Young Massive Clusters

Nate Bastian
(Liverpool, LJMU)

Research interests: YMCs, cluster populations, globular cluster formation and multiple populations, galaxy evolution

It's a school, so....

- Ask lots of questions (to teachers and other students)
- Let us know your interests, we can spend more/less time on any subject
- No set material to cover, so no need to rush
- Let us know if you have a hard time understanding (language or subject)

OB associations

- 20-500pc
- ρ ~0.1 stars/pc^3
- gravitationally unbound
- 12 within 650pc

open clusters

- core radii ~ 2pc
- mass = ~100 - 5000 $M_\odot$
- ~3 Myr < age < few Gyr - no gas leftover
- characteristic lifetime ~ few hundred Myr
- gravitationally bound

Embedded clusters

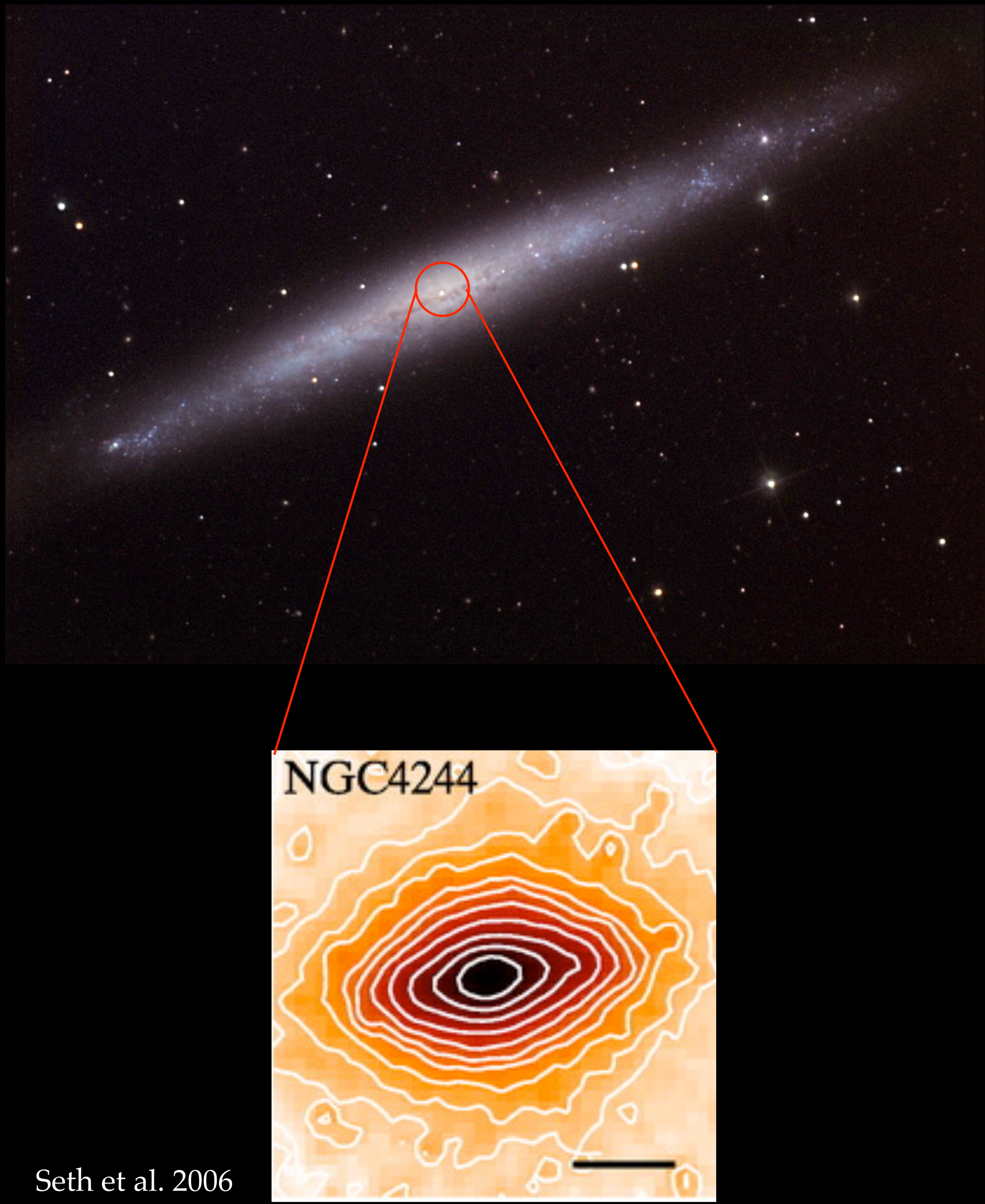
- few - 10 pc
- ρ ~ 100 - 1000 stars/pc^3
- age < 3-5 Myr
- may or may not be bound
- still gas in/around the cluster

globular clusters

- few to couple 10s of pc
- mass = ~10^4 - 10^6 $M_\odot$
- age ~ 10-12 Gyr
- gravitationally bound

nuclear clusters

- few to couple 10s of pc
- mass = ~10^5 - 10^8 $M_\odot$
- age ~ multiple epochs of star formation
- centers of some galaxies



Seth et al. 2006

Young Populous Clusters

NGC 1850 • Star Clusters in the Large Magellanic Cloud
Hubble Space Telescope • WFPC2

NASA, ESA and M. Romaniello (European Southern Observatory) • STScI-PRC01-25

- ~100 Myr old
- ~10^5 Msun
- in the LMC

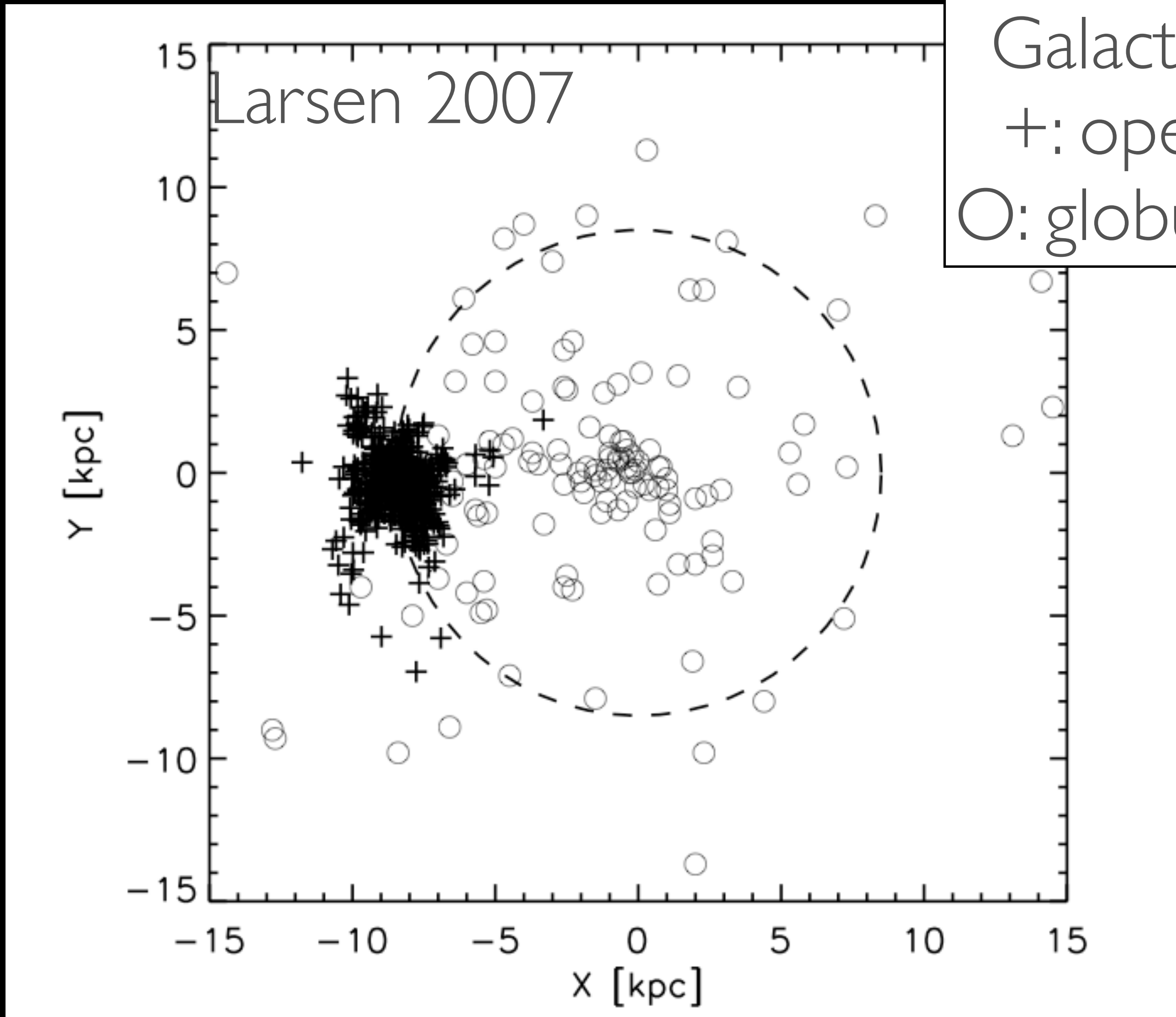
Young/intermediate age clusters in the LMC

NGC 1850 • Star Clusters in the Large Magellanic Cloud
Hubble Space Telescope • WFPC2
NASA, ESA and M. Romaniello (European Southern Observatory) • STScI-PRC01-25

Name	Age
R136	2 Myr
NGC 1850	90 Myr
NGC 1866	180 Myr
NGC 1856	280 Myr
NGC 1806	1.5 Gyr
NGC 1846	1.6 Gyr
NGC 1783	1.7 Gyr
NGC 419	1.5 Gyr (SMC)

All ~10^5 Msun

Where are they in the Galaxy?



Galactic Clusters
+: open clusters
O: globular clusters

Young Massive Clusters in the Galaxy

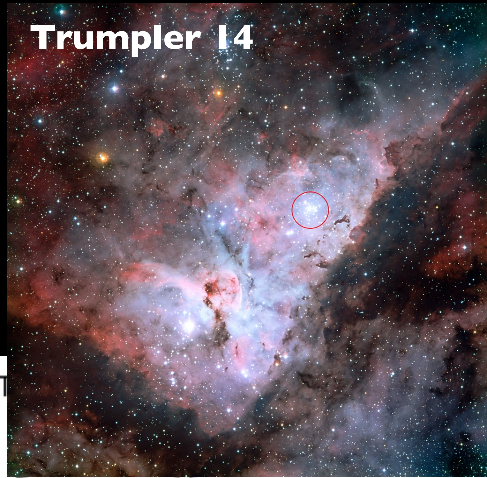
The Super Star Cluster Westerlund 1
(2.2m MPG/ESO + WFI)

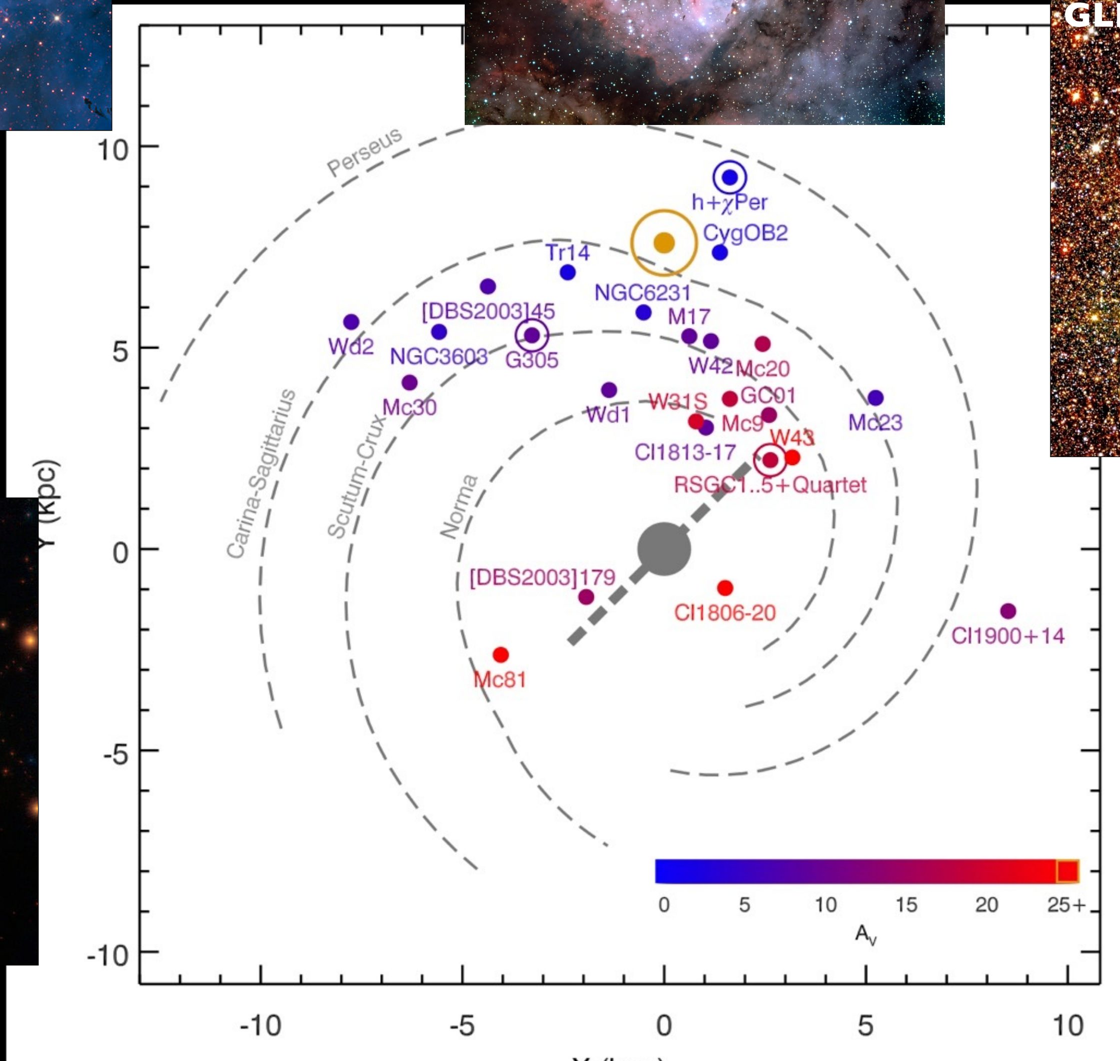
ESO PR Photo 09a/05 (22 March 2005) © European Southern Observatory

Name	Age
NGC 3603	2 Myr
Arches	2-4 Myr
Trumpler 14	2 Myr
Westerlund 1	5-7 Myr
RSGC 1	12 Myr
RSGC 1	17 Myr
Glimpse C01	0.5-2 Gyr

