# The Relation of Young Massive Clusters to the Ancient Globular Clusters

# Review of 2nd lecture

- YMC populations are dominated by size-of-sample effects, higher *SFR galaxies form more clusters*
- Need to be very careful of selection effects when studying cluster populations
- Clusters don't live forever, they disrupt which can be seen in their age distributions
- The IMF within YMCs appears to be normal

## *RELATION BETWEEN CLUSTERS AND STAR FORMATION FRACTION OF UV LIGHT: FIRST HINTS*

- 9 starburst galaxies observed with the FOC on HST
- 10-50% of UV light from compact sources
- fraction increases with $\Sigma_{SFR}$
- caveat: assumes clusters and the field have same extinction
- also found in other starbursts e.g. Zepf et al. 1999


Meurer et al. 1995

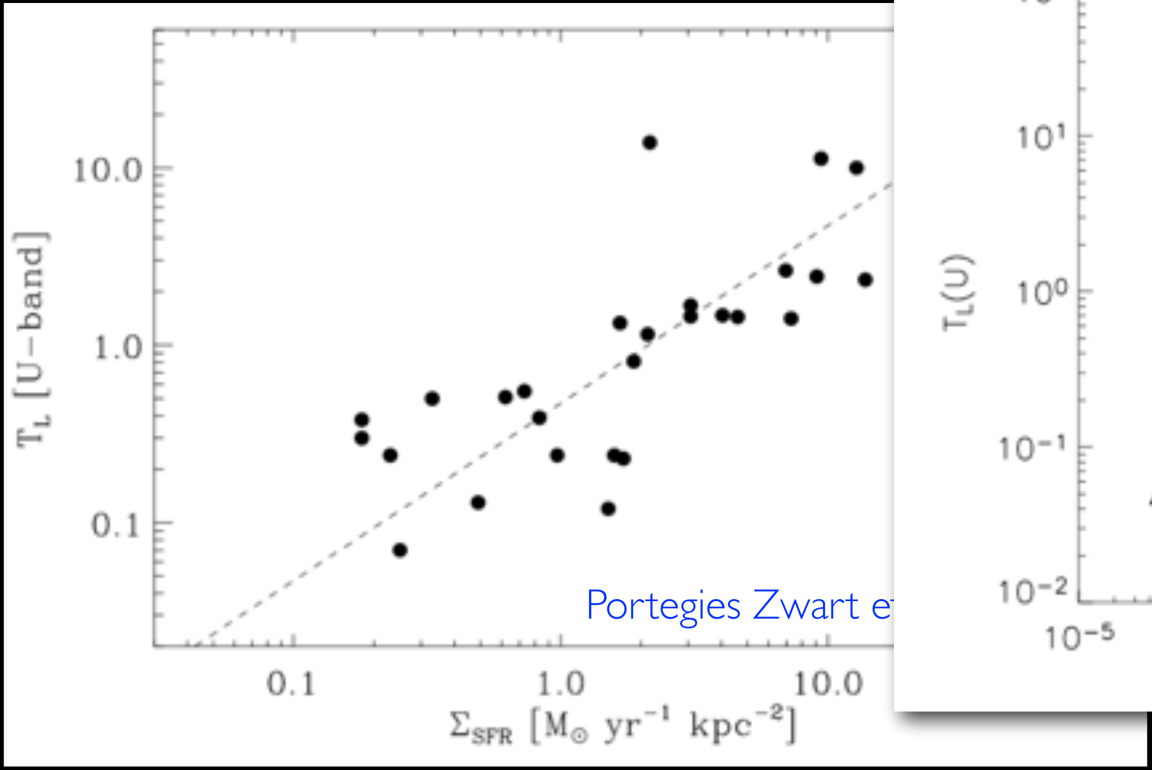
# QUANTIFYING CLUSTER POPULATIONS

- Specific luminosity for globular clusters (number of GCs per unit luminosity of the host galaxy)
- not very useful for YMCs, as their mass function is a power-law
- also the host galaxy luminosity depends on mean age
- Specific luminosity: $T_L = 100 * L_{clusters} / L_{galaxy}$ (Larsen & Ritchler 1999)
- Use a blue filter (U) to trace young populations

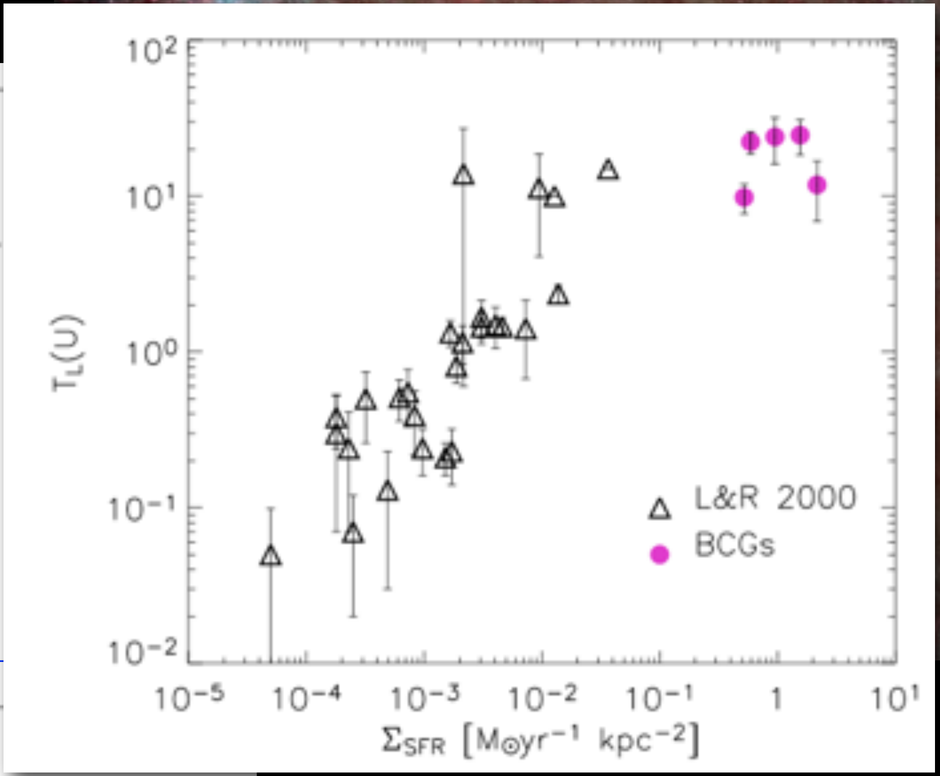
## *FRACTION OF U-BAND LIGHT: CONTINUED*

- Sample of 21 nearby spiral galaxies
- Specific luminosity: $T_L = 100*L_{clusters}/L_{galaxy}$
- Interpretation: cluster formation efficiency varies with $\Sigma_{sfr}$

Larsen & Richtler 1999, 2000, Larsen 1999




Portegies Zwart et




Larsen 2002

Adamo et al. 2011

# POTENTIAL PROJECT

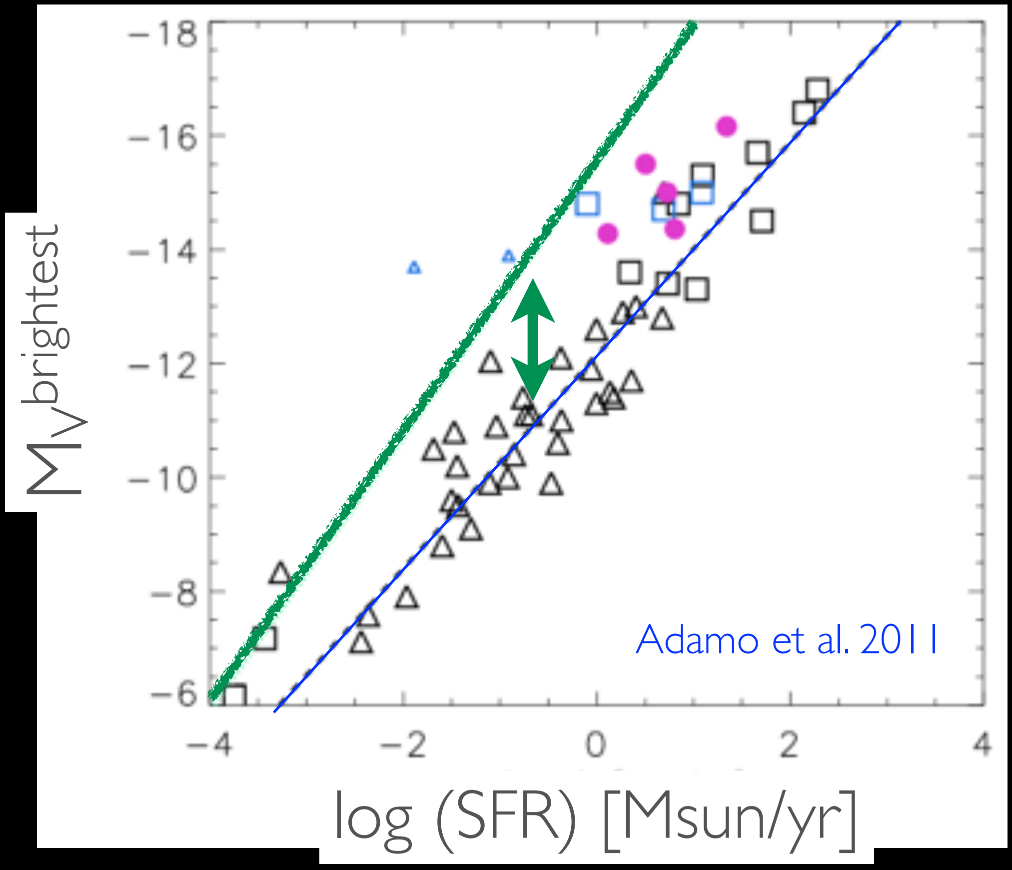
- relatively easy to model (building cluster populations)
- hasn't been done yet - looking for how TL(U) or other bands depend on the input parameters (star-formation history, fraction of stars in clusters)

# BRIGHTEST CLUSTER VS. STAR FORMATION RATE

- more star formation = more clusters
  = more luminous brightest cluster

- vertical offset corresponds to $\Gamma$

- overall $\Gamma \sim 0.08$ (the fraction of stars forming in clusters)



