Tidal structures of six globular clusters from the Wide Field Survey Telescope (WFST) pilot survey

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Outline

Introduction

Globular clusters (GCs)

- Globular clusters (GCs) serve as fossil records of the Milky Way's formation and evolution.
- They are accreted during galaxy mergers, preserving the chemical and dynamical signatures of progenitor systems.
- Strong tidal interactions reshape GCs and produce tidal tails, which trace the Milky Way's gravitational potential and merger history.
- These tidal features often show large-scale asymmetry, requiring deep photometry and wide-field surveys for unbiased studies.
- Combining photometric selection with spectroscopic follow-up enables detailed chemodynamical studies of GC formation and evolution.

Introduction

The Wide Field Survey Telescope (WFST)

- WFST is a new-generation optical survey instrument equipped with a 2.5-m primary mirror and a 9×9k CCD array, providing a 3° field of view.
- Located at the Lenghu Observatory, WFST will survey ~8000 deg² of the Northern sky down to >24 mag depth.
- Key scientific goals include:
  1. Detecting supernovae, tidal disruption events, and electromagnetic counterparts of gravitational waves;
  2. Studying AGN variability, variable stars, and Solar System objects;
  3. Systematically mapping faint Galactic structures, such as the halo, dwarf galaxies, and GC tidal features.

➢ The WFST GC project aims to:

A. Reach the main-sequence depth of Northern GCs;

B. Investigate their morphology and tidal signatures;

C. Identify short-period variables;

D. Analyze stellar populations using future deep *u*-band data.

Outline

Data

- Pilot survey period: March–July 2024
- Bands: g and r
- Total exposures: 214 frames

Cluster	Coordinate	$R_\odot$ (kpc)	R_{GC} (kpc)	Proper motion (mas yr^{-1})	V_{los} (km s^{-1})
NGC 4147	(182°.5262, 18°.5426)	18.54 ± 0.21	20.74 ± 0.19	$(-1.690 \pm 0.014, -2.092 \pm 0.013)$	179.35 ± 0.31
NGC 5024	(198°.2302, 18°.1681)	18.50 ± 0.18	19.00 ± 0.16	$(-0.131 \pm 0.005, -1.332 \pm 0.005)$	-63.37 ± 0.25
NGC 5053	(199°.1128, 17°.7002)	17.54 ± 0.23	18.01 ± 0.20	$(-0.338 \pm 0.007, -1.214 \pm 0.007)$	42.82 ± 0.25
NGC 5272	(205°.5484, 28°.3772)	10.18 ± 0.08	$12.09 \pm .06$	$(-0.153 \pm 0.007, -2.679 \pm 0.007)$	-147.20 ± 0.27
NGC 5904	(229°.6384, 2°.0810)	7.48 ± 0.06	6.27 ± 0.02	$(4.073 \pm 0.006, -9.872 \pm 0.006)$	53.50 ± 0.25
NGC 6341	(259°.2807, 43°.1359)	8.50 ± 0.07	9.85 ± 0.04	$(-4.934 \pm 0.012, -0.630 \pm 0.012)$	-120.55 ± 0.27

Cluster	Filter	Exp. time (s)	Epoch	FWHM (arcsec)
NGC 4147	g/r	60/60	12/15	~2.52/1.36
NGC 5024	g/r	60/60	12/15	~2.05/1.24
NGC 5272	g/r	30/30	25/25	~1.59/1.18
NGC 5904	g/r	30/30	25/25	~1.74/1.35
NGC 6341	g/r	30/30	30/30	~1.37/1.70

