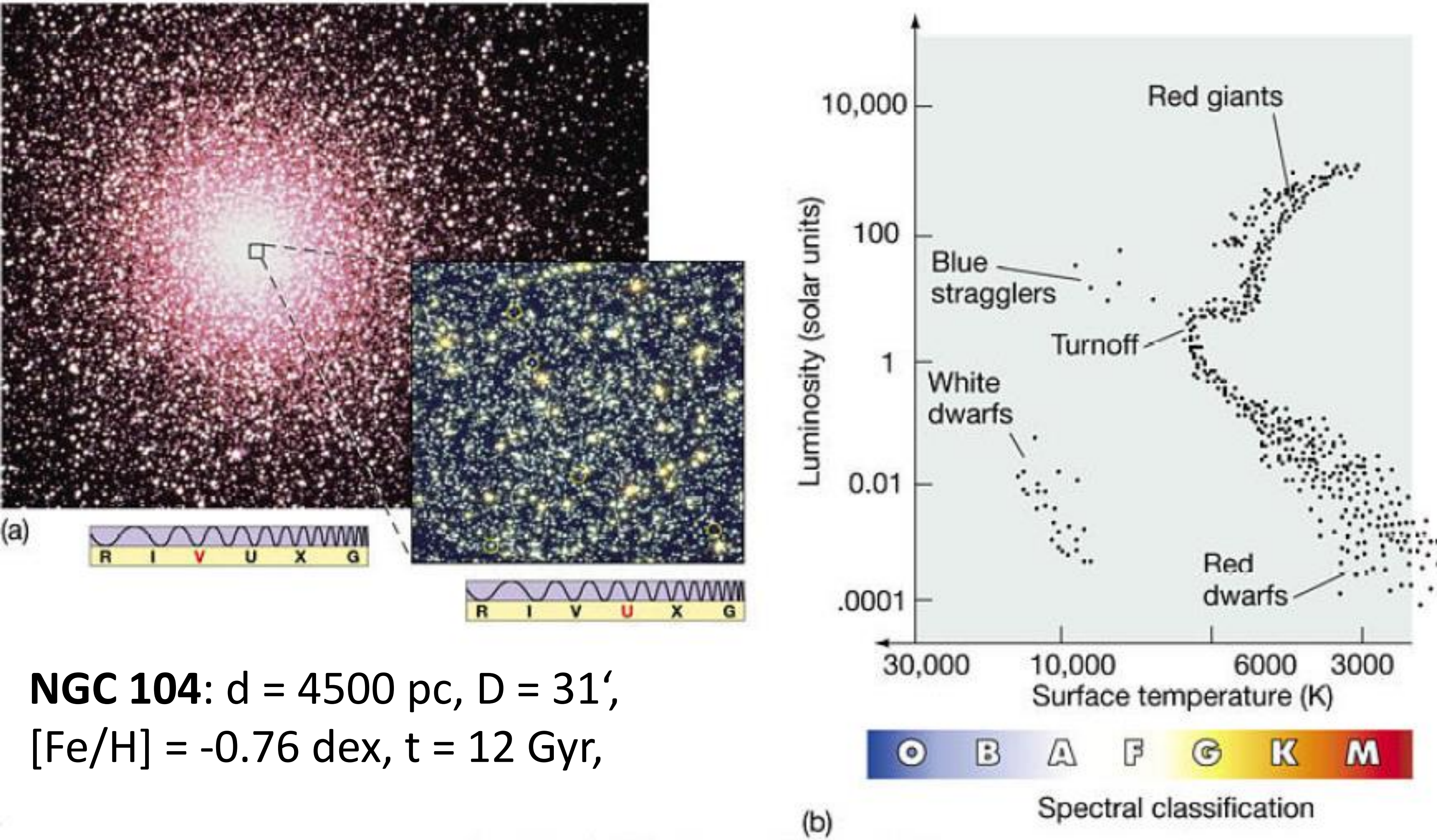
A classic Galactic Globular cluster



NGC 104: d = 4500 pc, D = 31‘,
[Fe/H] = -0.76 dex, t = 12 Gyr,

Introduction

- What we are dealing with?
  - Faint and normally red stars
  - Very crowded fields
  - Especially the cores are very hard to resolve
  - Large telescopes are needed for the core regions
  - Good spatial resolution is needed
- Excellent overview article about GCLs:
  https://ui.adsabs.harvard.edu/abs/2020arXiv200304093B/abstract
- A Galactic Globular Clusters Database

  http://gclusters.altervista.org/

How many GCLs are there?

- Harris GCL catalog (1996, AJ, 112, 1487) provides **157 objects**: http://physwww.mcmaster.ca/~harris/mwgc.dat
- But still new ones are discovered:

THE ASTROPHYSICAL JOURNAL LETTERS, 860:L27 (5pp), 2018 June 20 https://doi.org/10.3847/2041-8213/aacc68

CrossMark

Five New Globular Clusters Discovered in the Galactic Bulge

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THE ASTROPHYSICAL JOURNAL LETTERS, 863:L38 (5pp), 2018 August 20 https://doi.org/10.3847/2041-8213/aad8b7

CrossMark

Discovery of Two New Globular Clusters in the Milky Way

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Received 2018 August 1; revised 2018 August 7; accepted 2018 August 7; published 2018 August 21

New GCLs

Camargo, 2018, ApJL, 860, L27

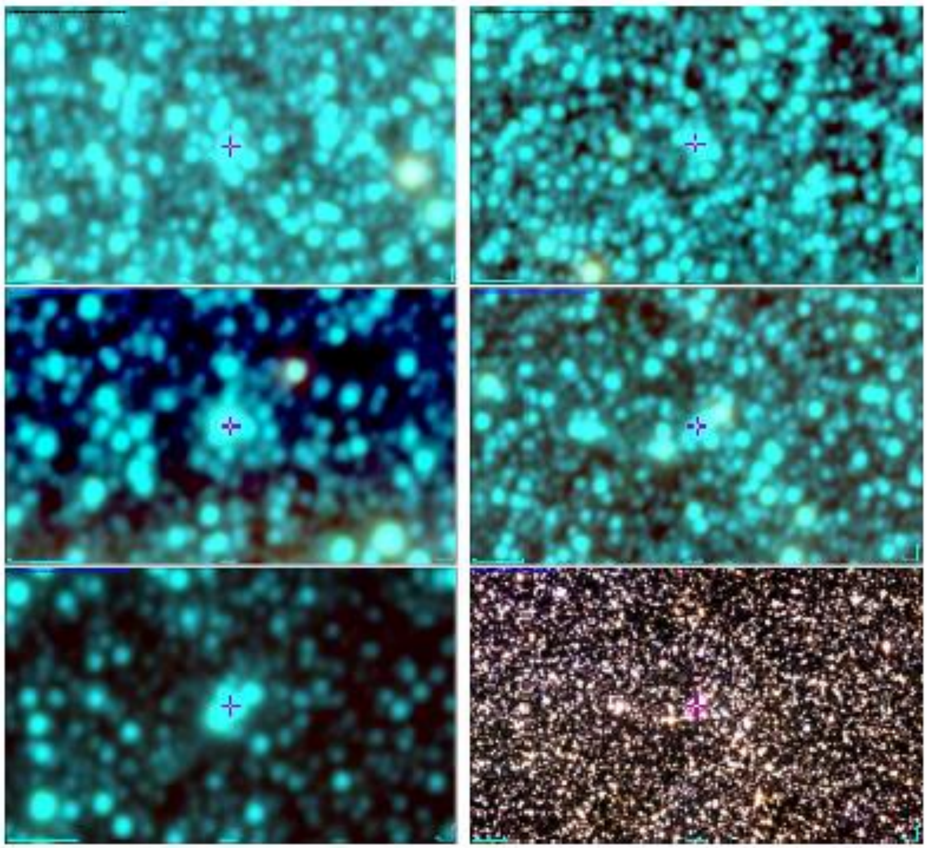
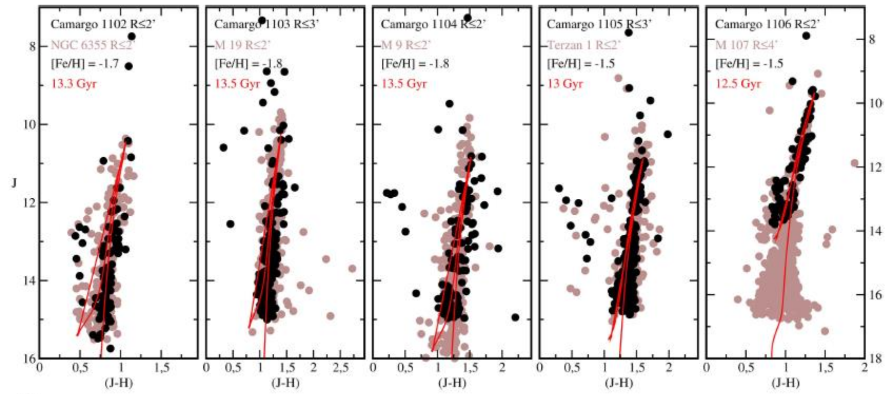


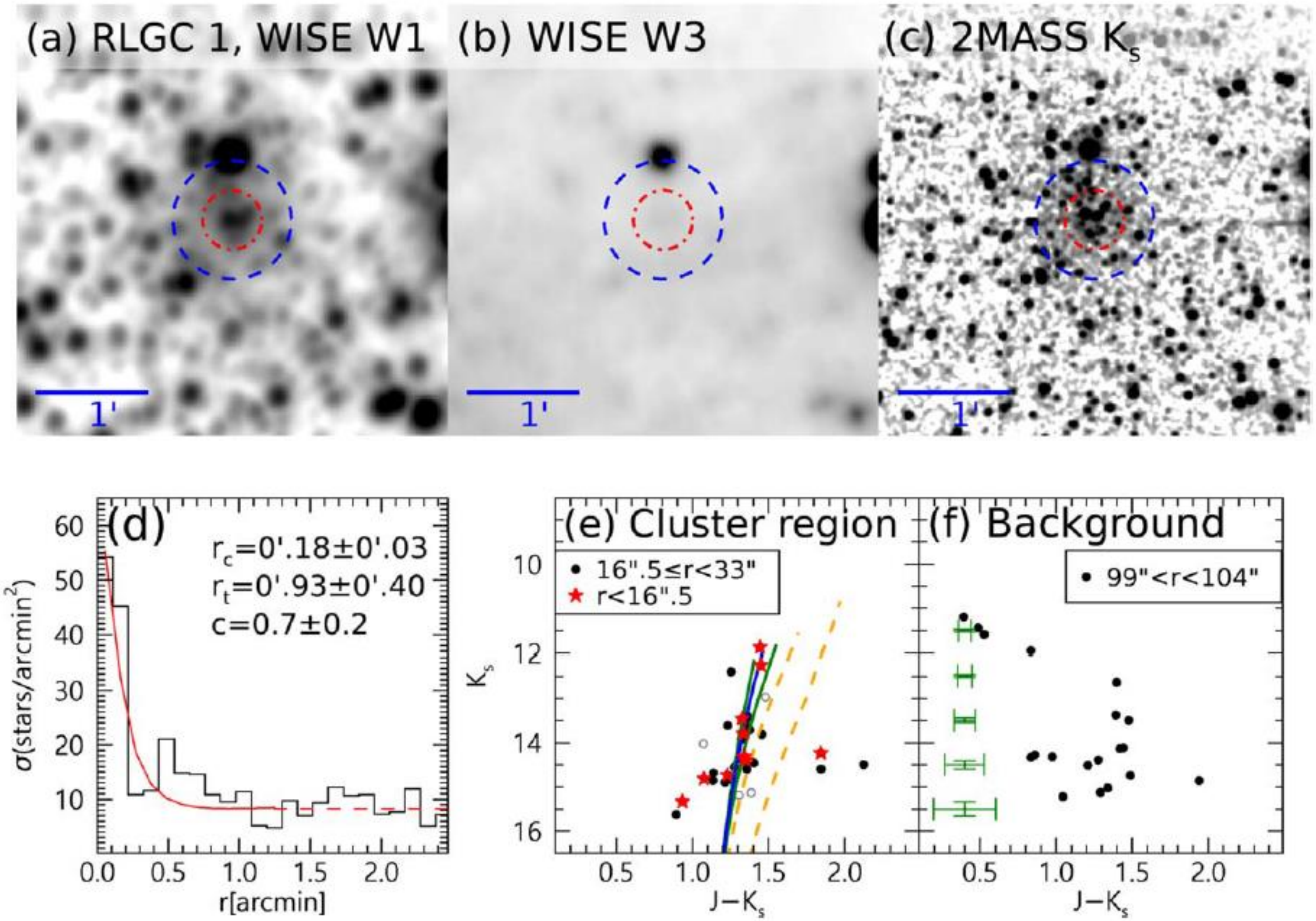
Figure 1. *WISE* multicolor images (7′ × 4′) centered on the coordinates of the new GCs. Top panels: Camargo 1106 (right) and Camargo 1105 (left). Middle panels: Camargo 1104 (right) and Camargo 1103 (left). Bottom panels: *WISE* (right) and 2MASS (left) images of Camargo 1102.



