Integrated Colors

As for distant Galaxies, we are able to observe integrated colors I(m) of star clusters. We are able to estimate the age and total mass.

Techniques:

1. "Aperture photometry" for distant star clusters
2. Sum up colors of members for resolved star clusters

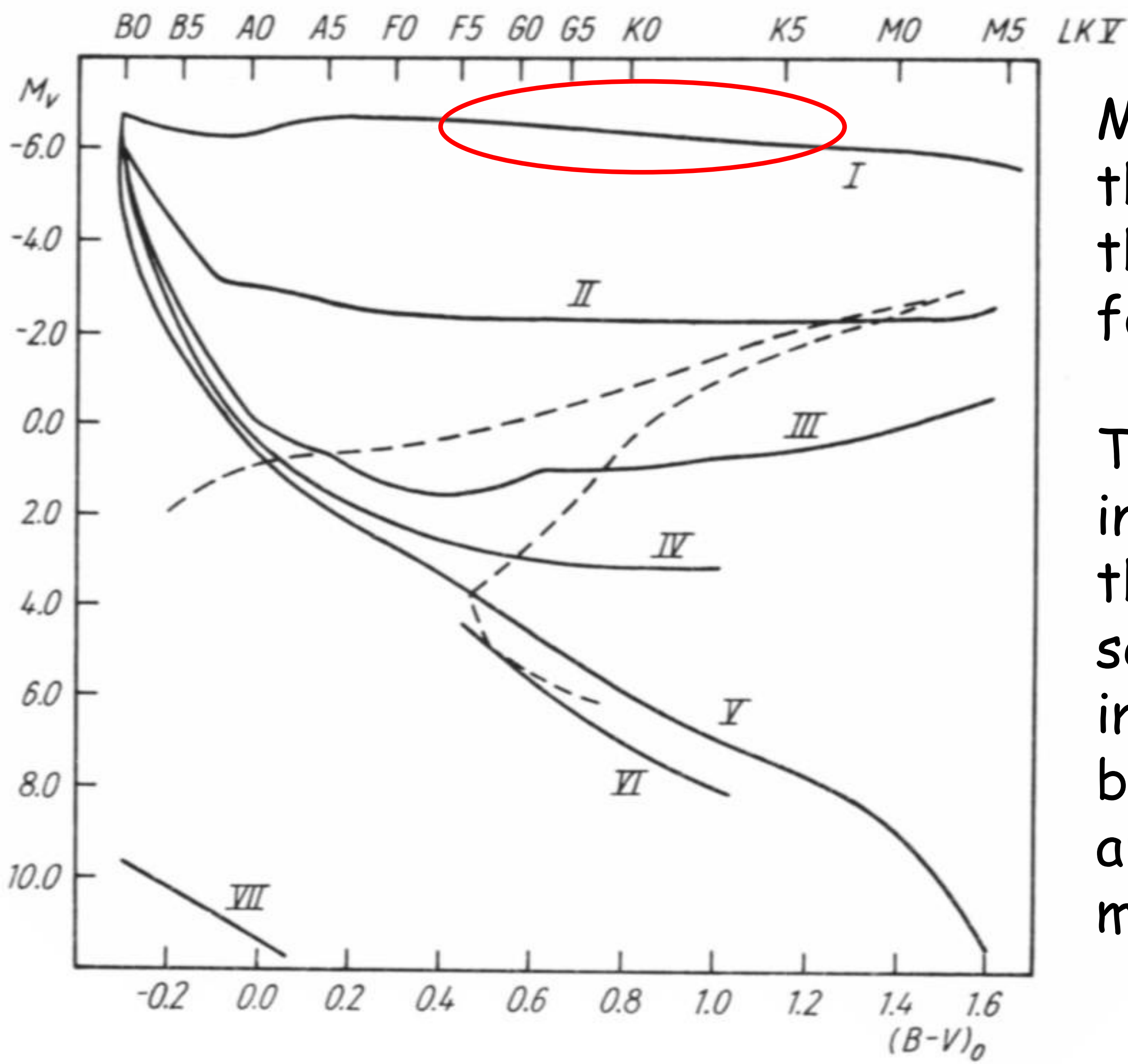
$$I(m) = -2.5 \ \log\left[\sum_i (10^{-0.4 m_i})\right]$$

Starting point are the dereddened colors and absolute magnitudes. For the dereddening, here are the relations from Lata et al. (2002, A&A, 388, 158) for the Johnson-Cousins UBVRI system:

$$E(U-B) = 0.72E(B-V) + 0.05E(B-V)^2$$
$$E(U-V) = 1.72E(B-V)$$
$$E(V-R) = 0.60E(B-V)$$
$$E(V-I) = 1.25E(B-V)$$

For the integrated colors we get:

$$I(B-V) = I(B) - I(V)$$
$$I(U-B) = I(U) - I(B)$$
$$I(V-R) = I(V) - I(R)$$
$$I(V-I) = I(V) - I(I)$$



Most important is the knowledge of the membership for giants

The incompleteness of the lower main sequence is not important because of low absolute magnitudes

Lata et al., 2002, A&A, 388, 158

Clearly defined upper and lower mass limits

"Standard lines" for total masses from isochrones and population synthesis codes

González Delgado et al., 2005, MNRAS, 357, 945

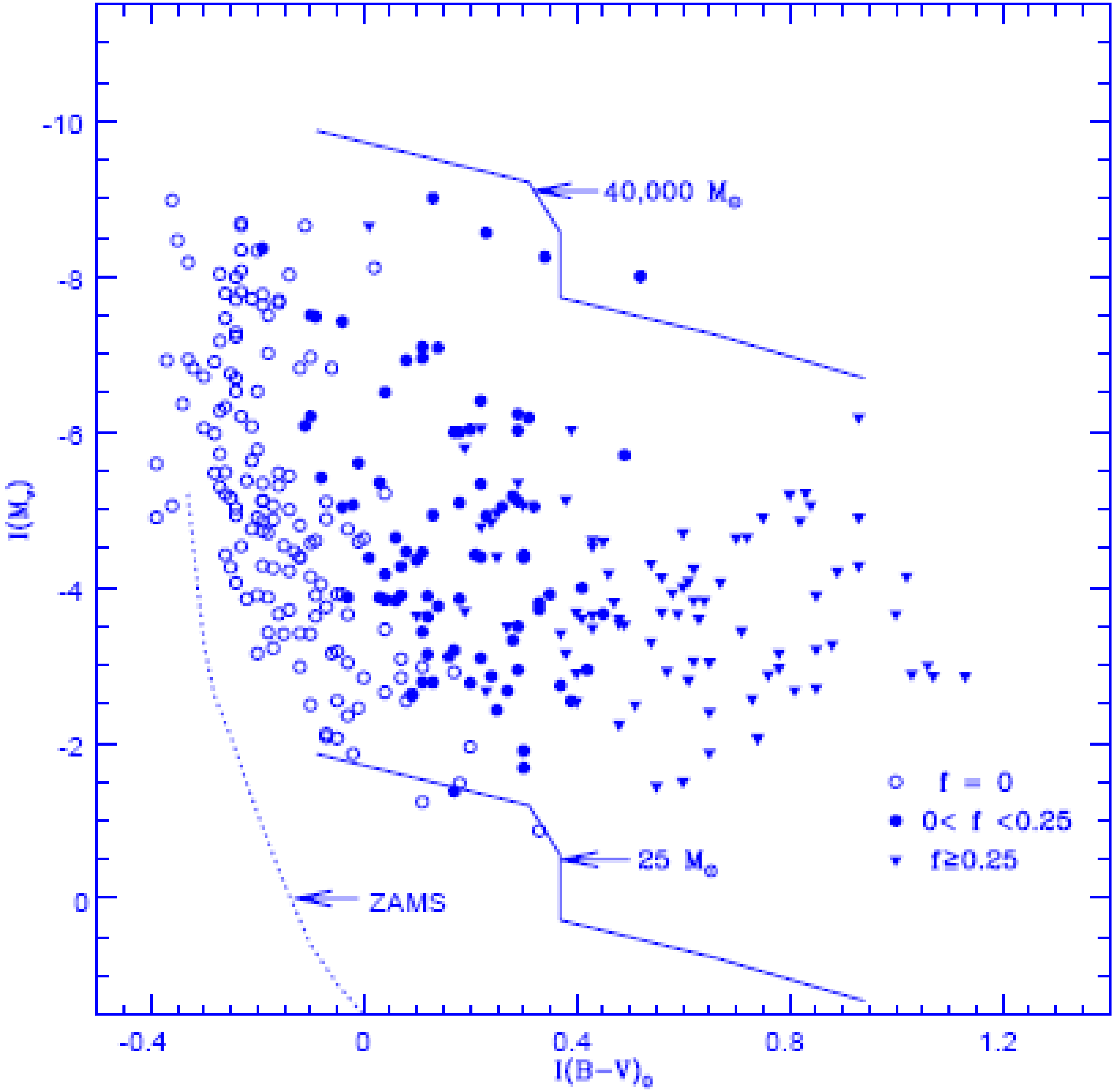


Fig. 2. The $I(M_V)$, $I(B-V)_0$ diagram. f is the fraction of red giants/supergiants in the open clusters.

