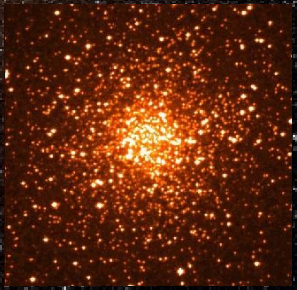
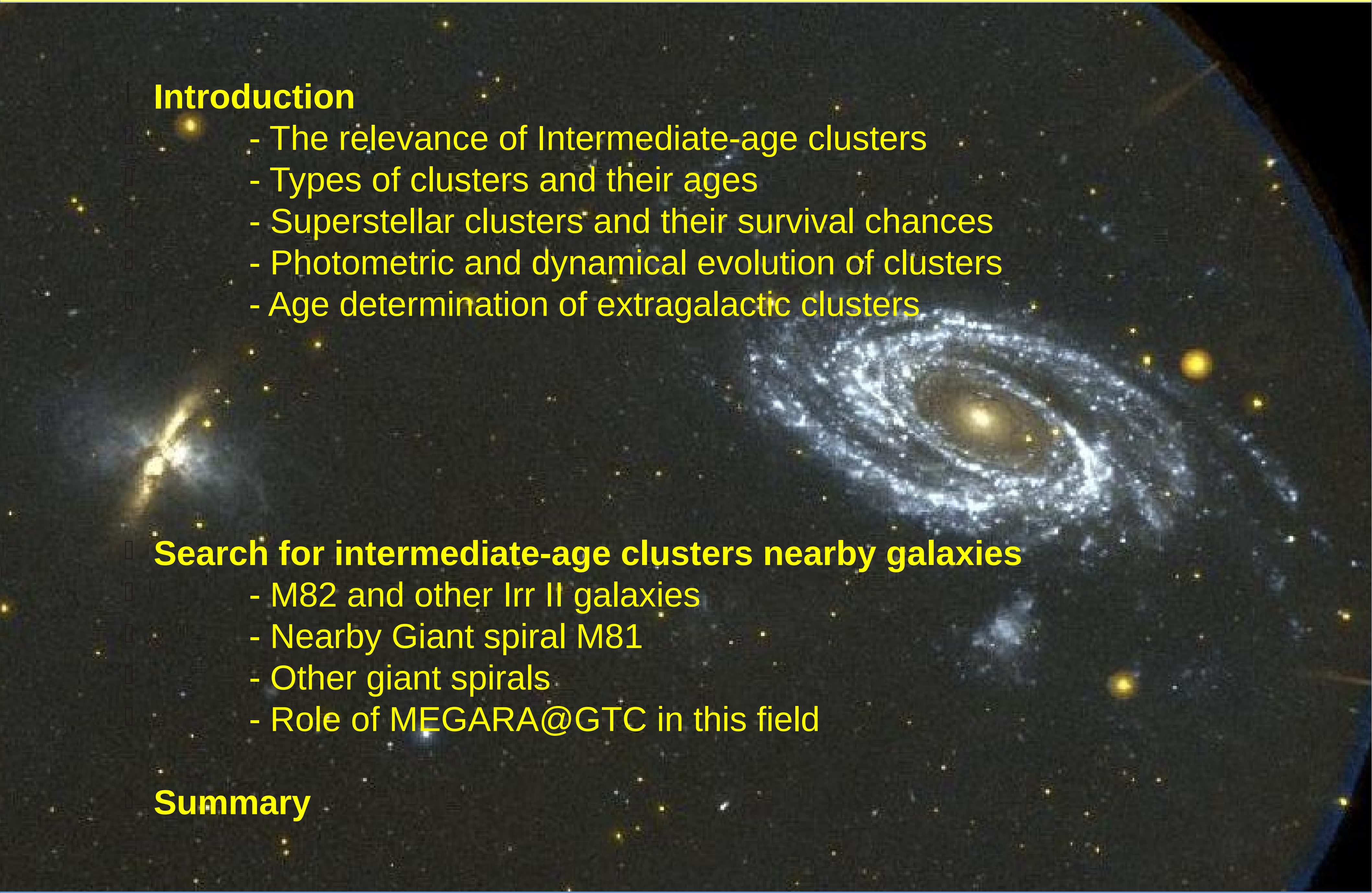
The missing link between Open clusters and globular clusters

Divakara Mayya
INAOE



Outline



Introduction

- The relevance of Intermediate-age clusters
- Types of clusters and their ages
- Superstellar clusters and their survival chances
- Photometric and dynamical evolution of clusters
- Age determination of extragalactic clusters

Search for intermediate-age clusters nearby galaxies

- M82 and other Irr II galaxies
- Nearby Giant spiral M81
- Other giant spirals
- Role of MEGARA@GTC in this field

Summary

The group

- **INAOE researchers:**
    - **Divakara Mayya**
    - **Daniel Rosa González**
    - **Lino Rodríguez**
    - **Ivanio Puerari**
    - **Luis Carrasco**
    - **Esperanza Carrasco**

- **Others**
    - **Alessandro Bressan (INAF, Italy)**
    - **Gustavo Bruzual (IryA, Morelia)**
    - **Juan Pablo Papaqui (U. de Guanajuato)**
    - **Armando Gil de Paz (UC Madrid)**

- **Ph.D. Students at INAOE (graduated and active):**
    - **Mayra Santiago-Cortés (graduated)**
    - **Mauricio Gomez-González (graduated)**
    - **Pedro Ovando (active)**
    - **Luis Lomelí (active)**
    - **Bolivia Cuevas (active)**

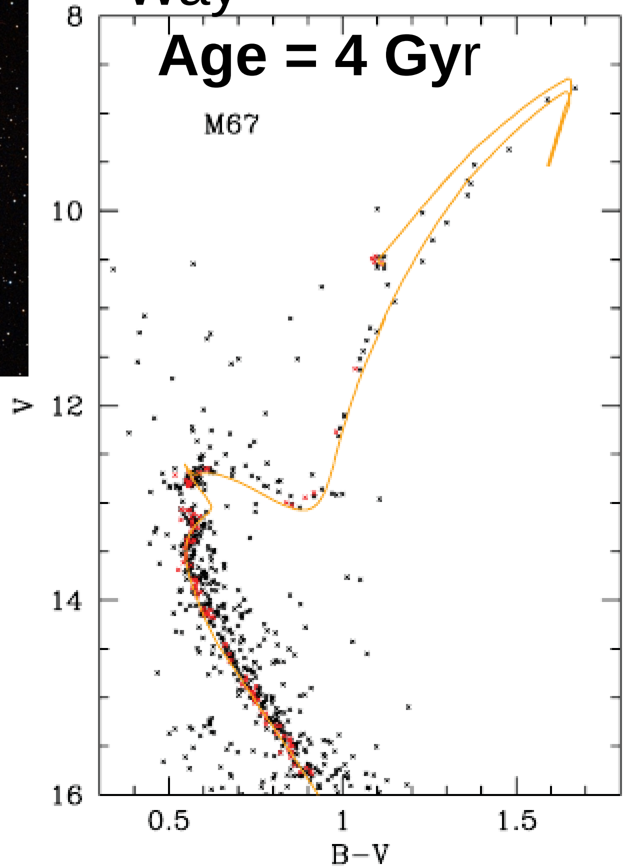
Are there significant population of stellar clusters of age between 1 to 10 Gyr in disks of galaxies?

Very few intermediate-age clusters exist in the Milky Way

Bressan et al. 2012

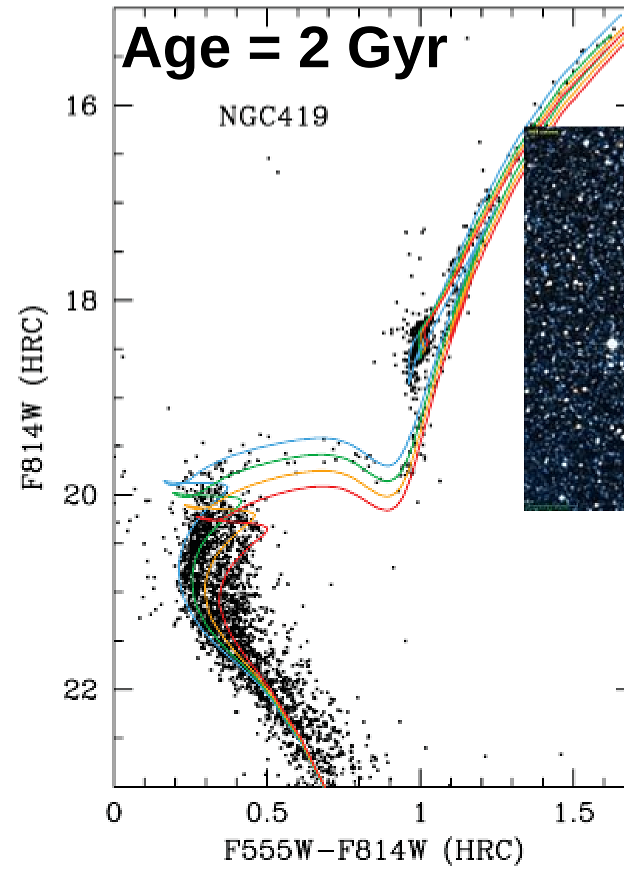
M67 in the Milky Way

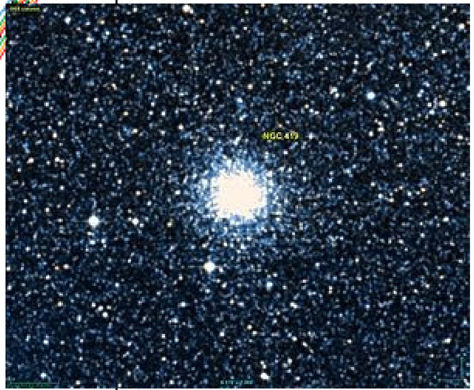
Age = 4 Gyr



NGC419 in SMC

Age = 2 Gyr





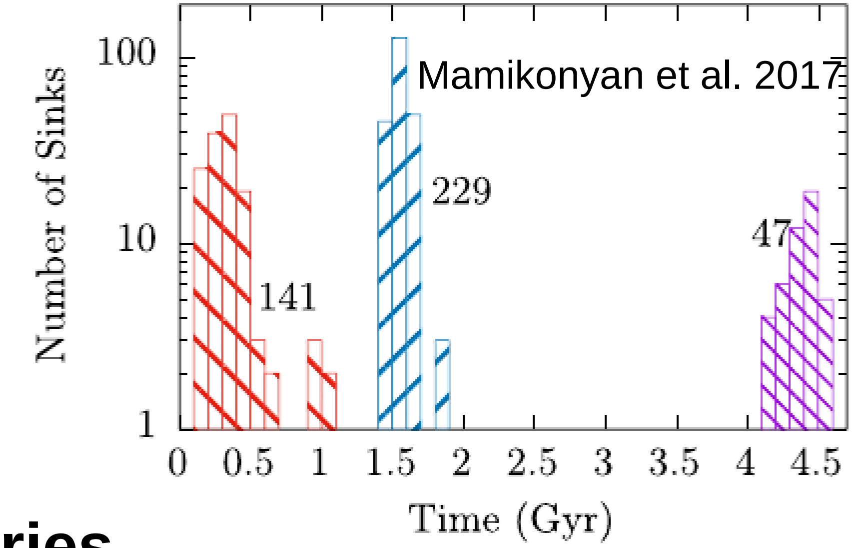
===> Are there many such clusters in other galaxies?

Relevance of missing-link clusters to modern Astrophysics

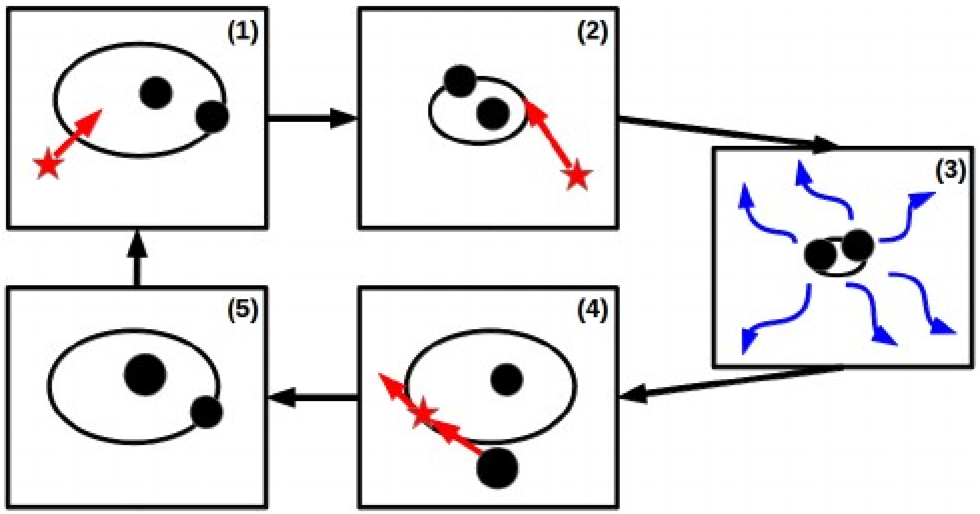
1. Hierarchical galaxy formation

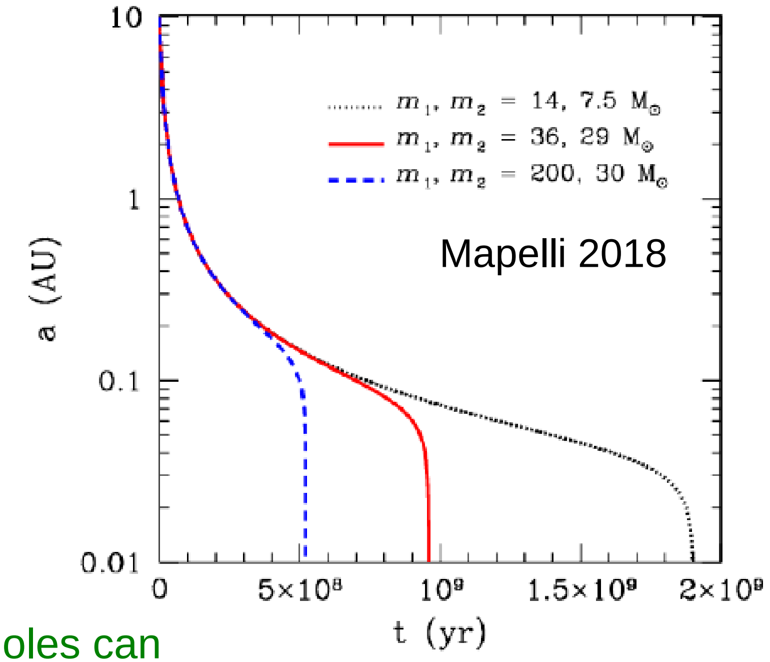
- Galaxies in the local Universe have gone through various episodes of mass acretion

- Accretion of gas-rich galaxies are expected to leave behind a population of Intermediate-age clusters



2. Formation of massive blackhole binaries
- sources of gravitational waves

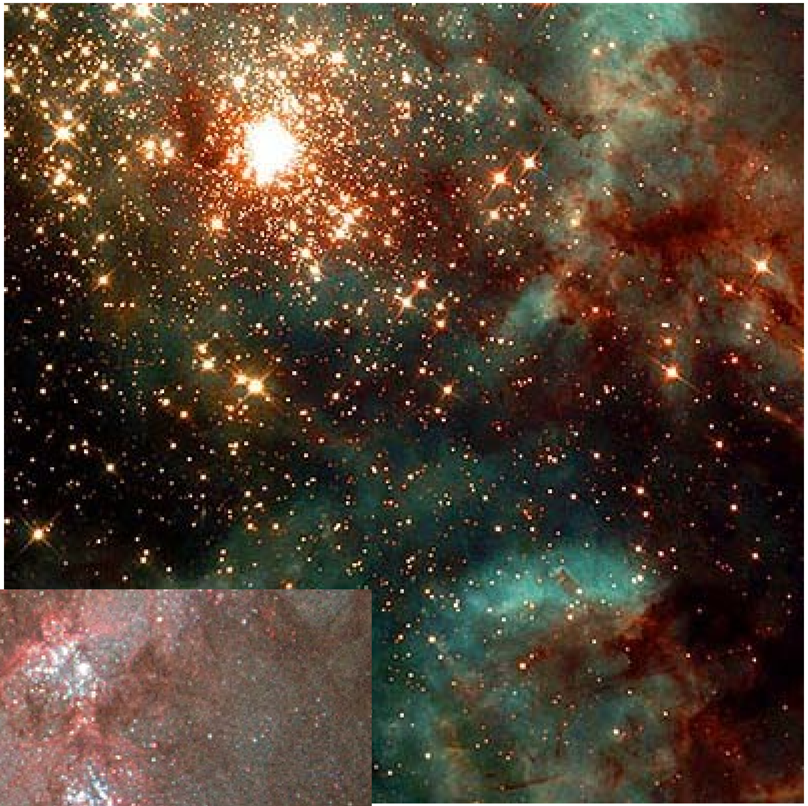




- Clusters older than 2 Gyr are principal locations where black-holes can merge and produce detectable gravitational emission

