Homogeneous photometry – VII. Globular clusters in the *Gaia* era

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Outline

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Introduction

Globular clusters (GCs)

- Globular clusters (GCs) are key astrophysical laboratories, once thought to be simple, spherical, single-population systems.
- Modern observations have revealed a more complex picture: deviations from spherical symmetry, internal rotation, anisotropy, and the presence of multiple stellar populations (MPs).

Existing Data

- Photometric and spectroscopic surveys have advanced our understanding, but limitations remain:
  - HST photometry: high precision, but small spatial coverage (cluster cores only).
  - Gaia: all-sky coverage, but broadband filters cannot separate MPs.
  - SDSS/other surveys: multiband, wide-field, but limited performance in crowded fields.

Introduction

Goal of this study

To provide wide-field, ground-based **UBVRI photometry** for 48 Galactic GCs, calibrated to millimag precision, bridging the gap between small-field, high-precision HST data and large-scale surveys (Gaia, SDSS, LSST).

- This catalogue enables:
  1. Full spatial coverage of clusters.
  2. Consistent multiband CMDs sensitive to MPs.
  3. Structural studies (density, brightness, morphology).

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Data

- **Based on >500,000 CCD images** (since 1983), covering dwarf galaxies, open clusters, globular clusters, supernova hosts, and standards.
- Images mostly from **public archives**, plus some proprietary data.

Site	Telescope	Instrument	Dates	n_U	n_B	n_V	n_R	n_I	n_o
Apache Point	ARCSAT 0.5m	APOGEE	2017	0	12	22	0	1	0
Apache Point	APO 3.5m	Arctic	2017	0	10	12	0	0	0
BNAO Rohzen	BNAO 2.0m	Photometrics CE200A	2001	0	212	213	2	168	0
Cerro Pachón	SOAR 4.1m	SOI	2008–2012	276	254	288	144	504	534
Cerro Tololo	CTIO 0.9m	TI1/2, Tek, Tek2k, RCA	1986–2012	39	2377	2630	416	930	876
Cerro Tololo	CTIO 1.0m	Y4KCam	2006–2013	29	2144	2654	349	1110	1362
Cerro Tololo	CTIO 1.3m	ANDICAM	2005–2008	0	270	294	0	257	0
Cerro Tololo	CTIO 1.5m	TI1/2, Tek, Tek2k, Site2K	1987–1998	16	234	234	20	143	0
Cerro Tololo	CTIO 4.0m	TI1/2, Mosaic1/2, Tek2k, DECam	1983–2016	457	1325	1688	178	1838	2958
DAO Victoria	DAO 1.8m	SITE1	1995–1996	0	7	12	8	8	0
ESO La Silla	Dutch 0.9m	Tektronic 33	1997	0	0	167	0	166	0
ESO La Silla	Danish 1.5m	MAT/EEV, DFOSC	1995–2005	8	2689	5079	2114	890	117
ESO La Silla	ESO/MPI 2.2m	WFI	1999–2012	2456	4000	5072	1096	3647	184
ESO La Silla	NTT 3.6m	EMMI, SUSI, EFOSC	1992–2014	184	1991	1159	321	819	108
ESO Paranal	VLT 8.0m	VIMOS, FORS1, FORS2	1999–2012	200	304	692	243	306	0
Kitt Peak	KPNO 0.9m	RCA, T2kA	1984–1999	0	179	188	0	93	92
Kitt Peak	KPNO 2.1m	CCD, T1kA	1992–1994	0	1	74	1	77	0
Kitt Peak	WIYN 3.5m	WIYNMiniMos	2001–2014	0	0	12	18	30	18
Kitt Peak	KPNO 4.0m	RCA, Mosaic1, T2kB	1984–2011	0	213	231	48	180	2075
La Palma	JKT 1.0m	GEC, EEV, SITE, TEK	1991–2003	5	137	240	118	190	2

Data

Target Cluster Selection

- **Prioritization Criteria (from GCs catalogue of Harris 1996, 2010):**

1. Low reddening → clearer CMD sequences
2. High luminosity → better number statistics
3. Small distance modulus → higher photometric precision
4. (RR Lyrae counts considered, but minor impact)

- **Practical Constraints:**

1. Required calibrated photometry in all UBVRI bands
2. U band crucial for detecting multiple populations (CN bands at 388 nm)
3. R band less essential, but mandatory for sample inclusion

➢ **48 GCs**

✓ 84,106 CCD images in UBVRI bands (plus 9,166 in other filters)

✓ Collected over 1327 nights / 390 observing runs with multiple telescopes & cameras

Cluster		RA (hh mm ss)	Dec (dd mm ss)
NGC 104	47 Tuc	00 24 03.63	−72 04 46.6
NGC 288		00 52 44.98	−26 35 04.8
NGC 1261		03 12 15.97	−55 12 57.6
NGC 1851		05 14 06.82	−40 02 47.0
NGC 1904	M 79	05 24 11.31	−24 31 29.3
NGC 2298		06 48 59.37	−36 00 20.0
NGC 2808		09 12 05.43	−64 51 53.9
E 3		09 20 55.81	−77 16 57.9
NGC 3201		10 17 36.35	−46 24 41.1
NGC 4147		12 10 06.34	+18 32 32.4
NGC 4372		12 25 50.56	−72 39 16.3
NGC 4590	M 68	12 39 28.00	−26 44 35.9
NGC 4833		12 59 35.26	−70 52 30.2
NGC 5024	M 53	13 12 54.91	+18 10 06.8
NGC 5053		13 16 26.63	+17 42 00.9
NGC 5139	ω Cen	13 26 47.15	−47 28 49.5
NGC 5272	M 3	13 42 11.54	+28 22 42.9
NGC 5286		13 46 25.76	−51 22 15.0
NGC 5634		14 29 36.95	−05 58 36.1
NGC 5694		14 39 36.87	−26 32 30.6
IC 4499		15 00 18.15	−82 12 55.6
NGC 5824		15 03 59.06	−33 04 06.3
NGC 5904	M 5	15 18 33.38	+02 04 52.0
NGC 5927		15 28 00.96	−50 40 12.3
NGC 5986		15 46 03.27	−37 47 10.0
Pal 14	AvdB	16 11 01.11	+14 57 31.0
NGC 6121	M 4	16 23 35.24	−26 31 33.3