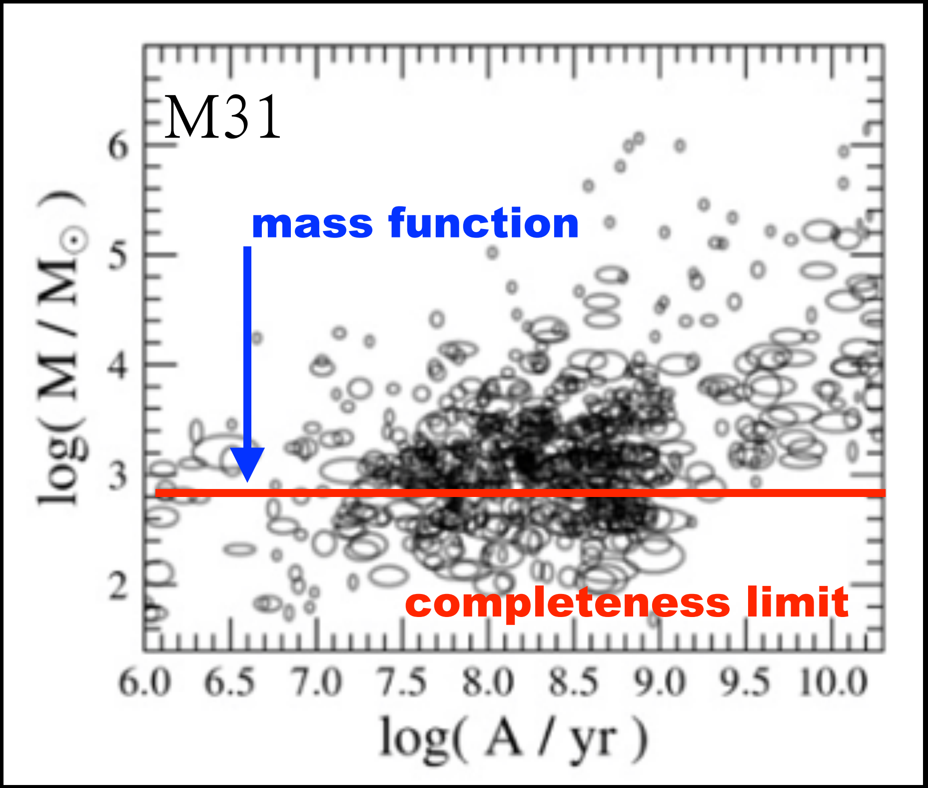

Larsen 2002
Weidner et al. 2004
Bastian 2008

# Cluster formation in galaxies

$\Gamma$ = fraction of stars formed in bound clusters

Bastian 2008

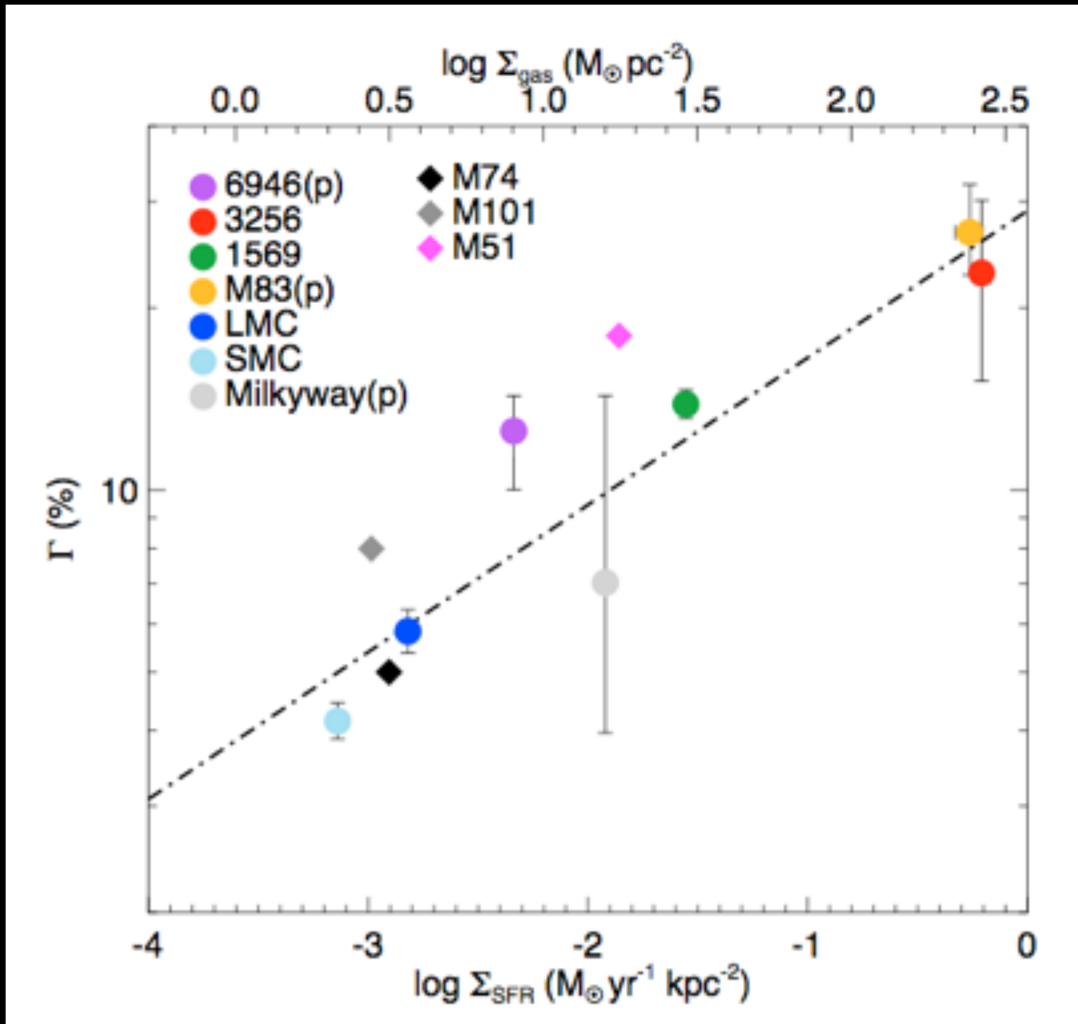
- $\Gamma$ = CFR/SFR
- Can be estimated in a number of ways
- Young samples (<10 Myr) suffer from contamination
- Old samples suffer from disruption effects



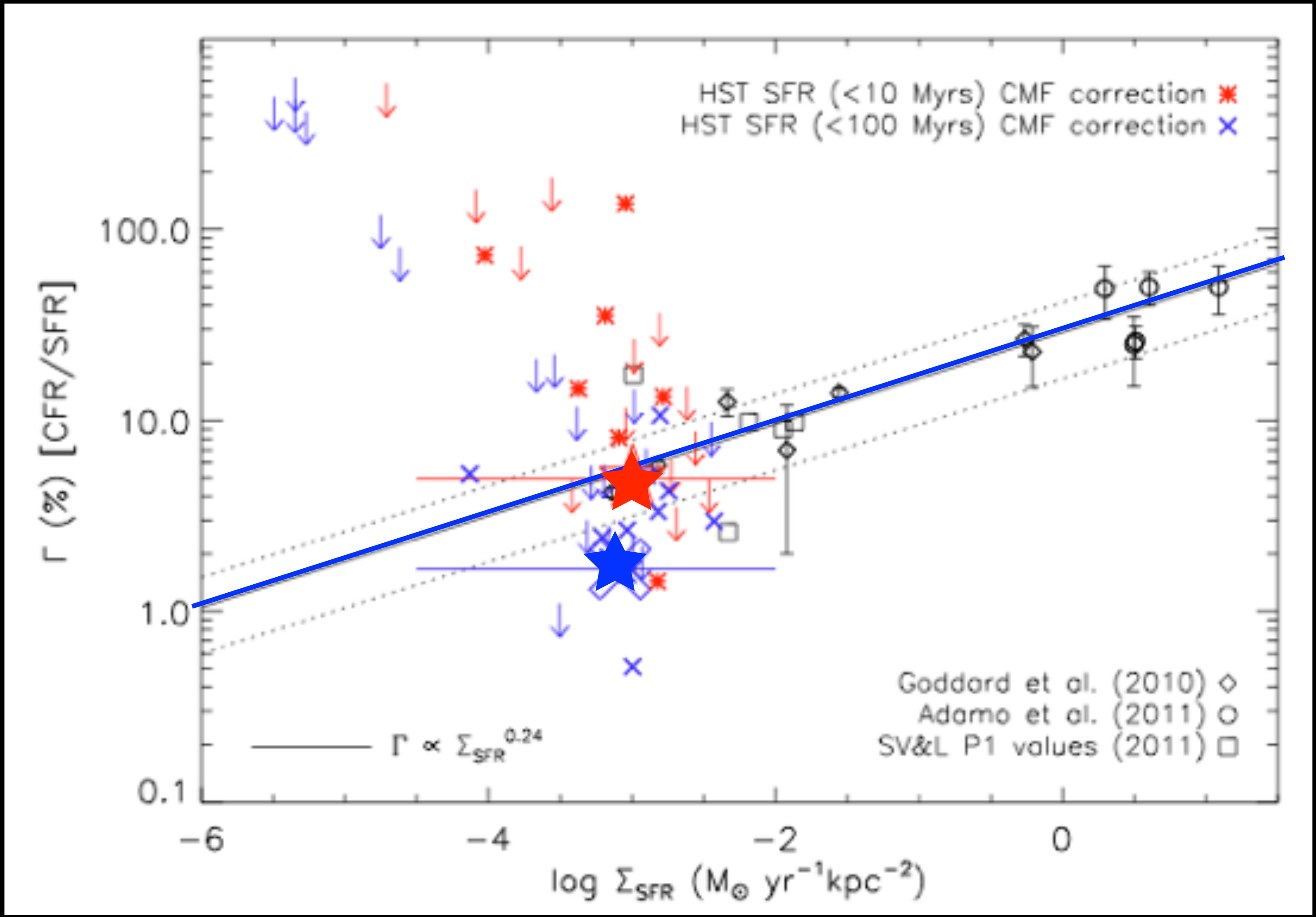

Fouesneau et al. 2014

# Estimating Γ

- Take a mass limited sample
- Sum up the mass in clusters in a given age range
- Correct for the clusters that are not observed (due to the completeness limit)
- Divide by the age range used, to get the cluster formation rate
- Compare this to the star-formation rate (SFR)