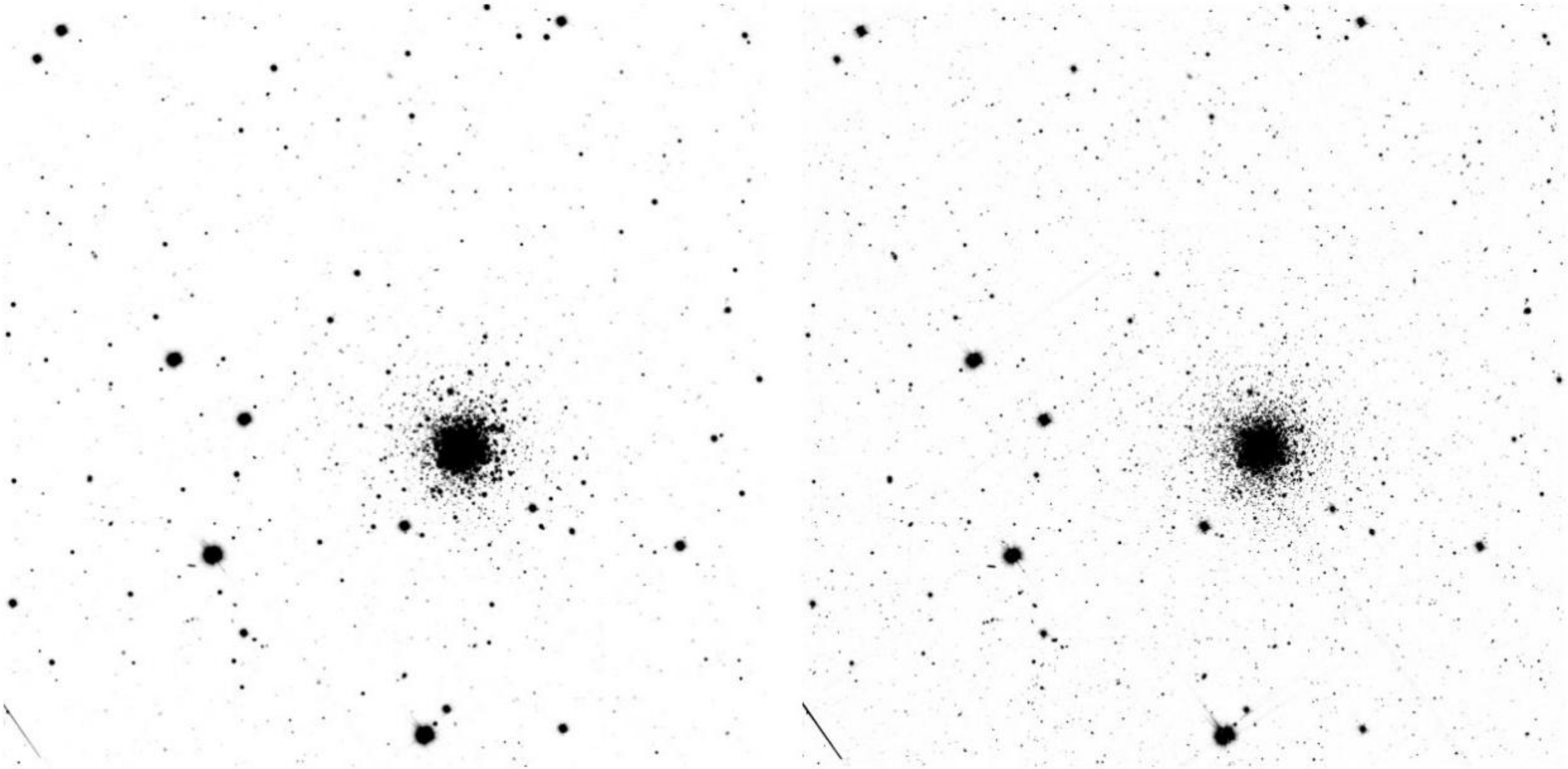


Figure 1. The stacked g (left) and r (right) images of central $\sim$100 arcsec $\times$ 100 arcsec of NGC 4147 are presented. The r-band exposure exhibits greater depth, primarily attributable to more favourable weather conditions during observation.

Outline

Data Reduction

WFST Data Reduction and Photometry Workflow

1. **Bias and Flat Calibration(***master bias, master flat)*
2. **photometry** is performed on the calibrated exposures primarily using the **PHOTUTILS**
3. **Estimate background** using **σ-clipped BACKGROUND2D** (200×200 pixel grid), Interpolate and subtract background map to produce clean science images
4. **Source Detection and PSF Characterization**
   Perform deeper detection using **DAOSTARFINDER**
   Select reliable sources with $(roundness_1^2 + roundness_2^2 < 0.3)$
   Cross-match detections with **Pan-STARRS DR2** (16–20 mag)
   Fit PSF using **CIRCULARGAUSSIANPRF** model on 15×15 pixel cutouts
   Derive per-exposure PSF from σ-clipped mean FWHM across CCDs
5. **PSF Photometry**
   Conduct PSF-fitting photometry with PSFPHOTOMETRY (fixed FWHM)
   Measure source position, PSF flux, and photometric quality metrics

Data Reduction

Photometric and Astrometric Calibratio

- The well-measured sources $-0.1 < \mathrm{cfit} < 0.1,$

  $2.5 < \log_{10}(\mathrm{flux}) < 5$ $\quad$ $\mathrm{qfit} < 0.1,$

  SNR ~ 10 $\quad$ $\mathrm{flags} = 0,$

  $\mathrm{mag_{err}} < 0.1.$

- cross-matched with the **Pan-STARRS DR2** catalogue to calibrate the **photometric zero-point**.
- cross-matched with the **Gaia DR3** catalogue to calibrate the **astrometric positions** and the world coordinate system (WCS) of the exposure.