Two fundamental facts about stars and clusters

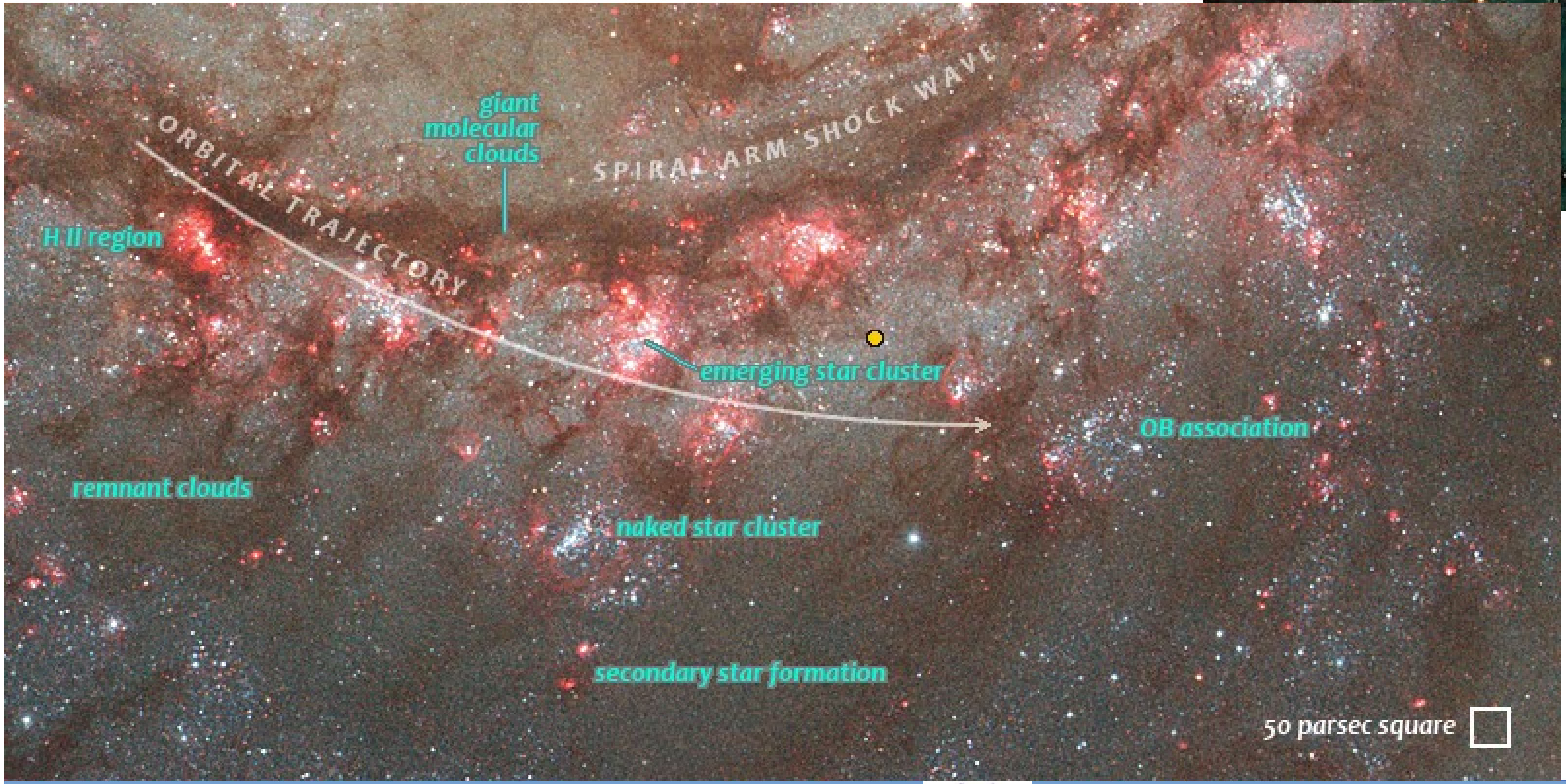
1. Stars form in clusters – Lada & Lada (2003)



30 Doradus in LMC

2. Majority of the stellar mass in galaxies is in field stars

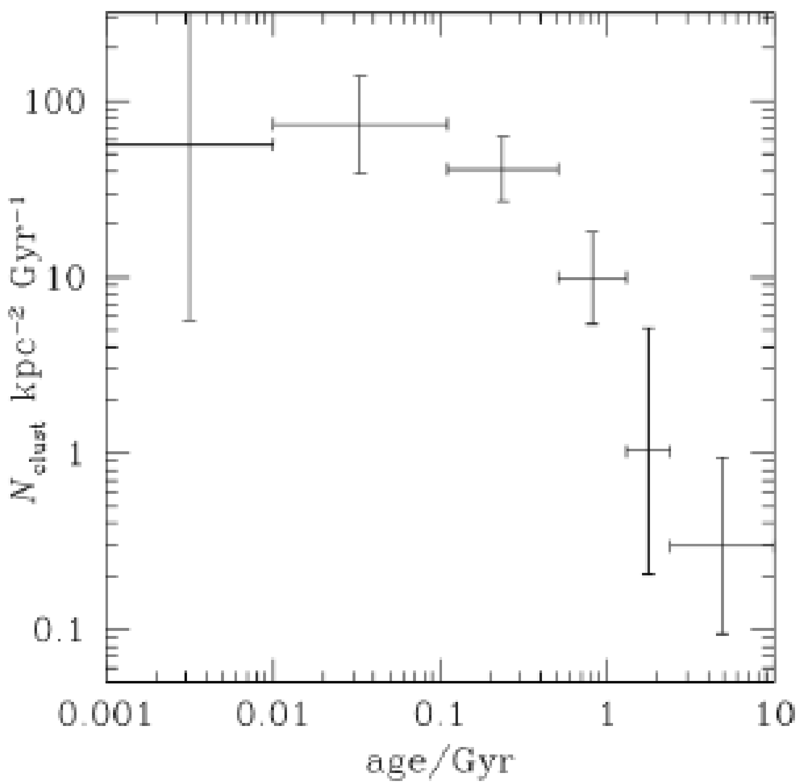
===> **Majority of the star clusters are short-lived**



M51 spiral arm

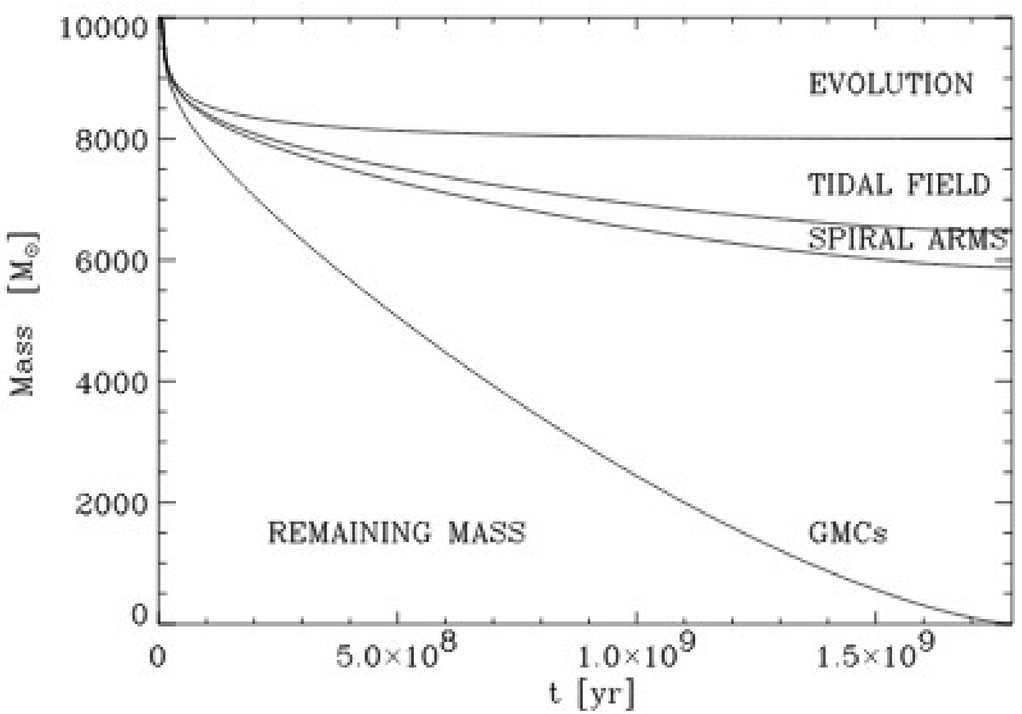
Observational evidence for dissolution of clusters

Binney & Merrifield (1998)



Mass evolution of a cluster of 104 Mo

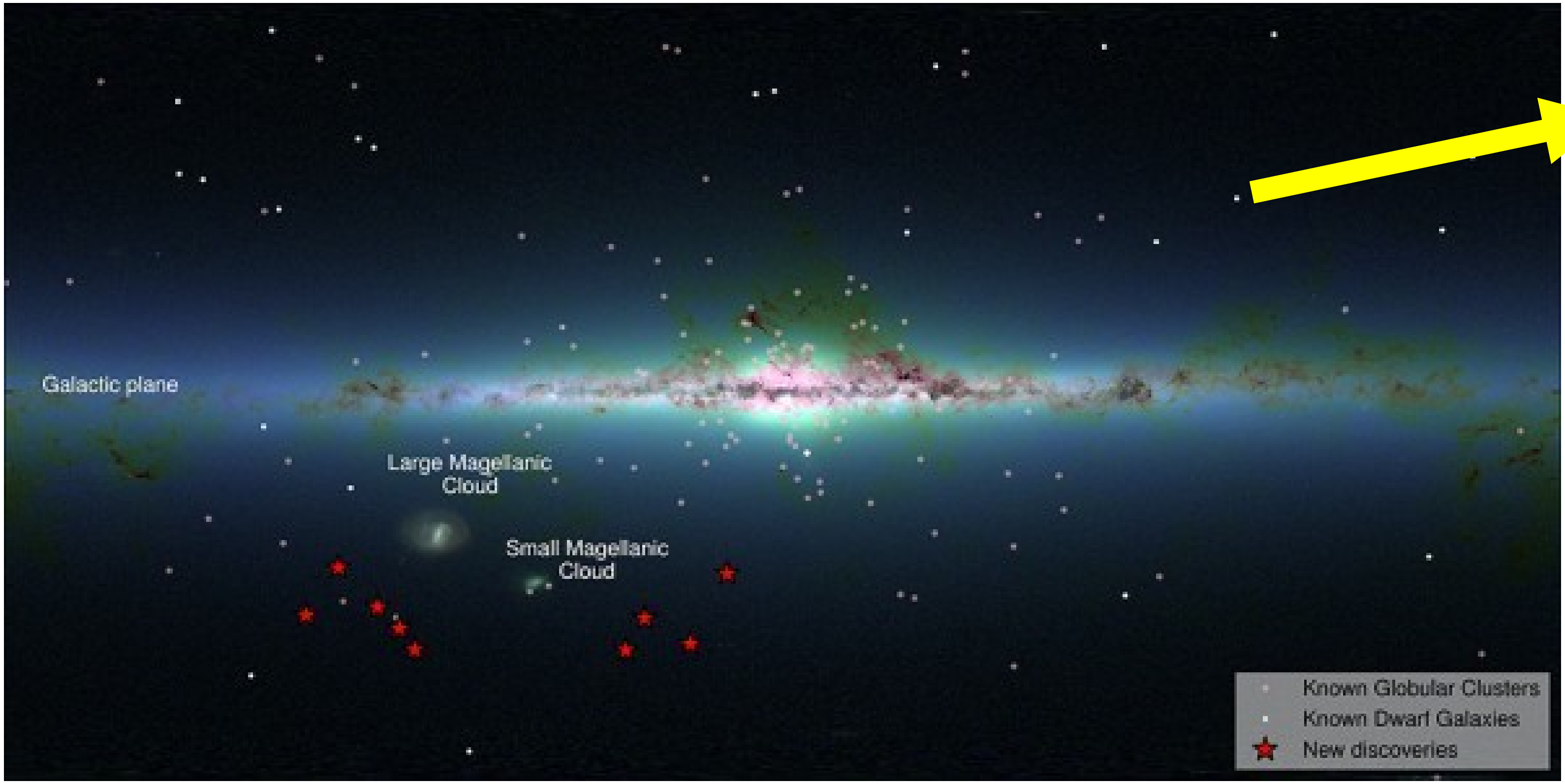
Lamers & Gieles (2006)

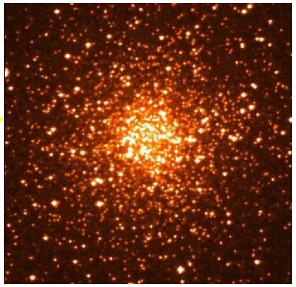


- Very few open clusters older than 1 Gyr present in the Milky Way

- Encounters with the GMCs is the dominant dissolution effect

Globular clusters are the oldest objects in the Universe





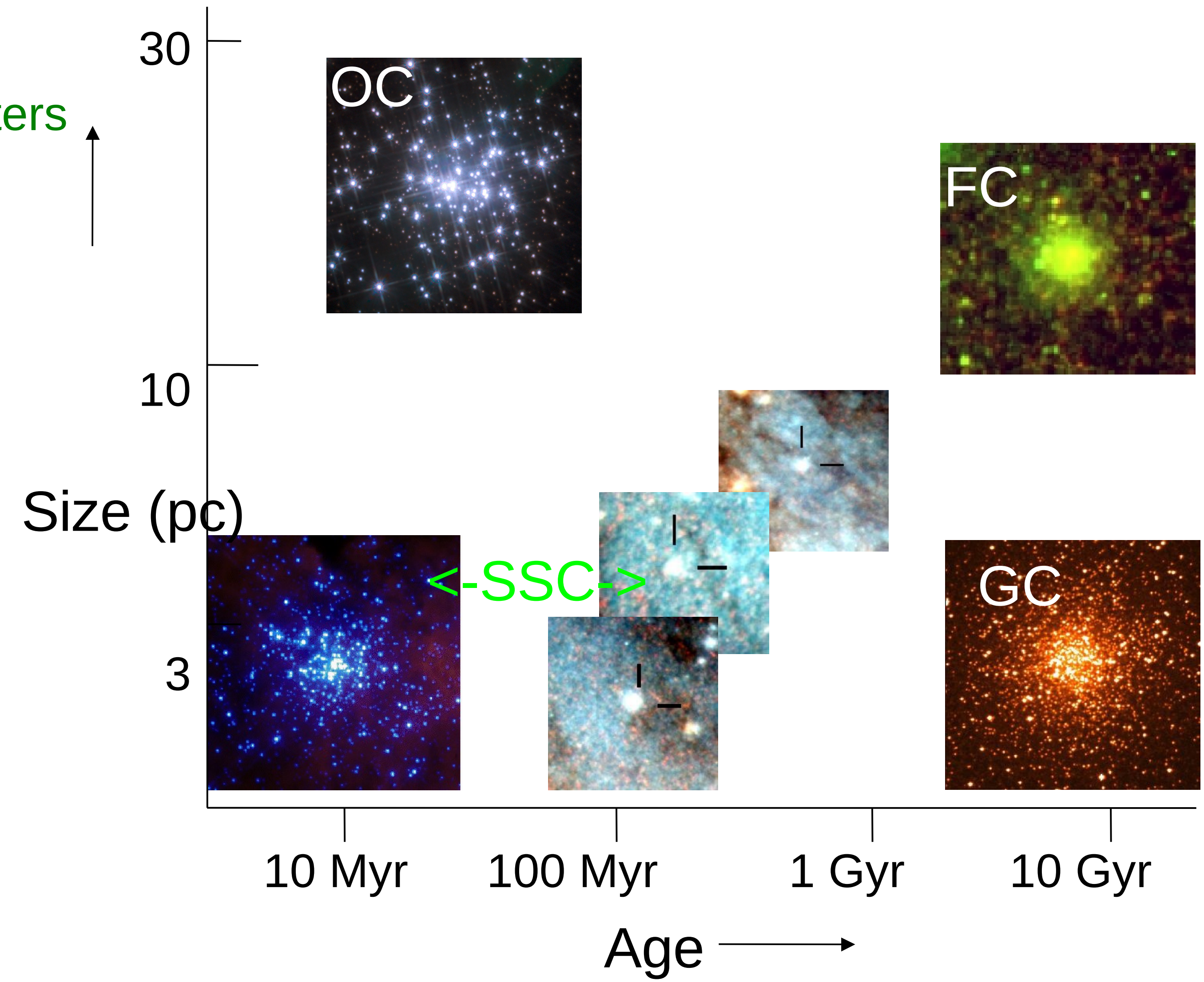
They survive because they are:

1. **massive**
2. **compact and**
3. **located in the halo**

===> Less affected by gravitational tidal effects

Current classification of stellar clusters

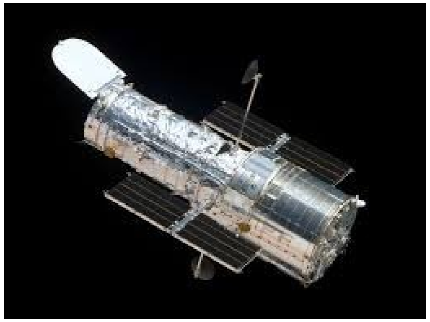
- Types of clusters in the Milky Way
  - Open clusters (OC)
  - Globular clusters (GC)
- Types of extra-galactic clusters
  - Open clusters
  - Super Star clusters (SSC)
    O'Connell et al. (1995)
  - Fuzzy Clusters (FC)
    Larsen & Brodie (2000)
  - Globular clusters

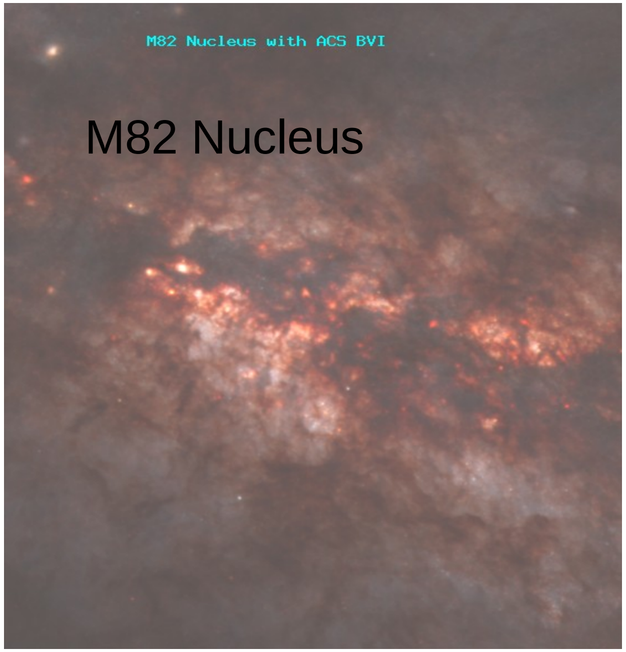


Super Stellar Clusters (SSCs)

Discovered (>100) using HST images
- in the Nuclear starburst of M82 (O' Connell et al. 1995)
- in Antennae by Whitmore & Schweizer (1995)

HST





*** Young (age<10 Myr)**

*** Massive (Mass>105 Msun)**

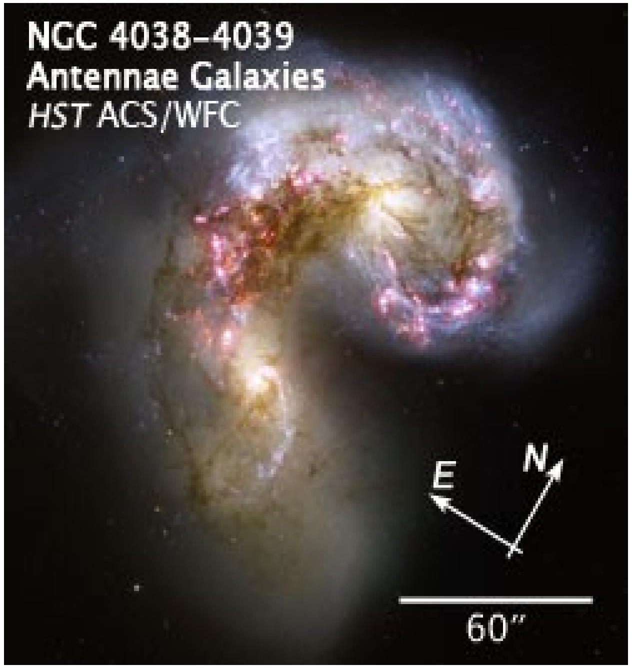
*** compact clusters (effective radius ~ 5 pc)**