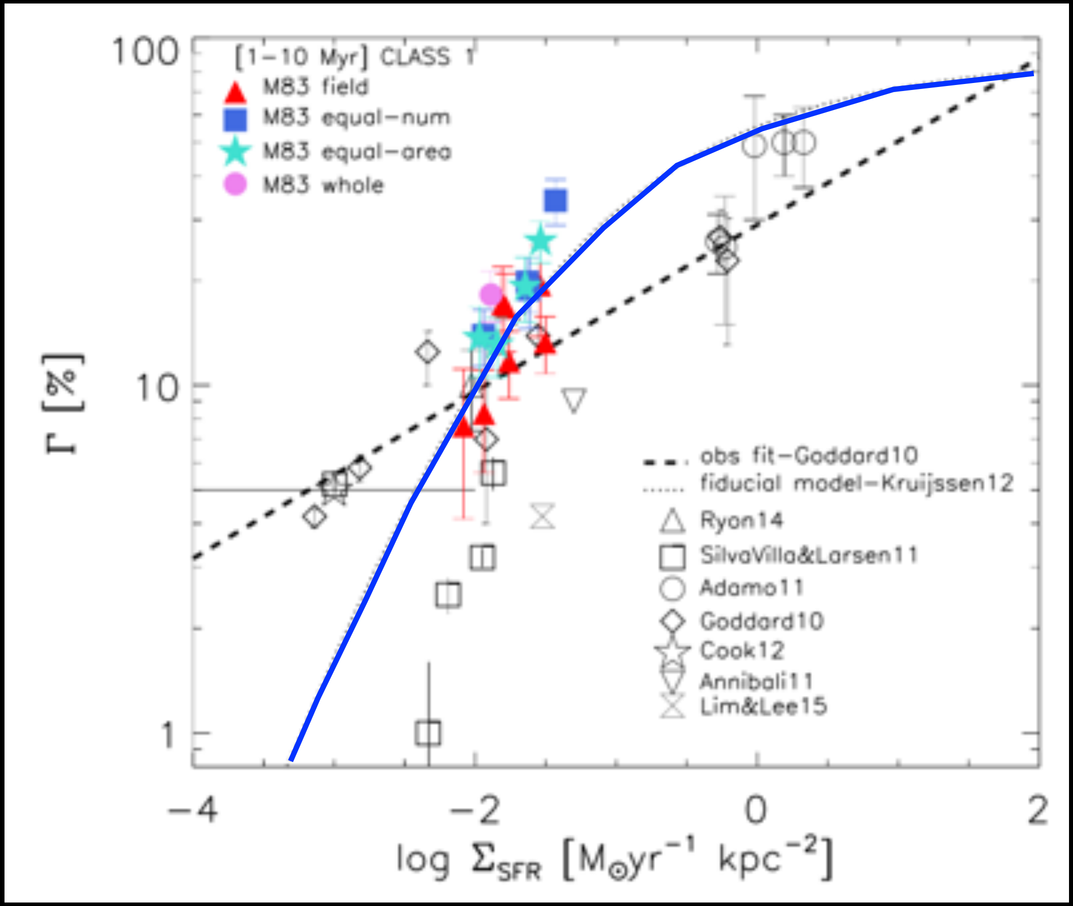

Goddard et al. 2010




Cook et al. 2012

Sample of nearby dwarf galaxies from the HST ANGST survey

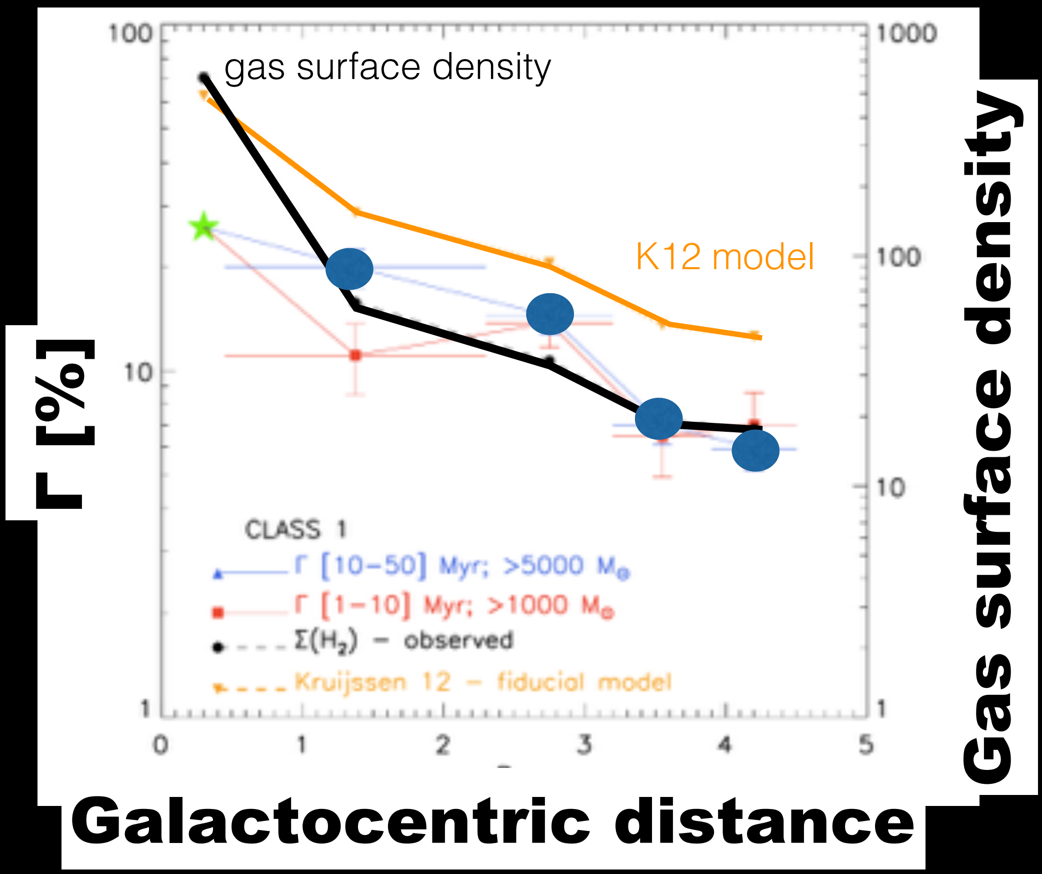
# Dependence on Galactic Properties




Adamo et al. 2015

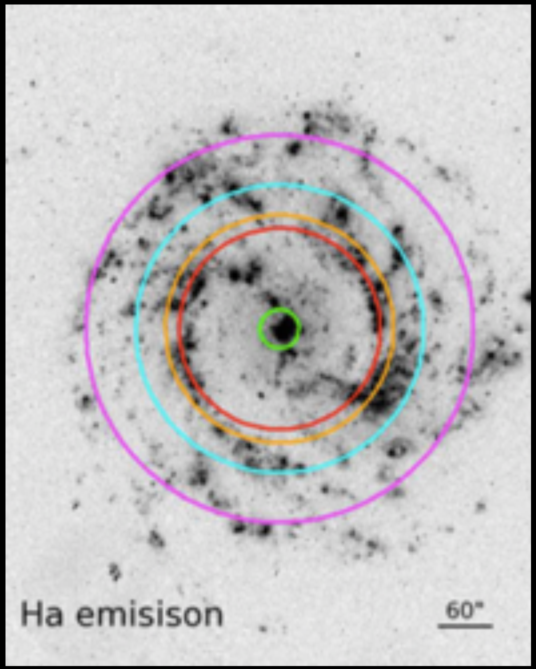
- Apparent increase of Γ with star−formation rate surface density
- Decent agreement with model predictions
- Still early days with observations
- $\Gamma_{max}$ ~50%

# Dependence on Galactic Properties




Adamo et al. 2015

- Γ varies within the same galaxy
- Correlated with gas surface density
- In agreement with predictions

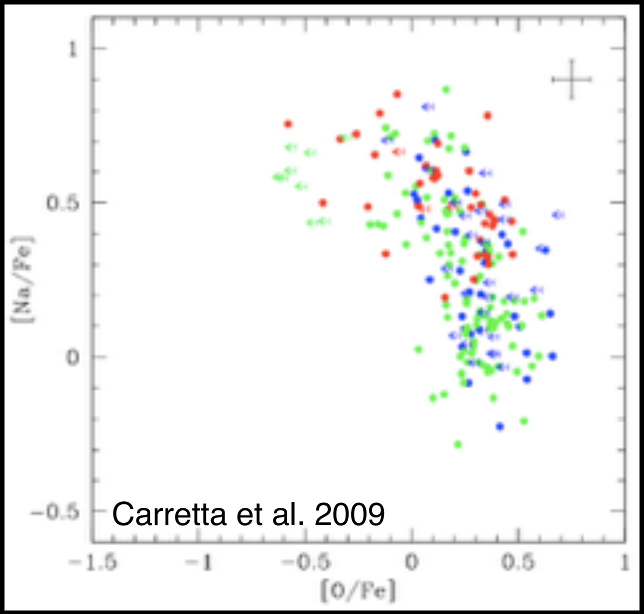


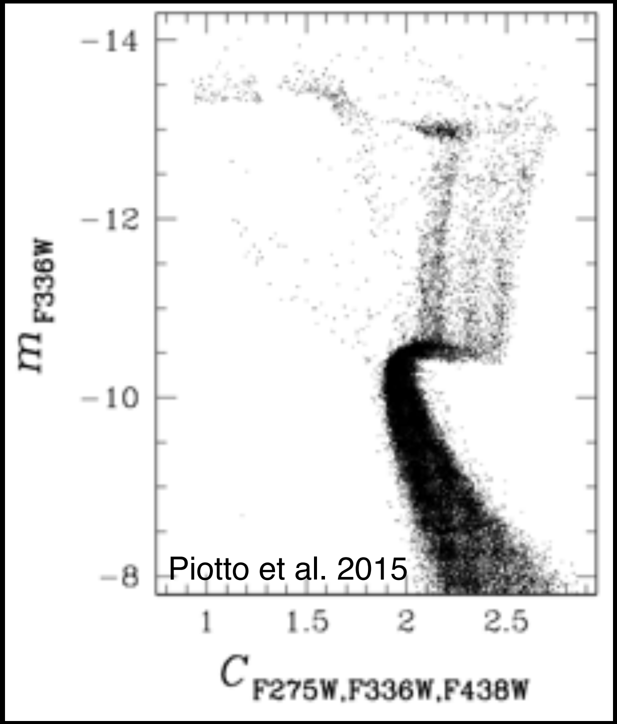
# $\Gamma$ Summary

- The fraction of stars that form in clusters in most galaxies is $\Gamma \sim 10\%$.
- This is difficult to measure though so the errors can be quite large and systematic
- Correlation between $\Gamma$ and the SFR surface density ($\Sigma_{SFR}$)
- More stars form in clusters at high $\Sigma_{SFR}$
- If more clusters are formed, then more higher mass clusters are formed
- Did GCs form in high SFR environments (starbursts)?

# Using YMCs to Constrain GC Formation

- Are GCs just the ancient analogues to YMCs?
- Many theories for GC formation invoke multiple epochs of star formation within them
- Is there any evidence for multiple (or continuous) star-formation within YMCs?



# From YMCs to GCs

- The typical mass of GCs today is $\sim 10^5$ Msun
- Known YMCs have masses between $10^4$ - $10^8$ Msun
- YMCs have similar sizes and densities

*While Globular Cluster formation (at high-z) may have been fundamentally different from massive clusters forming today,* ***all*** *main theories for the origin of multiple populations predict that it should be happening in young clusters today.*

*i.e. current theories do not invoke any special conditions/physics for GC formation.*

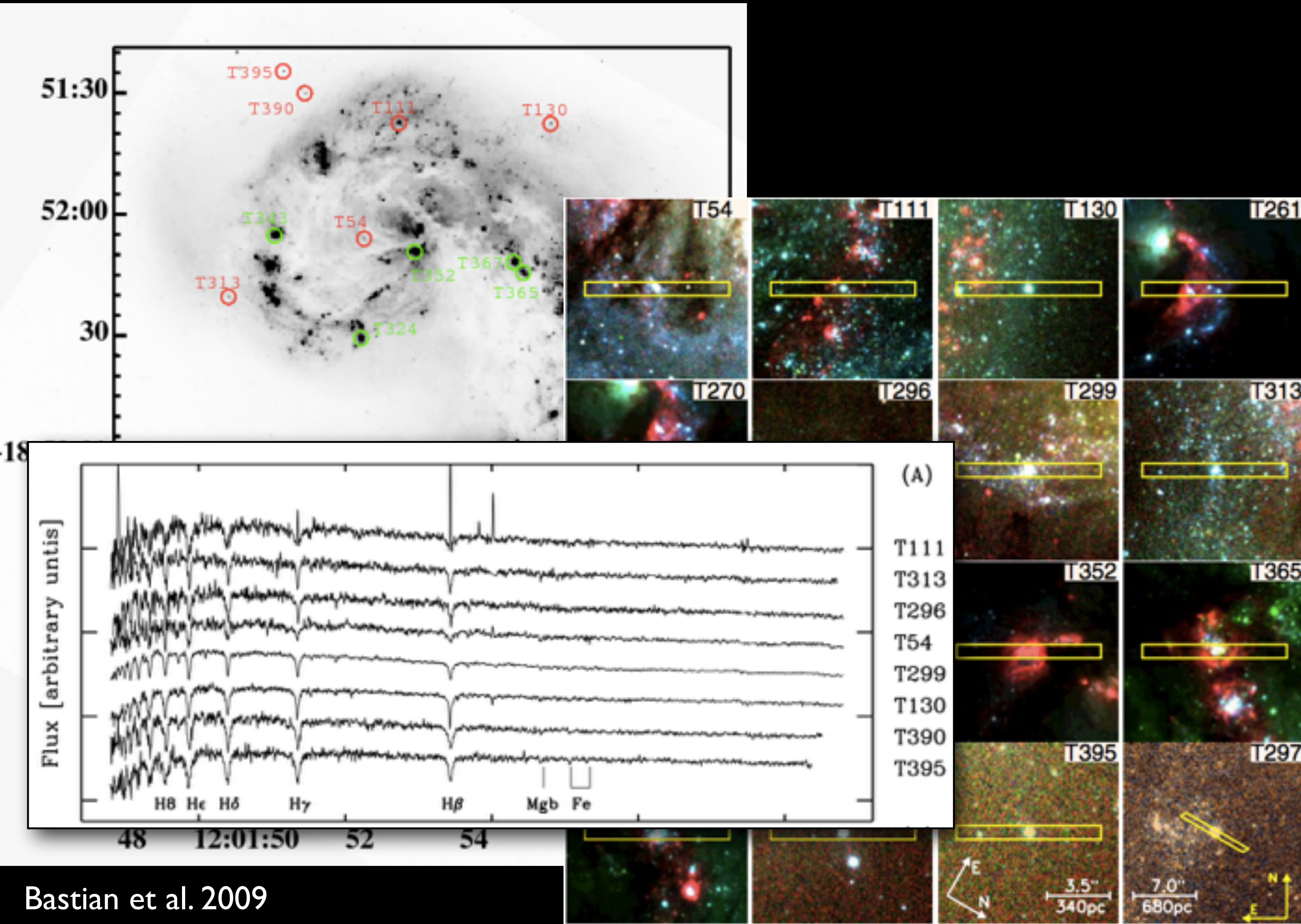
# Example: AGB Scenario

- Form a 1st generation of stars in a massive cluster
- Ejecta of AGB stars collects in the centre of the cluster (30-200 Myr after 1st generation formation)
- Form a 2nd generation (enriched stars) from this material