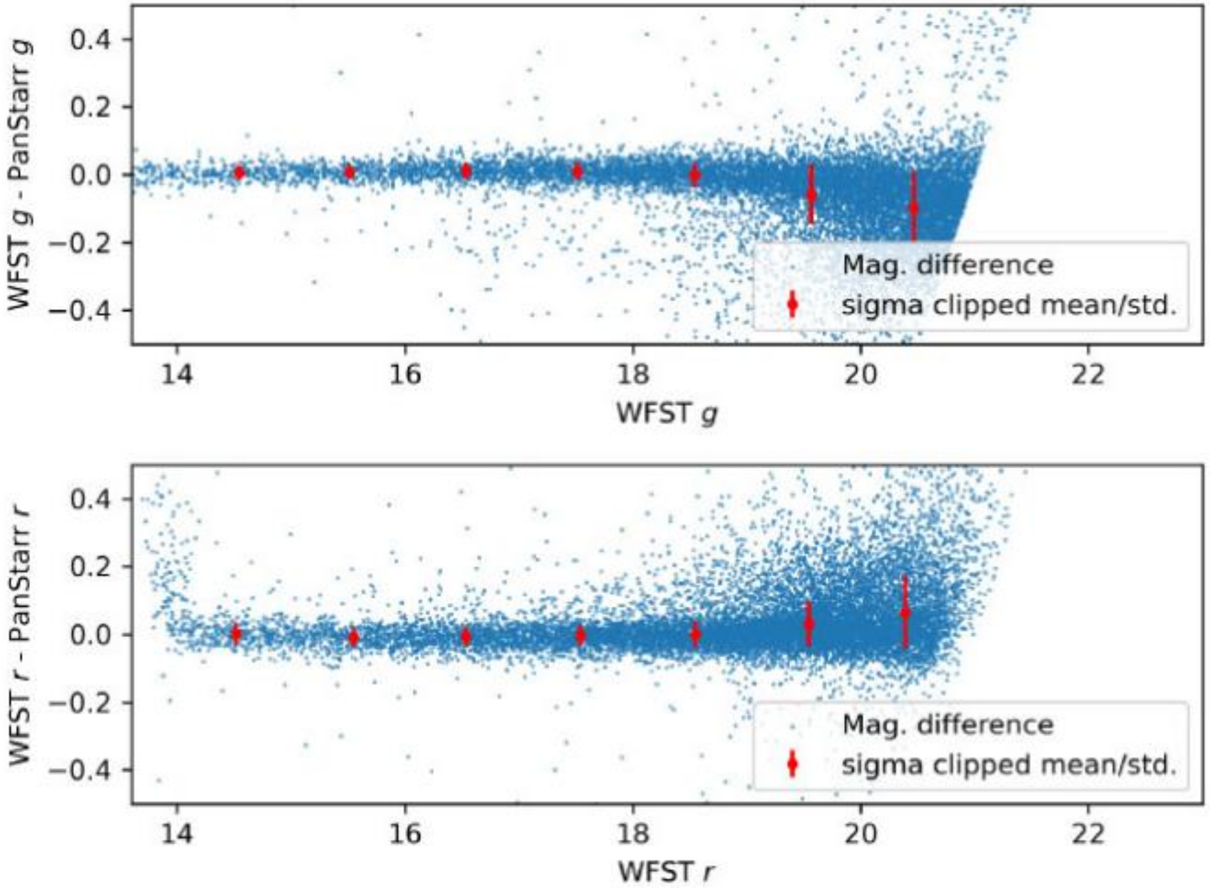


Image Stacking and Final Catalogues

- Stack calibrated exposures using **SWARP** with variance-based weights
- Perform photometry on stacked g and r images
- Cross-match multiband data → generate final source catalogues

Data Reduction

Cluster members selection

- **Construct CMD:** Build the colour–magnitude diagram (CMD) using two-band photometry.
- **Central Region Selection:**
  Select stars within 0.1° of cluster center as the initial sample.
  Apply Gaia DR3 proper motion and parallax cuts to remove obvious field stars.
- **clustering algorithm HDBSCAN (Pedregosa et al. 2011)**
  Compare all stars to fiducial sample in CMD using distance metric