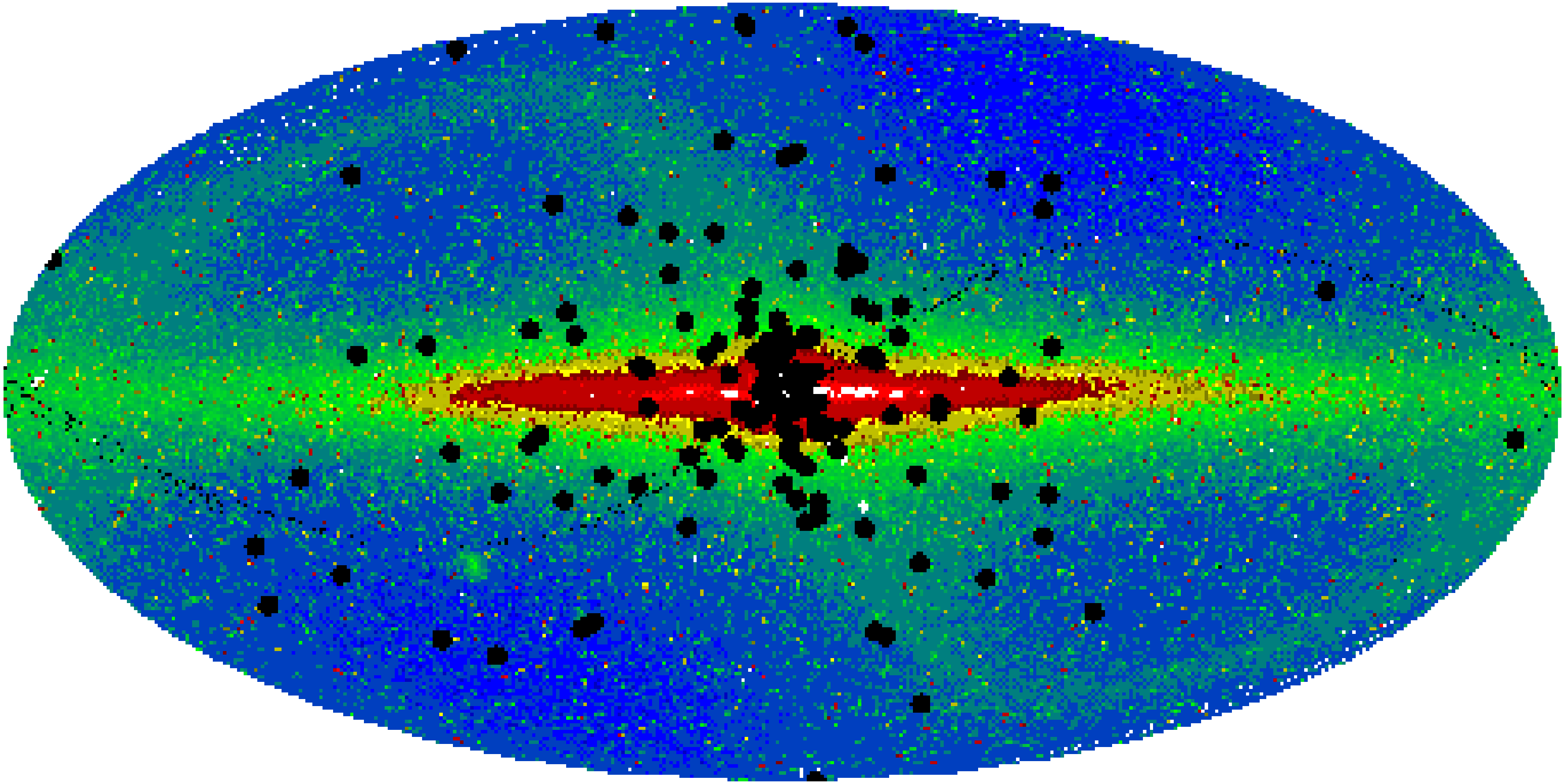
Very difficult to detect

New GCLs

Ryu & Lee, 2018, ApJL, 863, L38

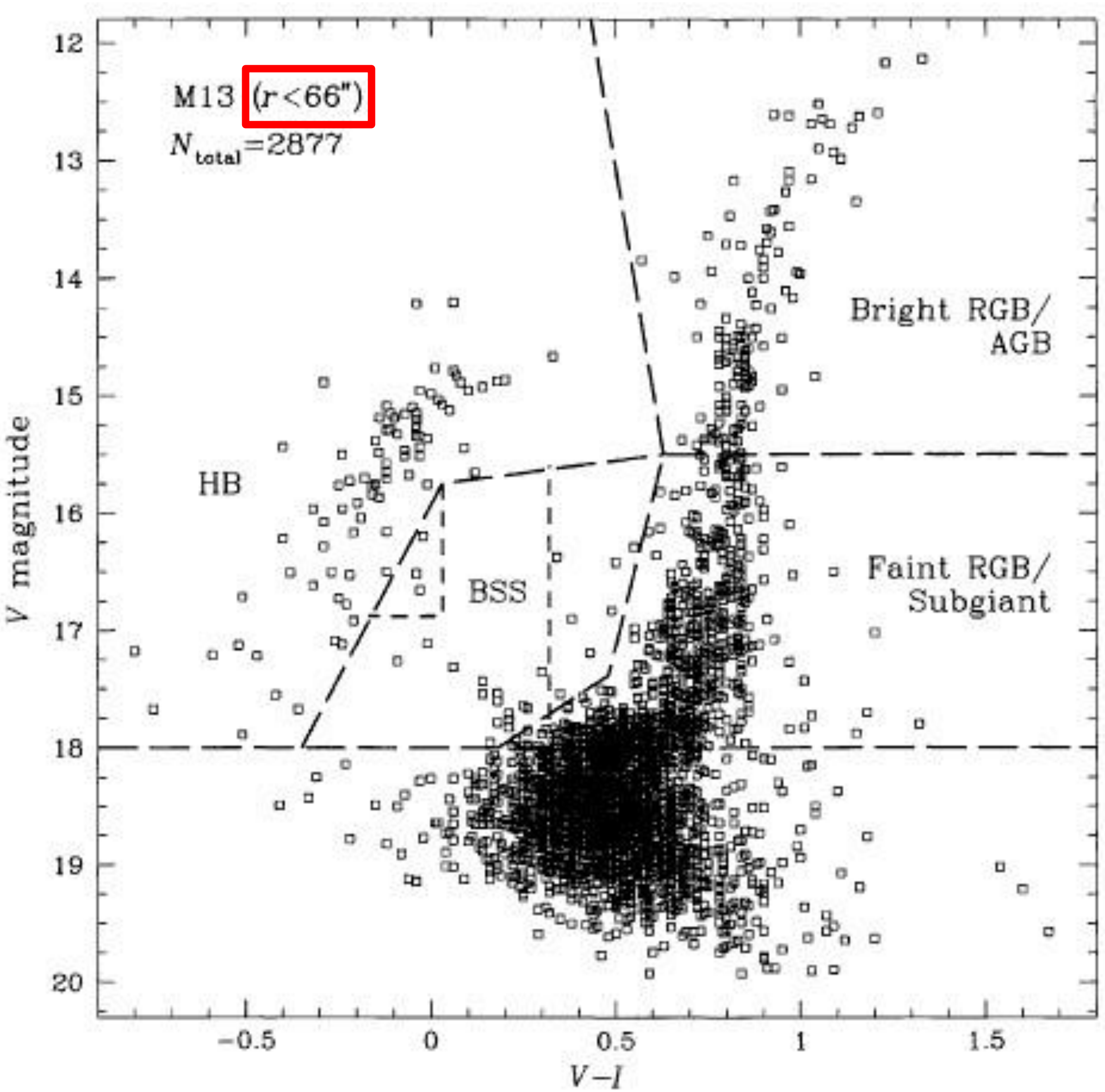


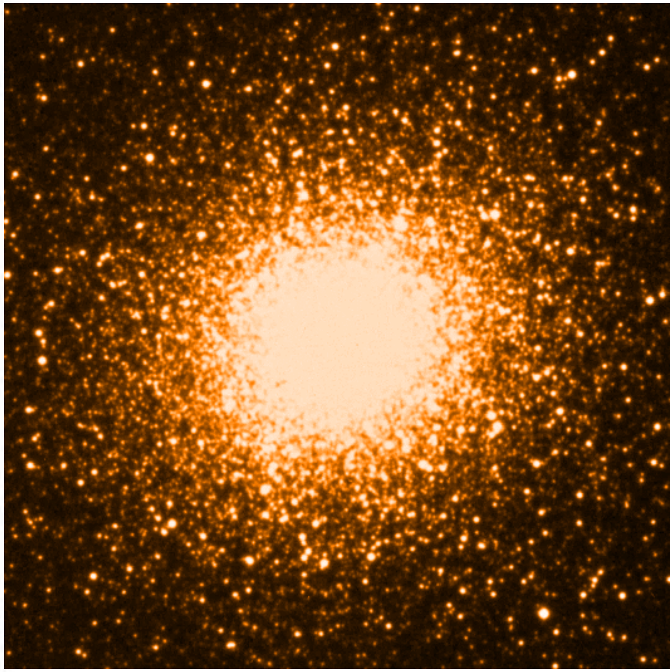
Only a few stars resolved



Remember: more GCLs in the Galactic Bulge

Faintness - Crowding





15’

Definition - Radii

- **Core Radius**: Distance at which the apparent surface luminosity has dropped by half
- **Half-Light Radius**: Distance from the core within which half the total luminosity from the cluster is received
- **Half-Mass Radius**: The radius from the core that contains half the total mass
- **Tidal Radius**: Distance from the center at which the external gravitation of the galaxy has more influence over the stars in the cluster than does the cluster itself

Density – Profile (King Profile)

- Heuristic description of the density law of star clusters (open and globular) by Ivan King (1962, AJ, 67, 471):

$$f = f_1[(1/r - 1/r_t)^2]$$

f … Stars per square unit or surface density; f_1 … Constant; r_t … Radius f(r) = 0

- General formula:

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

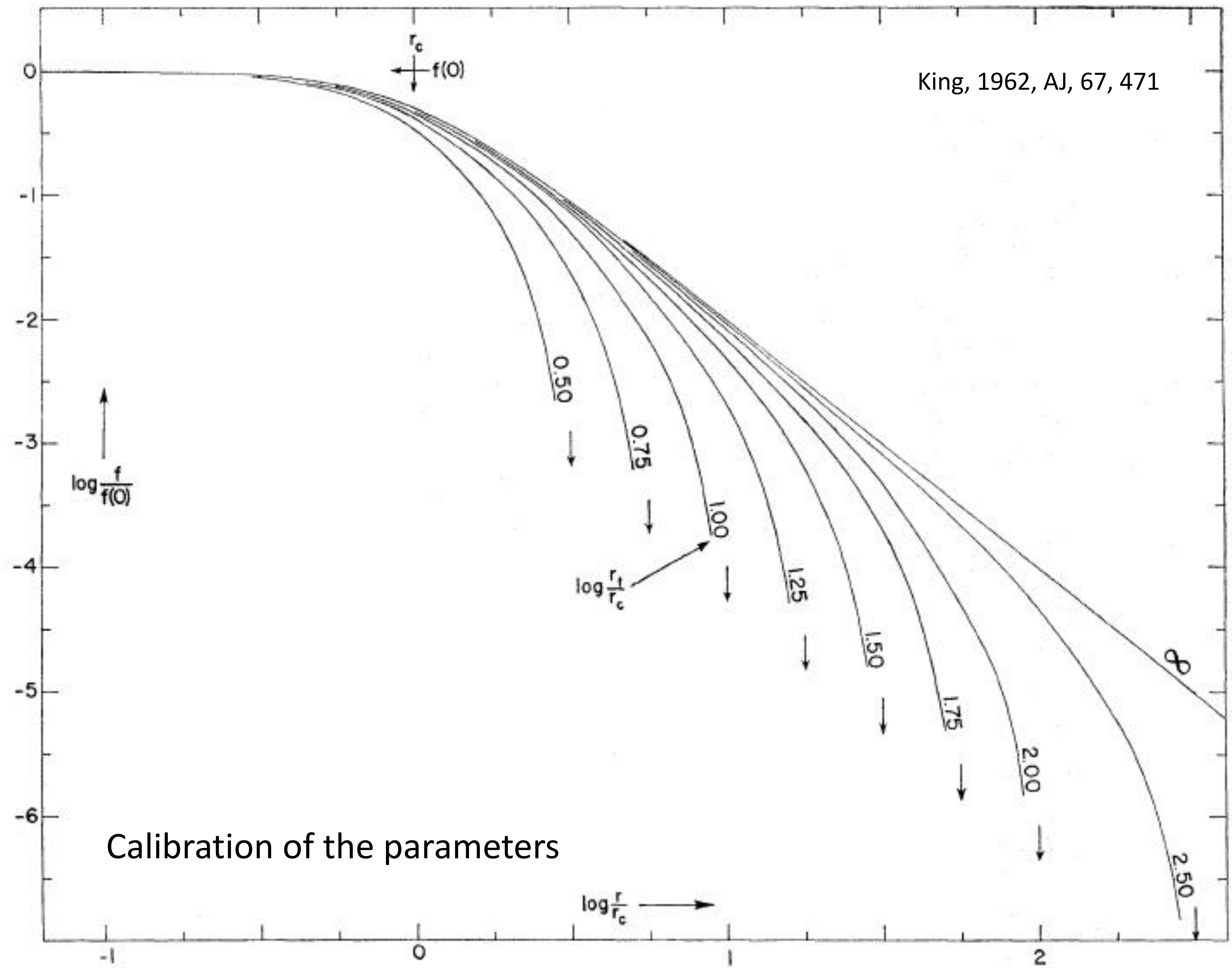
k … Constant; r_c … core radius

Density – Profile (King Profile)

- Typical Globular Cluster:
  1. $r_t/r_c \sim 30$
  2. Unit for k is V = 10 mag per square arc minute
- The parameters r_t and r_c can be treated within numerical simulations and can be converted into an „astrophysical quantity“, for example:

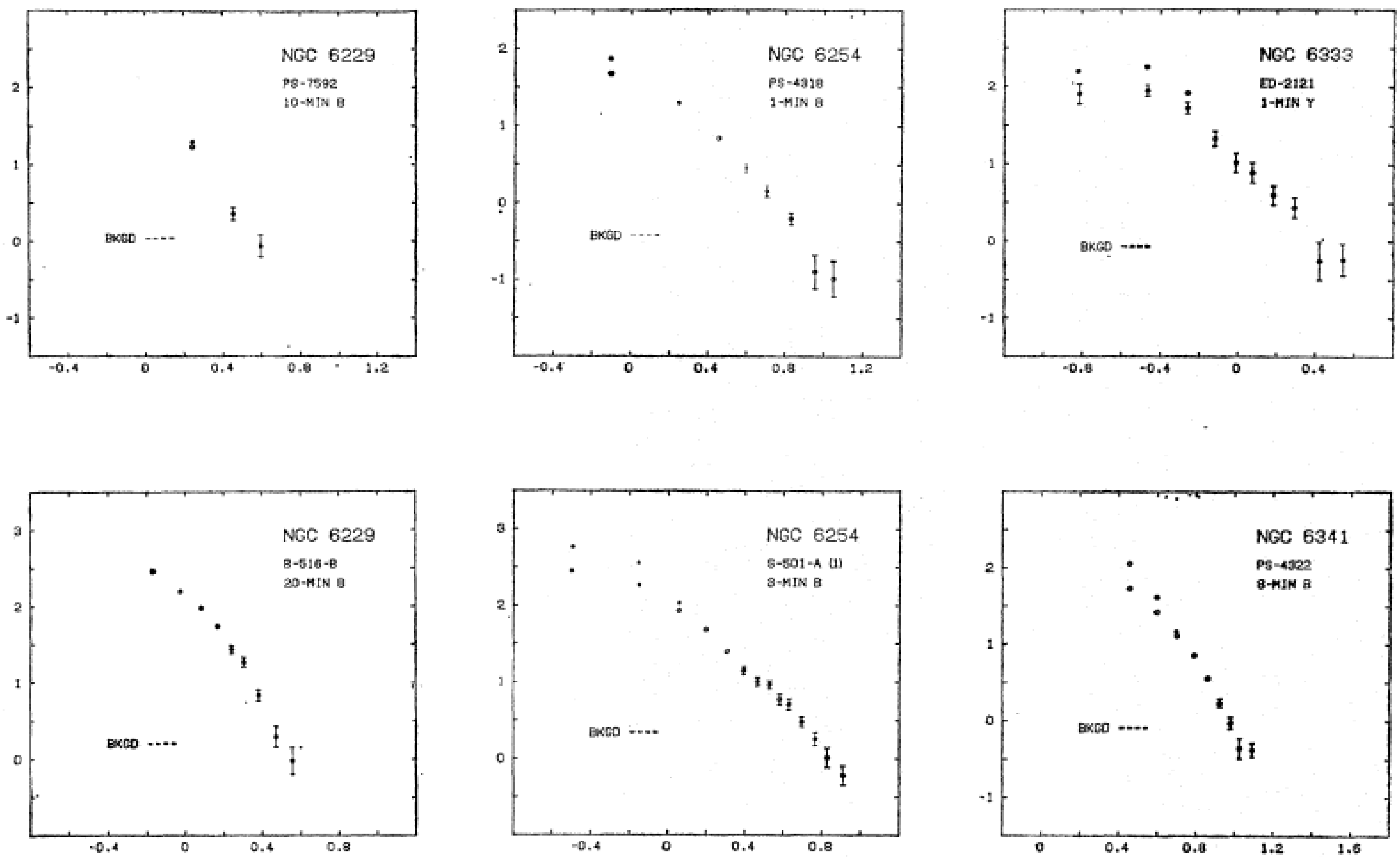
$$r_t = R(M/2M_g)^{\frac{1}{3}}$$

R … Distance from the Galactic center; M … Mass of the Globular Cluster; M_g … Mass of the Milky Way



Calibration of the parameters

King et al., 1968, AJ, 73, 456



King profiles – Gaia DR2

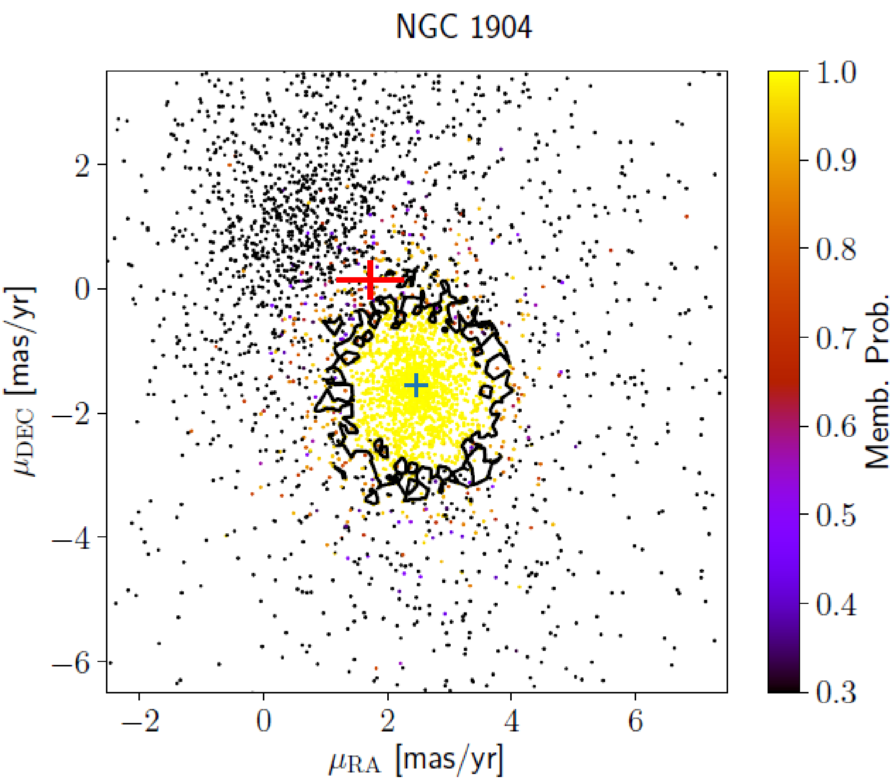
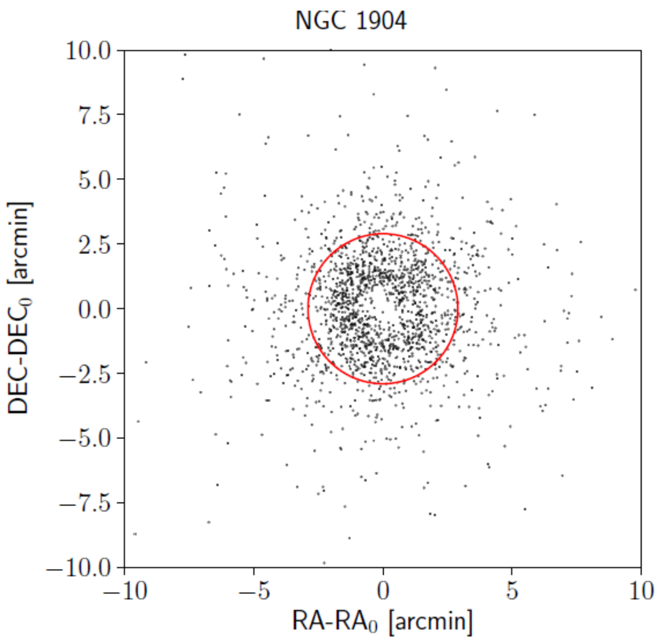


Figure 1. The proper motion distribution of stars in our NGC1904 sample, coloured with the computed membership probability. The sample shown has already been cleaned using CMD isochrone cuts and parallax selections. The blue marker indicates the peak of the GC PM distribution, while the red marker indicates the peak of the background distribution. A contour is drawn for membership probability of 0.9 for reference.