➡ Predicts that multiple epochs of star-formation should be in massive clusters

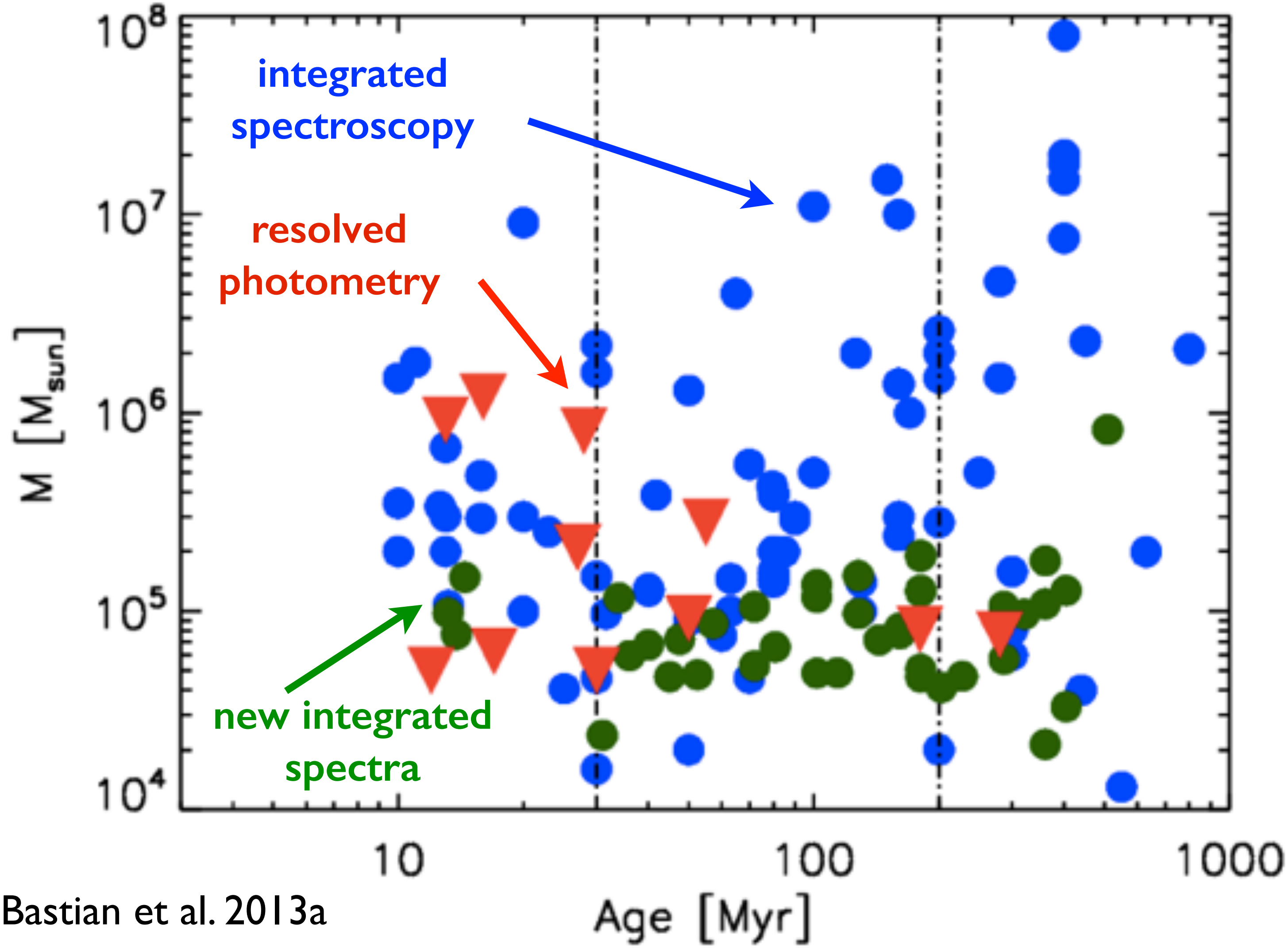
➡ Massive clusters should be gas rich

➡ Clusters were 10-100x more massive at birth



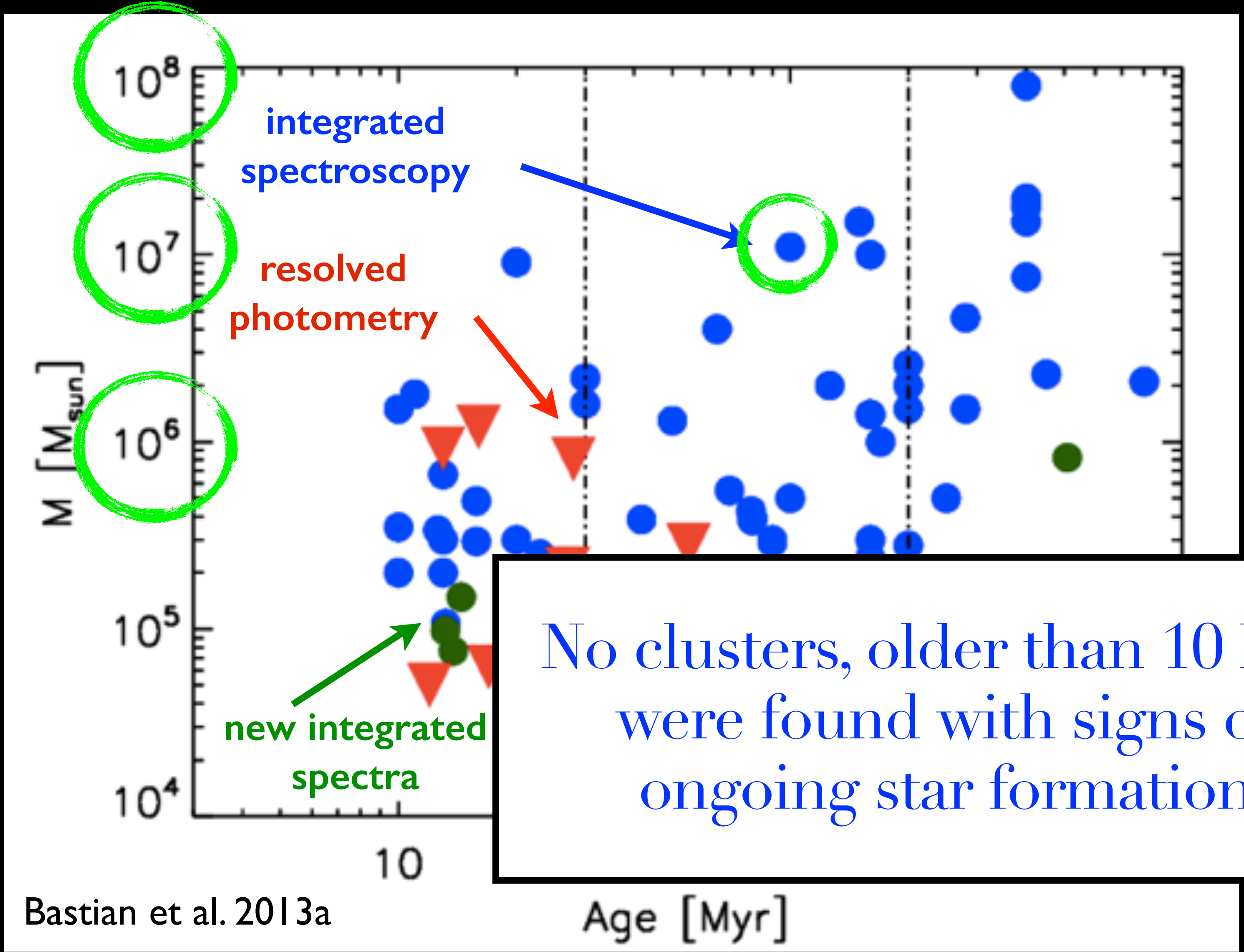

Bastian et al. 2009

# Constraints on Ongoing Star-Formation (i.e. 2nd generation)




Bastian et al. 2013a

# Constraints on Ongoing Star-Formation (i.e. 2nd generation)



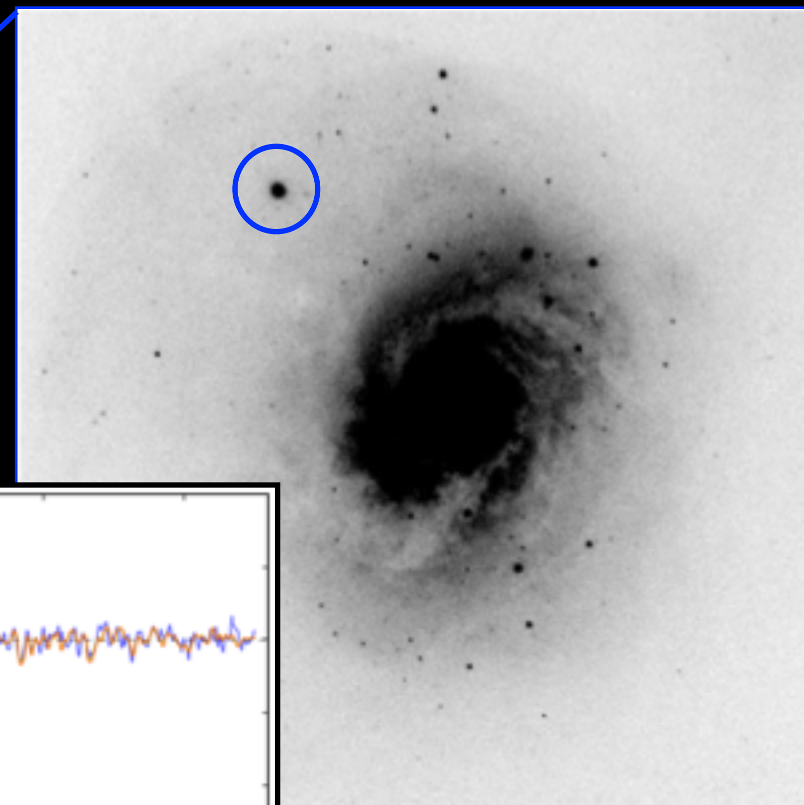

Bastian et al. 2013a

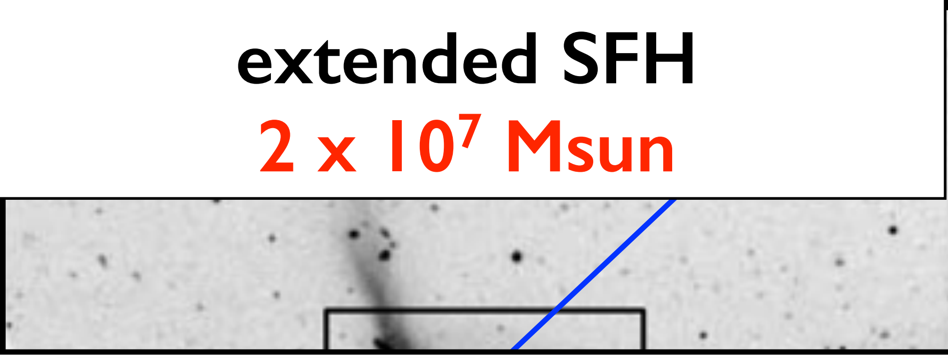
No clusters, older than 10 Myr, were found with signs of ongoing star formation