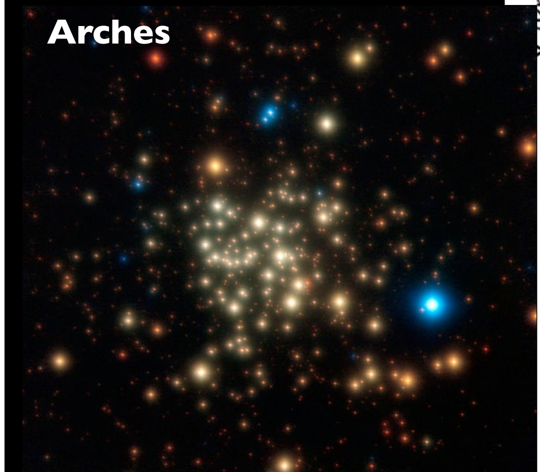
All between 10^4-10^5 Msun

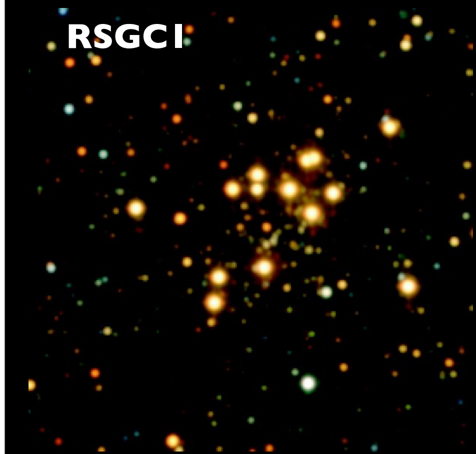
Young massive clusters (YMCs) in the Galaxy





Davies et al. 2011





also see Portegies Zwart, McMillan, & Gieles 2010

Reviews of YMCs and their properties

- Portegies Zwart et al. (2010, ARAA) - PZMG10
- Adamo & Bastian (2015, http://www.astro.ljmu.ac.uk/~njb/Reviews.html)
- Longmore et al. (2014, PPVI review of YMCs)
- Larsen 2010 (arXiv:0911.0796)
  - Whitmore 2001 - (astro-ph/0012546)

Historical development

- Have been known in the LMC for a long time (e.g. R136 in 30dor)
- Schweizer (1987) - GCs may form in galaxy mergers, bright blue sources in ongoing mergers - young globular clusters
- Holtzman et al. (1992) - HST WFPC imaging of NGC 1275
  - hundreds of “bright blue clusters”, sizes < 15pc, bluer than any globular clusters, and brighter than the “blue” LMC clusters

Active Galaxy NGC 1275

NASA and The Hubble Heritage Team (STScI/AURA) • Hubble Space Telescope WFPC2 • STScI-PRC03-14

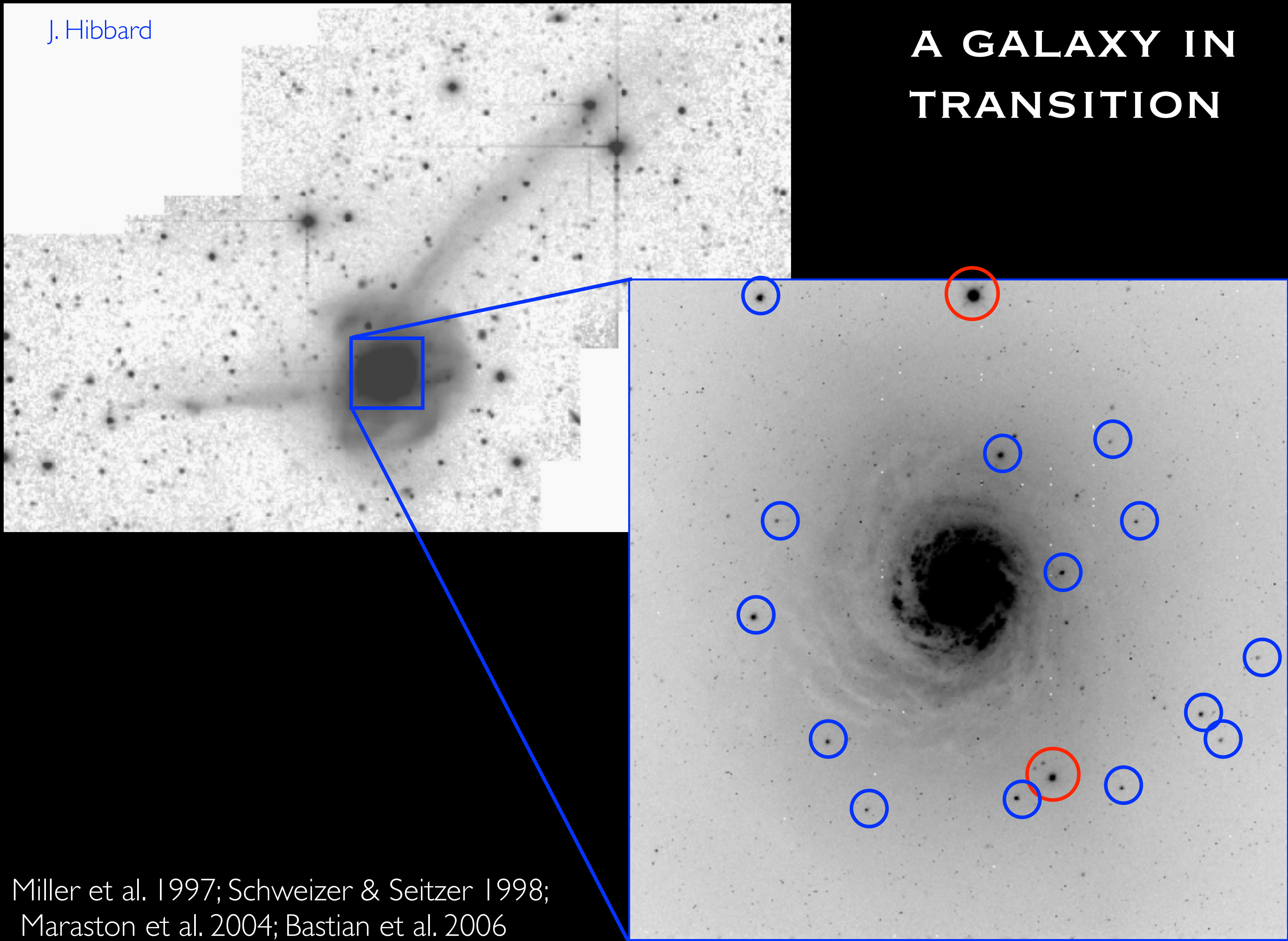
Historical development

- Ashman & Zepf (1992) - "The formation of globular clusters in merging and interacting galaxies"
  Theory
- Zepf & Ashman (1993) - "Globular Cluster Systems Formed in Galaxy Mergers"
  Observation

Abstract

We show that current observations support the hypothesis that globular clusters form in galaxy mergers. In a previous paper, we presented a model in which globular cluster formation is a result of interactions and mergers of galaxies. Here, this model is compared with new observations of the globular cluster systems of recent galaxy mergers and normal elliptical galaxies. We find that our model is consistent with the number and luminosity of young globular clusters in currently merging galaxies. If elliptical galaxies form through mergers of spiral galaxies, the model also predicts that the globular cluster systems of normal elliptical galaxies should have at least two peaks in the metallicity distribution. We show that observations of the globular cluster systems of nearby elliptical galaxies support this prediction. More generally, the presence of more than one peak in the globular cluster metallicity distribution strongly argues against a single formation epoch for globular clusters in elliptical galaxies. Instead, these observations favour formation models in which globular clusters form in two or more bursts, as is the case in our merging model.

NGC 7252
A GALAXY IN TRANSITION



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

NGC 4038/39
The Antennae

Whitmore et al. 1999; 2010

NGC 3256

Zepf et al. 1999; Trancho et al. 2007

NGC 1316

“Young” elliptical galaxy
Major merger ~3 Gyr ago

Goudfrooij et al. 2001

Young GCs Forming Today

- Young cluster populations forming today
- Some have similar properties to the ancient GCs
- Globular cluster populations forming (at least partially) in galaxy mergers
- It was the spatial resolution of HST that opened this field

We also see Young Massive Clusters forming in nearby spirals

Larsen & Richtler 1999; 2000; Bastian et al. 2005

NGC 1569

And also in ‘starbursting’ dwarf galaxies

Anders et al. 2004

Young GCs Forming Today

- Not just in galaxy mergers though
- Also in normal spirals and star bursting dwargs
- Wherever the star-formation rate is high, young GCs are forming

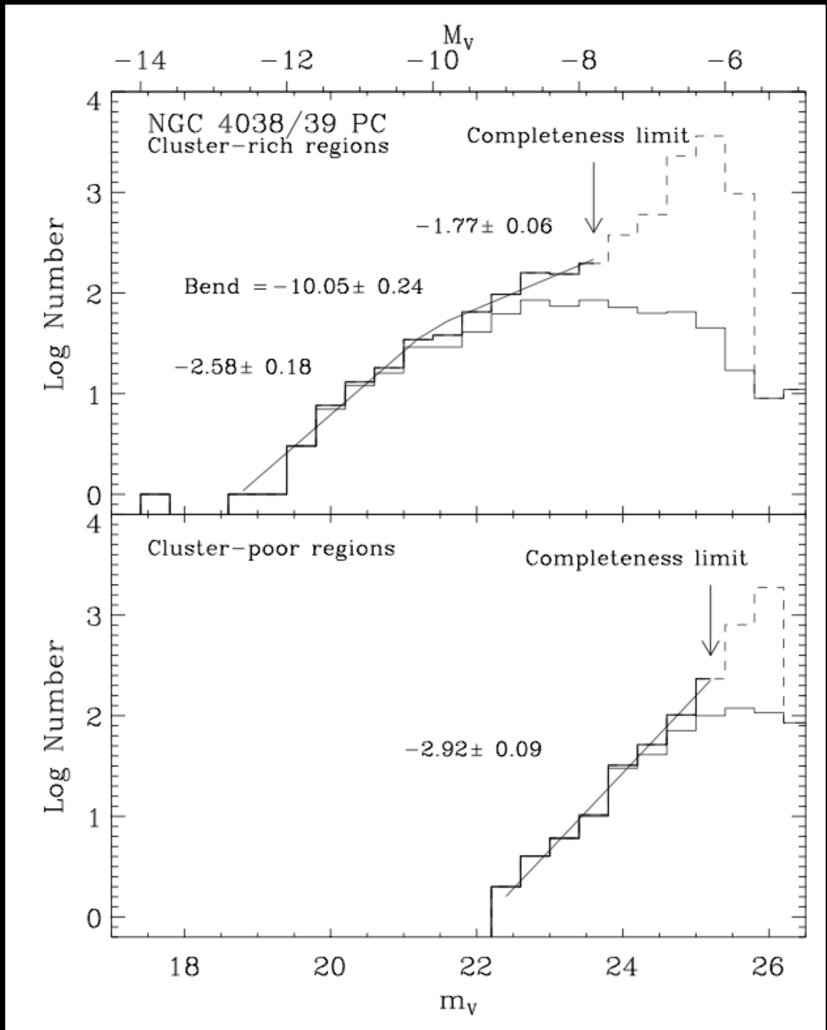
Their properties: Luminosity function

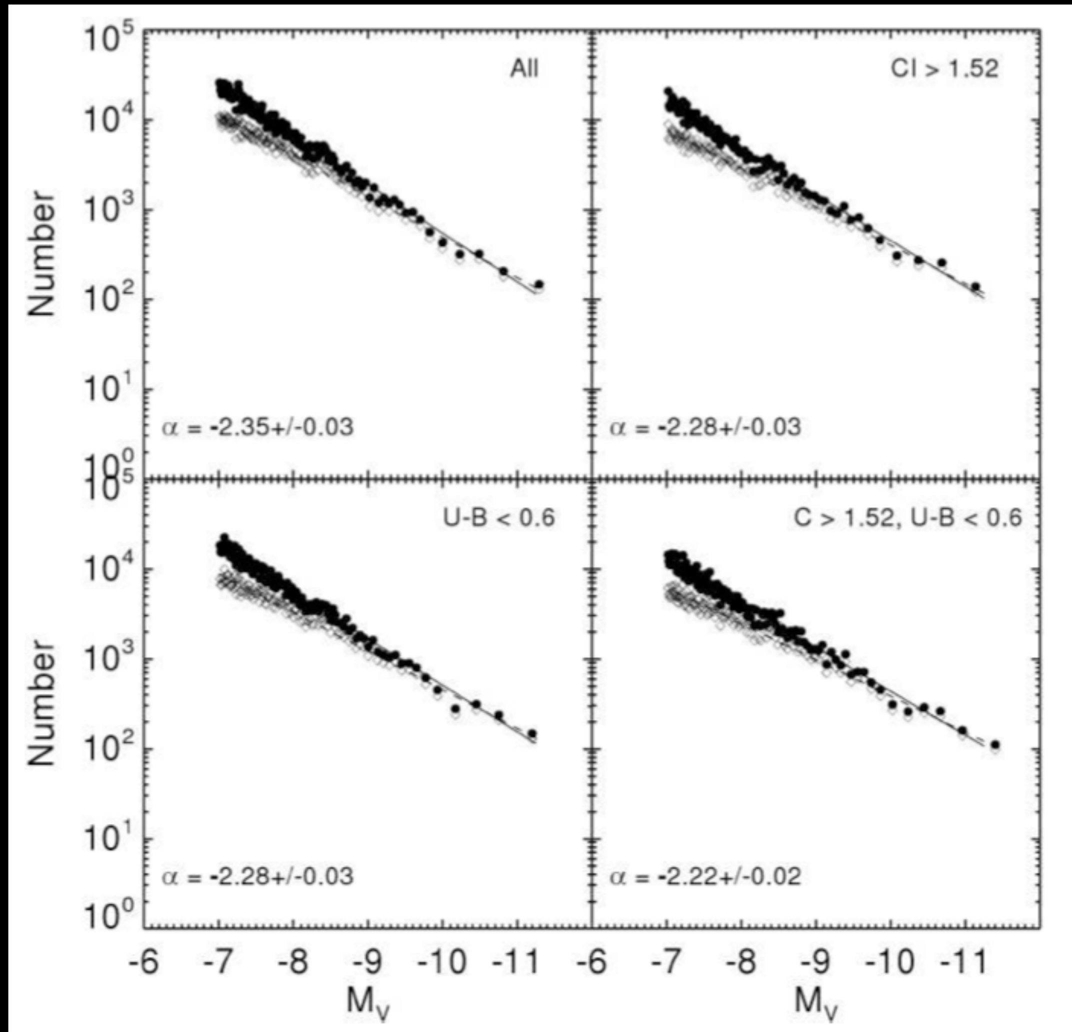
- The number of clusters as a function of luminosity
- Basic property, directly from the observations, no ‘fitting’ is necessary.