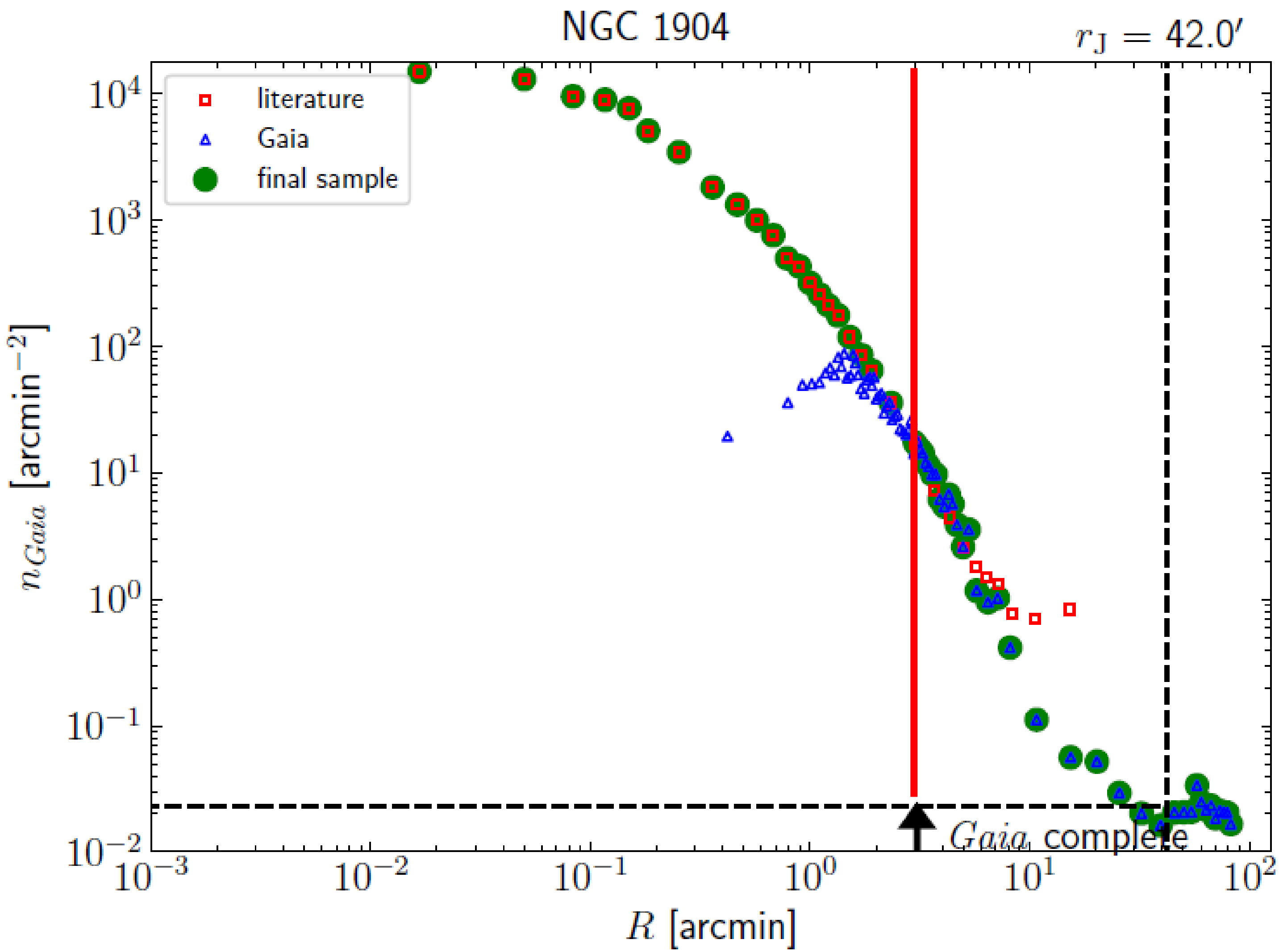


Core not resolved, but still very good coverage

82 GLCs analyzed

de Boer et al., 2019, MNRAS, 485, 4906

King profiles – Gaia DR2



Gaia will never give any results for the cores

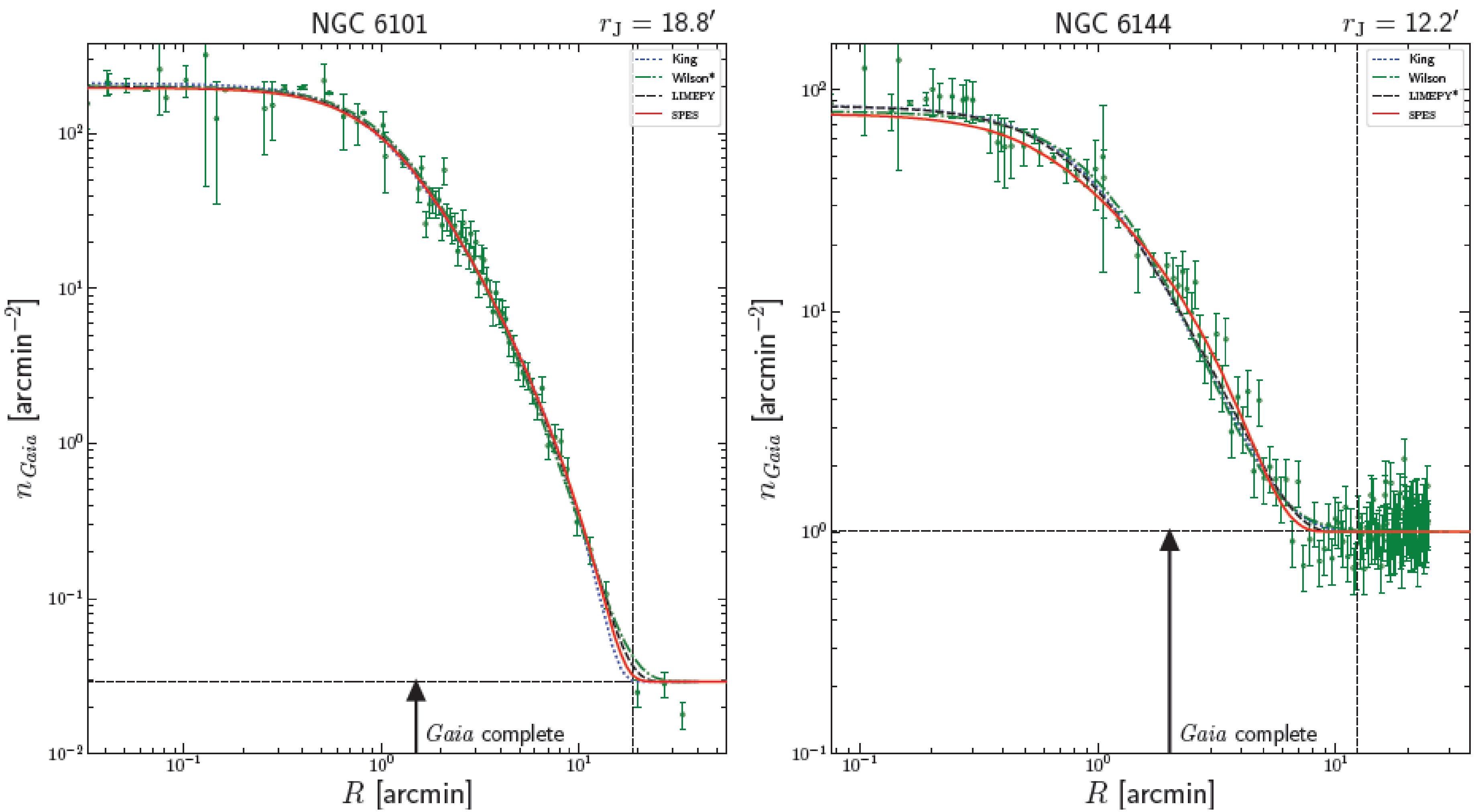
=>

Additional observations needed

de Boer et al., 2019, MNRAS, 485, 4906

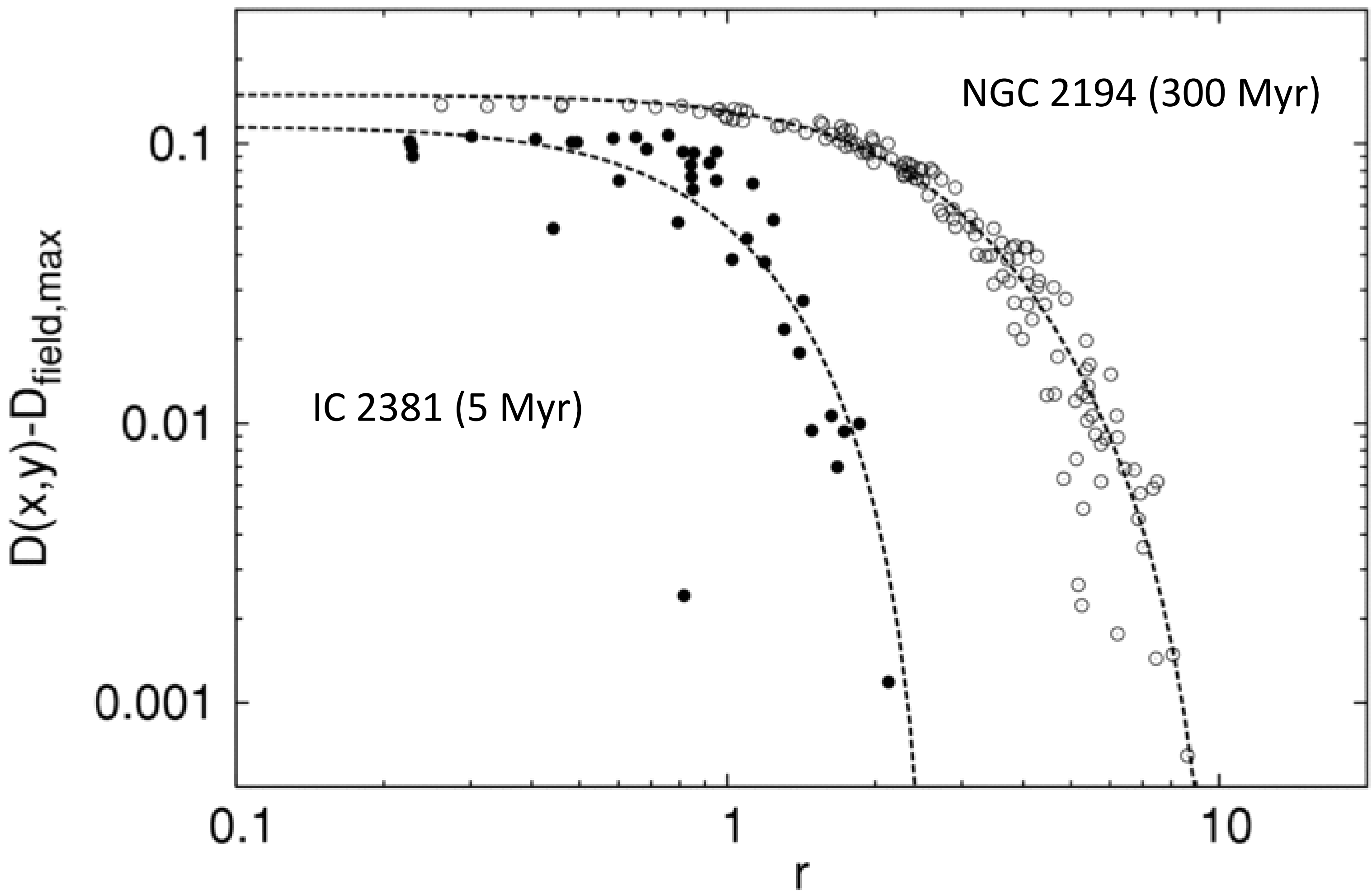
King profiles – Gaia DR2

de Boer et al., 2019, MNRAS, 485, 4906



Examples of different shapes

Sánchez & Alfaro, 2005, ApJ, 696, 2086

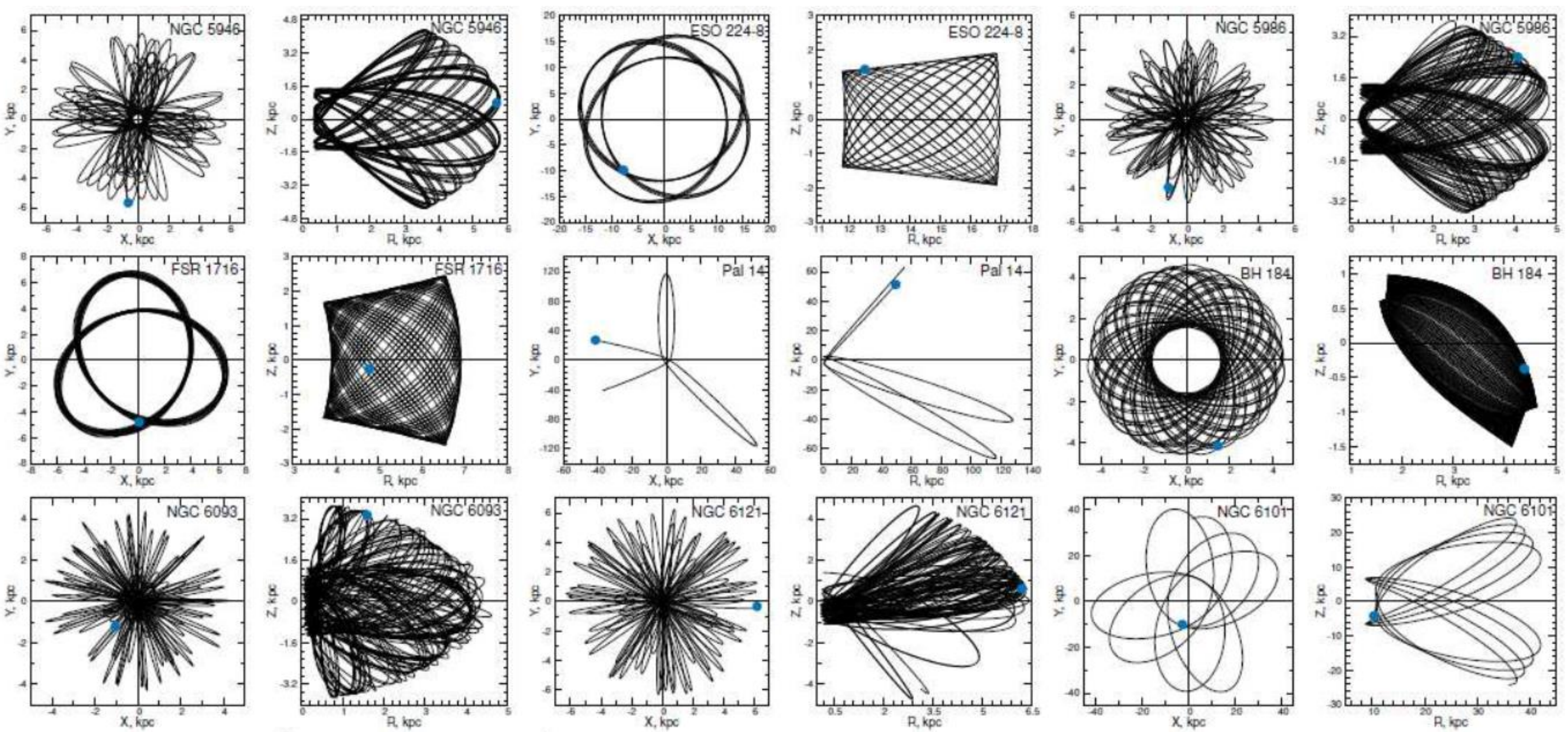


Also works for open clusters

Motions of star clusters

- Position in Galactic coordinates
- Position in the Milky Way [XYZ], distance from the Sun needed
- Radial velocity
- Proper Motion
- Model for the gravitional potential of the Milky Way
- Includes: spherical bulge, disk, and spherical dark-matter halo
- Bajkova et al., 2020, ApJ, 895, 69

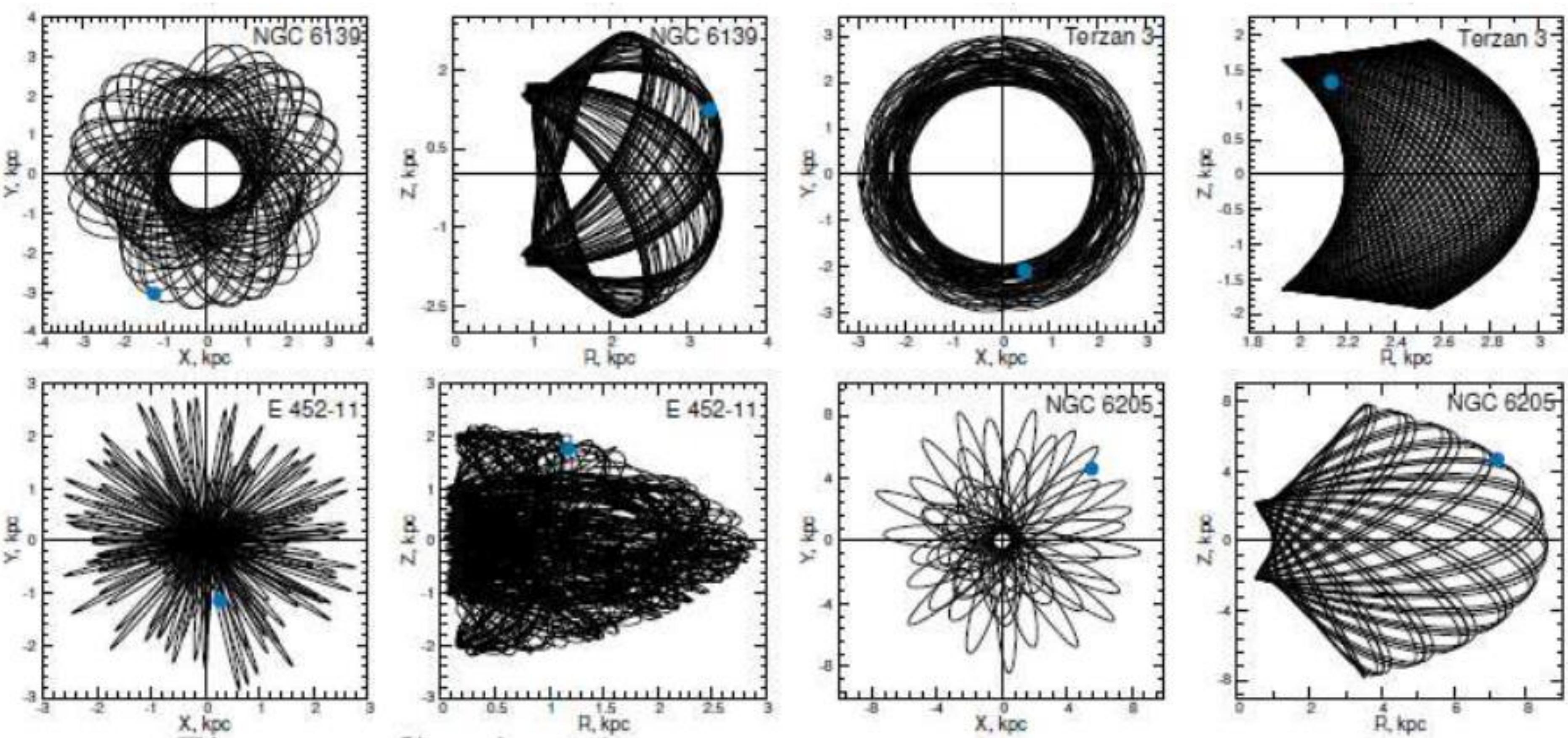
Motion of Globular clusters



Sun at [XYZ] = [8, 0, 0]

