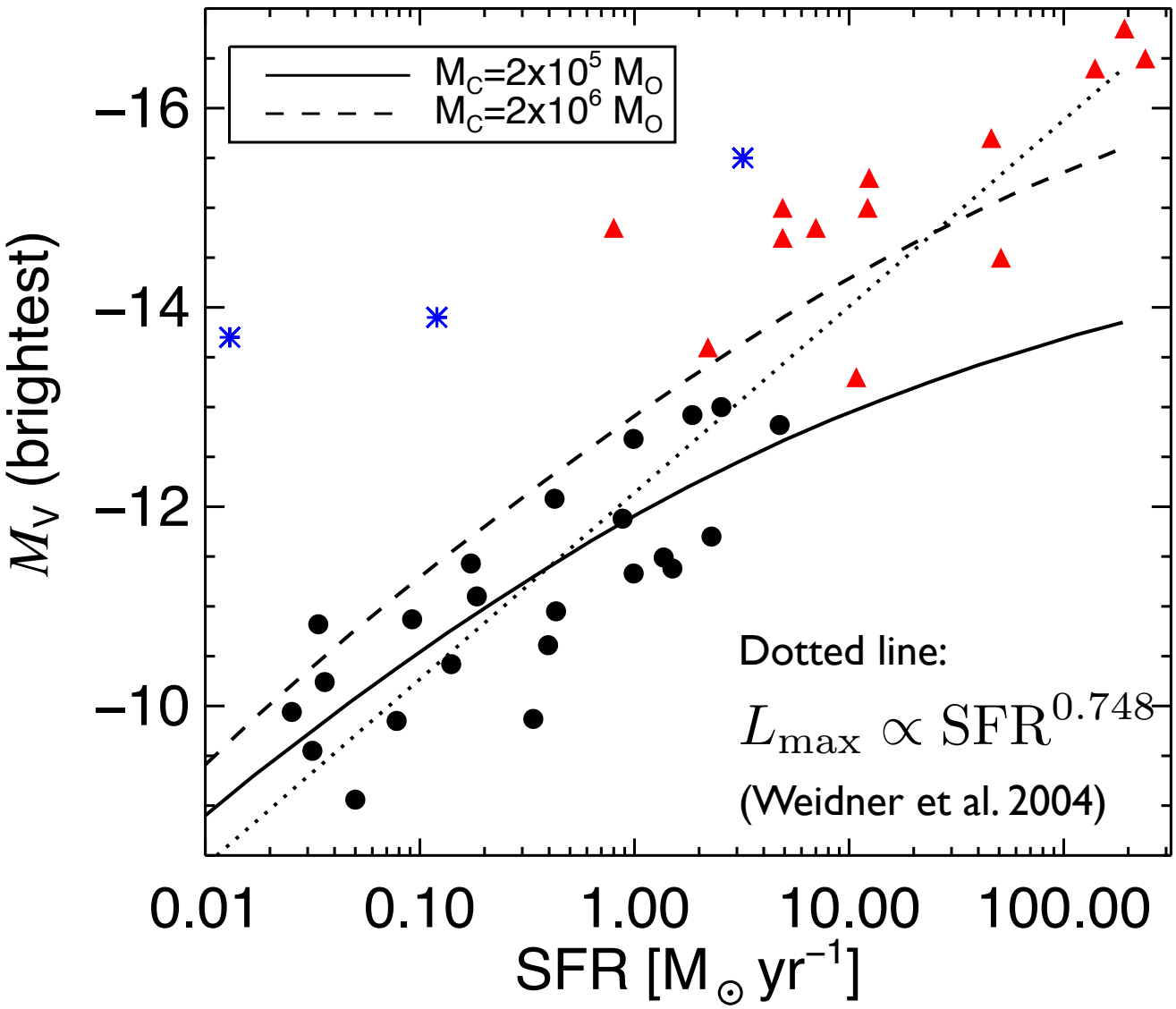
(Weidner et al. 2004)



ICMF with α=-2 does not match observed M_V(brightest) vs SFR relation.