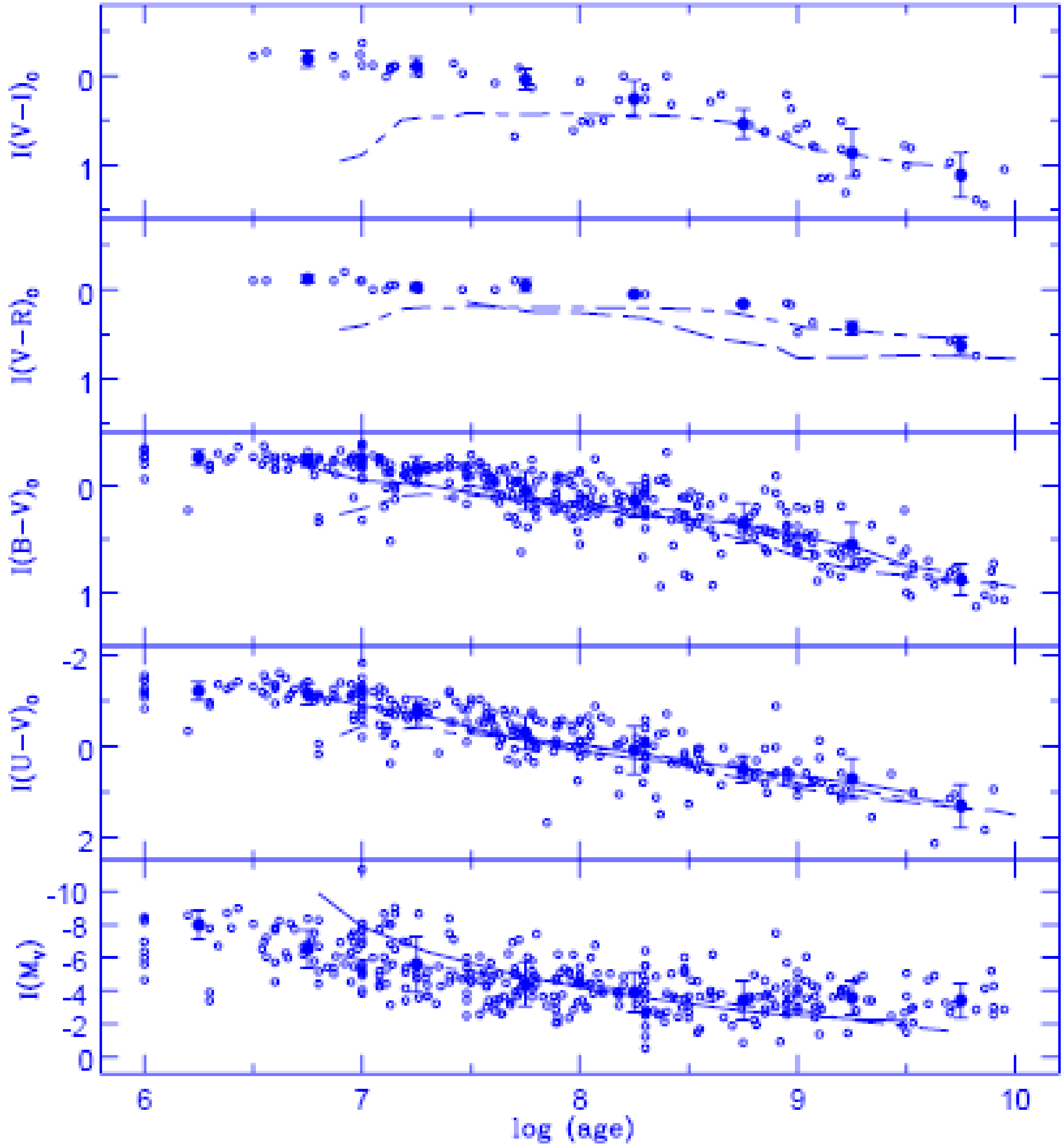
Lata et al., 2002, A&A, 388, 158

Relations for 352 galactic open clusters

The age and reddening were taken from the literature

Error given by Lata et al. (2002):

$\sigma I(M_V) < 0.5$ mag
$\sigma I(\text{colors}) < 0.2$ mag



Results from Lata et al. (2002, *A&A*, 388, 158), important are the errors for the determination of the uncertainties in log t:

$$I(M_V) = (1.20 \pm 0.08)(\log\ t) + (-14.12 \pm 0.66)$$

with $\chi^2 = 2.017$

$$I(U - V)_0 = (0.74 \pm 0.03)(\log\ t) + (-6.07 \pm 0.23)$$

with $\chi^2 = 0.171$

$$I(B - V)_0 = (0.31 \pm 0.01)(\log\ t) + (-2.36 \pm 0.09)$$

with $\chi^2 = 0.037$

$$I(V - R)_0 = (0.22 \pm 0.02)(\log\ t) + (-1.65 \pm 0.17)$$

with $\chi^2 = 0.011$

$$I(V - I)_0 = (0.44 \pm 0.03)(\log\ t) + (-3.25 \pm 0.25)$$

with $\chi^2 = 0.048$

where t is the age (in years) of the cluster.

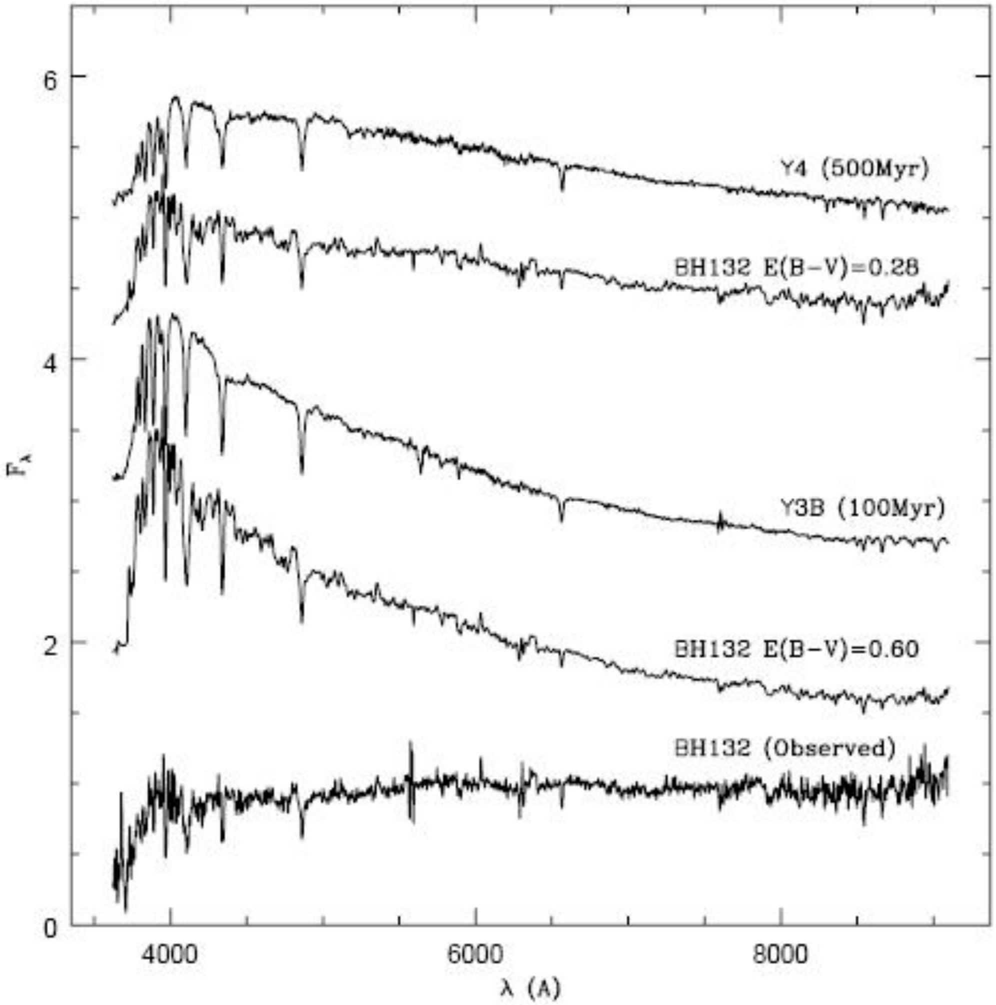
Integrated spectra of Star Clusters I

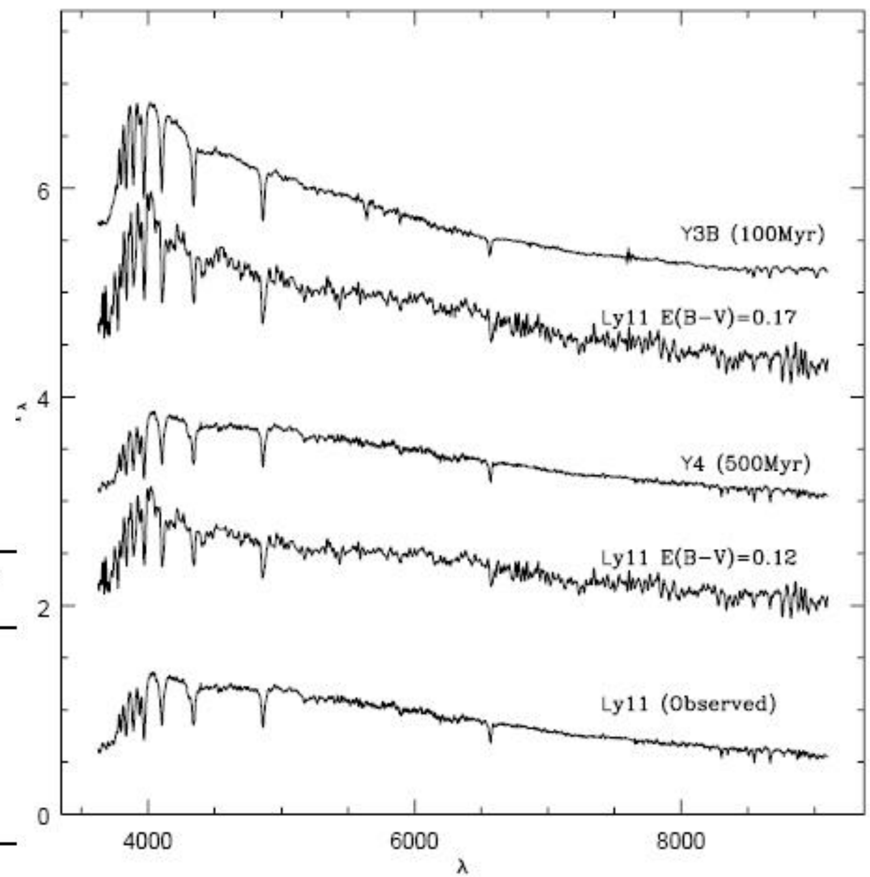
- Idea: clusters of different ages have different stellar content
- Example: old clusters (log t > 100 Myr) will not have any very hot (O and B) type stars any more as members because they have evolved
- Technique: slit spectrum over cluster => integrated spectrum of all members
- Assumption: slit covers a representative sample for the cluster