Bajkova & Bobylev, 2020, arXiv:2008.13624

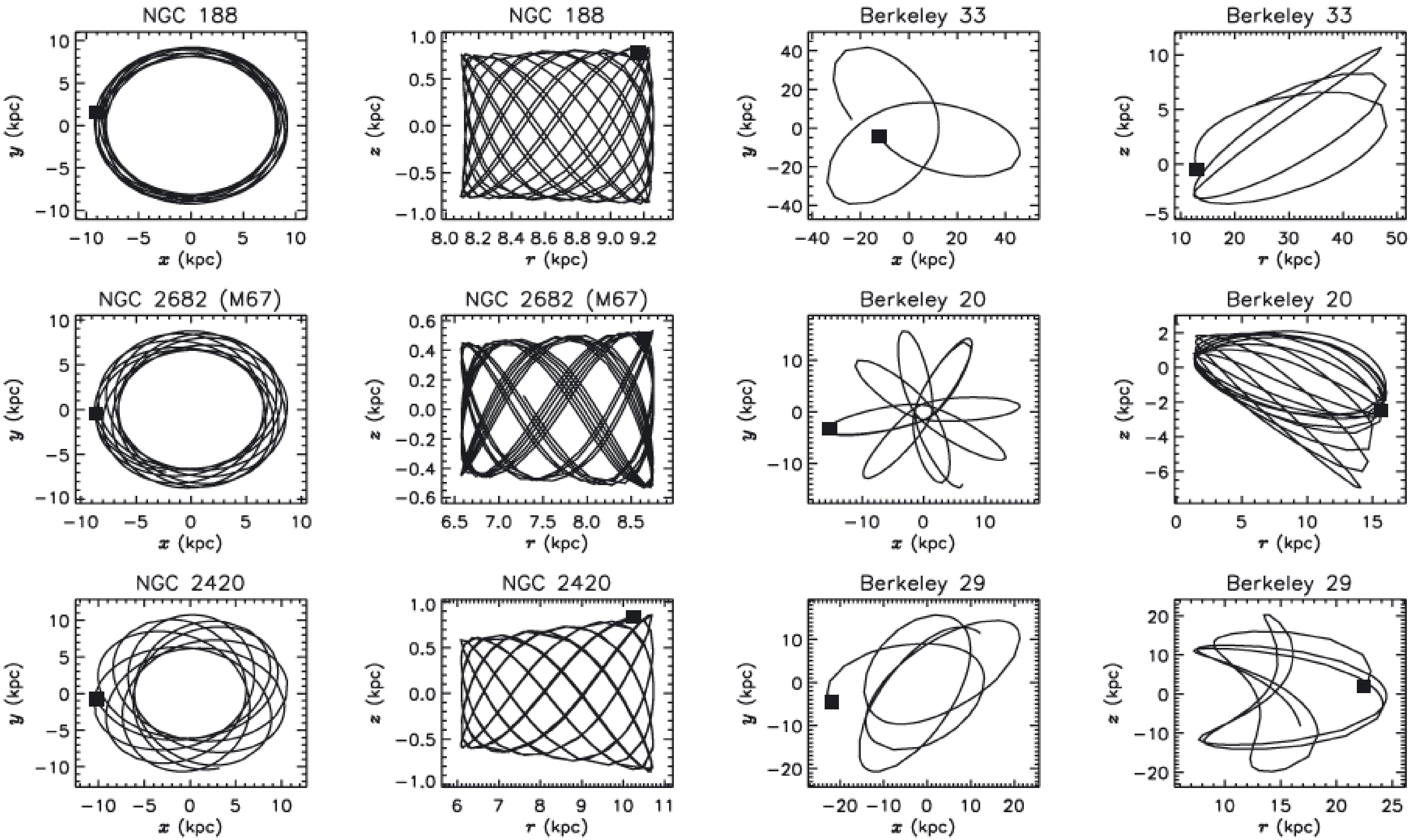
Motion of Globular clusters



Sun at [XYZ] = [8, 0, 0]

Bajkova & Bobylev, 2020, arXiv:2008.13624

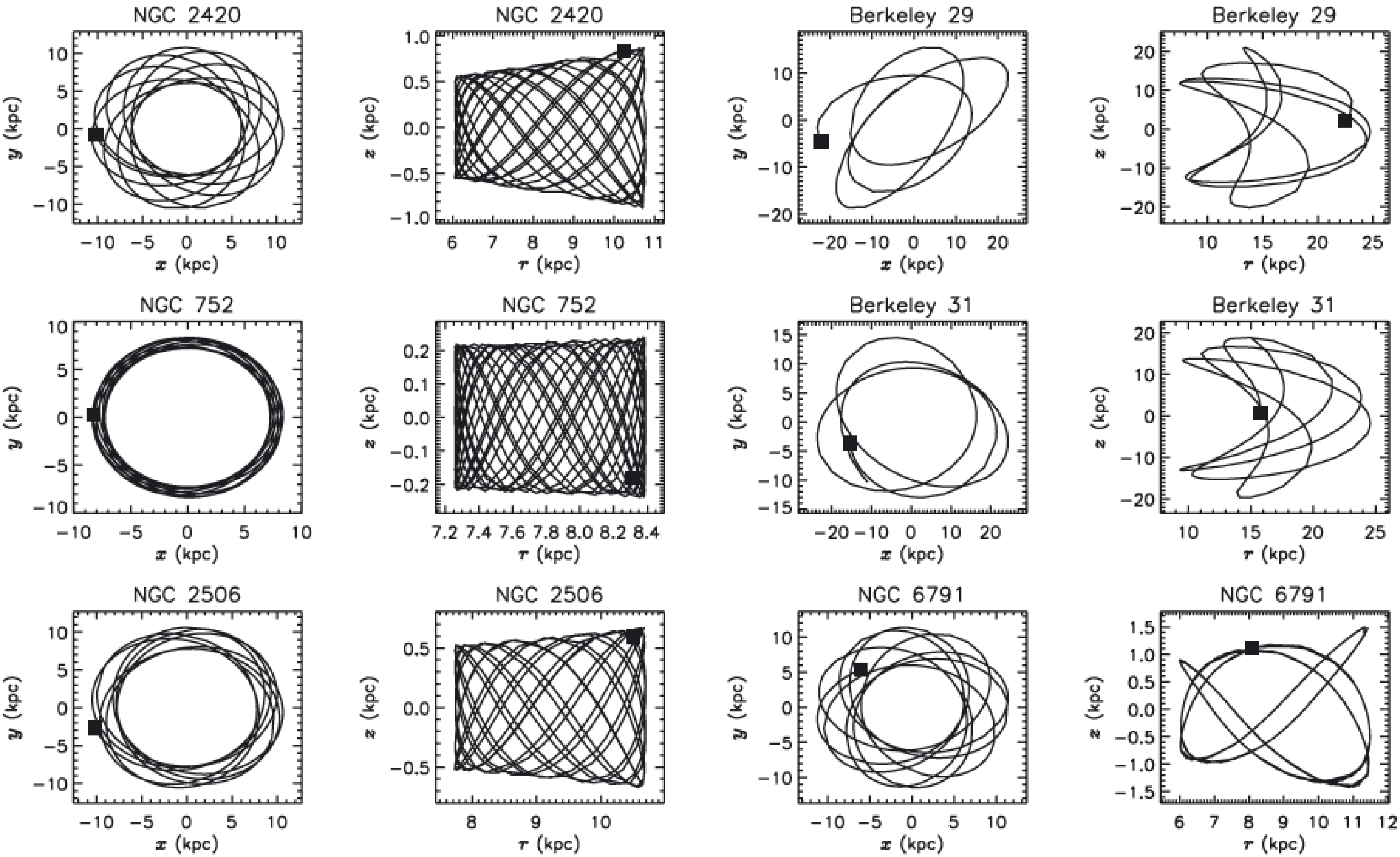
Motion of Open clusters



Sun at [XYZ] = [0, 0, 0] and r = 8 kpc

Wu et al., 2009, MNRAS, 399, 2146

Motion of Open clusters



Sun at [XYZ] = [0, 0, 0] and r = 8 kpc

Wu et al., 2009, MNRAS, 399, 2146

Ellipticity

Goodwin, 1997, MNRAS, 286, L39

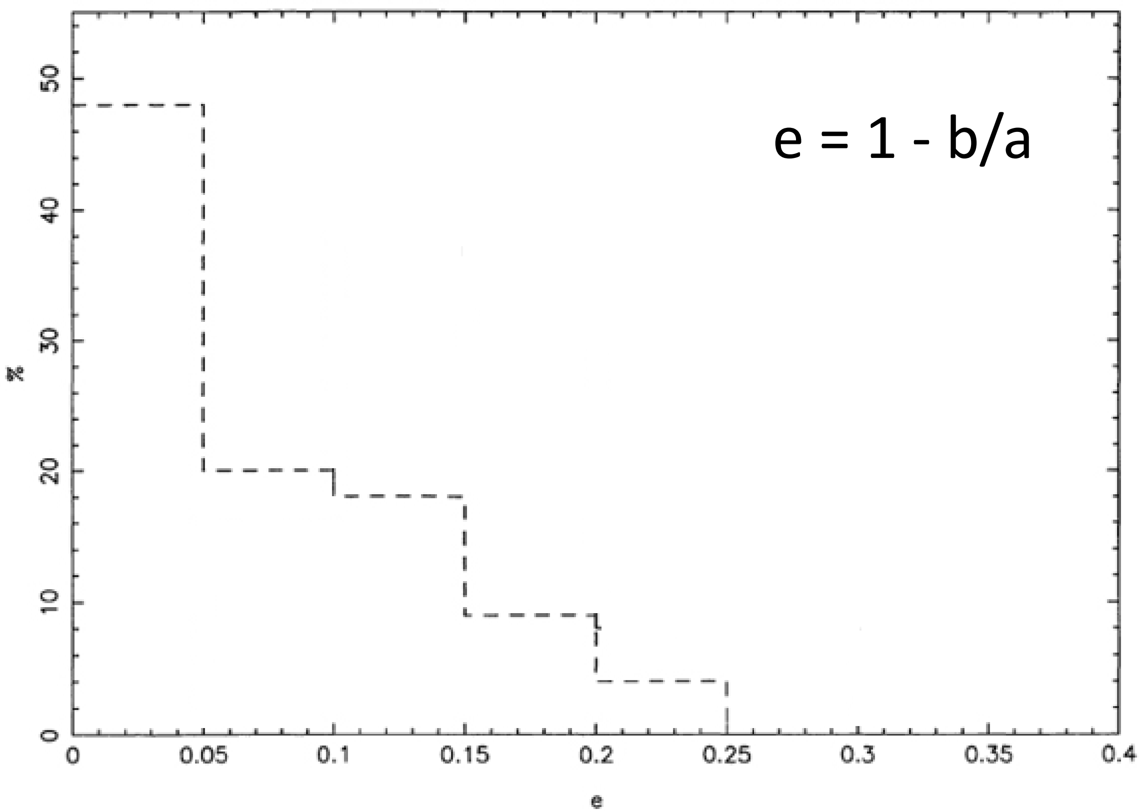
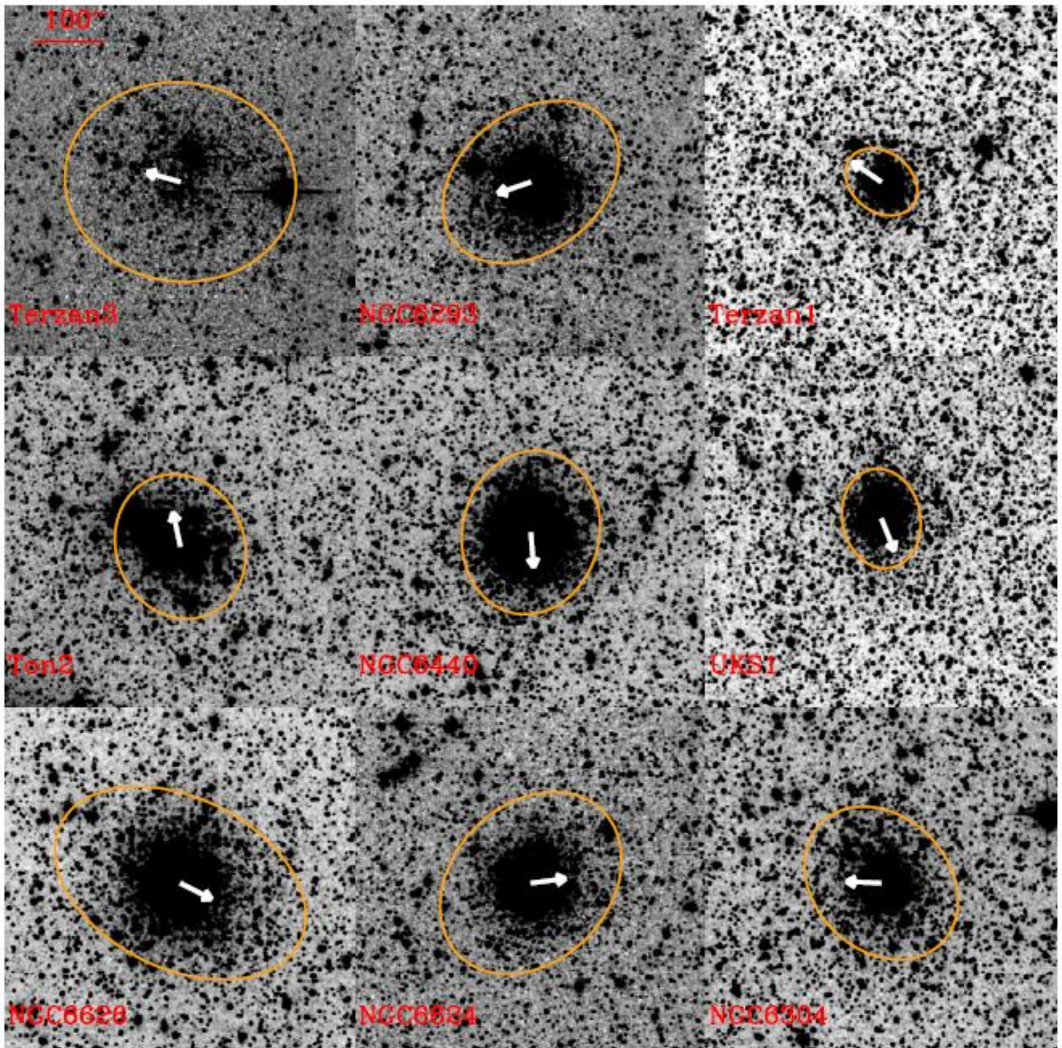


Figure 1. The ellipticity distributions of globular clusters in the Galaxy (dashed line) from data in White & Shawl (1987) and Kontizas et al. (1989).

a, b are the semimajor and semiminor axes of the ellipse

Ellipticity

Chen & Chen, 2010, ApJ, 721, 1790



Globulars in the Galactic Bulge are misaligned due to the gravity of the Galactic center (direction of the white arrows)

Ellipticity

Chen & Chen, 2010, ApJ, 721, 1790

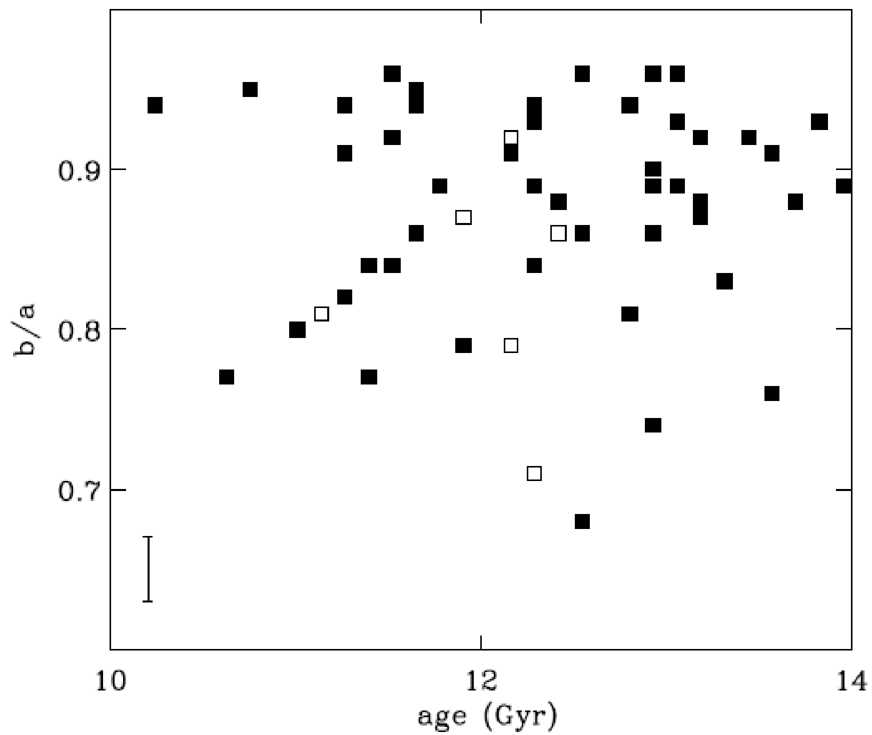


Figure 12. Axial ratios vs. ages. Filled symbols represent reliable cases. The median value of the errors of axial ratios is shown in the lower left corner.

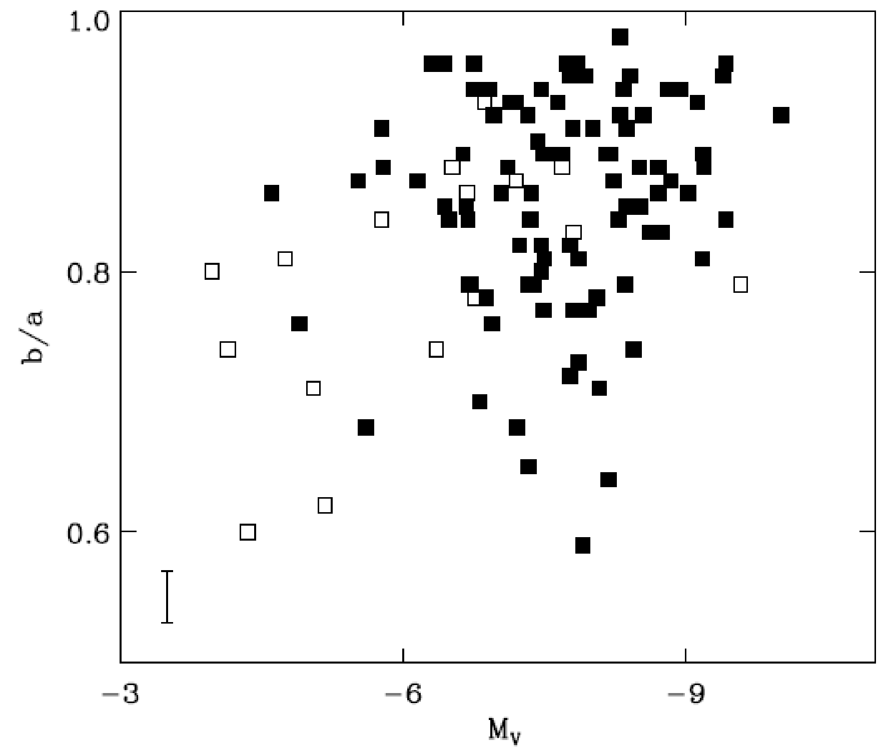
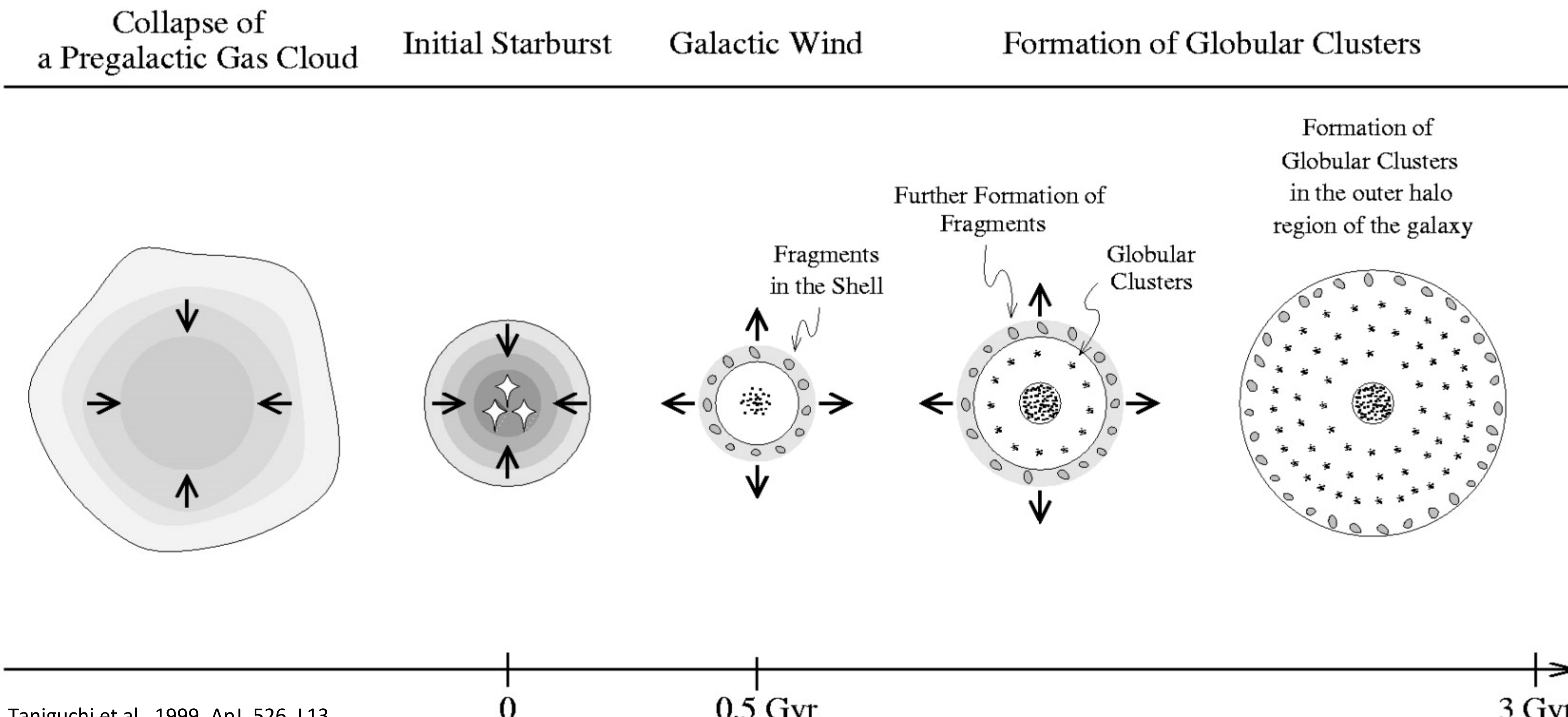


Figure 13. Axial ratio of a GC vs. its absolute magnitude. Filled symbols represent reliable cases. The median value of the errors of axial ratios is shown in the lower left corner.