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PHOTOMETRY

Photometry Procedure

- Instrumental magnitudes measured with **DAOPHOT, ALLSTAR, ALLFRAME**.
- PSF derived from bright, isolated stars and applied to all frames.
- Aperture corrections obtained from growth-curve analysis.

ALLFRAME Photometry

Multiple images registered to a common reference frame (3rd-order polynomial).

Final PSF magnitudes measured with **ALLFRAME** using a **common star list** across all images.

Advantages of **ALLFRAME**:

Improves depth and precision of photometry.

Best-seeing images provide stronger positional constraints.

Enables consistent deblending in crowded regions.

PHOTOMETRY

Photometric calibration

- **Goal**

  provide final calibrated magnitudes on a photometric system as similar to that of +δx + y as possible.

- **Selection of Standards**

  1. Provisional calibration using Landolt primary standards.
  2. Criteria: ≥5 observations, σ_mean < 0.02 mag, no intrinsic variability >0.05 mag.

- **Method**

  1. Colour and extinction corrections

  $$v = V + z_V + \alpha_V(B - V) + \beta_V(B - V)^2 + k_V X,$$
  $$u = U + z_U + \alpha_U(U - B) + \beta(B - V) + \gamma_U(B - V)^2 + k_U X.$$

  2. Spatial corrections

  $$+\delta x + \epsilon y$$

  3. Calibration to Landolt Magnitudes

     Use all images, all nights, all runs to solve simultaneously

     Iterative least squares → derive best V, B

PHOTOMETRY

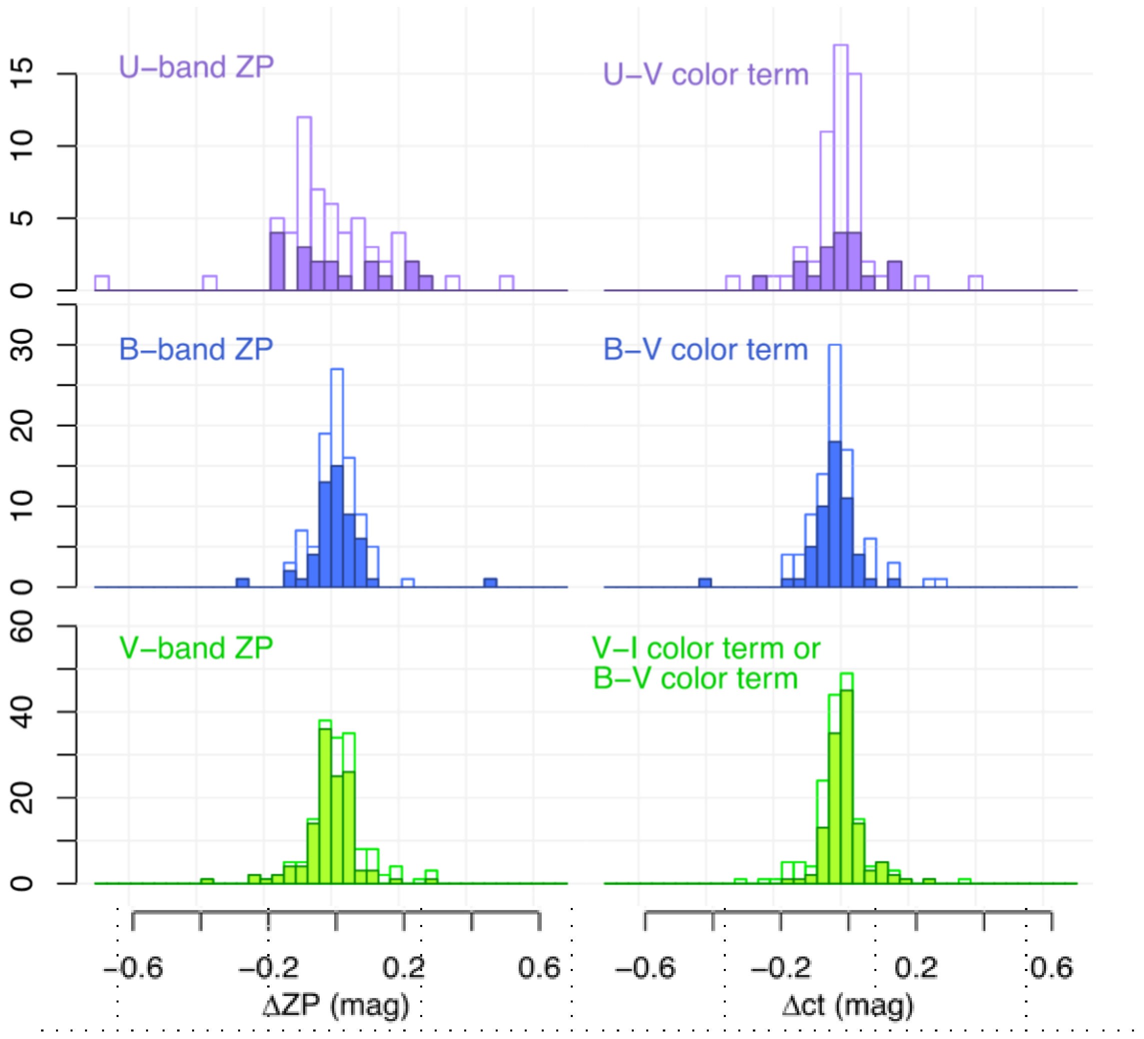
Calibration Results

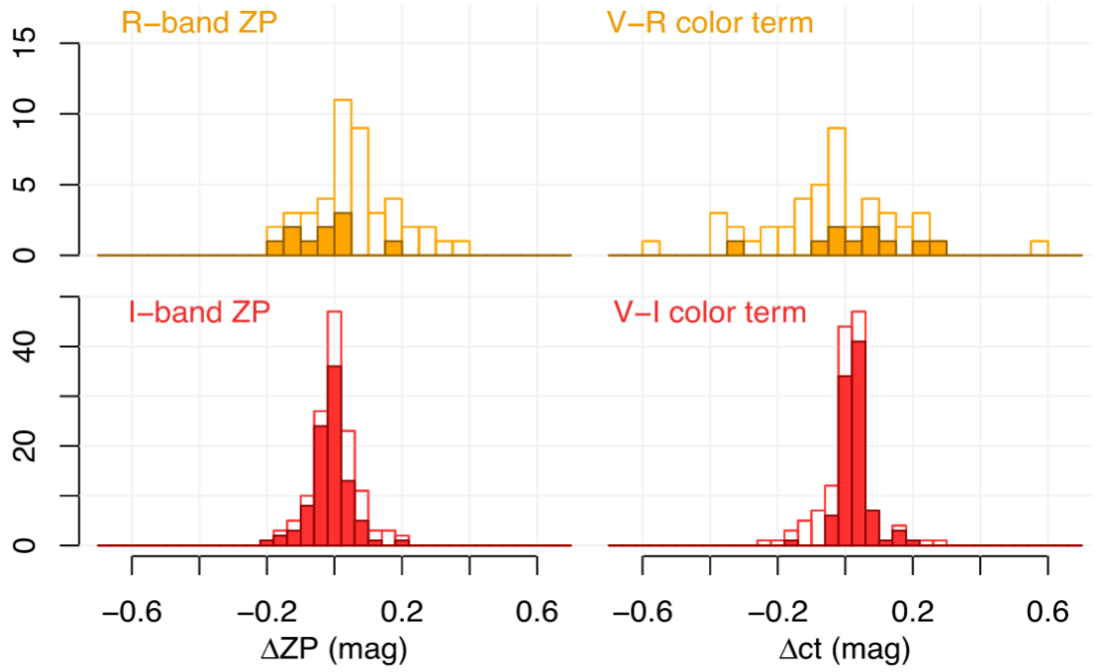
- Local secondary standards: 48 GCs → 61,514 stars.
