Recent developments in star cluster research

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Definition of Star Clusters

Star clusters are physically related groups of stars held together by mutual gravitational attraction.

The number of all star clusters in the Milky Way is about 10 000 but only 3000 in catalogues. From these, about 180 Globular Clusters.

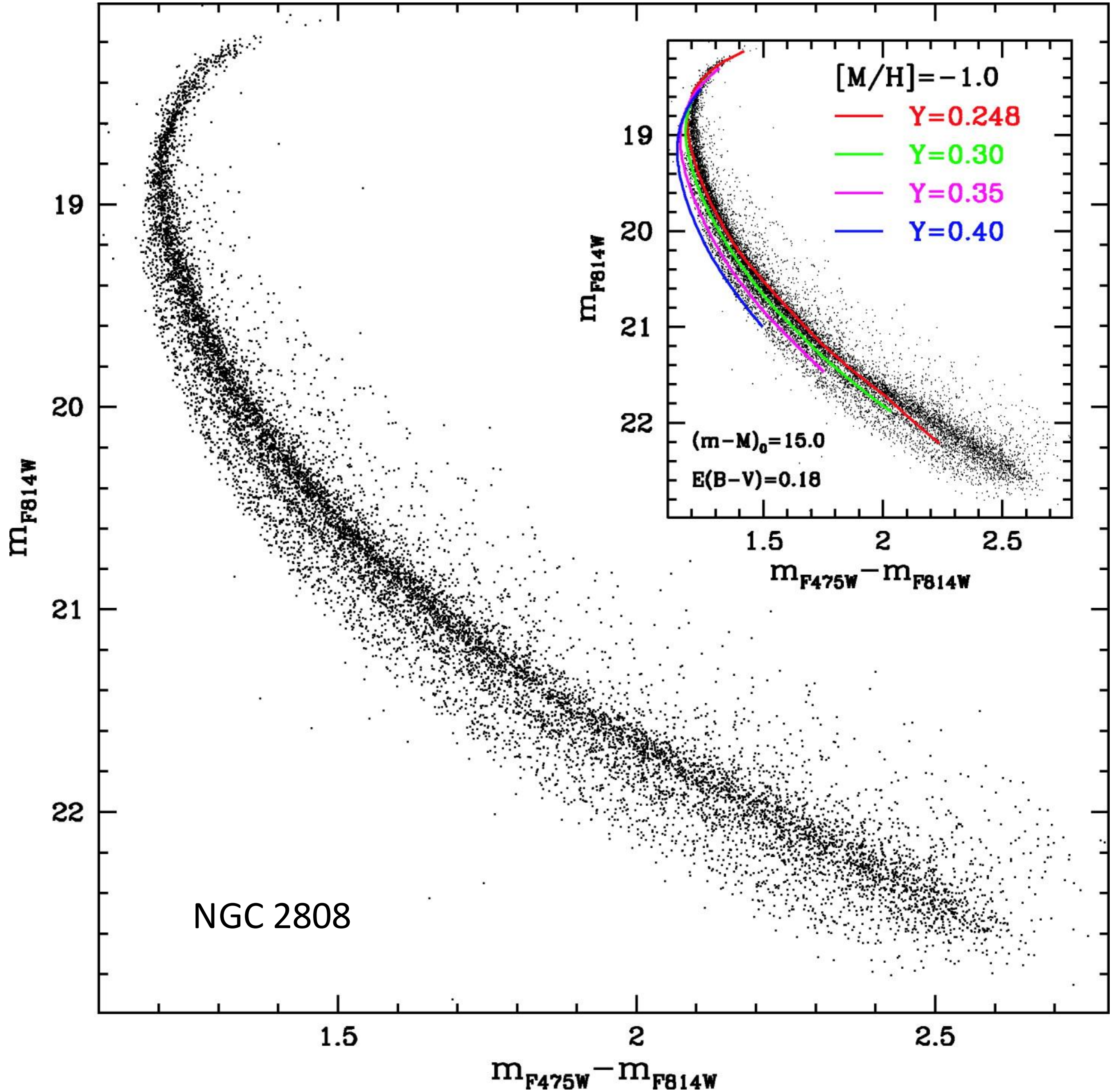
Working Hypothesis

All members of an individual Star Cluster are born within one Giant Molecular Cloud (GMC) over a time scale of some few Myrs.

What are the immediate conclusions?

All members of an individual star cluster have:

- ***Identical distance from the Sun:*** +- The volume expansion of the cluster
- ***Identical age:*** +- Time scale of star formation
- ***Identical metallicity:*** +- Inhomogeneities of the initial GMC and the chemical evolution of the giant branch
- ***Identical kinematical characteristics:*** +- Intrinsic spread
  - Radial velocity
  - Proper motion