$$d = \sqrt{((g-r)-(g-r)_i)^2 + (r-r_i)^2}.$$

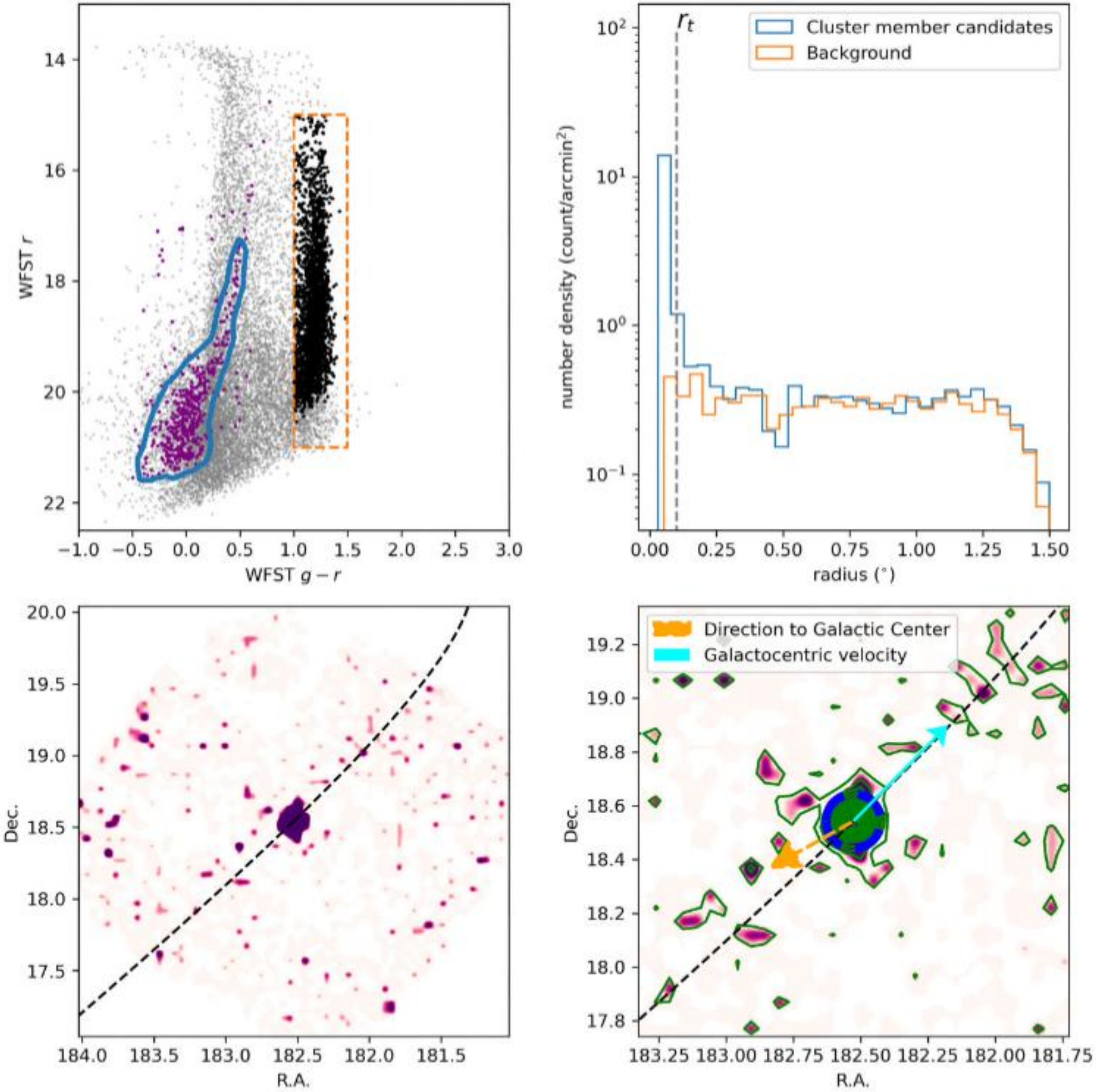
  Select candidate members with ≥3 fiducial stars satisfying distance threshold ($d < 0.02$, relaxed to 0.08 for NGC4147).
- **Background Estimation and Final Density Map:**
  Select CMD region dominated by Galactic thick disc.
  Compute background number density and scale to match cluster density at 0.6°–1.2° from cluster center.
  Subtract scaled background from candidate stars to obtain clean member density distribution.
- **Notes on Uncertainties:**
  Photometric errors, CCD effects, PSF variations.
  Differential reddening is negligible for these clusters.