- Individual CCD image ZPs: median based on 155 local standards.
- Median magnitude residual per star:

  U: 0.009 mag | B: 0.004 mag | V: 0.003 mag | R: 0.007 mag | I: 0.005 mag
- Typical ZP uncertainty for one image: 0.0015 mag.
- Overall precision dominated by readout noise, photon statistics, and crowding.

PHOTOMETRY

Literature comparisons





- The median values of the ZPs are close to zero
- The distributions of the colour terms are narrow, with deviations in most passbands smaller than 0.02 mag.
- The largest discrepancies are mainly seen in the U and R bands, due to filter differences and the limited availability of literature data.

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THE CATALOGUE

Column	Units	Description
Cluster		GC name
Star		Star ID (unique for each GC)
X	(s)	*X* coordinate in arcseconds
Y	(s)	*Y* coordinate in arcseconds
U	(mag)	Johnson U magnitude
σ_U	(mag)	U magnitude error
n_U		Number of U measurements
B	(mag)	Johnson B magnitude
σ_B	(mag)	B magnitude error
n_B		Number of B measurements
V	(mag)	Johnson V magnitude
σ_V	(mag)	V magnitude error
n_V		Number of V measurements
R	(mag)	Cousins R magnitude
σ_R	(mag)	R magnitude error
n_R		Number of R measurements
I	(mag)	Cousins I magnitude
σ_I	(mag)	I magnitude error
n_I		Number of I measurements
χ		DAOPHOT's χ parameter
sharp		DAOPHOT's sharp parameter
vary		Welch–Stetson variability index
weight		Weight of variability index
RA	(hh mm ss)	Right ascension
Dec	(dd mm ss)	Declination

The final photometric catalogue for each GC was obtained by robust weighted averages of the calibrated magnitudes obtained from the individual images