Piotto et al., 2007, ApJ, 661, L53

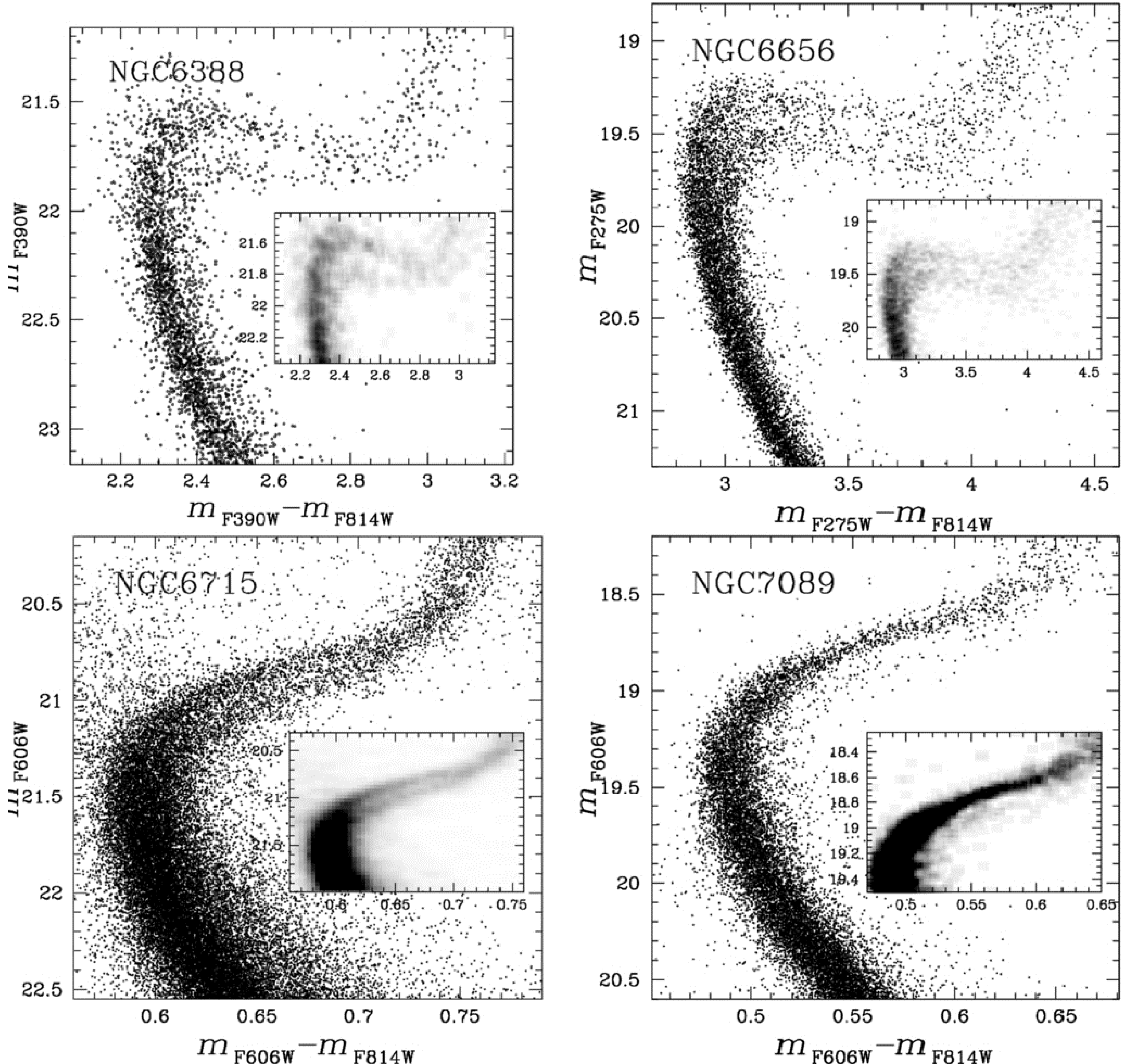
Possible explanation

Different He-abundances

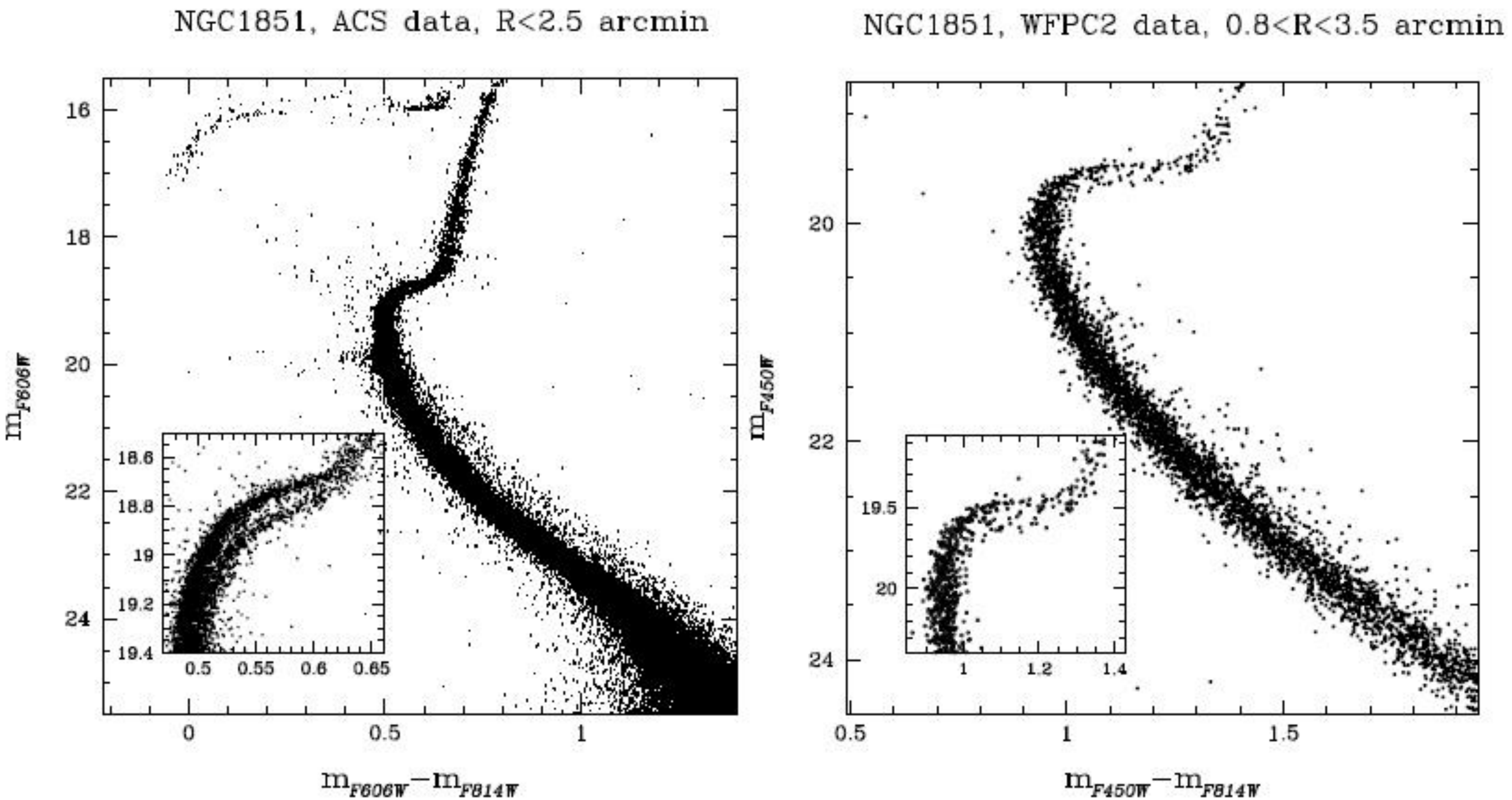
But also Fe and C abundances

Dotter et al., 2015, MNRAS, 446, 1641

Milone et al., 2017, MNRAS, 469, 800



Piotto et al., 2012,
ApJ, 760, 39

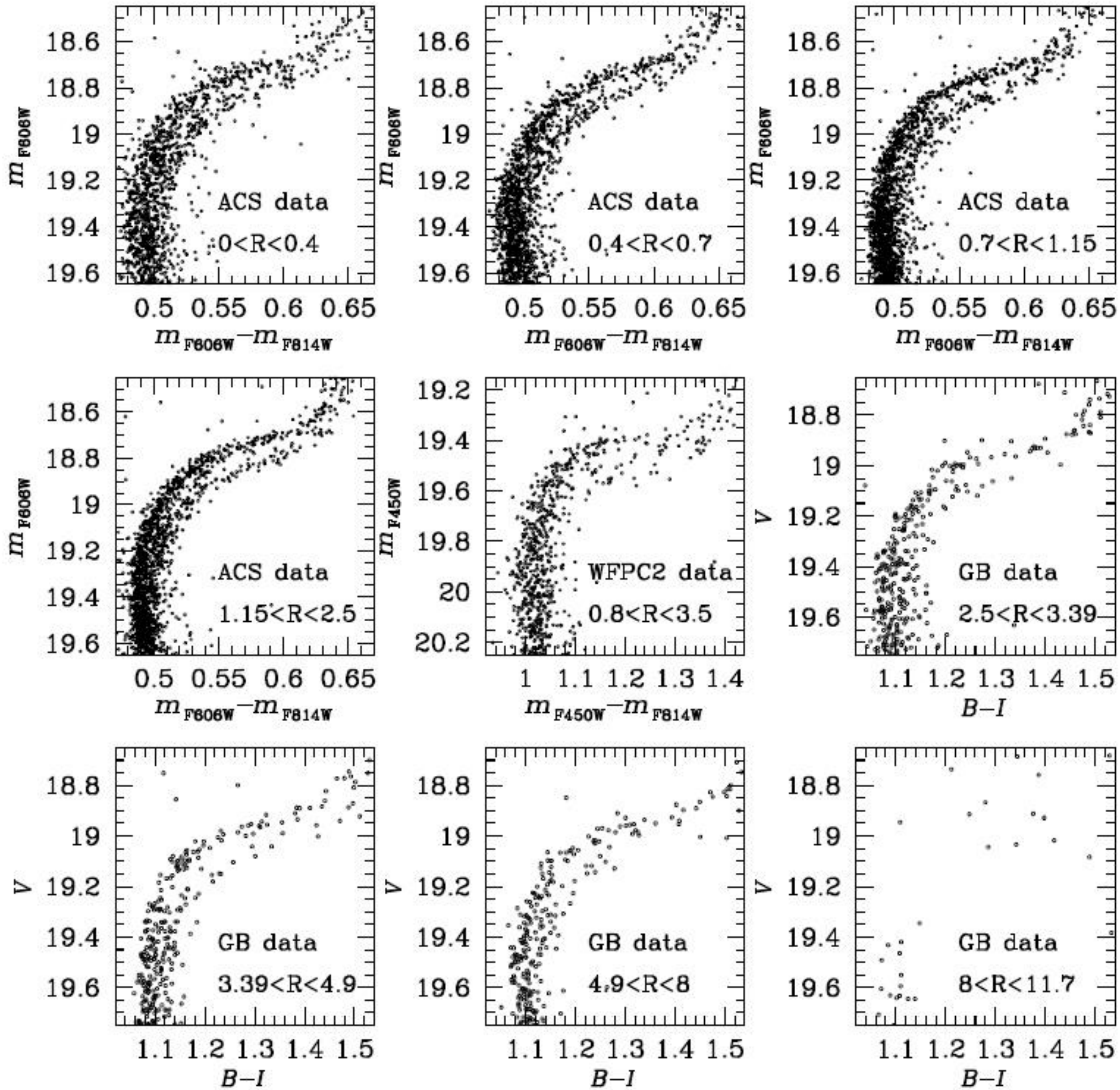