Their properties: Luminosity Function

$$NdL \sim L^{-\alpha}dL$$

The Antennae





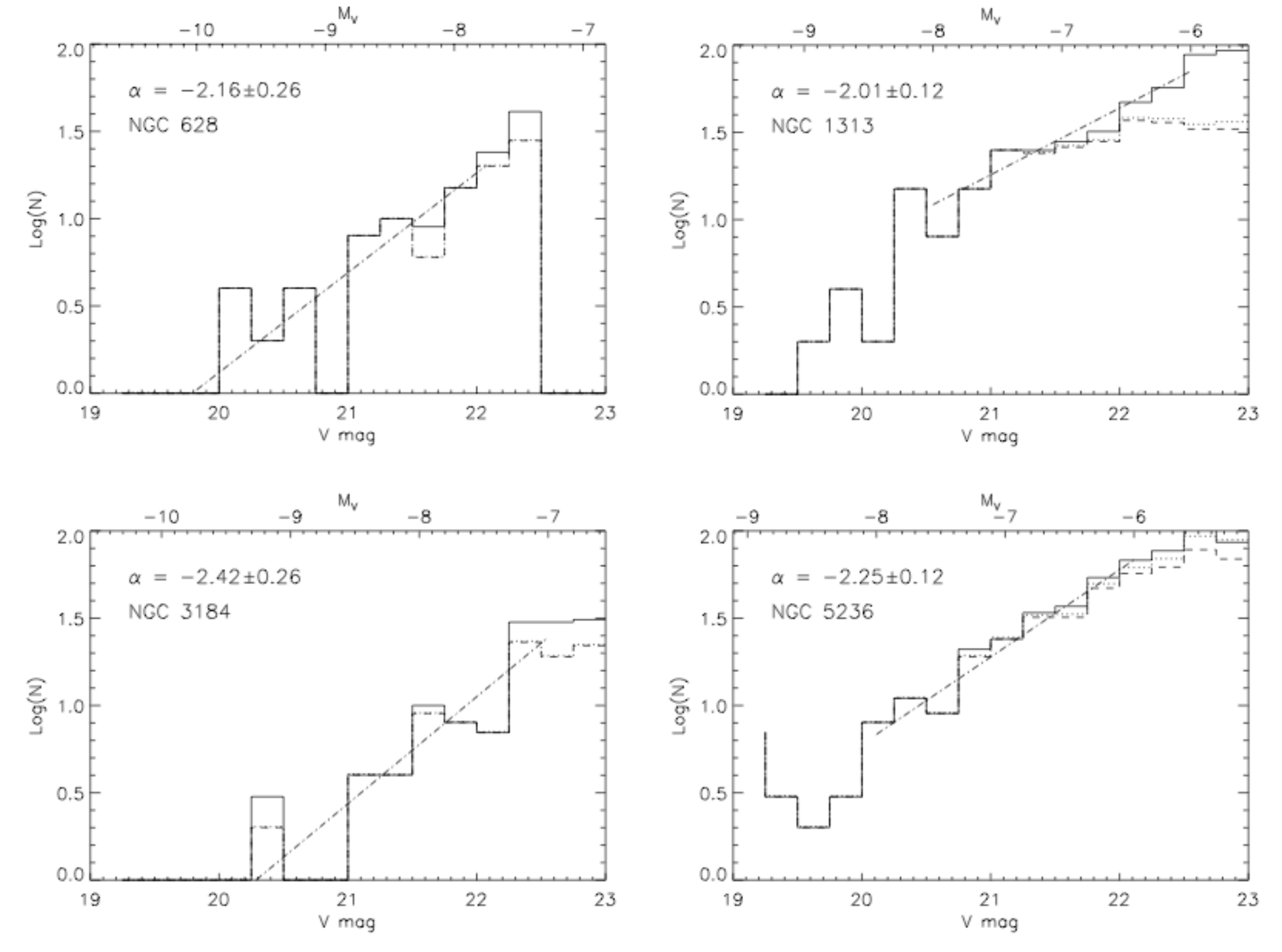
Whitmore et al. 1999

Whitmore et al. 2010

Their properties: Luminosity Function

$$N dL \sim L^{-\alpha} dL$$

4 spiral galaxies

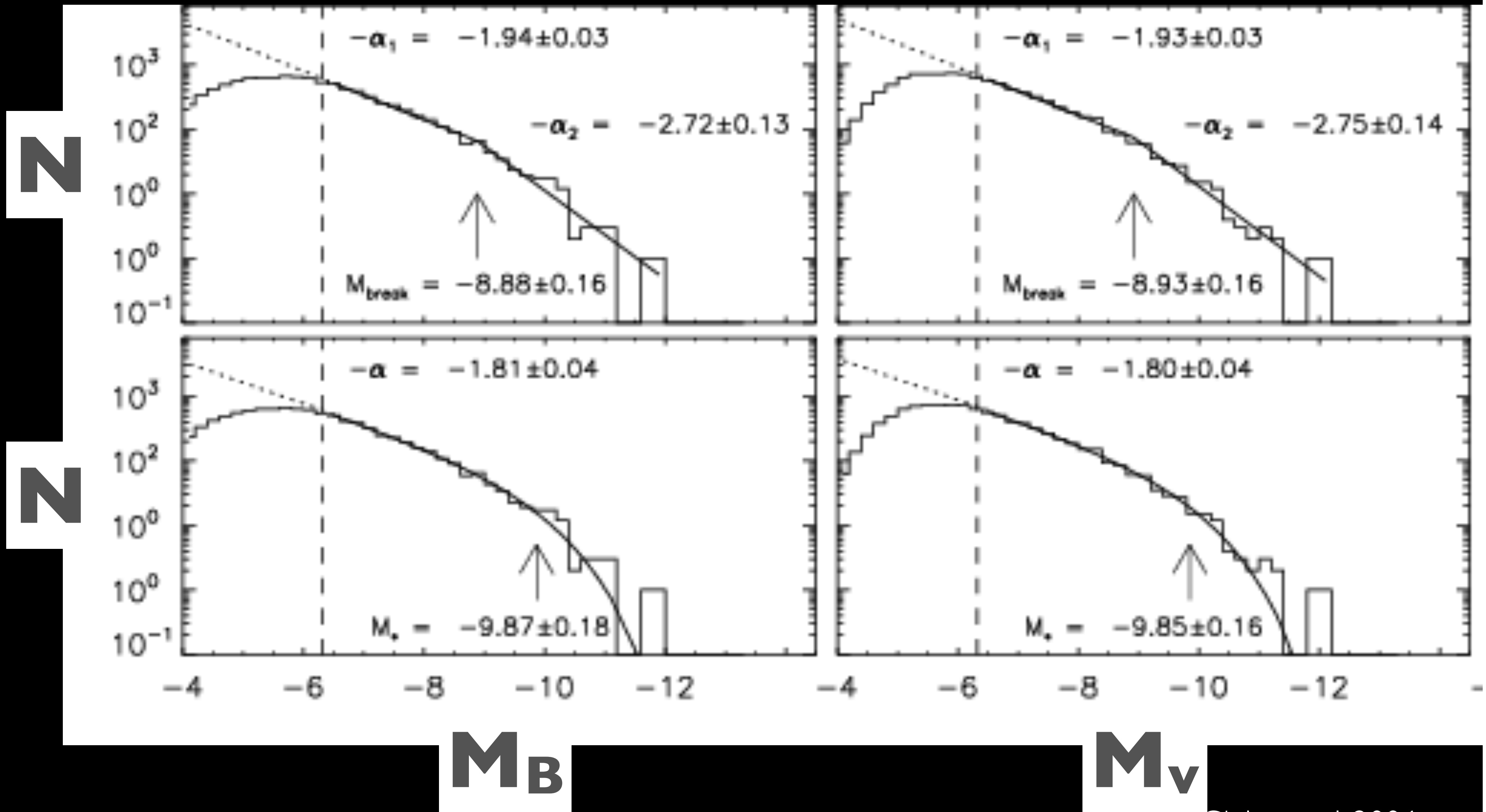


Larsen 2002

Their properties: Luminosity Function

$$N dL \sim L^{-\alpha} dL$$

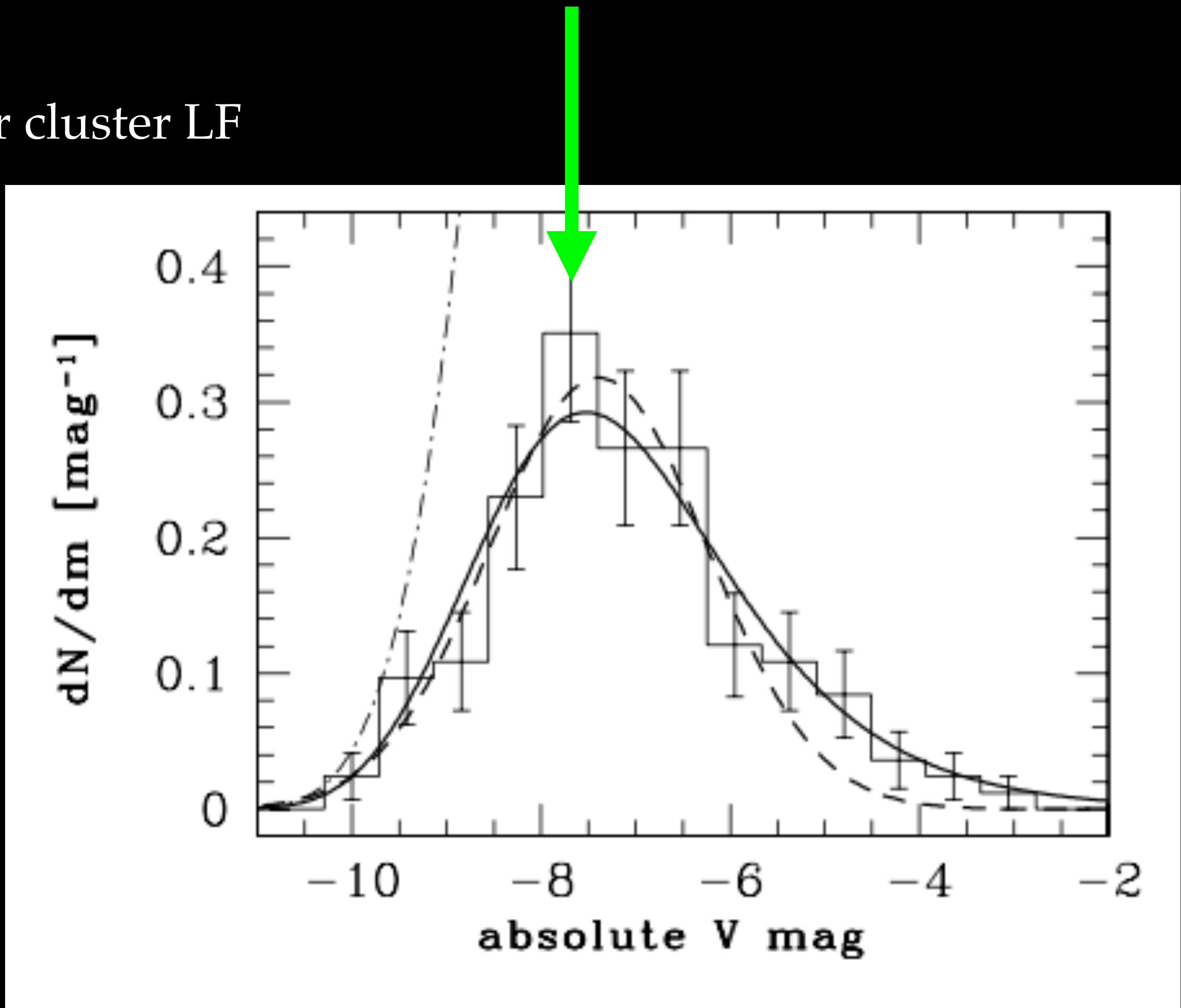
M51 (spiral galaxy)



Gieles et al. 2006

Their properties: Luminosity Function

Globular cluster LF



Jordan et al. 2007

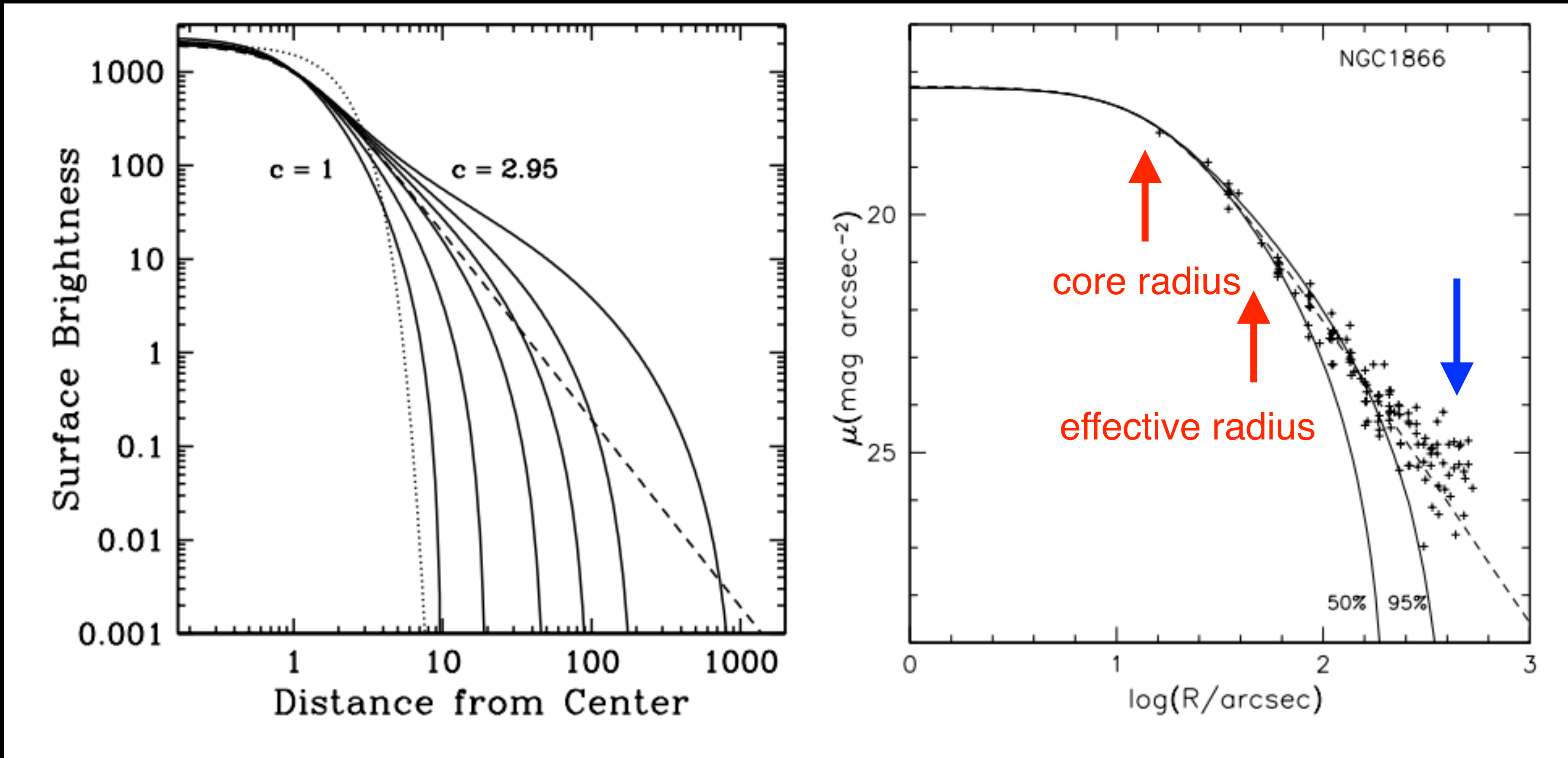
Their properties: Luminosity Function

- Power-law, $N dL \sim L^{-\alpha} dL$, with index $\alpha = 2$
- Some evidence for steeping at bright luminosity (Schechter type distribution)
- Very different from the ancient GCs, which have a Gaussian luminosity function