No obvious correlation of the ellipticity with the age or absolute magnitude

Formation of Globular Clusters

- Globular Clusters also formed from one GMC
- But how are GCLs formed in Galaxies?



Taniguchi et al., 1999, ApJ, 526, L13

Formation of Globular Clusters

A&A 630, L4 (2019)
https://doi.org/10.1051/0004-6361/201936135

Astronomy & Astrophysics

Letter to the Editor

Origin of the system of globular clusters in the Milky Way

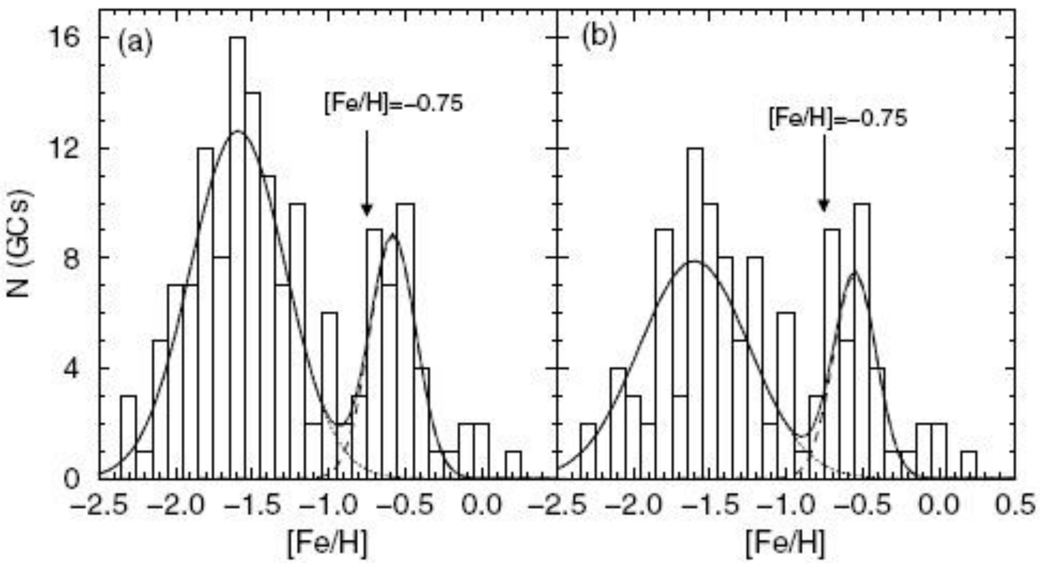
D. Massari[1,2,3], H. H. Koppelman[1], and A. Helmi[1]

Methods. To this end, we combined the kinematic information provided by *Gaia* for almost all Galactic clusters, with the largest sample of cluster ages available after carefully correcting for systematic errors. To identify clusters with a common origin we analysed their dynamical properties, particularly in the space of integrals of motion.
Results. We find that about 40% of the clusters likely formed in situ. A similarly large fraction, 35%, appear to be possibly associated to known merger events, in particular to *Gaia*-Enceladus (19%), the Sagittarius dwarf galaxy (5%), the progenitor of the Helmi streams (6%), and to the Sequoia galaxy (5%), although some uncertainty remains due to the degree of overlap in their dynamical characteristics. Of the remaining clusters, 16% are tentatively associated to a group with high binding energy, while the rest are all on loosely bound orbits and likely have a more heterogeneous origin. The resulting age–metallicity relations are remarkably tight and differ in their detailed properties depending on the progenitor, providing further confidence on the associations made.

Possible interpretation: the results are inconclusive

Two „external Populations“

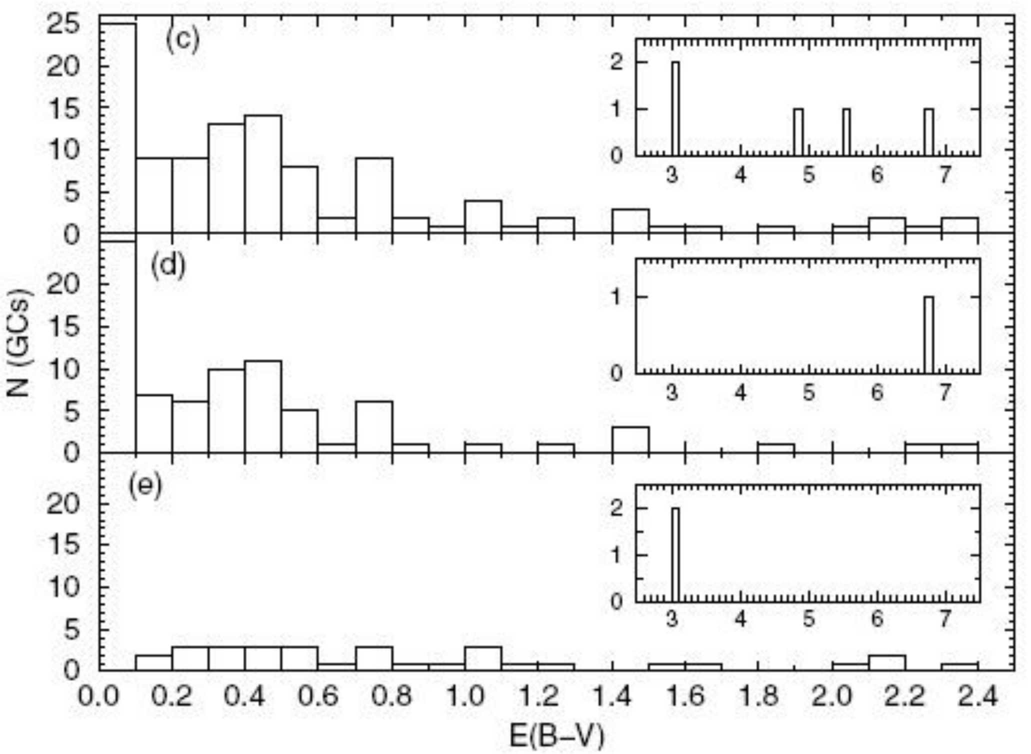
- Halo Population:
  - Spherical around the center of the Milky Way
  - Very extended (Halo)
  - $-2.5 < [Fe/H] < -1$ dex
  - $10 < \text{Age} < 15$ Gyr
- Disk Population (Bulge):
  - More concentrated around the center of the Milky Way
  - $-0.7 < [Fe/H] <$ +0.5 dex
  - Age about 10 Gyr
- Continuous transition!



Bica et al., 2006, A&A, 450, 105

153 Globulars

Two Populations



Reddening

Although the large distance, no reddening, Halo

New Globulars with large reddening and large distance detected

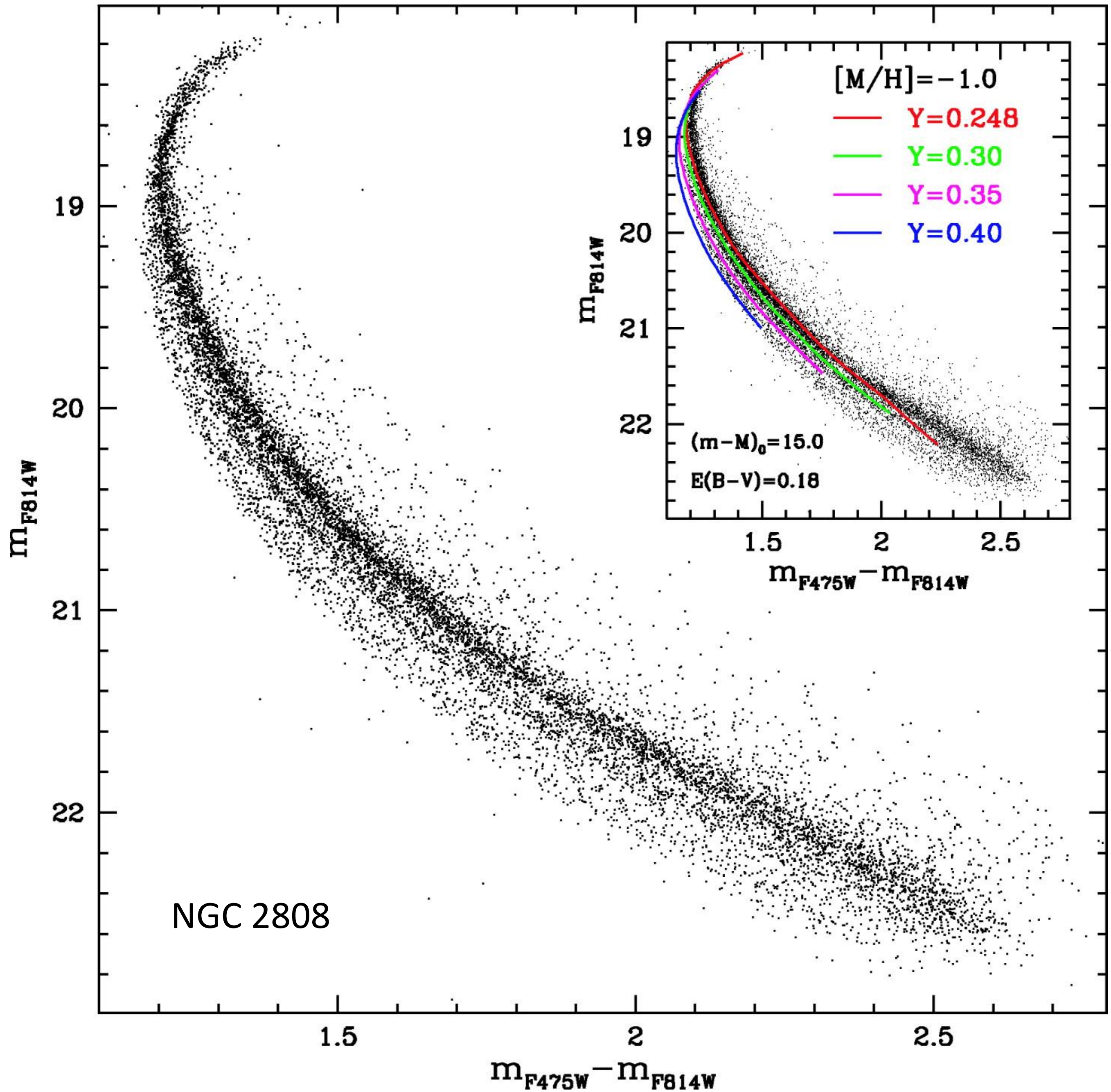
Multiple „ internal Populations“

- Multiple Main, AGB and HB Sequences within one Globular were found
- Not for all Globulars although same observational quality
- No clear morphology detected yet
- Also indications for the oldest OCLs

Multiple „ internal Populations“

- The ACS Globular Cluster Survey: https://archive.stsci.edu/prepds/acsggct/
- The Gaia-ESO survey

  https://www.gaia-eso.eu/
- Project SUMO: http://www.iac.es/proyecto/sumo/index.html

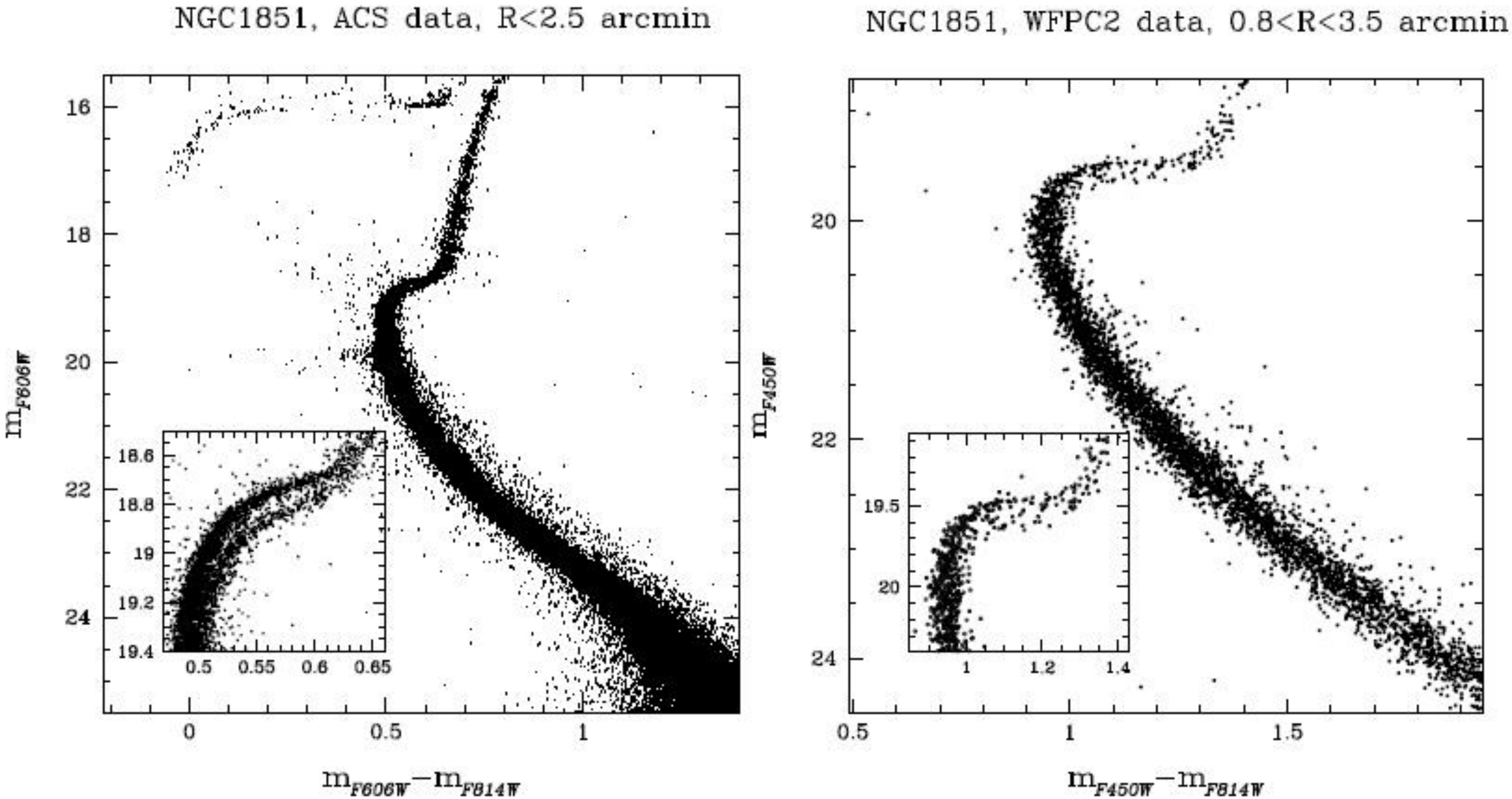


Piotto et al., 2007, ApJ, 661, L53

Different He content (Y) can explain the multiple MS

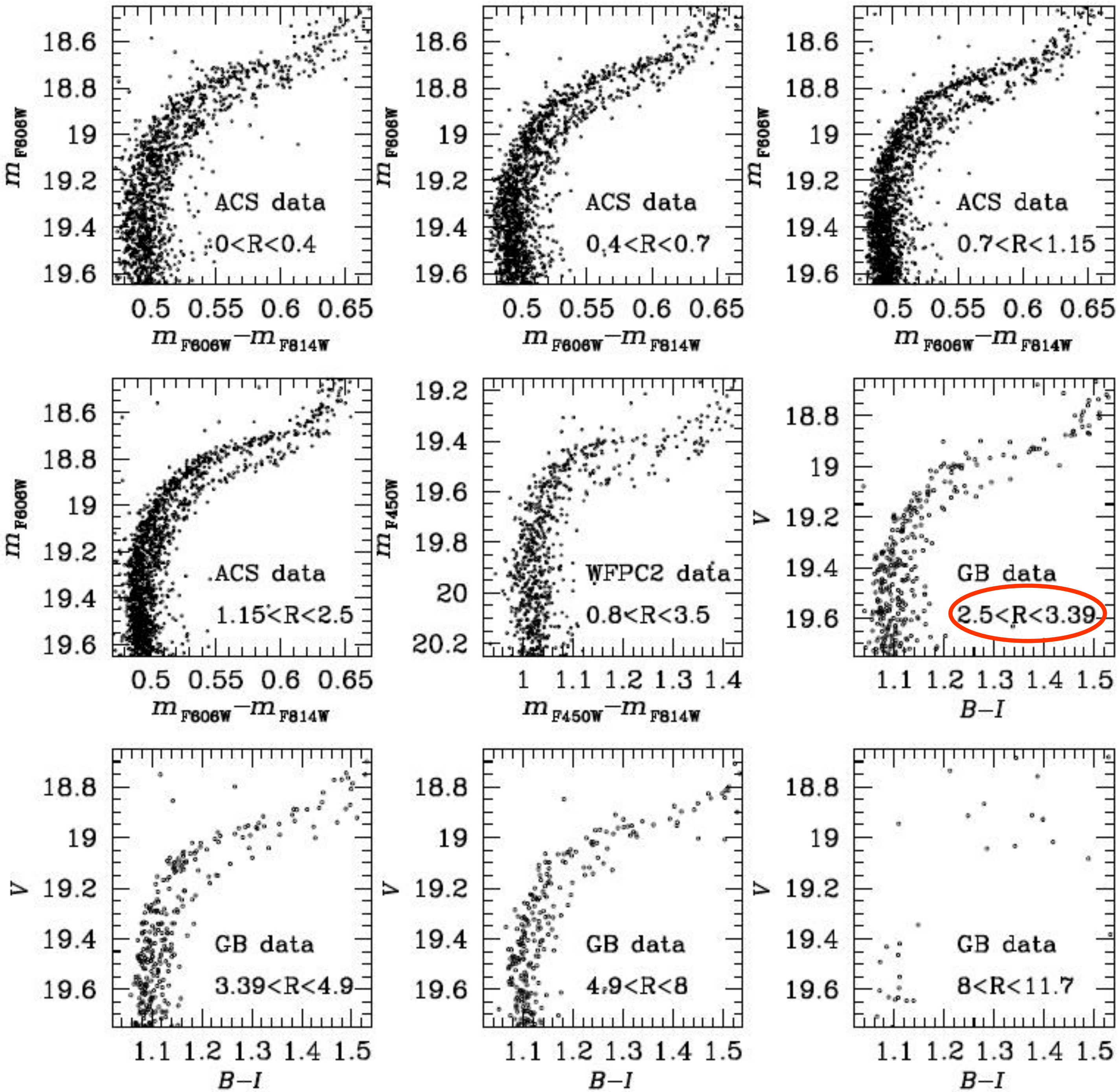
Open questions

- How can you produce such He abundances?
- Different populations (age)?
- Intrinsic of the star cluster which means are they formed within the cluster?
- Merging processes?
- Only in Globular Clusters?
- Depending on metallicity?