- mainly found in starburst environments

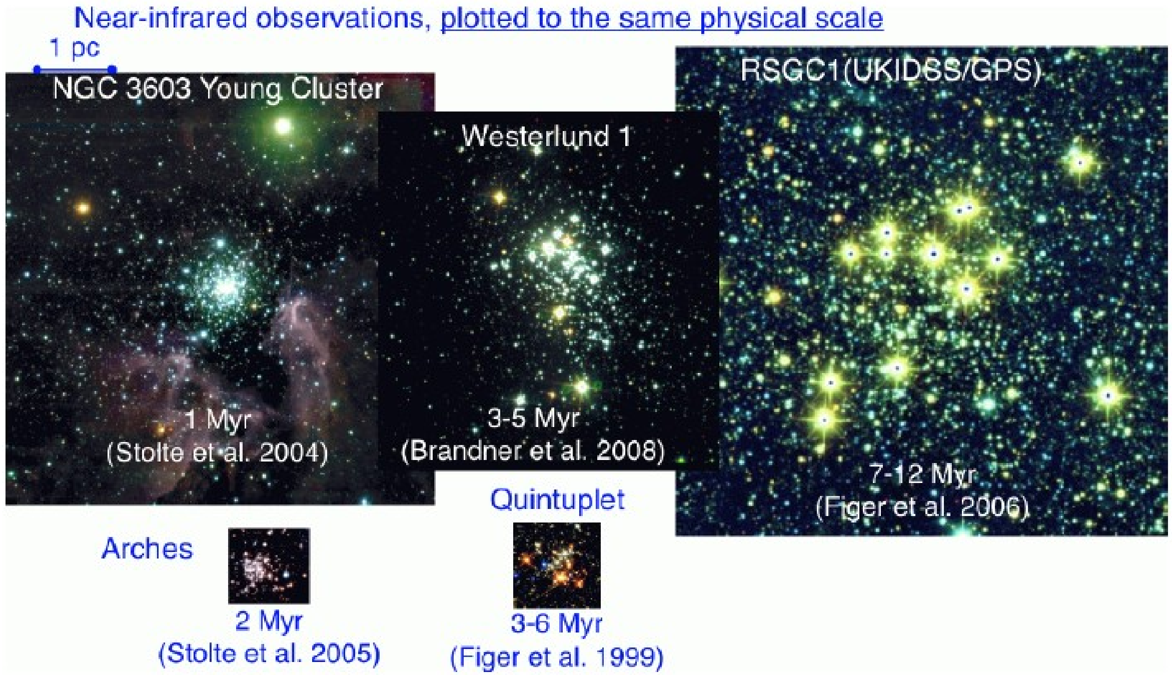
Clusters in spiral arms

Young Massive Clusters (Giant HII regions)
- Massive, but not necessarily compact

Compact Stellar Clusters (CSCs)
- Compact, but of l**ower mass (104 Msun)** **clusters** found in normal galaxies like MW, LMC, M31, M51, M81 etc. (Larsen 2010)

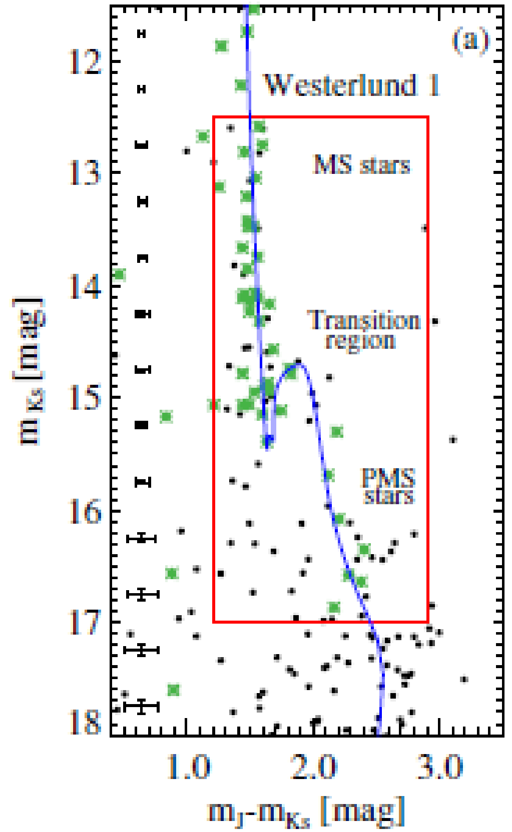


Population of compact clusters in the Milky Way



Cluster	log $M1$ ($M_\odot$)	log $M2$ ($M_\odot$)	Radius (pc)	Age (Myr)
Wd 1	3.8	4.75	0.6	3.5–5
Quintuplet	3.0	3.8	1.0	3–6
Arches	3.7	4.3	0.19	2–3
Center	3.0	4.0	0.23	3–7
NGC 3603	3.1	3.7	0.23	2.5
R136	3.4	4.5	1.6	<1–2

Westerlund 1:
Age-spread < 1 Myr

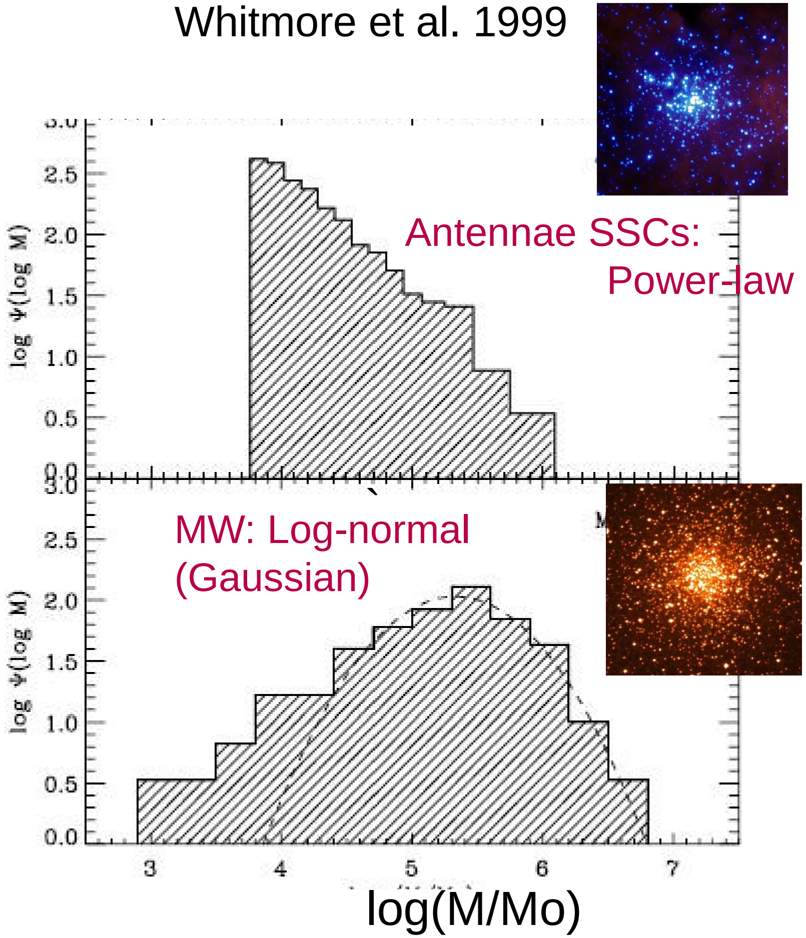


Kudryavtseva et al. 2012

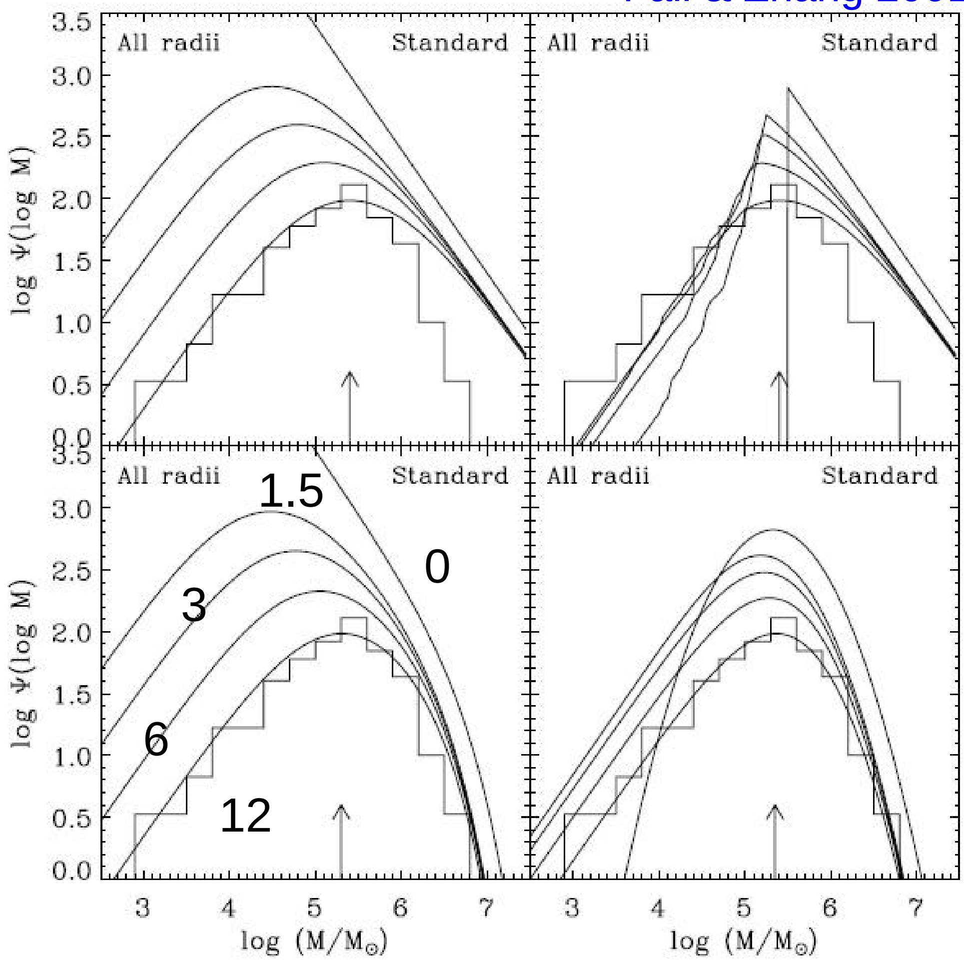
Survival chances of SSCs:

Comparison of Mass Functions of SSCs and GCs

Whitmore et al. 1999

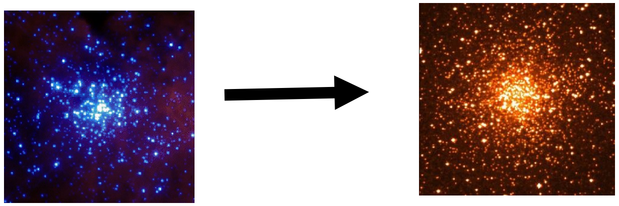


Fall & Zhang 2001



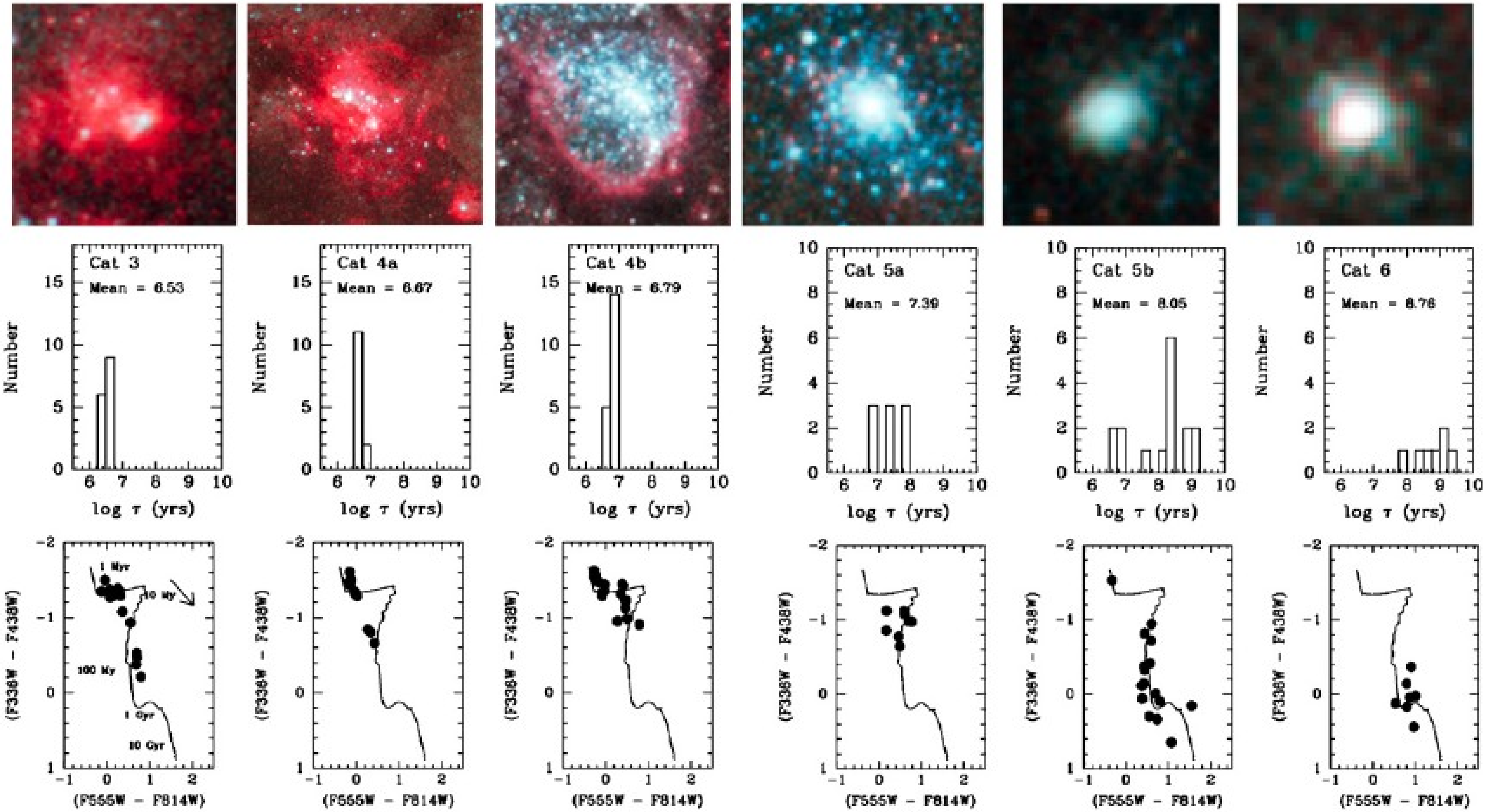
Intrinsic power-law mass functions take log-normal form due to selective destruction of low-mass clusters

===> SSCs more massive than ~105 Mo could be future GCs



Evolutionary properties of stellar clusters

3 Myr 5 Myr 10 Myr 25 Myr 100 Myr 600 Myr

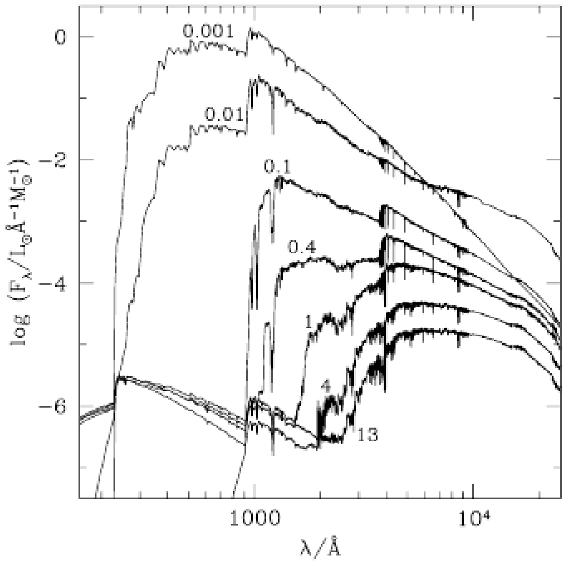


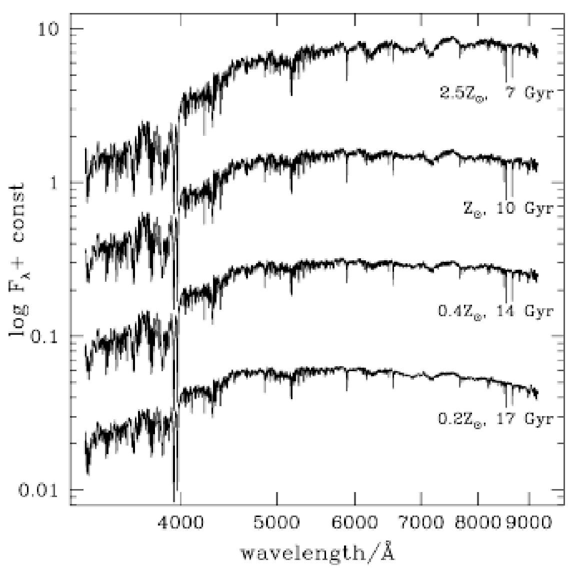
M83: Whitmore at al. 2011

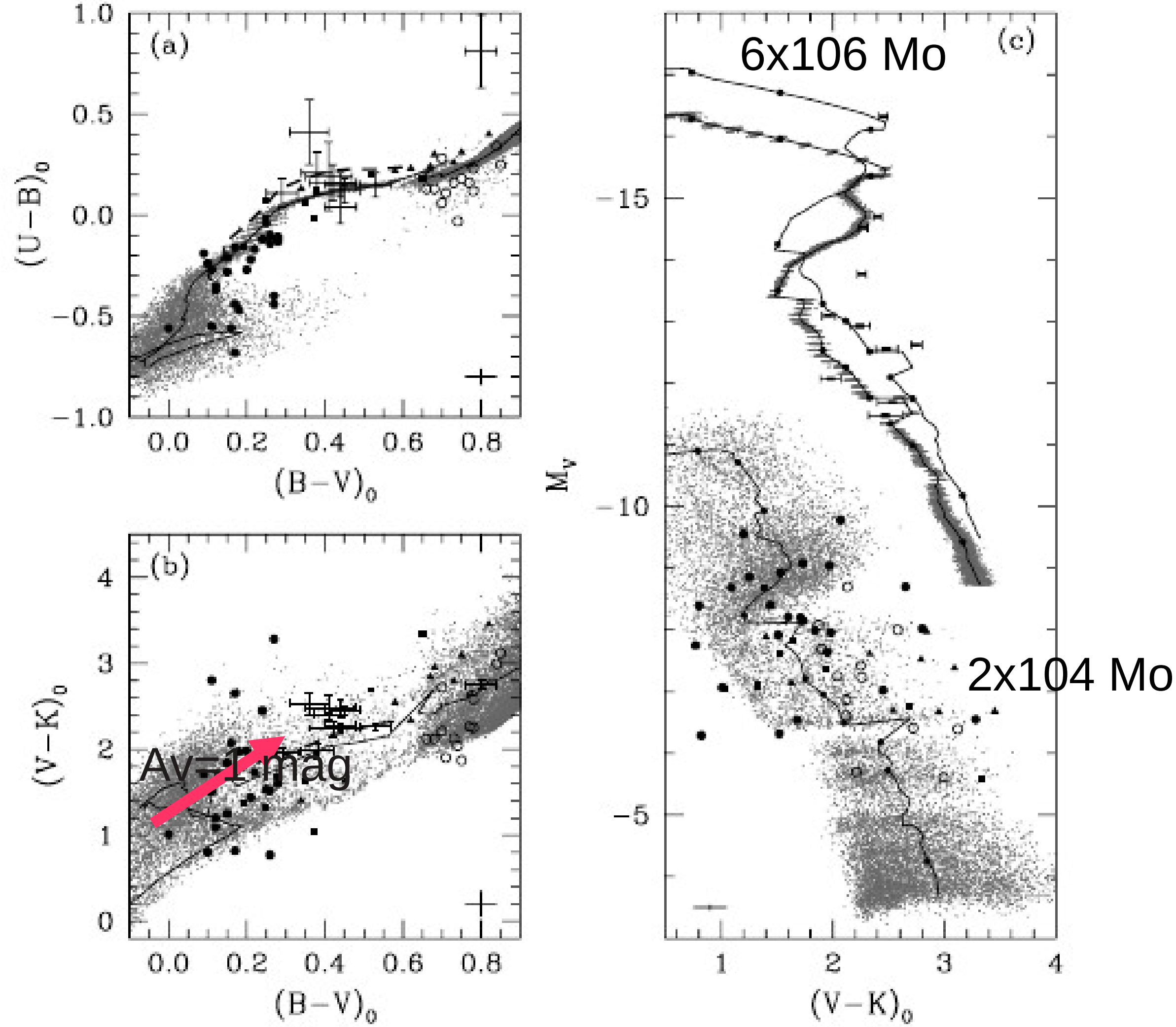
1. **Spectrophotometric evolution**
2. **Structural (or morphological) evolution**

