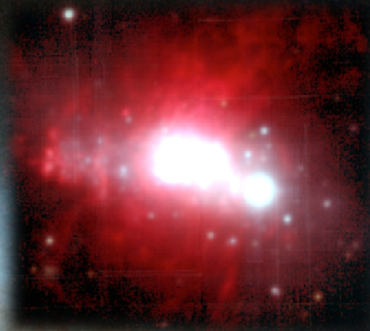
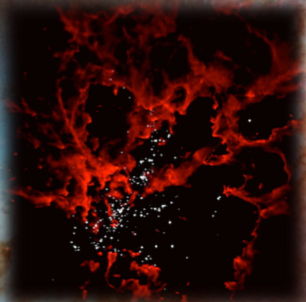
THE ROLE OF FEEDBACK ON STELLAR CLUSTER FORMATION, EVOLUTION AND INTERACTION WITH THE HOST GALAXY



Sexten (Italy) ~~July 26-29~~, 2016

July 18th - 22nd



SOC

Prof. Nate Bastian (LJMU)
Dr. James Dale (UOM)
Dr. Angela Adamo (SU)
Dr. Linda Smith (STScI)
Dr. Steve Longmore (LJMU)

+ Interpreting feedback-driven structures - pillars, shells and bubbles. + Star formation rates and efficiencies and gas expulsion. + Structure and dynamics of young clusters. + The connection between SSCs and globular clusters. + Impact of cluster feedback at galactic and cosmological scales.

SEXTEN CENTER FOR ASTROPHYSICS

Multiple Populations in Globular Clusters
Where do we stand?

July 25th - 29th, 2016

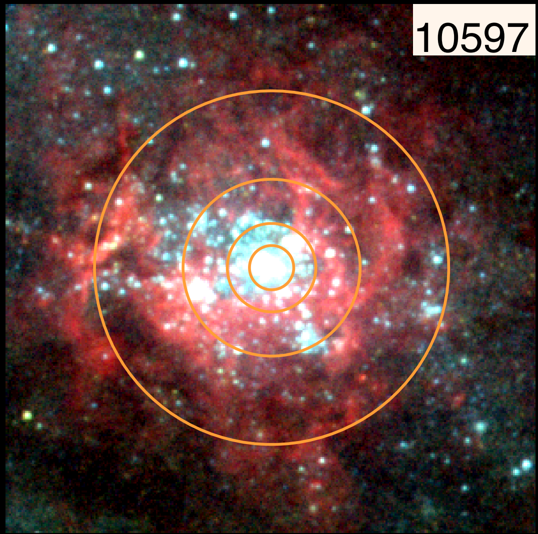
SOC: Carmela Lardo, Nate Bastian, Alessio Mucciarelli, Soeren Larsen, Elena Pancino

Review of 1st lecture

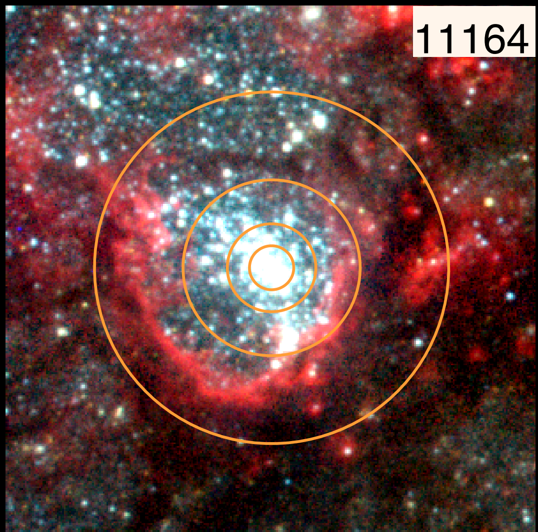
- Young massive clusters, with masses up to 10^8 Msun are sizes similar to GCs are still forming today
- The exist within our Galaxy (up to ~10^5 Msun), but are difficult to find, easier in external galaxies
- Found in starbursts, mergers, dwarfs and spirals
- In some cases can use CMDs to derive properties, but in most cases we use integrated properties
- Derive their ages, masses, extinctions, metallicity
- Luminosity and mass function of YMCs is a power-law with index of -2, with a truncation at the bright/high-mass end

Constraints on Gas within YMCs

Hollyhead et al. 2015



YMCs are gas free (expelled any remaining gas left over from the formation of the cluster) within ***<3-4 Myr***, independent of mass



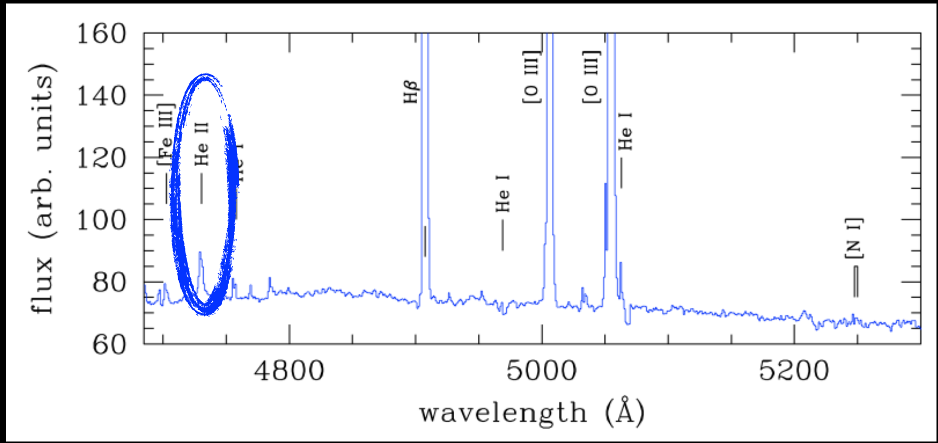
Before the first SNe

Whitmore et al. 2011
Bastian et al. 2014

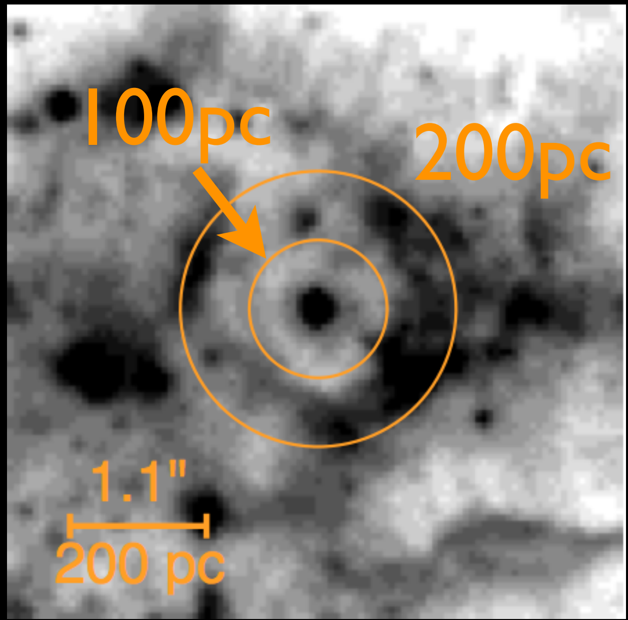
Westerlund 2
~1-2 Myr old

ESO 338-IG04 - Cluster 23

$t = 6^{+4}_{-2}$ Myr
$A_V = 0$
M~ 1×10^7 Msun
R_{bubble} ~ 120-200pc
$Z = 0.2\ Z_{sun}$



- Bubble began expanding 1-3 Myr after formation
- Efficiently removed any pristine material out to hundreds of parsecs (still expanding at 40 km/s)
- Metallicity below that of Galactic globular clusters that show anomalies



Östlin et al. 2007

Bastian, Hollyhead, & Cabrera-Ziri 2014

Constraints on Gas within YMCs

- Clusters are gas free with 3-4 Myr of their lives

Hollyhead et al. 2015

- Independent of cluster mass from 10^4 - 10^7 Msun

Bastian, Hollyhead, Cabrera-Ziri 2015

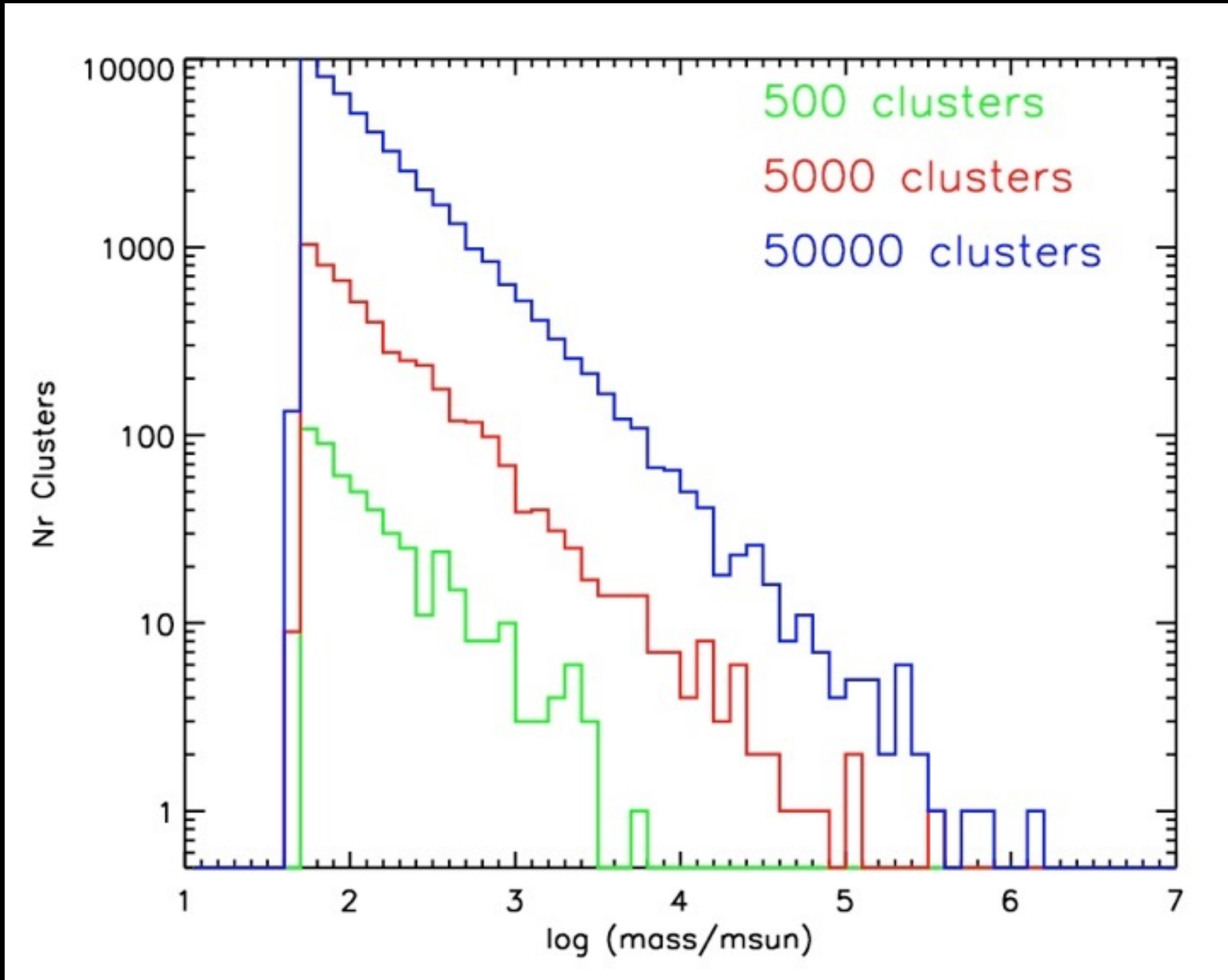
- Searches for gas in older clusters (10-200 Myr) reveal no gas, so clusters are never ever to retain stellar ejecta or accrete new material.