Double sub-giant branch, but only one main sequence

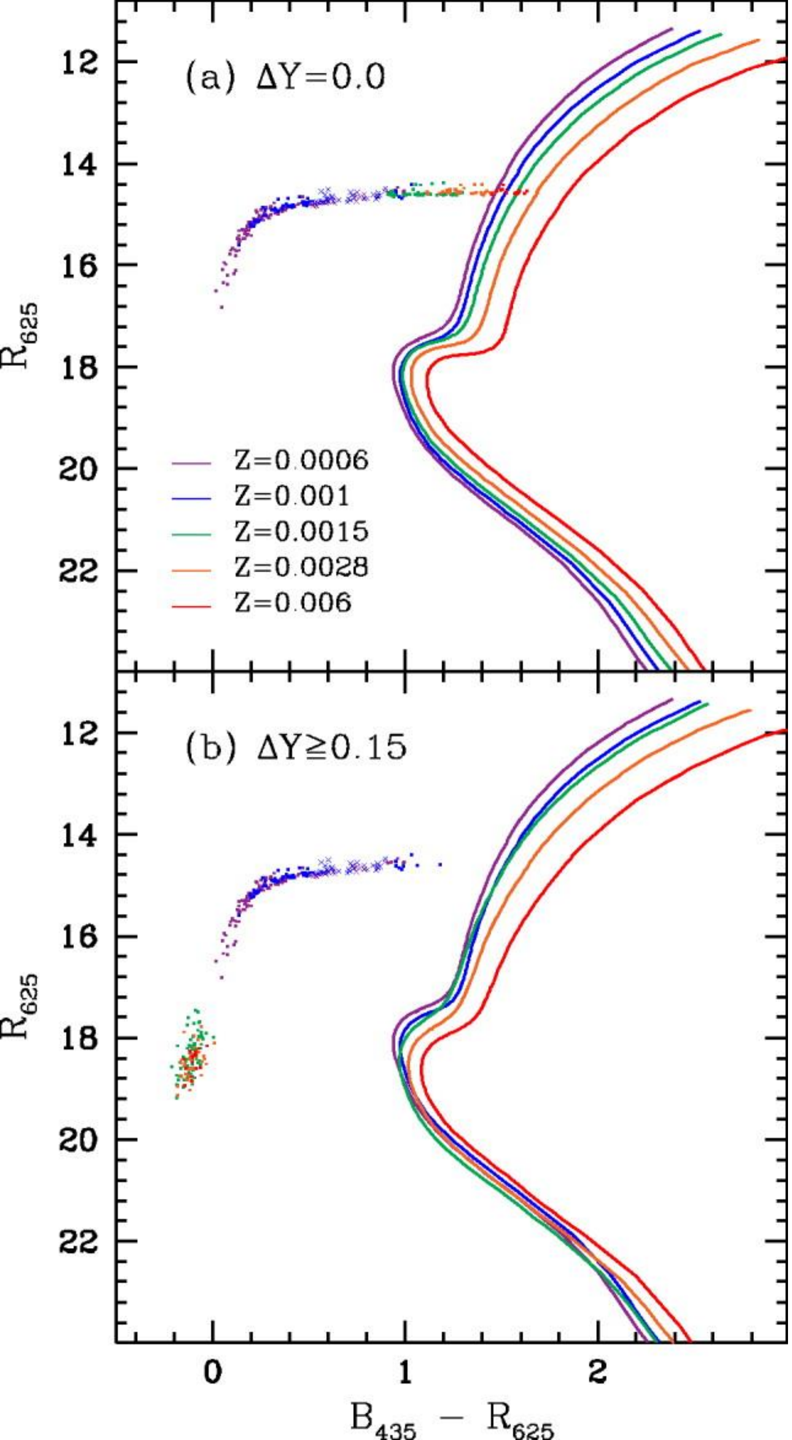
Milone et al., 2009, A&A, 503, 755

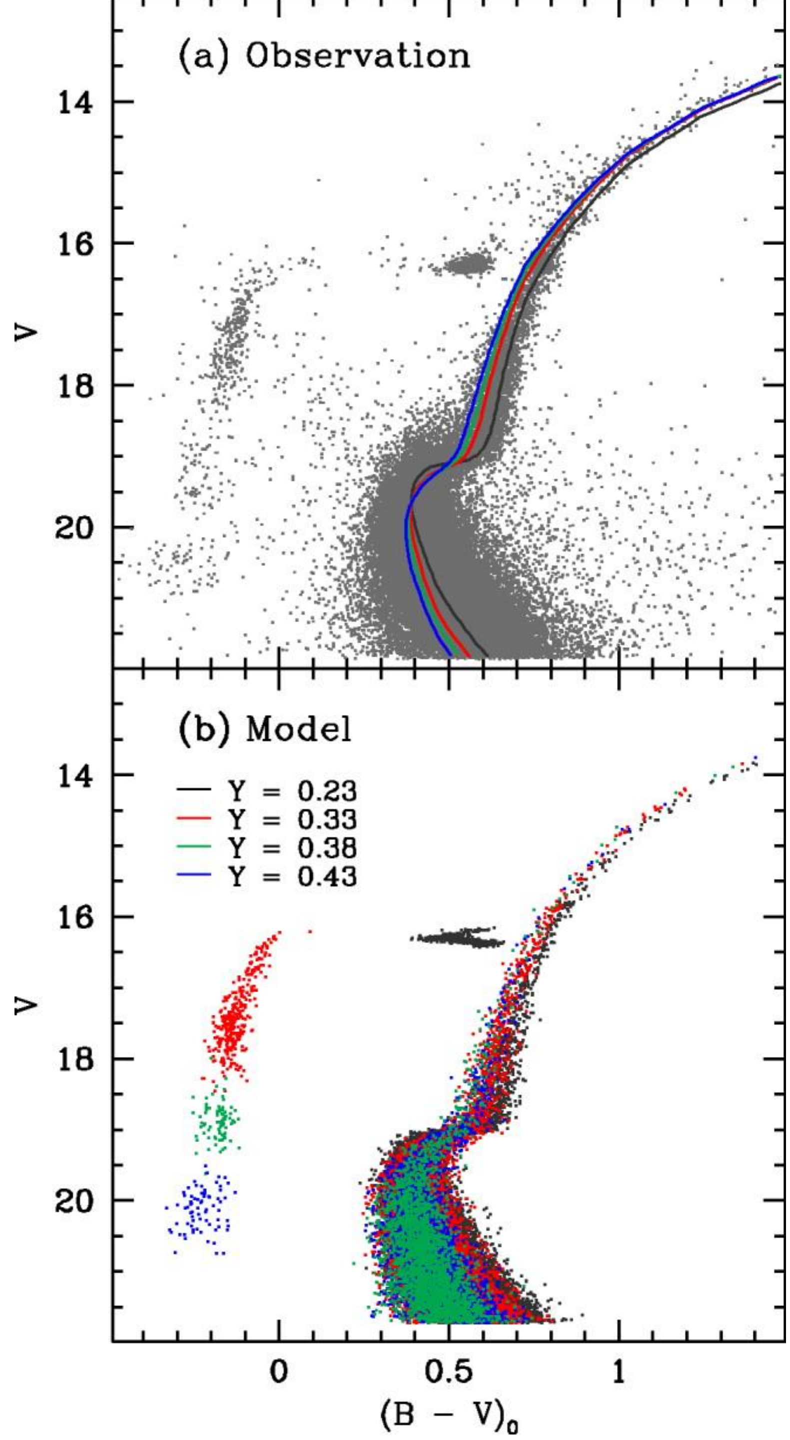
Open Questions

- How can you produce such He abundances?
- Different populations?
- Intrinsic of the star cluster?
- Merging processes?
- Only in Globular Clusters?
- Depending on metallicity?