Integrated spectra of Star Clusters II

- How to get a standard library?
  1. Use isochrones together with Initial Mass Function (= statistical knowledge how much star form with a specific mass)
  2. Let the cluster evolve
  3. Calculate an integrated spectrum of „what's left“ in the cluster taking into account the luminosity of a star.
  4. Do this for a wide variety of ages and metallicities

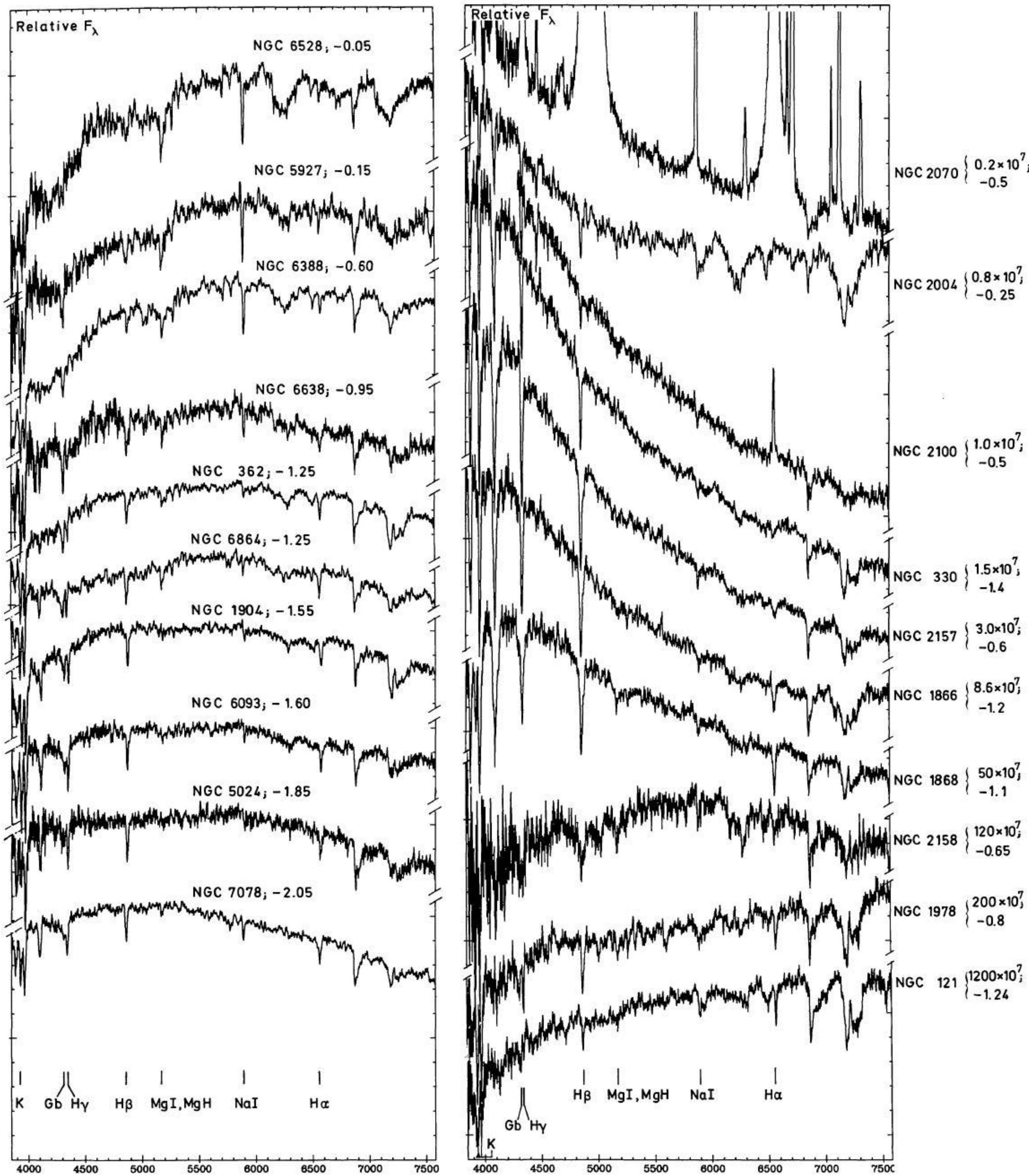
Ahumada et al., 2000, A&AS, 141, 79



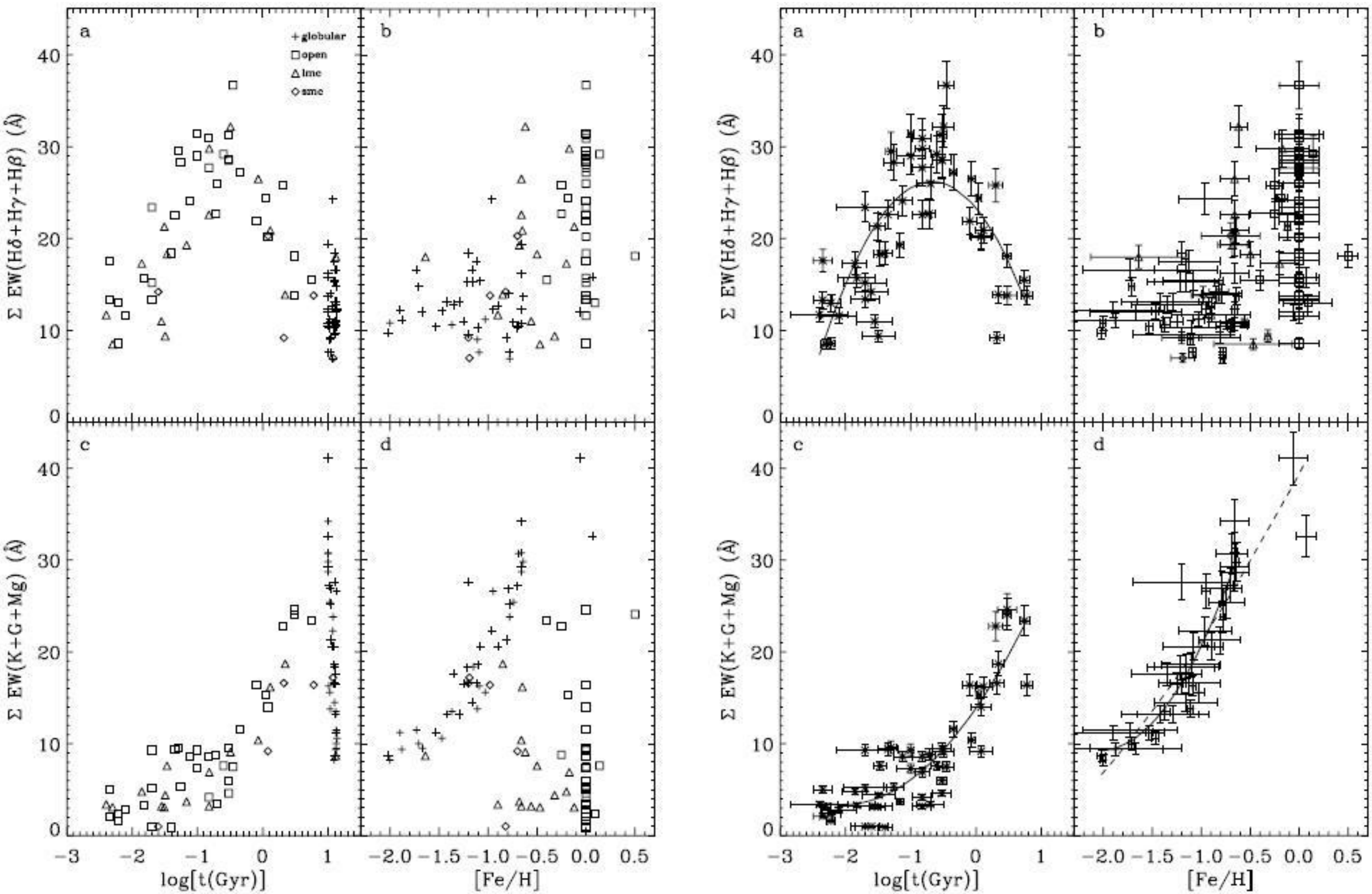


Cluster	$E(B-V)$	Age (Balmer) (Myr)	Age (template match) (Myr)	Adopted age (Myr)
Ruprecht 144	0.32 ± 0.02	200	100	150 ± 50
Melotte 105	0.31 ± 0.02	300	100	200 ± 100
BH 132	0.60 ± 0.05	200	100	150 ± 50
Hogg 15[a]	1.05 ± 0.05	30	3−6	5 ± 2
Pismis 21	1.50 ± 0.03	110	50	80 ± 30
Lyngå 11	0.12 ± 0.03	400	500	450 ± 50
BH 217	0.80 ± 0.03	20	50	35 ± 15