Bastian (2008)

The L_{max} vs. SFR relation for Schechter MFs



Filled circles: spirals
Triangles: starbursts/ mergers

N assumed to scale with SFR

Larsen (2010)

Summary

Summary

- *An M^{-2} power-law ICMF in spirals is contradicted by:*
  - Luminosity functions (too steep)
  - Direct MF determinations
  - L_{max} vs. SFR (or N) relation ("size-of-sample effect")
  - Mean L_{max} vs. age trend (brighter clusters younger)

Summary

- *An M^{-2} power-law ICMF in spirals is contradicted by:*
  - Luminosity functions (too steep)
  - Direct MF determinations
  - L_{max} vs. SFR (or N) relation ("size-of-sample effect")
  - Mean L_{max} vs. age trend (brighter clusters younger)
- But a Schechter fct with $M^* \sim 200{,}000\ M_\odot$ fits well

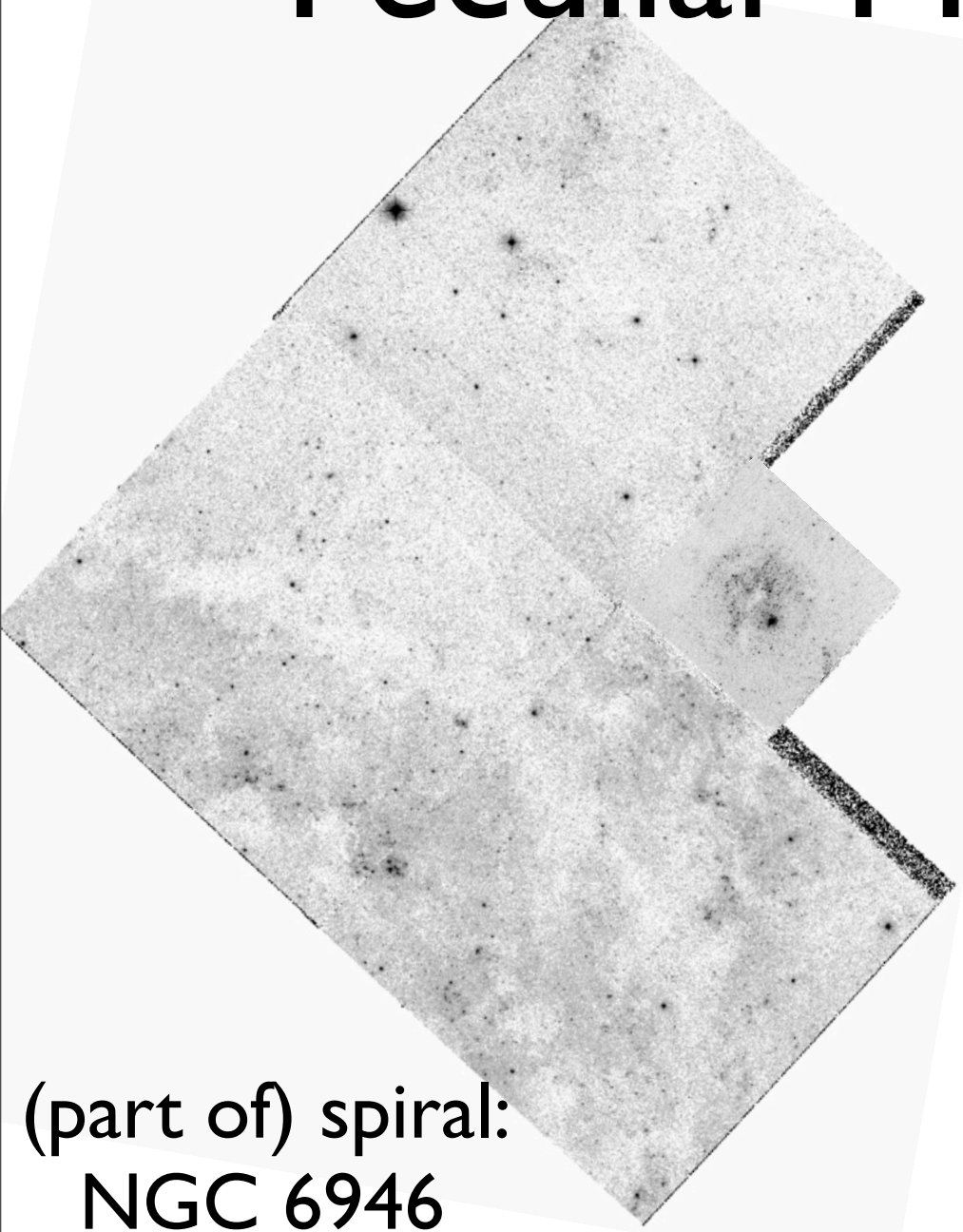
Summary

- *An M^{-2} power-law ICMF in spirals is contradicted by:*
  - Luminosity functions (too steep)
  - Direct MF determinations
  - L_{max} vs. SFR (or N) relation ("size-of-sample effect")
  - Mean L_{max} vs. age trend (brighter clusters younger)
- But a Schechter fct with $M^* \sim 200{,}000\ M_\odot$ fits well
- The ICMF does not appear to be universal. Cut-off at higher masses in starburst/merger environments.