Cabrera-Ziri et al. 2014
Bastian & Strader 2014

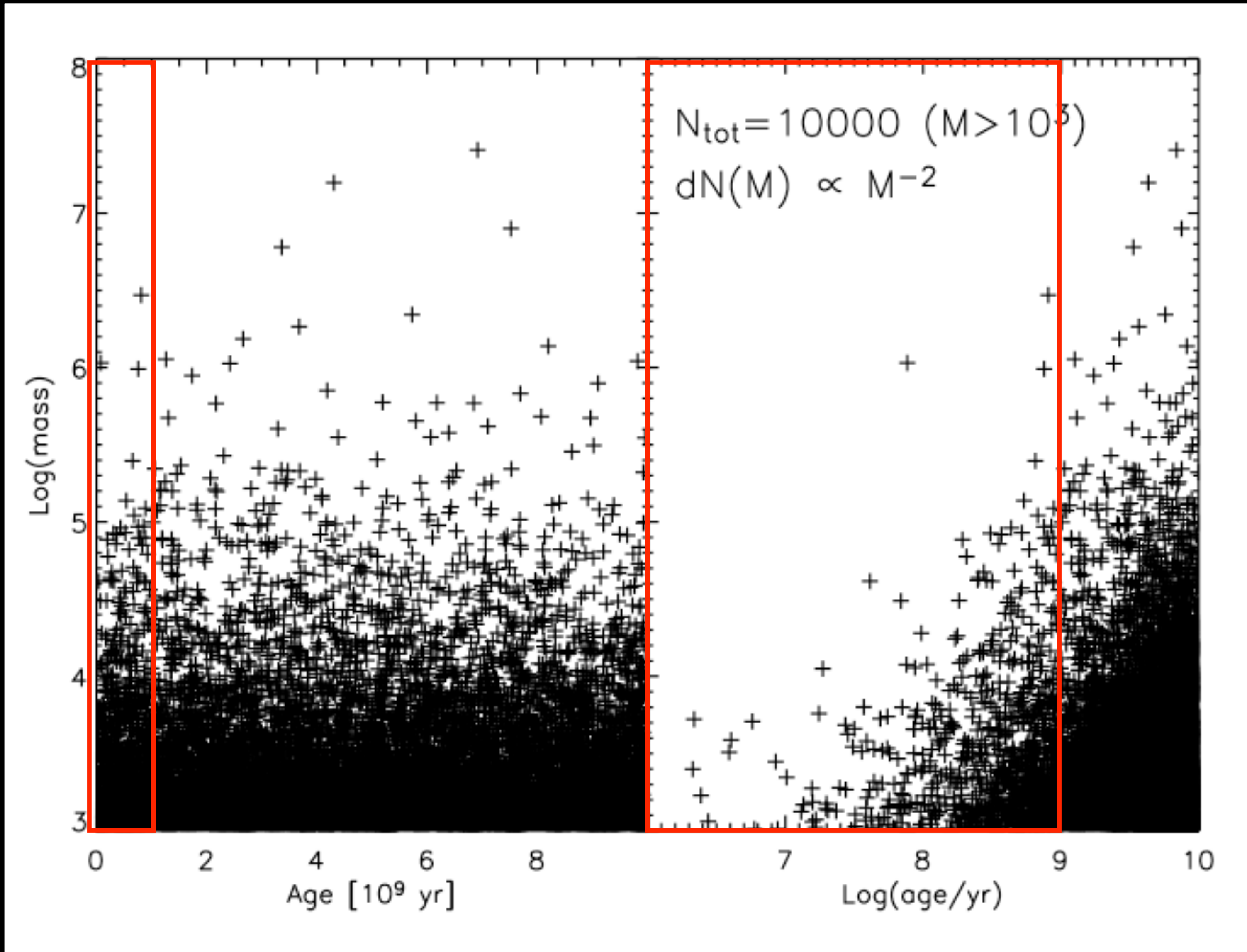
Cluster Populations

Size-of-Sample Effects

$$NdM \sim M^{-\beta}dM$$

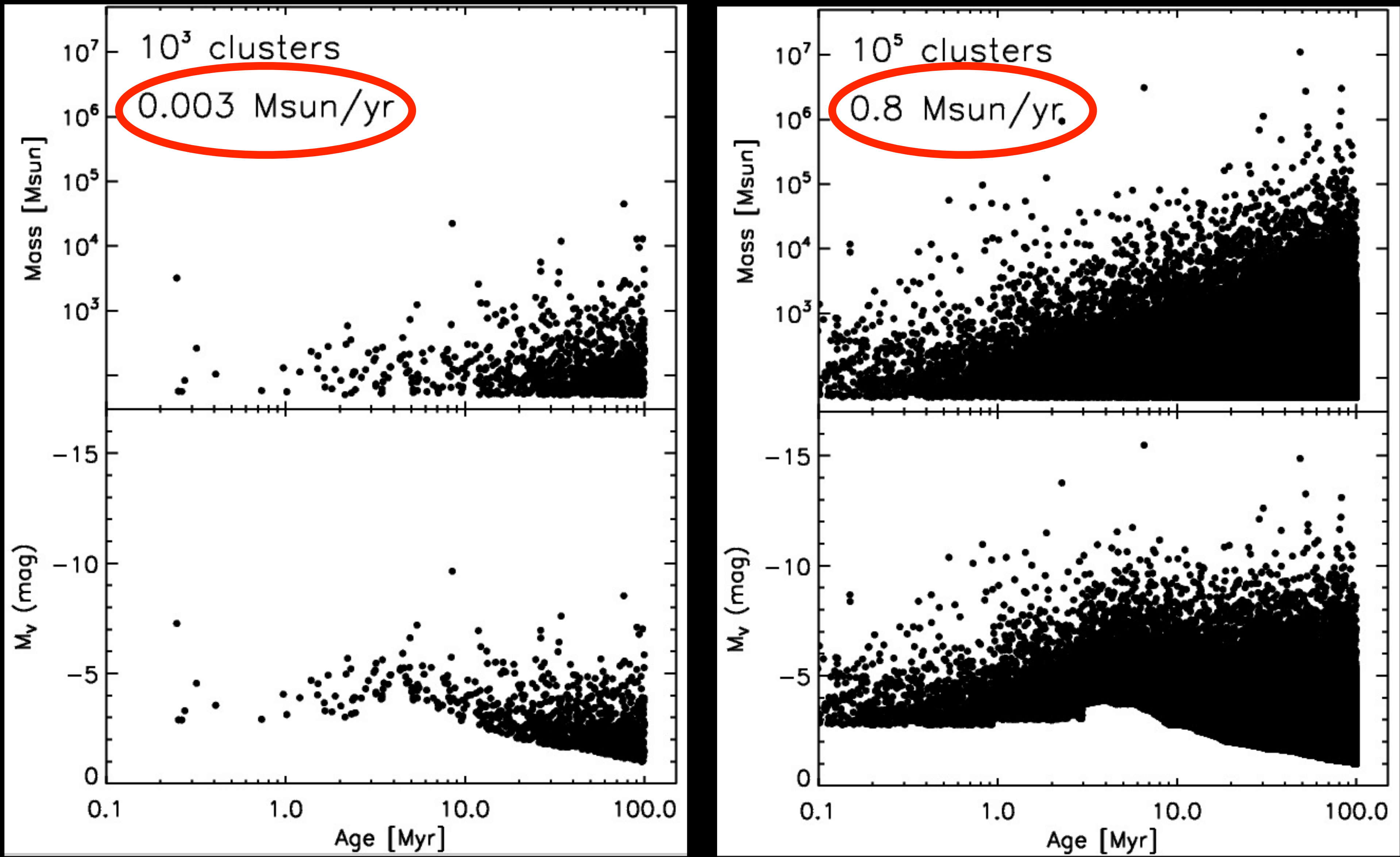


Age/Mass diagram



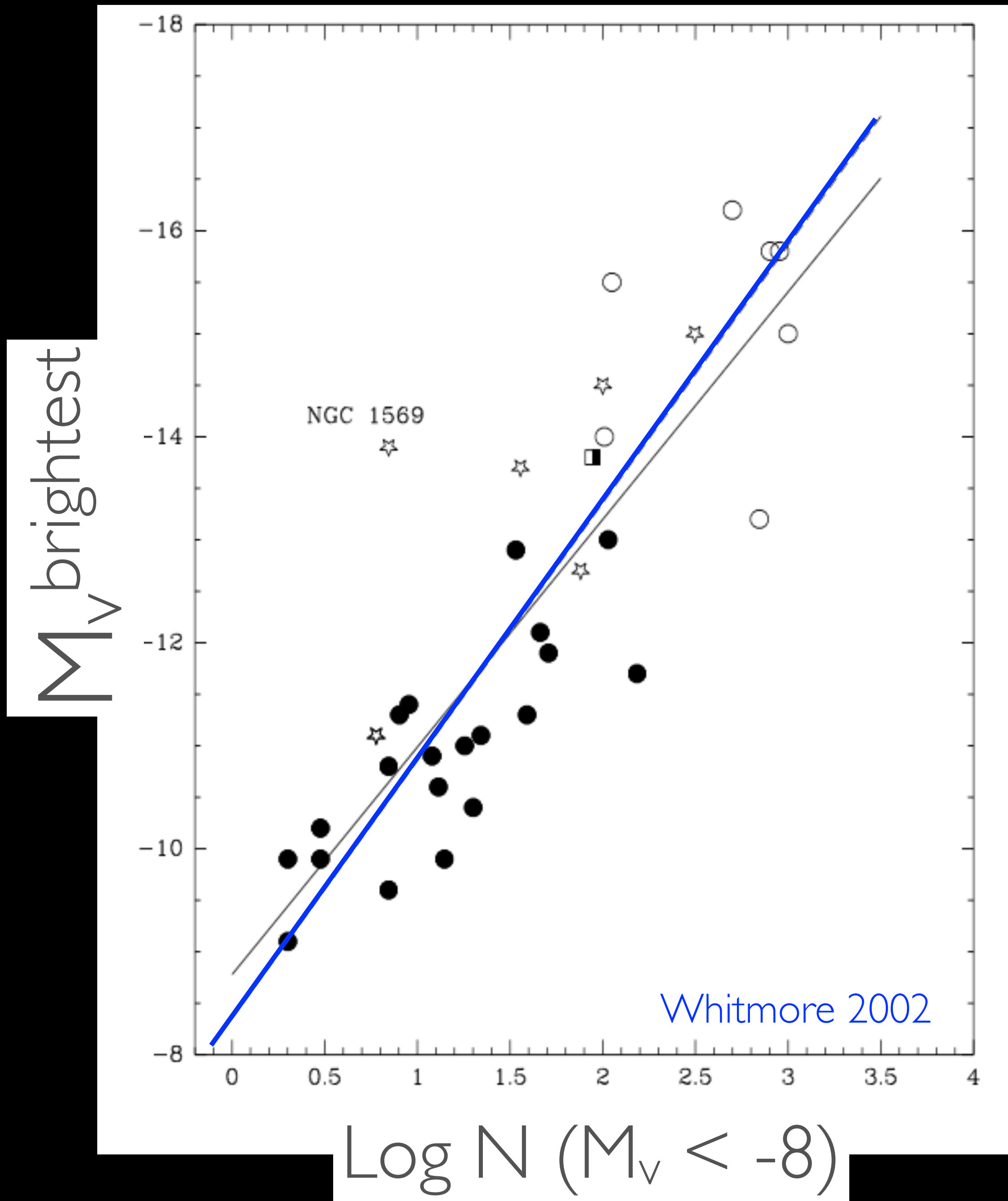
Gieles et al. 2006

Age/Mass diagram



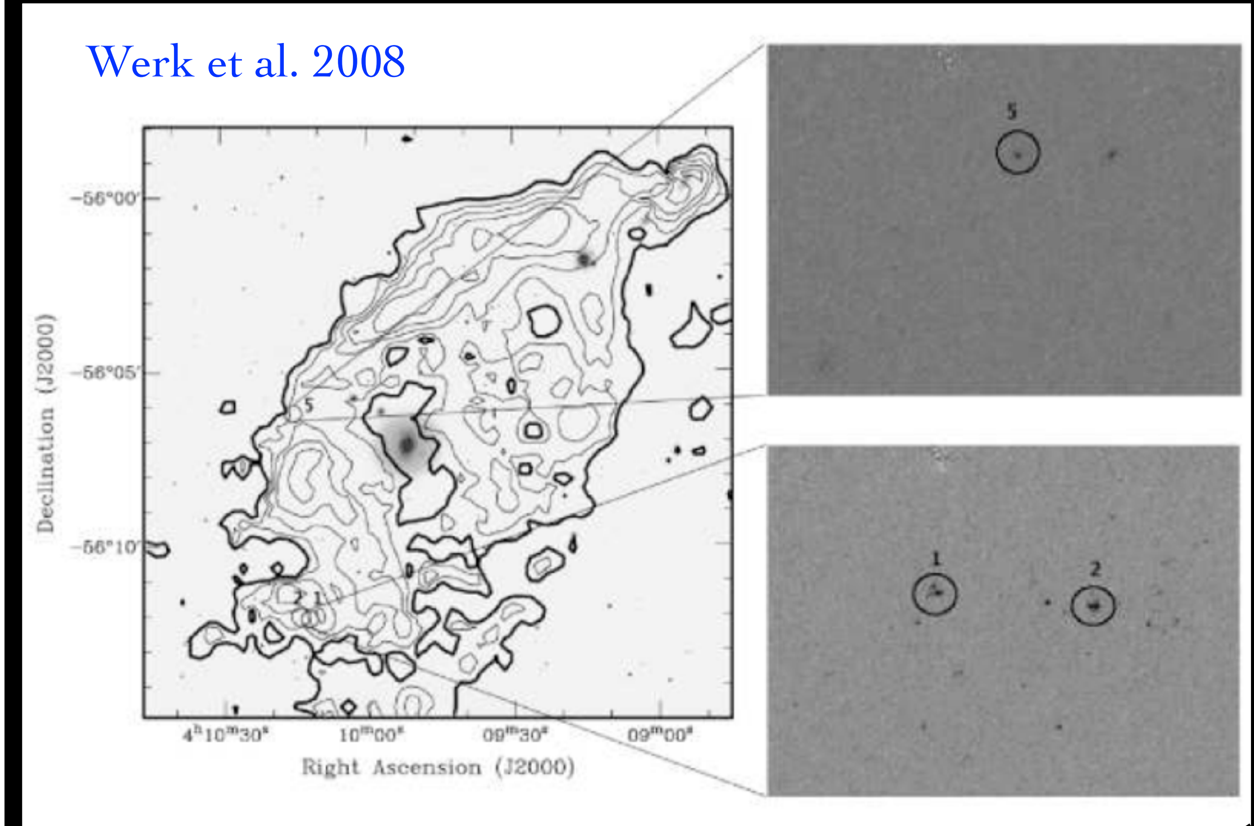
BRIGHTEST CLUSTER VS. NUMBER

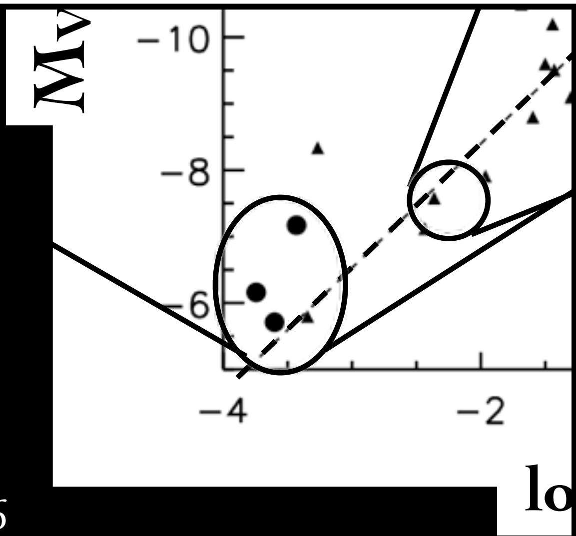
- Luminosity of the brightest cluster in a population is related to the number of clusters
- Larger populations have brighter clusters
- slope gives the index of the luminosity function
- size of sample effect

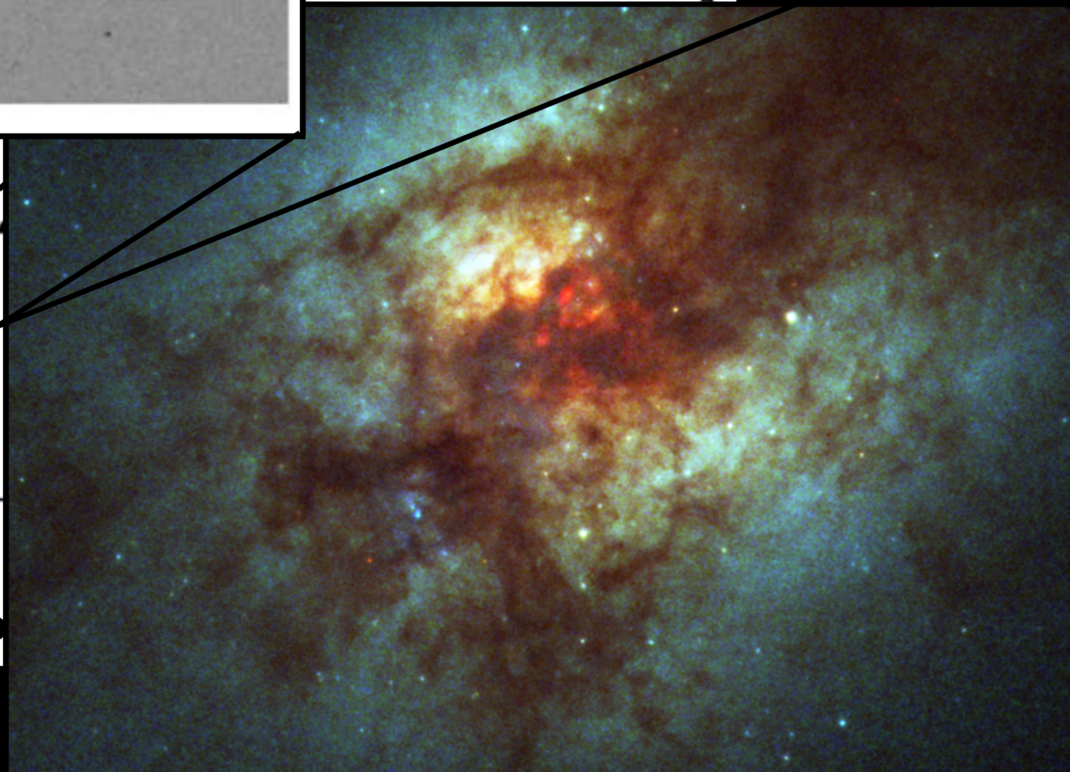


Size-of-sample effect

- Larger cluster populations sample further into their distribution functions (i.e. can sample the extreme ends)
- Galaxies with more clusters also have more massive and brighter clusters
- So we would expect that galaxies forming more stars (clusters) should have brighter/ more massive clusters







Wilson et al. 2006

Larsen 2002
Whitmore 2003
Gieles et al. 2006
Bastian 2008
Weidner et al. 2004

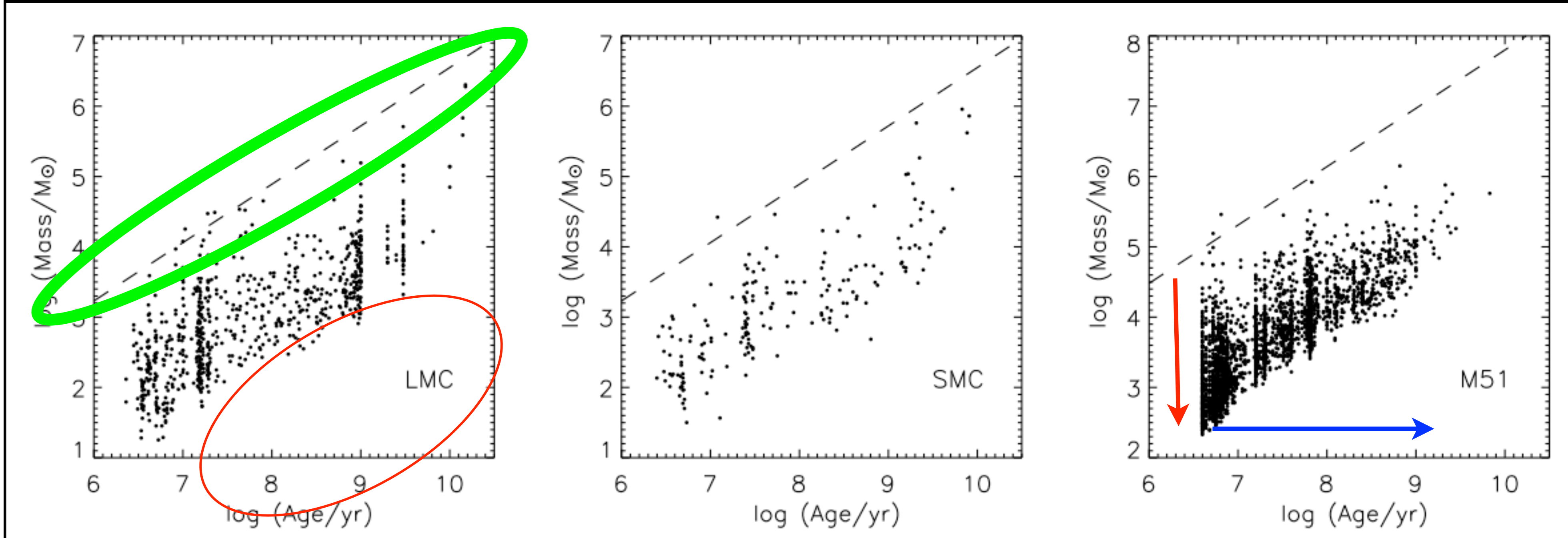
Size-of-sample effect

- Indeed, higher SFRs result in more luminous "brightest" clusters.