Their properties: Size distribution

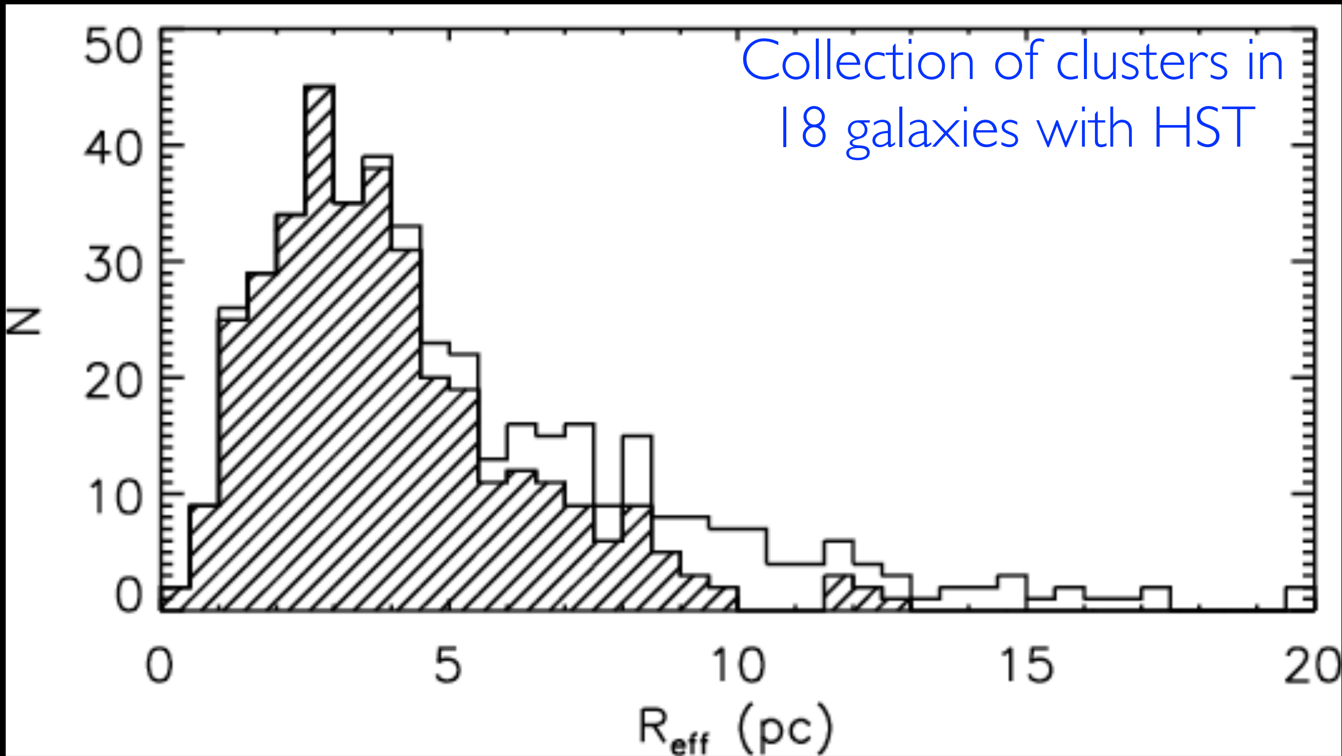
Luminosity profiles

Schweizer 2004



Old GCs show truncations (King profiles), young GCs show power-law profiles (with index η)

Their properties: Size distribution

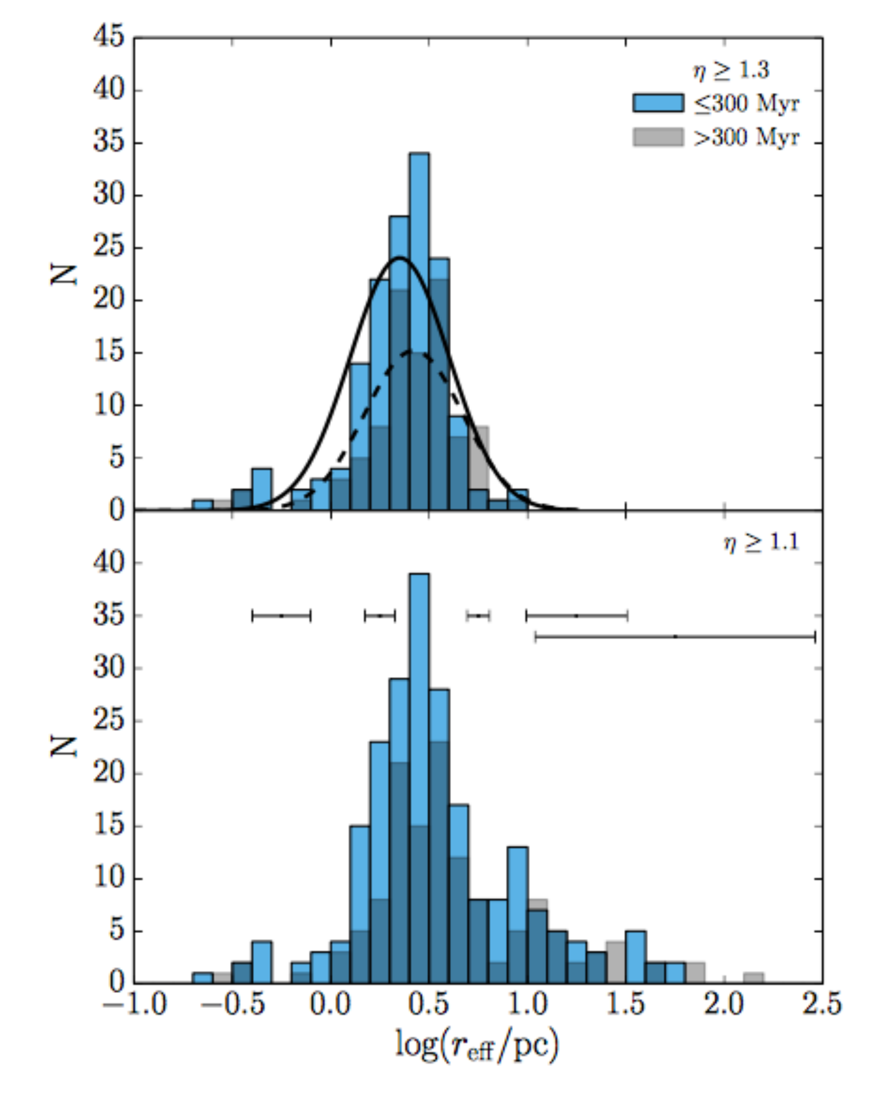


Larsen 2002

R_{eff} is the radius containing half the light of the cluster

Surprisingly Universal: mean R_{eff} = ~2.5 pc (similar to GCs)

Their properties: Size distribution



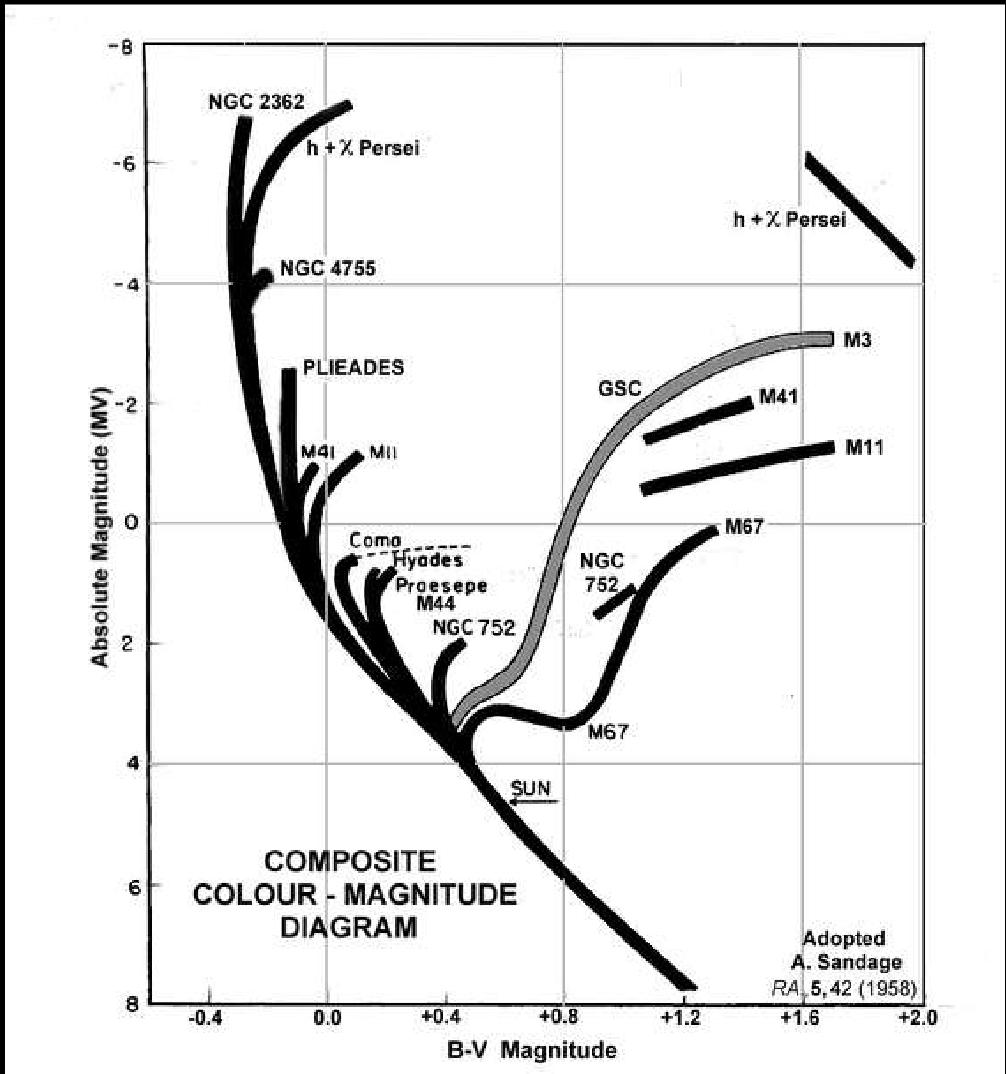
Ryon et al. 2015

M83 (spiral galaxy) cluster population

Their properties: Cluster sizes

- Gaussian or ‘log-normal’ with a peak at ~2.5 pc
- GCs and YMCs show the same basic size distribution
- However, YMCs show extended luminosity profiles (Elson, Fall and Freeman - EFF) while GCs generally show a truncation (King profile)

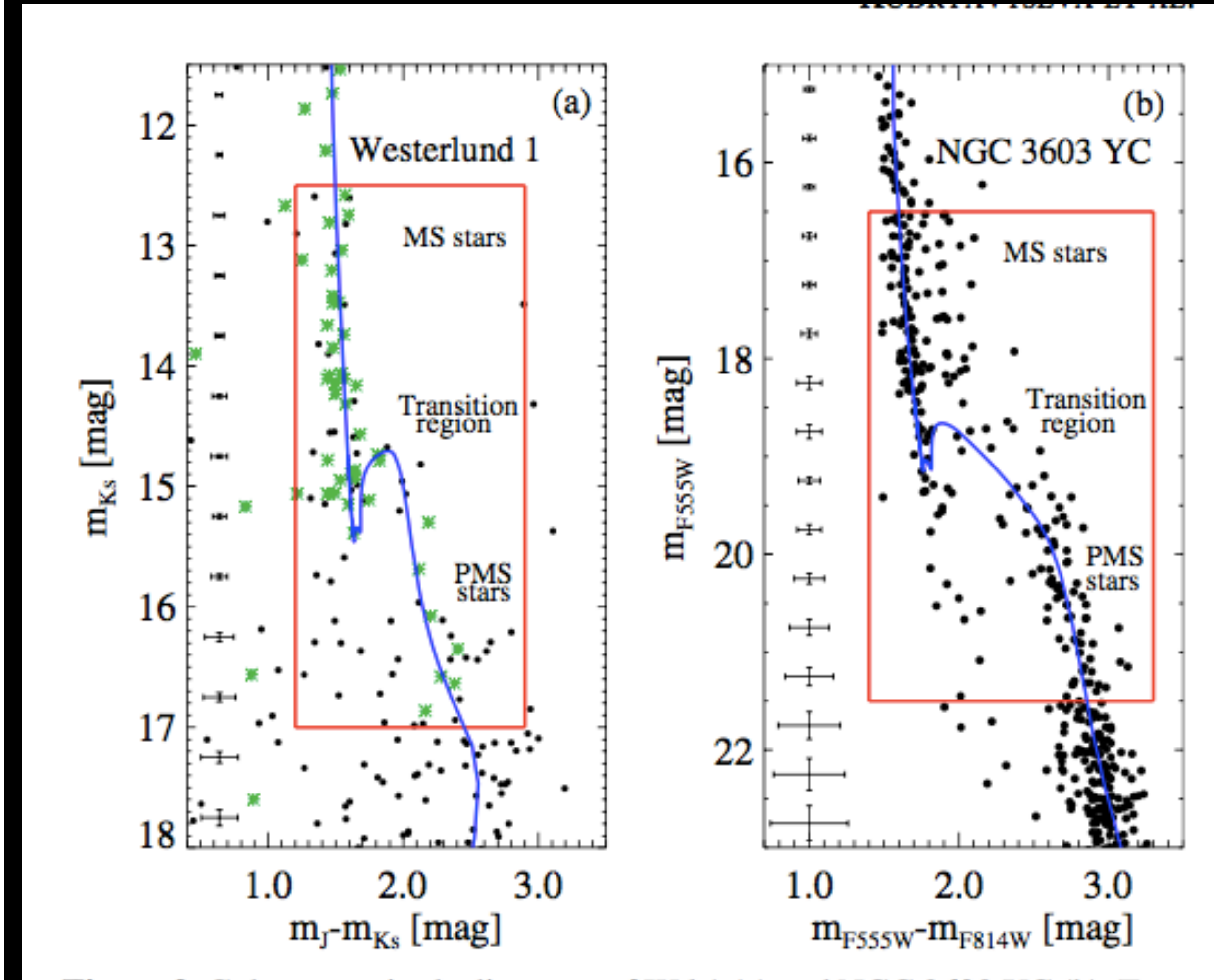
Deriving cluster ages, extinctions and masses



Colour Magnitude Diagram (CMD)

Deriving cluster ages, extinctions and masses

Colour Magnitude Diagram (CMD)