Bica & Alloin, 1986, A&A, 162, 21



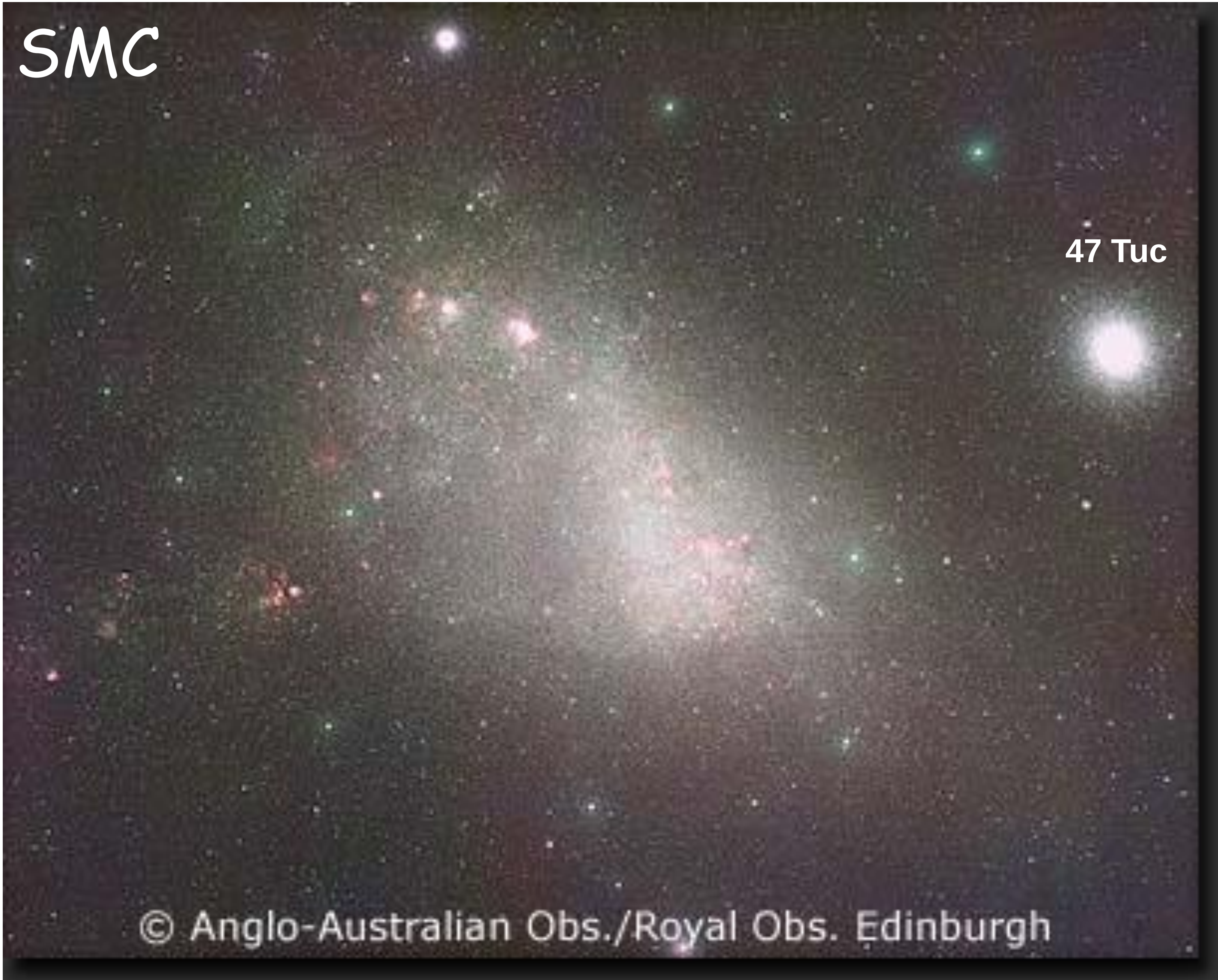
Age



Santos & Piatti, 2004, *A&A*, 428, 79

6 Degrees on the Sky

5.4 Degrees on the Sky



4 Arc minutes

30 Dor:

Star cluster in the LMC

About 2000 listed in catalogues

NGC 1866

LMC, Age about 100 Myr

NGC 2298

Milky Way, Age about 15 Gyr

Open clusters in the MCs have the same morphology as GCs in the Milky Way

Distance and Reddening

- LMC:
  - $V-M_V$ = 18.5 mag
  - E(B-V) = 0.05 to 0.1 mag
  - Distance about 50000 pc
- SMC:
  - $V-M_V$ = 19.0 mag
  - E(B-V) = 0.05 to 0.1 mag
  - Distance about 60000 pc
- Intrinsic reddening up to 0.2 mag for "normal" regions in the bulge

Characteristics

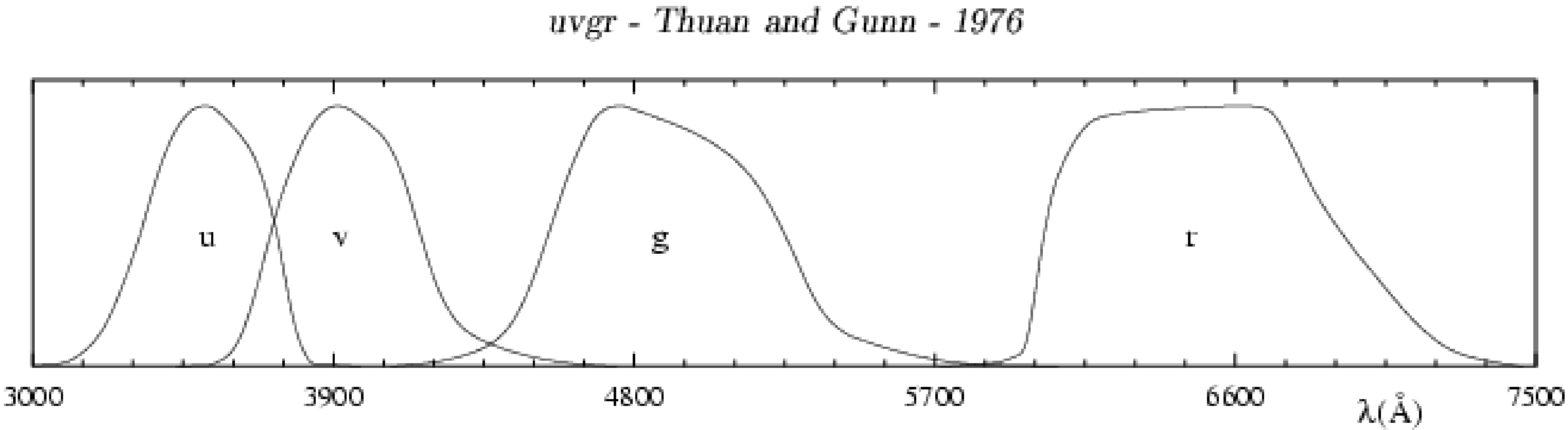
- Irregular Galaxies
- Disintegrate because of gravitational interaction with the Milky Way
- Global elemental abundance is lower than in the Milky Way:
  $-2 < [Fe/H] < -0.3$ dex
- Total masses about 20 times lower than in the Milky Way
- No significant differential rotation

	Cluster	SWB class	R (arcsec)	N_{star}	V_{TO} (mag)	age (Myr)
LMC	KMHK265	...	30	303	16.5	$50 \div 100$
	NGC 1902	II	40	440	17	$100 \div 150$
	KMHK264	...	30 7 pc	241	17.5	$150 \div 200$
	NGC 1777	IV B	$25 \div 70$	804	19.5	$700 \div 800$
	IC 2146	V	60	2023	20.25	$1200 \div 1500$
	NGC 2155	VI	$16 \div 50$	1085	20.5	$1500 \div 2000$
SMC	NGC 299	...	25	271	14.5	$15 \div 20$
	NGC 220	III	30	511	16.5	$70 \div 100$
	NGC 222	II-III	25	361	16.5	$70 \div 100$
	NGC 231	...	30	449	16.5	$70 \div 100$
	NGC 458	III	65	1288	17.0	$100 \div 150$
	L45	...	30	334	17.0	$100 \div 150$
	L13	...	35	300	19.25	$450 \div 550$
	NGC 643	...	70 20 pc	1127	19.5	$600 \div 700$
	L9	...	35	374	$20.25 \div 20.5$	$1000 \div 1300$
	NGC 152	IV B	60	1862	$20.25 \div 20.5$	$1000 \div 1300$

Matteucci et al., 2002, A&A, 387, 861

- Impact for the study of star clusters in the Magellanic Clouds
    1. The diameters of star clusters are normally below 1′
    2. The core regions are difficult to resolve
    3. The distance is no free parameter any more
    4. There are almost no “foreground objects”
    5. The membership determination on a kinematical basis is almost impossible
    6. Star clusters are most suitable to perform “statistical investigations”