Age/mass diagrams

- Basic tools to study a cluster population
- Many of the basic properties of the population can be seen, and many biases are visible (that need to be taken into account)

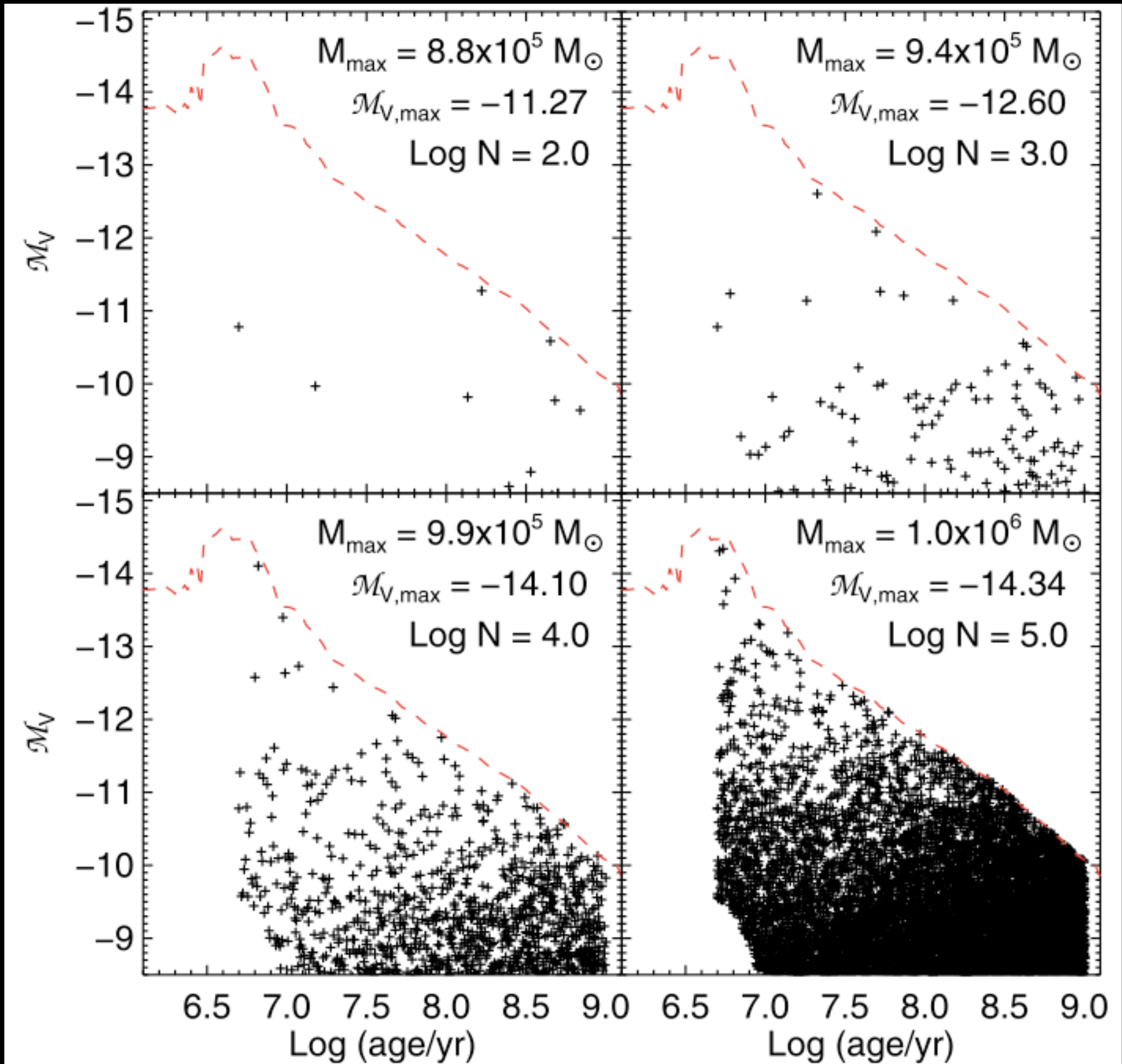
Size-of-sample effect



cluster mass function

logarithmic binning

Incompleteness

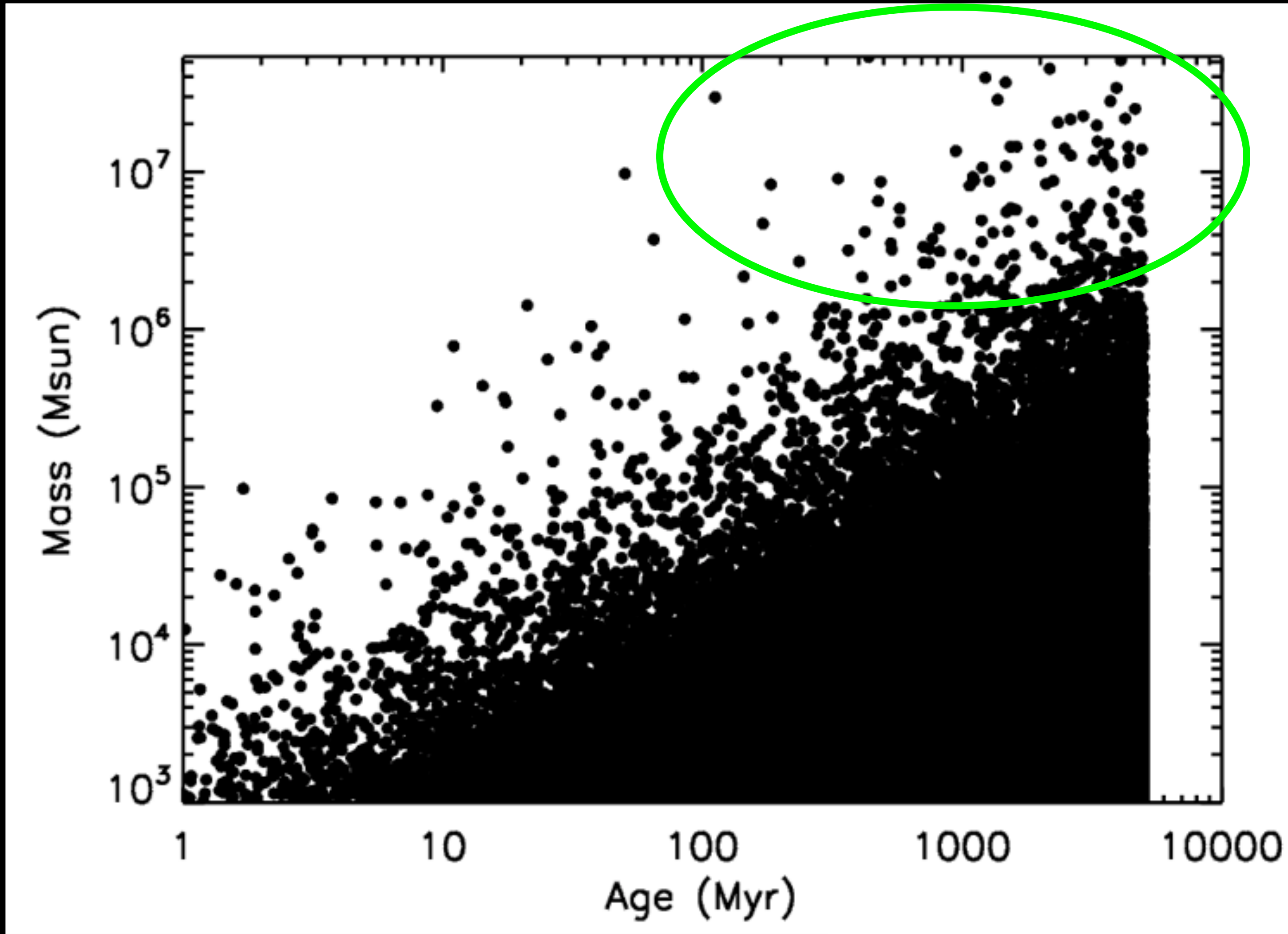


Cluster population simulations

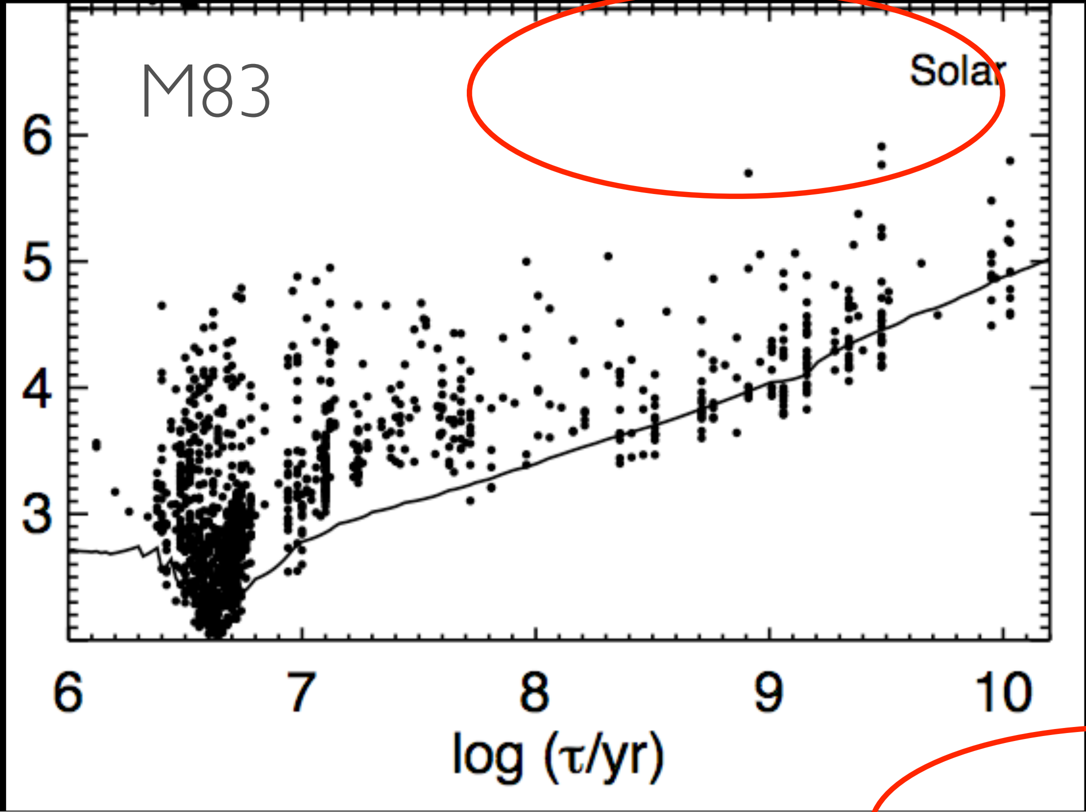
Effect of an upper mass limit of $M=10^6$ Msun

Larsen 2009

M51 - like cluster population

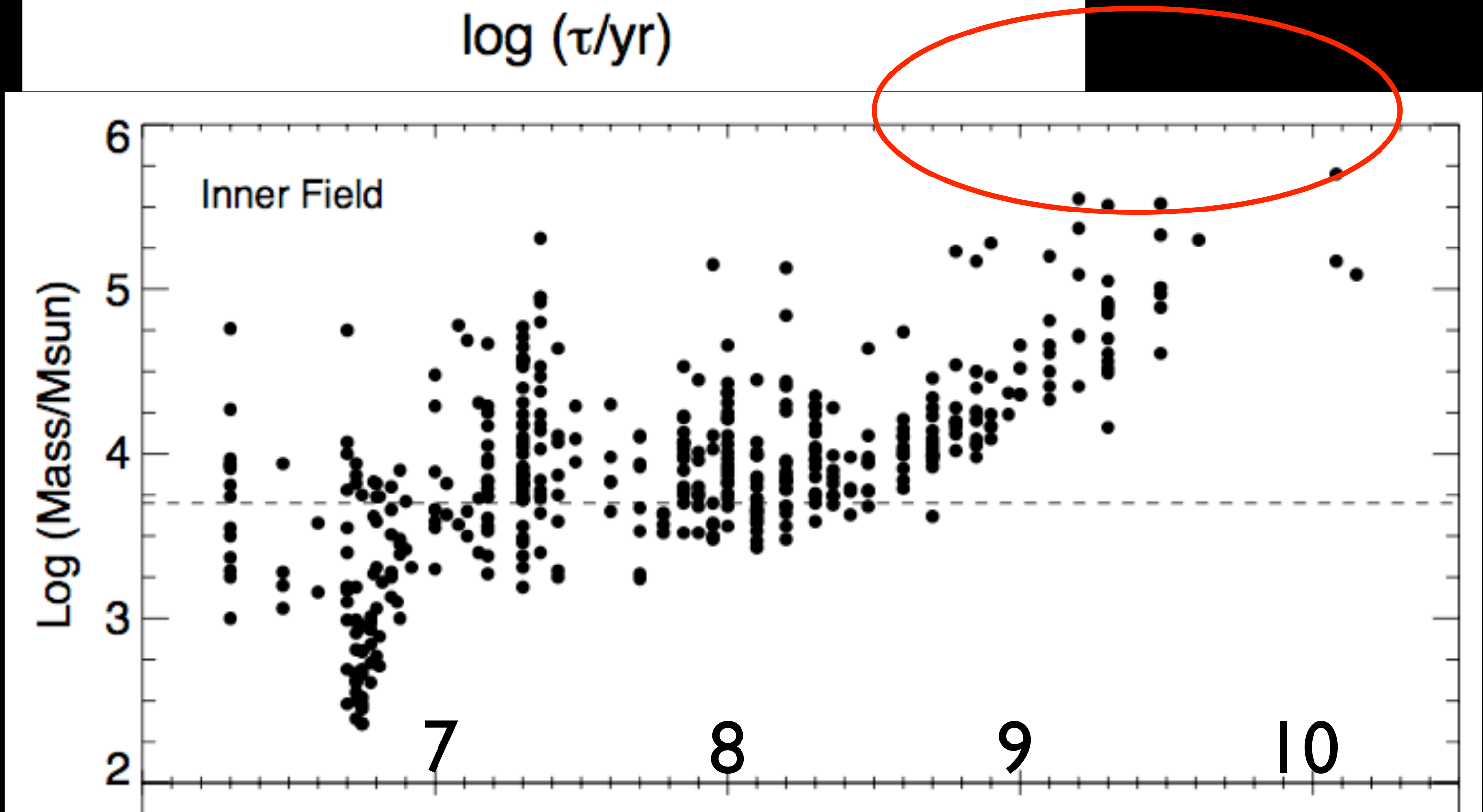


If size-of-sample was the only thing, we would expect many old extremely high mass clusters



Chandar et al. 2010

Not observed, suggesting that an upper mass limit exists within populations



Bastian et al. 2012

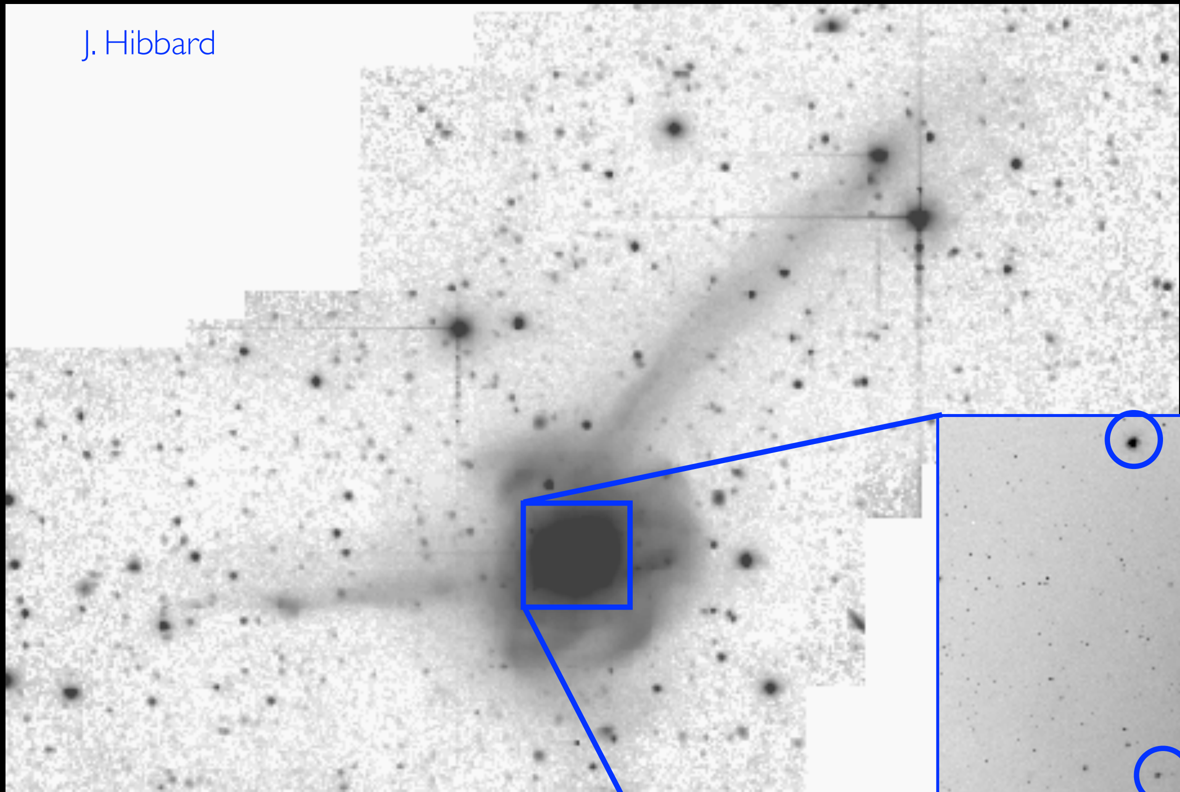
Cluster populations

- When looking at age/mass/luminosity functions, need to be very careful about biasing your sample
- Size-of-sample effects dominate cluster populations
- But we can see the influence of a truncation in the upper end of the mass function.