Bruzual & Charlot 2003

- Stellar clusters are co-eval population satisfying an IMF







- Colors suffer from age-reddening degeracy

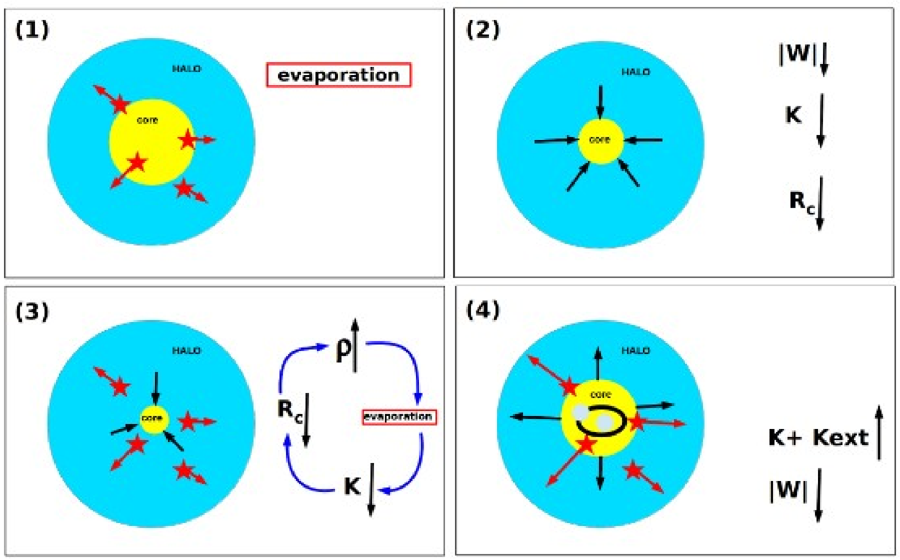
- Require spectra to determine reliable ages

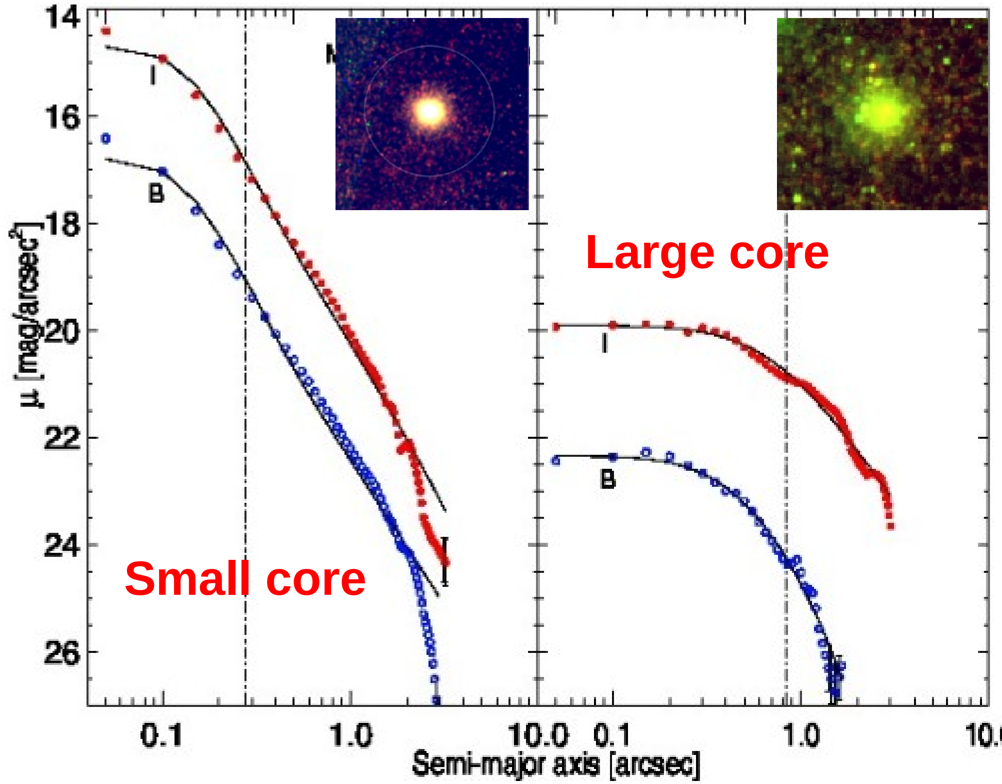
2. Structural (or morphological) evolution

Isothermal spheres of lowered energies - King (1966)

$$\mu(r) = k\left\{\frac{1}{\left[1+(r/r_c)^2\right]^{1/2}} - \frac{1}{\left[1+(r_t/r_c)^2\right]^{1/2}}\right\}^2$$

Mapelli 2018





Mo/pc2

50000

500

1

M81 GC radial intensity profiles in B & I bands fit very well with King profiles

- Core collapse and halo expansion
- Relaxed systems follow King profile

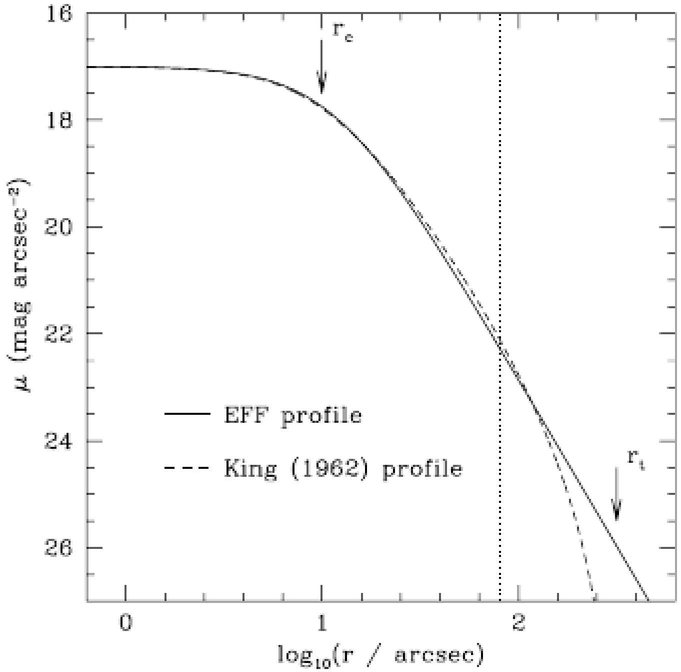
Structure of young and intermediate-age superstellar clusters

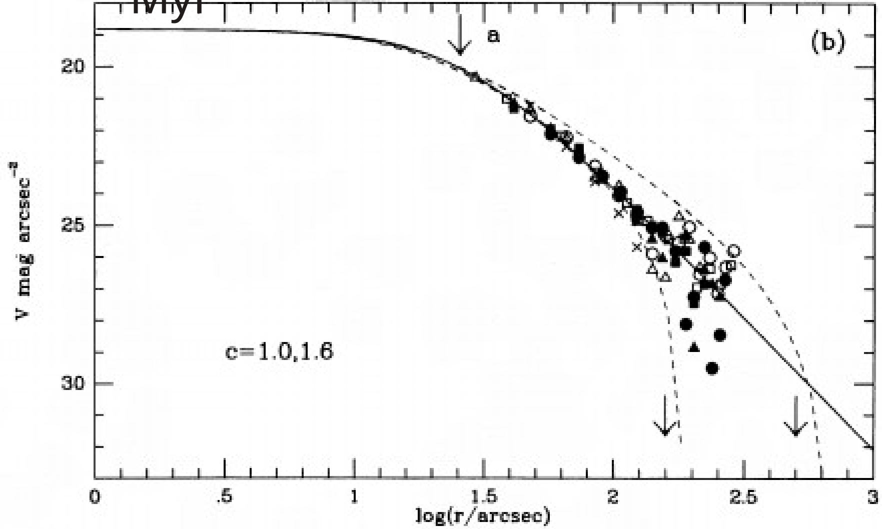
LMC clusters follow Moffat/EFF profiles

(Elson, Fall & Freeman 1987)

$$\mu(r) = \mu_0 \left(1 + \frac{r^2}{a^2}\right)^{-\gamma/2}$$

NGC1831 in LMC Age=200 Myr





Mackey & Gilmore 2003

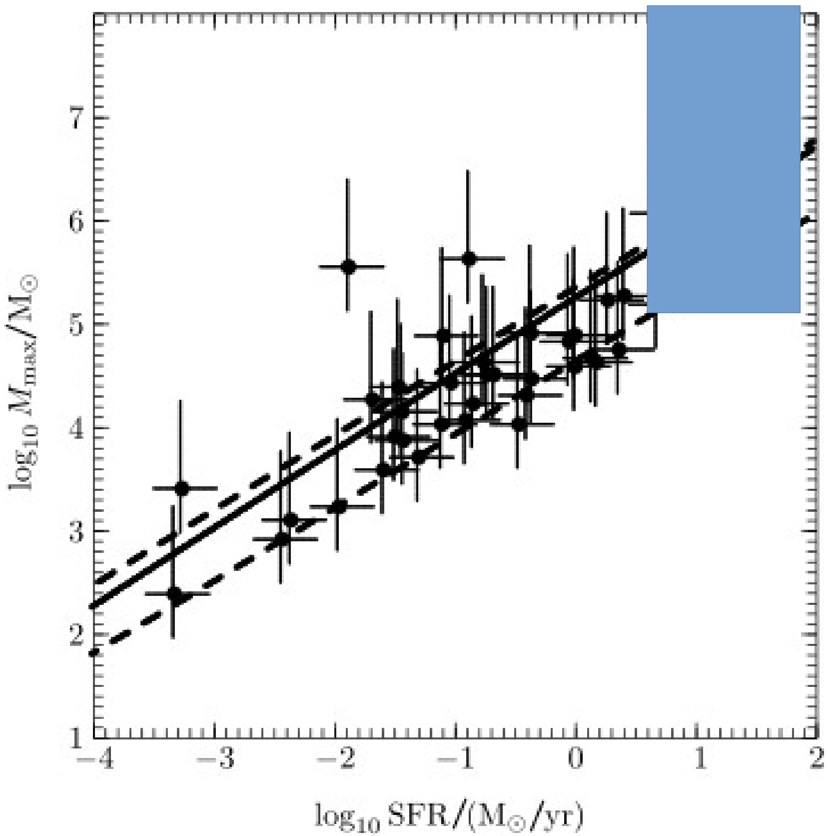
Where to look for the intermediate-age SSCs?

* age > 100 Myr)

* Massive (Mass>105 Msun)

* compact clusters (effective radius ~ 5 pc)

The brightest cluster vs SFR relation



Maschberger & Kroupa (2007).

Bastian et al. 2008

105 Msun

Galaxies that had SFR>10 Mo/yr in the past

===> post starburst galaxies
===> post-mergers/interacting galaxies

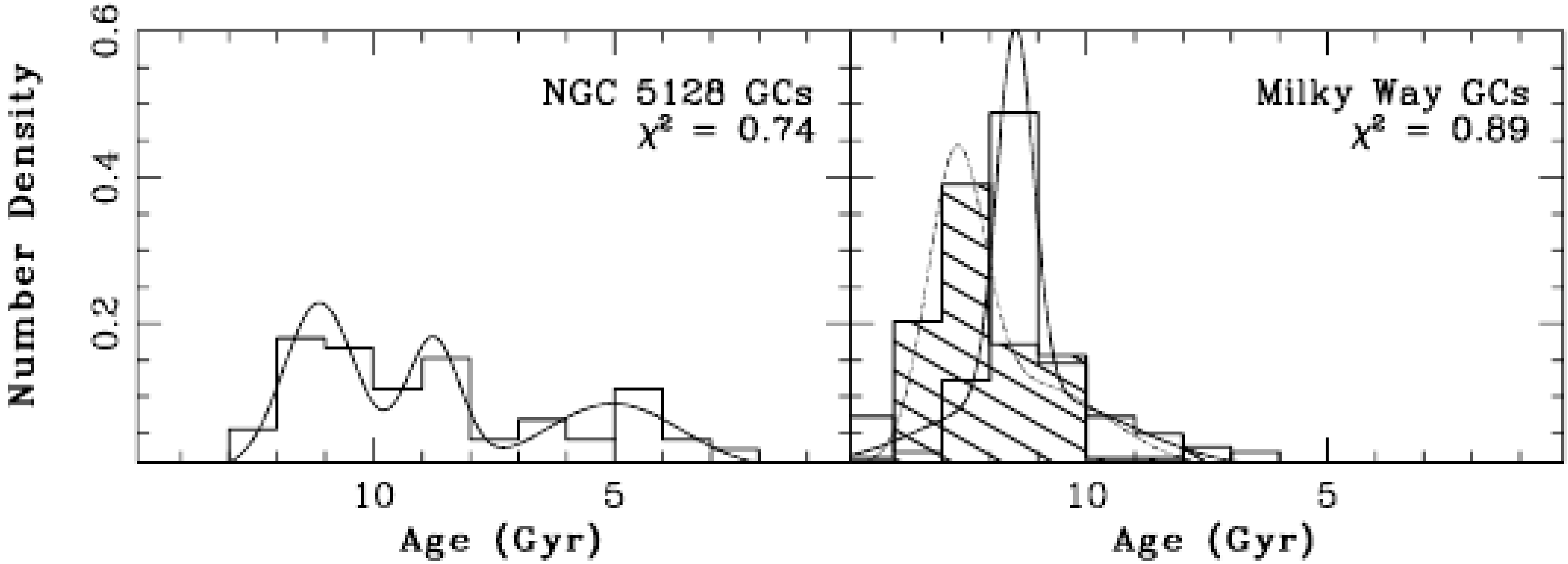
Disks of giant spiral galaxies if they had past episodes of major mergers

NGC5128: Nearby Giant elliptical with a rich population of intermediate age SSCs

Woodley et al. 2010

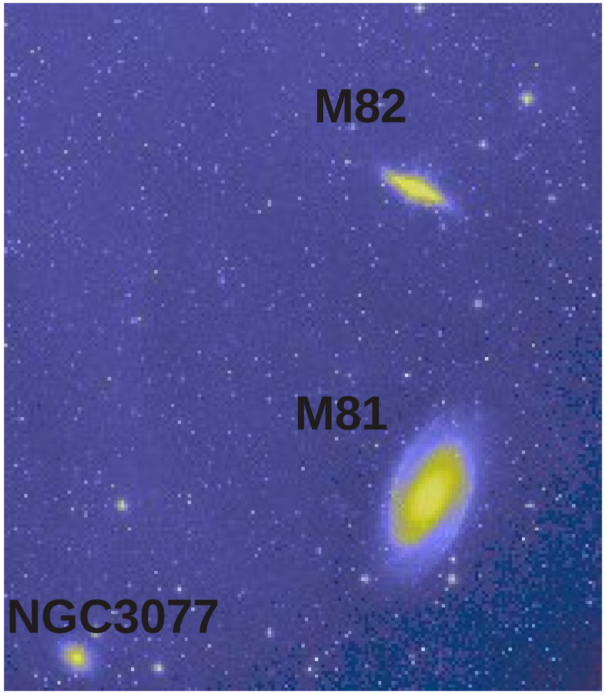
Among 72 GC candidates analyzed spectroscopically:

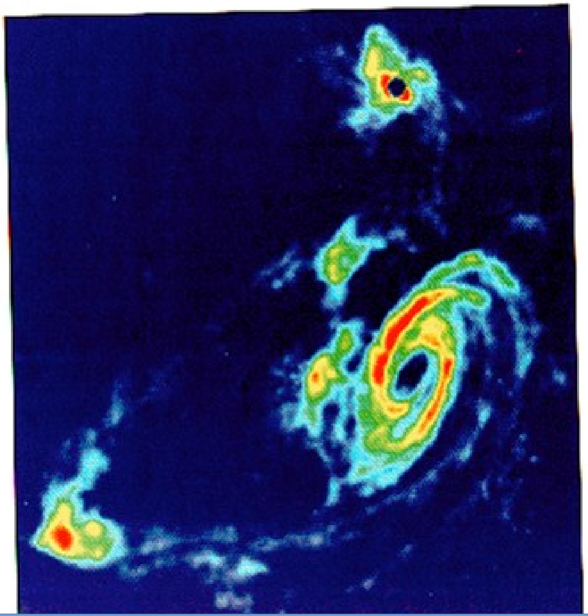
68% - Age > 8 Gyr (GCs)
14% - Age 5-8 Gyr
18% - Age < 5 Gyr