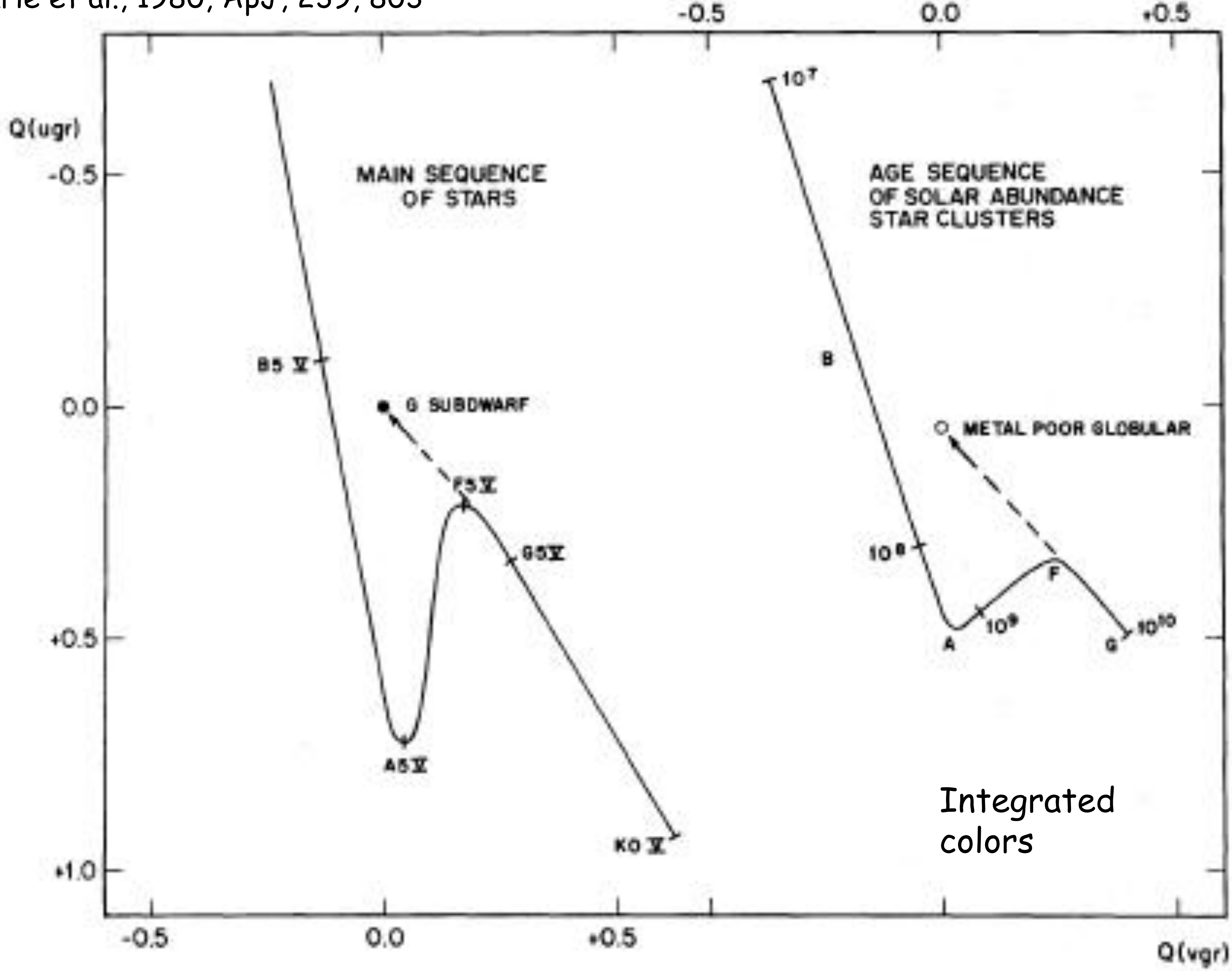
Classification of Star Clusters



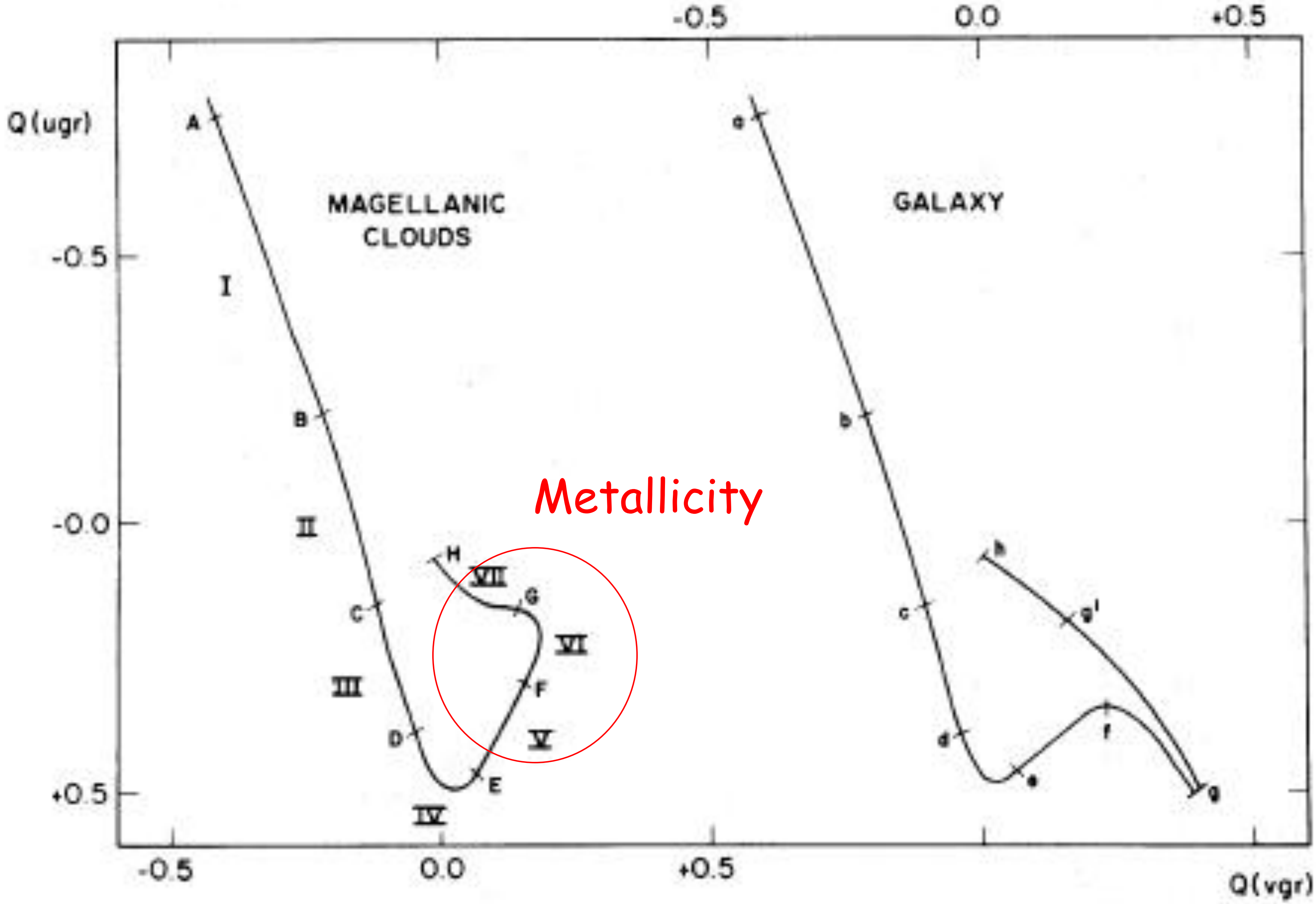
Reddening free indices

$$Q(ugr) = (u - g) - 1.08(g - r)$$
$$Q(vgr) = (v - g) - 0.68(g - r)$$

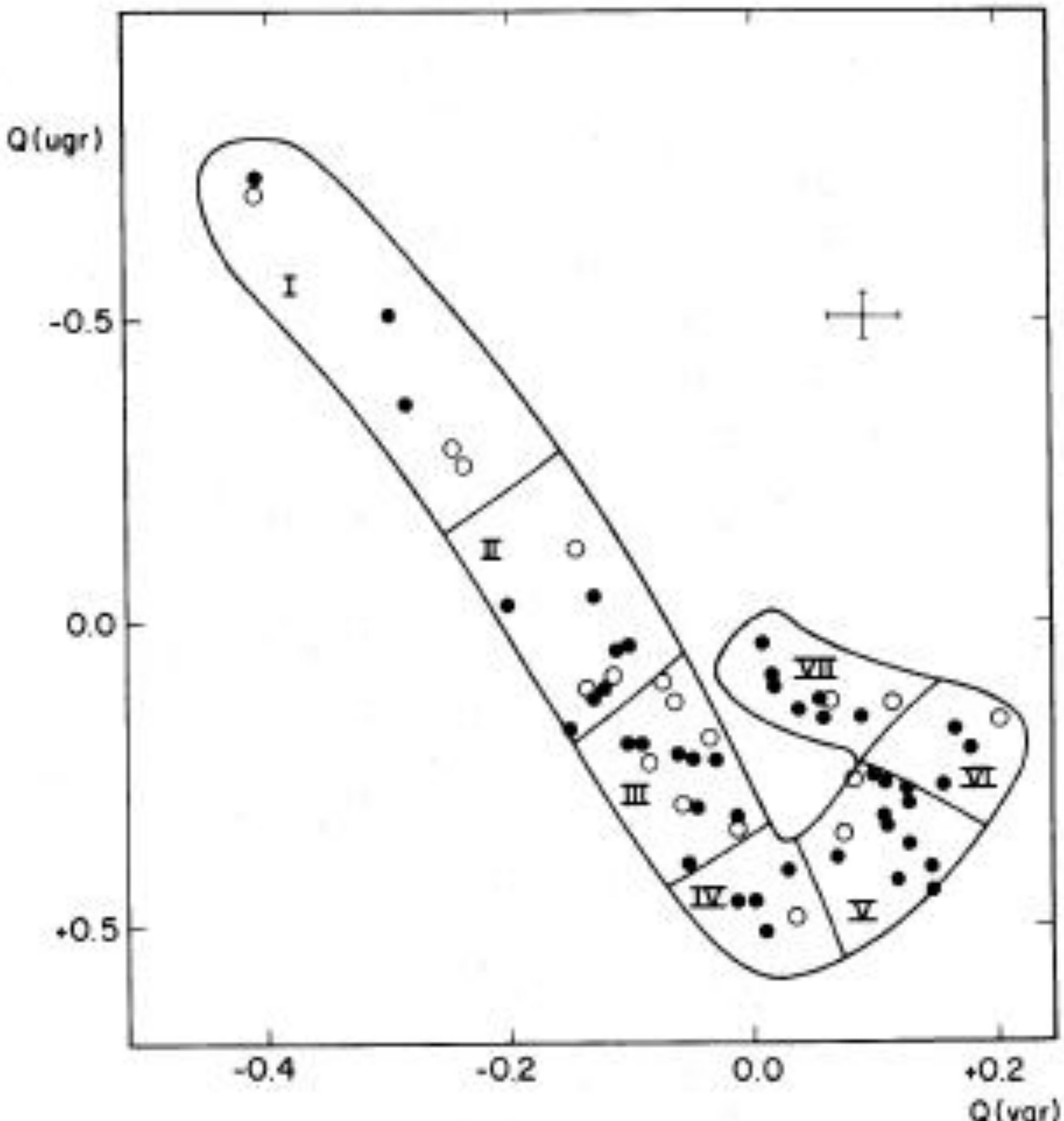
Searle et al., 1980, ApJ, 239, 803



Integrated colors



Searle et al., 1980, ApJ, 239, 803

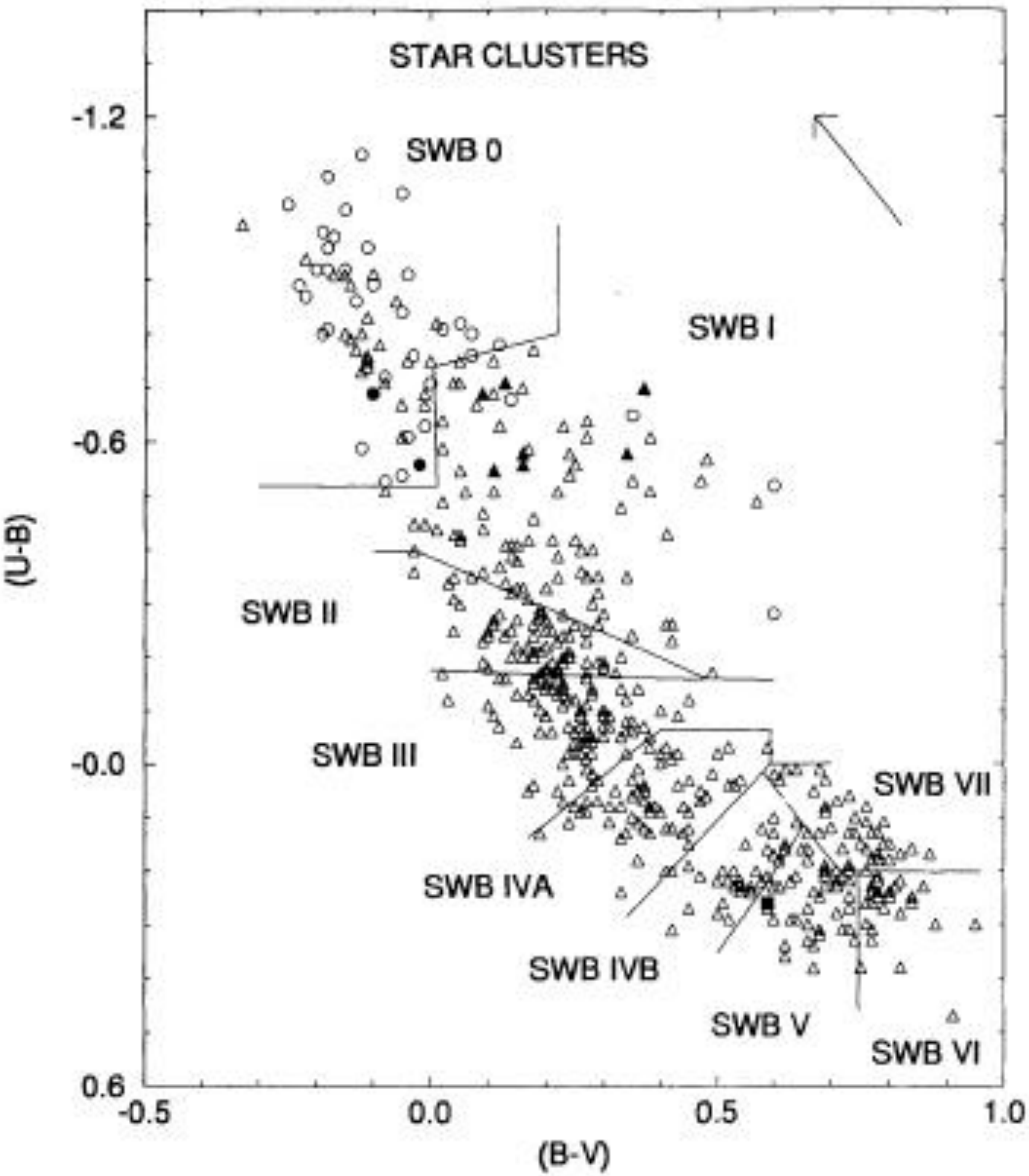


Seven "regions"

For LMC and SMC (open circles)

Age: I, II and III
Age and Metallicity: IV - VII

Searle et al., 1980, ApJ, 239, 803



Integrated colors of 624 Star Clusters in the LMC

Each "region" can be calibrated in terms of the age and the metallicity

Bica et al., 1996, ApJS, 102, 57