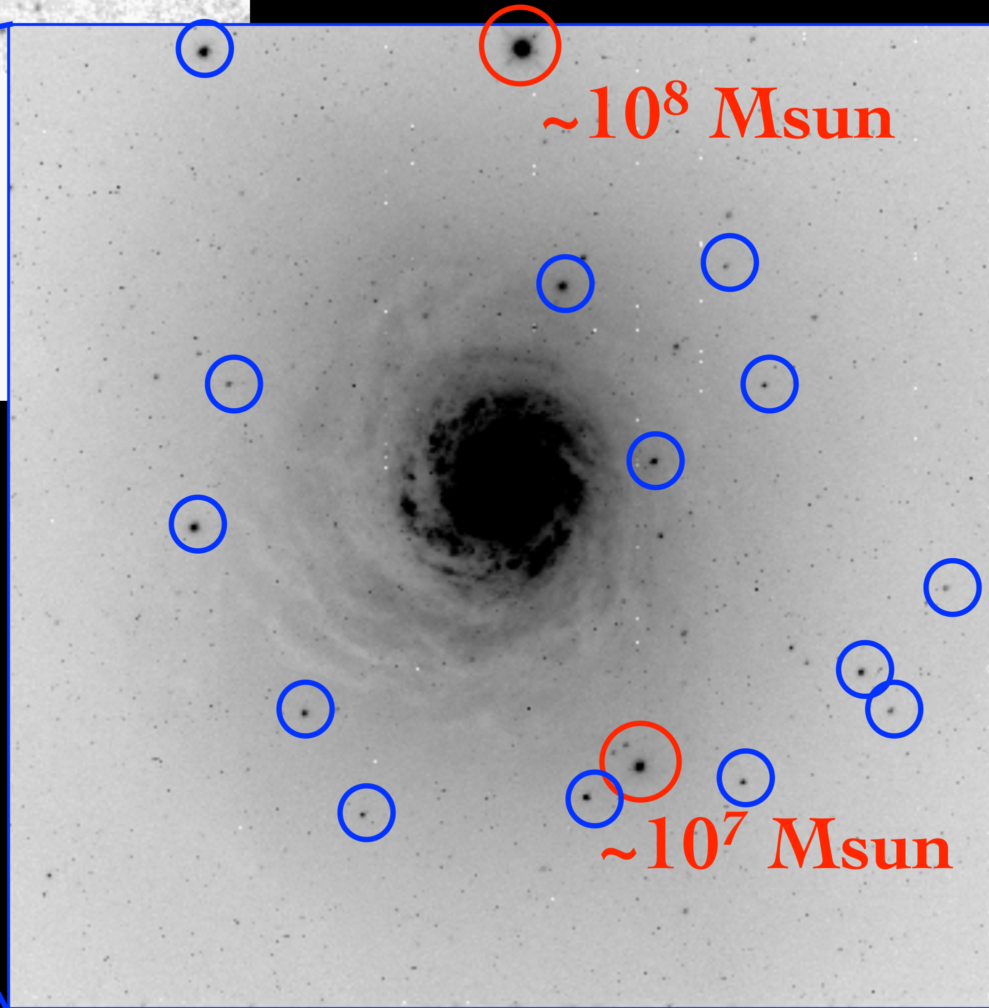
Cluster Age Distributions

- Since clusters are bright (and SSPs) they are easy to find and derive their properties
- This offers the chance to use clusters to estimate the star-formation history of the galaxy (with some assumptions)

NGC 7252
A GALAXY IN TRANSITION



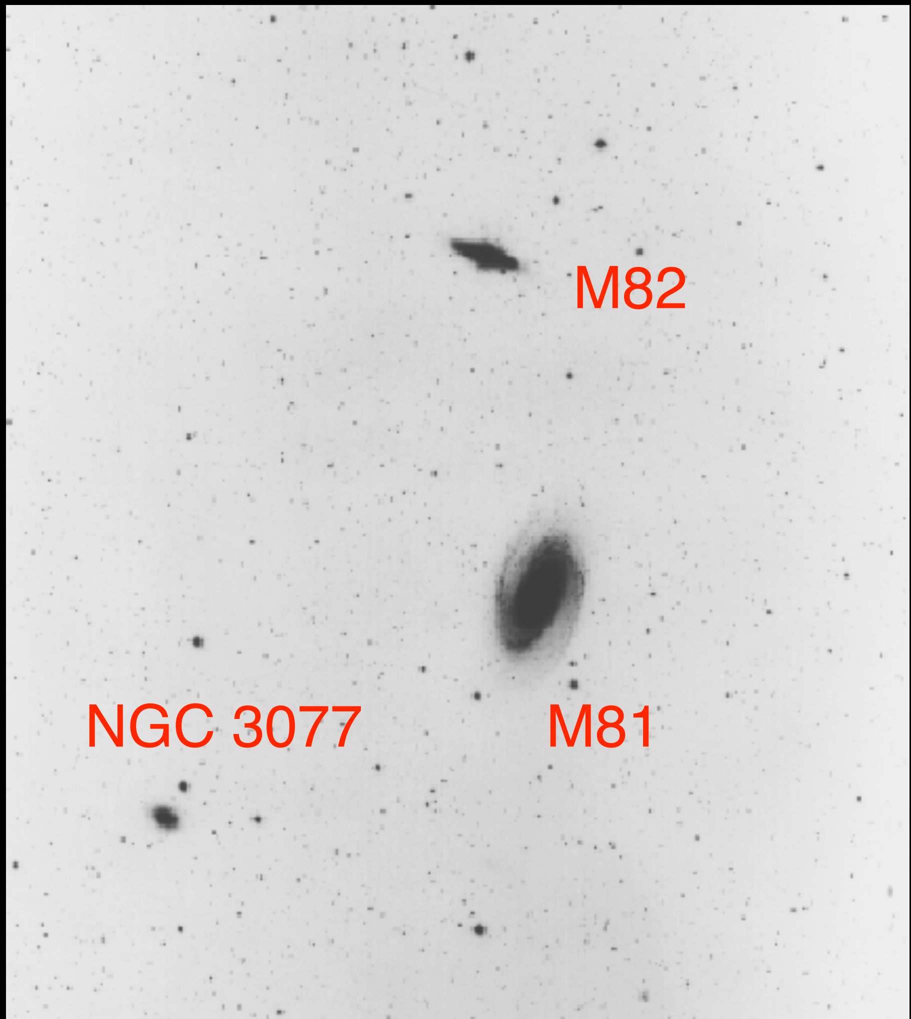
500±200 Myr



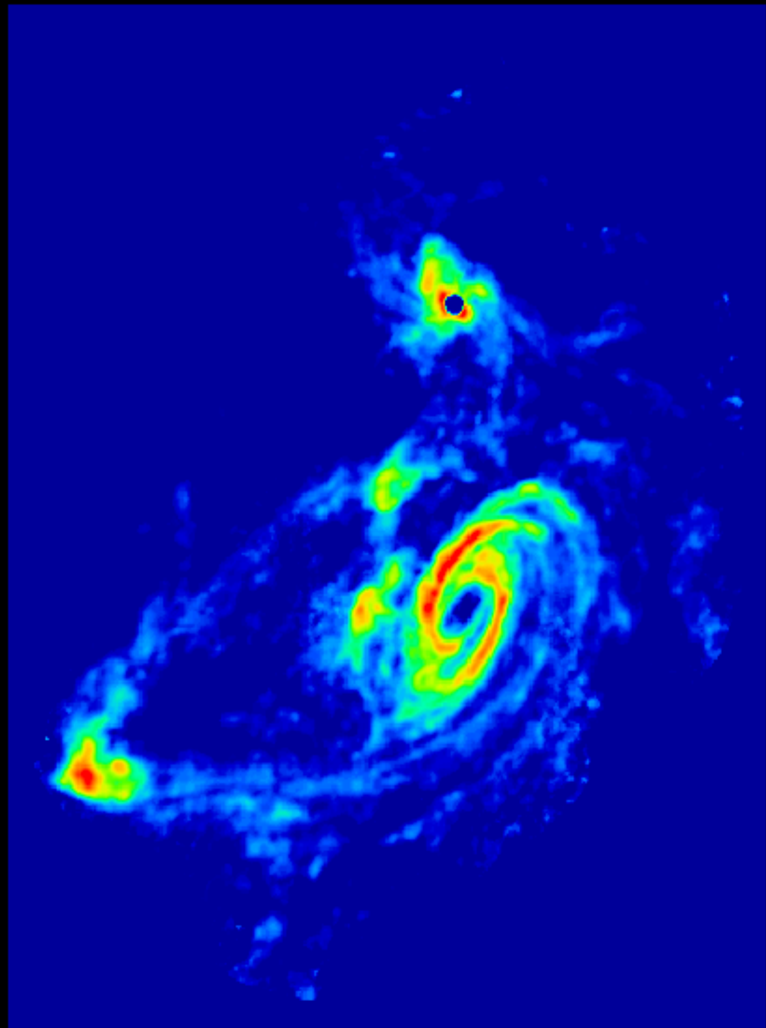
Miller et al. 1997; Schweizer & Seitzer 1998; Maraston et al. 2004; Bastian et al. 2006