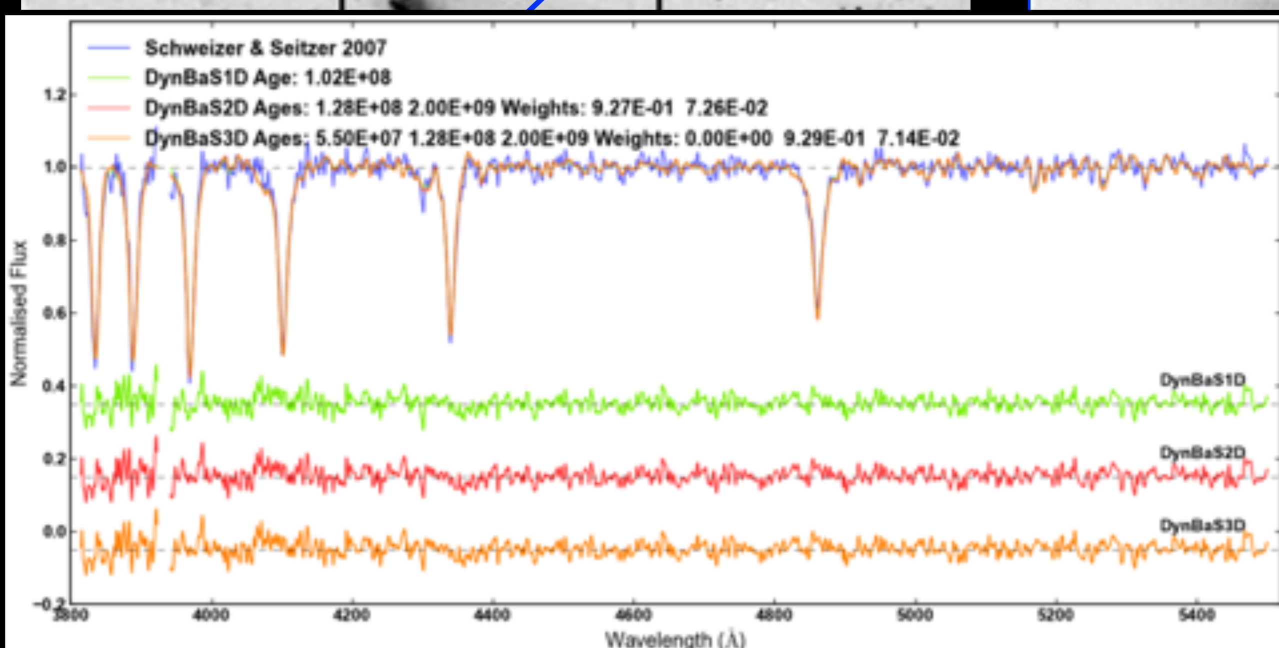
# Constraints from the SFH of clusters (NGC 34-1)

Single population - 100 Myr
No evidence for an extended SFH
2 x $10^7$ Msun

Cabrera-Ziri et al. 2014



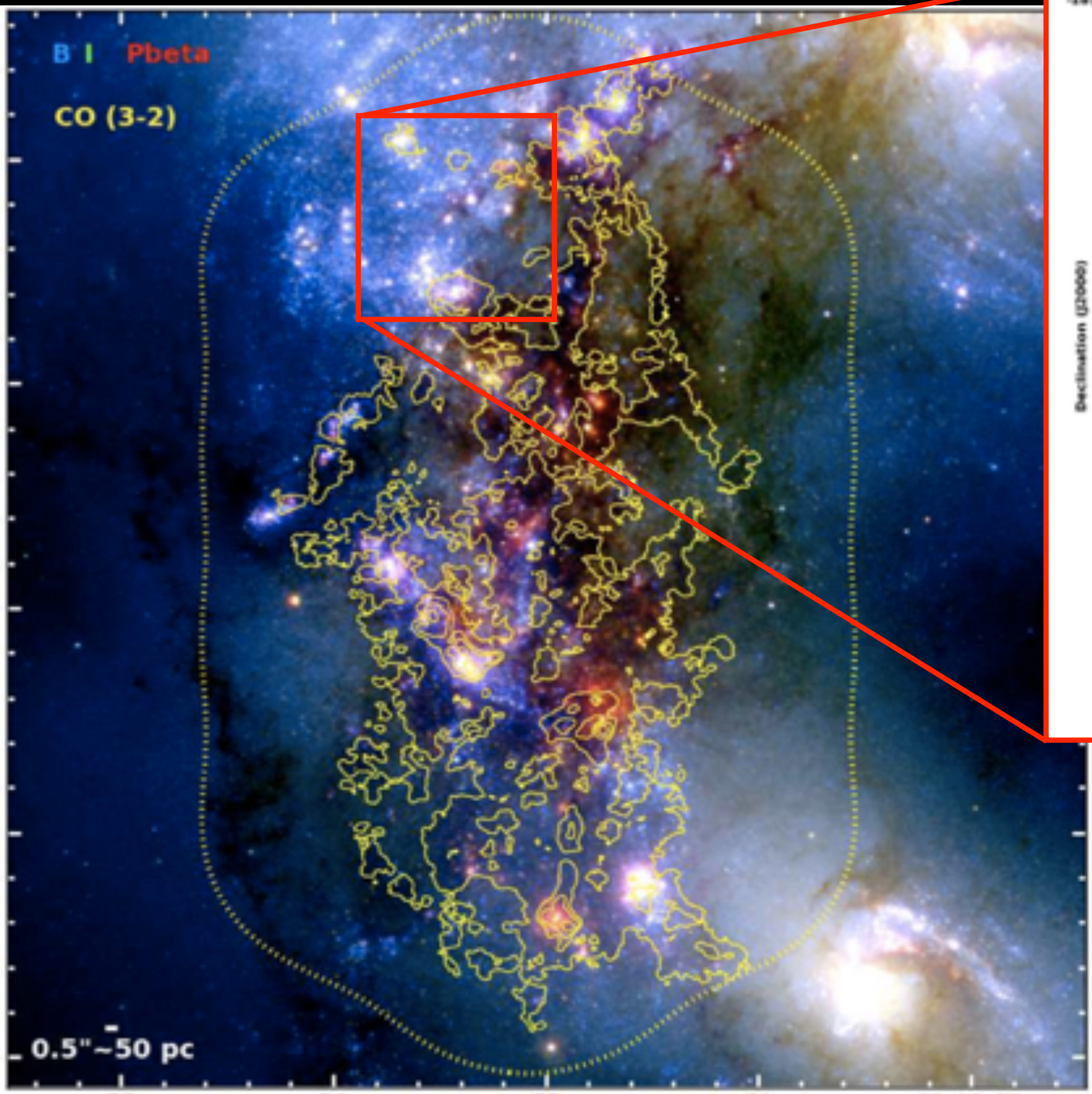




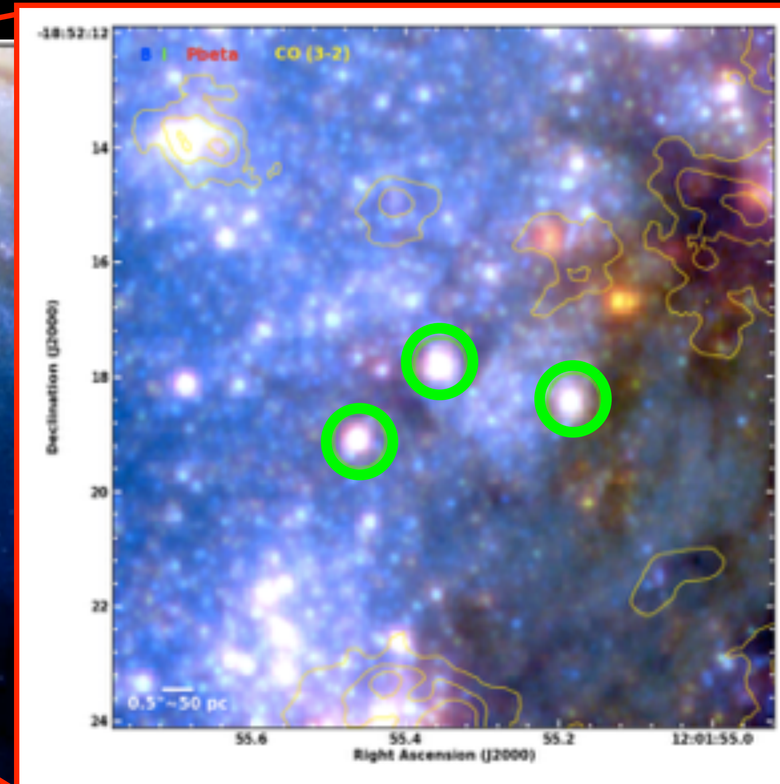

…eitzer 2007

# Constraints on Gas within YMCs

Cabrera-Ziri et al. 2015




Whitmore et al. 2014




50-200 Myr

1-3 x $10^6$ Msun

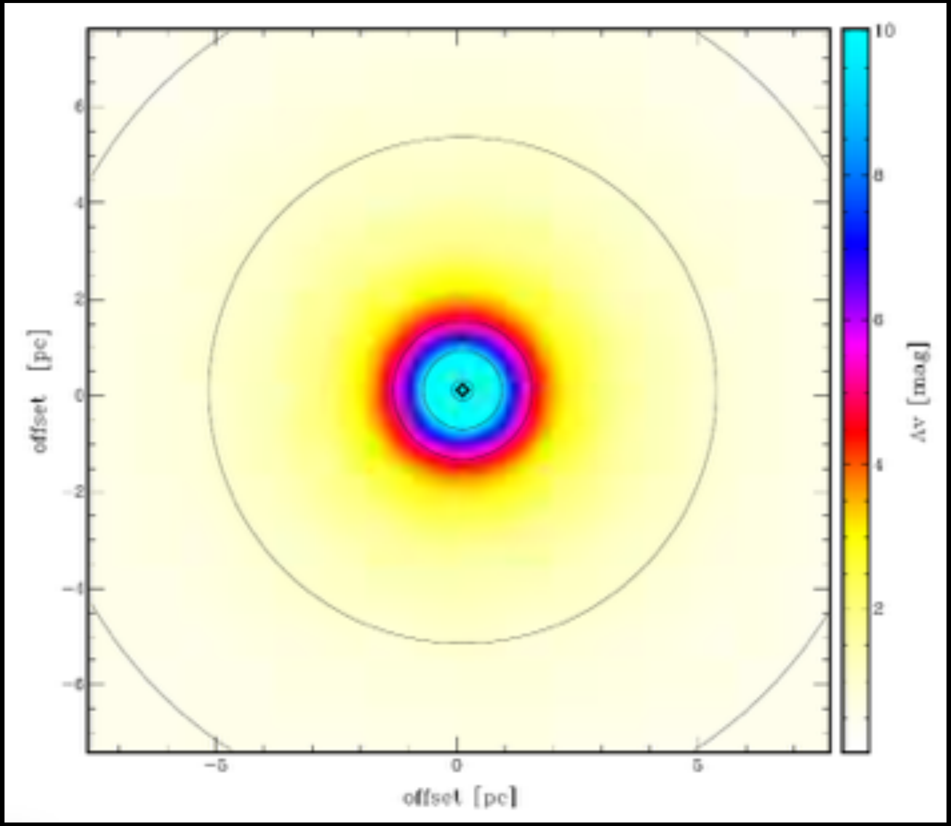
No gas detected

(<1-10% cluster mass)

see also Bastian & Strader 2014

# Constraints on Gas within YMCs

Longmore 2015




Extinction profile expected of a YMC

Used the D'Ercole et al. (2008) simulation of the 'AGB scenario' which predicts a gas profile

