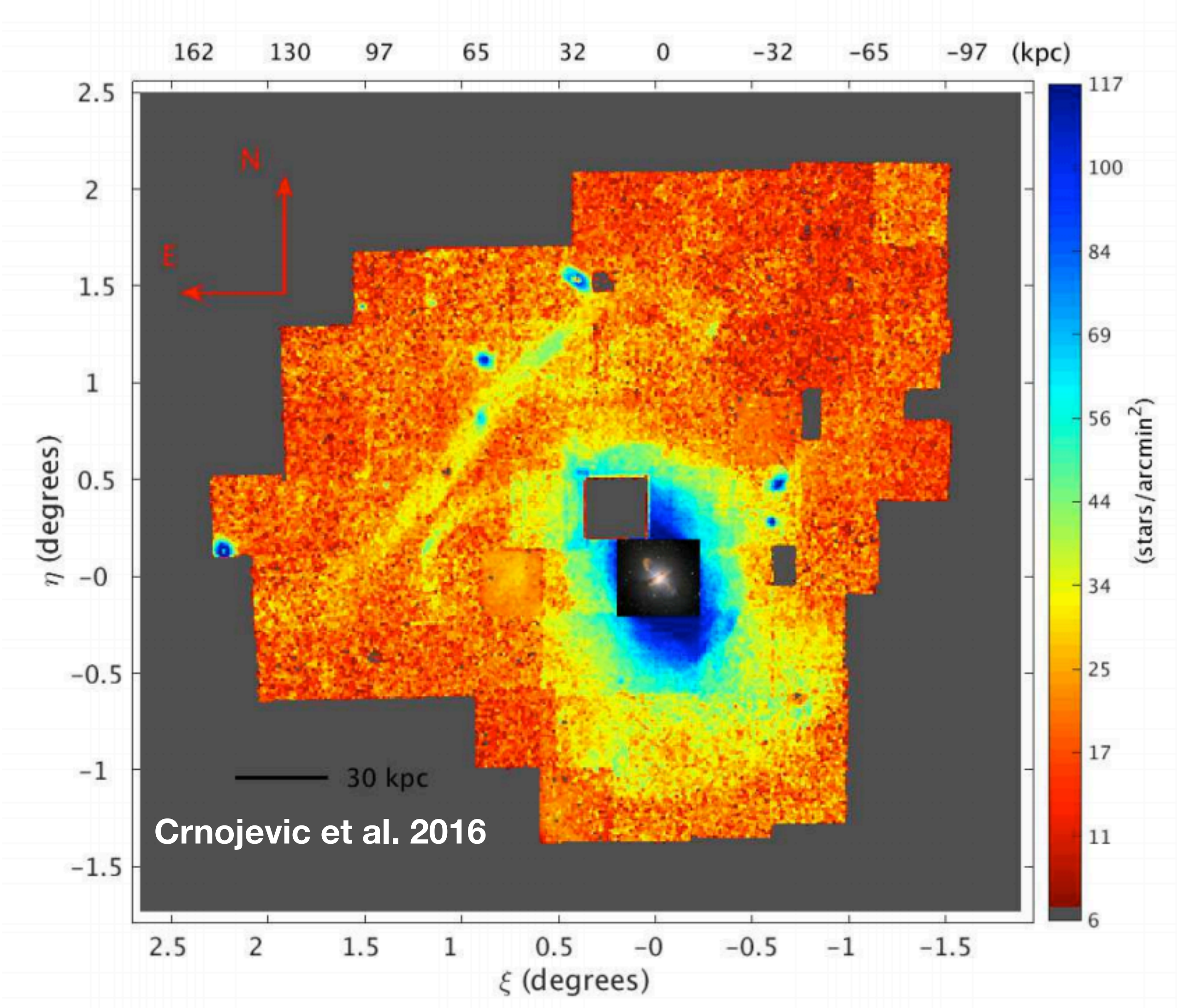
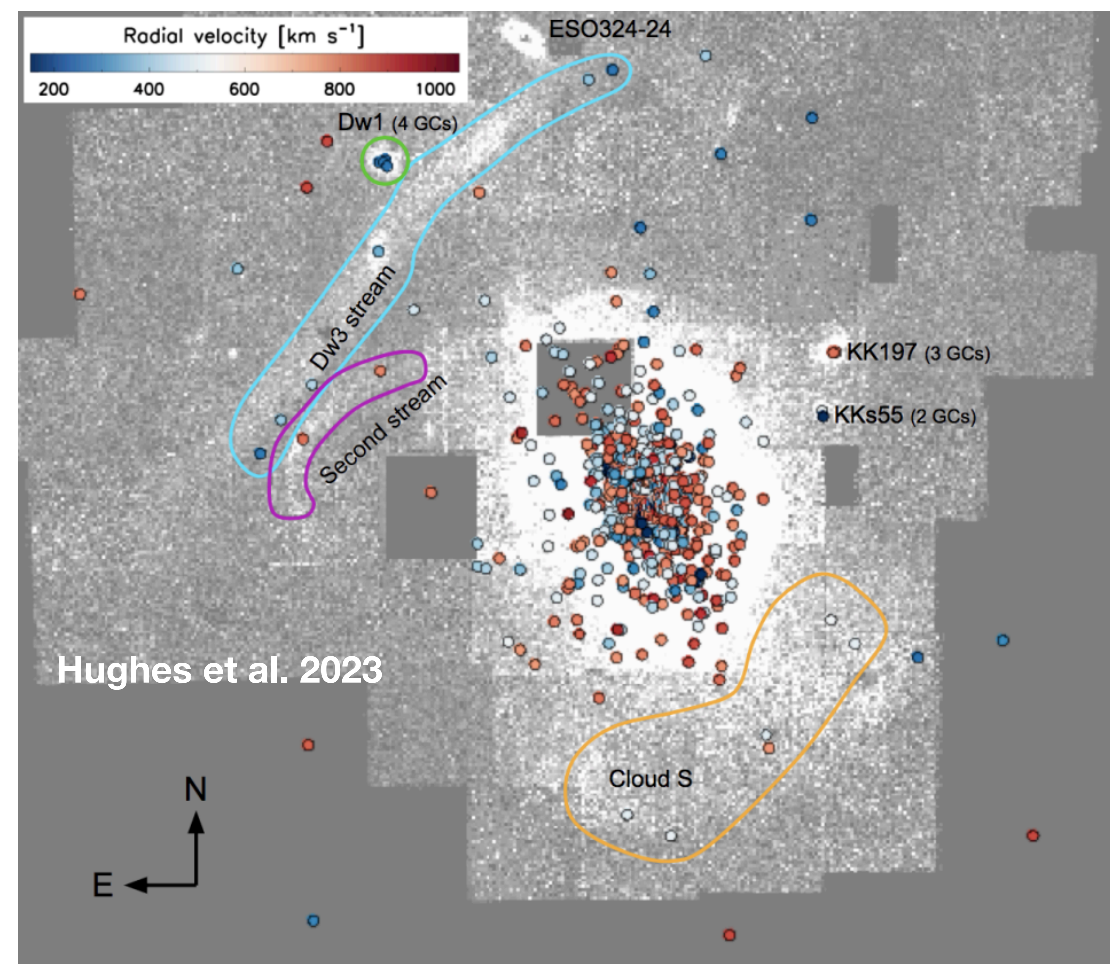
A Novel Technique for Identifying Globular Clusters in the Local Universe: Centaurus A