M81/M82 Interaction

Yun et al. 1994

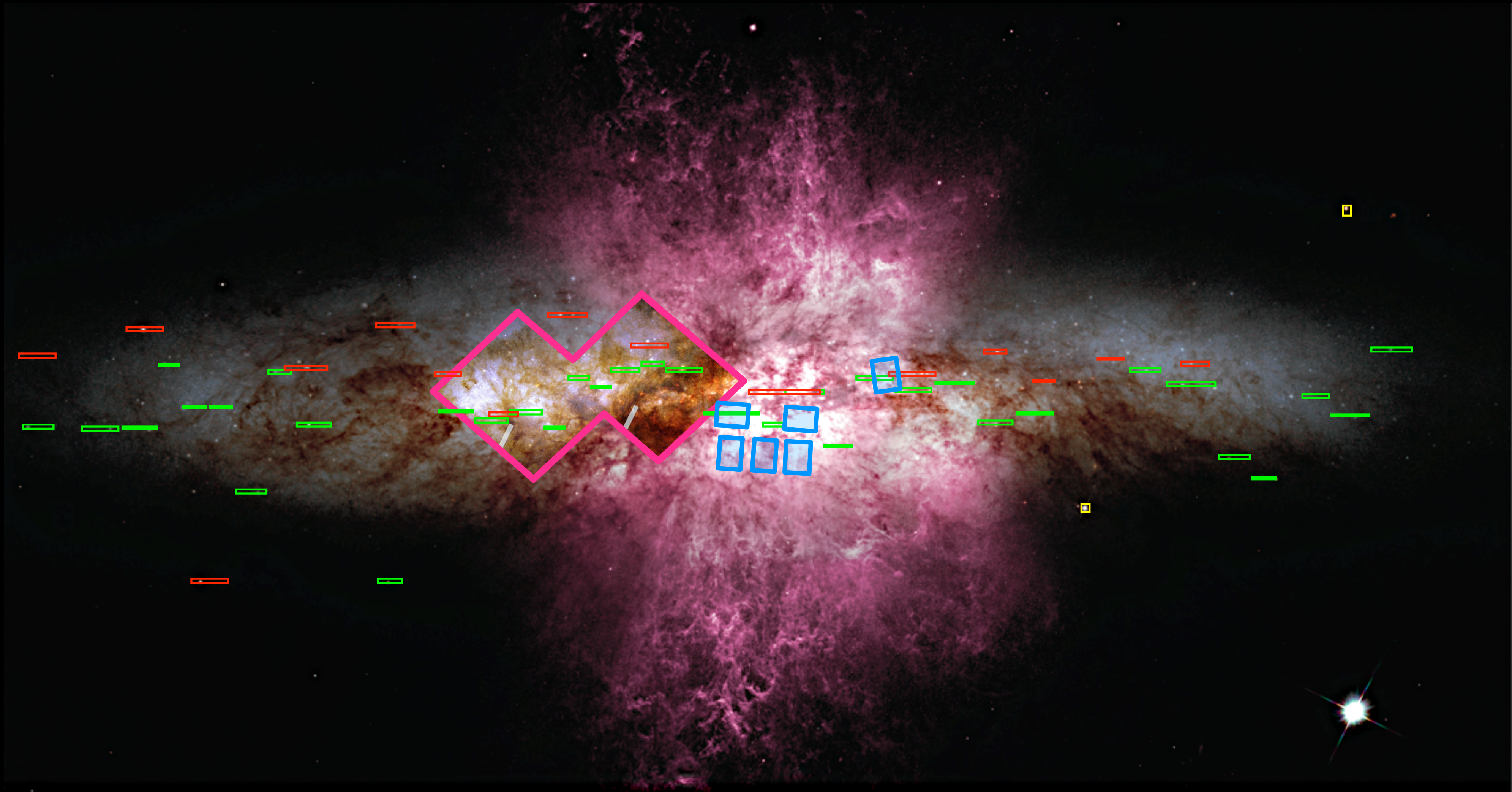


Optical



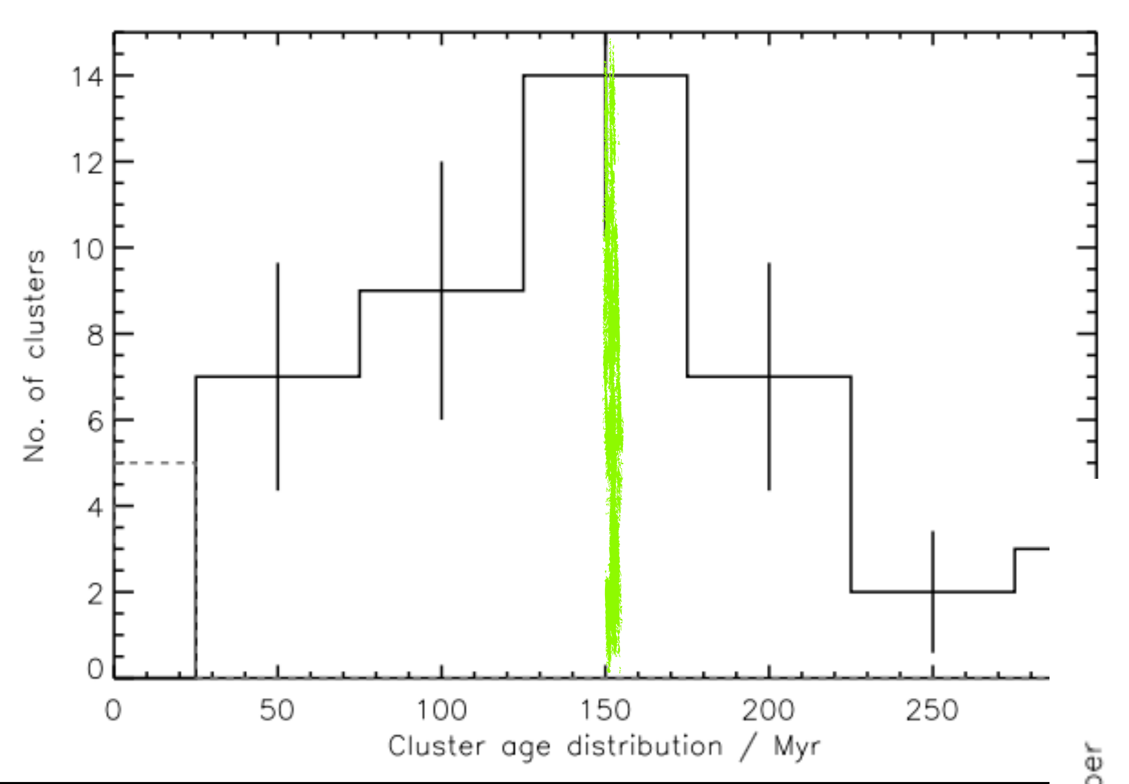
HI

M82



Smith et al. 2007 Konstantopoulos et al. 2008, 2009

Westmoquette et al. 2009, 2010



Konstantopoulos et al. 2009

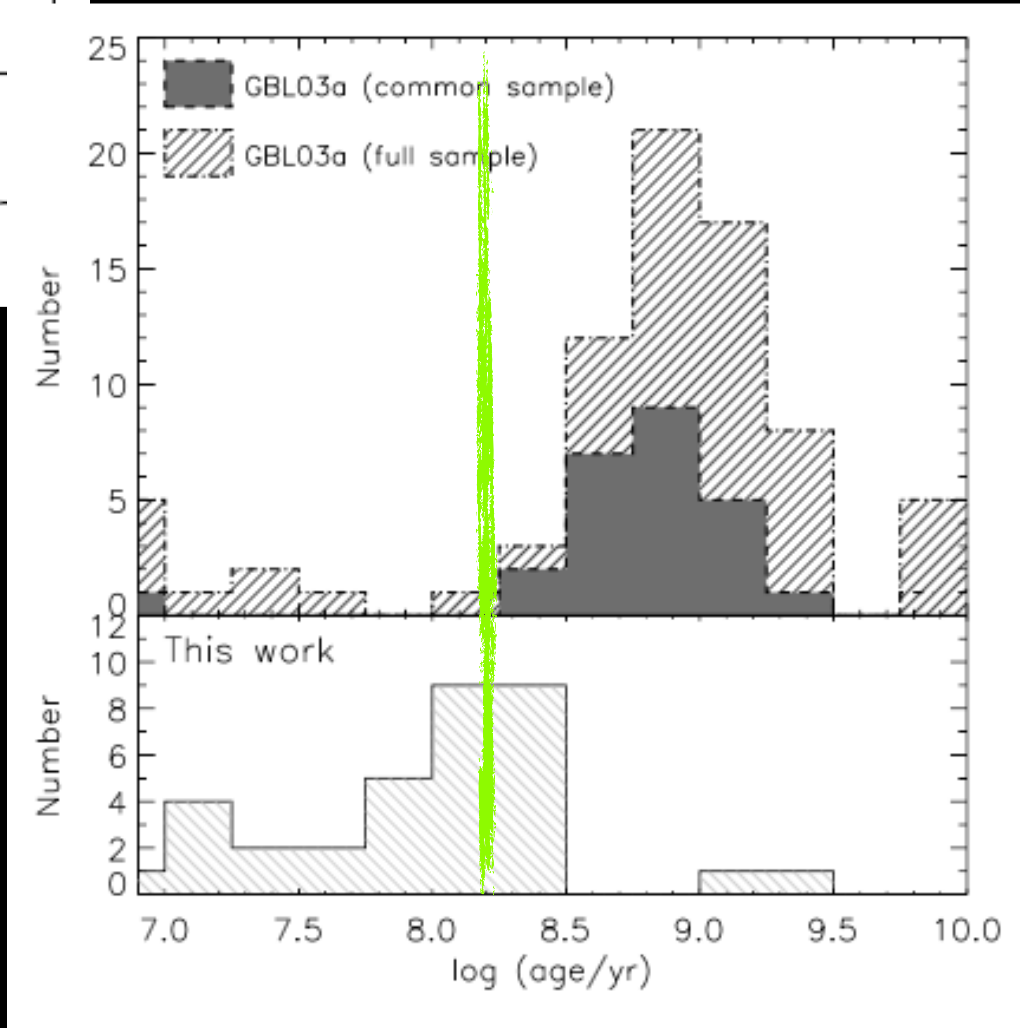
Spectroscopy

Interaction took place
~200-300 Myr ago

Consistent with
numerical models

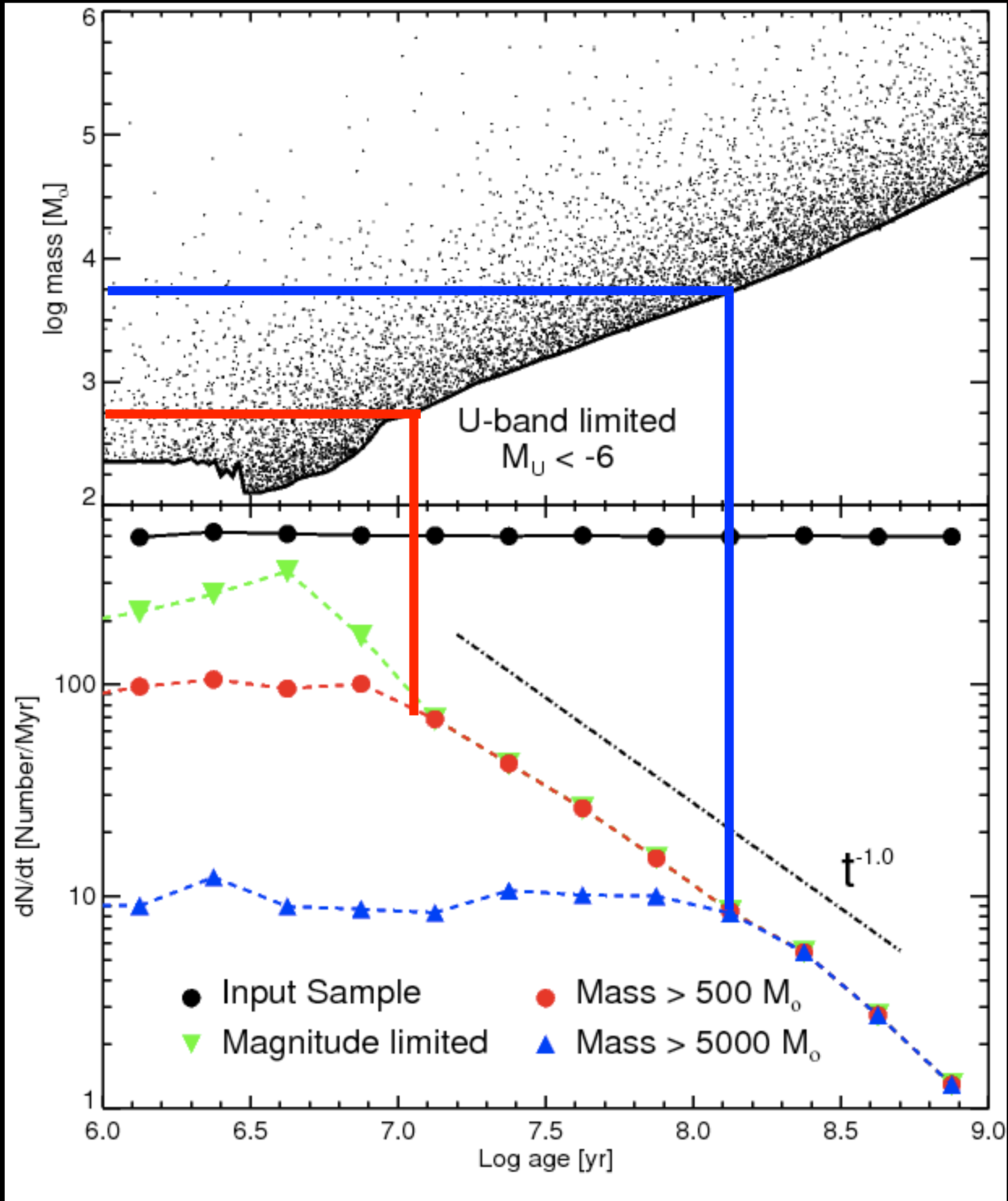
Photometry

Smith et al. 2007



Cluster Age Distributions

- In many post-starburst systems there is clear evidence for a previous burst (lasting 100-500 Myr)
- But in other environments the age distribution is more tricky to analyse
- As the ages are determined in logarithmic age, we need to take that into account
- Take a mass limited sample, count the number of clusters in your age bins, and divide the bin by the linear age width of the bin

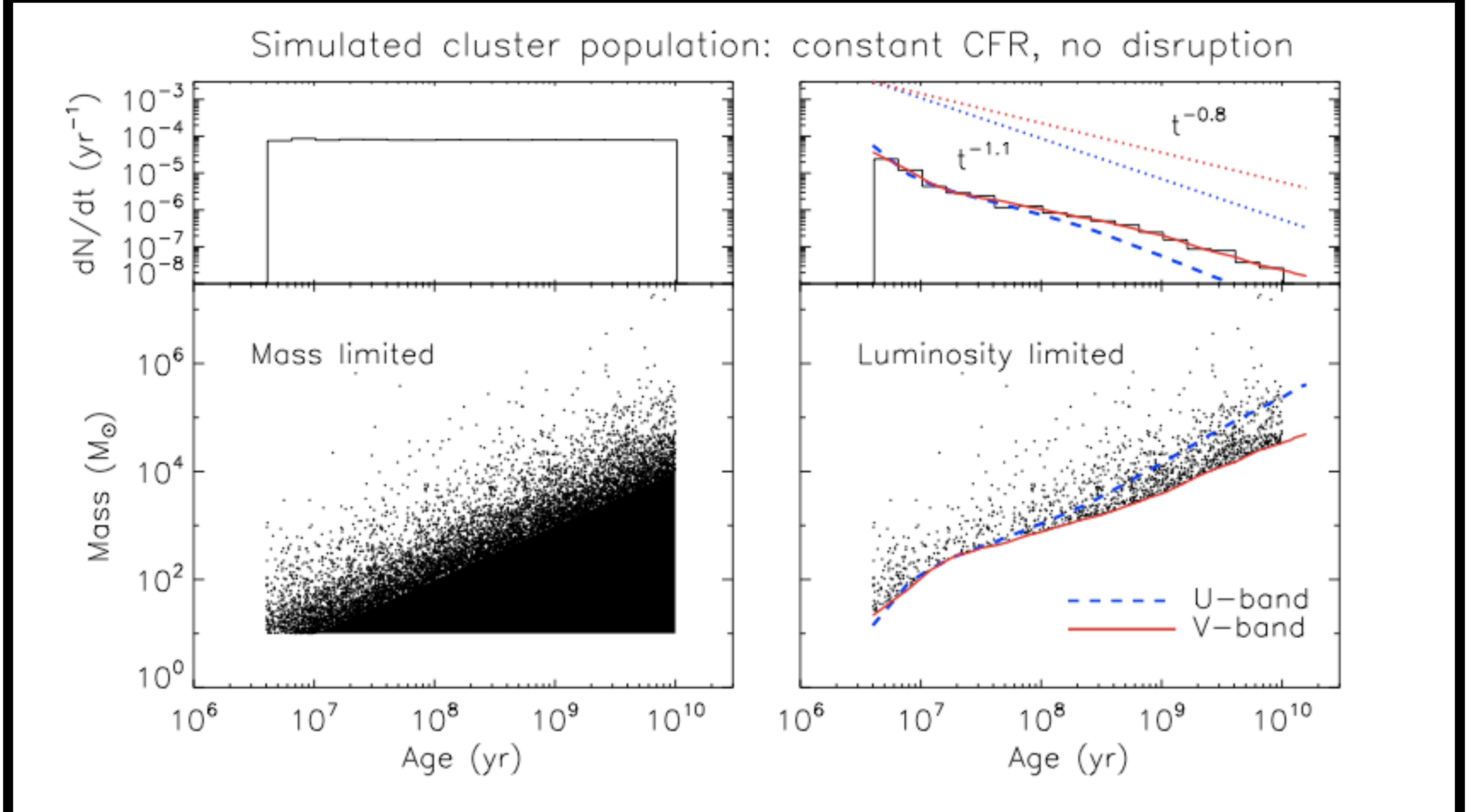


input constant SFR

apply 'observational' detection limits

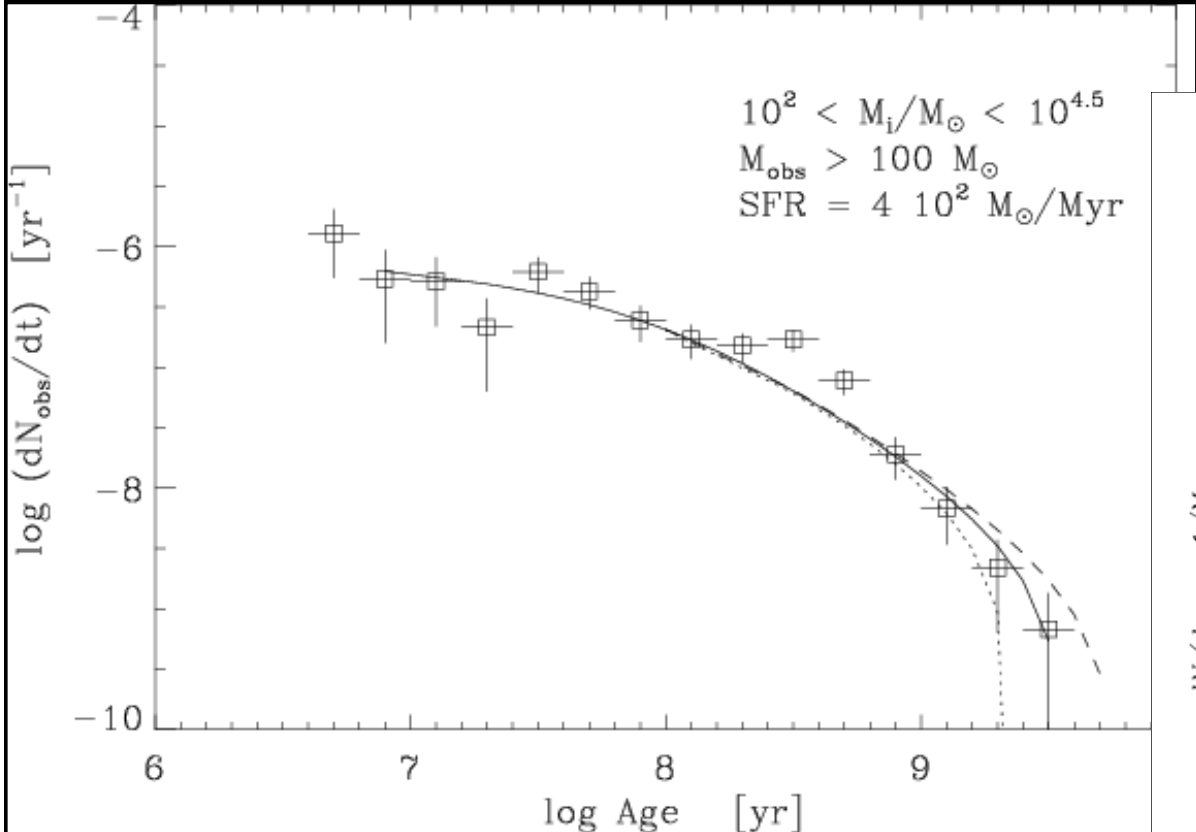
apply mass cut

apply higher mass cut

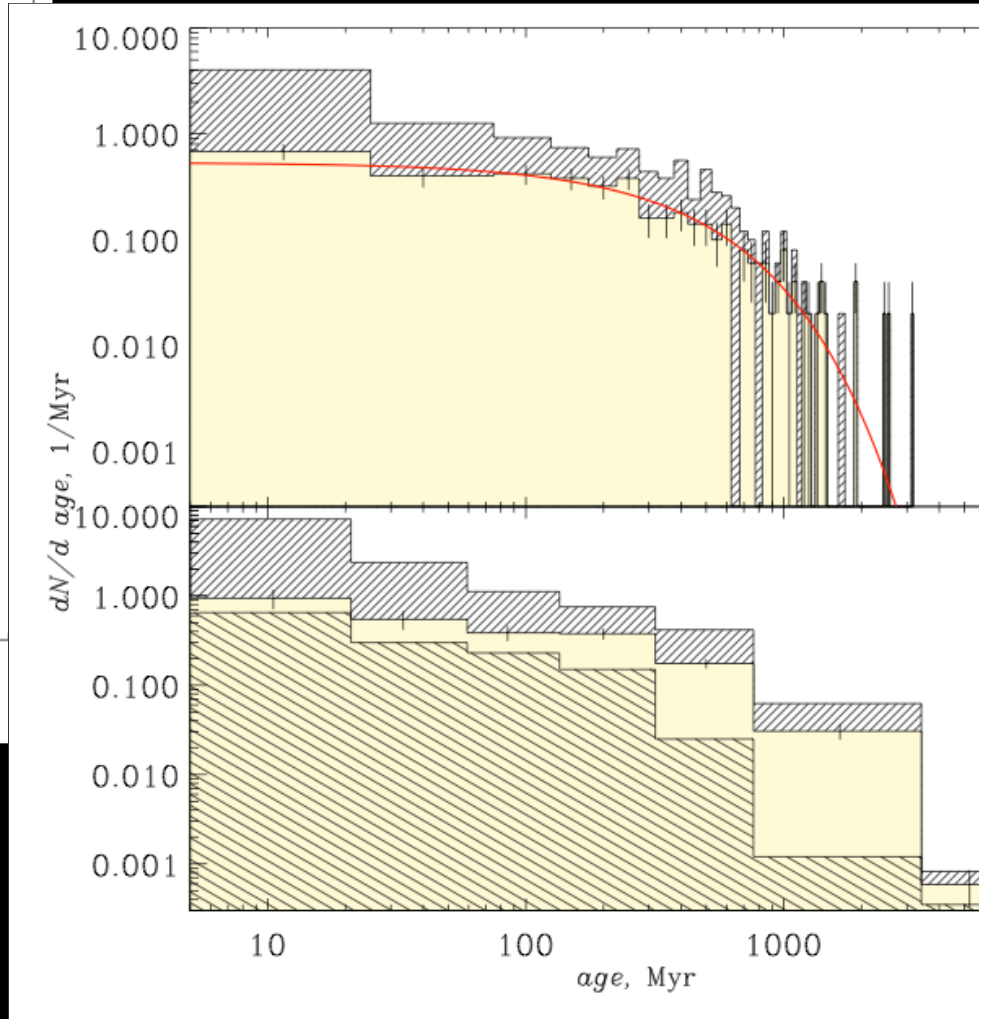


dN/dt = number of clusters per linear unit time

Open clusters

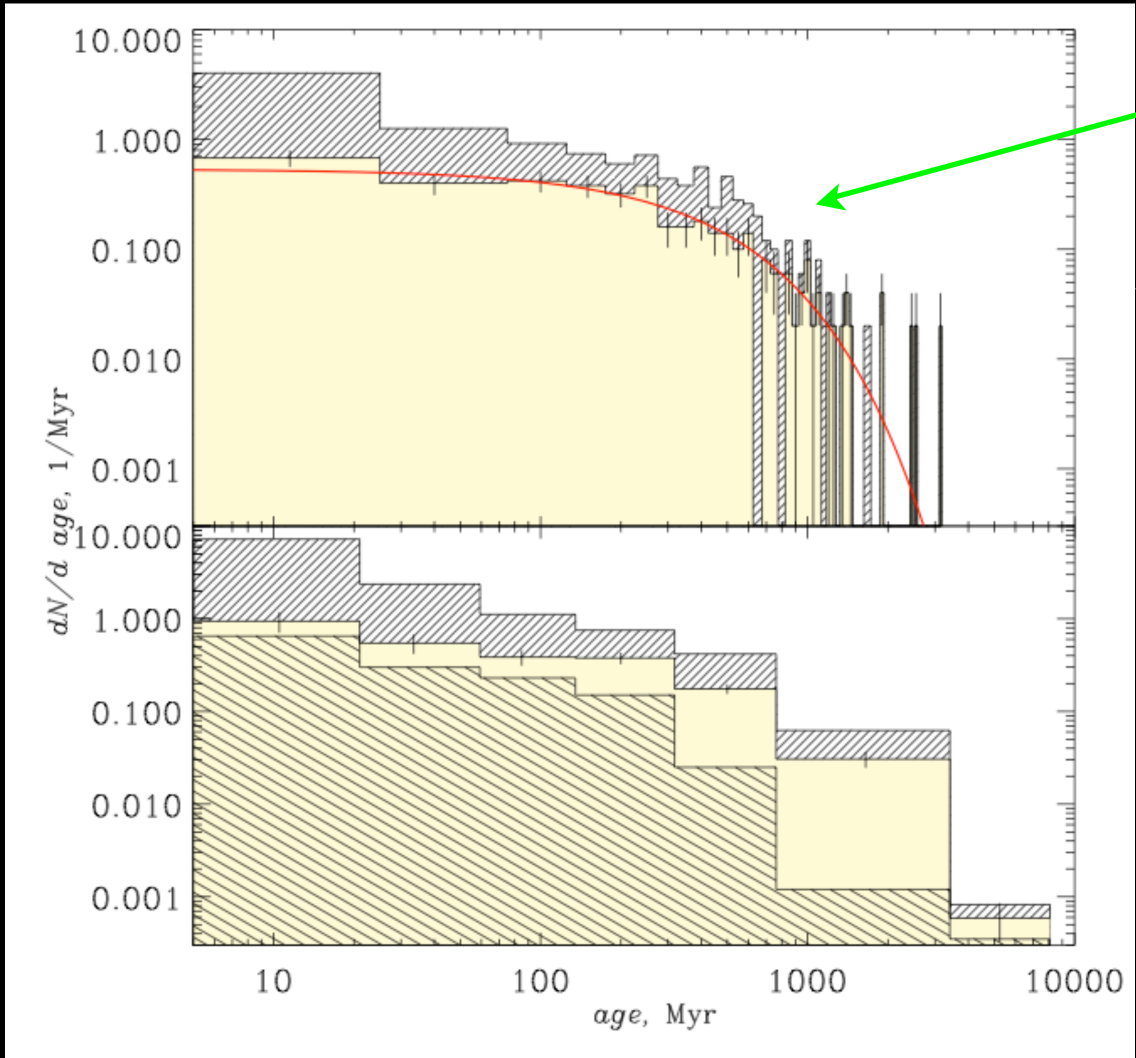


Lamers & Gieles 2006



Röser et al. 2010

Compare to local SFR, ~10% of stars forming in open clusters



Cluster disruption

$t_{dis} \sim 300$ Myr

(700 $M_\odot$ cluster)