This is a lower limit based on the assumptions adopted

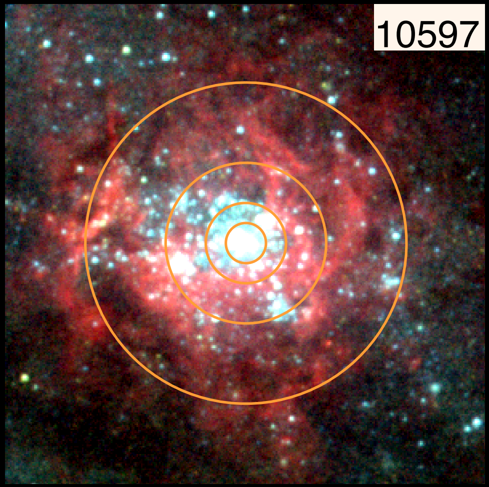
Calculated expected extinction

$A_V > 8$ in inner pc

$A_V > 3$ in inner 3 pc

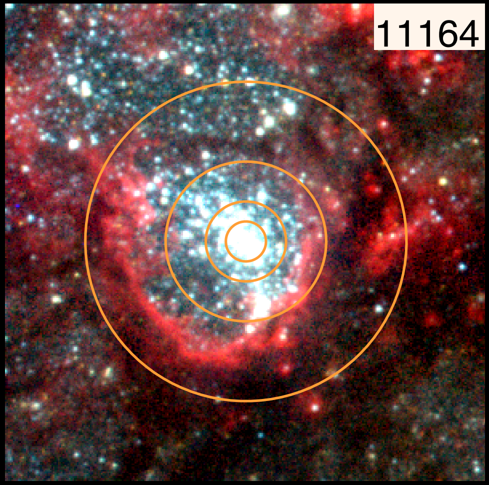
Inconsistent with YMC observations ($A_V < 0.2$)

# 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




Whitmore et al. 2011
Bastian et al. 2014

Before the first SNe

Westerlund 2
~2 Myr

# Summary of young massive clusters

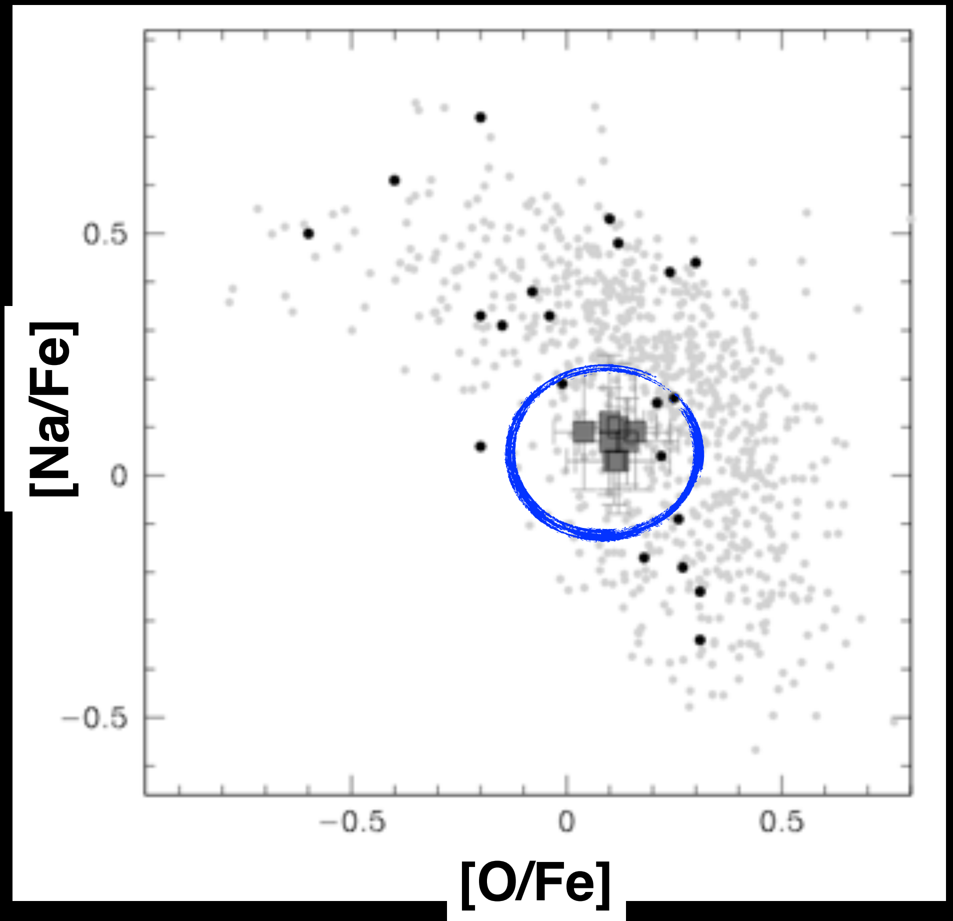
- Appear to be gas free at young ages (<3 Myr)
  -a problem for the FRMS scenario - Hollyhead et al. 2015
- No evidence for ongoing star formation in *any* young massive cluster studied to date (older than 10 Myr) Bastian et al. 2013
- Integrated spectroscopy of YMCs (>$10^7$ Msun) shows no evidence for multiple bursts or exteneded SFH Cabrera-Ziri et al. 2014
- Models with multiple star formation events are disfavoured by CMDs of YMCs Niederhofer et al. 2014
- No gas reservoirs found in YMCs Cabrera-Ziri et al. 2015

# Previous (popular) models all ruled out

# Multiple Populations in Young in Intermediate Age Clusters?

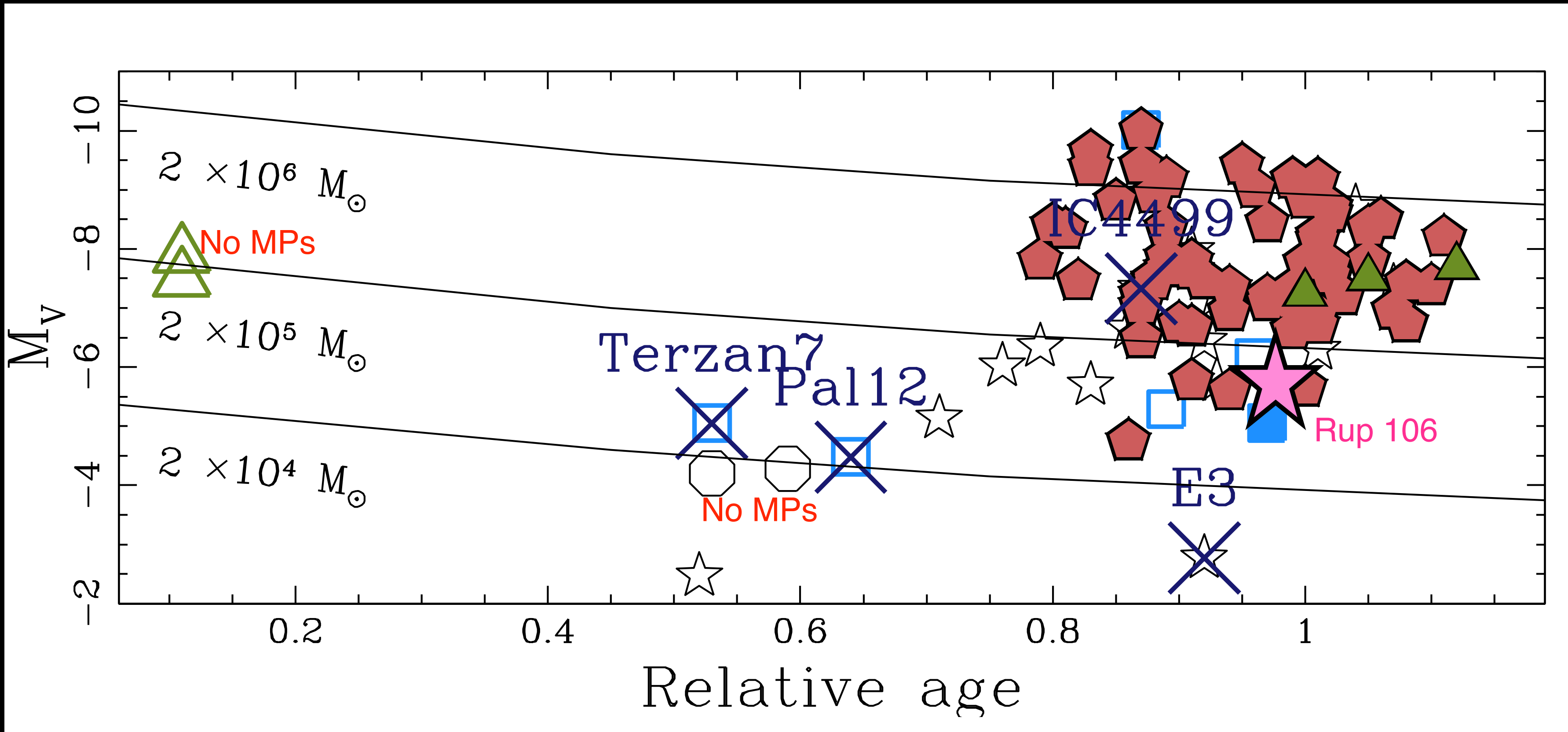
NGC 1806
eMSTO LMC cluster
$2 \times 10^5$ Msun
~1.5 Gyr

No abundance spreads!




Mucciarelli et al. 2014

Also true of NGC 1846, 1866, 1651, 1783, 1978, 2173



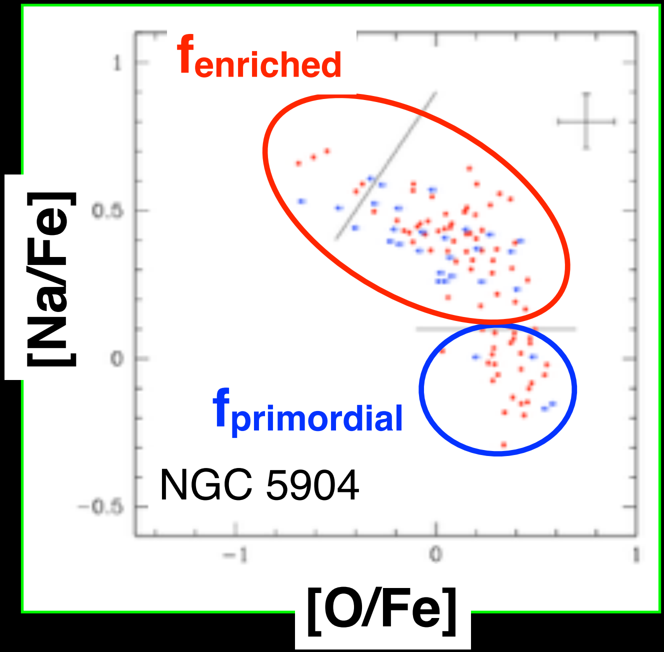

- Rup 106 - No MPs! Old, relatively high mass GC
- $10^5$ Msun LMC clusters (1-2 Gyr): No Mps!
- Not a simple mass limit
- Maybe an age limit?