Intermediate-age SSC populations in M82 and Irr II galaxies

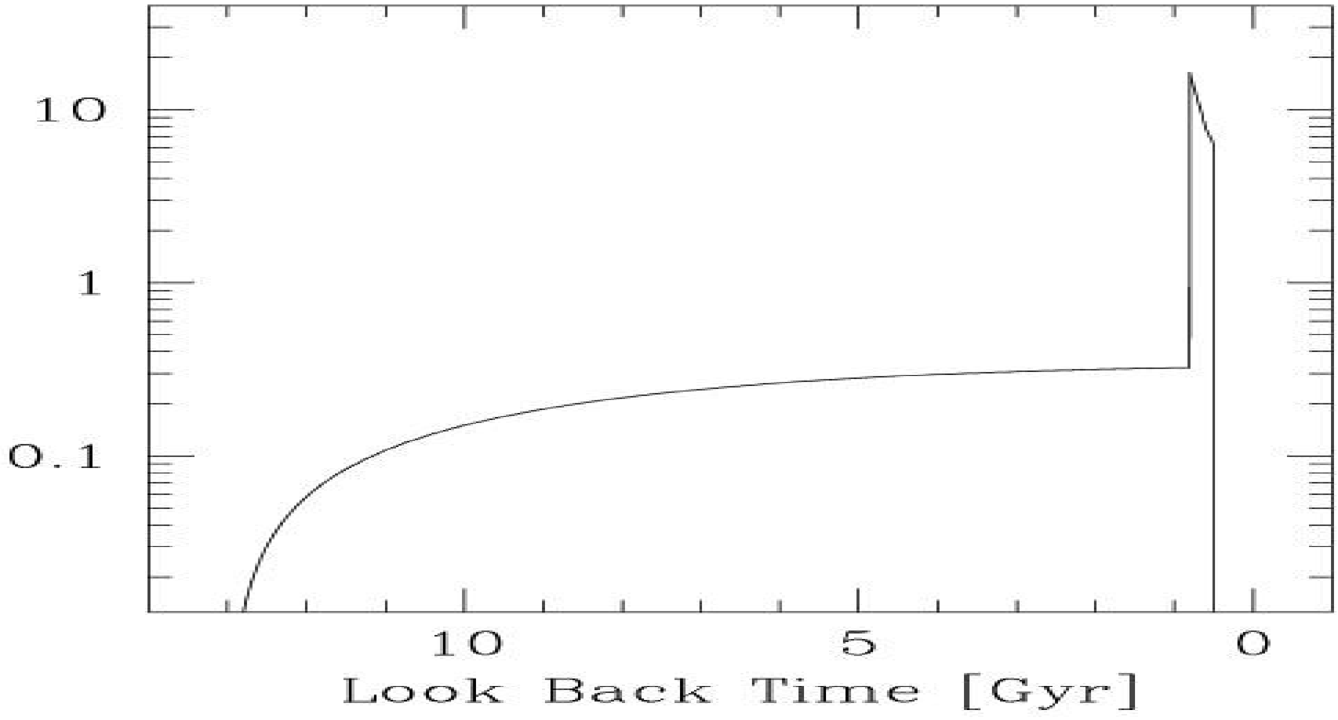
History of star formation in the disk of M82





Interaction between galaxies in M81 group ~0.3 to 1 Gyr ago (Yun et al. 1993)

Post-interaction formation of disk-wide starburst and massive SSCs in M82 disk (Mayya et al. 2006)



SSC population (~400) in the post starburst disk of M82

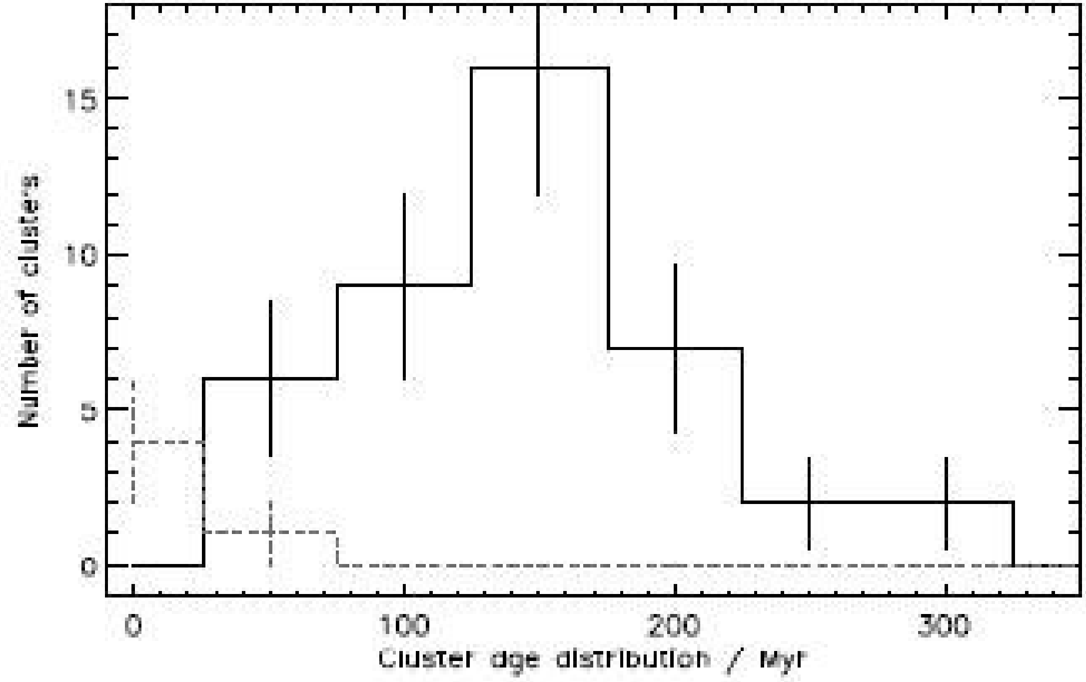
Mayya et al. 2008

Ages of the disk SSCs of M82

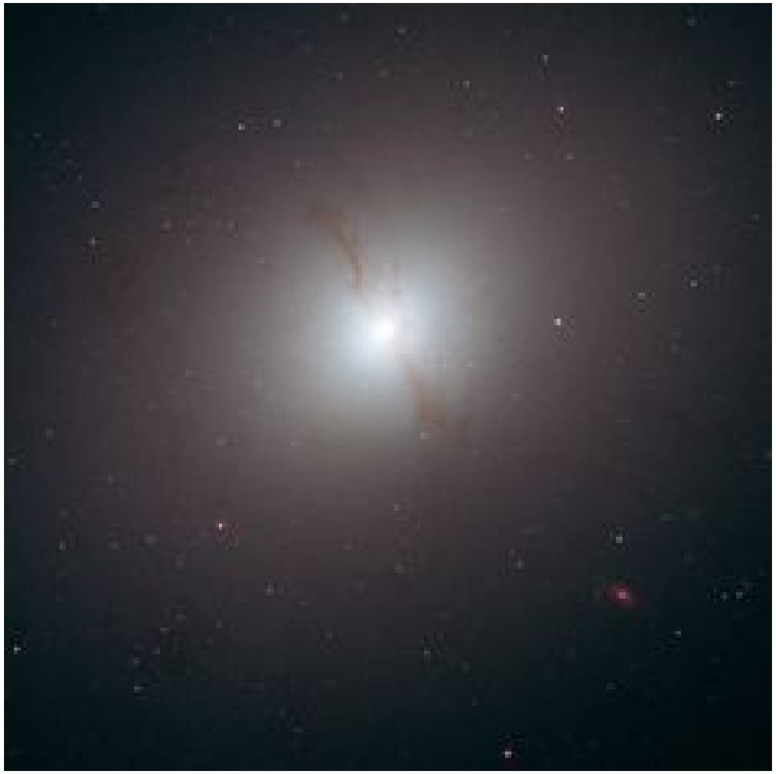
Spectroscopic ages:
50 – 300 Myr
===> consistent with burst model for the formation of the disk

Thus SSCs are good tracers of past events of star-formation activity and interaction

Konstantopoulos et al. 2009



Search for intermediate-age SSCs in Irr II galaxies



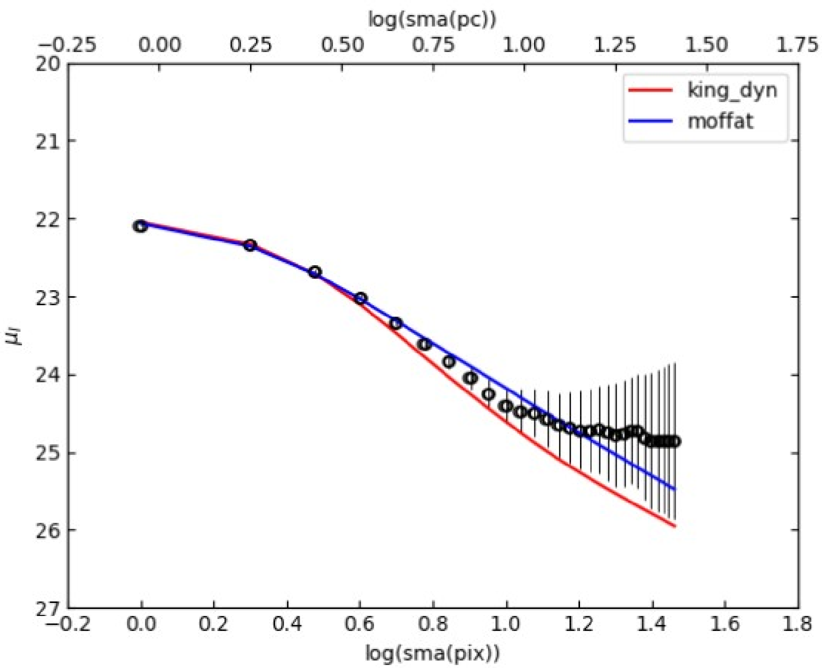
NGC3077

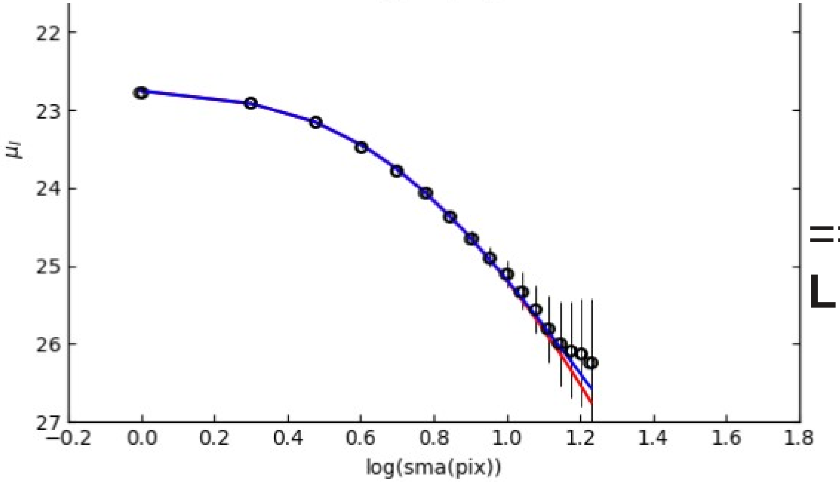
NGC5253

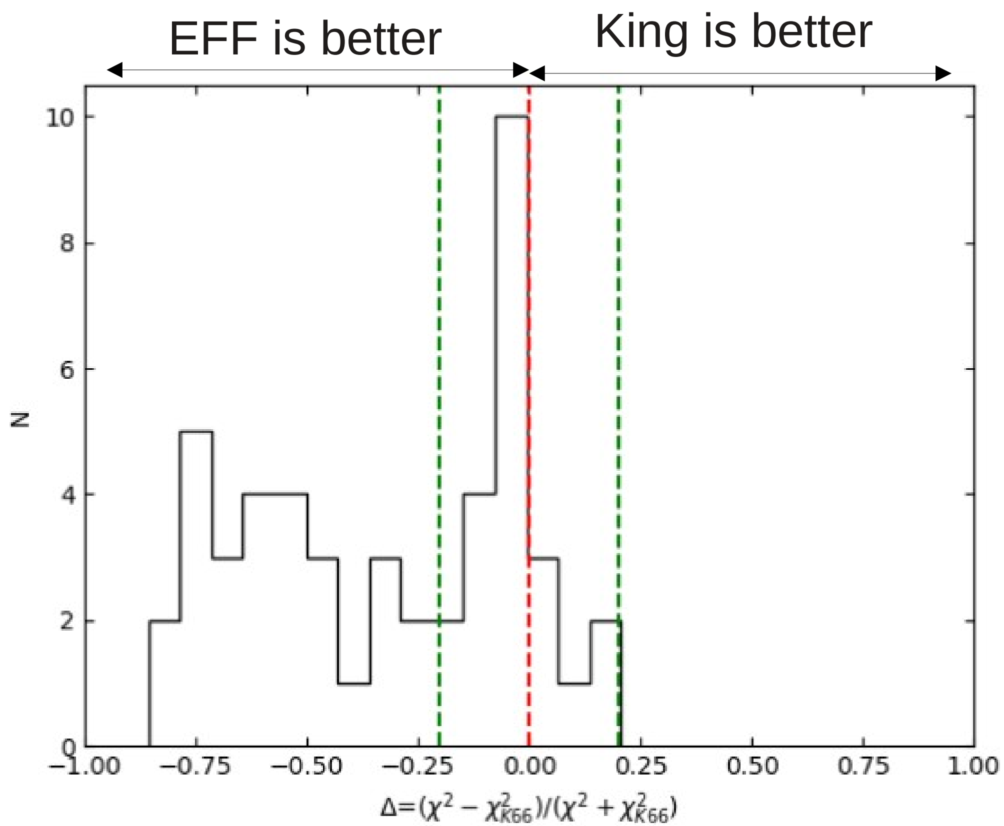
See poster of Pedro Ovando

Evolutionary stage inferred from Radial Intensity profiles

Intensity profile analysis of ~50 M82 disk SSCs







Moffat/EFF profile is a better fit to majority of M82 SSCs

===> **Similar to that found for ~108 yr clusters in LMC**

Work in progress (Ph.D. thesis of Bolivia Cuevas)

Intermediate-age SSC populations in giant spiral galaxies

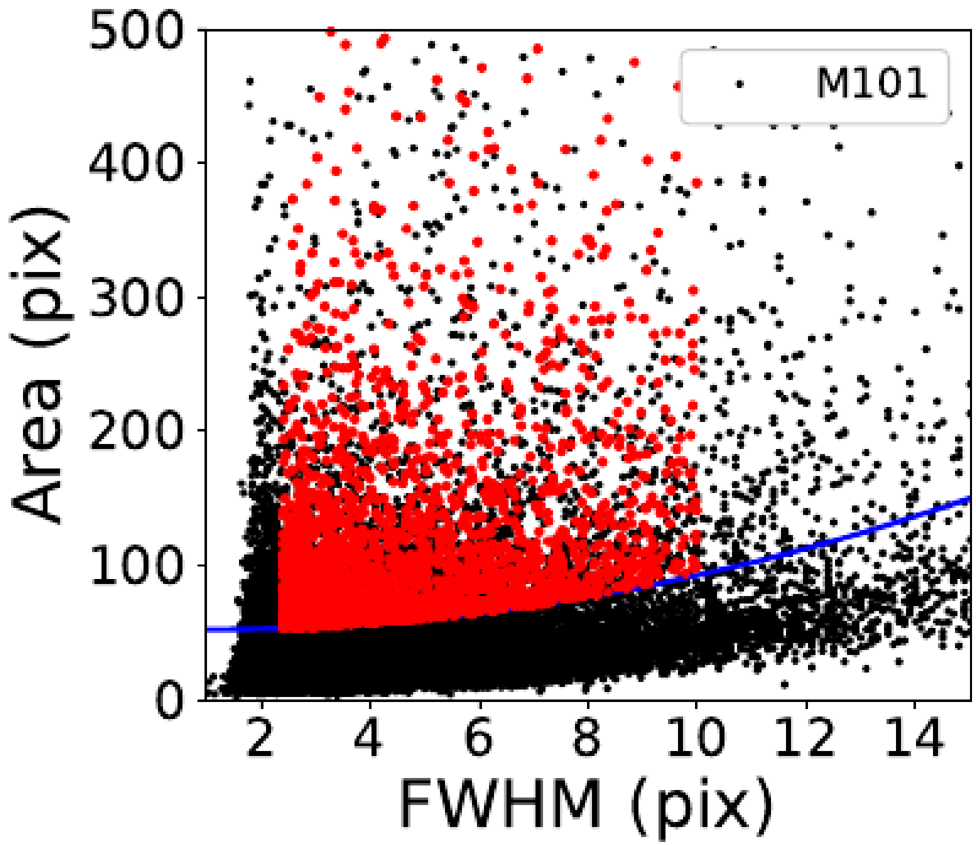
Search for intermediate-age SSCs in nearby galaxies

HST Legacy Archive (HLA) https://hla.stsci.edu/

Resolution ~ 0.1 arcsec (0.05 arcsec/pix) ===> 5 pc @ 10 Mpc

Sextractor catalog of all sources available at HLA

Selecting the SSCs from Sextractor catalog Mayya et al. (2008)



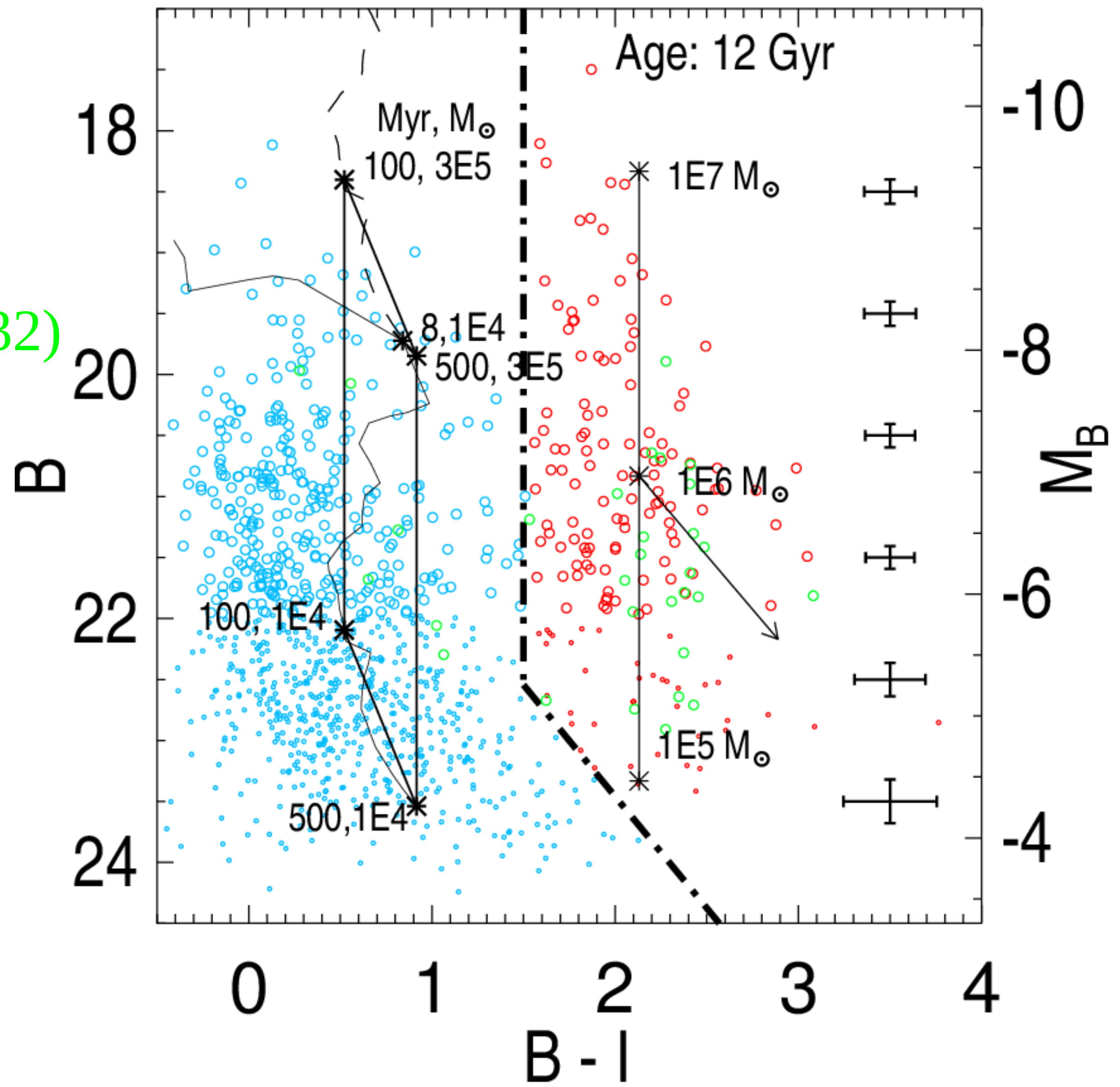
$$AREA > (52.5 - 1.0\mathrm{FWHM} + 0.50\mathrm{FWHM}^2)$$

$$2.4 < FWHM < 10, ELLIPTICITY < 0.3$$

Stellar cluster populations in M81

M.Santiago-Cortes, Y.D.Mayya &
D. Rosa-Gonzalez (2010)