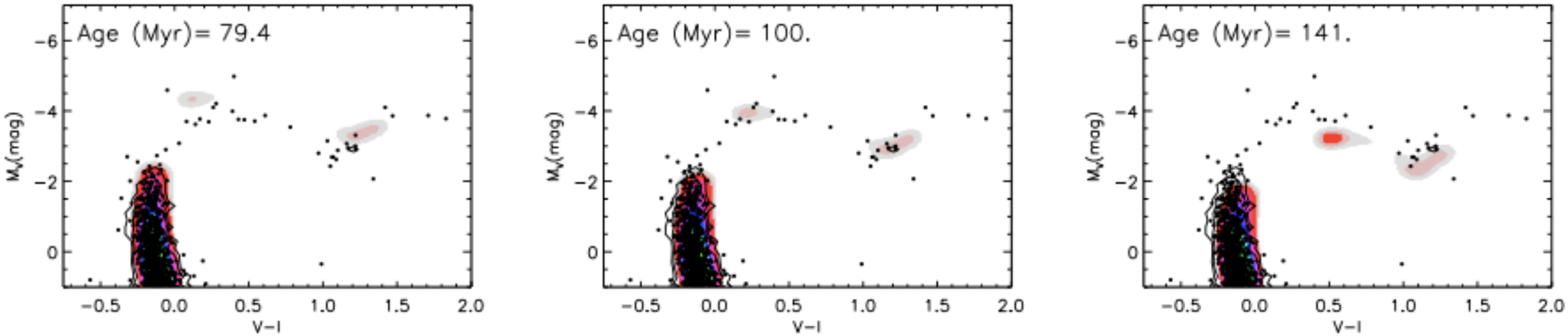


From Galactic YMCs (<10 Myr) age spreads < 1-2 Myr

Kudryavtseva et al. 2012

Deriving cluster ages, extinctions and masses

Colour Magnitude Diagram (CMD)

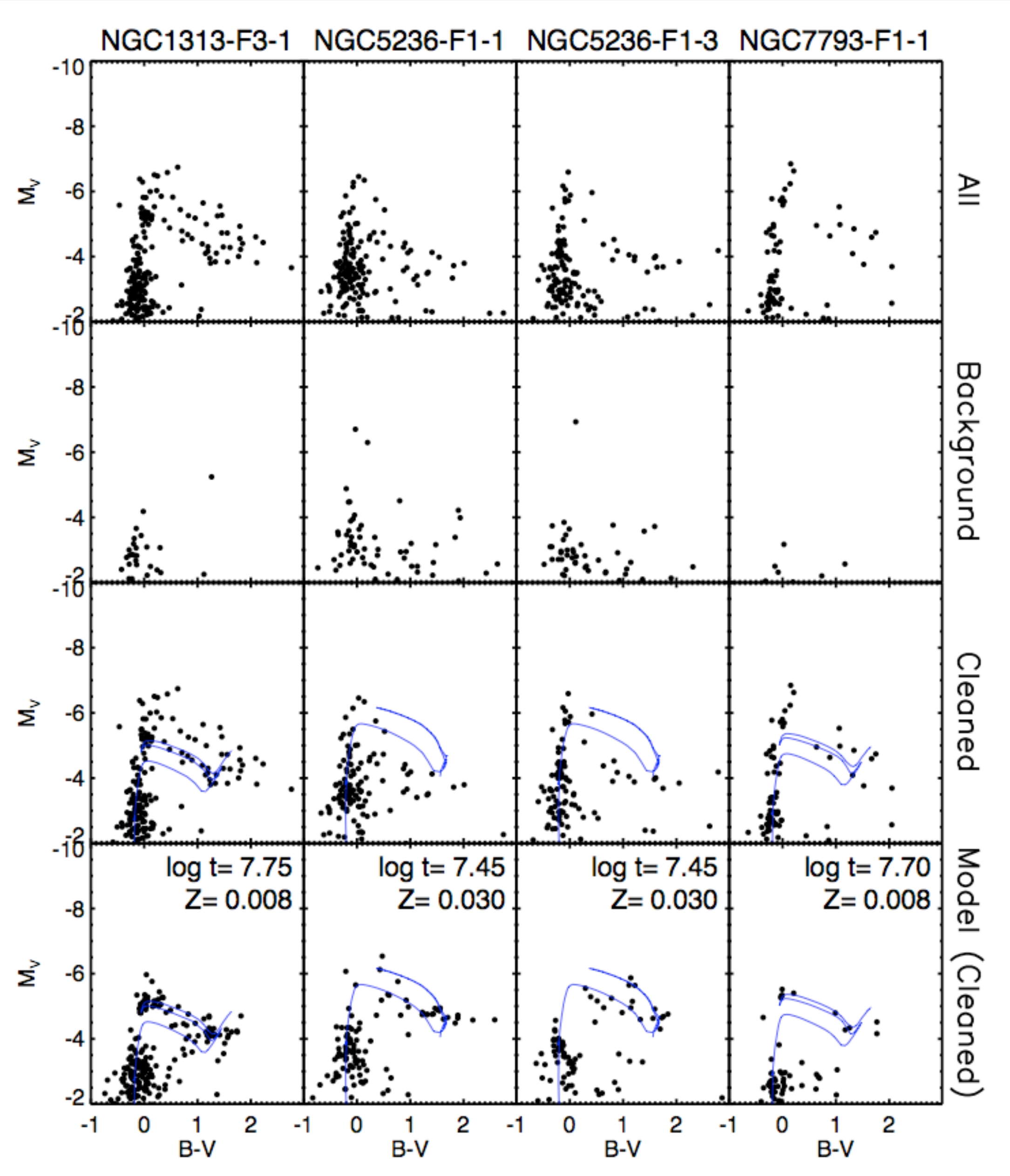


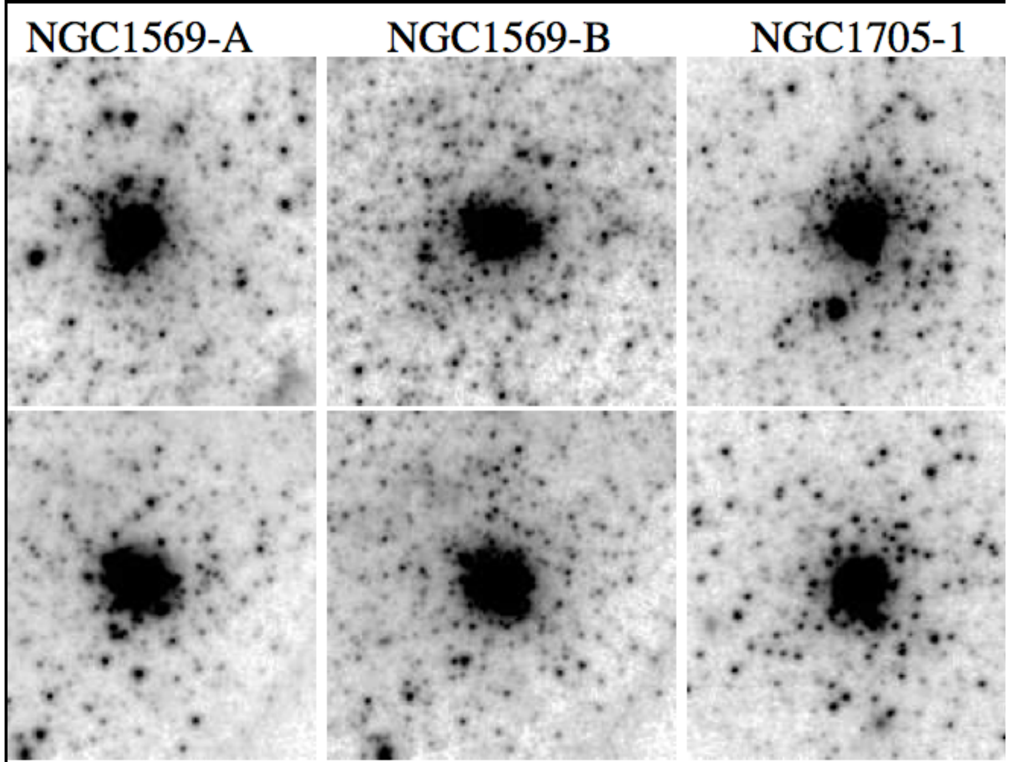
NGC 2157
Niederhofer et al. 2015

From LMC YMCs (<300 Myr) age spreads < 50 Myr

Deriving cluster ages, extinctions and masses

Colour Magnitude Diagram (CMD)





Larsen et al. 2011

CMD summary

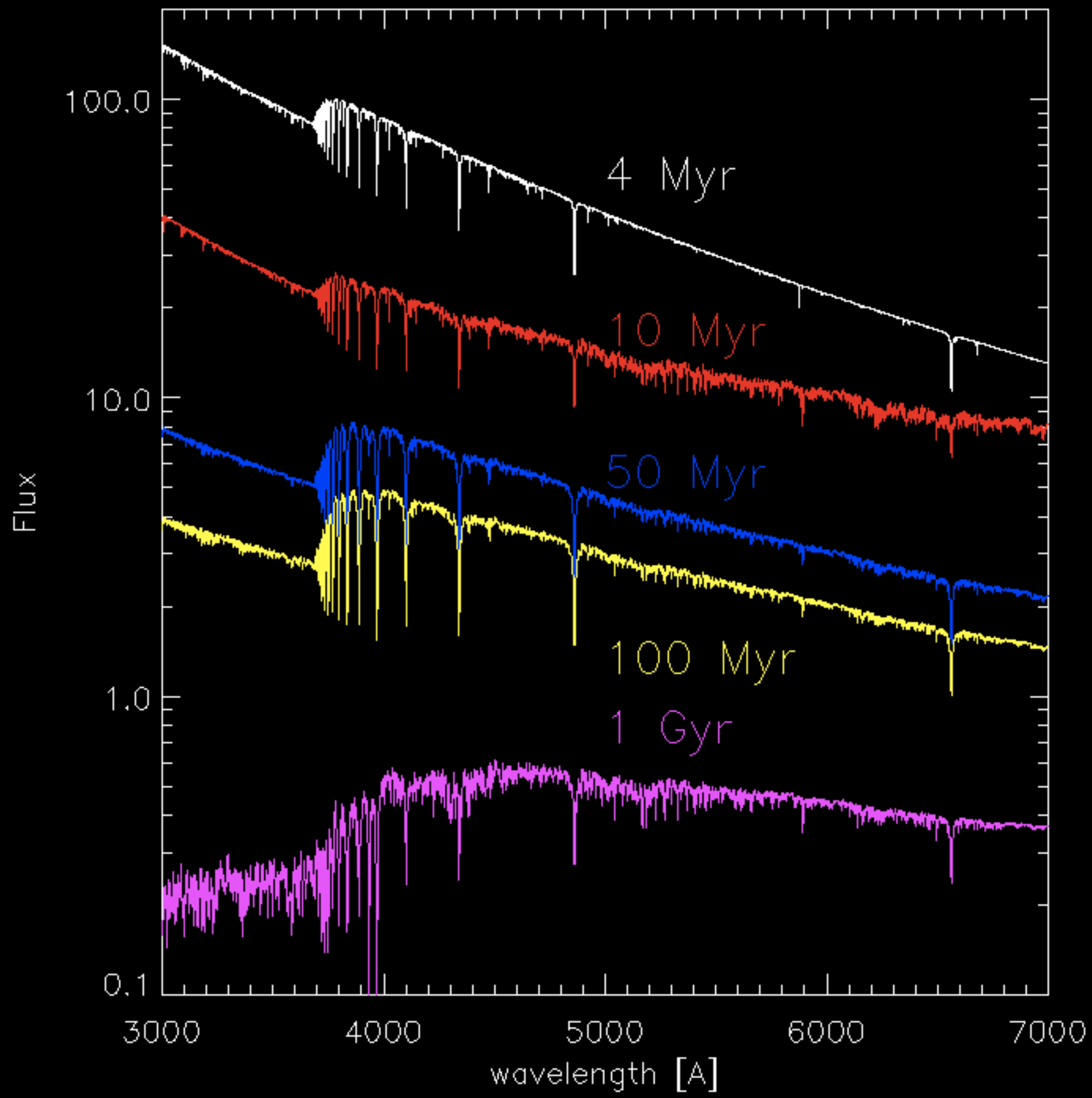
- in young massive clusters that can be resolved, their CMDs show small (or non-existant age spreads)
- the constraints that can be put depend on the age of the cluster, best constraints for youngest clusters
- consistent with no age spreads, but their are CMD features that are not fully explained yet

population synthesis

- for each mass/age a star has a given colour/Teff, magnitude and spectra
- for "simple stellar population models", all stars have the same age and metallicity
- 'make' a bunch of stars populating an IMF
- assign each star a weight (based on the luminosity) at each wavelength
- sum everything up

ignore the problems...

- binaries
- uncertain aspects of stellar evolution
- cluster effects on evolution (stellar exotica)
- assume a fully sampled initial mass function of stars