Outline

NGC4147

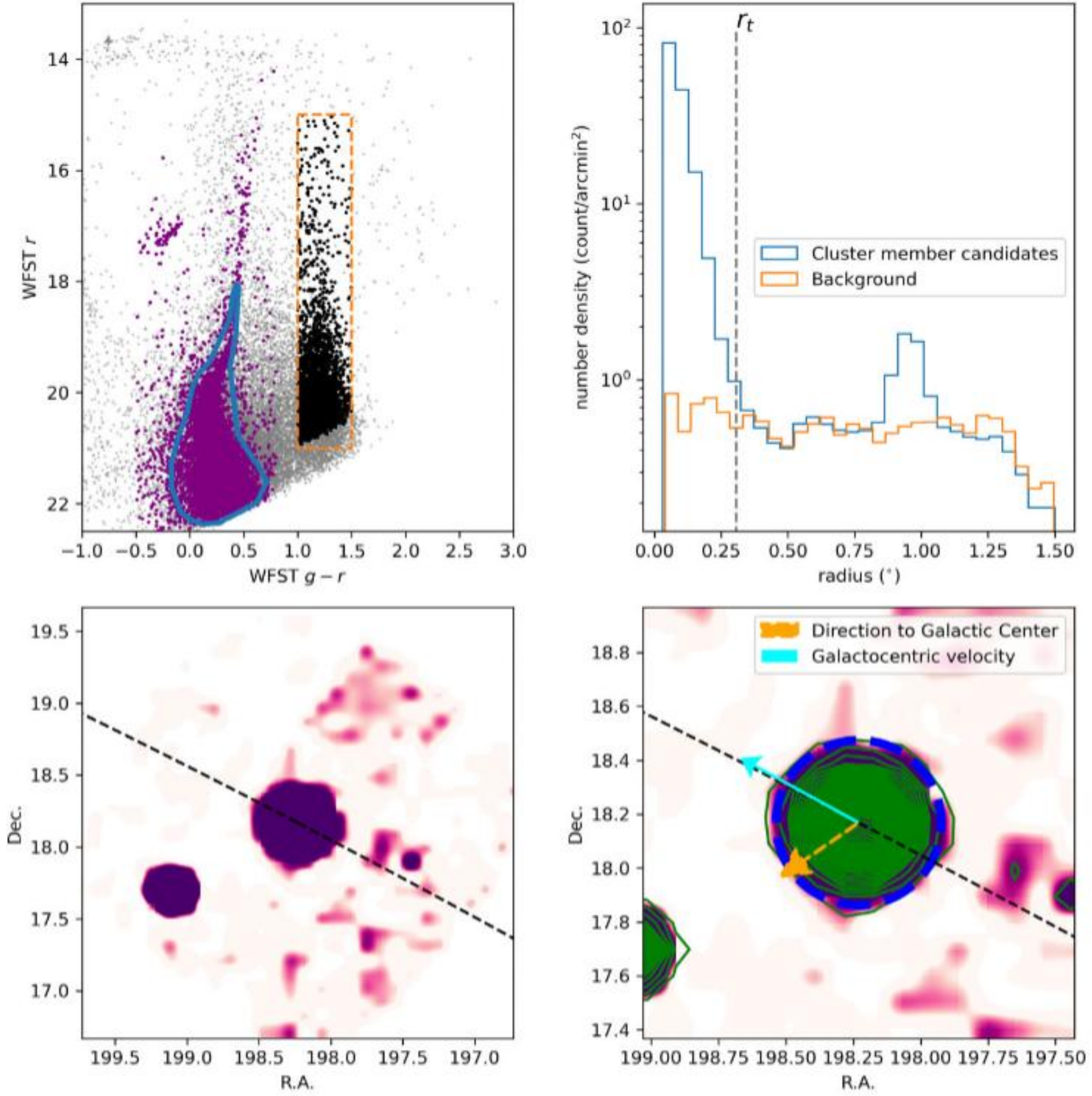
Morphological Features

- Heliocentric distance: 18.54 ± 0.21 kpc
- Orbit eccentricity: e ≈ 0.87
- Clear **extension of member stars beyond the tidal radius (~0.2°)**
- **Arm-like overdensity** consistent with previous detections
- **Northern arm** aligns with **Galactocentric velocity**, extends beyond **0.5°**
- **Eastern weak arm** suggests **multi-arm structure**, consistent with simulations (Montuori et al. 2007)
- **Low-significance overdensities** along the orbit direction may trace **tidal tails**