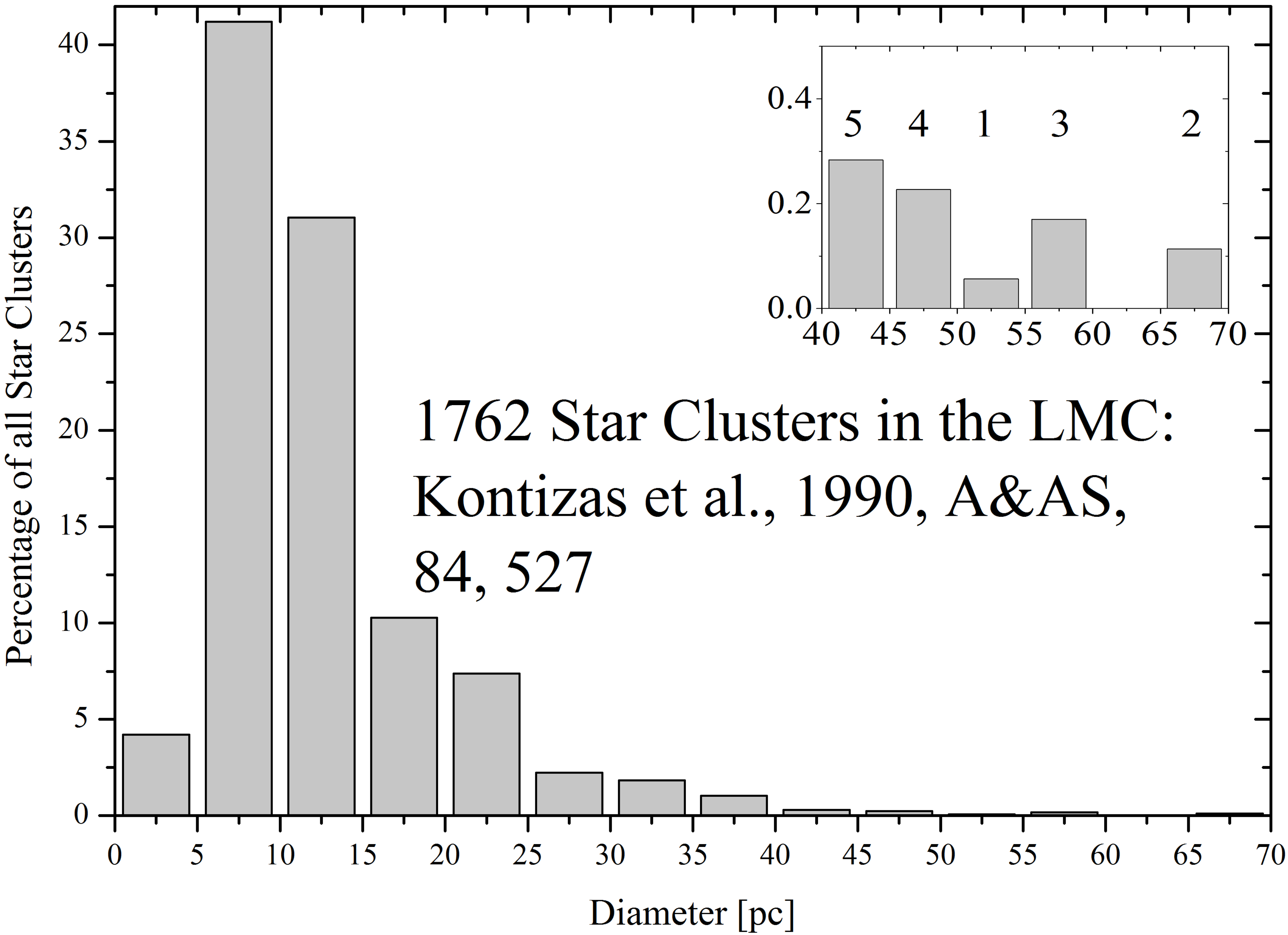
Group (SWB)	Age (Myr)	Clusters[a]	Associations[a]	Total	M	m	M/m	PA	x_c	y_c
0	0–10	61	77	138	6°3	6°3	1.00	140°	−0°11	1°14
I	10–30	89	41	130	6.7	6.3	1.00	150	−0.13	1.08
II	30–70	64	1	65	8.6	6.7	1.28	80	0.01	0.64
III	70–200	86	1	87	9.3	7.0	1.33	40	−0.40	0.48
IVA	200–400	62	0	62	11.6	8.0	1.45	10	−0.29	1.00
IVB	400–800	33	0	33	12.4	8.0	1.55	40	−0.76	−0.28
V	800–2000	41	0	41	13.3	10.5	1.27	40	−0.66	−0.55
VI	2000–5000	30	0	30	12.4	9.7	1.28	0	−0.47	−0.98
VII	5000–16000	38	0	38	17.0	10.7	1.59	40	−0.86	1.34
					(25.5[b])	(15.6[b])	(1.63[b])	(0[b])	(−0.64[b])	(1.16[b])
Total	0–16000	504	120	624	25.5[b]	15.6[b]	15.6[b]	0[b]	−0.28	0.68