D. Sand & Allie Hughes (U of Arizona)

N. Caldwell, D. Crnojevic, A. Dumont, A. Seth, J. Strader, K. Voggel

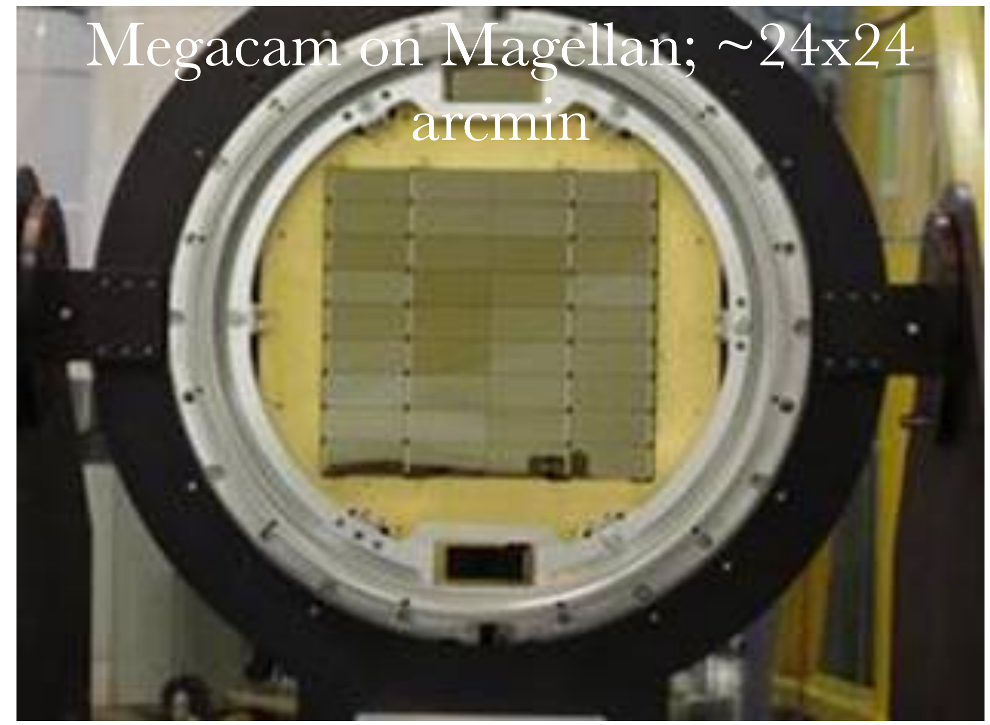
B. Mutlu-Pakdil, C. Fielder, M. Jones

Rare Gems May 2024

See: Hughes+21, 23. Also Voggel+20, Dumont+22,23

- A new globular cluster identification technique that combines high-res ground-based data + color information + Gaia astrometric information.
- Apply to Centaurus A (D=3.8 Mpc), the nearest accessible elliptical galaxy.
- Spectroscopic follow-up has identified 122 new CenA GCs.
- Correlate GCs with stellar substructures, look for kinematic signals.
- Future!! Looking to the nearby universe to build maps of structure formation, GC kinematics, mass measurements, etc.

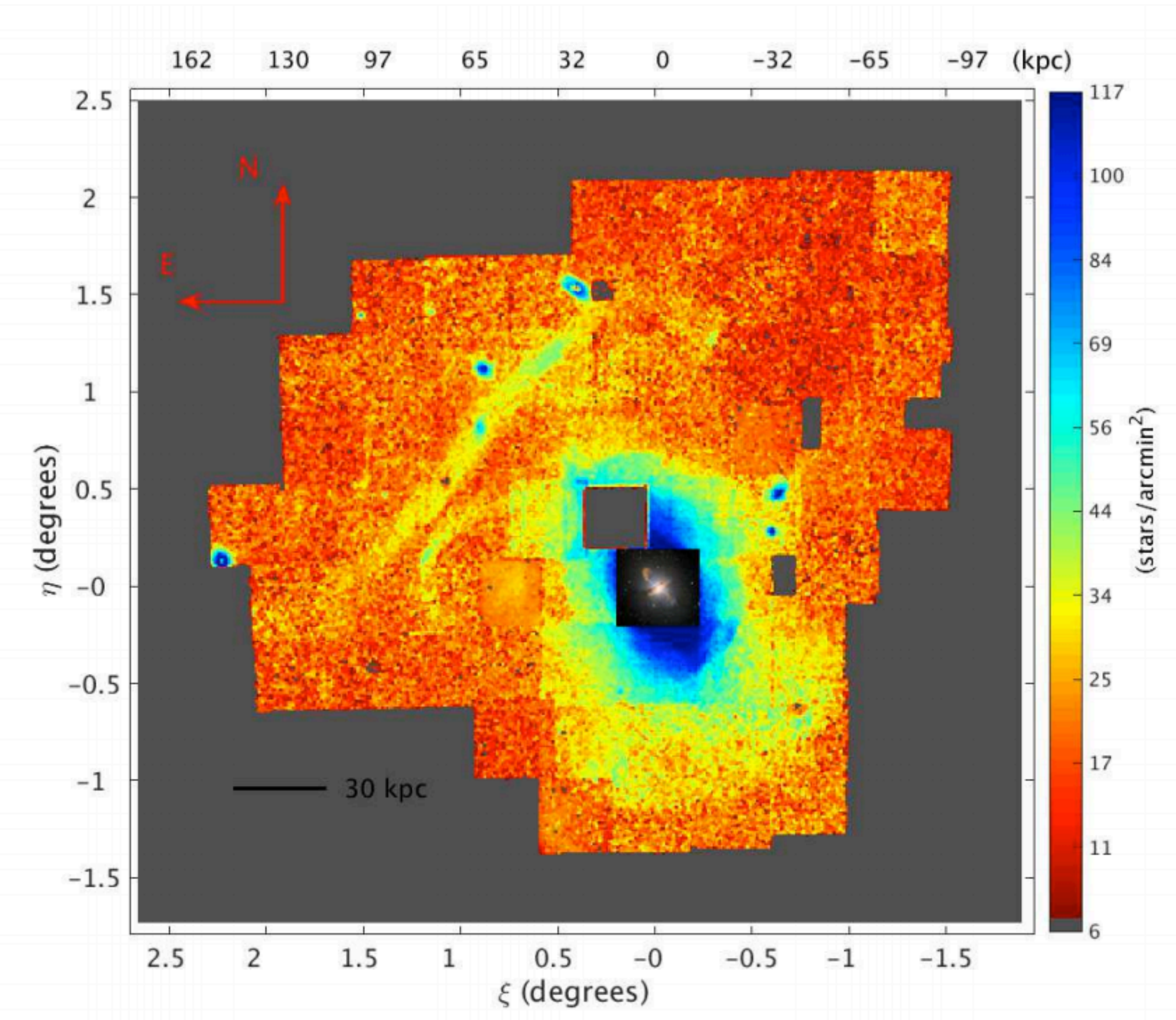
Observing Galaxy Substructure — dwarfs, streams, etc — to Probe Structure Formation