THE CATALOGUE

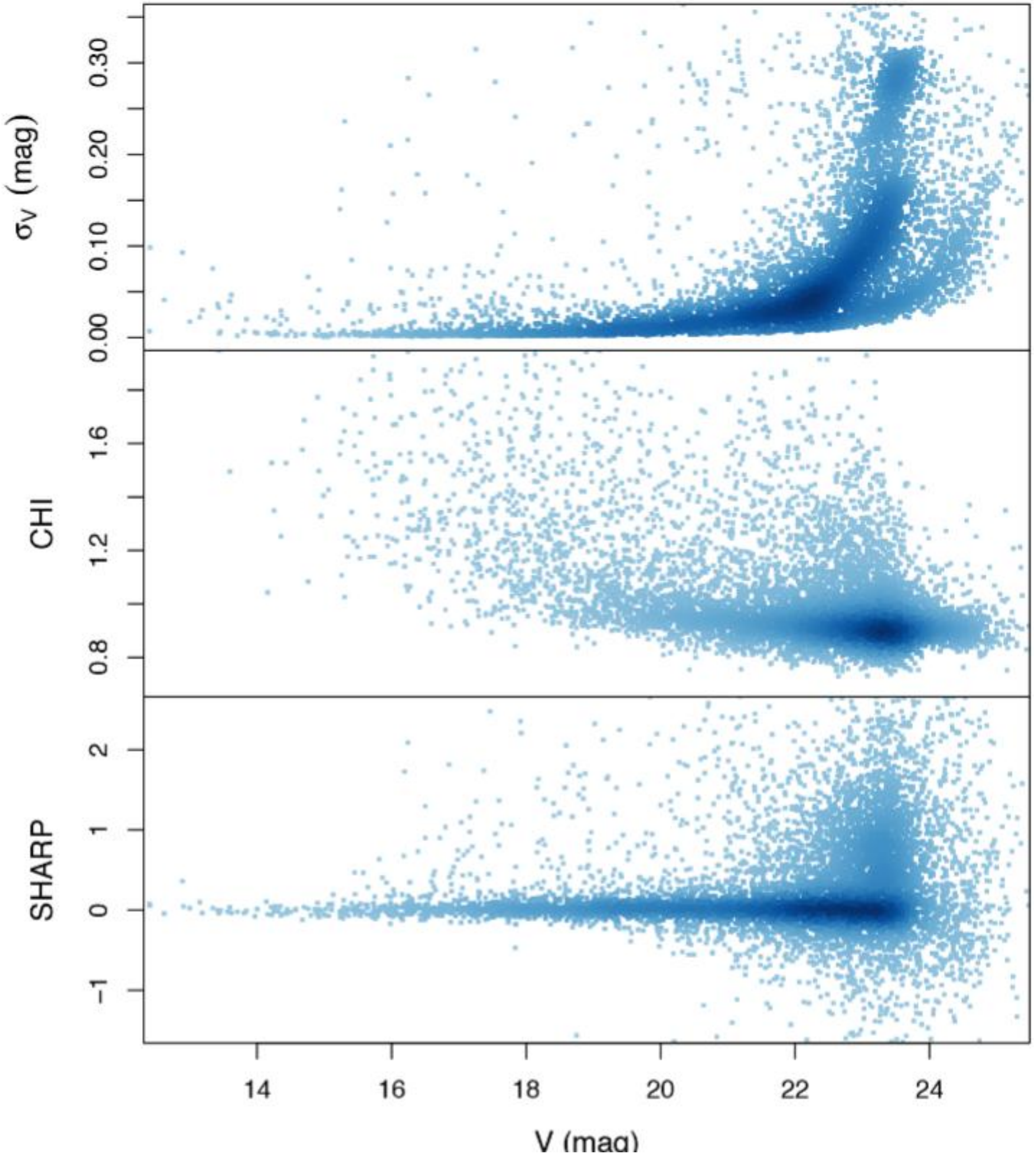
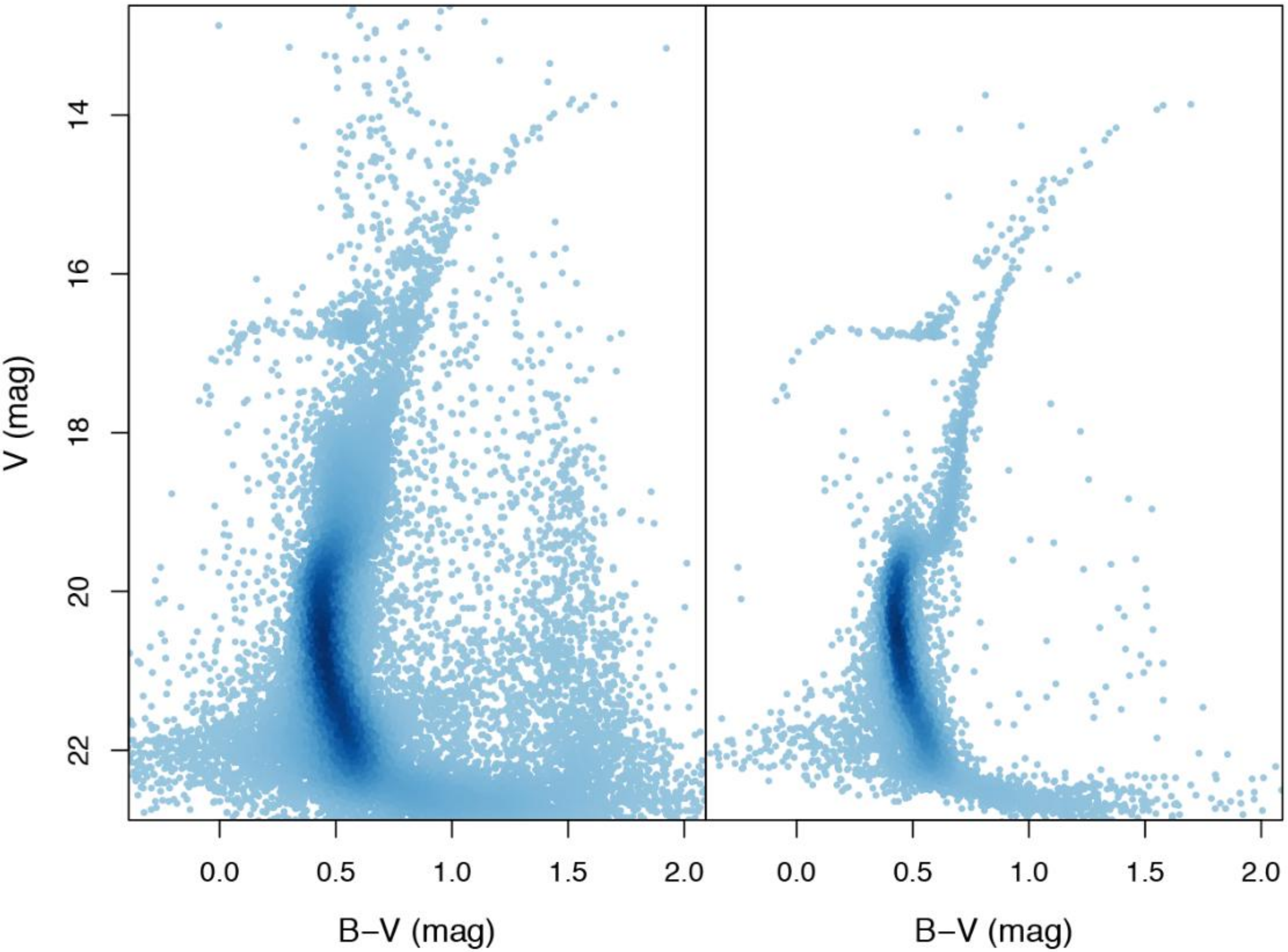