Lamers & Gieles 2006

Wielen 1971

Röser et al. 2010

The dissolution time in different environments

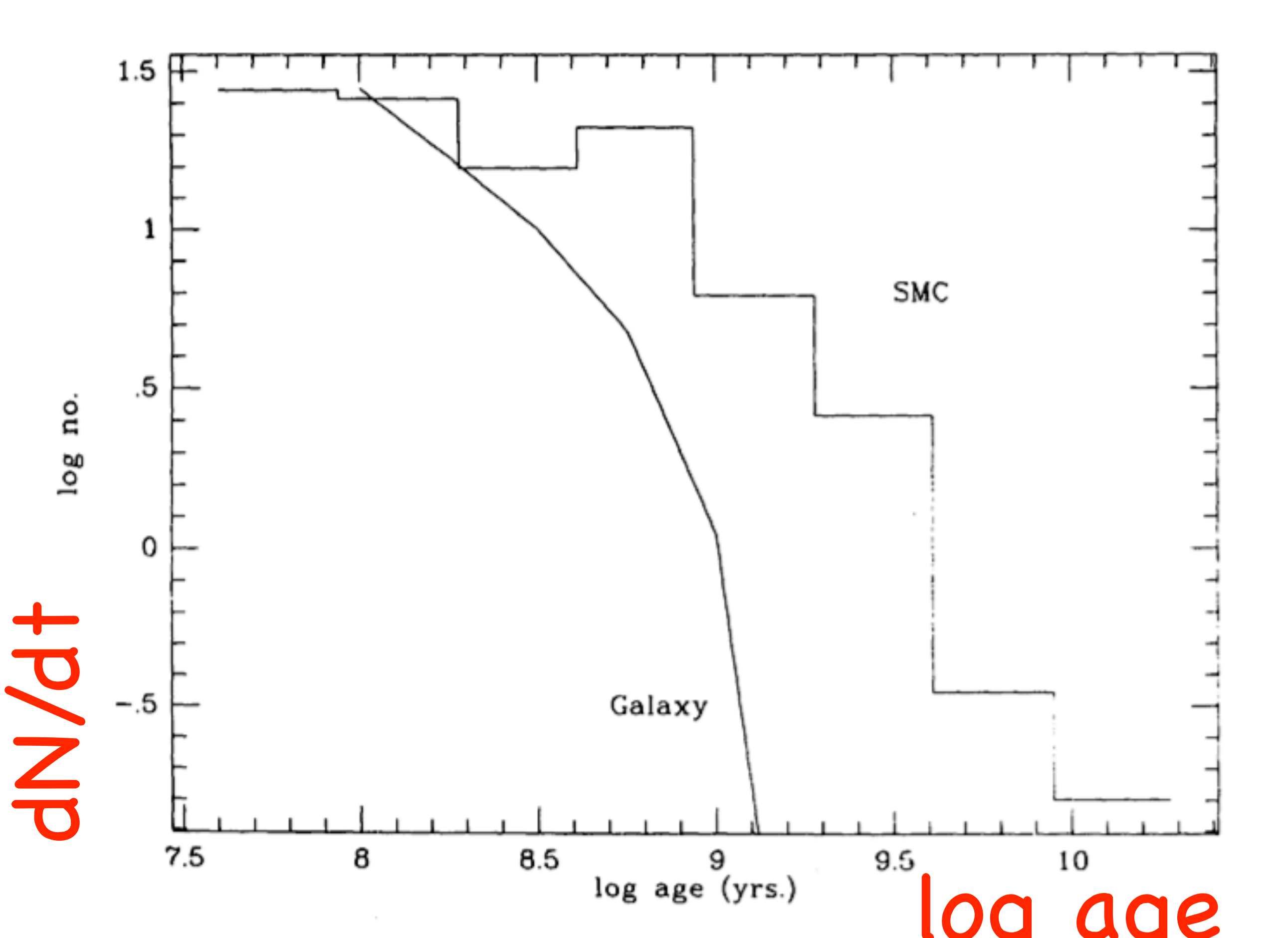
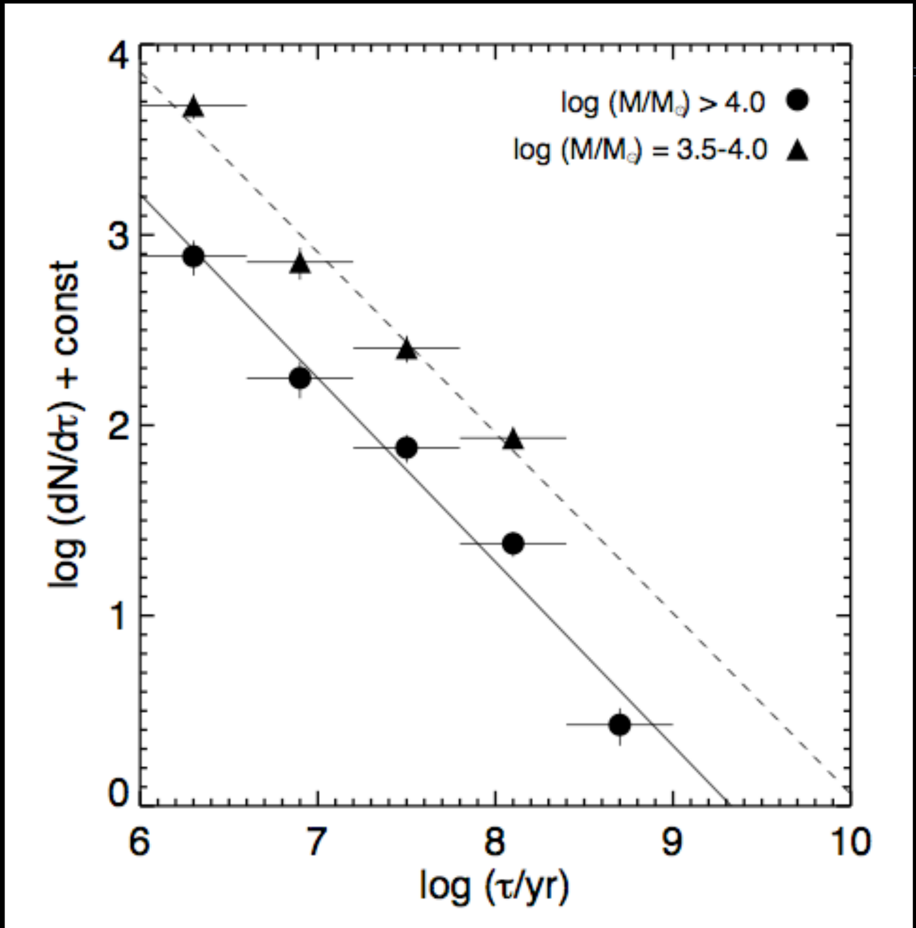


FIG. 4–The age distribution for all SMC clusters in the 4-m fields. Wielen's (1971) distribution for Galactic clusters is also shown, normalized at 10^8 yrs. Units in the ordinate are clusters per 10^8 yrs.

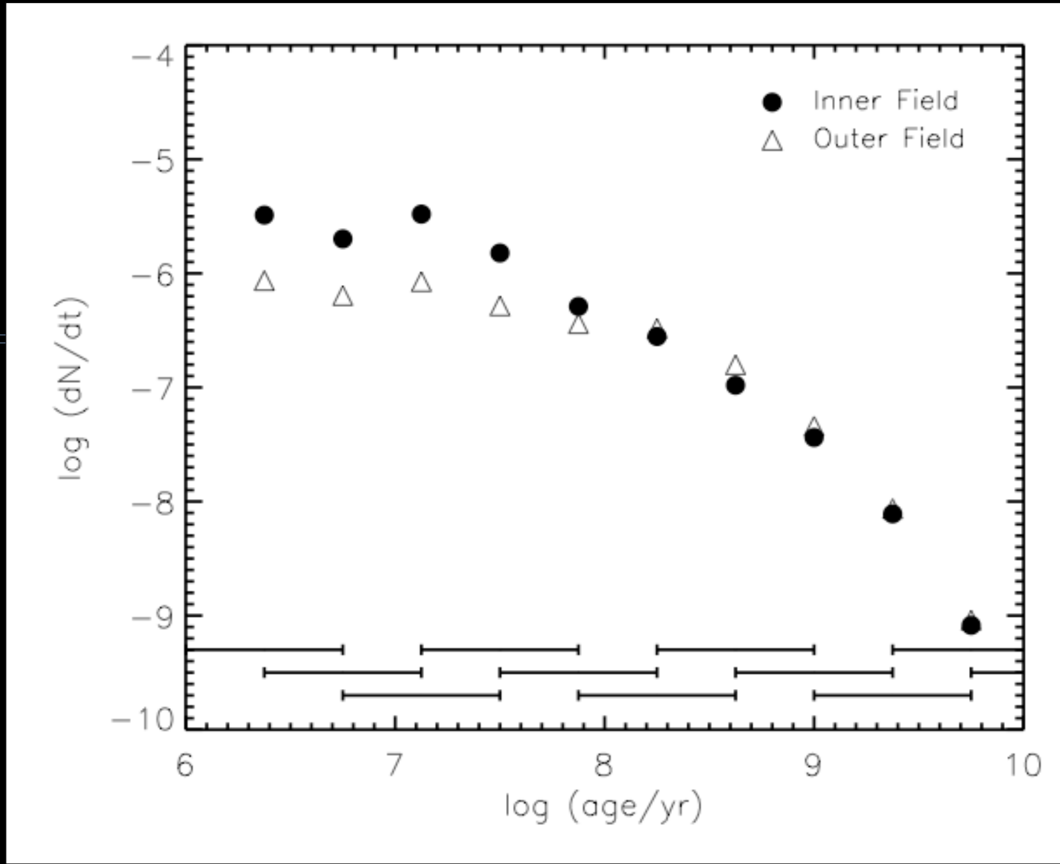
Hodge (1987)

Elson & Fall (1985)
Boutloukos & Lamers (2003)
Lamers, Portegies Zwart & Gieles (2005)

M83



Chandar et al. 2010



Bastian et al. 2012

$dN/dt \sim t^{-\zeta}$

Cluster Dissolution

- As seen in Holger's lectures, clusters do not live forever, but are expected to dissolve on timescales that depend on their environment
- For cluster populations (mass limited) this should result in a flat portion (dN/dt) followed by a decrease as disruption begins to 'eat into' the population
- So we would not expect a single power law to fit the data well.
- High mass clusters are expected to live longer than lower mass clusters

Mass Dependent Disruption (MDD)

- Cluster lifetime depends on mass and enviroment
- Age/mass distributions evolve and change
- This is what is expected from theory/ simulations

Boutloukos & Lamers 2003
Lamers et al. 2005
Gieles et al. 2007
Bastian et al. 2012

$$0 < \zeta < 1$$

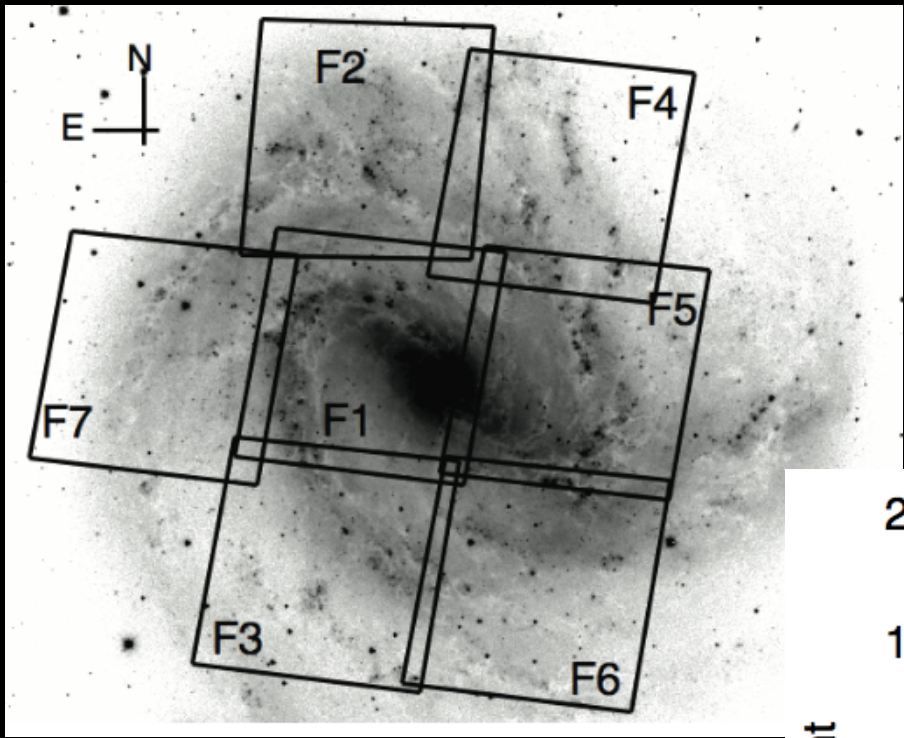
Mass Independent Disruption (MID)

- Cluster lifetime ***does not*** depend on mass or environment
- Age/mass distributions are "universal" $g(M,t) \sim M^{-2}\, t^{-1}$

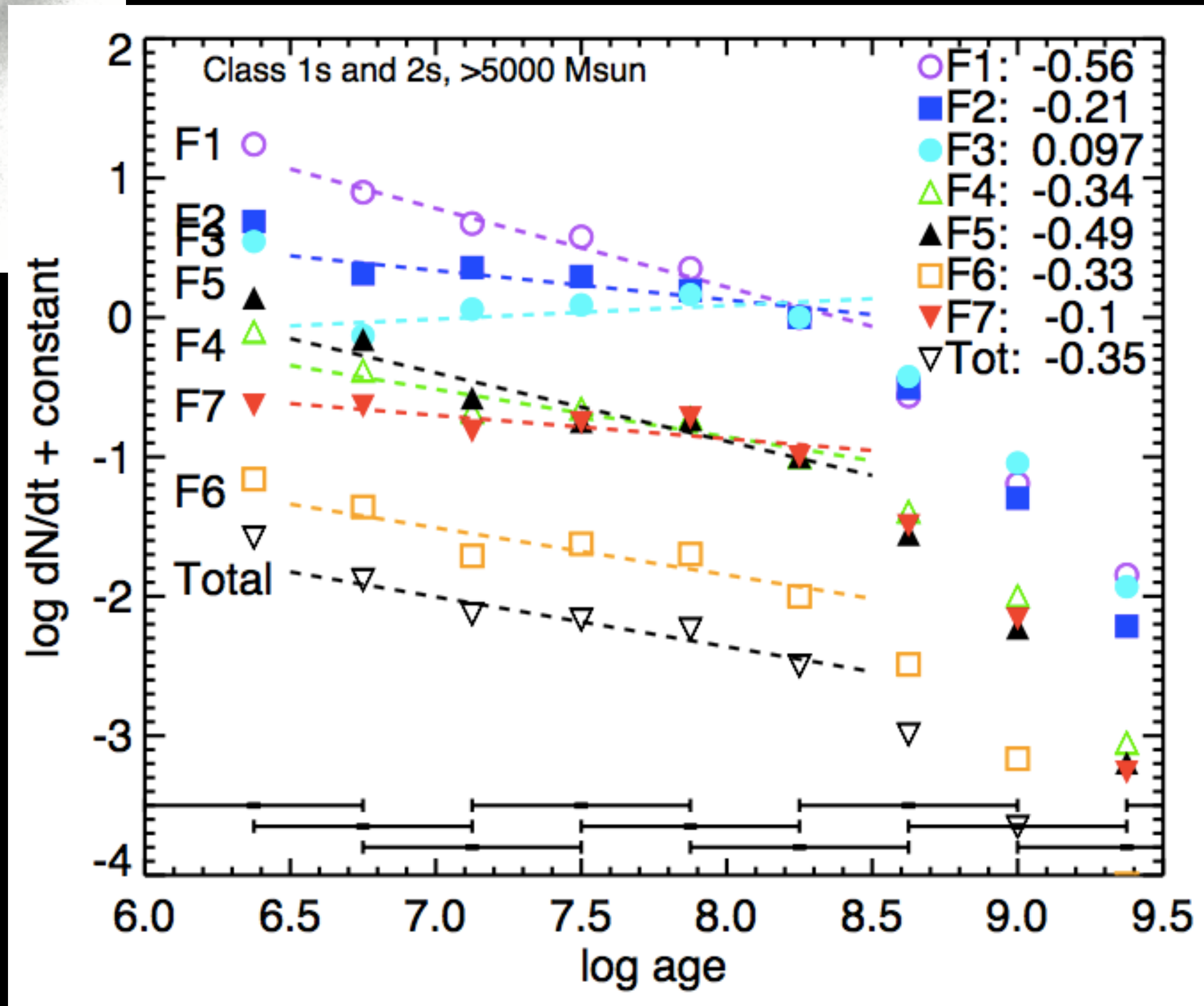
Fall et al. 2005, 2006
Whitmore et al. 2007
Chandar et al. 2010