Blue- SSCs (263)
Red – GCs (172)
Green – Fuzzy clusters (32)



Ages from CMDs suffers from mass-age-extinction degeneracy

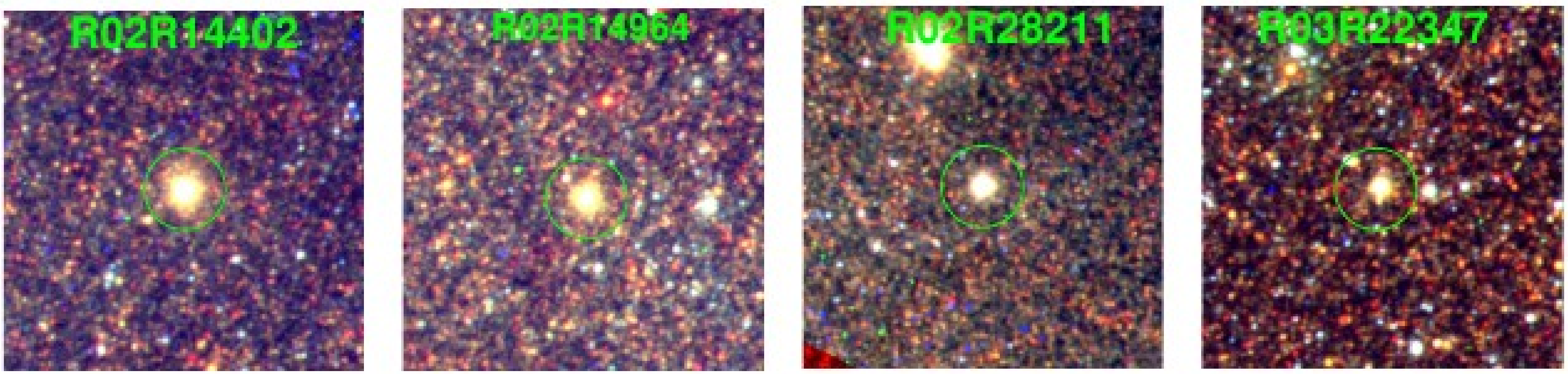
Stellar cluster populations in M81

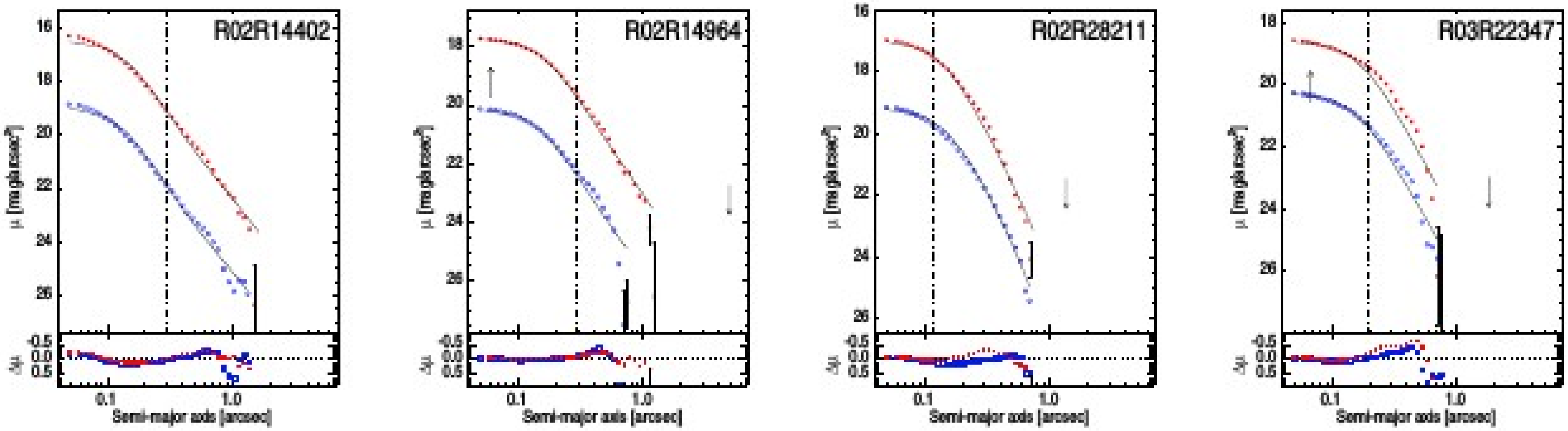
Are all red clusters in M81 are classical GCs?

- Morphology and Structural parameter analysis of

Ph.D. thesis of
Mayra Santiago-Cortes (2017)

M.Santiago-Cortes,
Y.D.Mayya &
D. Rosa-Gonzalez
(2018) submitted

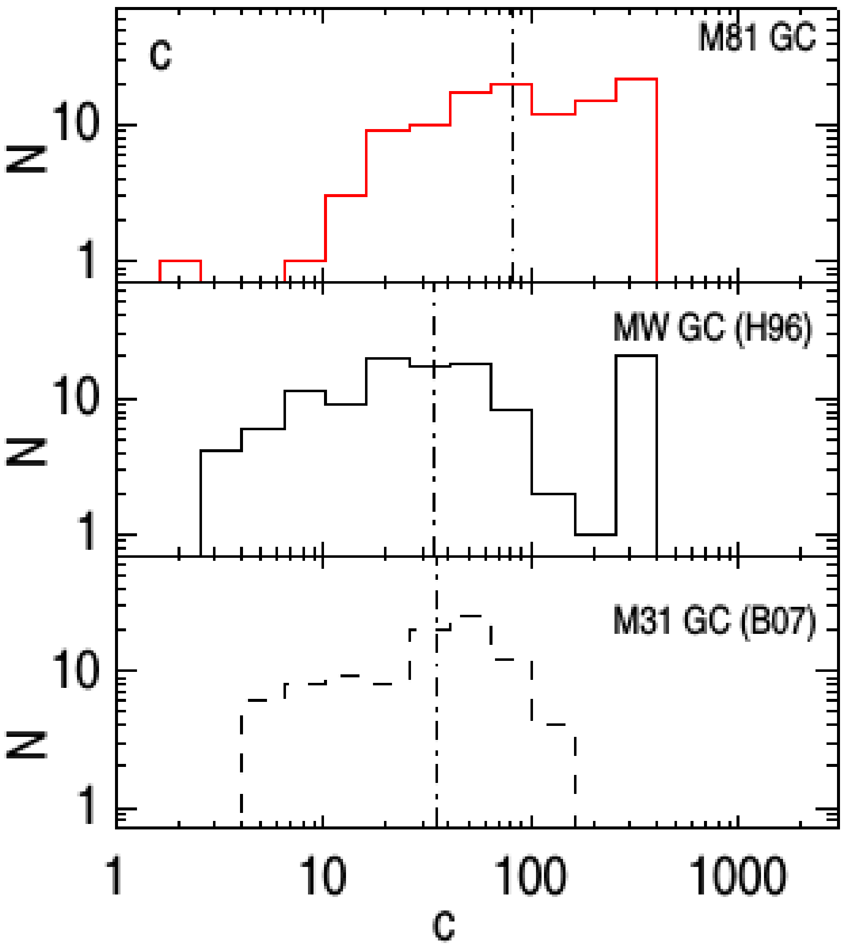




===> Objects photometrically classified as GCs (B-I > 1.7) have structural parameters of dynamically evolved stellar systems.

Hence all red clusters are indeed GCs.

Stellar cluster populations in M81



- **King Concentration parameter c=rt/rc=80 for M81 GCs**

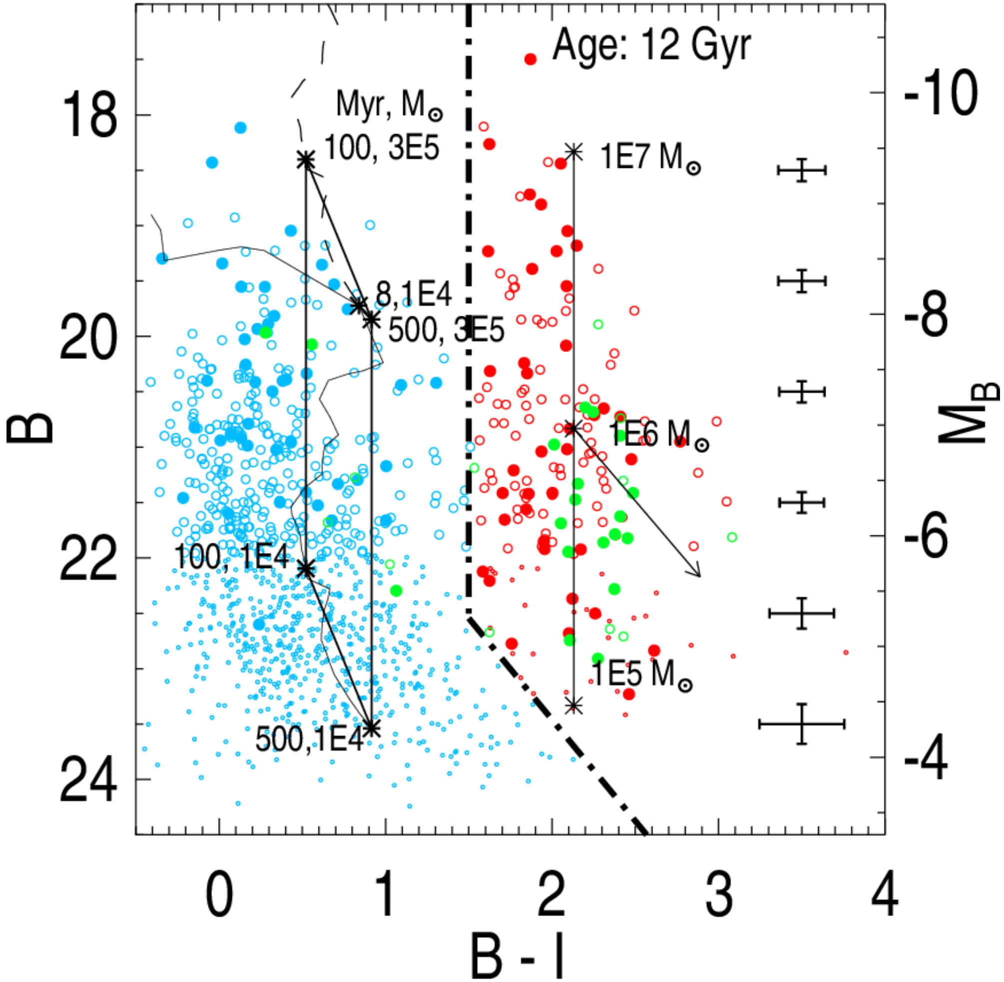
==> M81 GCs are more dynamically evolved as compared those in the Milky Way

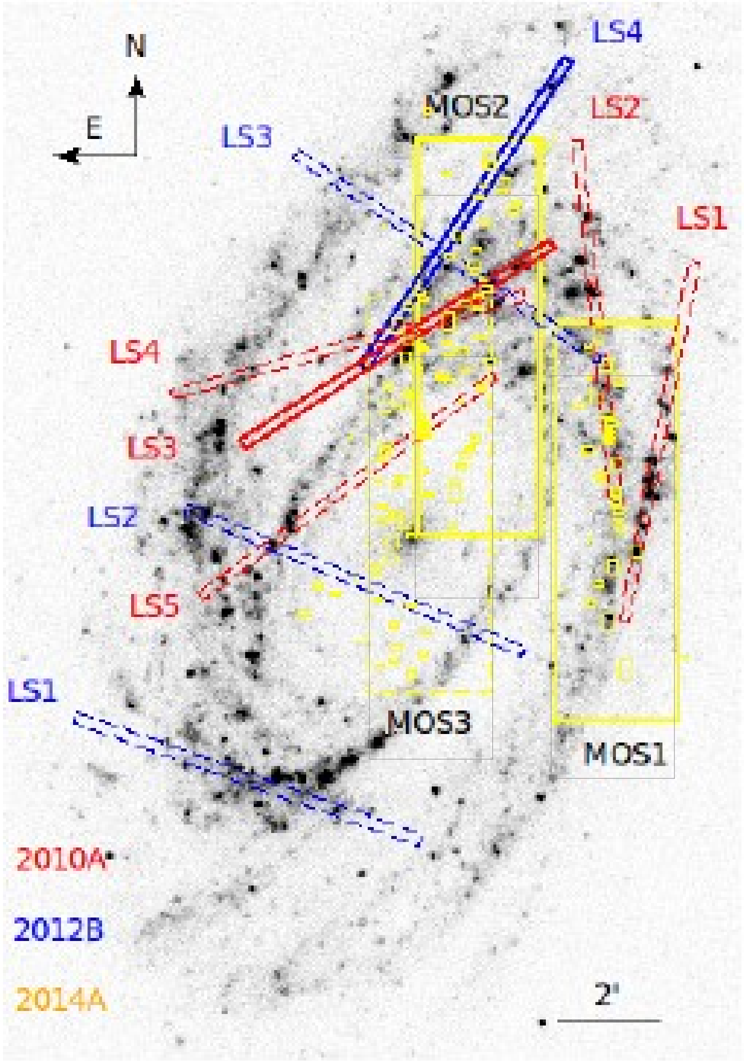
• GTC/OSIRIS observations of M81 clusters

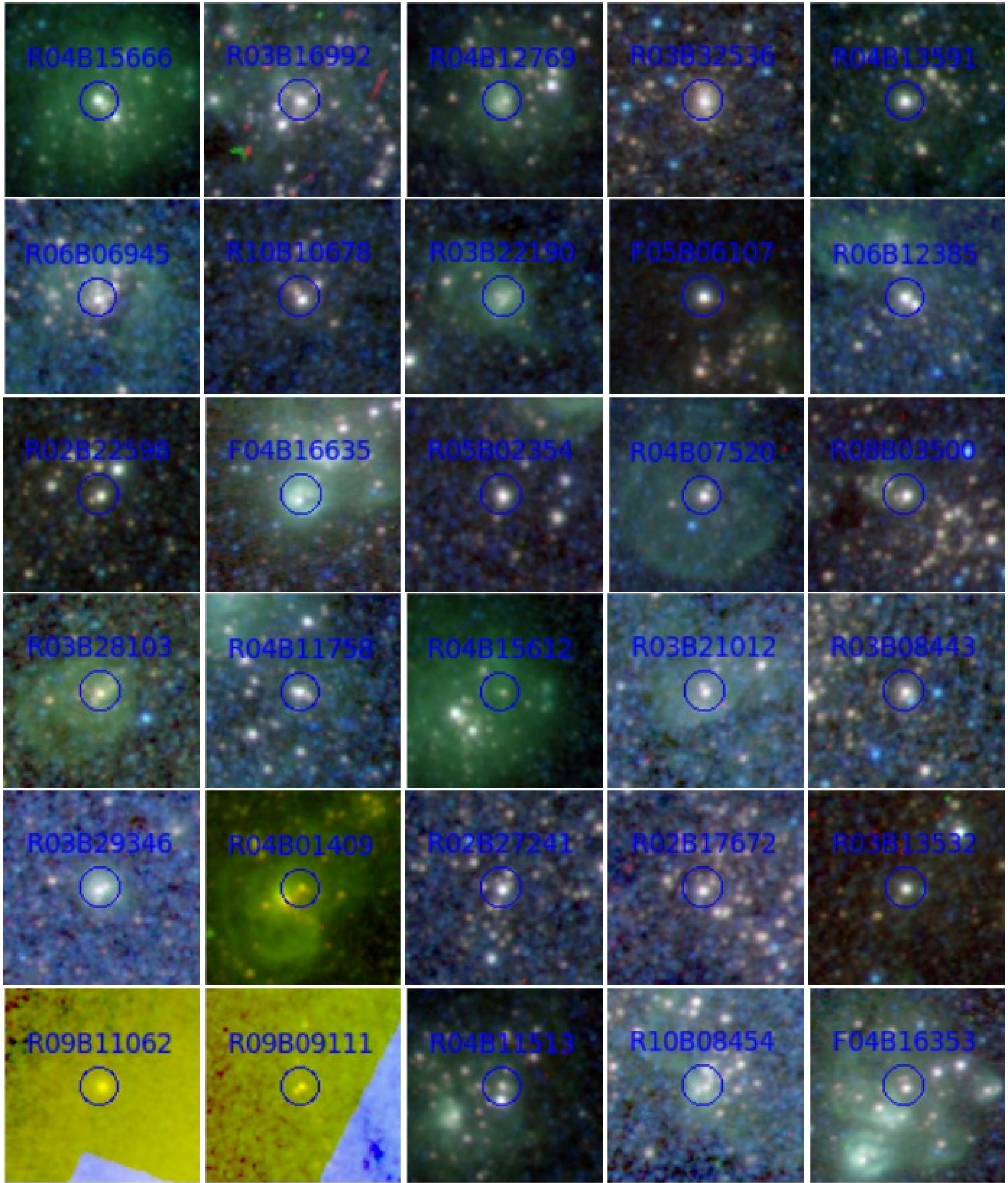
Run	PI	Mode	#OBs	T(hrs)	#clusters
2010A	D.Rosa-Gonzalez	longslit	5	6	15 (11+4+0)
2012B	Y.D. Mayya	longslit	4	6	23 (9+3+11)
2014A	Y.D. Mayya	MOS	3	4	68 (24+36+8)