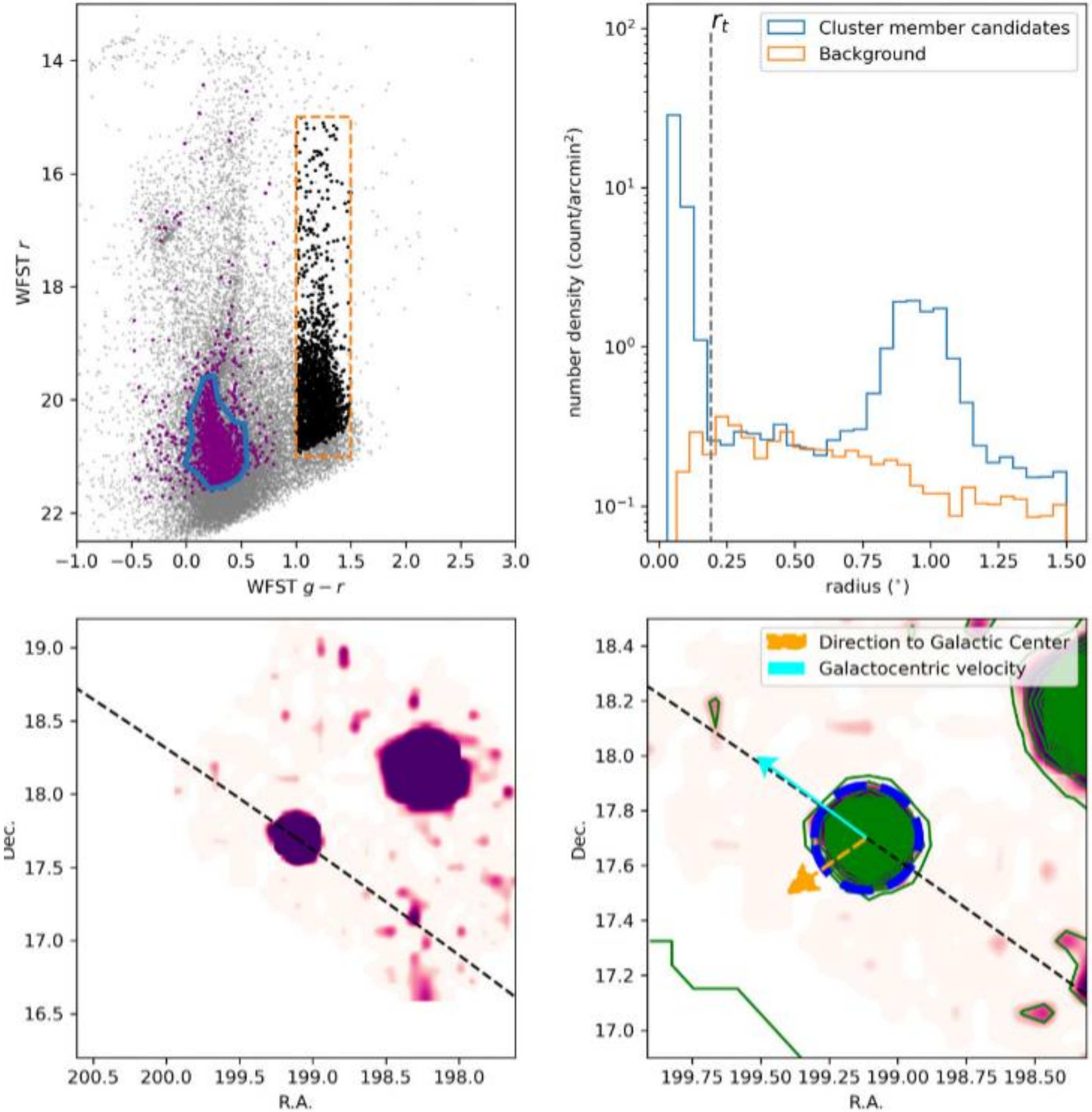
NGC5024

- Heliocentric distance: **18.50 ± 0.18 kpc**
- Orbital eccentricity: **e ~ 0.42**
- Tidal features: Extended stellar extensions beyond tidal radius (0.3°–0.4° annulus)
- Detected high-significance outer overdensities at:
- **(RA, Dec.) = (197.60°, 18.05°)**
- **(RA, Dec.) = (197.40°, 18.00°)**
- Overdensities aligned with orbital path → likely tidal debris



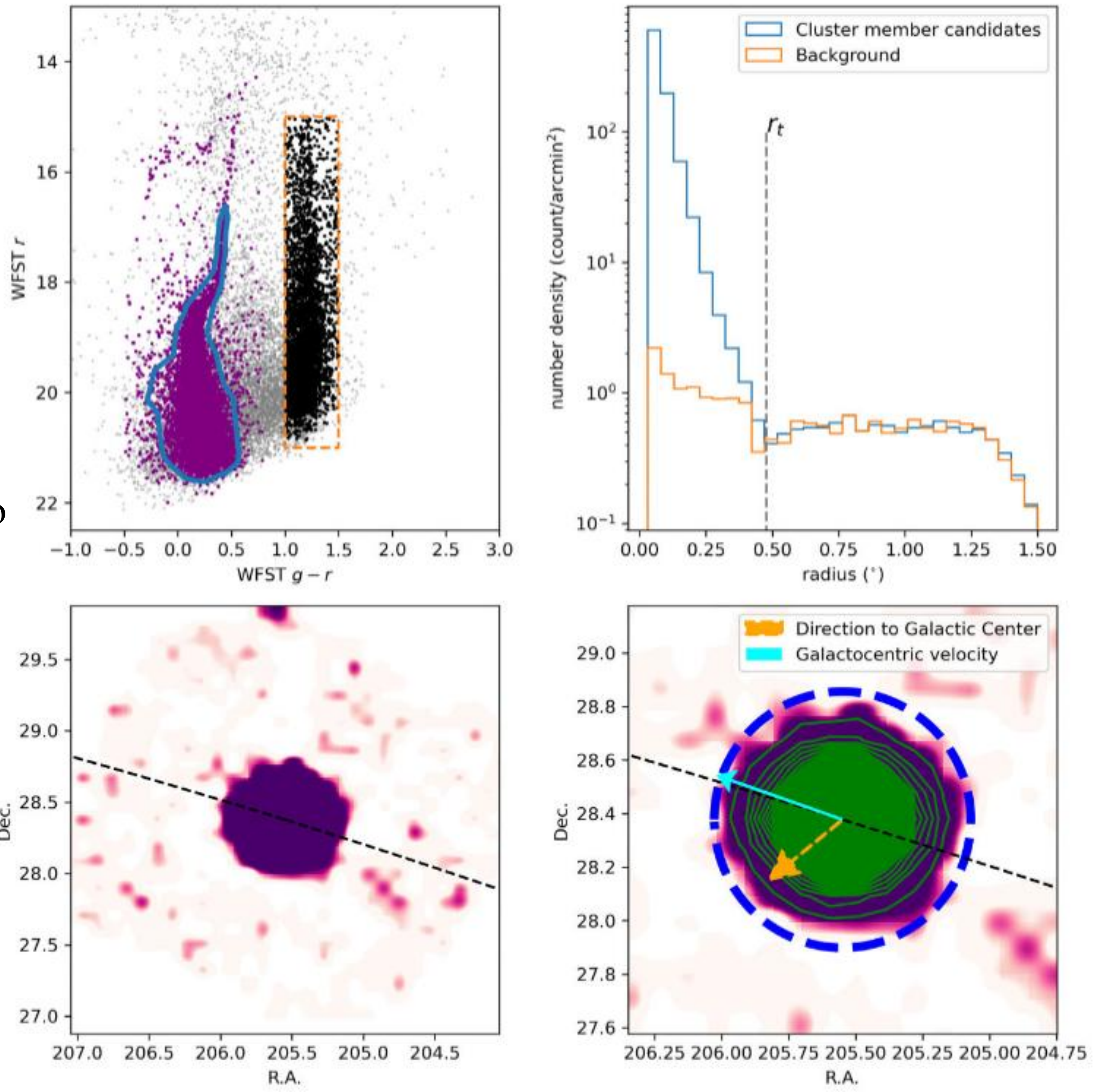
NGC5053

- Heliocentric distance: **17.54 ± 0.23 kpc**
- Orbital eccentricity: **e ~ 0.25**
- Photometric overlap with NGC 5024 → minor contamination in sample
- Mild elongation along western axis
- Overdensity detected at **(RA, Dec.) = (197.75°, +17.40°)** → probable tidal debris