$$\zeta = 1$$

$$dN/dt \sim t^{-\zeta}$$

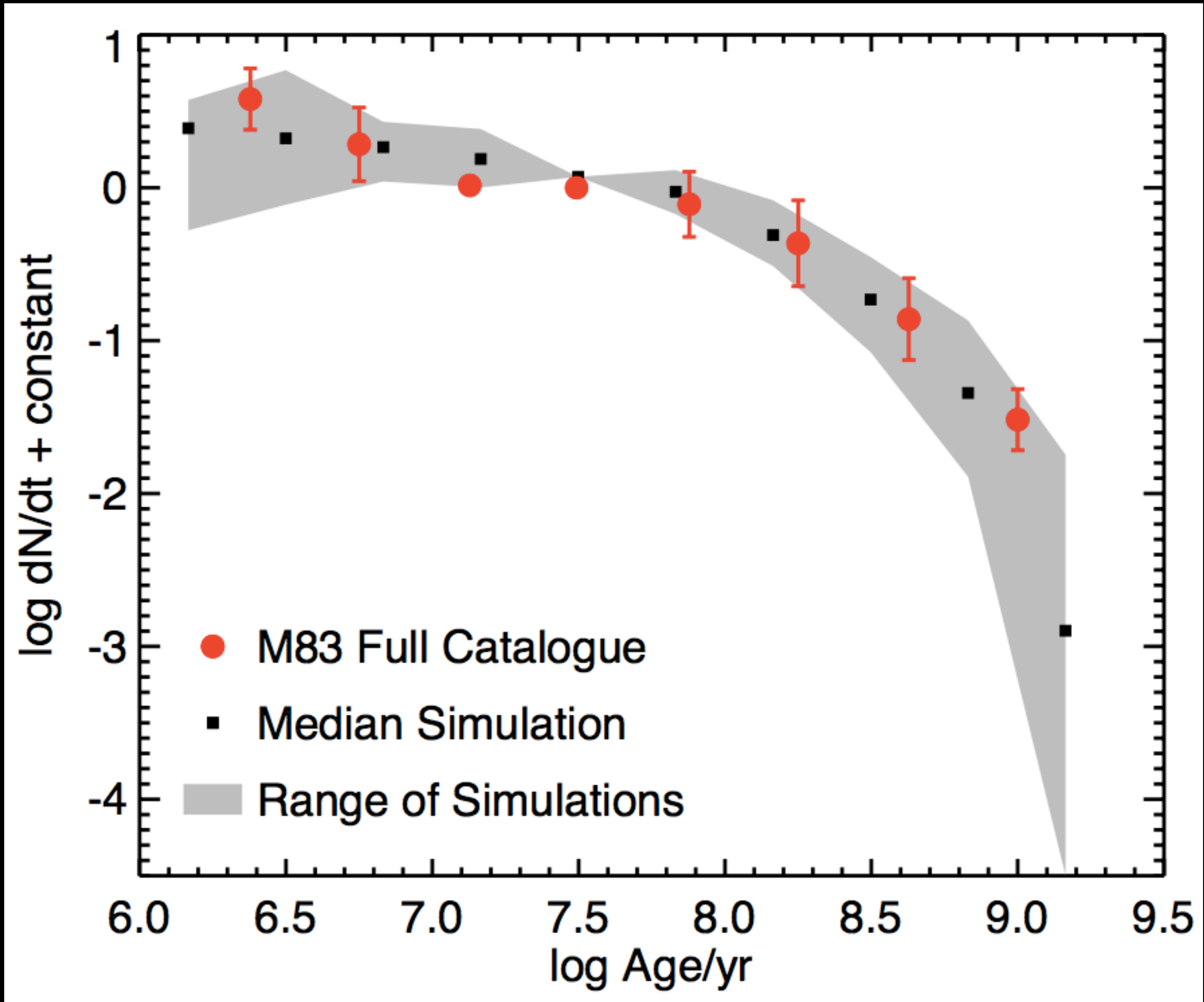


Silva-Villa et al. 2014



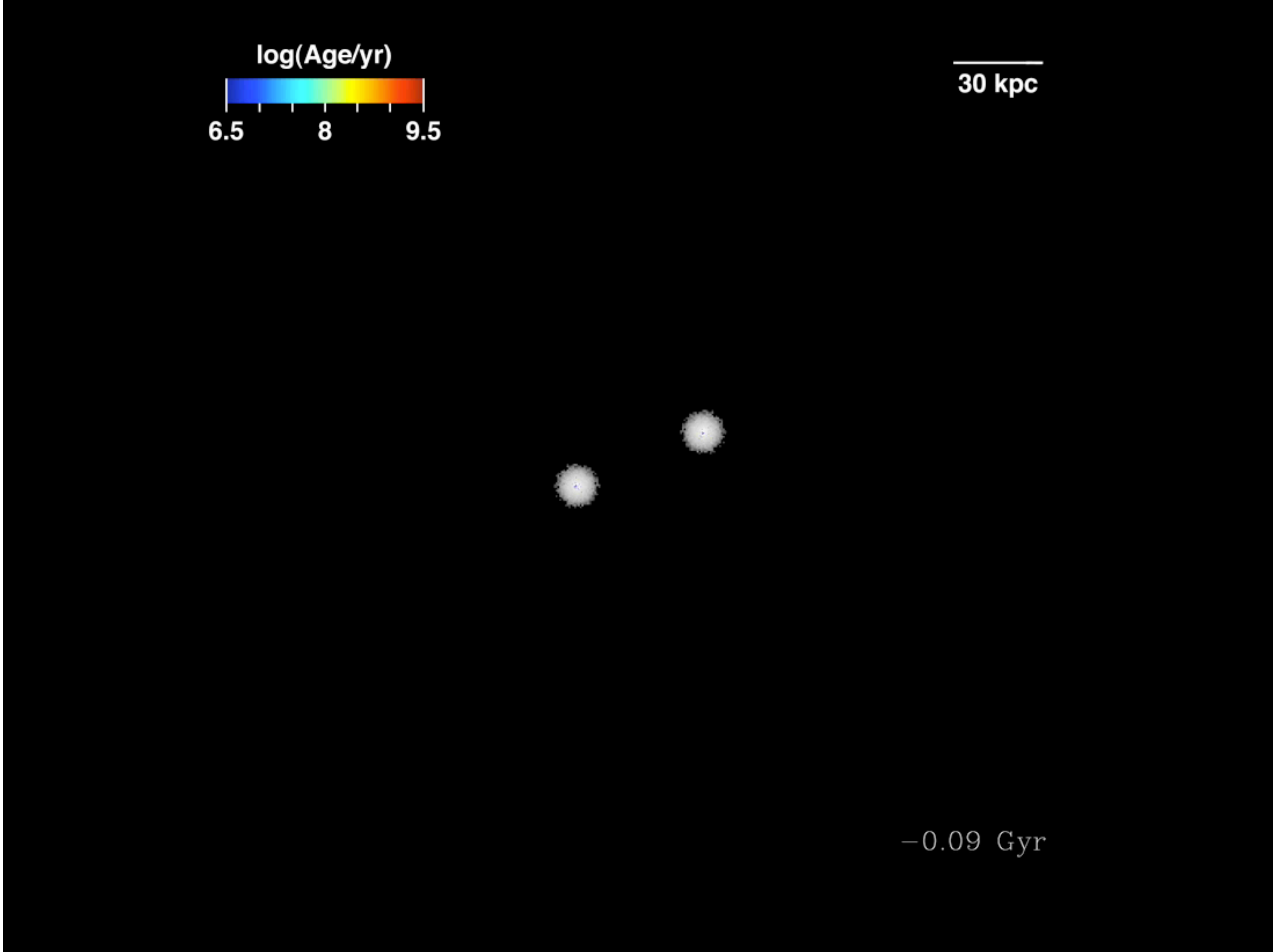
Galaxy	age range	ζ	Reference
SMC	20 – 1000 Myr	0.0 ± 0.1^c	[Gieles et al.(2007)]
M31	5 – 100 Myr	0 – 0.15	Fouesneau et al. 2014
NGC 2997	10 – 100 Myr	0.1 ± 0.2	Ryon et al. 2014
M51	10 – 300 Myr	0.15 ± 0.2	Hwang & Lee 2010
Solar neighbourhood	5 – 300 Myr	0.3 ± 0.15	Lamers et al. 2005
LMC	10 – 100 Myr	0.3 ± 0.15	Baumgardt et al. 2013
M33	10 – 100 Myr	0.3 ± 0.2^a	Gieles & Bastian 2008[b]
NGC 1566	5 – 300 Myr	0.4 ± 0.15	Hollyhead et al. in prep.
NGC 4041	5 – 200 Myr	0.4 ± 0.2	[Konstantopoulos et al.(2013)]
NGC 4449	5 – 500 Myr	0.5 ± 0.15^a	Annaballi et al. 2011
NGC 7793	10 – 500 Myr	0.55 ± 0.2	Silva-Villa & Larsen 2011
NGC 1313	10 – 500 Myr	0.6 ± 0.1	Silva-Villa & Larsen 2011
M83	10 – 500 Myr	0.25 ± 0.1	Silva-Villa & Larsen 2011
M83 F1	1 – 1000 Myr	0.9 ± 0.2	Chandar et al. 2010b
M83 F2	10 – 1000 Myr	0.5 ± 0.2	Chandar et al. 2014
M83 F2	5 – 300 Myr	0.15 ± 0.15	Chandar et al. 2014 catalogue
M83 (F1-F7)	10 – 300 Myr	0 – 0.6	Silva-Villa et al. 2014
M83 (Full sample)	10 – 300 Myr	0.35 ± 0.15	Silva-Villa et al. 2014
Antennae	5 – 500 Myr	0.85 ± 0.15	Whitmore et al. 2007, 2010

Adamo & Bastian 2015



Adamo & Bastian 2015

simulations from Kruijssen et al. 2012


log(Age/yr)
6.5
8
9.5
30 kpc
−0.09 Gyr

Cluster Dissolution Summary

- Cluster's don't live forever, but disrupt due to internal and external processes
- Interactions with GMCs are the biggest killer of young clusters
- Two empirical cluster disruption scenarios, 1) where disruption depends on mass/environment (MDD) and 2) where it doesn't (MID)
- The observed age distributions agree with the MDD scenario, which is good as this also agrees with theory/ expectations

Stellar populations within YMCs

- See Estelle's lecture on stellar pops and the stellar IMF
- As YMCs are extreme, we might expect that the form of the IMF within them is different.
- Perhaps they are over/under abundant in low mass stars?

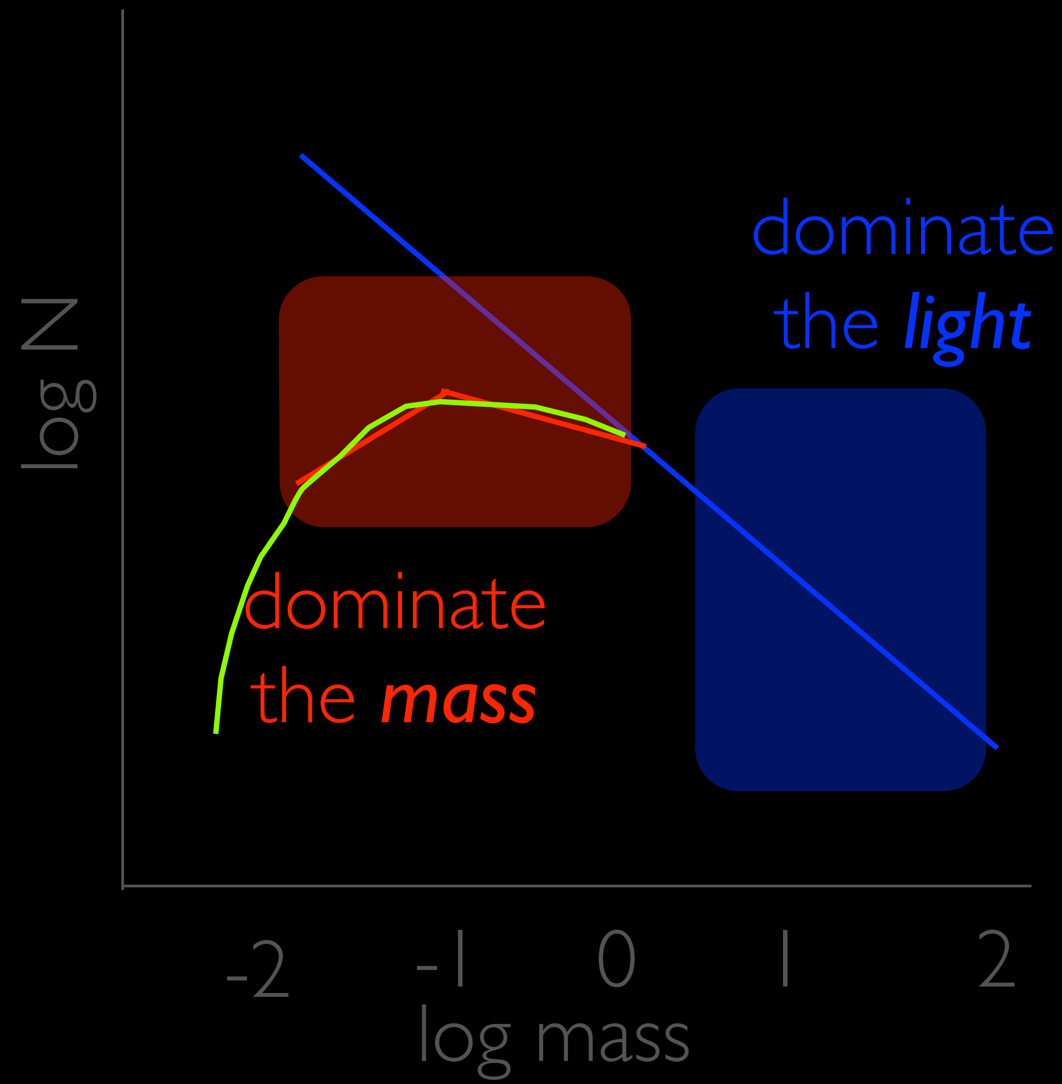
FAMOUS FORMS OF THE IMF

Salpeter (1955) -
$N(dM) \sim M^{-\alpha} dM$ - pure power law

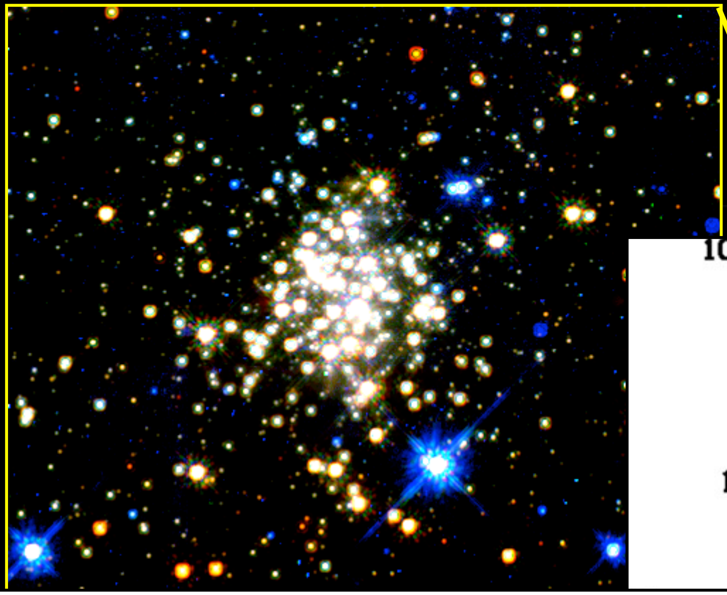
Chabrier (2003/2005) - power-law above a certain mass (~0.8 Msun), log-normal below