No correlation with the position within the cluster



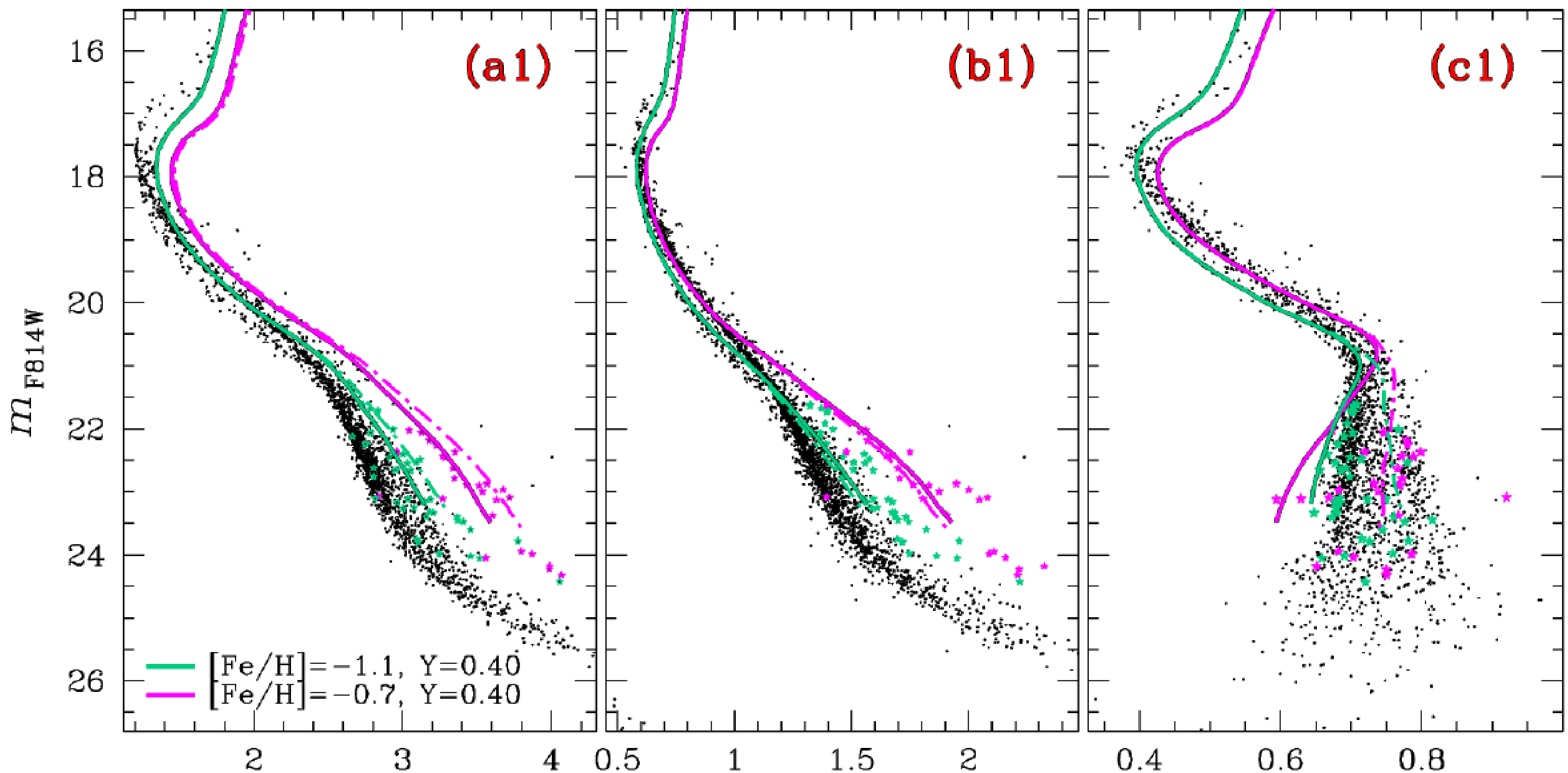


Lee et al., 2005, ApJ, 621, L57

Milone et al., 2017, MNRAS, 469, 800

ω Centauri

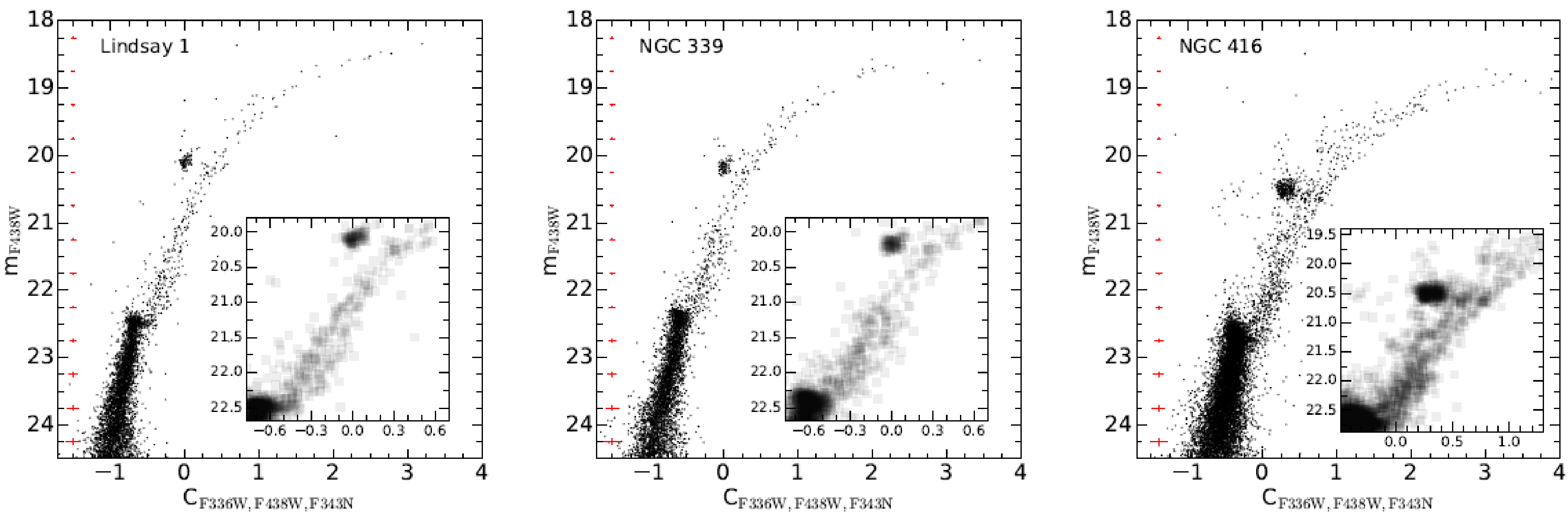
ω Centauri



Milone et al., 2017, MNRAS, 469, 800

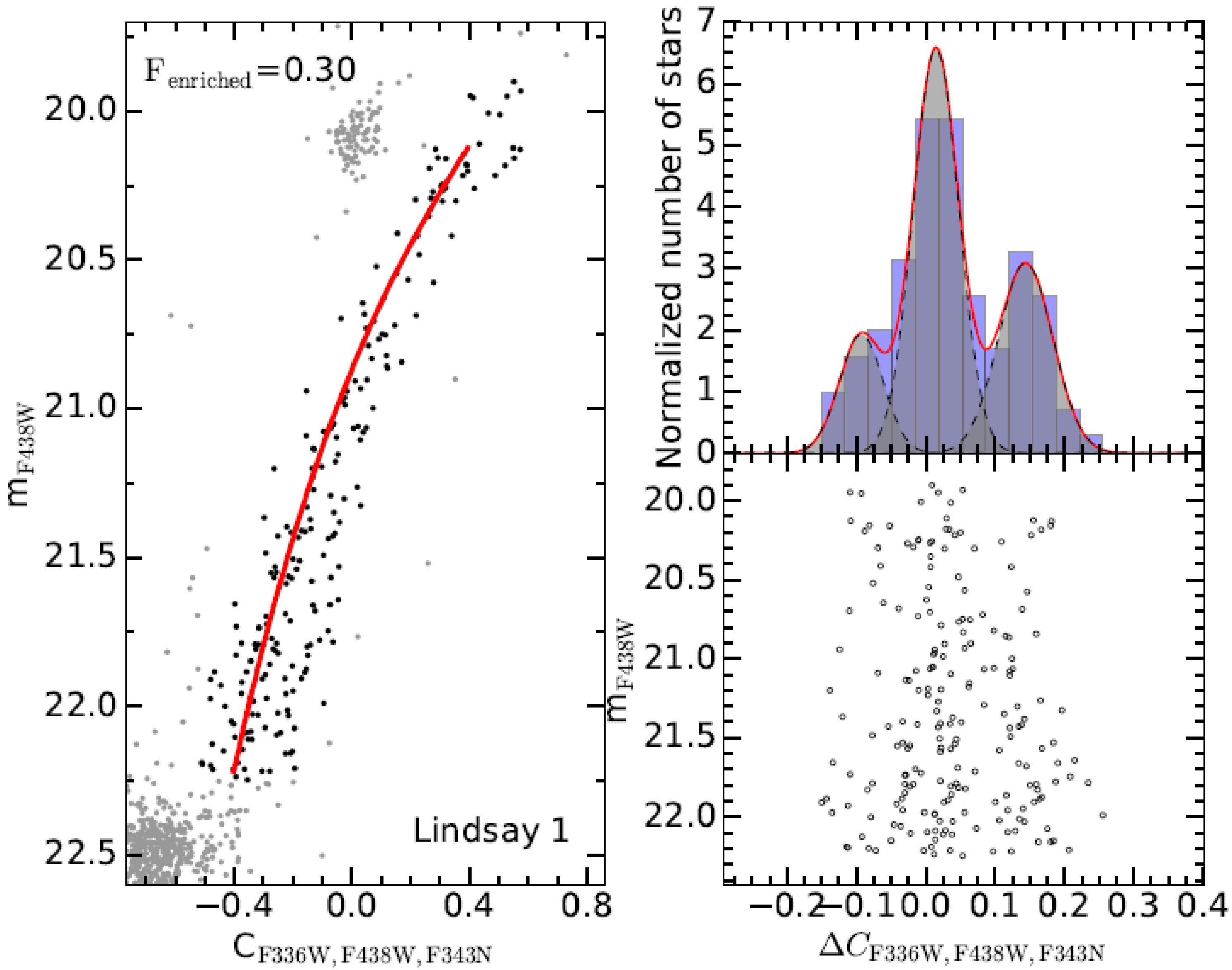
SMC

Cluster Name	RA	Dec	Age [Gyr]	Ref.	Mass [10^5 $M_\odot$]	Ref.	Metallicity Z	Ref.
Lindsay 1	$00^h\ 03^m\ 54^s.0$	-73° 28′ 18″	7.5	(1)	~2.0	(2)	0.001^a	(1)
NGC 339	$00^h\ 57^m\ 48^s.90$	-74° 28′ 00.2″	6.0	(1)	0.8	(3)	0.001^a	(1)
NGC 416	$01^h\ 07^m\ 54^s.98$	-72° 20′ 50.6″	6.0	(1)	1.6	(3)	0.002^a	(1)