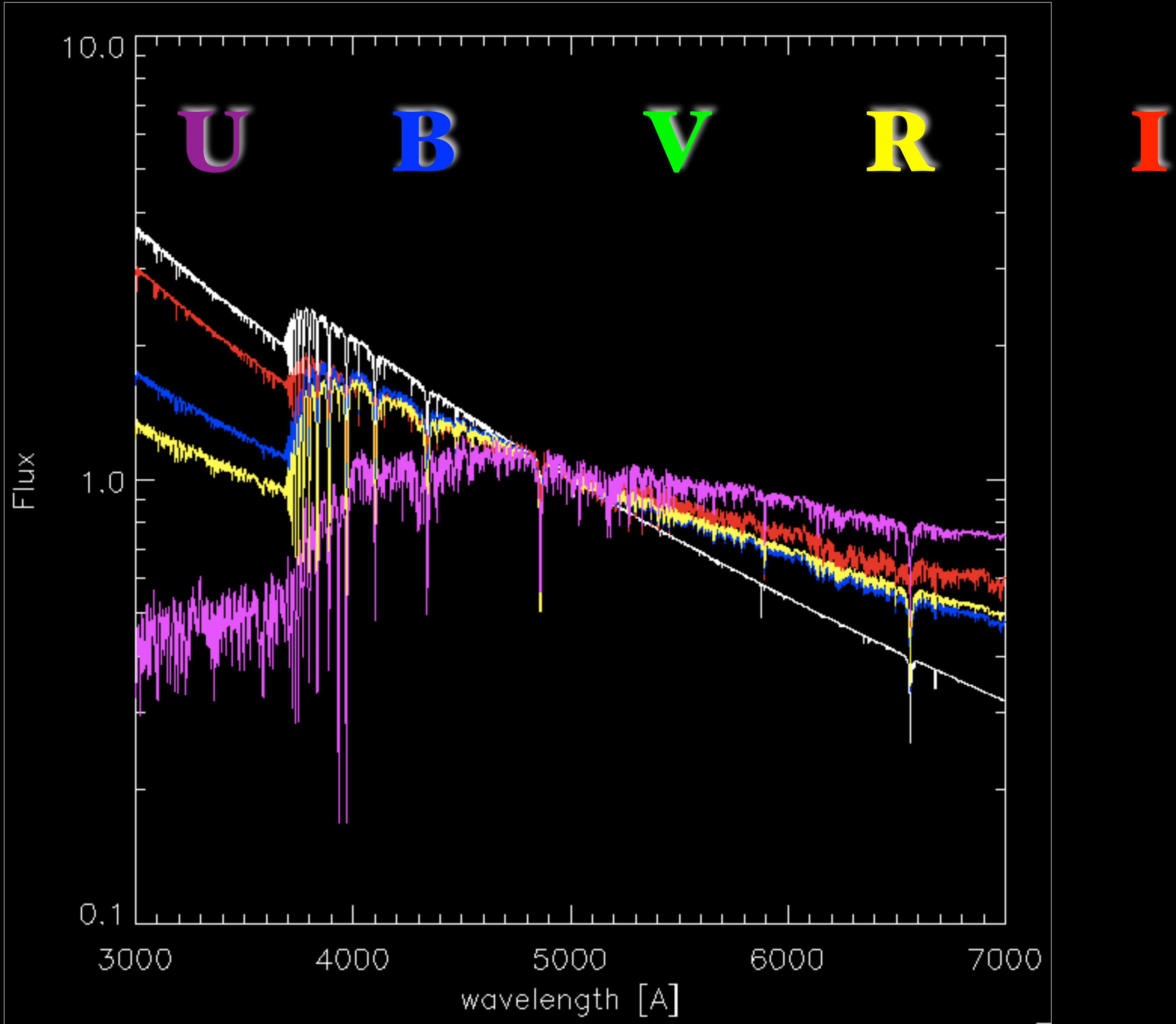
continuum shape

absorption line strengths

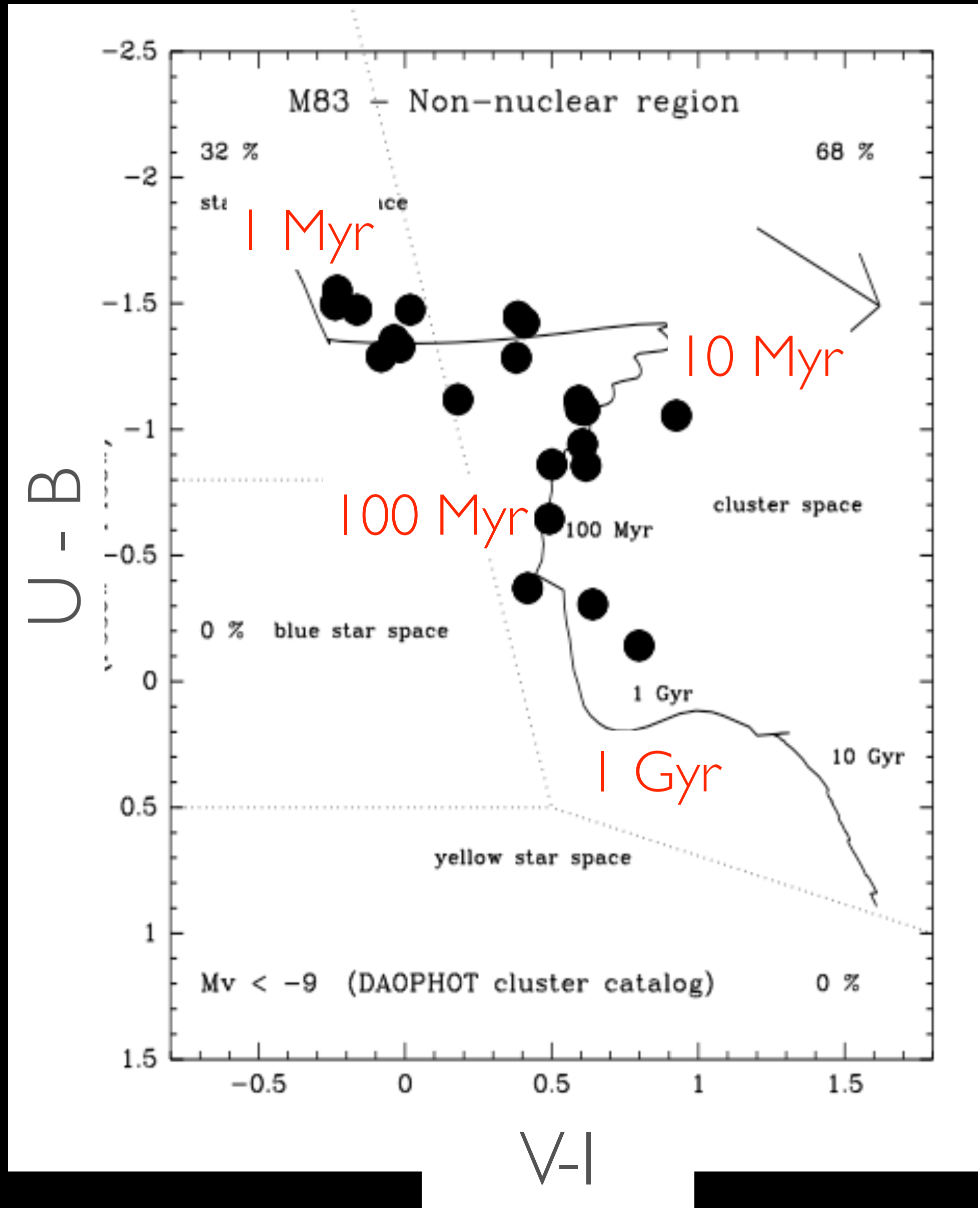
can get age, metallicity simultaneously (<1 Gyr)

above ~2 Gyr strong degeneracy between age and metallicity

González-Delgado et al. 2005


U
B
V
R
I
10.0
1.0
0.1
Flux
3000
4000
5000
6000
7000
wavelength [A]

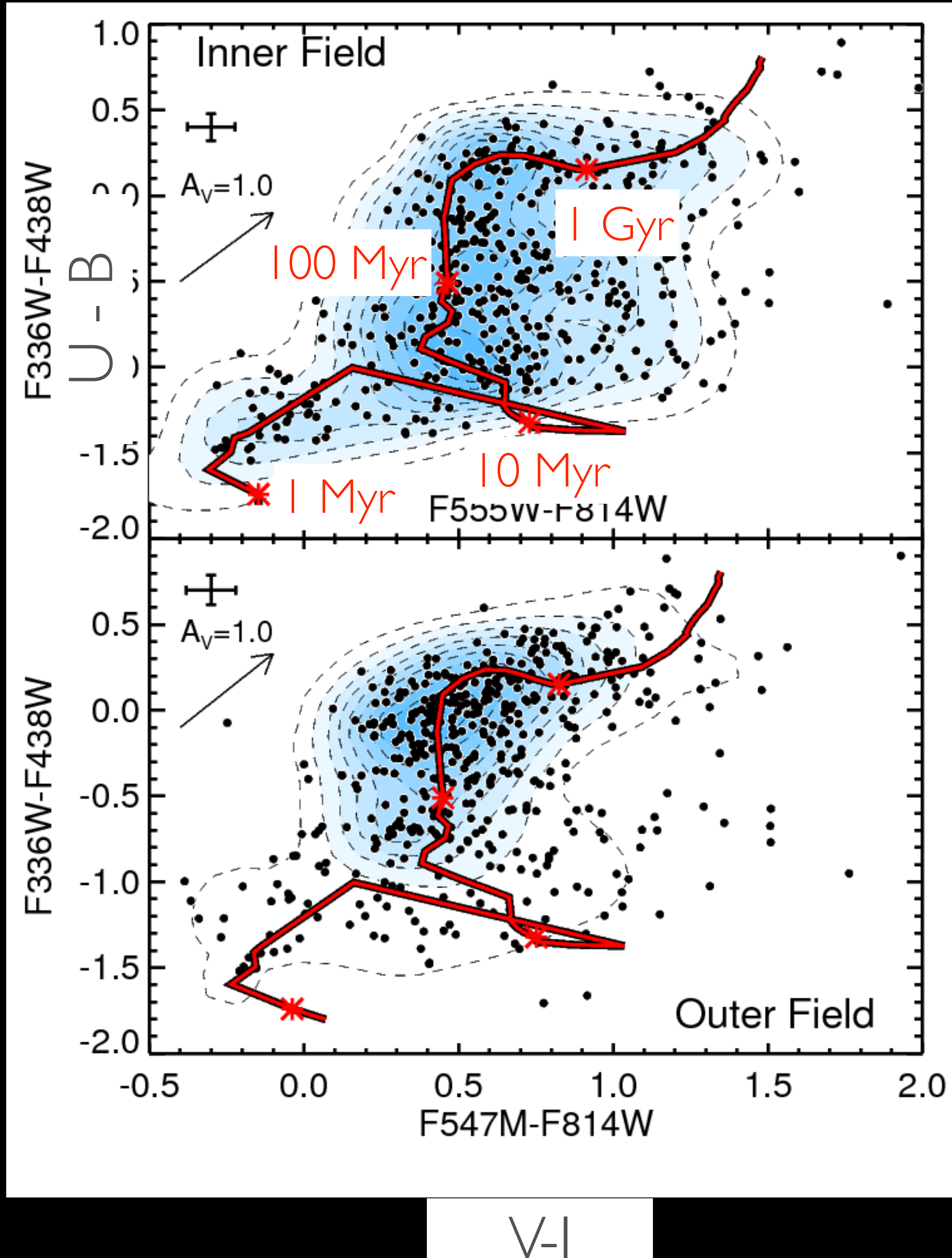
- locate a cluster in colour space
- move it along extinction vector until you hit the SSP model
- sometimes multiple solutions exist
- once you have the age and extinction, you get the mass by comparing the observed luminosity to that of the models



Chandar et al. 2010

Colour-colour plots of cluster populations in 2 parts of M83 (spiral galaxy)

What can we see about the relative average age in each region?



Bastian et al. 2011

- locate a cluster in colour space
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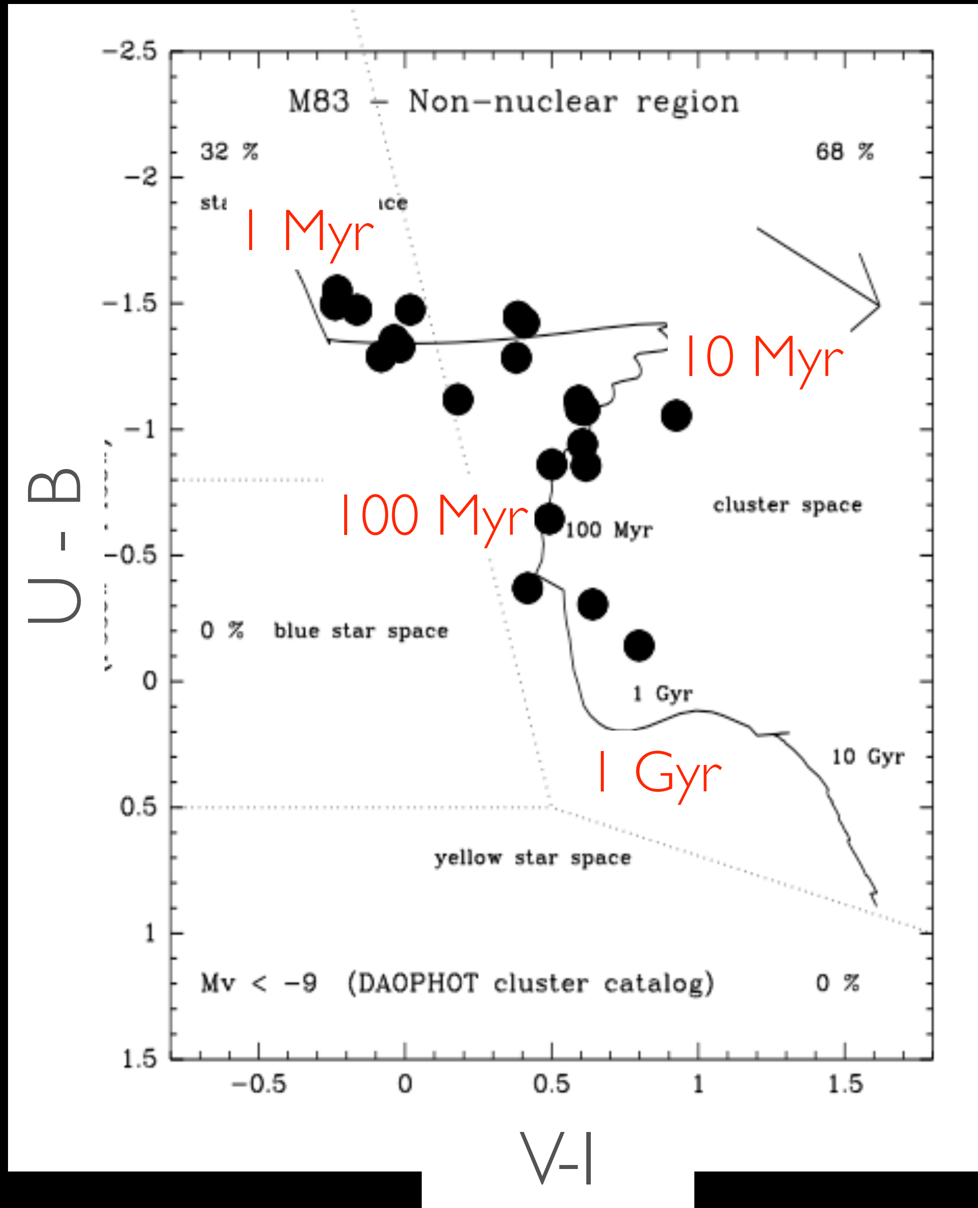
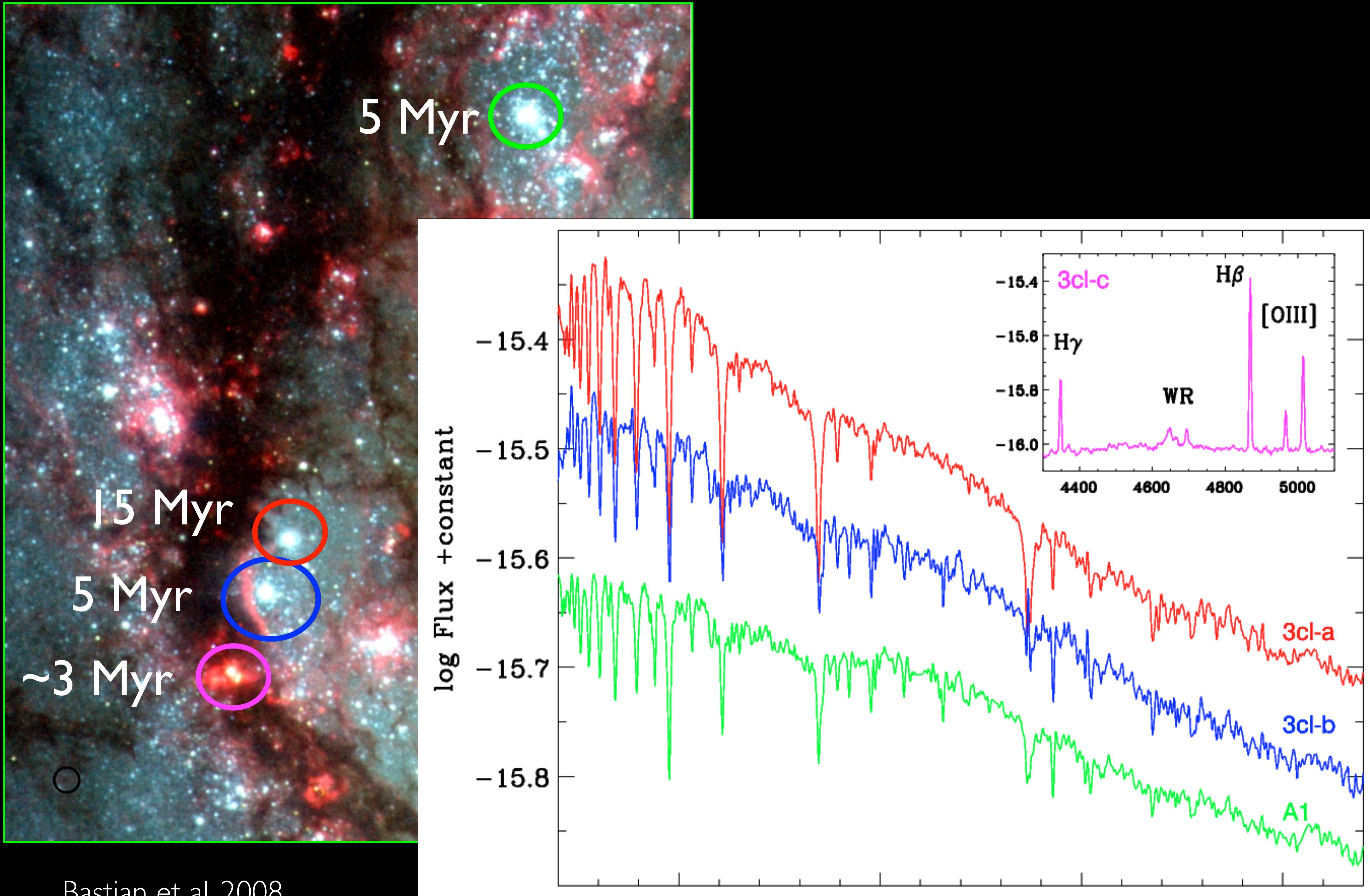