M and m, semimajor and semiminor axis
PA positional angle of M, North = 0°, East = 90°

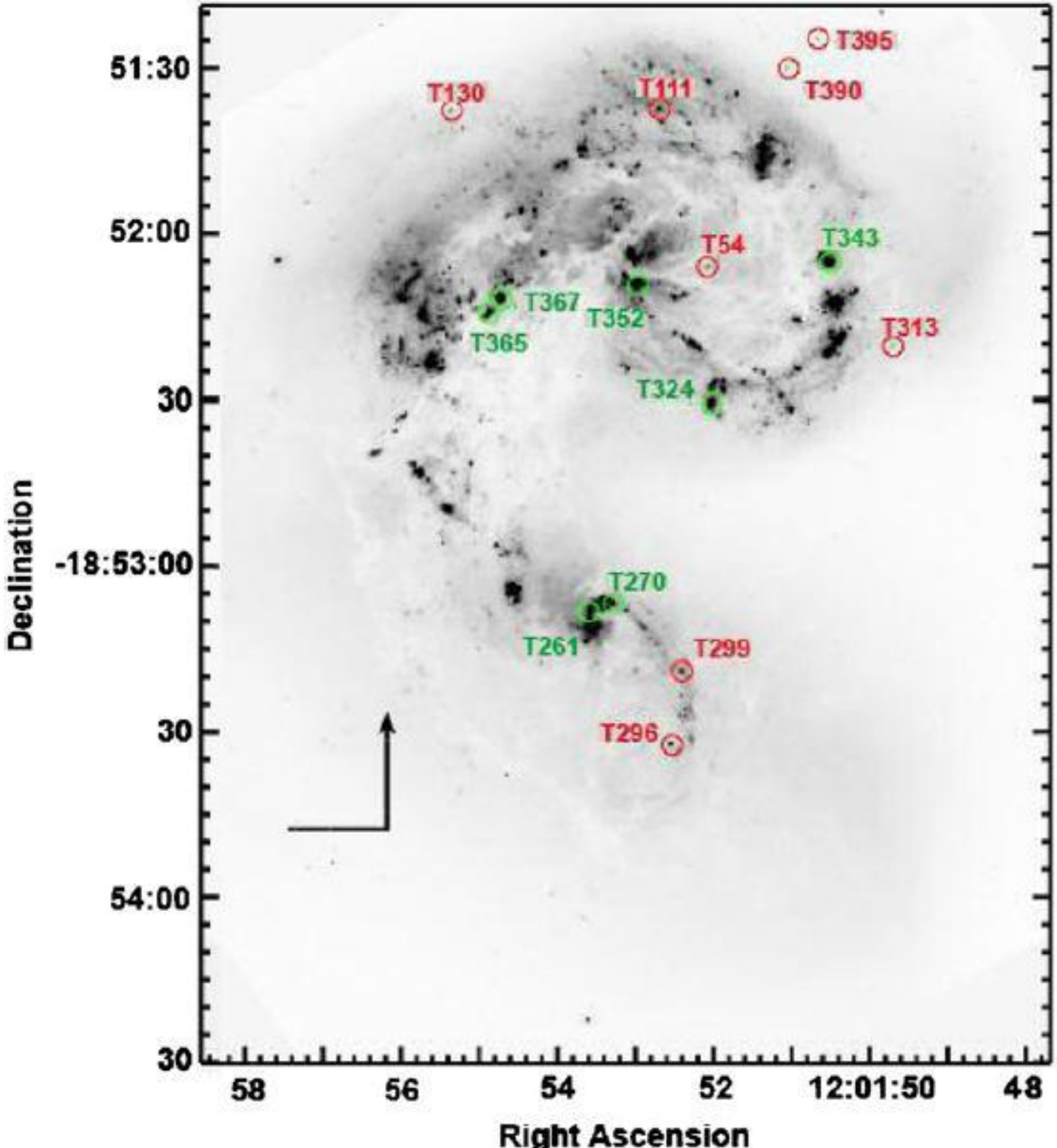
Conclusions:

1. Age: continuous up to 16 Gyr
2. Star clusters do not dissipate because of the local rotation

Bica et al., 1996, ApJS, 102, 57



Percentage of all Star Clusters
Diameter [pc]
0
5
10
15
20
25
30
35
40
45
50
55
60
65
70
1762 Star Clusters in the LMC:
Kontizas et al., 1990, A&AS,
84, 527
5
4
1
3
2
0.0
0.2
0.4