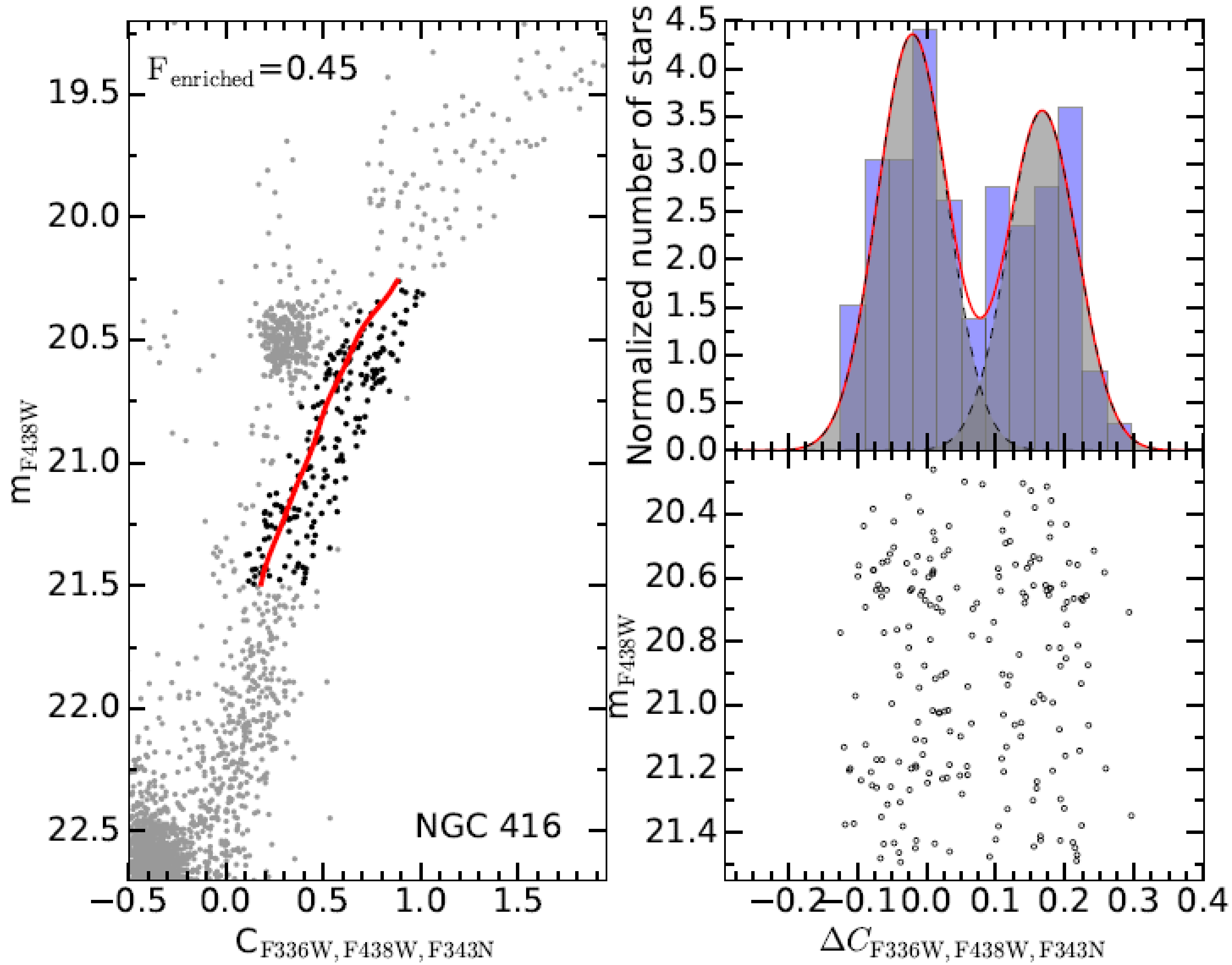
Niederhofer et al., 2017, MNRAS, 465, 4159

SMC



Niederhofer et al., 2017, MNRAS, 465, 4159

SMC



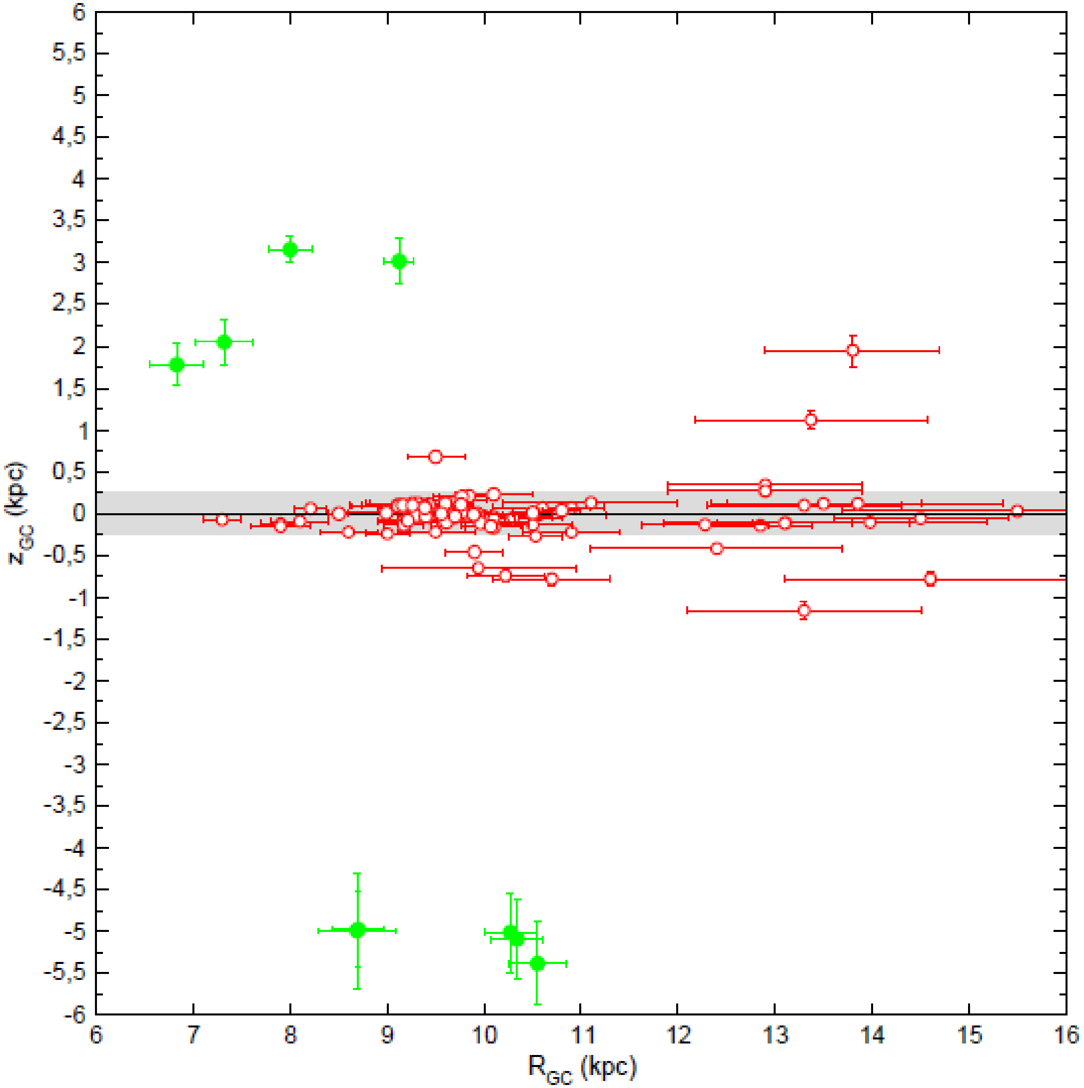
Niederhofer et al., 2017, MNRAS, 465, 4159

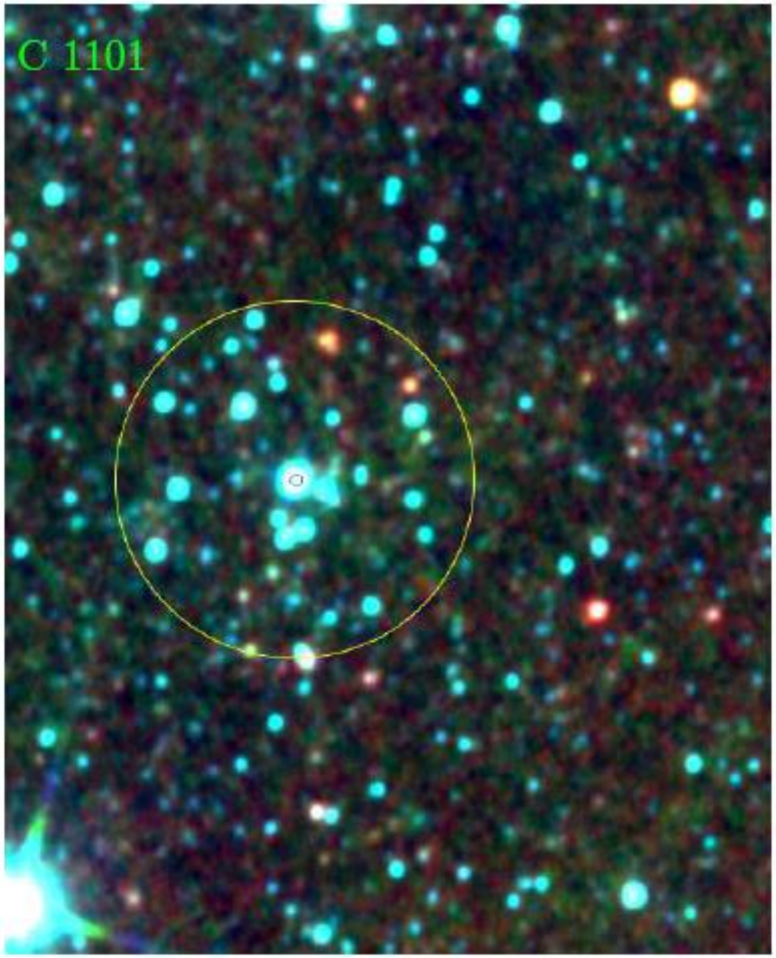
Young embedded clusters in the Galactic Halo?