Chandar et al. 2010

Their properties: Ages and Extinction

- In a limited number of cases can get all the basic info from resolved star CMDs
- But for most extragalactic YMCs we need to compare their integrated light (spectroscopy or photometry) with simple stellar population models (SSPs)
- Allows us to get the age, extinction and mass, but there are some important caveats (degeneracies) to keep in mind.
- Spectroscopy and line diagnostics can break the degeneracies in most cases - but expensive

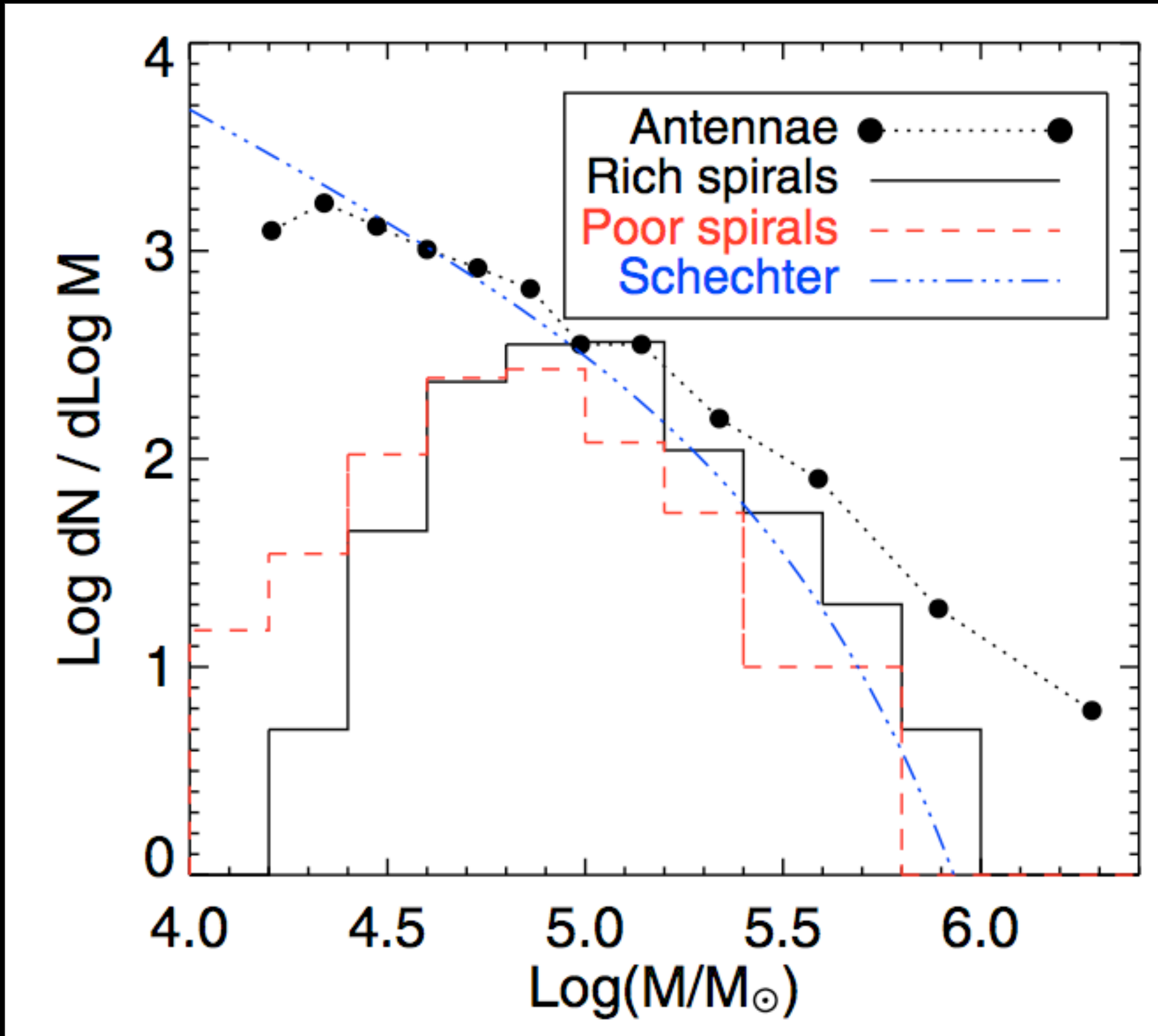


Bastian et al. 2008

Their properties: Mass functions

- Similar to Luminosity functions
- Need to convert observables (luminosity) to physical properties
- Extinction and age effects have been taken into account