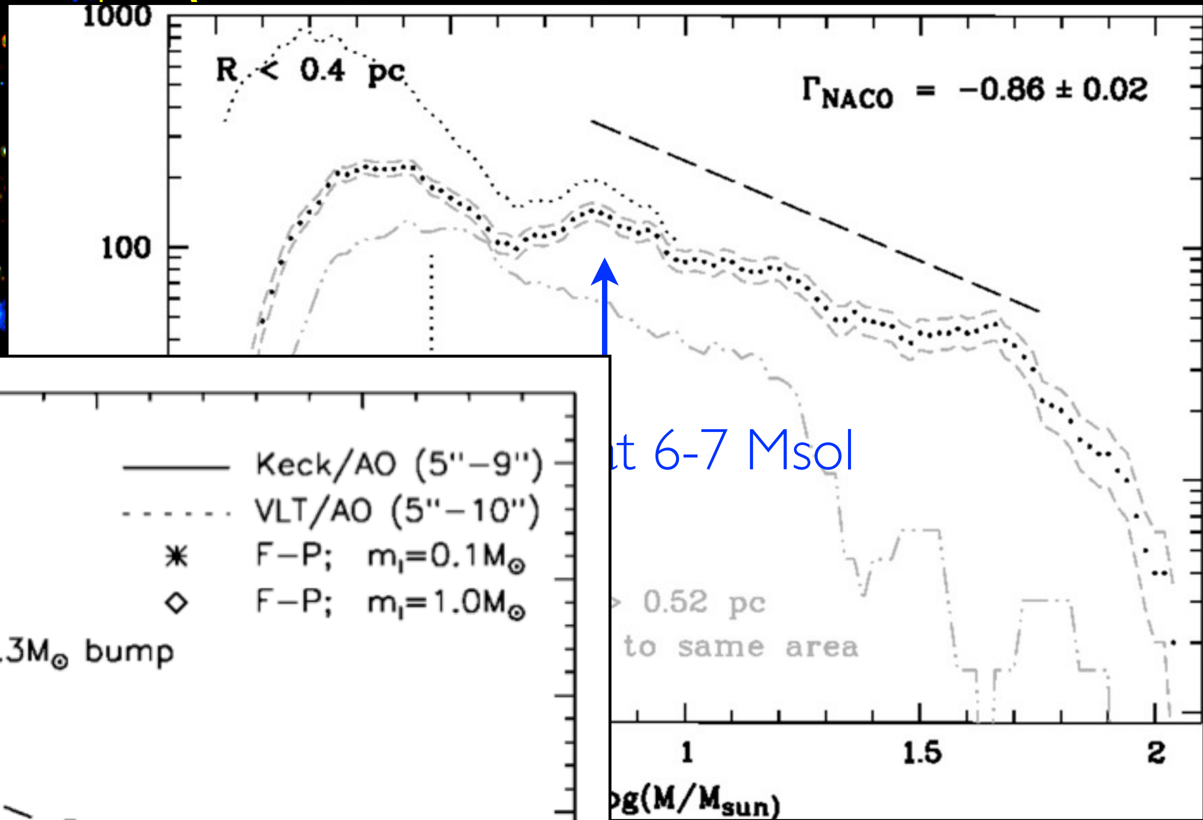
Kroupa (2001) - Multiple power-law segments

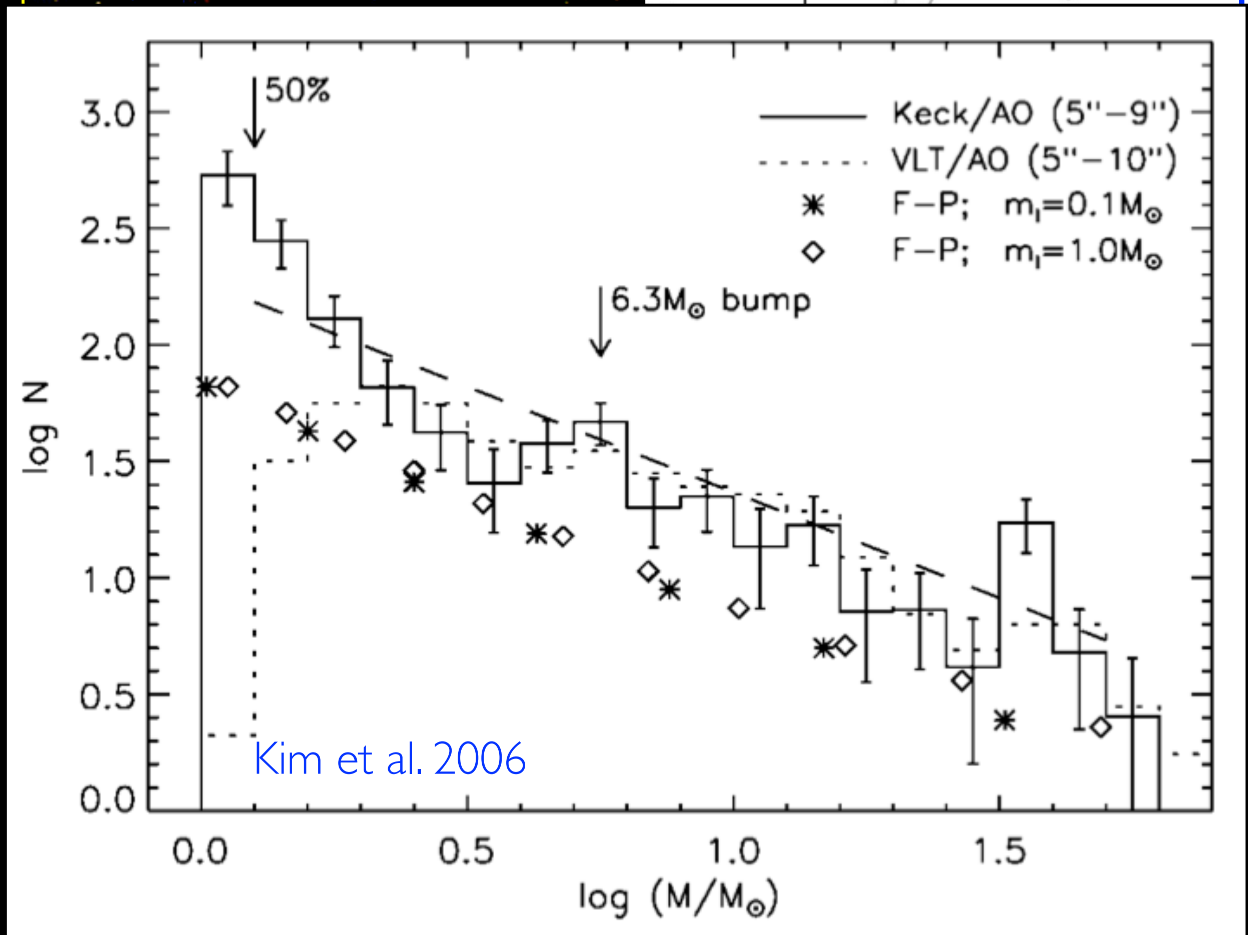
de Marchi et al. (2005) - Tapered power-law



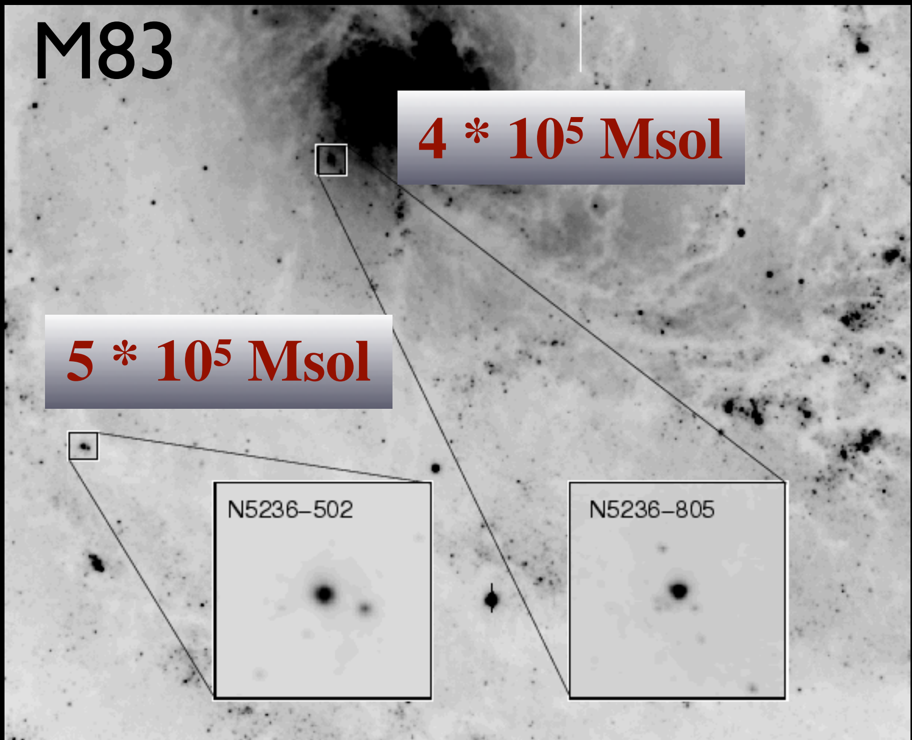
EXTREME STAR FORMATION IN THE GALAXY





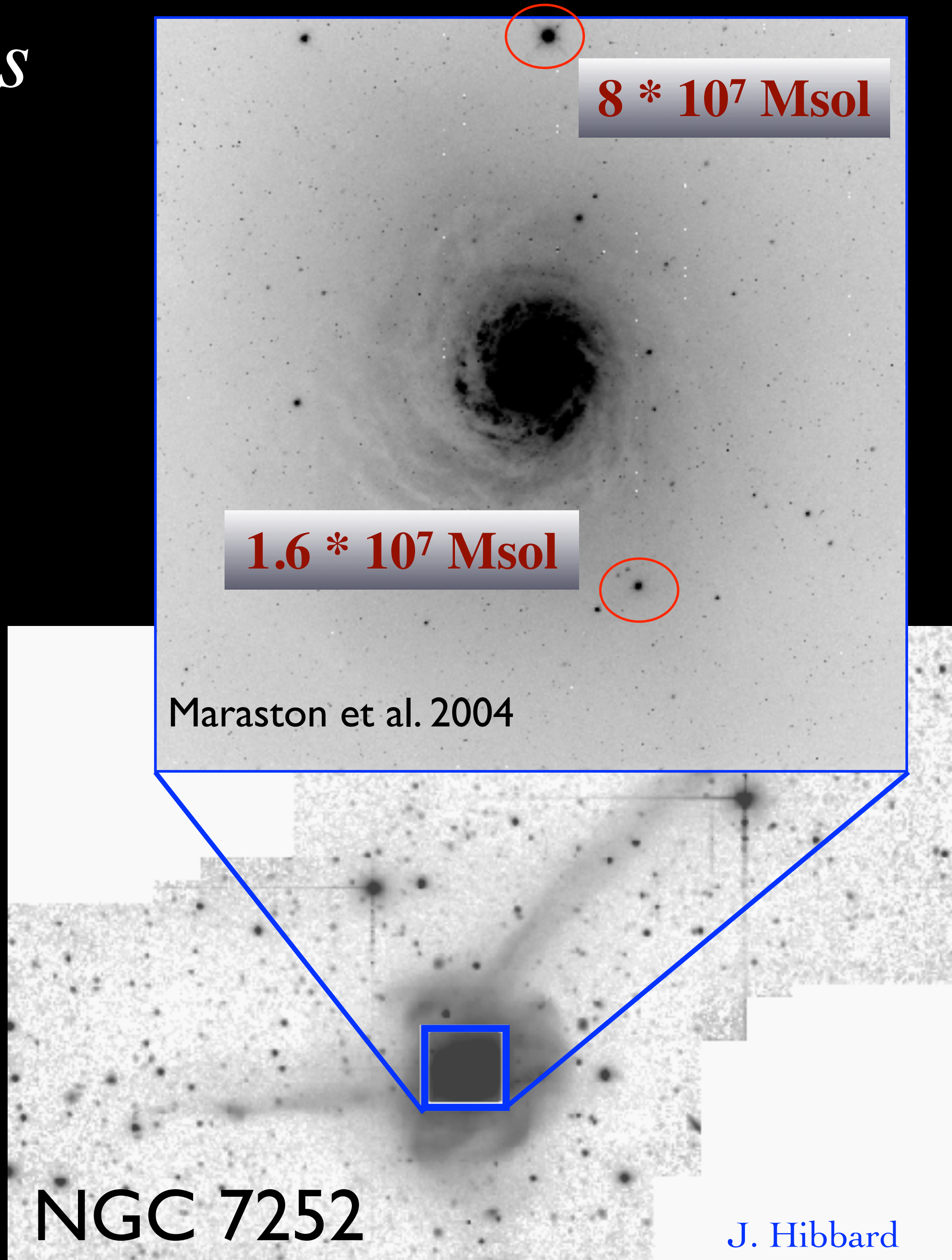


Young massive clusters



Larsen & Ritchler 2004

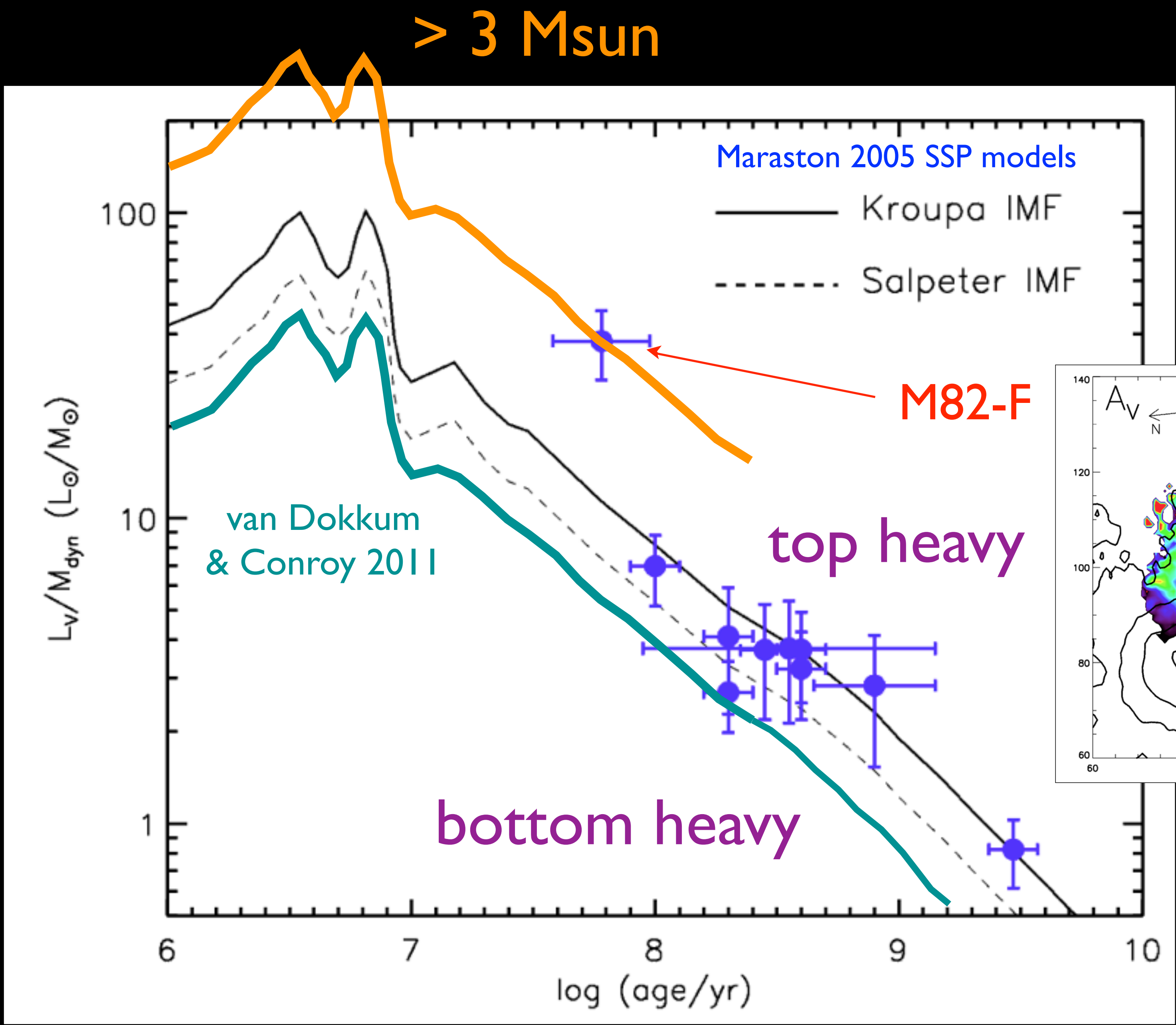
$$\mathcal{M}_{\mathrm{dyn}} = \eta \frac{\sigma_{\mathrm{x}}^2 r_{\mathrm{eff}}}{G}$$

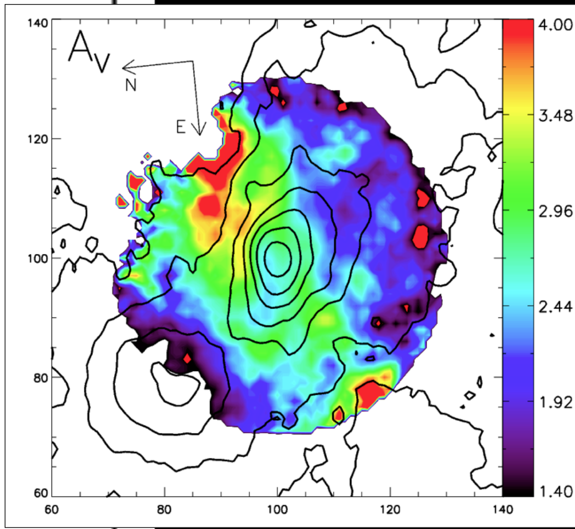


The IMF within YMCs

- Measure the velocity dispersion (a measure of the gravitational potential well) and radius of a cluster
- Use the Virial Theorem to work out the "dynamical mass"
- Compare this to the mass estimated through use of SSP models (i.e., compare the mass-to-light ratio of the clusters to that expected from models of that age)

Young massive clusters (>20 Myr)





Bastian et al. 2007

Smith & Gallagher 2001

Stellar IMF with YMC Summary

- While YMCs are extreme environments, there stellar mass functions do not appear to be very different than more typical star-forming regions/low mass clusters
- Resolved clusters in the Galaxy appear to be mass segregated
- GCs and YMCs have the same stellar IMF in the visible mass range (<0.8 Msun) if dynamical evolution is taken into account.
- However, there is evidence for very massive stars in YMCs, >300 Msun (Crowther et al. 2010)