- Camargo et al., 2016, A&A, 593, A95: “New detections of embedded clusters in the Galactic halo”
- Embedded in gas and dust => NIR and IR
- Almost no extinction towards $|b| > 50^o$
- Challenge for our knowledge of the evolution and formation of the Milky Way

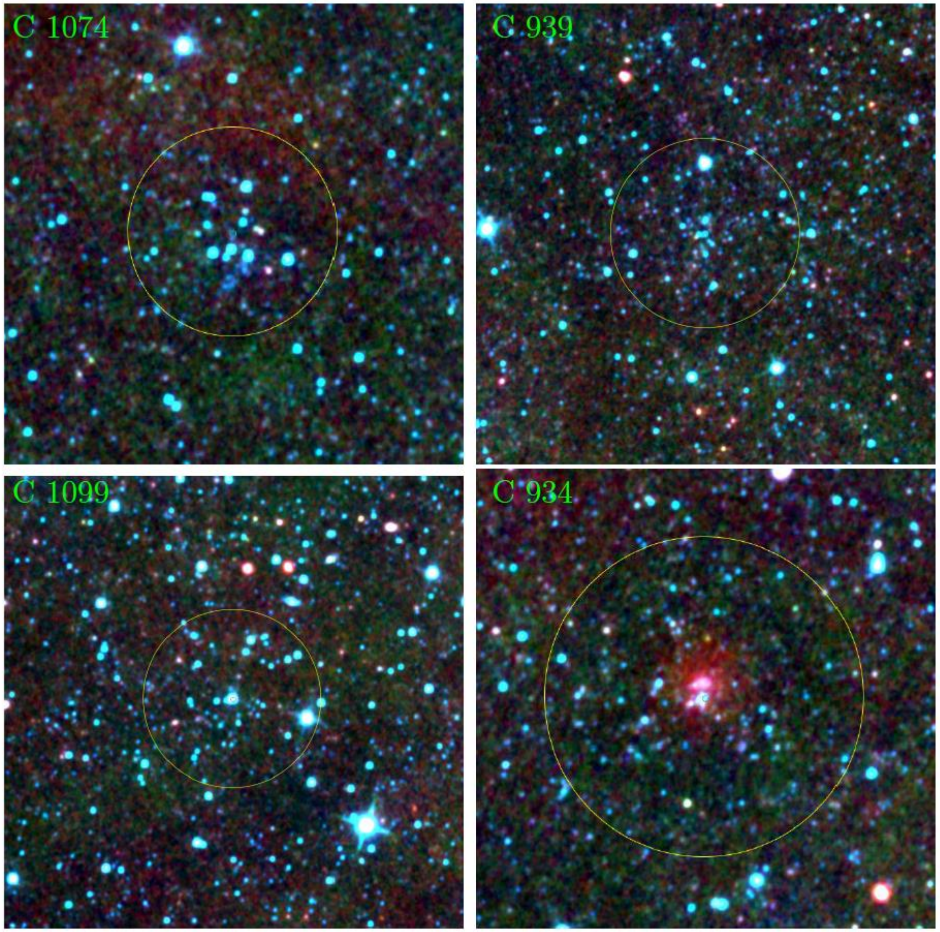
Young embedded clusters in the Galactic Halo?

Camargo et al., 2016, A&A, 593, A95





WISE + 2MASS



WISE

Table 1. Positions of the present star clusters or candidates.

Target (1)	α(2000) (h m s) (2)	δ(2000) (° ′ ″) (3)	ℓ (°) (4)	b (°) (5)
C 932	2:05:02	-18:09:26	188.89	-70.83
C 934	2:05:54	-17:56:17	188.65	-70.54
C 939	2:07:08	-18:13:15	189.83	-70.43
C 1074	10:39:27	-2:00:39	250.15	46.89
C 1099	11:49:55.7	-32:41:42.8	288.23	28.41
C 1100	12:11:39.9	-34:44:45.5	293.73	27.41
C 1101	12:14:24.5	-35:02:04.2	294.41	27.22

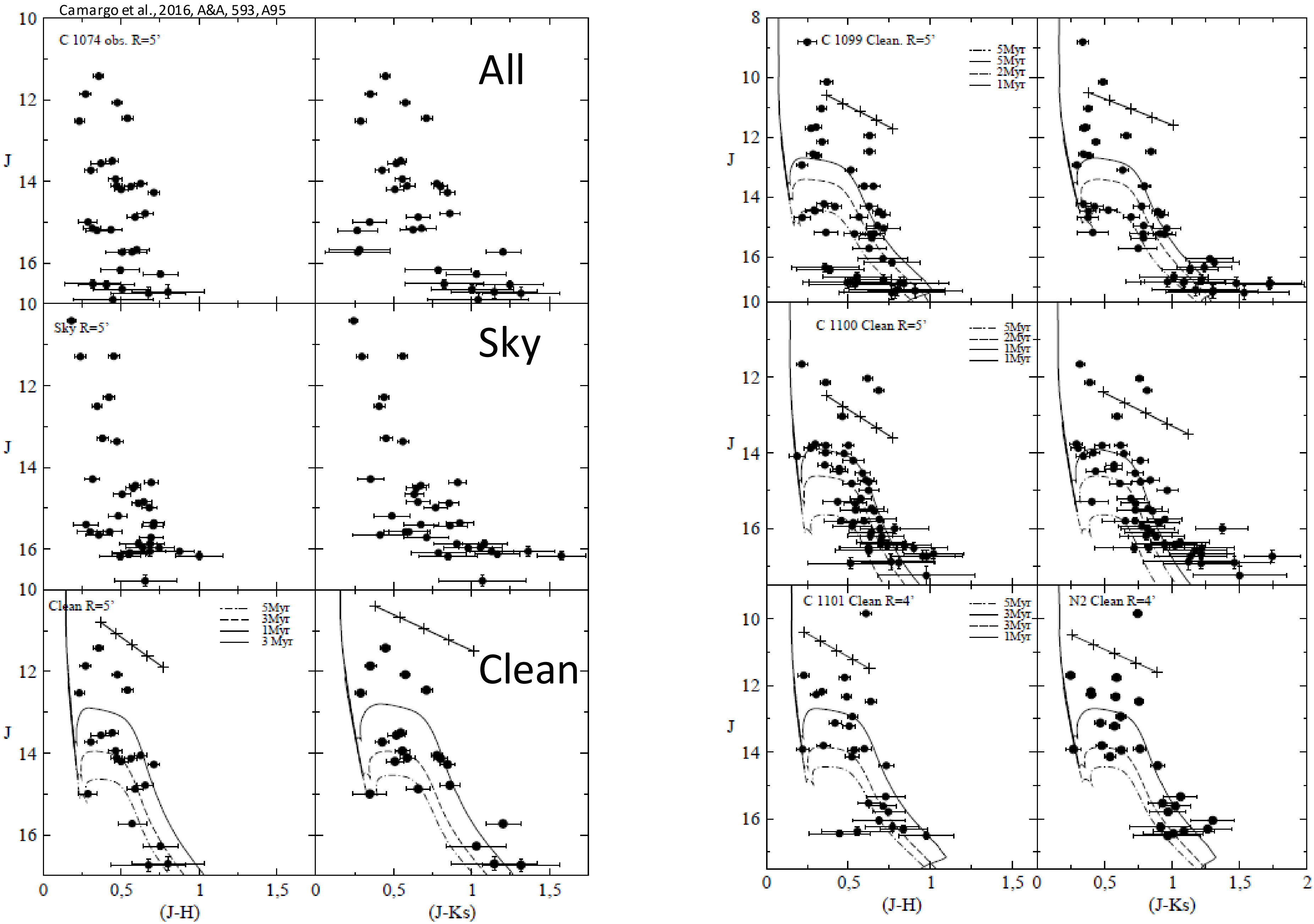
Table Notes. Cols. 2 – 3: Central coordinates. Cols. 4 – 5: Corresponding Galactic coordinates.

Camargo et al., 2016, A&A, 593, A95

Table 2. Fundamental parameters and Galactocentric components for the ECs in this work.