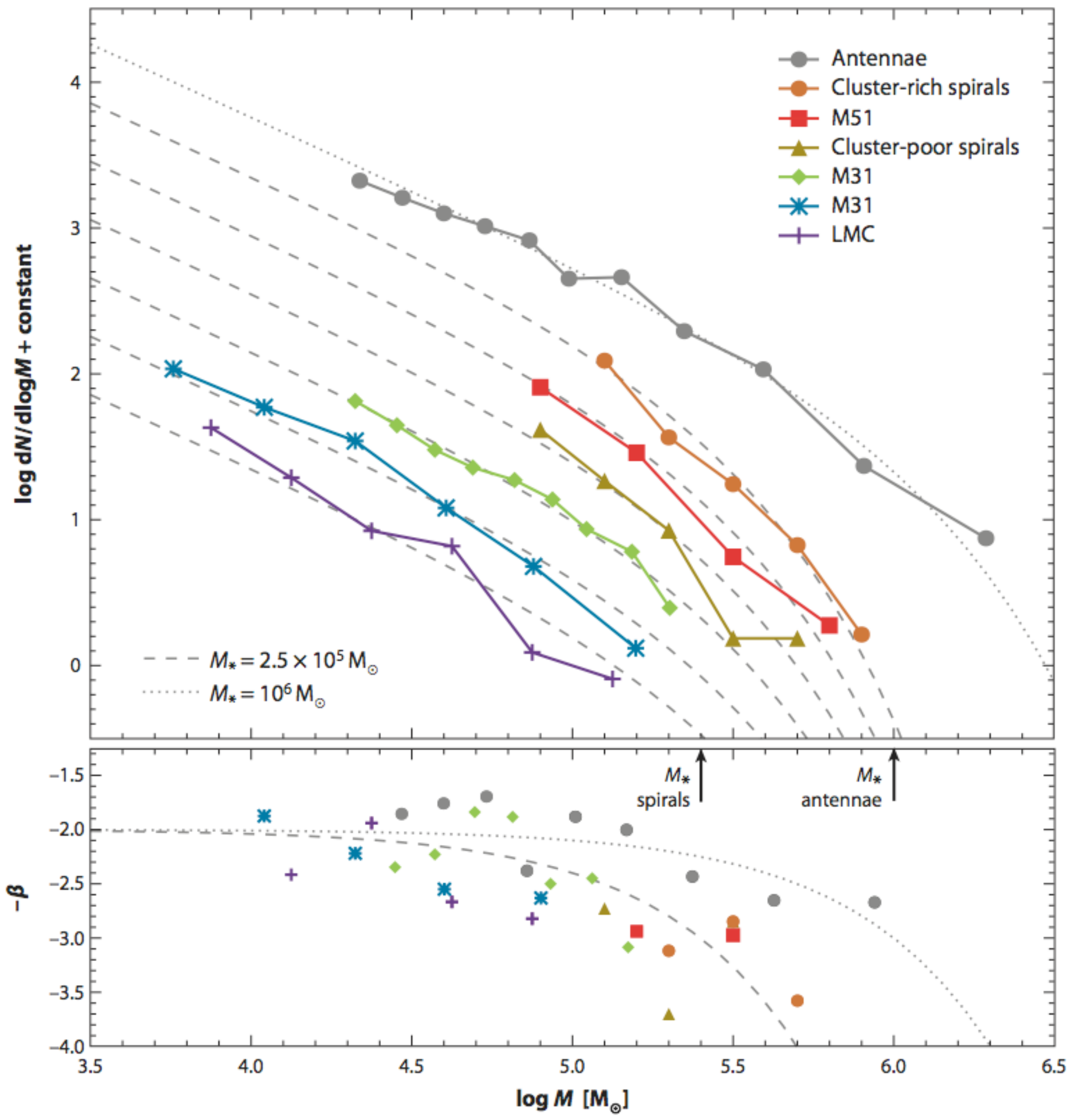
$$\boxed{NdM \sim M^{-\beta}dM}$$



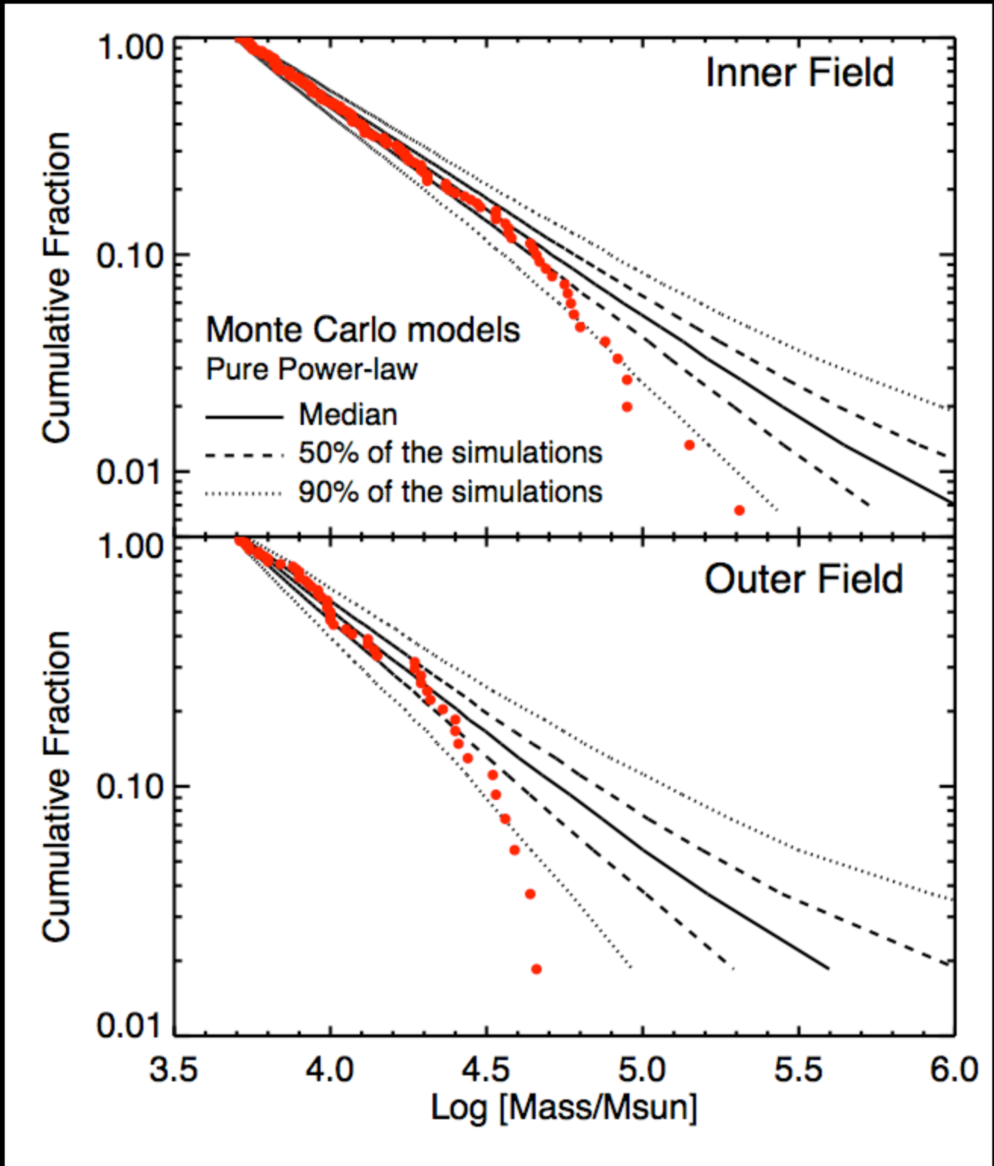
Mass functions

Larsen 2009

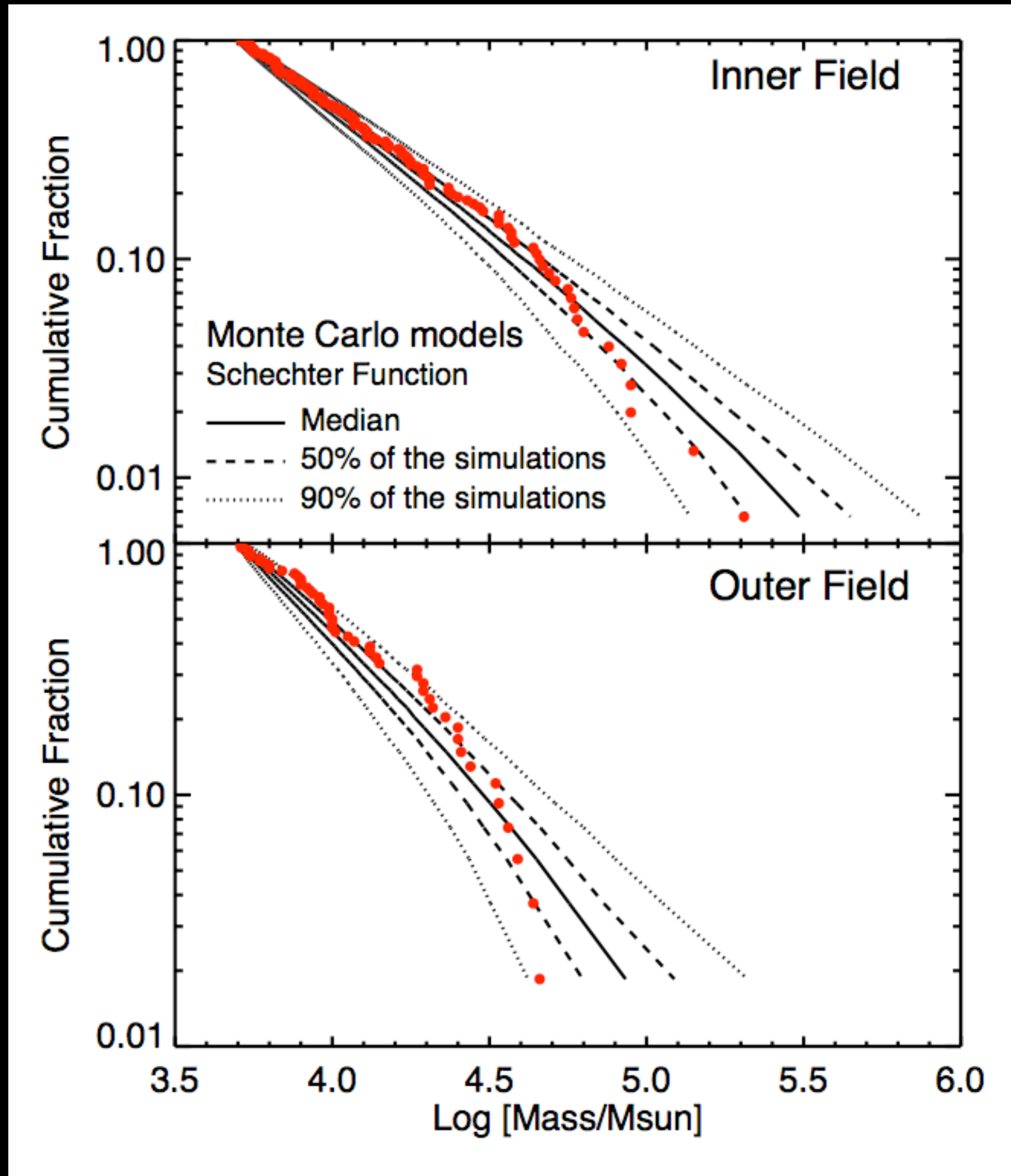
Mass functions



PZMG10



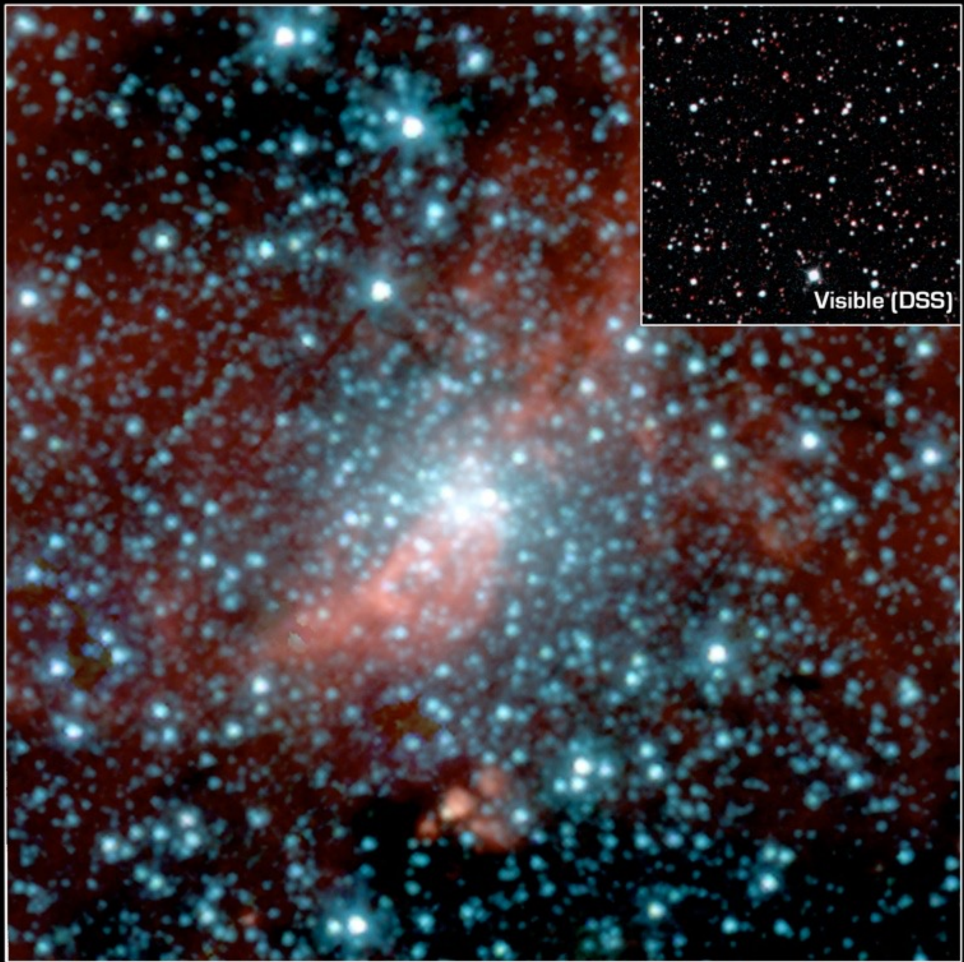
Bastian et al. 2012



Their properties: Mass functions

- $NdM \sim M^{-\beta}dM$, with $\beta = 2$ for most of the observable mass range
- Evidence for a turn-down at high masses, similar to a Schechter function, M_c
- M_c appears to vary with environment, ~2×10^5 Msun in spirals and dwarfs and $>10^6$ Msun in mergers/starbursts
- M_c also varies within the same galaxy
- The turn-down is a small effect, but it has important implications in the luminosity and age distributions

GLIMPSE CLUSTER-01



New Globular Cluster **Spitzer Space Telescope • IRAC**

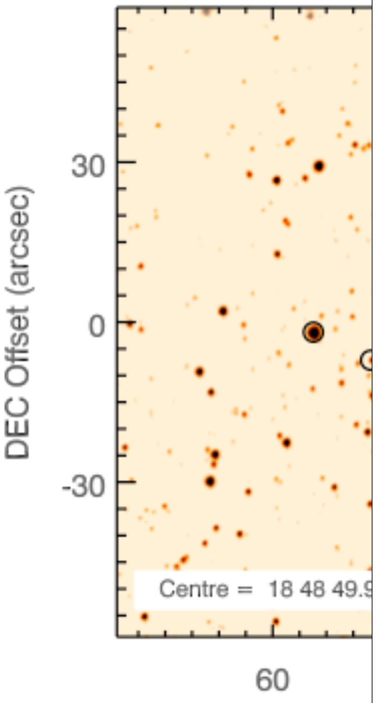
NASA / JPL-Caltech / H. Kobulnicky (Univ. of Wyoming) ssc2004-16a

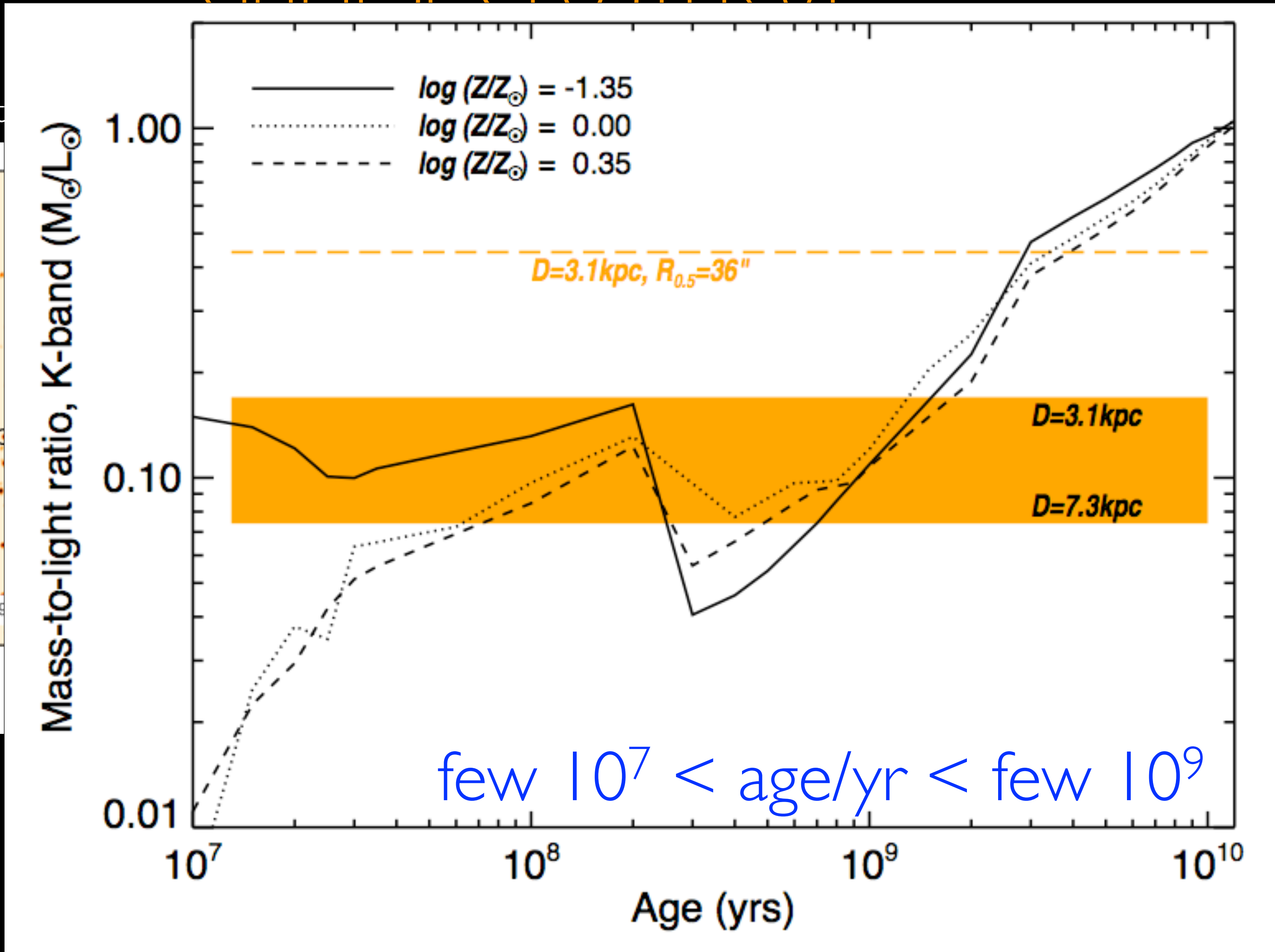
- located within 0.1 degrees of the Galactic plane
- can rule out very young ages (< 20 Myr)
- assumed then to be an old globular crossing the plane

Davies et al. 2011

GLIMPSE CLUSTER-01

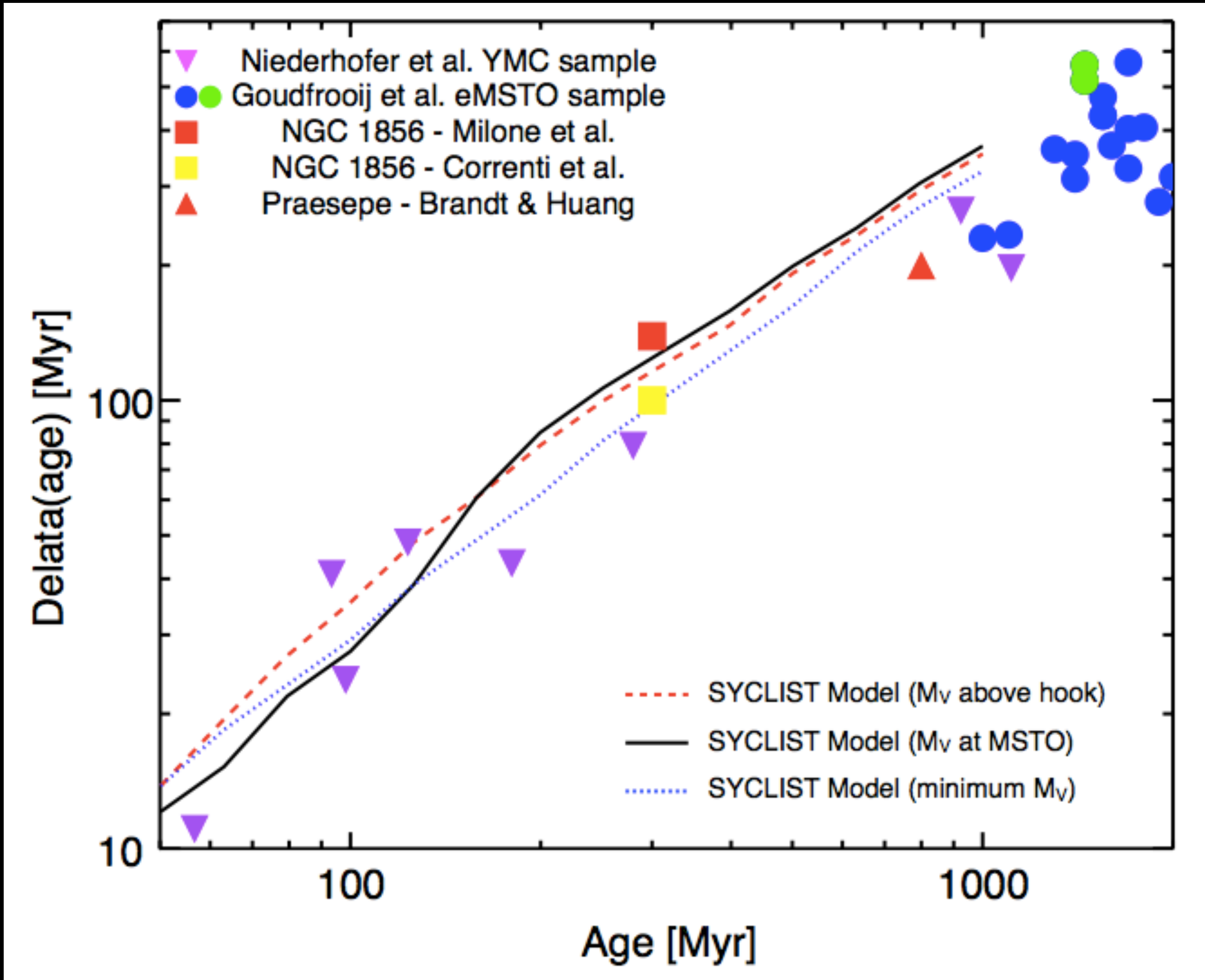
Davies et al. submit





few 10^7 < age/yr < few 10^9

Age spreads from CMDs?



Niederhofer et al. 2015b