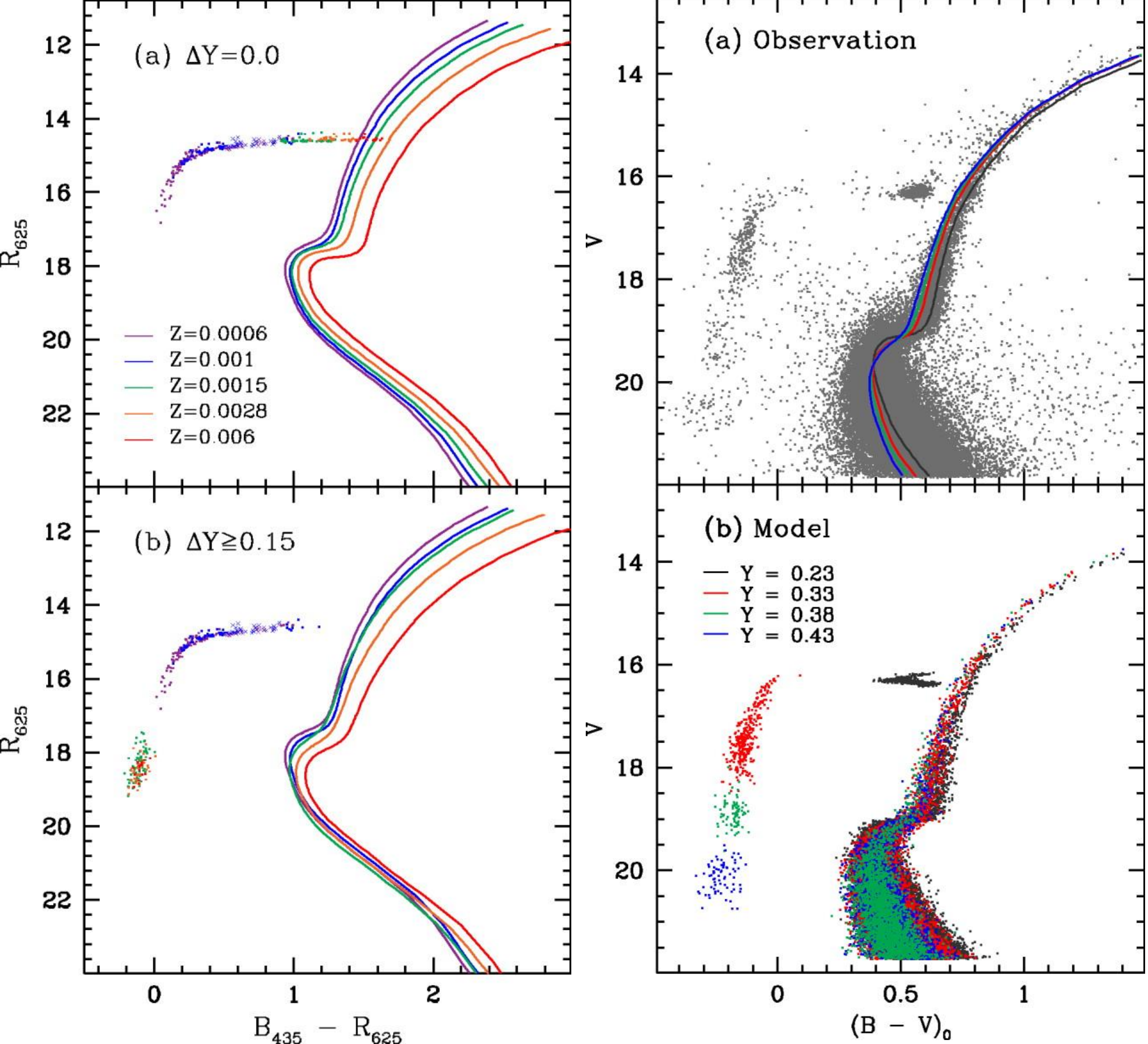
Double sub-giant branch but no double Main Sequence

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



No correlation with the position within the cluster

R … radius from the center



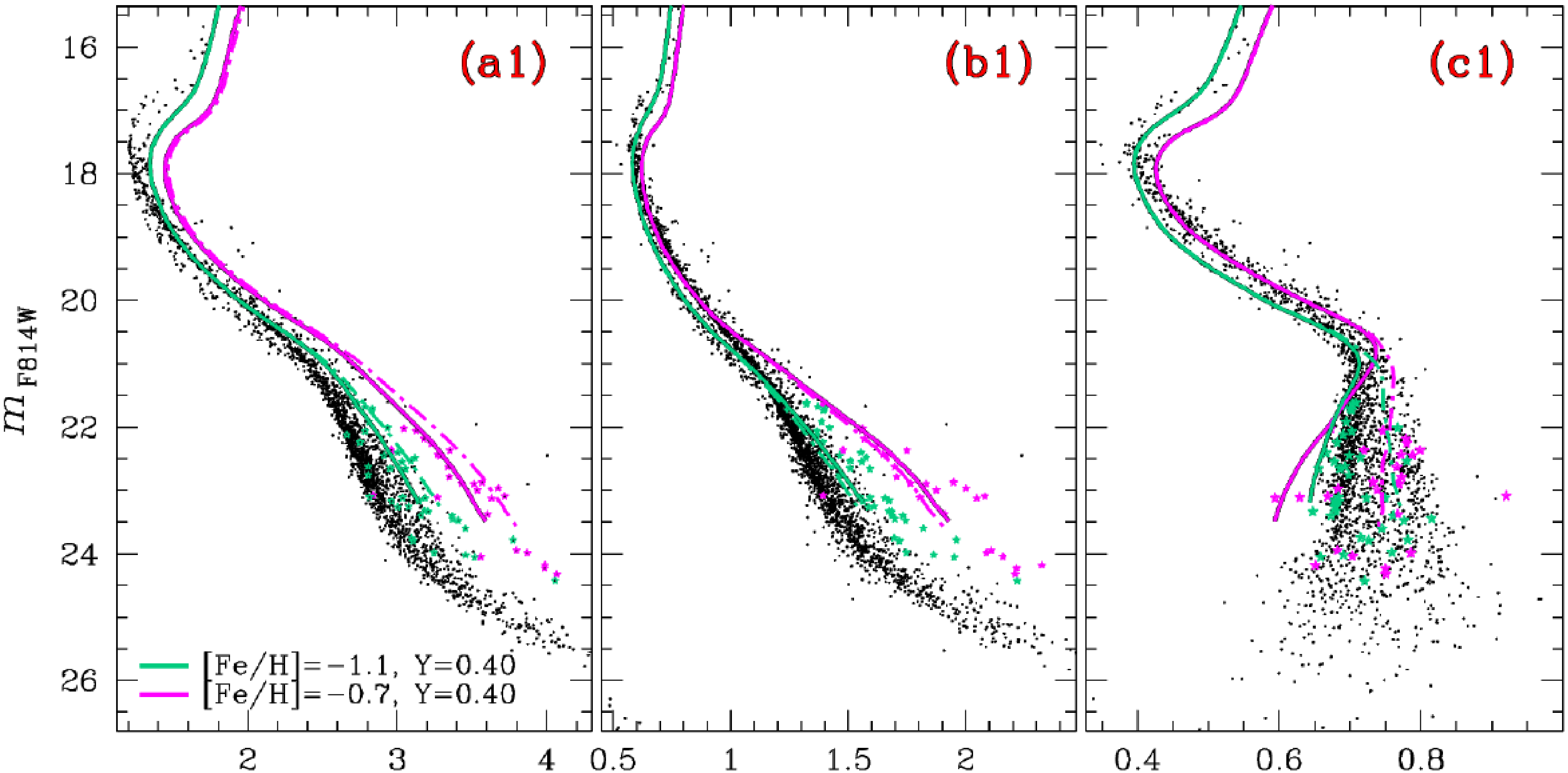
Lee et al., 2005, ApJ, 621, L57

ω Centauri

Observations fit different isochrones very well

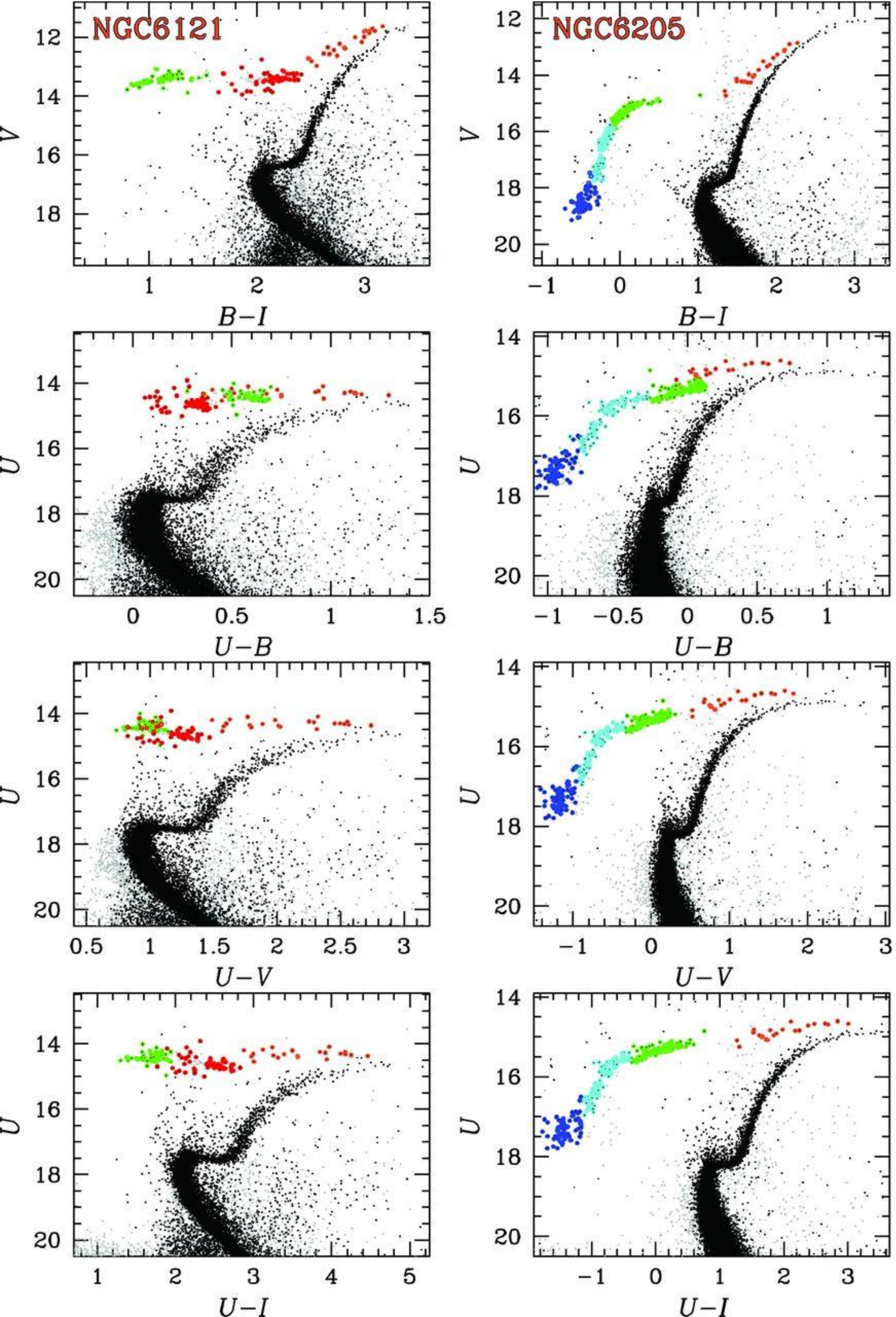
Notice different Z and Y values

ω Centauri



Different colors

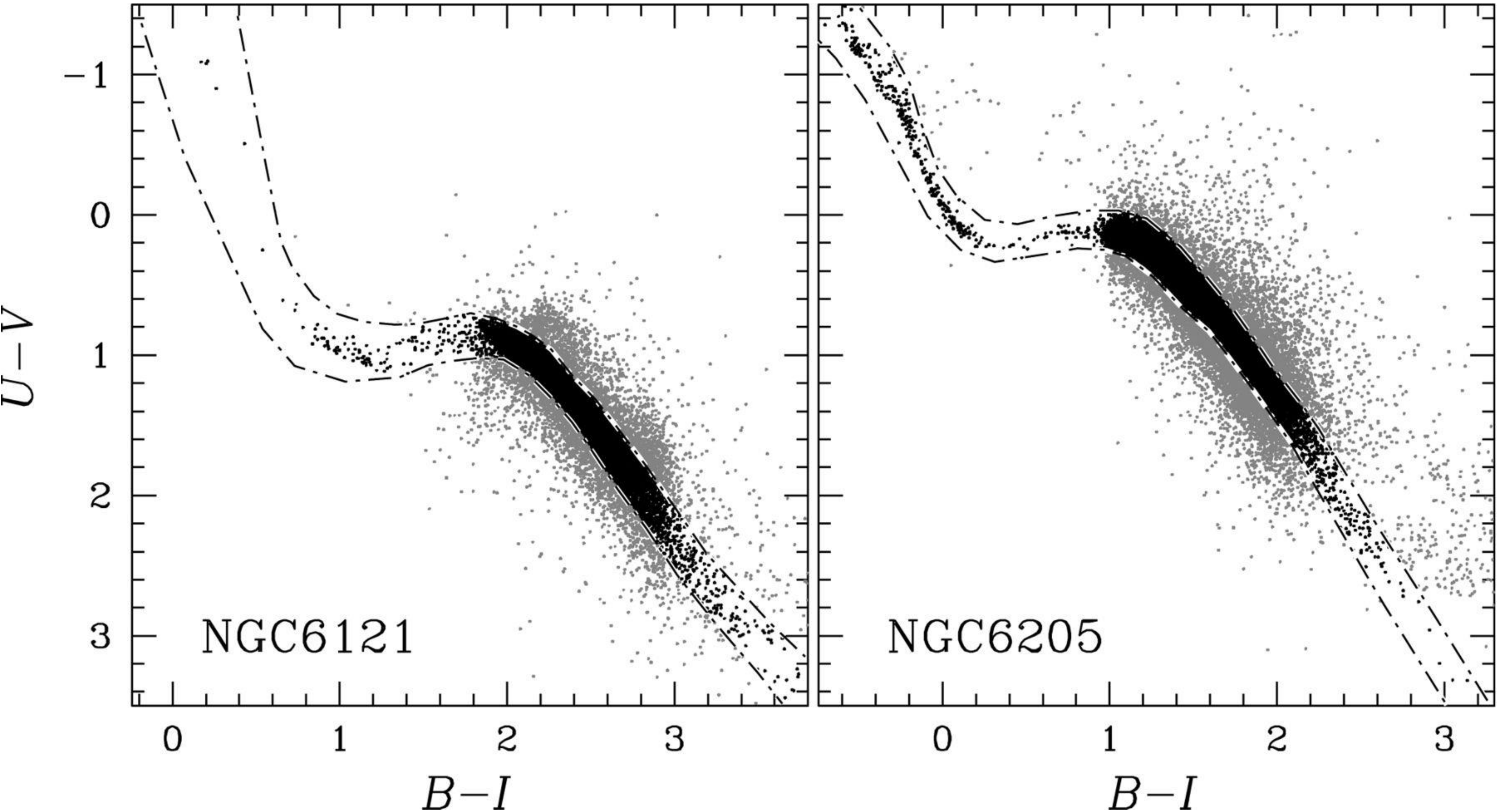
Milone et al., 2017, MNRAS, 469, 800



SUMO (SUrvey of Multiple pOpulations in Globular Clusters)

Monelli et al., 2013, MNRAS, 431, 2126 (first paper)