Cluster (1)	A_V (mag) (2)	Age (Myr) (3)	$d_\odot$ (kpc) (4)	R_{GC} (kpc) (5)	x_{GC} (kpc) (6)	y_{GC} (kpc) (7)	z_{GC} (kpc) (8)
C 932	1.40 ± 0.03	2 ± 1	5.7 ± 0.53	10.55 ± 0.29	-9.07 ± 0.17	-0.29 ± 0.03	-5.38 ± 0.50
C 934	1.46 ± 0.06	2 ± 1	5.31 ± 0.51	10.27 ± 0.27	-8.97 ± 0.17	-0.27 ± 0.03	-5.01 ± 0.48
C 939	1.30 ± 0.06	3 ± 2	5.40 ± 0.50	10.34 ± 0.27	-9.00 ± 0.17	-0.31 ± 0.03	-5.09 ± 0.47
C 1074	0.93 ± 0.06	3 ± 1	4.14 ± 0.39	9.12 ± 0.15	-8.18 ± 0.09	-2.66 ± 0.25	3.02 ± 0.28
C 1099	0.71 ± 0.06	5 ± 1	4.32 ± 0.61	7.32 ± 0.30	-6.03 ± 0.17	-3.61 ± 0.51	2.05 ± 0.28
C 1100	0.93 ± 0.06	1 ± 1	6.87 ± 0.36	8.00 ± 0.23	-4.76 ± 0.13	-5.59 ± 0.29	3.16 ± 0.16
C 1101	0.96 ± 0.06	3 ± 1	3.91 ± 0.55	6.83 ± 0.27	-5.78 ± 0.20	-3.16 ± 0.44	1.78 ± 0.25

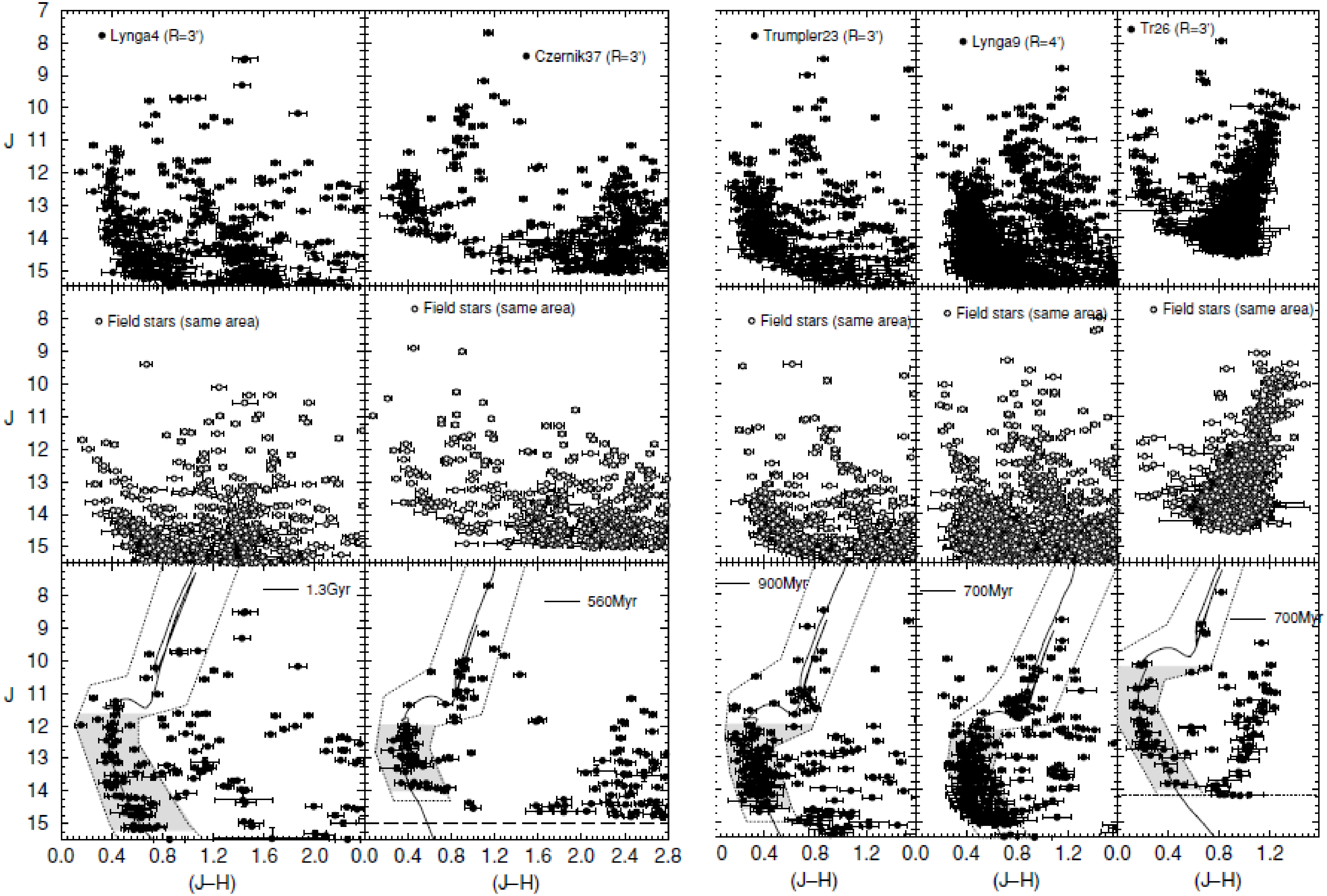
Table Notes. Col. 2: A_V in the cluster central region. Col. 2: age, from 2MASS photometry. Col. 3: distance from the Sun. Col.



Cleaning of CMDs – Star Counting method

Criticism - Method

- Blackbox
- Problems in dense fields (2MASS) and for young star clusters
- How it works (van den Bergh & Sher, 1960, Publications of the David Dunlap Observatory, 2, 230):
  - Take cluster and field nearby of same size
  - Count stars in rings
  - Apply „subtraction method“