Total = 106; **44 SSCs**, 43 GCs and 19 FCs

- Seeing ~ 0.8-1.0”
- Slit-width~1”
- Spectral resolution (1000B)~7 Ang
- Total of 14 hours





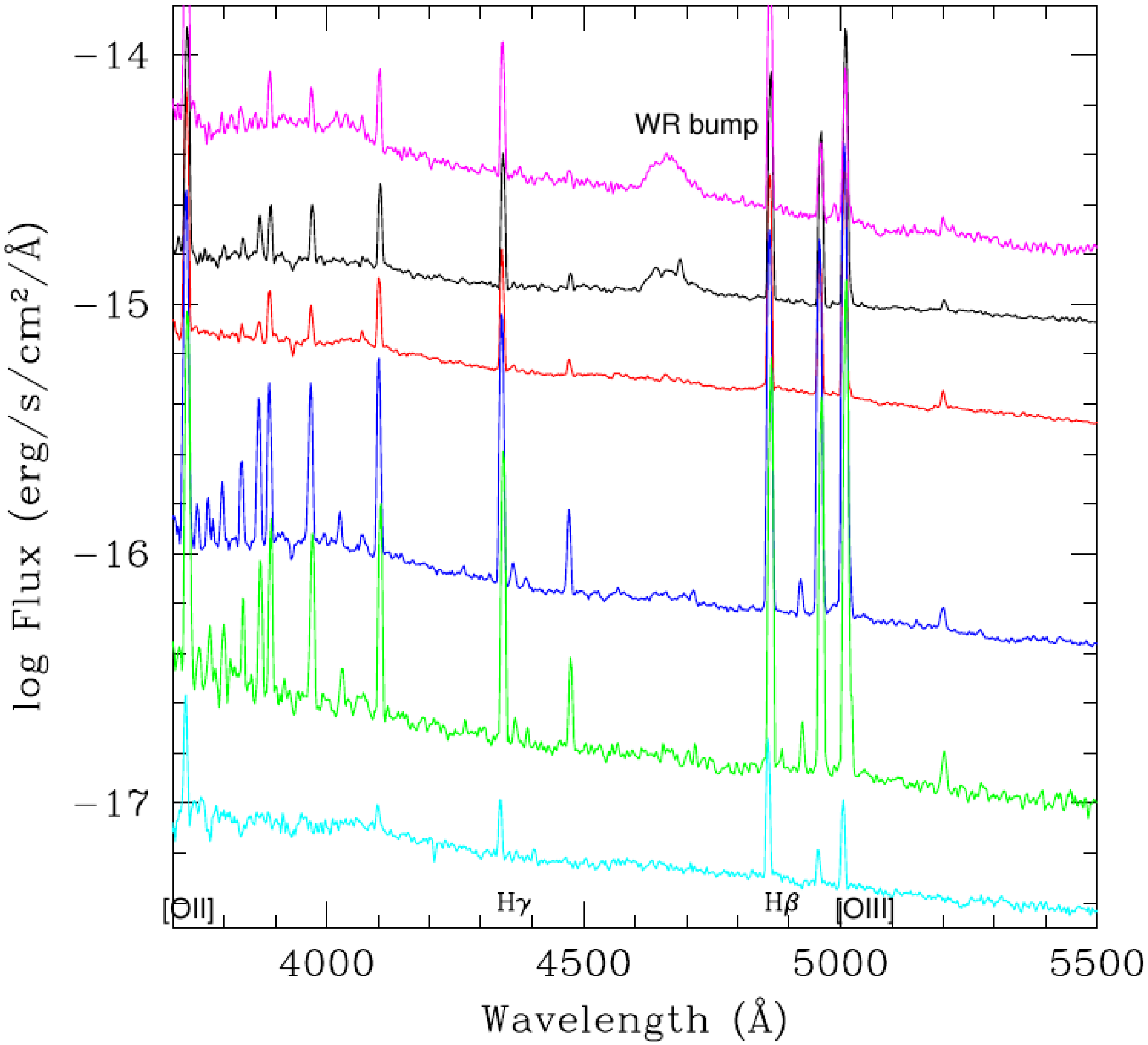


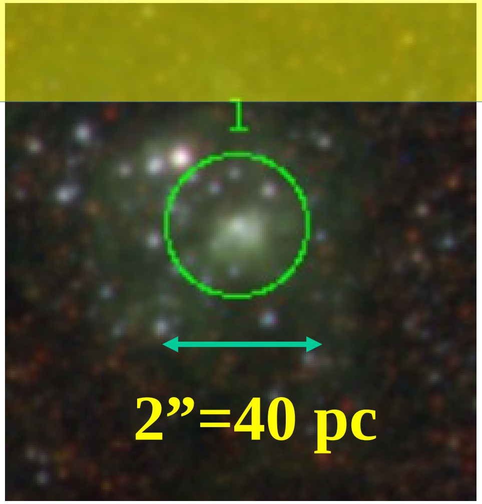
HST/ACS stamps of M81 SSCs

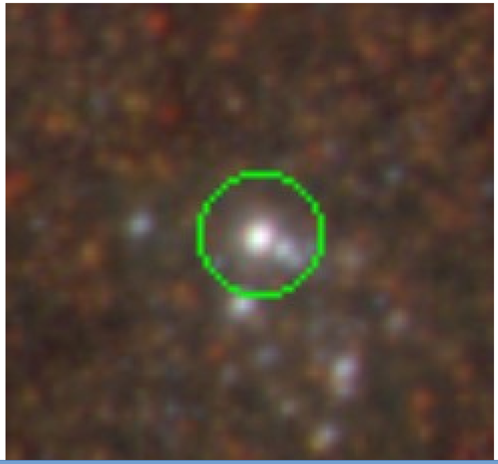
R (F814W)
G (F606W) Hα
B (F435W)

1” diameter = 17.6 pc

Young SSCs (age < 10 Myr; nebular and WR phase)



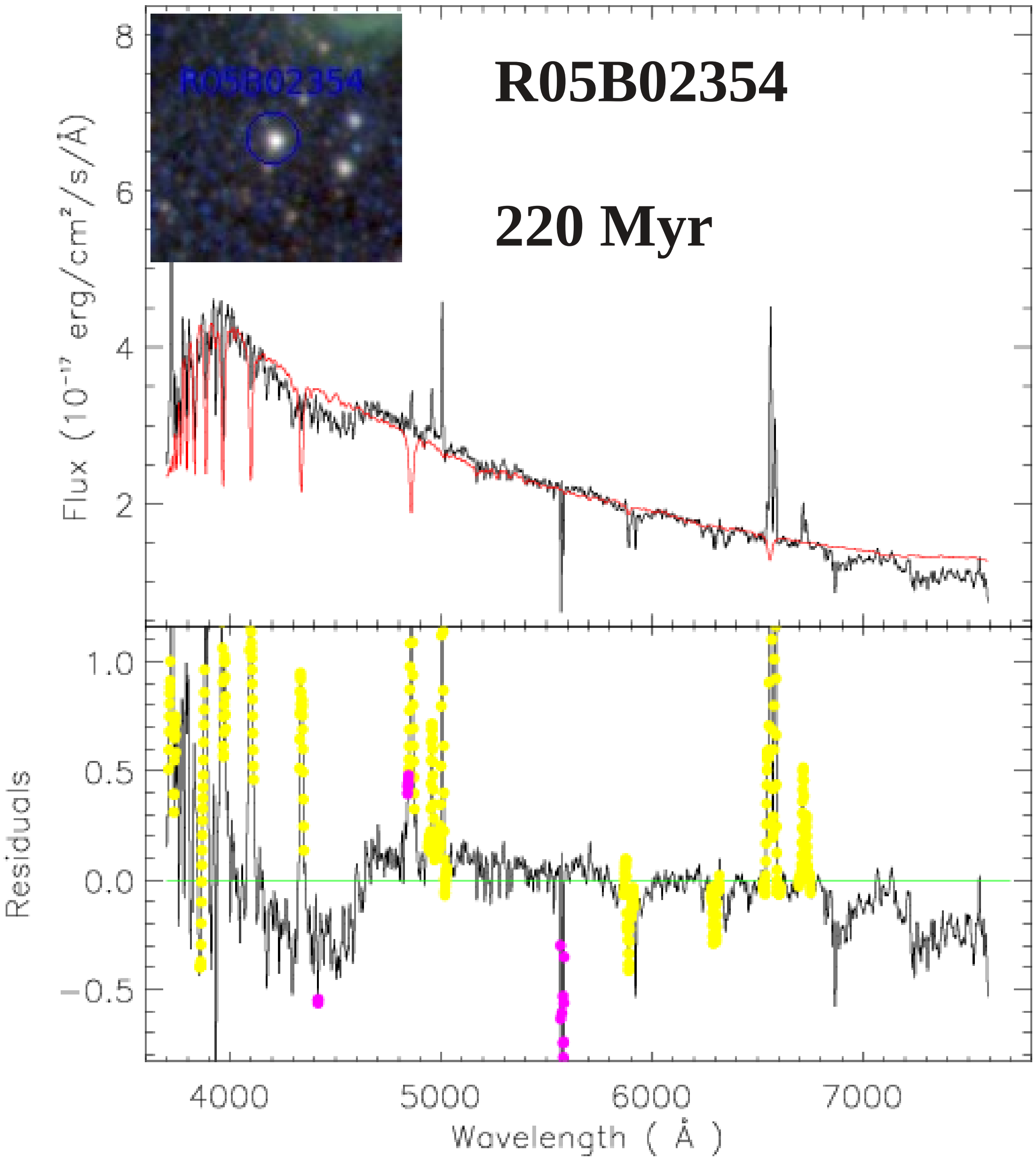


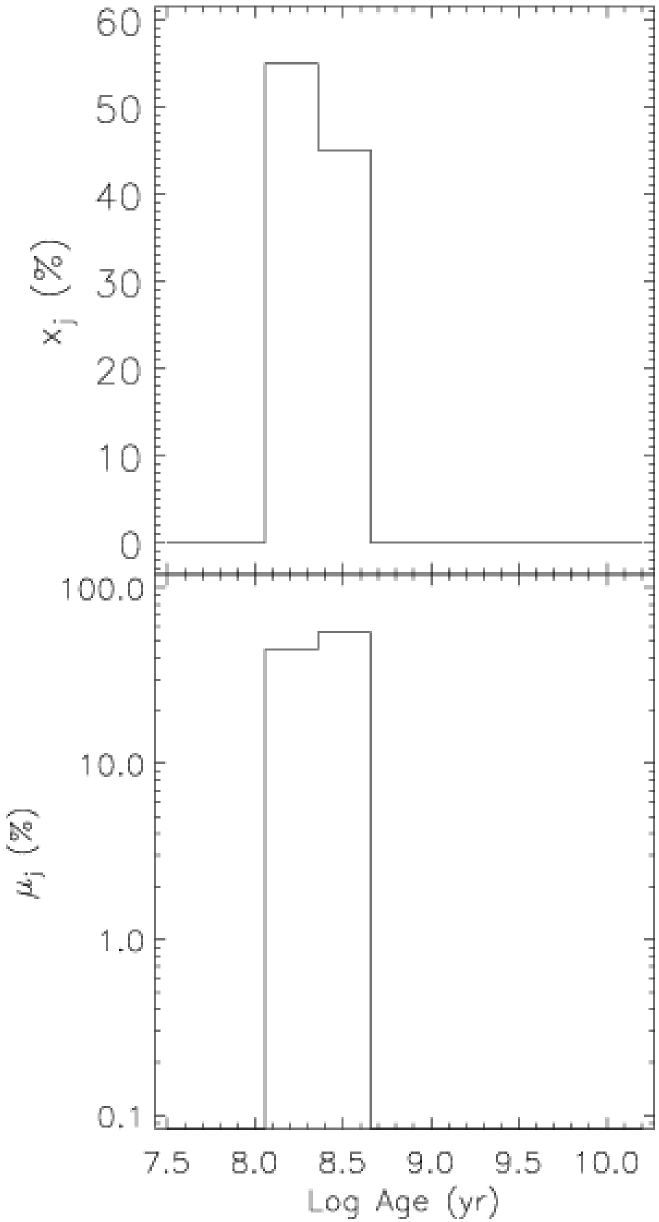


- Majority (~65%) of M81 SSCs are younger than 10 Myr
  - 14 W-R stars are detected in the observed clusters (Gómez González et al. 2016)