The Panoramic Imaging Survey of Centaurus and Sculptor (PISCeS)

- Deep imaging (r~26.5) in g,r out to 150 kpc in two of our next nearest neighbors (NGC253 and CenA).
- ~1.5-2 mag below TRGB
- Directly comparable to PAndAS, MW and simulations.

The field of Streams of CenA



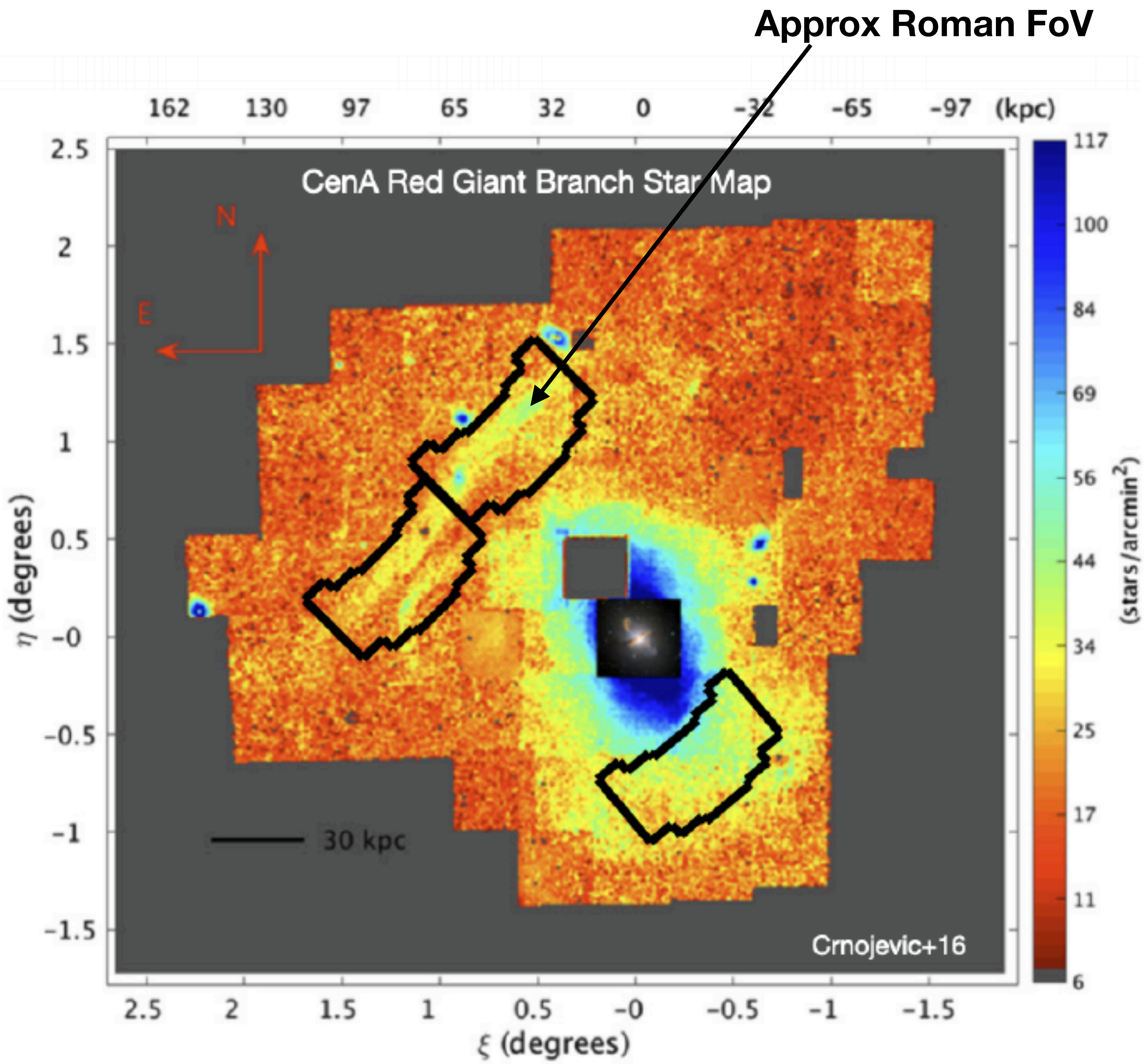
Crnojevic et al. 2016

A clearly disrupting dwarf galaxy -- detected not by low surface brightness measurements but in individual resolved stars!

There are clearly other streams emerging.