Image Quality Indicators (NGC 5694)

- ➢ σ: the standard error associated with each magnitude measurement
- ➢ χ :measures the observed pixel-to-pixel scatter in the profile fits compared to the expected scatter from readout noise and photon statistics.
- ➢ sharp : a measure of how much of the badly modelled light is concentrated in the central pixels compared to the surrounding ones.

- the substructure in σ at faint magnitudes due to varying CCD depth.
- Bright stars deviate more from PSF; disturbed PSFs at all magnitudes.
- Sharp parameter: negative → cosmic rays / bad pixels; positive → diffuse objects.

THE CATALOGUE



CMD Cleaning Example (NGC 1261)
Raw CMD includes cluster + field stars + poor-quality detections.

Selection excludes:

- Stars within core radius / outside 80% tidal radius.
- Objects with $-0.3 < sharp < 0.3$, $\chi \leq 3$.
- Measurements with σV or $\sigma B \leq 0.2$ mag.

Cleaned CMD shows improved cluster sequence.

THE CATALOGUE

Variability indicators

- Welch–Stetson (W/S) variability index (Welch & Stetson 1993): based on the correlation of the normalized residuals relative to the UBVRI average magnitudes for observations obtained close in time.
- Weight: equal to the number of residual pairs plus one-half the number of singleton residuals used to build the W/S index.
- variability evidence: define as the logarithm of the W/S index times its weight.

the lines of evidence equal to 2 (gold), 3 (orange), and 4 (tomato) are overplotted for reference.

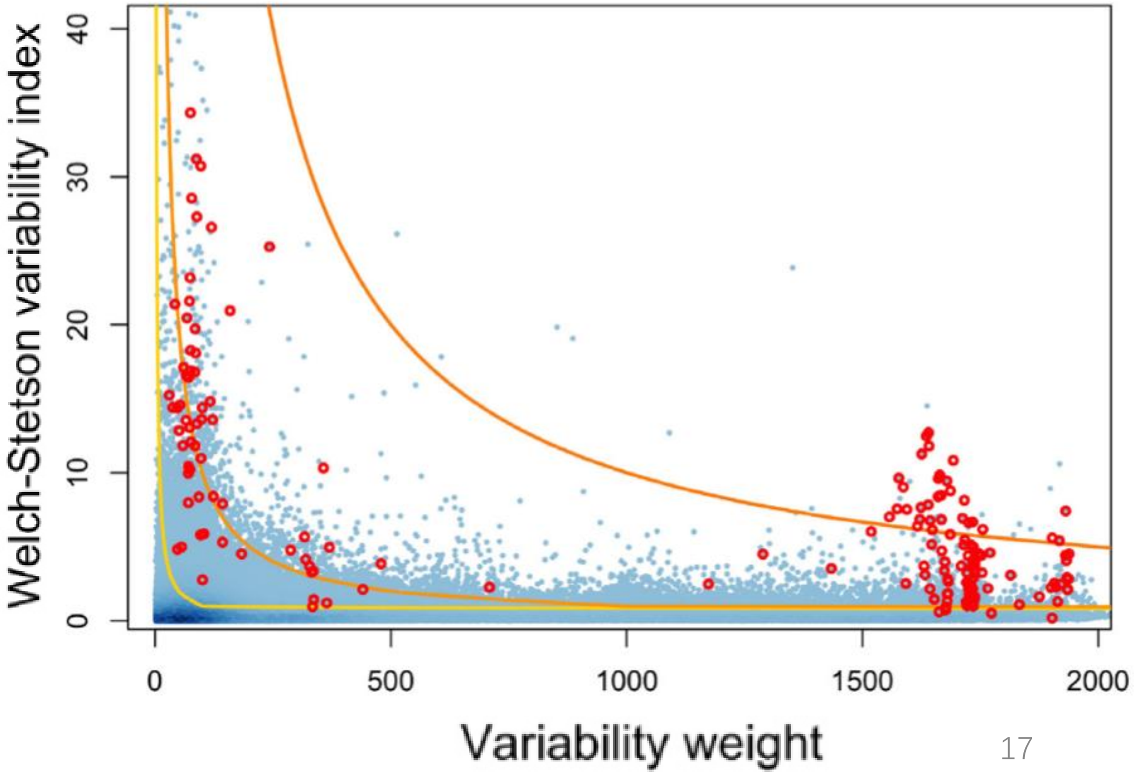
Known RR Lyrae : they mostly have variablity weight above 30 and evidence higher than 2.