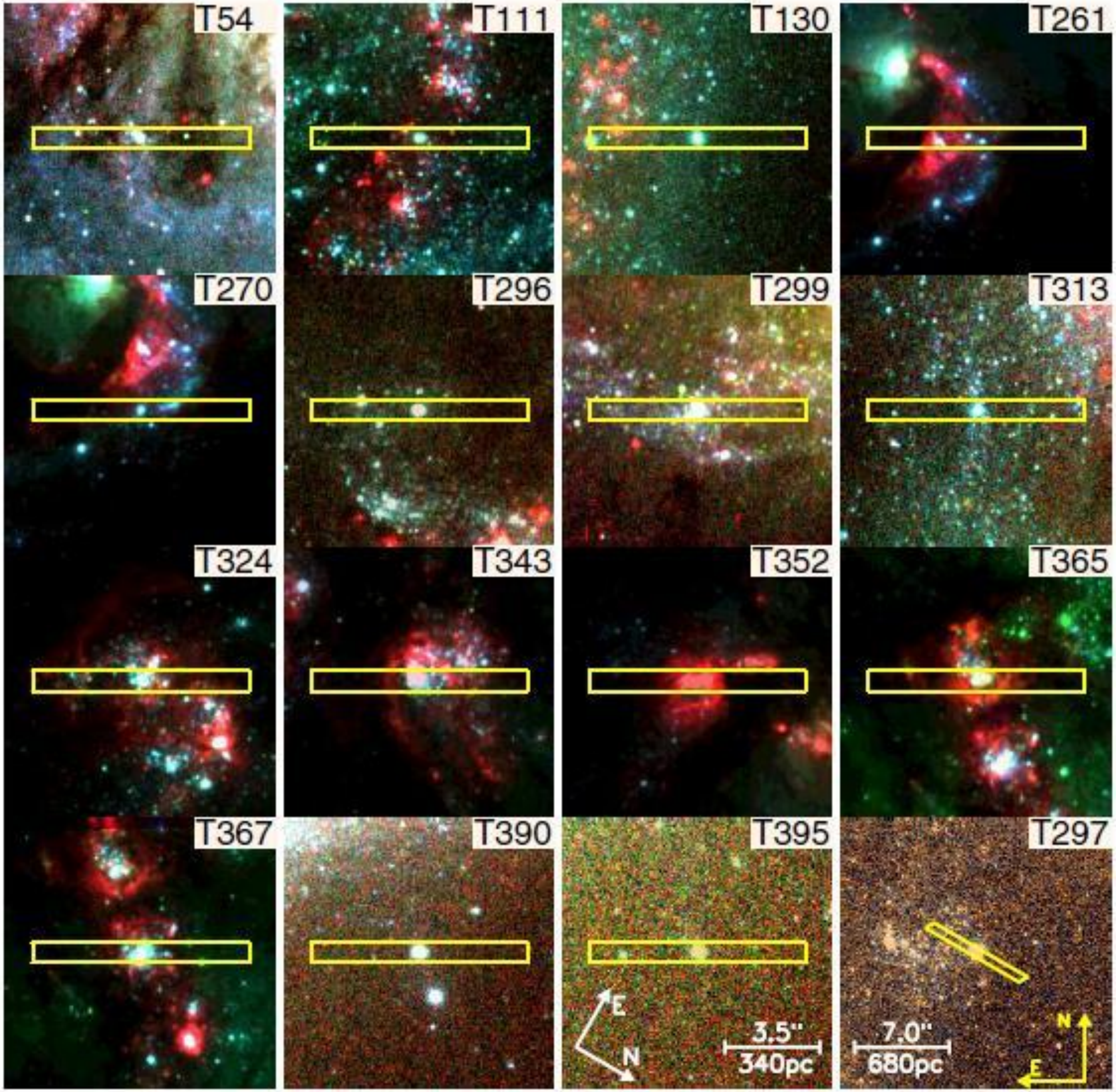


Star Clusters in NGC 4038/9

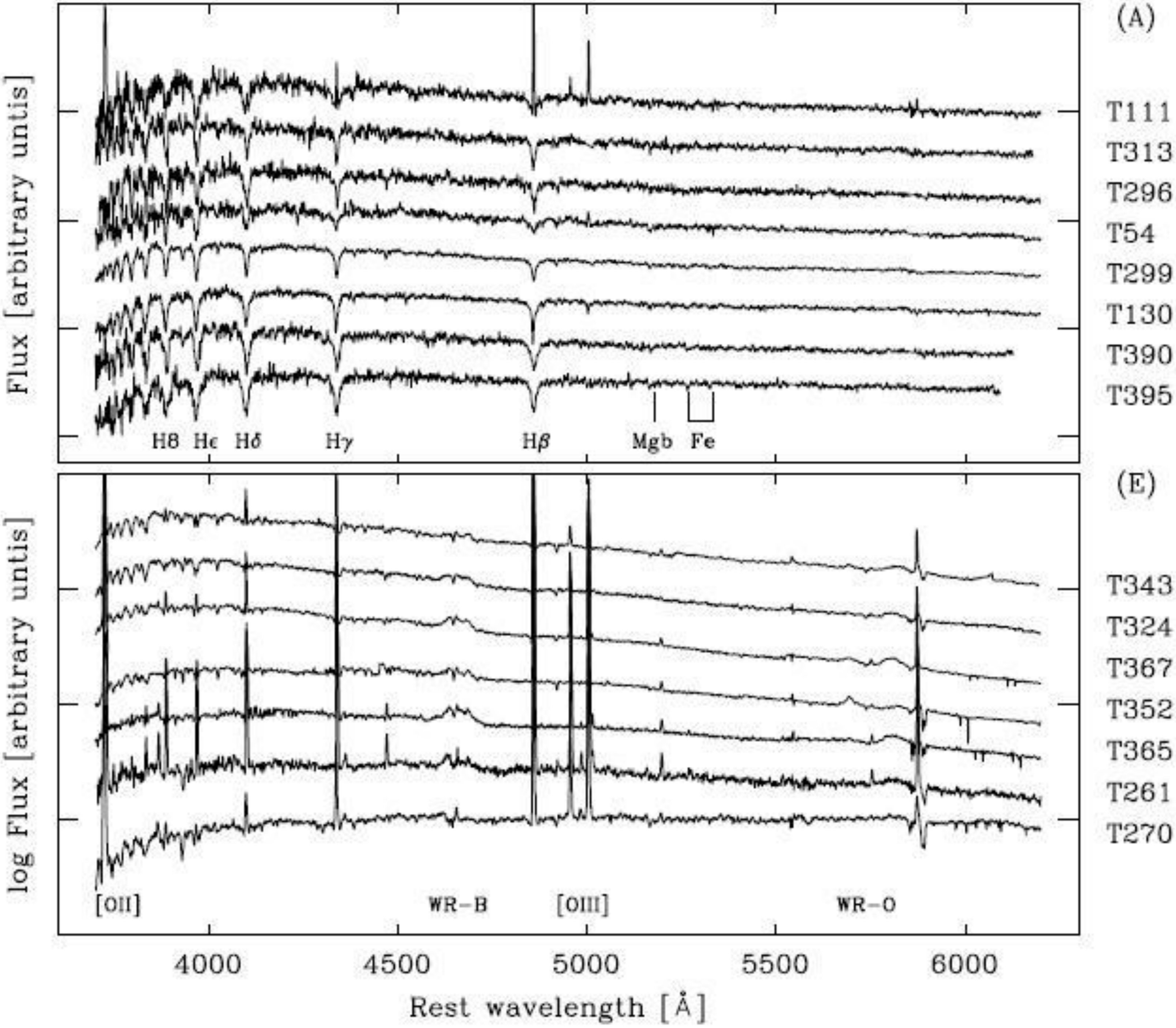
Antennae Galaxy

D = 20 Mpc

Bastian et al., 2009, ApJ, 701, 607



Positions of the slit



8 m GEMINI

t = 4 h

ID	H + Hϵ[a] (Å)	K[a] (Å)	H8[a] (Å)	$H\gamma_A$[b] (Å)	Mgb5177[b] (Å)	Fe5270[b] (Å)	Fe5335[b] (Å)
T54	5.18 ± 0.19	0.75 ± 0.09	3.26 ± 0.19	4.12 ± 0.11	0.42 ± 0.07	0.90 ± 0.08	1.21 ± 0.12
T111	7.60 ± 0.29	0.91 ± 0.17	6.71 ± 0.30	7.02 ± 0.21	0.37 ± 0.11	1.02 ± 0.14	1.48 ± 0.22
T130	9.83 ± 0.31	0.76 ± 0.18	8.73 ± 0.31	8.65 ± 0.22	0.64 ± 0.12	1.05 ± 0.15	1.46 ± 0.22
T296	7.02 ± 0.19	0.77 ± 0.01	6.10 ± 0.20	6.57 ± 0.14	0.30 ± 0.08	0.96 ± 0.00	1.23 ± 0.06
T297	...	...	...	9.07 ± 0.41	0.73 ± 0.15	1.00 ± 0.07	1.36 ± 0.23
T299	5.88 ± 0.11	0.77 ± 0.06	4.70 ± 0.11	4.94 ± 0.08	0.20 ± 0.04	0.57 ± 0.06	0.67 ± 0.09
T313	7.48 ± 0.25	0.71 ± 0.04	7.00 ± 0.61	7.47 ± 0.40	0.44 ± 0.22	1.02 ± 0.27	1.51 ± 0.21
T390	9.43 ± 0.43	0.72 ± 0.25	8.35 ± 0.45	8.50 ± 0.29	0.45 ± 0.15	1.08 ± 0.19	1.46 ± 0.28
T395	11.20 ± 0.72	2.97 ± 0.41	9.94 ± 0.78	9.16 ± 0.51	0.77 ± 0.21	1.58 ± 0.26	1.86 ± 0.37

In addition: integrated colors from HST photometry

ID	A/E[a]	ΔR.A. (J2000)	ΔDecl. (J2000)	F336W (mag)	F435W (mag)	F550M (mag)	F814W (mag)	F658N (mag)	A_V (mag)	Z ($Z_\odot$)	Log(age) (year)
T54	0	$12^h01^m52^s.119$	$-18^d52^m07^s.3$	21.10	21.53	21.15	20.30	20.65	1.0	0.9 ± 0.1	6.9 ± 0.1
T111	0	$12^h01^m53^s.379$	$-18^d51^m39^s.2$	20.80	21.18	21.09	20.77	20.89	0.0	0.9 ± 0.3	7.9 ± 0.1
T130	0	$12^h01^m55^s.360$	$-18^d51^m38^s.9$	20.33	20.82	20.72	20.37	20.43	0.0	1.0 ± 0.1	8.4 ± 0.1
T261	1	$12^h01^m53^s.561$	$-18^d53^m07^s.9$	18.90	20.17	20.29	20.14	18.76	0.3	1.1 ± 0.2	<6.8
T270	1	$12^h01^m53^s.345$	$-18^d53^m07^s.6$	19.61	20.14	19.70	18.91	19.38	1.7	1.1 ± 0.2	<6.8
T296	0	$12^h01^m52^s.624$	$-18^d53^m33^s.8$	19.85	20.43	20.29	19.87	19.92	0.2	1.0 ± 0.0	7.9 ± 0.1
T297	0	$12^h02^m00^s.112$	$-18^d54^m33^s.3$	...	...	22.22[b]	21.60[b]	...	1.0	1.1 ± 0.1[c]	8.5 ± 0.2[c]
T299	0	$12^h01^m52^s.480$	$-18^d53^m20^s.2$	19.43	20.26	20.14	19.69	19.86	0.2	0.9 ± 0.1	7.35 ± 0.07
T313	0	$12^h01^m49^s.744$	$-18^d52^m21^s.9$	21.29	21.88	21.80	21.35	21.59	0.2	1.0 ± 0.1	7.8 ± 0.1
T324	2	$12^h01^m52^s.085$	$-18^d52^m31^s.9$	17.76	19.01	18.97	18.74	18.40	0.6	1.2 ± 0.2	6.5–6.8[d]
T343	2	$12^h01^m50^s.537$	$-18^d52^m06^s.6$	17.23	18.43	18.44	18.30	17.73	0.4	1.3 ± 0.2	6.5–6.8[d]
T352	1	$12^h01^m53^s.022$	$-18^d52^m10^s.6$	16.33	17.69	17.54	17.57	17.01	0.3	1.3 ± 0.2	<6.8
T365	2	$12^h01^m54^s.928$	$-18^d52^m15^s.4$	17.78	19.04	18.92	18.66	18.48	0.7	1.1 ± 0.2	6.5–6.8[d]
T367	2	$12^h01^m54^s.749$	$-18^d52^m12^s.9$	16.78	18.27	18.45	18.51	17.78	0.0	1.3 ± 0.2	6.5–6.8[d]
T390	0	$12^h01^m51^s.076$	$-18^d51^m31^s.5$	21.37	21.50	21.35	20.94	21.15	0.0	1.1 ± 0.4	8.3 ± 0.1
T395	0	$12^h01^m50^s.681$	$-18^d51^m26^s.0$	21.78	21.77	21.62	21.19	21.34	0.1	1.1 ± 0.2	8.8 ± 0.1

Determination of the extinction, metallicity and age possible

ID	Agreement[a]	cz(H I)[b] (km s^{-1})	czhel (km s^{-1})	deltcz (km s^{-1})	log(Mass) $\mathcal{M}_\odot$	R_{eff} (pc)
T54	0	1700	1697 ± 54	−3	4.8 ± 0.3	3.7
T111	0	1560	1595 ± 115	+35	5.3 ± 0.3	6.7
T130	0	1565	1617 ± 61	+52	5.7 ± 0.3	6.0
T261	0	1670	1621 ± 13	−49	4.6 ± 0.3	···
T270	0	1715	1711 ± 19	−4	5.4 ± 0.3	9.3
T296	0	1755	1733 ± 35	−22	5.6 ± 0.3	4.0
T297	1	1675	1553 ± 41	−122	5.2 ± 0.3	···
T299	0	1795:[c]	1810 ± 38	+15:	5.4 ± 0.3	8.4
T313	0	1695	1657 ± 33	−38	5.0 ± 0.3	12.8
T324	0	1690	1679 ± 24	−11	5.2 ± 0.3	7.7
T343	0	1630	1613 ± 16	−17	5.4 ± 0.3	8.8
T352	0	1640	1679 ± 24	+39	5.7 ± 0.3	···
T365	0	1630	1572 ± 15	−58	5.3 ± 0.3	4.3
T367	0	1630	1657 ± 13	+26	5.2 ± 0.3	6.6
T390	1	1530:	1689 ± 35	+159:	5.4 ± 0.3	8.9
T395	1	1580:	1727 ± 42	+147:	5.3 ± 0.3	7.5

R_V

Bastian et al., 2009, ApJ, 701, 607