NGC5272

- Heliocentric distance: **10.18 ± 0.08 kpc**
- Orbital eccentricity: **e ~ 0.50**
- No clear extension beyond tidal radius
- SE direction: intriguing aligned overdensities (RA, Dec.) = (204°.7, +27°.9)
    - Three aligned high-density regions. Close to cluster orbit, possible tidal extension
- Opposite direction: slight elongation, potentially symmetric tidal tail
- Low brightness and spatial coherence suggest a faint tidal feature
- If confirmed, could provide insight into cluster's dynamical history



NGC5904

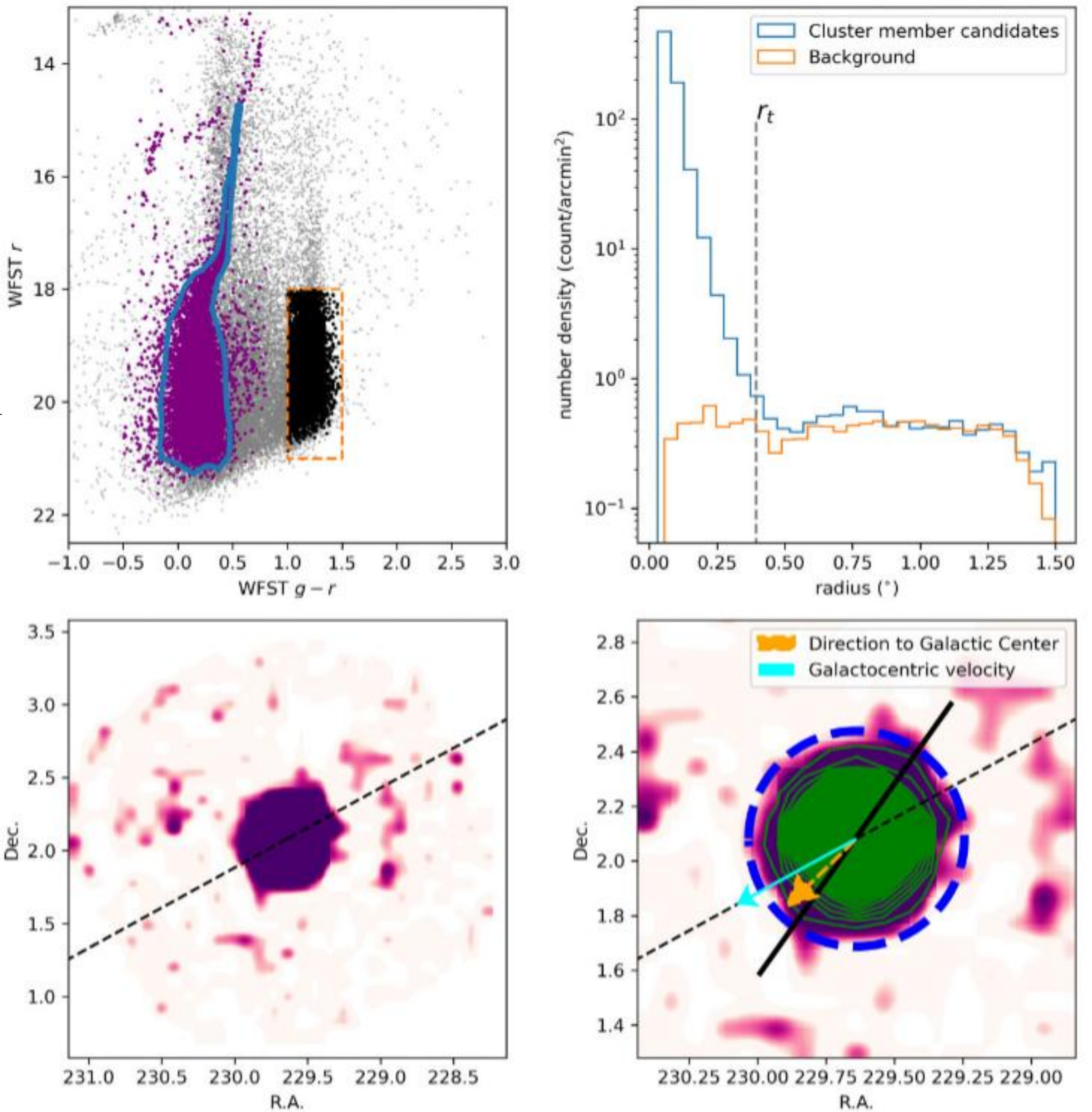
- Heliocentric: **7.48 ± 0.06 kpc**
- Galactocentric: **6.27 ± 0.02 kpc**
- Orbital eccentricity: **e ~ 0.76**

Tidal Features & Density Distribution

- Clear stellar extensions beyond tidal radius (0.6°–0.8° annulus)
- Peripheral deformation with north–south tidal arms
- Multiple overdensities beyond tidal radius, Symmetric features at (RA, Dec.) = (230°.6, +2°.2) east and (229°.1, +1°.9) west