$$\delta b_i = \frac{b_i - \bar{b}}{\sigma_{b,i}}, \quad (3)$$

$$\delta v_i = \frac{v_i - \bar{v}}{\sigma_{v,i}}. \quad (4)$$

We may then define the variability index, I, by

$$I = \sqrt{\frac{n}{n-1}} \frac{1}{n} \sum_{i=1}^{n} (\delta b_i \, \delta v_i) = \sqrt{\frac{1}{n(n-1)}} \sum_{i=1}^{n} (\delta b_i \, \delta v_i). \quad (5)$$



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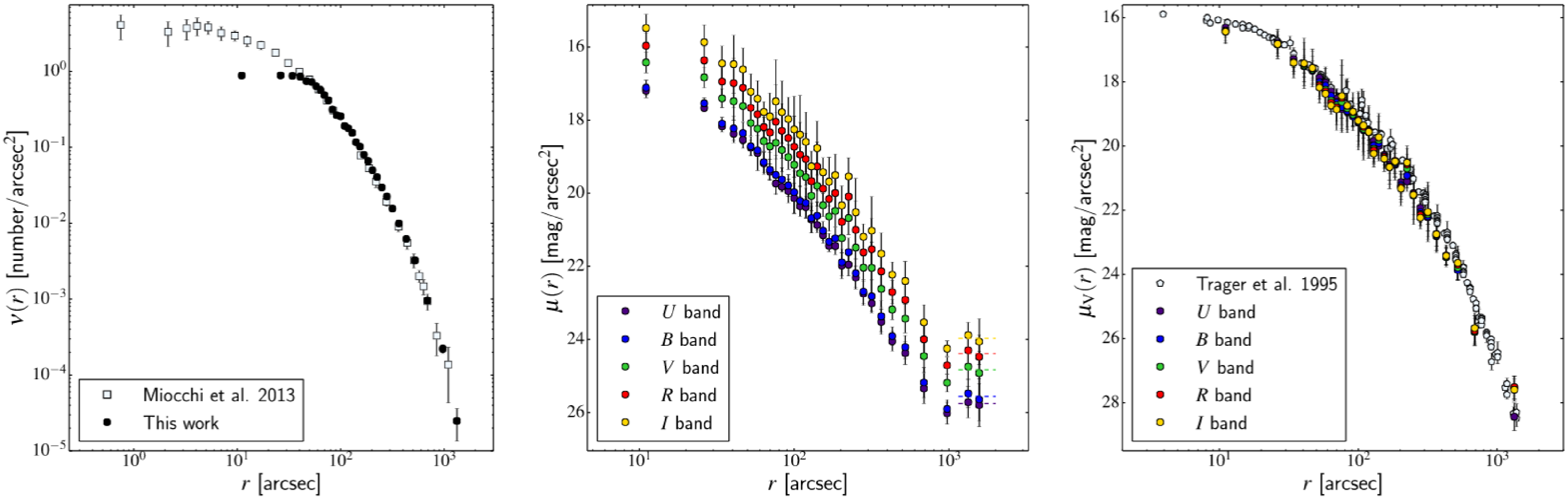
RESULTS

Derive **structural properties** of GCs using number-density and surface-brightness profiles

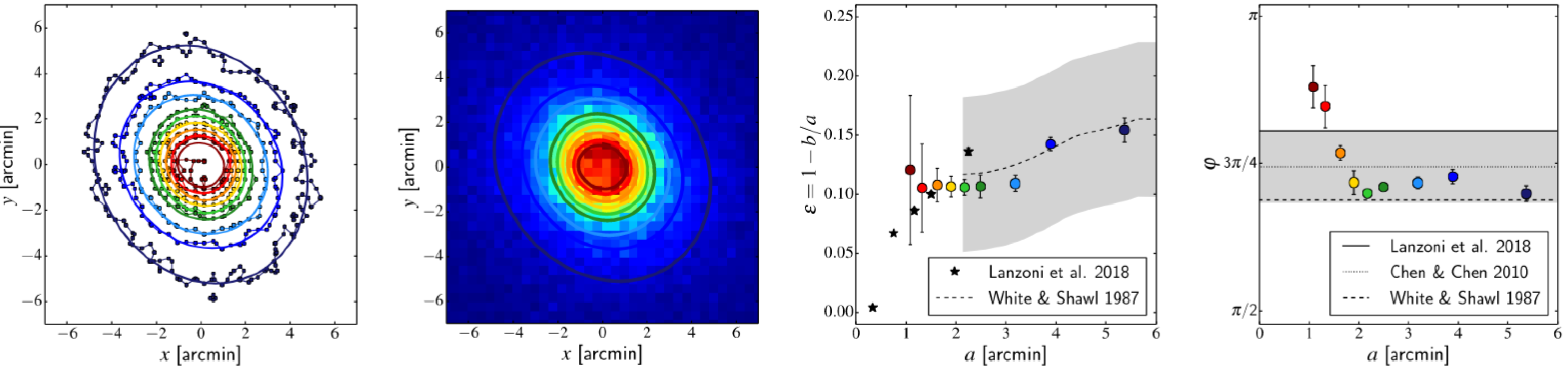


Results (M5 as example)