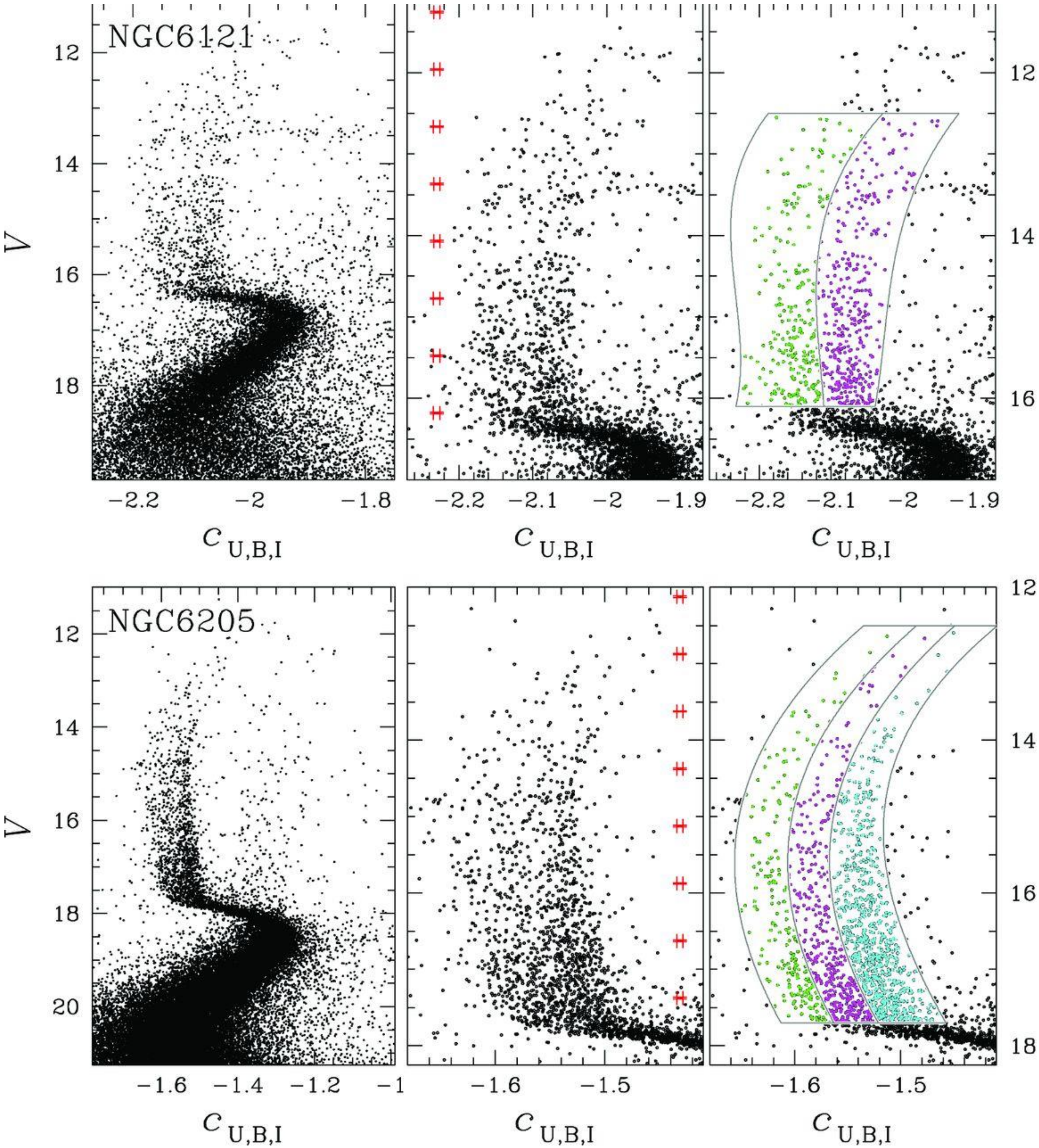
Cluster	RA	Dec.	*U*	*B*	*V*	*I*
NGC 104 [47 Tuc]	00 24 05.67	−72 04 52.6	21	106	115	103
NGC 288	00 52 45.24	−26 34 57.4	9	63	100	68
NGC 362	01 03 14.26	−70 50 55.6	11	140	162	151
NGC 2808	09 12 03.10	−64 51 48.6	48	652	545	203
NGC 3201	10 17 36.82	−46 24 44.9	13	4	4	4
NGC 4590 [M 68]	12 39 27.98	−26 44 38.6	14	48	48	35
NGC 5904 [M 5]	15 18 33.22	+02 04 51.7	28	75	132	127
NGC 6093 [M 80]	16 17 02.41	−22 58 33.9	21	25	45	22
NGC 6121 [M 4]	16 23 35.22	−26 31 32.7	12	1026	1425	41
NGC 6205 [M 13]	16 41 41.24	+36 27 35.5	20	58	54	67
NGC 6218 [M 12]	16 47 14.18	−01 56 54.7	46	196	212	166
NGC 6254 [M 10]	16 57 09.05	−04 06 01.1	17	18	27	29
NGC 6366	17 27 44.24	−05 04 47.5	8	9	30	18
NGC 6397	17 40 42.09	−53 40 27.6	11	42	36	28
NGC 6541	18 08 02.36	−43 42 53.6	12	33	36	23
NGC 6681 [M 70]	18 43 12.76	−32 17 31.6	13	28	48	38
NGC 6712	18 53 04.30	−08 42 22.0	35	38	49	–
NGC 6752	19 10 52.11	−59 59 04.4	35	84	1176	28
NGC 6809 [M 55]	19 39 59.71	−30 57 53.1	12	40	40	36
NGC 6934	20 34 11.37	+07 24 16.1	15	38	42	39
NGC 6981 [M 72]	20 53 27.70	−12 32 14.3	6	241	277	218
NGC 7078 [M 15]	21 29 58.33	+12 10 01.2	31	277	271	196
NGC 7099 [M 30]	21 40 22.12	−23 10 47.5	9	38	48	20



Reddening determination also works for these indices, not only for (U – B) versus (B – V)

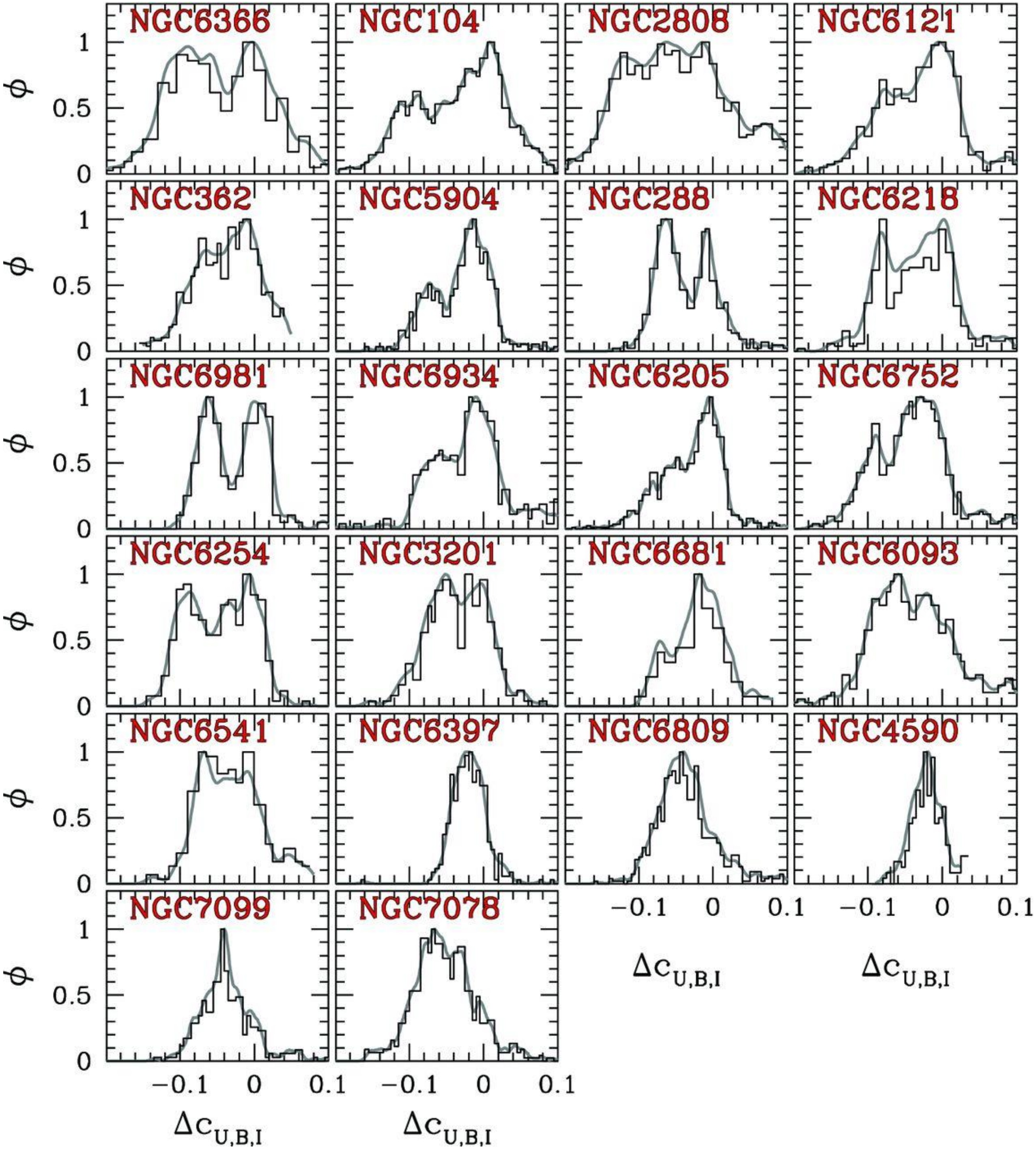
Monelli et al., 2013, MNRAS, 431, 2126

Red Giant Branch



$$C_{U,B,I} = (U - B) - (B - I)$$

Monelli et al., 2013, MNRAS, 431, 2126



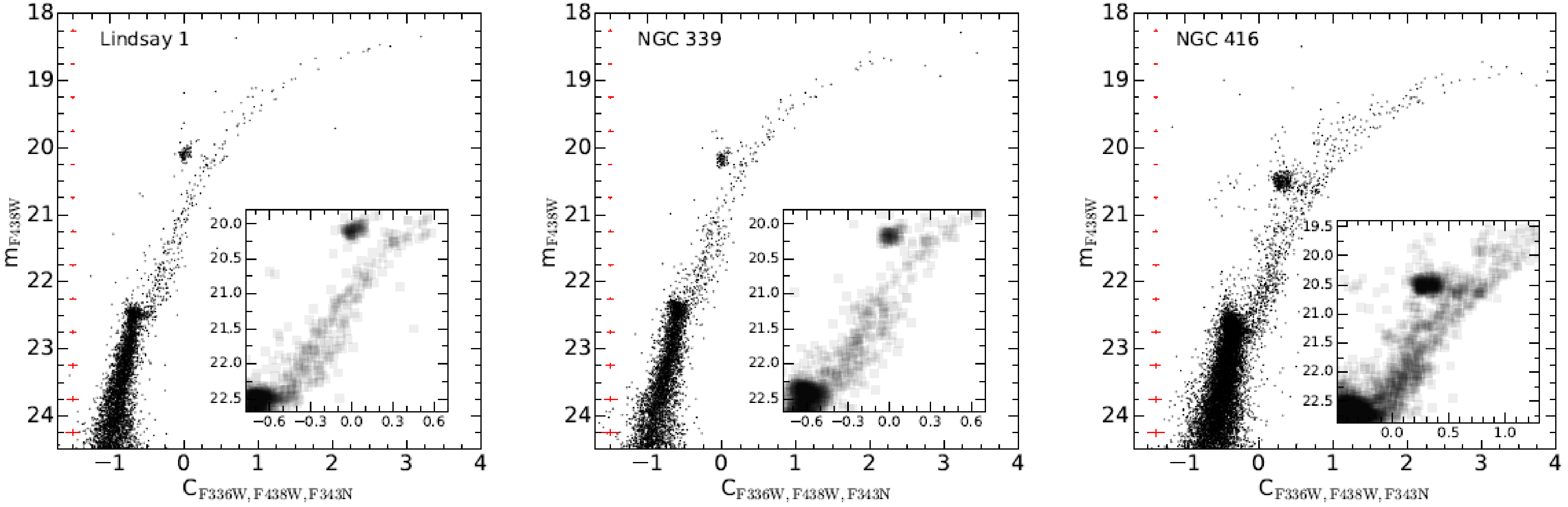
Individual populations

Very different characteristics

Monelli et al., 2013, MNRAS, 431, 2126

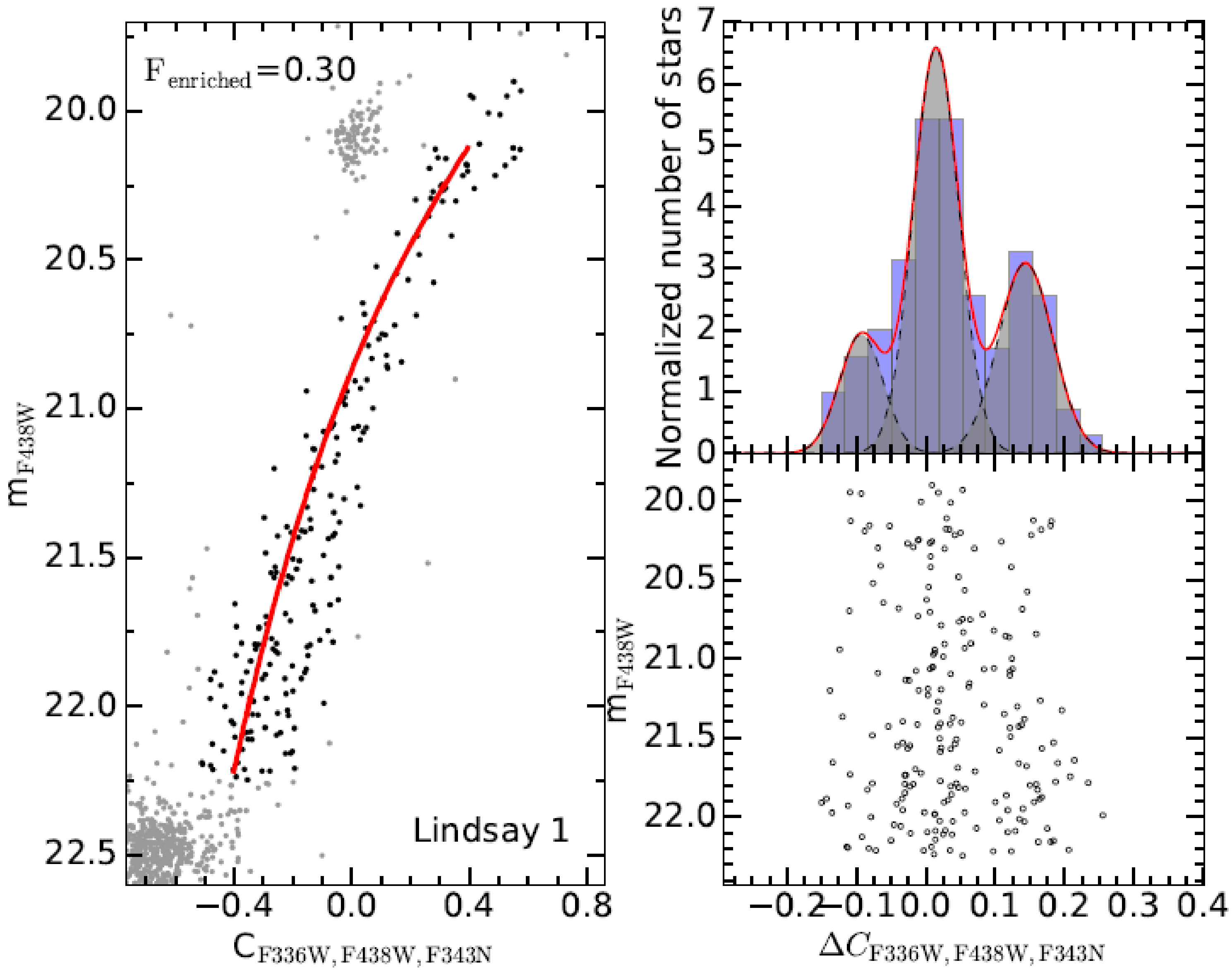
Results for old star clusters in the Small Magellanic Cloud

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)



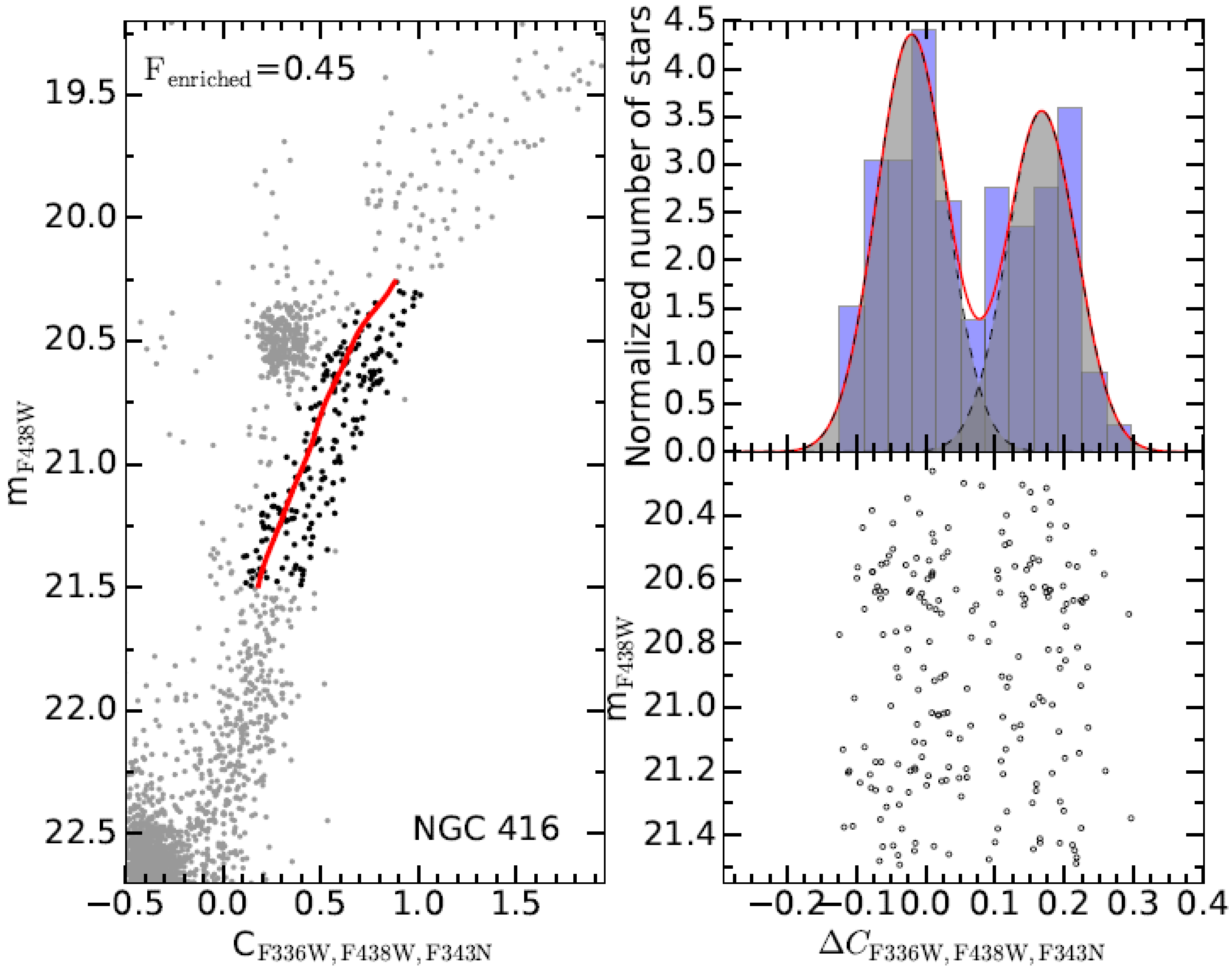
Niederhofer et al., 2017, MNRAS, 465, 4159