# Multiple Populations in YMCs

- So far none found - perhaps GC formation was different than YMCs?
- None found in resolved YMCs up to ~$2 \times 10^5$ Msun
- Difficult to see in more massive YMCs, requires detailed spectral modelling - early days.
- Not a simple mass limit where MPs are found/not found

# Constraints from the GC Population

## The Remarkable Constancy of the enriched fraction of stars in GCs




$f_{enriched}$ (initial) ~ 0.05
$f_{enriched}$ (observed) ~ 0.6

Models that invoke nucleosynthesis in 1st generation stars to pollute 2nd generation stars, require that GCs were much more massive at birth (**>10x**) than presently

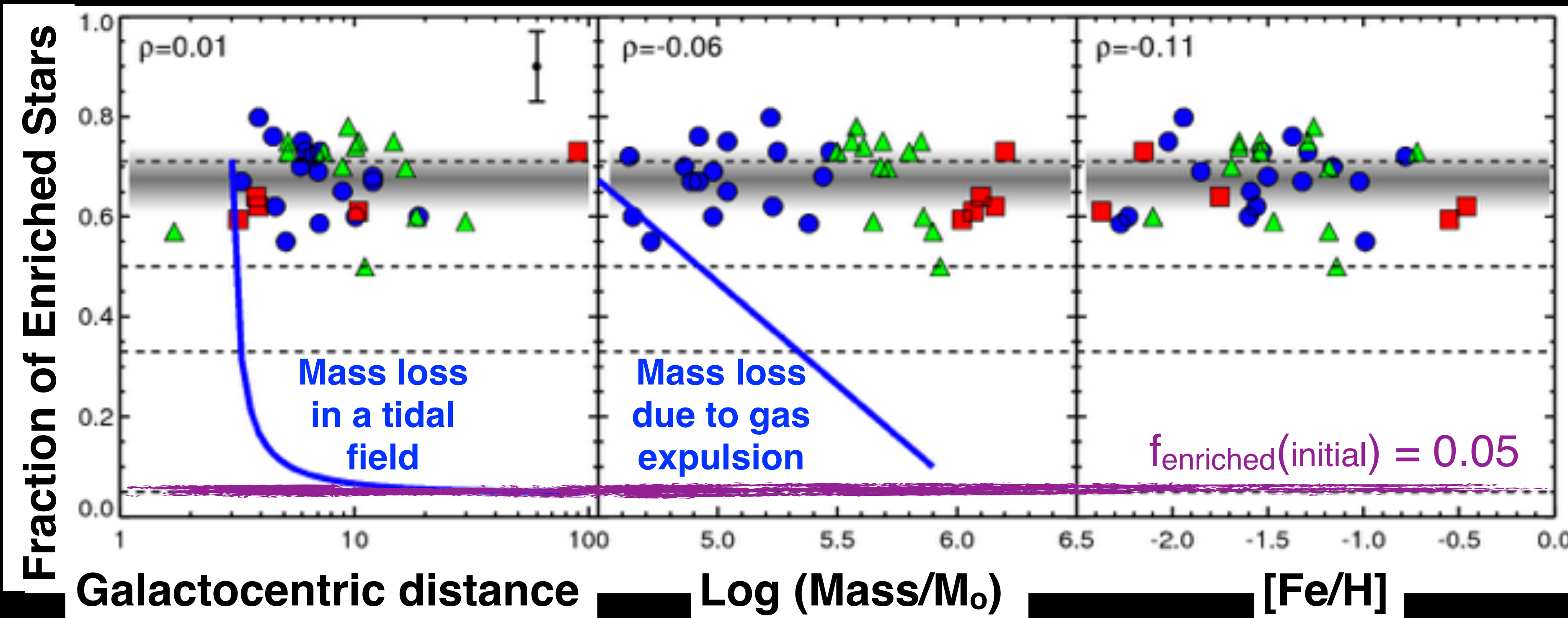
e.g. Caloi & D'Antona 2011

All GC mass loss mechanisms will leave an imprint on the GC properties ($f_{enriched}$ will vary from cluster to cluster)

e.g. Khalaj & Baumgardt 2015

# Constraints from the GC Population

## The Remarkable Constancy of the enriched fraction of stars in GCs



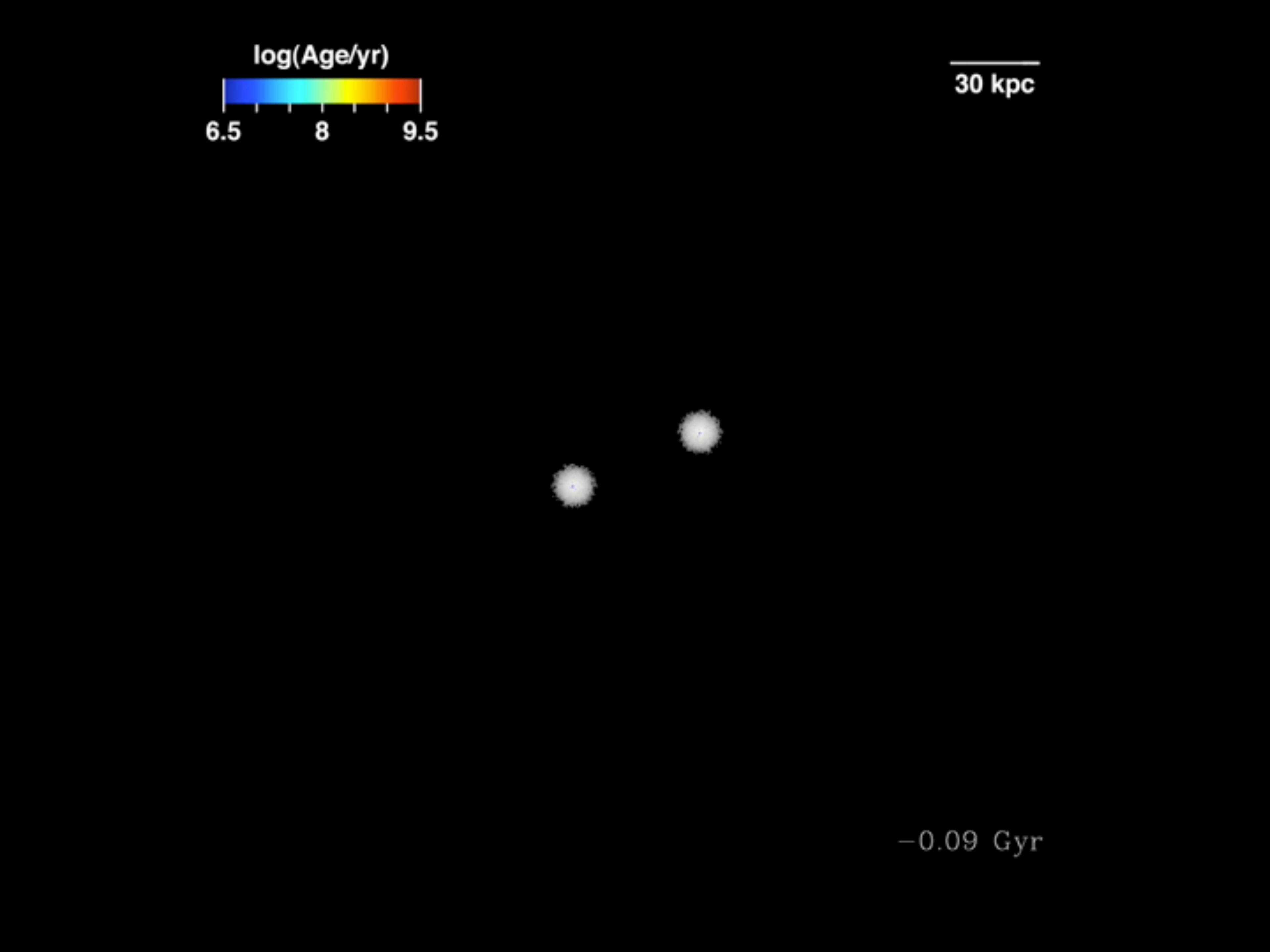

35 GCs (without Fe spreads)

Bastian & Lardo 2015

No evidence of heavy mass loss in GCs

Observed $f_{enriched}$ likely represents initial value

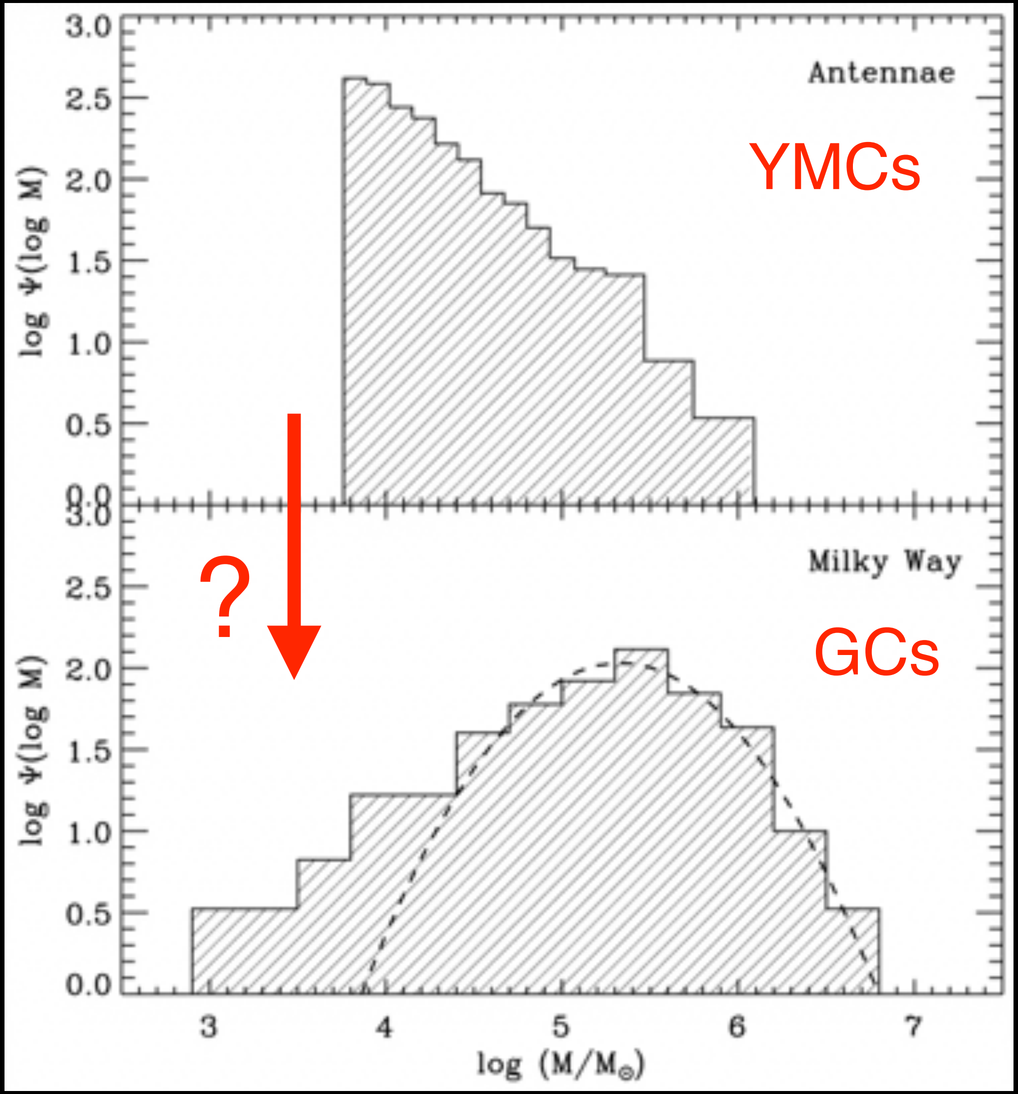
| | YMCs | Abundances | Variety/stochasticity | Mass budget | He spread correlation with GC mass | Constant $F_{enriched}$ | Lack of trends with metallicity | Radial profiles |
|---|---|---|---|---|---|---|---|---|
| AGB | ✗ | ✗ | ✗ | ✗ | ✗ | ✗ | ✗ | ✗ |
| FRMS | ✗ | ✗ | ✗ | ✗ | ✗ | ✗ | ✗ | ✗ |
| VMS | ● | ✗ | ✗ | ✗ | ✗ | ✗ | ✗ | ✗ |
| EDA | ● | ✗ | ✗ | ✗ | ✗ | ✗ | ✗ | ✗ |