- Number-density profile consistent with Miocchi+2013 (except inner crowding)
- Surface-brightness profiles in UBVRI show similar shapes across bands
- After color shifting, profiles agree with Trager+1995

RESULTS

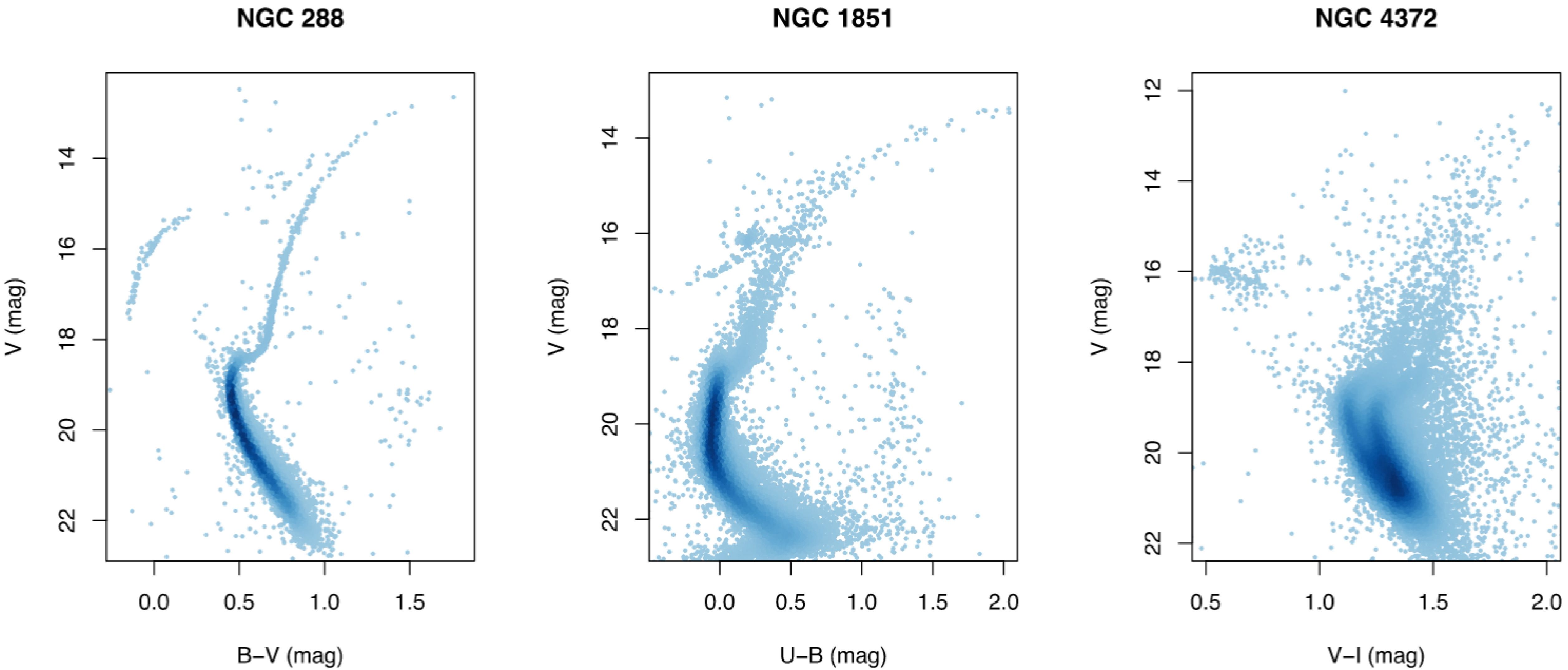
Cluster shape （M5）



- Isodensity contours fitted with ellipses
- Ellipticity ε increases at lower densities (outer regions flatter)
- Position angle φ roughly constant in outer regions (~135°)
- Global ellipticity: ε ≈ 0.11–0.12, consistent with literature (ε = 0.14)

RESULTS

Colour–magnitude diagrams



RESULTS

Multiple populations

- Catalogue allows **separation/classification of MPs** using **CUBI index** = (U−B) − (B−I)

  For G/K stars: B−I & U−B mainly depend on temperature → CUBI removes temperature effects

$$\frac{d(U-B)}{d(B-I)} \sim 1.10$$

  CUBI highlights **C, N, He variations** (e.g., CN band at 388 nm, Balmer jump)

- Differential reddening weakens CUBI effectiveness (E(U−B)/E(B−I) ~ 0.4)

$$E(U-B)/E(B-I) \sim 0.4$$

➢ Two well-separated branches observed.(NGC 288, NGC 6981.)