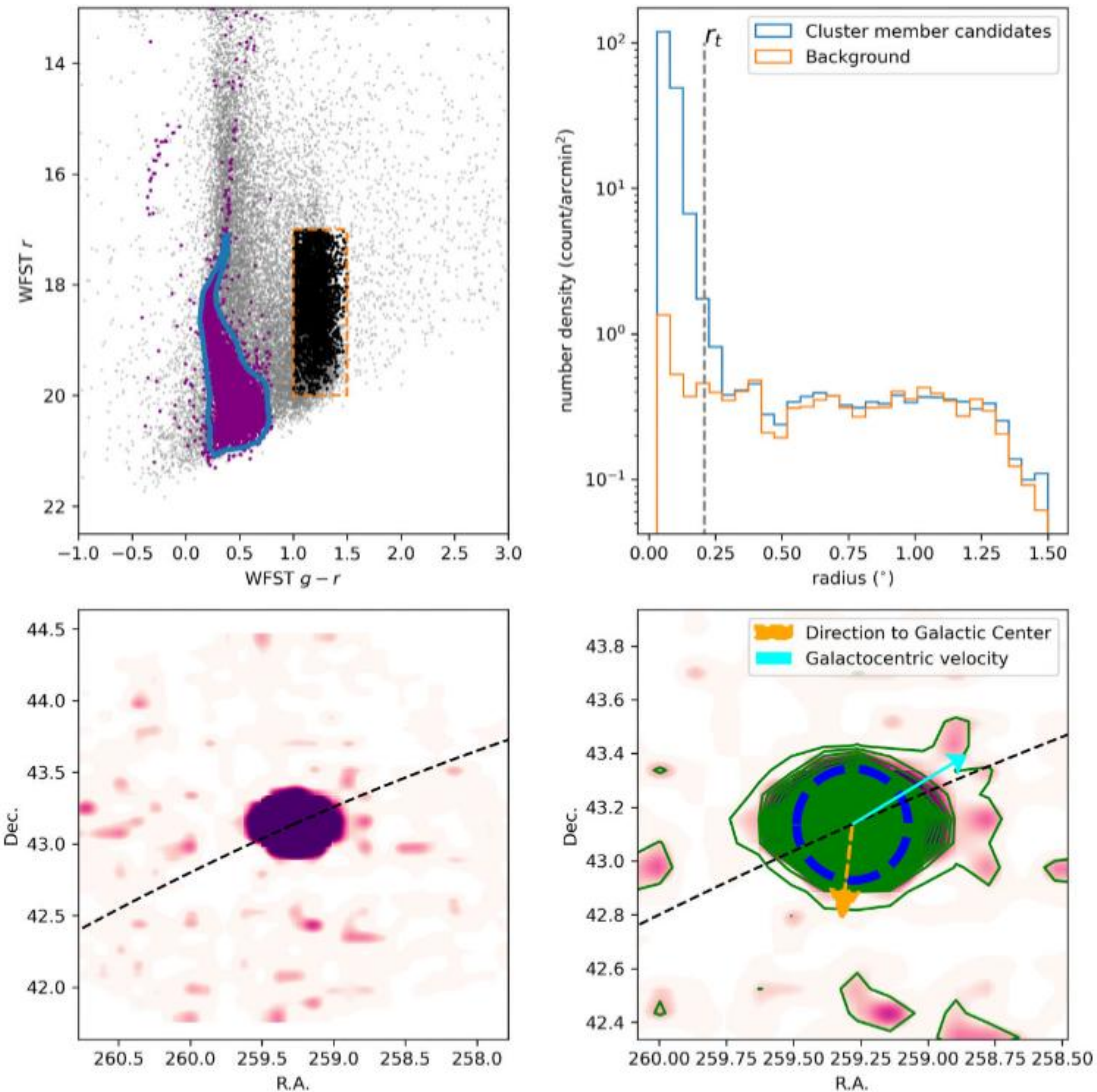
Dynamics vs. Tidal Features

- Structures aligned with known rotational axis (Lanzoni+2018)
- North–south tidal arms ≈ rotation axis direction
- East–west symmetric overdensities ≈ perpendicular to rotation axis
- Suggests link between internal rotation and external tidal morphology



NGC6341

- Heliocentric: **8.50 ± 0.07 kpc**
- Galactocentric: **9.85 ± 0.04 kpc**
- Orbital eccentricity: **e ~ 0.79**
- Cluster member candidates detected beyond tidal radius
- Spatial distribution shows elliptical density extension
- Low-confidence three-branched extension along Galactocentric velocity direction
- Physical reality uncertain due to low surface brightness



Outline

Conclusions

- WFST completed a pilot survey, conducting deep imaging of five GCs in the Northern sky.
- Each cluster's center was covered within a 1.5° radius; exposure limits were ~21.5–22 mag, with future surveys expected 2 mag deeper.
- Member candidates were selected from specific CMD regions; background density estimated from thick disc fields.
- NGC 4147 shows northern and southern tidal arms and a mild multi-arm structure, potentially linked to the Milky Way or the Sgr stream.
- NGC 5024, NGC 5053, and NGC 5272 show no direct tidal connections, but potential overdensities exist near their orbital paths.
- NGC 5904 exhibits symmetric north-south arm-like structures aligned with its rotational axis; overdensities may be related to velocity gradients along tidal arms.
- NGC 6341 displays an elliptical contour beyond the tidal radius, possibly from internal rotation or tidal arm extensions; peripheral stars may no longer be gravitationally bound.
- WFST demonstrates strong capabilities for deep photometry, crucial for GC population studies, multiple populations, and time-series variable star investigations.

Thanks！