Results in the Small Magellanic Cloud



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

Results in the Small Magellanic Cloud



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

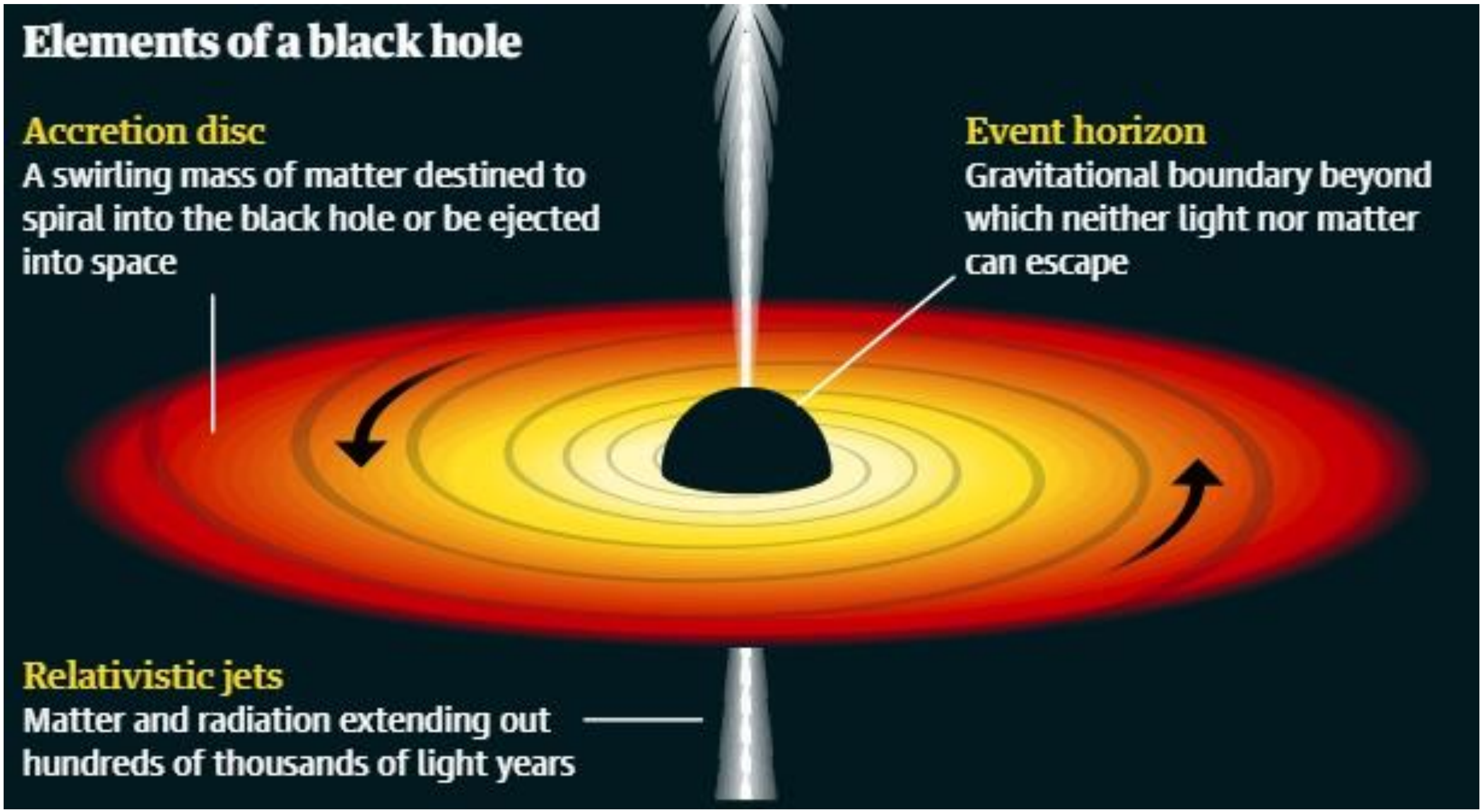
IMBH – Globular Clusters

- Intermediate Black Holes (IMBH) as seeds for massive Black Holes
- Mass: 100 – 100 000 $M_\odot$
- 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 of gas

IMBH – Globular Clusters

- Zocchi et al., 2017, MNRAS, 468, 4429: ω Cen, *no identication*
- Baumgardt et al., 2019, MNRAS, 488, 5340: ω Cen and NGC 6624, *no identication*
- Wu & Zhao, 2021, ApJ, 908, 224: 35 Globulars investigated, *4 "weak candidates"*

IMBH – Globular Clusters



Stars close to the IMBH should accelerate

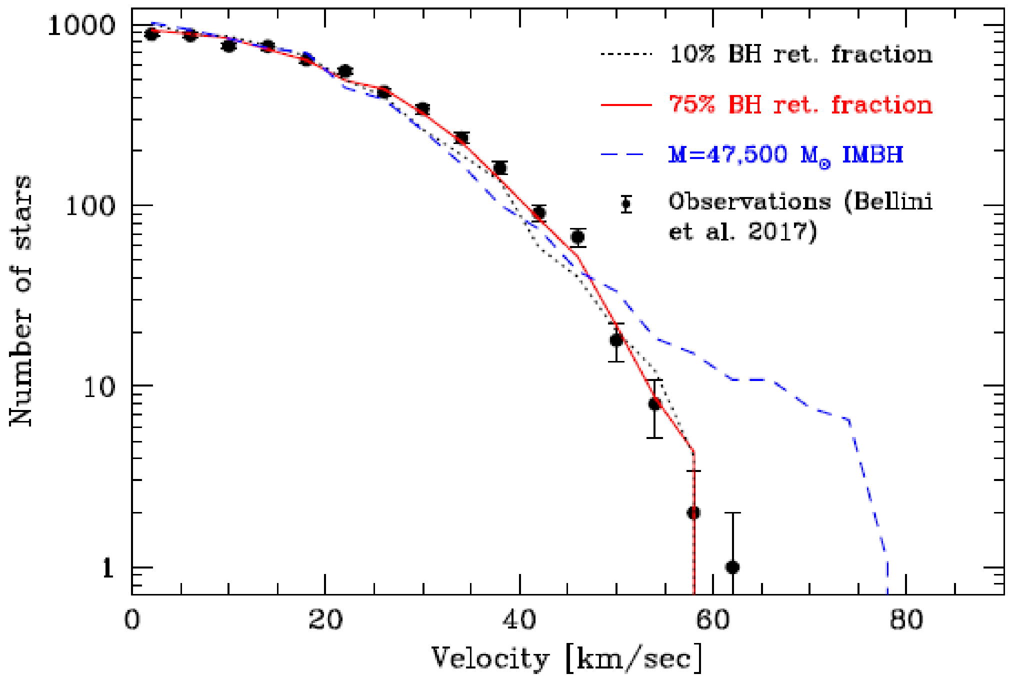
IMBH – Globular Clusters

- 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 (Gaia)

IMBH – Globular Clusters

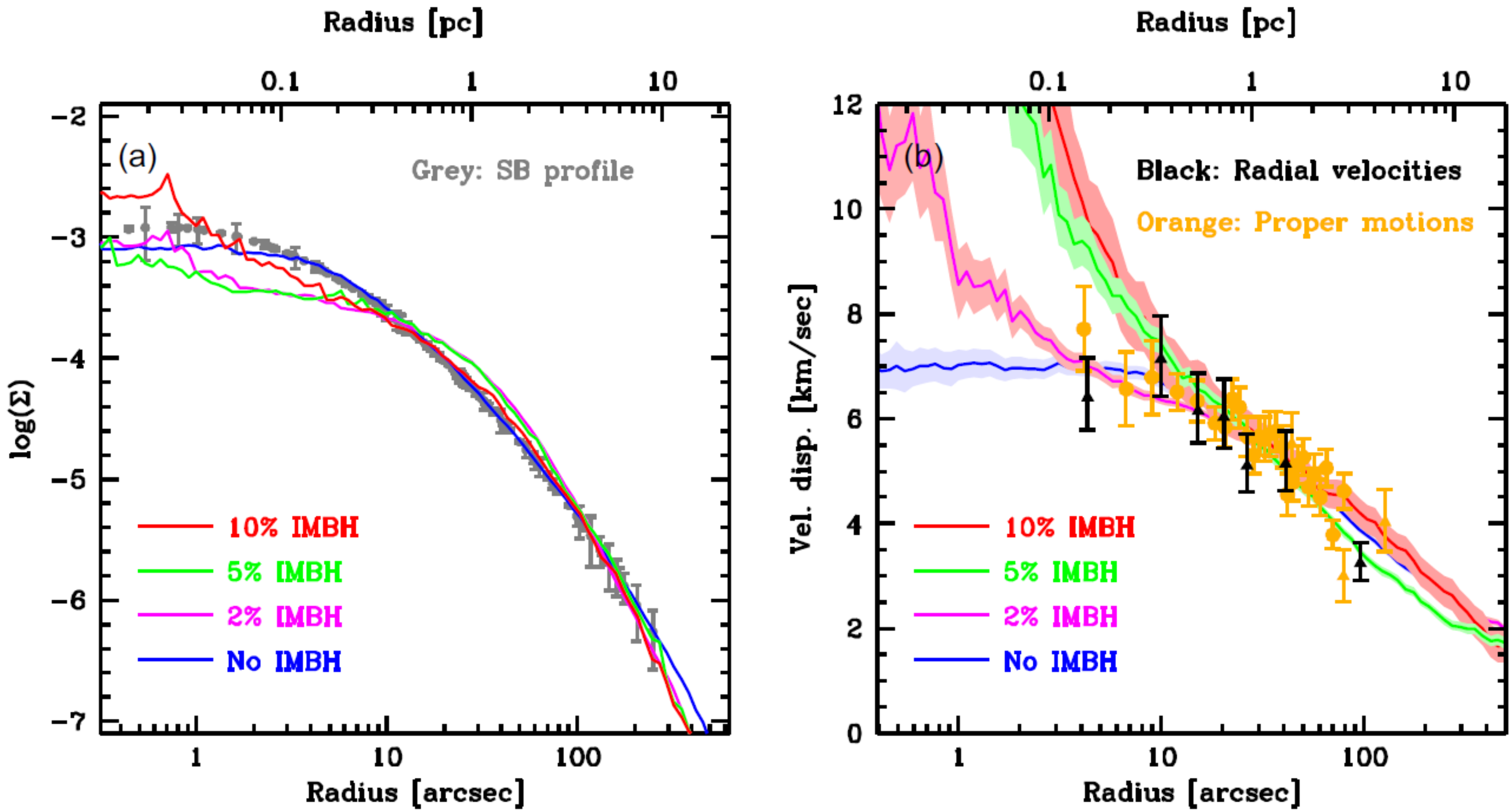


Retention fraction ... fraction of Black Holes that are inside a certain radius

Figure 2. Velocity distribution of stars within 20 arcsec of the centre of *ω* Cen. Shown is the 1D velocity distribution for the stars with measured proper motions by Bellini et al. (2017) (black dots) and the best-fitting *N*-body model with an IMBH (blue dashed line) and with 10 per cent and 75 per cent BH retention fractions (black dotted and red solid lines). The model with a high retention fraction of stellar-mass black holes provides the best fit to the observed distribution.

Baumgardt et al., 2019, MNRAS, 488, 5340

IMBH – Globular Clusters



NGC 6624

Baumgardt et al., 2019, MNRAS, 488, 5340

IMBH – Globular Clusters

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

Notice the differences of the listed cluster parameters from the literature

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 $f_{\mathrm{T}}^{(\nu)}$ 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

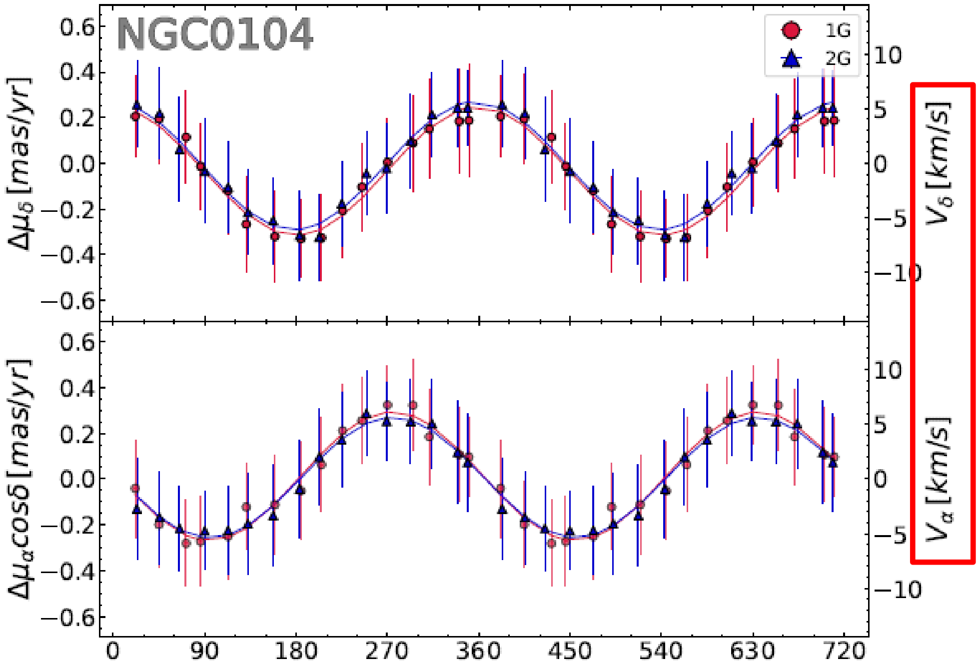
Result: no evidence for an IMBH in ω Cen

The rotation of GCLs

- Rotation as dissolving mechanism for GCLs
- Sollima et al., 2019, MNRAS, 485, 1460
  - 15 of 62 investigated GCLs are rotating
  - Used radial velocities and proper motions
- Cordoni et al., 2020, ApJ, 880, 18
  - 2 of 6 investigated GCLs are rotating
  - Used radial velocities and proper motions
  - Analysis of two different internal populations

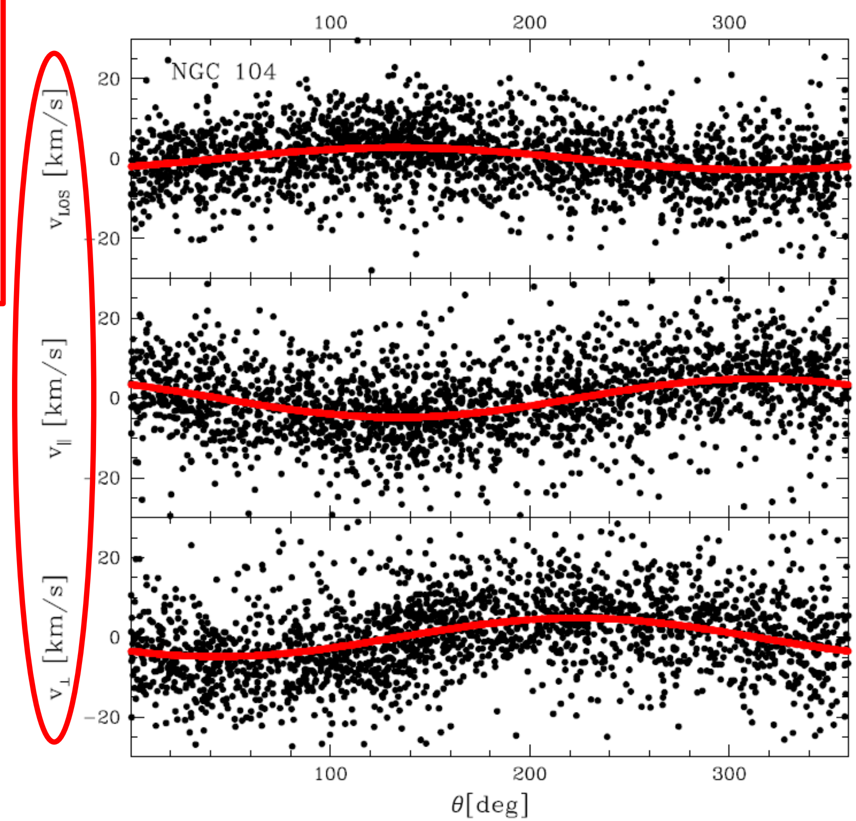
Rotating GCLs

Cordoni et al., 2020, ApJ, 880, 18



Different parameter spaces

Sollima et al., 2019, MNRAS, 485, 1460



Both populations (1G and 2G) seem to rotate differently, only on 2.5σ

Rotating GCLs

GCL   Code of different references

Name	L10	B12	F14	L15	K15	K18	F18	G18	B18	V18	this work
NGC 104	✓	✓			✓	✓		✓	✓	✓	✓
NGC 288	X	X			X		✓		X	X	X
NGC 362					X	∼	✓		X	X	X
NGC 1261							∼				X
NGC 1851		✓		✓		✓			∼	X	X
NGC 1904		X					✓		X		(✓)
NGC 2808		✓		✓	X	✓			X	X	✓
NGC 3201		✓				✓	✓		∼	X	∼
NGC 4372				X					✓	∼	∼
NGC 4590	X	✓			X				X	X	X
NGC 5024	X	X	✓		X						∼
NGC 5139		✓				✓		✓	✓	✓	✓
NGC 5272			✓		X		✓	✓	✓	∼	(✓)
NGC 5286									∼	X	X
NGC 5466					✓						X
NGC 5824											(✓)
NGC 5904		✓	✓		✓	✓		✓	✓	✓	✓
NGC 5927				✓			∼		X	X	X
NGC 5986									X	X	∼
NGC 6093			✓			✓			∼	X	(✓)
NGC 6121	✓	✓			∼	∼			∼	X	X
NGC 6171		∼					✓		X	X	X
NGC 6205			✓						∼	X	✓
NGC 6218	X	X	✓		X				X	X	(✓)
NGC 6254		X	✓			✓	∼		∼	X	X
NGC 6266						✓			∼	✓	✓

Different references find rotation or not (X) for the same GCL

Sollima et al., 2019, MNRAS, 485, 1460