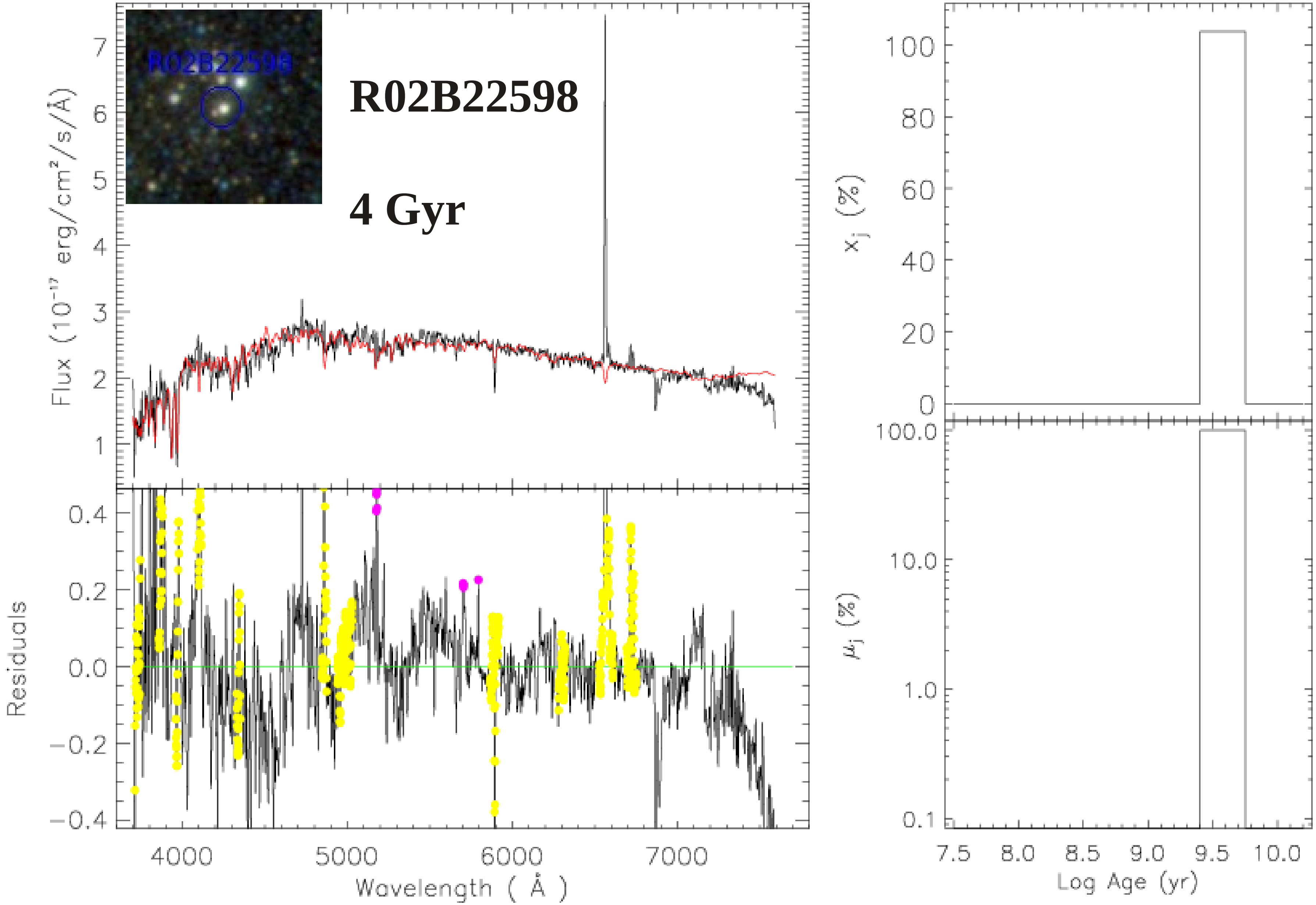
Age of the SSCs using STARLIGHT

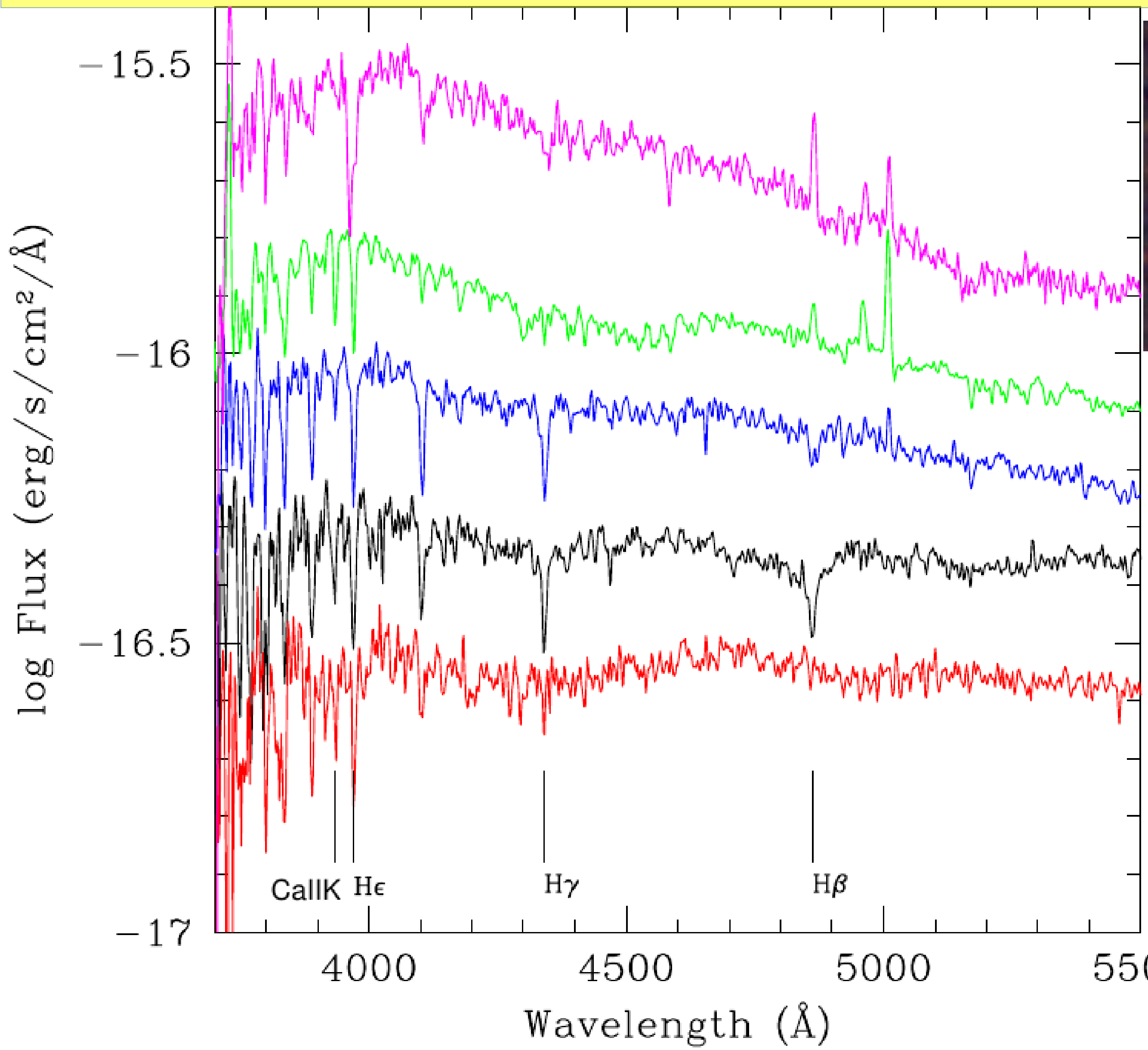
Cid Fernandez et al. 2005

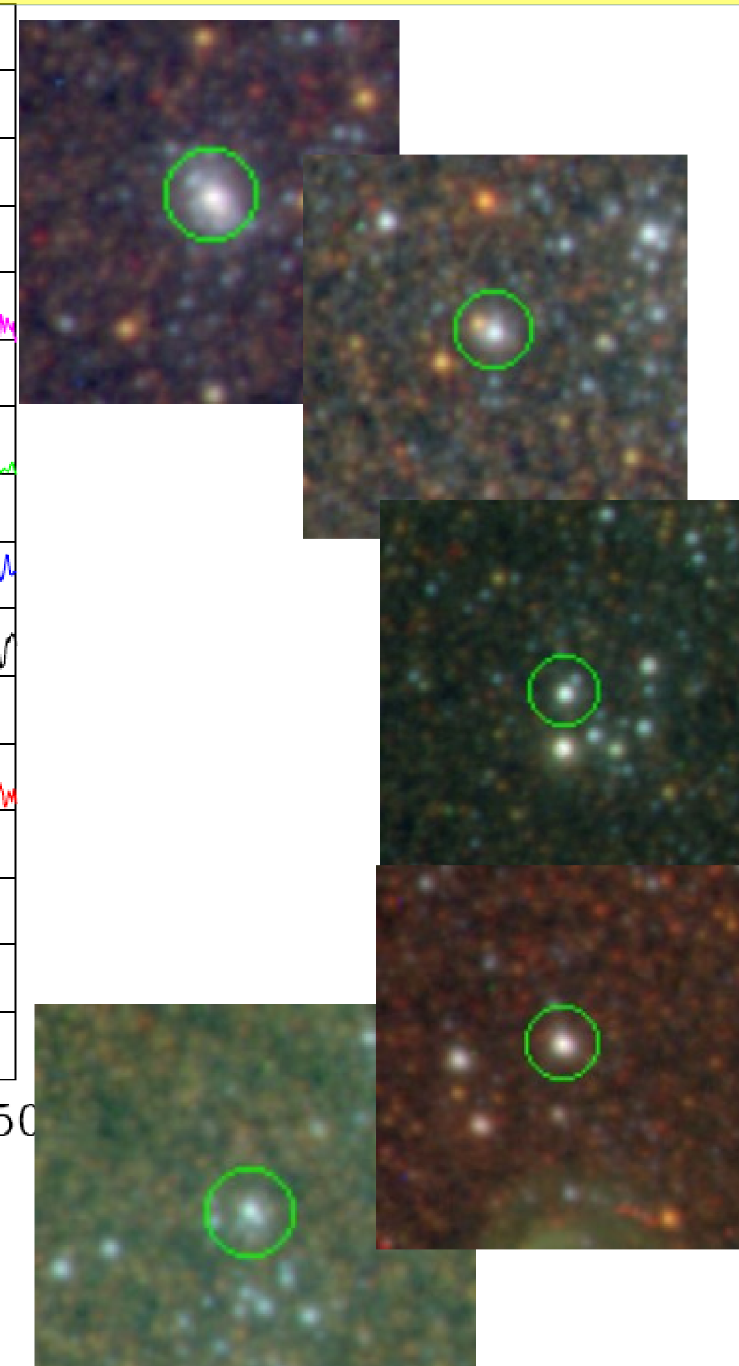




Age of the SSCs using STARLIGHT

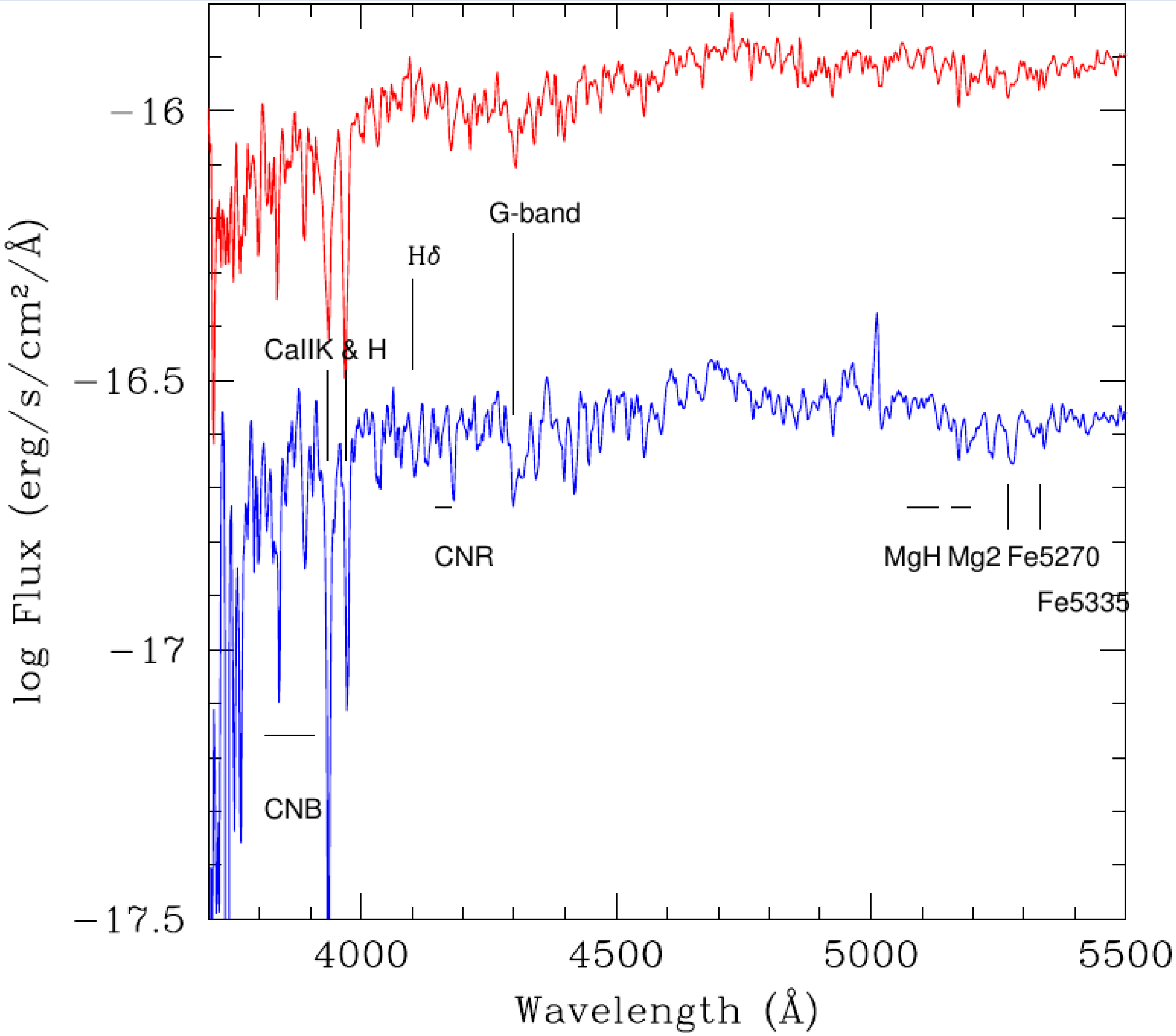


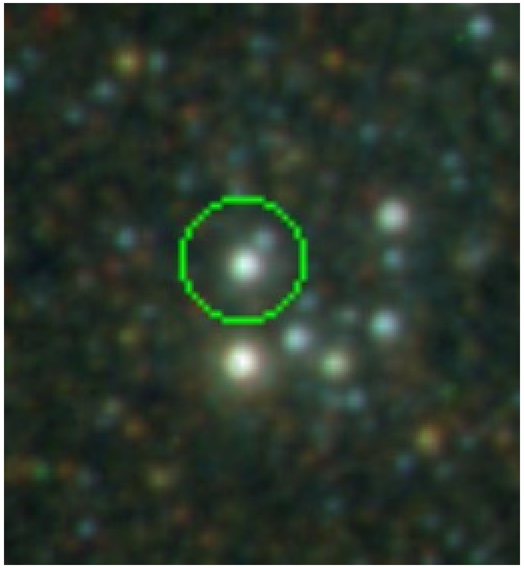


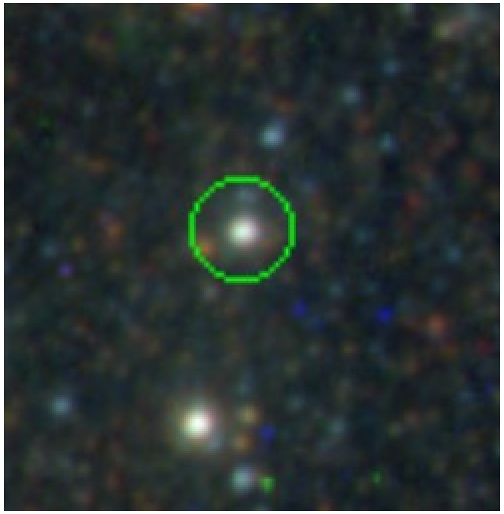


25% are younger than 1 Gyr

Old SSCs (age > 1 Gyr; metallic absorption lines)



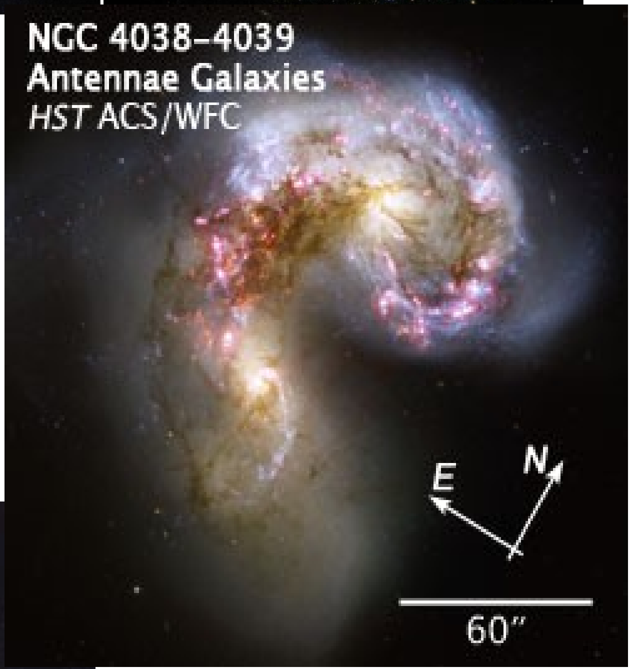




❾ Only ~10% observed SSCs are older than 1 Gyr

So far no compelling evidence for a rich-population of age > 1 Gyr superstellar clusters in M81

Search for intermediate-age SSCs in nearby galaxies



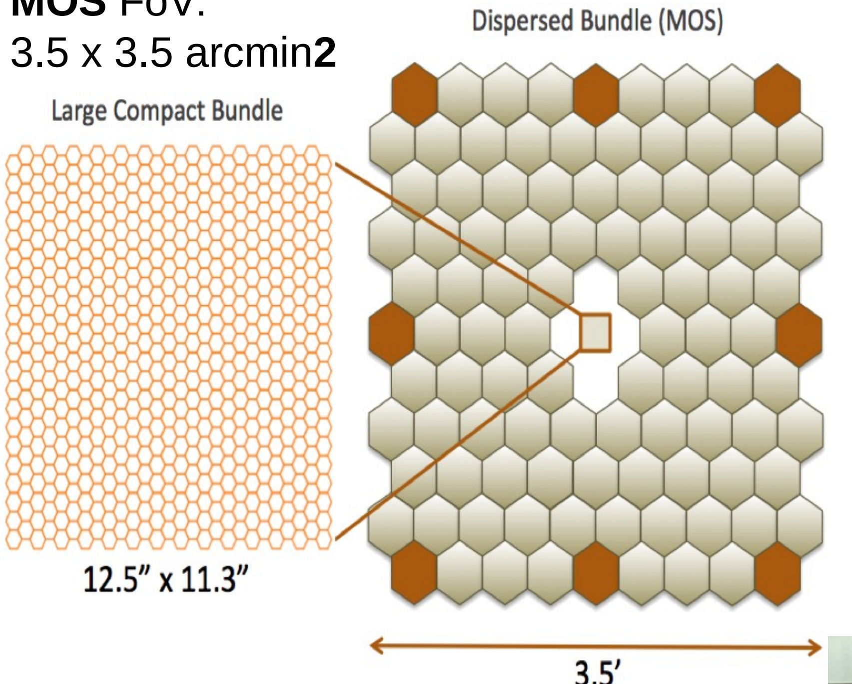
Galaxy	RA(J2000)	DEC(J2000)	(m-M)	Type
M101	210.802267	54.348950	29.14	SAB(rs)cd
NGC 1300	49.921167	-19.411361	30.85	SB(rs)bc
NGC 1309	50.527333	-15.400056	32.13	SA(s)bc
NGC 1483	58.198500	-47.477528	31.52	SB(s)bc
NGC 2397	110.333250	-69.001472	31.70	SB(s)b
NGC 4038	180.470875	-18.867611	31.56	SB(s)m_pec
NGC 4258	184.739602	47.303973	29.29	SAB(s)bc

Whitmore et al .2015

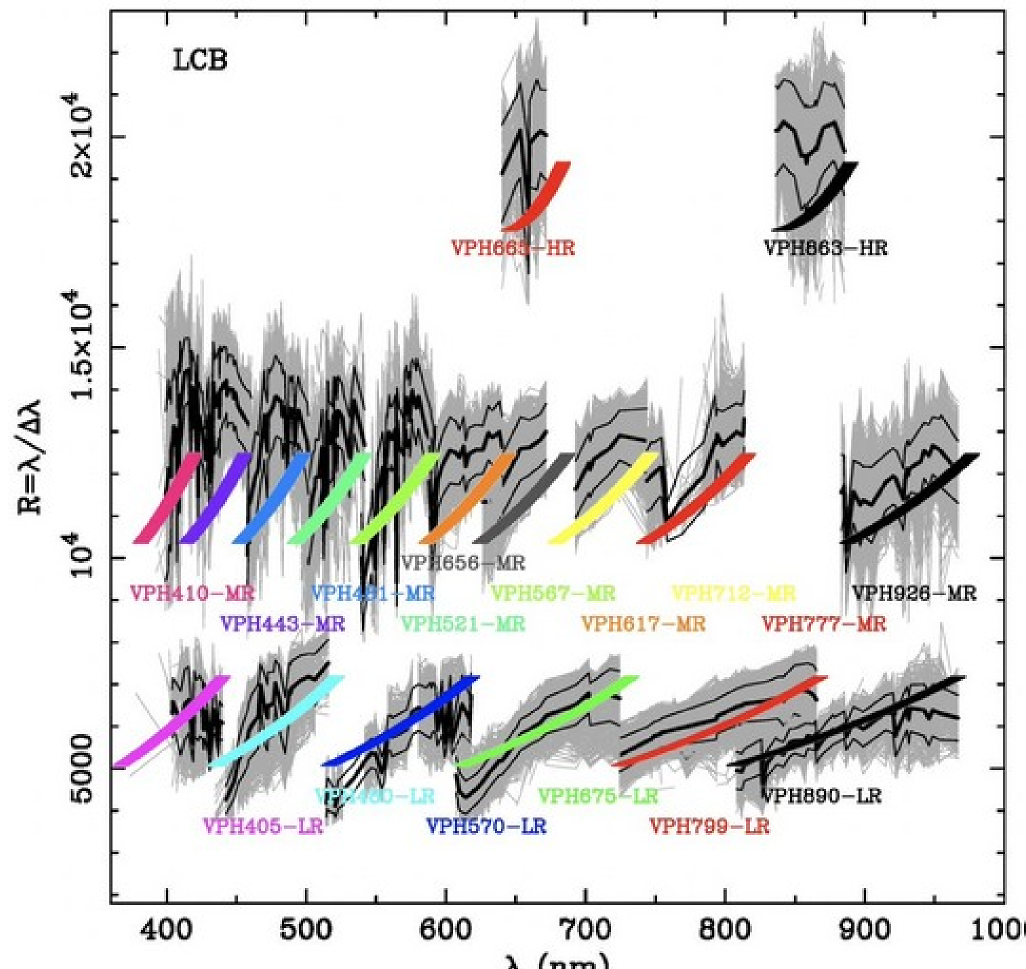
Ph.D. thesis of Luis Lomelí
(see poster of Luis Lomelí)

Optical Components y Cryostat constructed at INAOE

MOS FoV:
3.5 x 3.5 arcmin**2**



644 fibers for **spaxe**l: 0.62 arcsec
 92 mini-ifus of 7 fibers
 92 x 7 fibers identical to LCB
 92 robotic positioners



MEGARA@GTC offers great opportunities for identifying spectroscopically intermediate-age clusters in nearby galaxies

Summary

- **We have carried out photometric, spectroscopic and structural analysis of extragalactic superstellar clusters to identify clusters odler than 100 Myr**
- **The disks of M82 and other Irr II galaxies have SSCs of age 0.1-1 Gyr**
- **The radial intensity profiles of M82 SSCs are better fit by EFF profiles, rather than King profiles**
- **Objects classified as GCs in giant spiral M81 have morphological and spectroscopic characteristics of classical GCs.**
- **We identify 25% SSCs of age 0.1-1 Gyr and 10% older than 1 Gyr in the spectroscopically observed sample (43) of SSCs in M81.**
- **A photometric analysis of SSCs in a sample of 7 spiral galaxies shows strong evidence for the presence of SSCs older than 2 Gyr in majority of the galaxies.**
- **Giant galaxies do contain a population of missing link clusters**
- **MEGARA@GTC offers a great opportunity to spectroscopically identify**
- **Intermediate-age SSCs in nearby galaxies.**

Thanks