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

# GC Formation

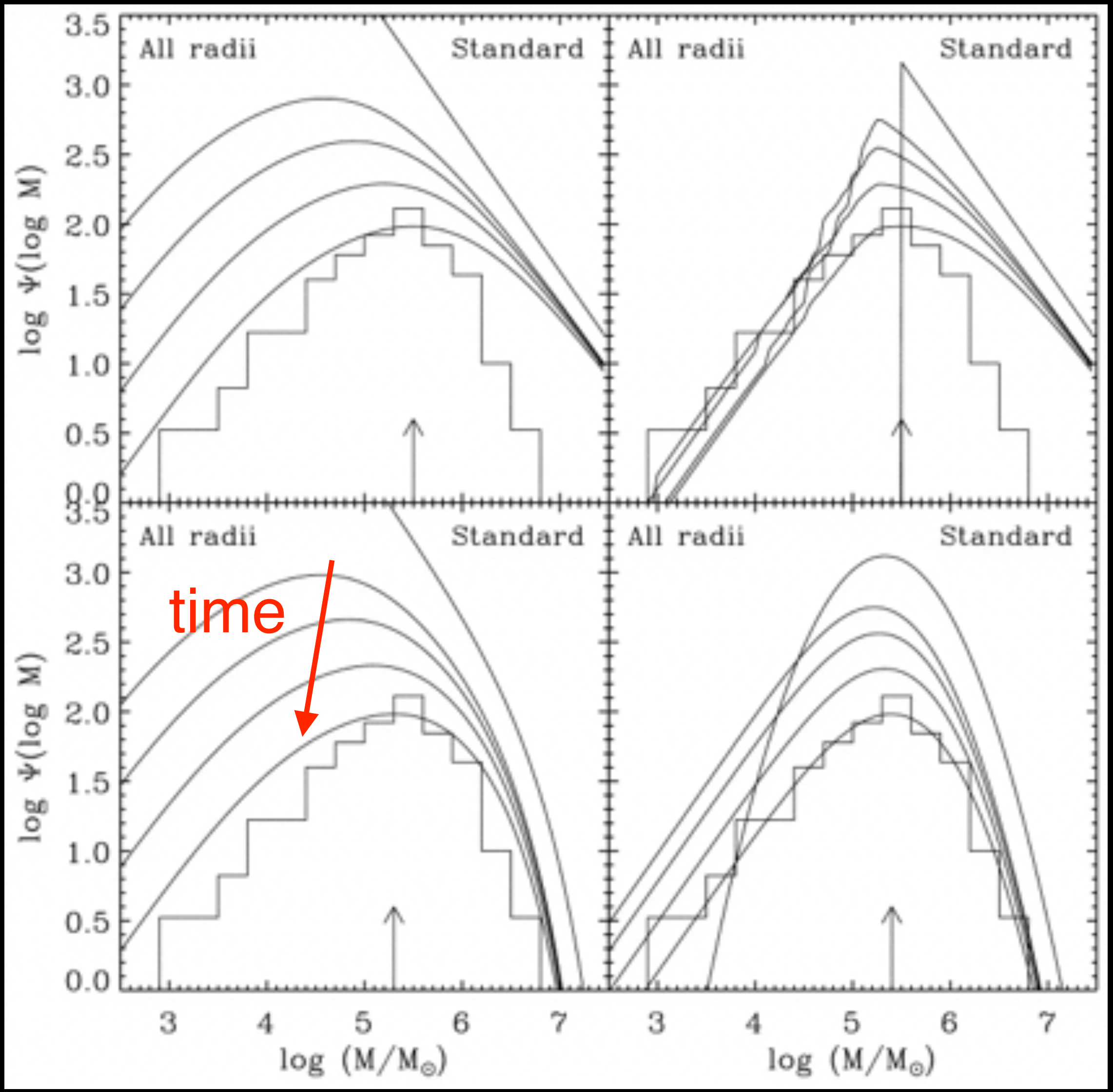
- Are GCs just the ancient analogues to YMCs?
- Similar size distribution, high masses, similar densities
- Similar stellar mass functions within them (stellar content)
- Overlapping metallicity distributions
- Very different mass functions
- Currently unknown if YMCs host multiple populations

# GC/YMC Mass Functions



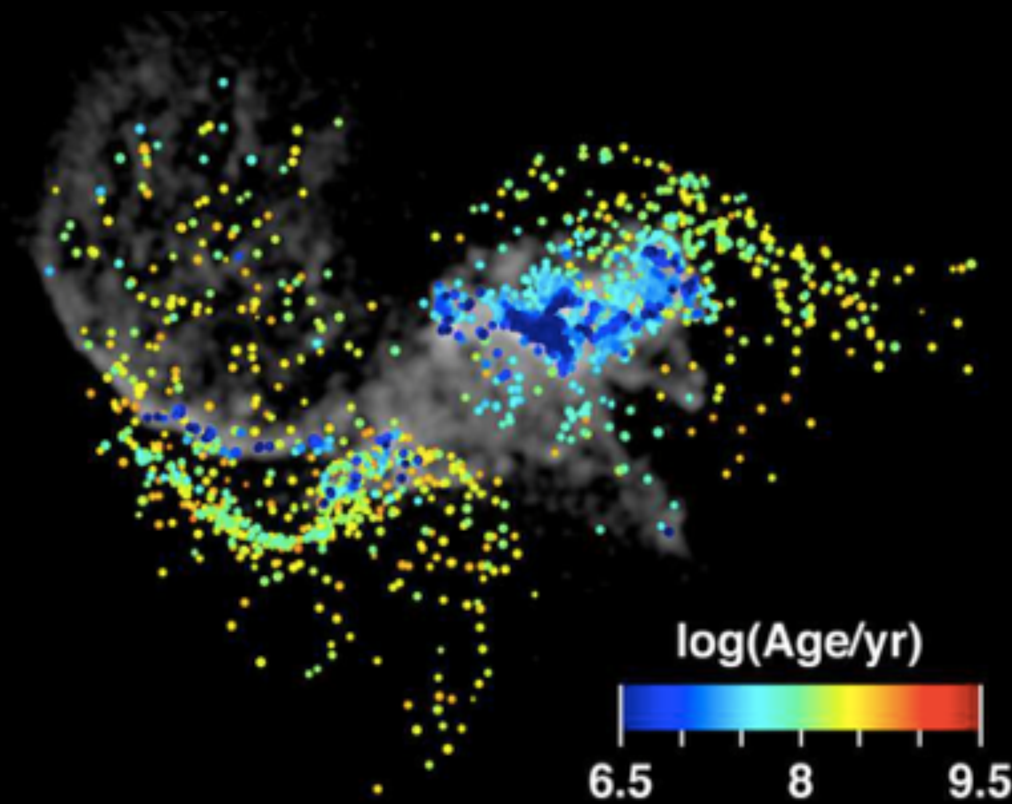

Can cluster disruption remove the low mass clusters in order to turn the power-law YMC MF into the log-normal seen in the GCs?

Fall & Zhang 2001



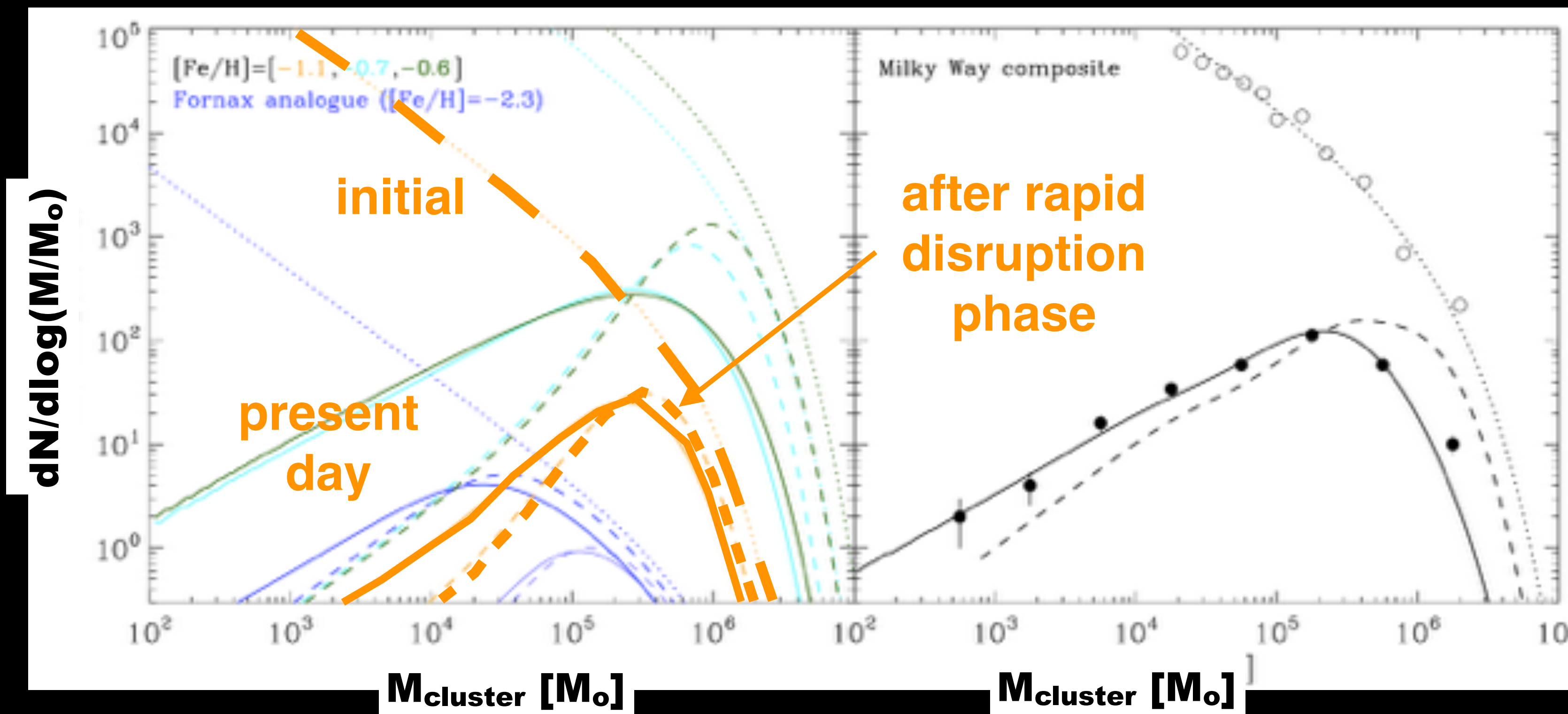

Fall & Zhang 2001

# GCs as normal YMCs at High-Z




- proto-GCs form in discs
- most are disrupted within 10s of Myr due to interactions with the ISM
- galaxy interactions/mergers 'liberate' GCs into the halo where they are able to survive
- clusters that remain in disks are disrupted and do not become GCs

# GCs as normal YMCs at High-Z




Elmegreen & Hunter 2010
Elmegreen 2010
Kruijssen 2015

Evolution of the mass function

Most cluster mass loss/disruption takes place in the gas rich disk of the galaxy

## EAGLE: Evolution and Assembly of GaLaxies and their Environments

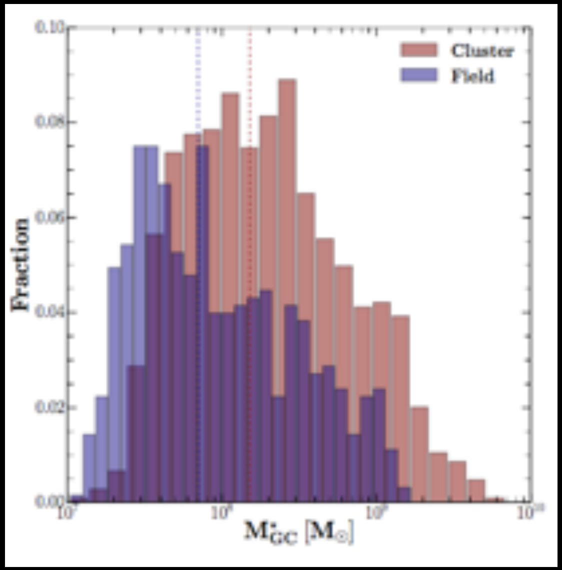
Gas associated with a typical spiral galaxy (colour encodes temperature)
Simulation by Rob Crain & the EAGLE collaboration

z = 29.9
t = 0.1 Gyr
L = 2.0 cMpc

Visualised with Typhoon (Geach & Crain)

# Implications of Gamma - $\Sigma_{SFR}$ Relation

| | Galaxy 1 | Galaxy 2 |
|---|---|---|
| Stellar mass | $10^9$ Msun | $10^9$ Msun |
| Location | Galaxy cluster | Field |
| SFH | High SFR burst | Continuous low SFR |
| GCs | **many** | **few** |




Mistani et al. 2015