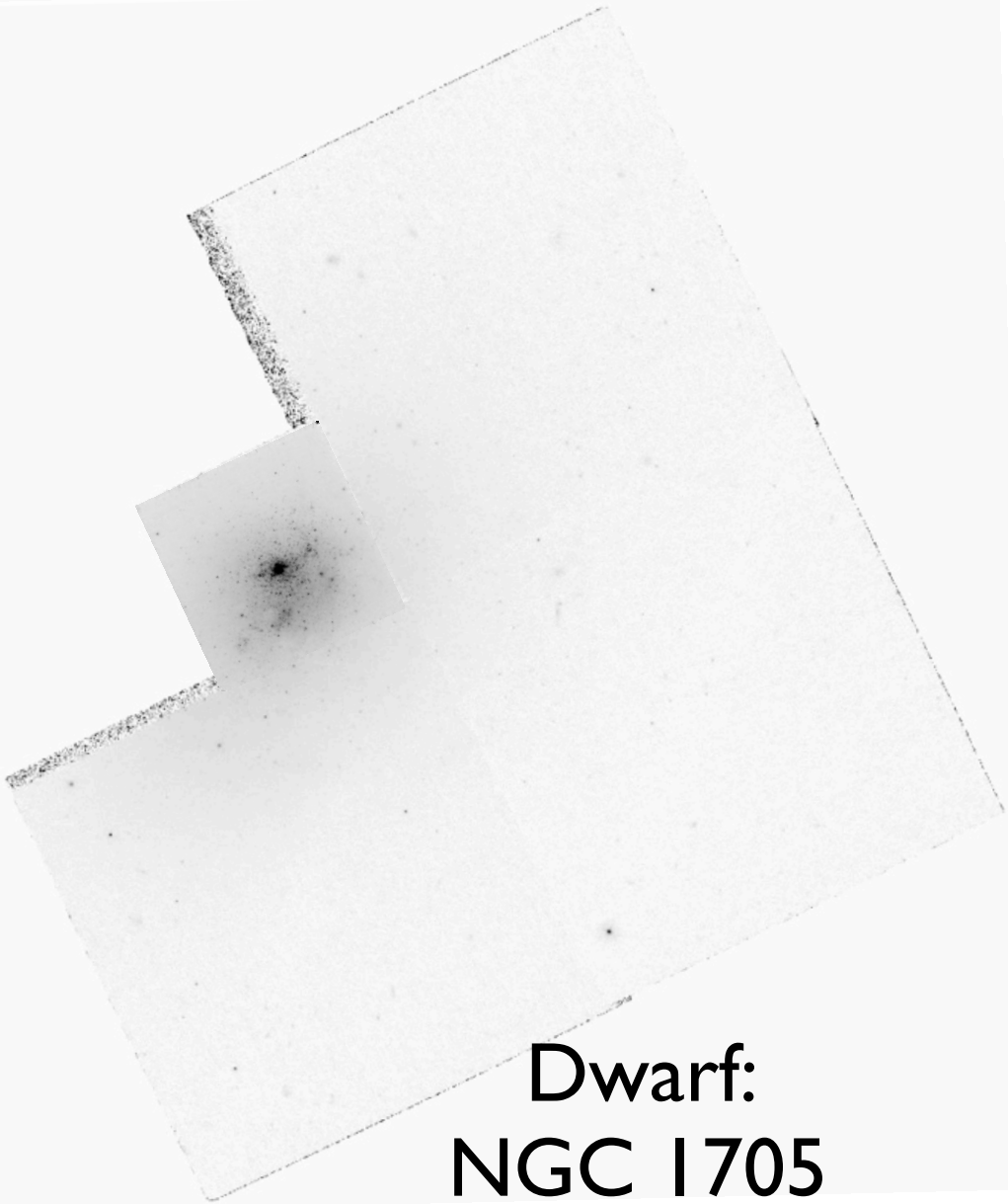
Summary

- *An M^{-2} power-law ICMF in spirals is contradicted by:*
  - Luminosity functions (too steep)
  - Direct MF determinations
  - L_{max} vs. SFR (or N) relation ("size-of-sample effect")
  - Mean L_{max} vs. age trend (brighter clusters younger)
- But a Schechter fct with $M^* \sim 200{,}000\ M_\odot$ fits well
- The ICMF does not appear to be universal. Cut-off at higher masses in starburst/merger environments.
- But: No cluster system has data from the lowest ($<10^2\ M_\odot$) to the highest ($>10^6\ M_\odot$) masses

Peculiar MF in dwarfs?



(part of) spiral:
NGC 6946



Dwarf:
NGC 1705

Peculiar MF in dwarfs?