Bonatto & Bica, 2007, MNRAS, 377, 1301

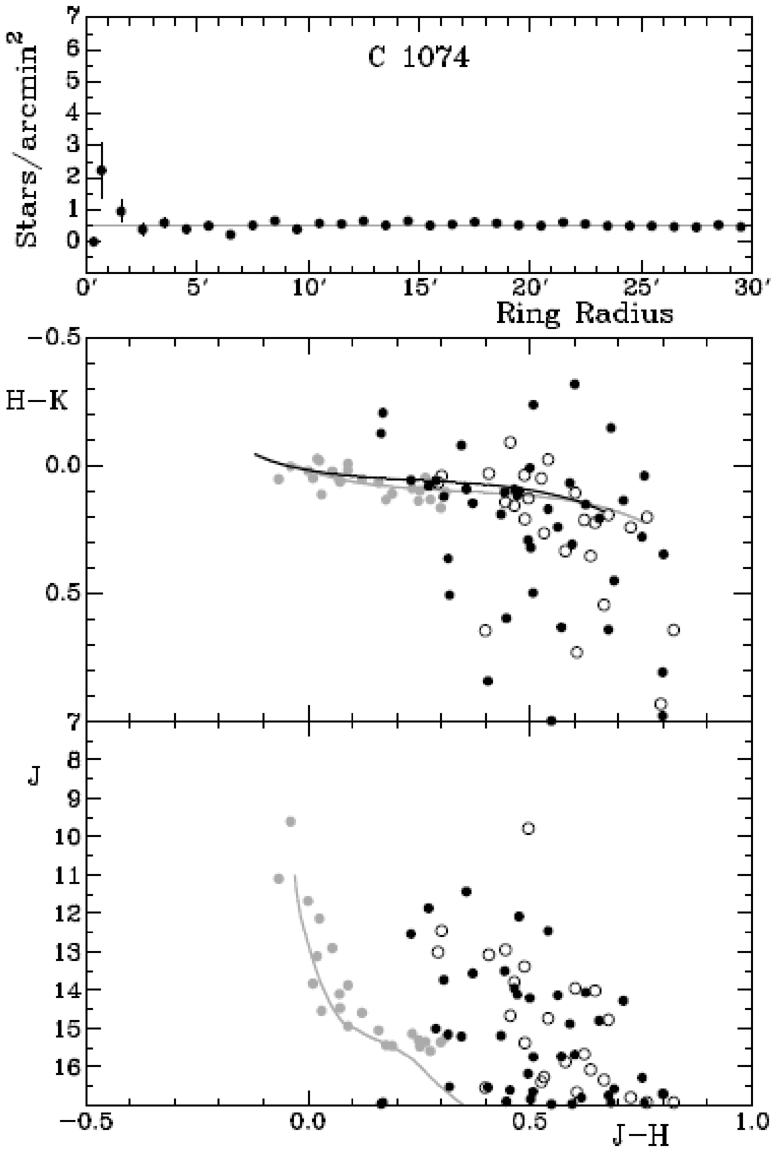
Well known clusters

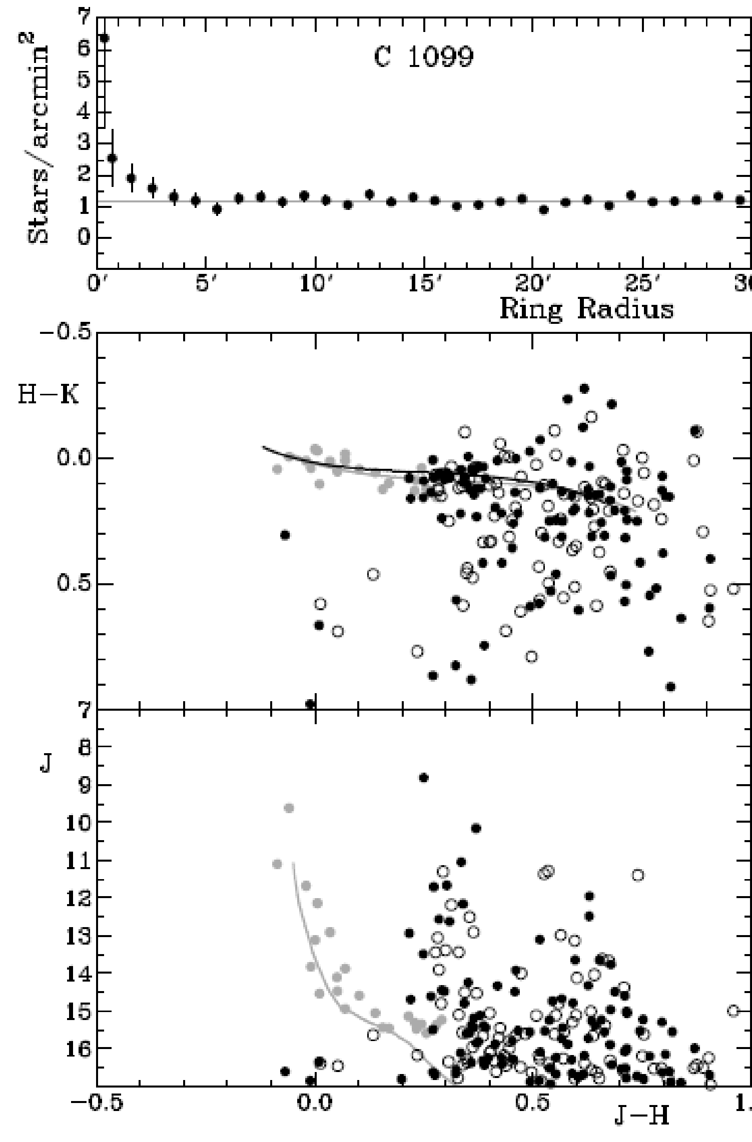
Young embedded clusters in the Galactic Halo?

- Turner et al., 2017, MNRAS, 470, 481 (https://arxiv.org/abs/1705.06748)
- Analysis of the same data sets as Camargo et al. (2016)
- Using well known young cluster Stock 16 as comparison

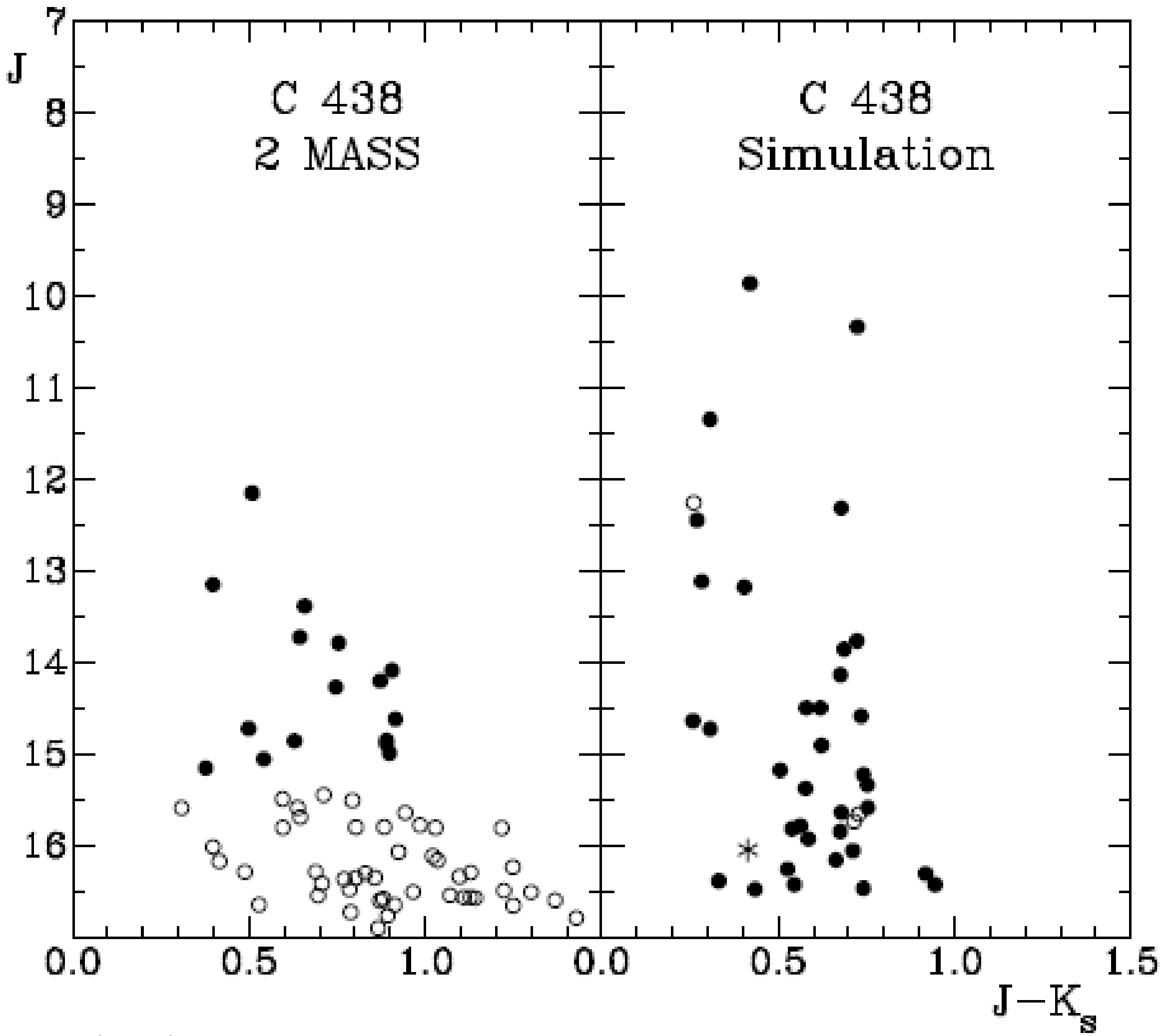
Young embedded clusters in the Galactic Halo?

Turner et al. (2017)





Young embedded clusters in the Galactic Halo?



Comparison

Observation and simulated field using TRILEGAL

Summary:
Three clusters might be true ones

Turner et al. (2017)

IMBH – Globular Clusters

- Intermediate Black Holes as seeds for massive Black Holes
- Important for formation and evolution of Galaxies
- Detection via kinematics of central Globular Clusters stars or X-ray emission from the center due to accretion

IMBH – Globular Clusters

- What is needed?

1. Total mass
2. Mass/Luminosity ratio
3. Distance
4. Model for the kinematics after many Gyrs

- And then look for anisotropy
- Kinematics from HST only
- Gaia will not improve (?) the situation

IMBH – Globular Clusters

- Zocchi et al., 2017, MNRAS, 468, 4429

Reference	M [10^6 M$_\odot$]	M/L [M$_\odot$/L$_\odot$]	d [kpc]	Models
Meylan (1987)	3.9	2.9	[5.2]	multi-mass anisotropic Michie (1963) models
Meylan et al. (1995)	5.1	4.1	[5.2]	multi-mass anisotropic Michie (1963) models
van de Ven et al. (2006)	2.5 ± 0.3	2.5 ± 0.1	4.8 ± 0.3	axisymmetric rotating orbit-based models
van der Marel & Anderson (2010)	2.8	2.62 ± 0.06	4.73 ± 0.0	anisotropic models (Jeans)
Watkins et al. (2013)		2.71 ± 0.05	4.59 ± 0.08	anisotropic models (Jeans)
Bianchini et al. (2013)	1.953 ± 0.16	2.86 ± 0.14	4.11 ± 0.07	rotating models (Varri & Bertin 2012)
Watkins et al. (2015)	$3.452^{+0.145}_{-0.143}$	2.66 ± 0.04	$5.19^{+0.07}_{-0.08}$	isotropic models (Jeans)
de Vita et al. (2016)	3.116	2.87	[5.2]	anisotropic $f_T^{(\nu)}$ models
Baumgardt (2017)	2.95 ± 0.02	2.54 ± 0.26	5.00 ± 0.05	N-body simulations
this work	$3.24^{+0.51}_{-0.47}$	$2.92^{+0.36}_{-0.32}$	5.13 ± 0.25	anisotropic LIMEPY models

Result: no evidence for an IMBH