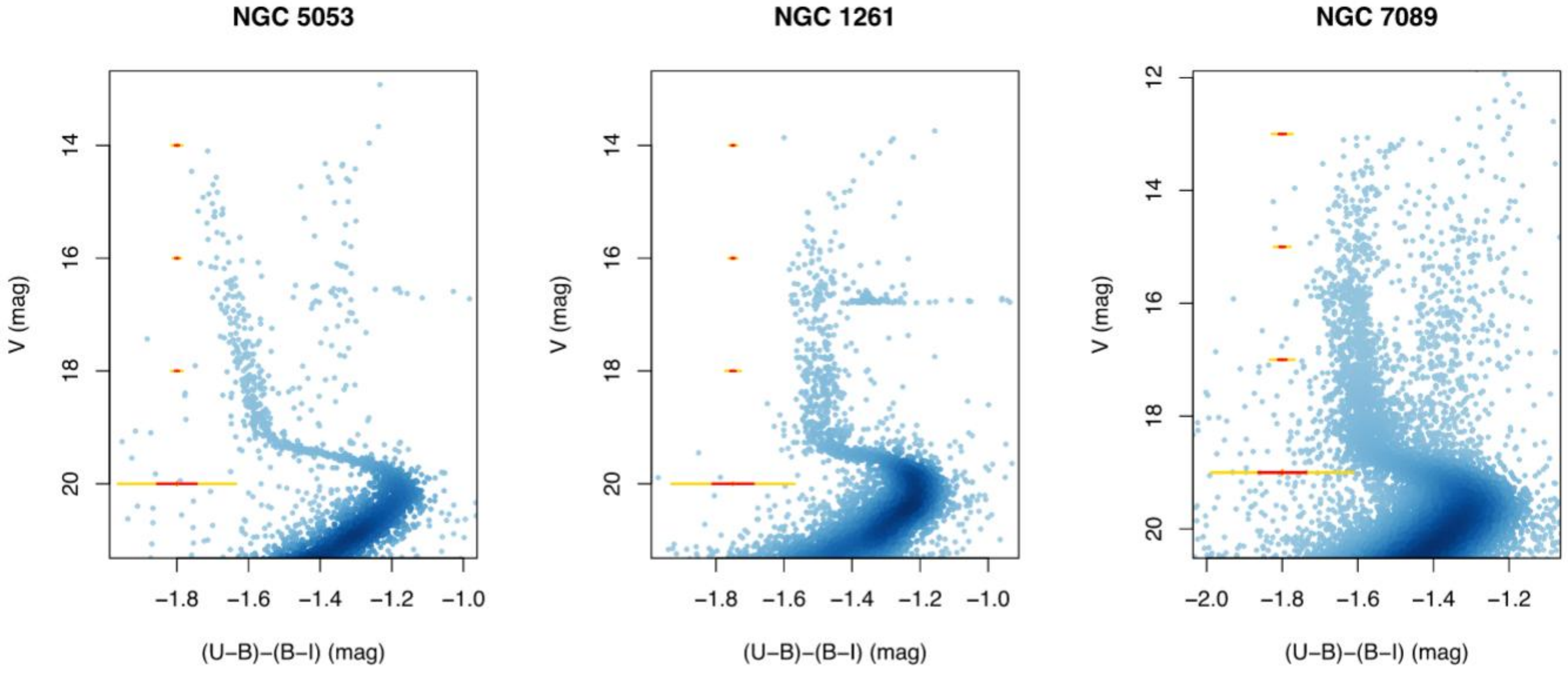
➢ Multiple RGBs (≥3 branches)(NGC 6205, NGC 1851, NGC 2808, ω Cen, 47 Tuc.)

➢ Complex but not discrete morphologies,RGB not clearly split, showing more continuous/complex structures.

➢ Blurred RGB due to external effectsCaused by differential reddening and/or field contamination .Requires dedicated treatment before detailed MP studies.

RESULTS

Multiple populations



Conclusions

Data set

- Wide-field Johnson–Cousins multiband photometry & astrometry for 48 Galactic GCs.
- Based on 93,272 images calibrated with 61,514 secondary standards.
- Typical calibration uncertainties: few mmag, ZP variations ≤ 0.04 mag.

Catalogues

- First public multiband catalogues for several GCs (esp. **U, R bands**).
- Include **quality indicators** → filtering by PSF residuals, variability, contamination.

Science potential

1. **Star selection** – tailored cleaning with radial + color–color cuts.
2. **Structural studies** – density & surface brightness profiles over large radii.
3. **Morphology** – e.g. NGC 5904 ellipticity profiles with unprecedented detail.
4. **Caution** – data depth & filters vary; allow for mmag-level calibration residuals.
5. **Multiple Populations (MPs)** – no GC can be assumed MP-free; even Terzan 8, NGC 5694 show **broad RGBs** beyond errors.

Impact

- Bridges gap between **HST high-resolution studies** and **wide surveys (Gaia, SDSS, LSST)**.
- Enables synergy with Gaia astrometry + spectroscopy for **comprehensive GC studies** in the Gaia era.

Thanks!

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PHOTOMETRY

Photometry Procedure
Instrumental Magnitudes
Measured with **DAOPHOT, ALLSTAR, ALLFRAME** (Stetson 1987, 1992, 1994).
Star Detection & PSF Modeling
Candidate stars identified in images.
Initial flux & sky background estimated via **synthetic-aperture photometry**.
PSFs derived from the **brightest, isolated, unsaturated stars**.
Iterative improvement:
Stars missed by algorithm added manually.
New PSFs obtained after provisional subtraction of all other stars.
PSF variation modeled **quadratically with position** (exceptions: early small CCDs, or no significant residuals).
Aperture Correction
PSF magnitudes corrected to aperture magnitudes via **growth-curve analysis**.

Frame Registration
Astrometric Alignment
Multiple images registered to a **common geometric system**.
Used **3rd-order polynomial transformations** (10 parameters in x & y).
Simplified for early/small CCDs (few stars, negligible distortions).