All in resolved RGB stars

The field of Streams of CenA

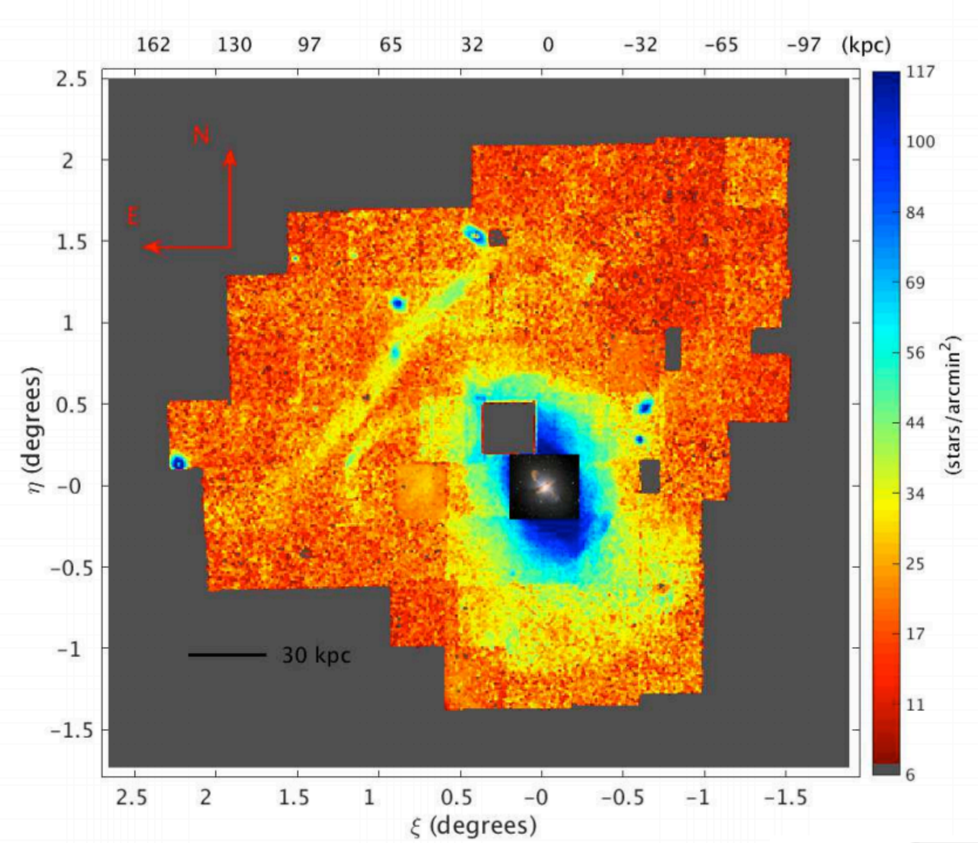


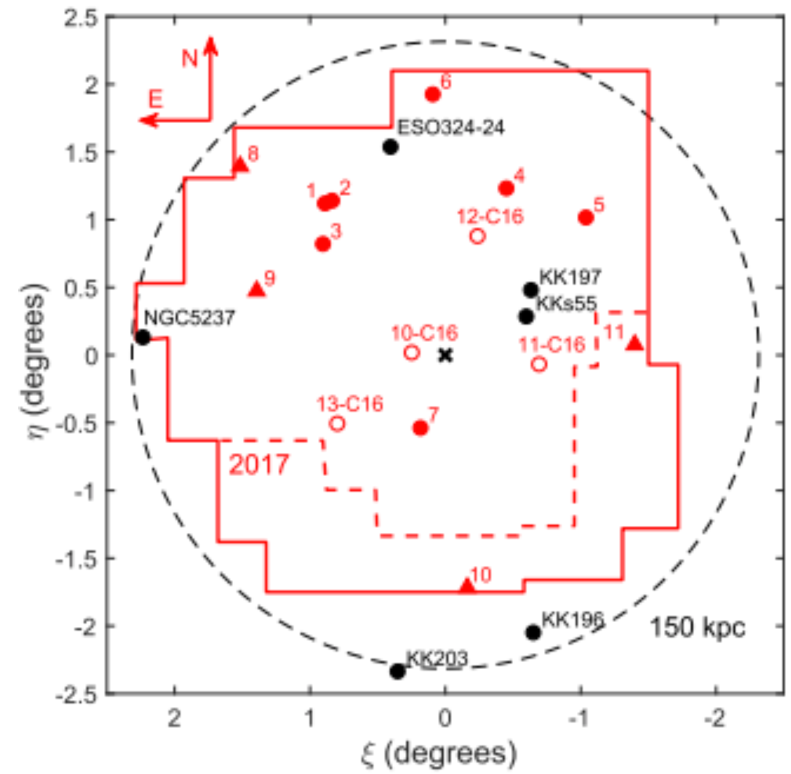
Crnojevic et al. 2016

Full Halo Mapping of NGC5128 with Roman WFI:

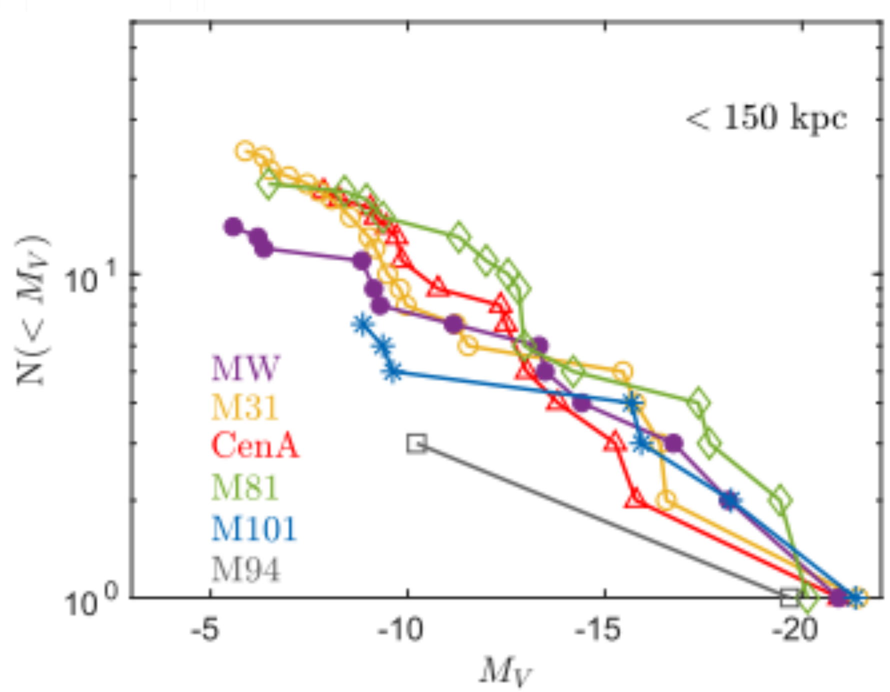
- Complete satellite luminosity function down to MV~-4 mag, deep into regime to test DM models.
- Full stellar halo luminosity/mass measurement! Prediction of galaxy formation models
- Complete GC identification ~3 mag below the peak of the GC luminosity function.
- 45 WFI pointings, 90 hours.

Eleven new CenA dwarfs down to M_V~-7.5 mag





Satellite luminosity function comparable to M81 and M31

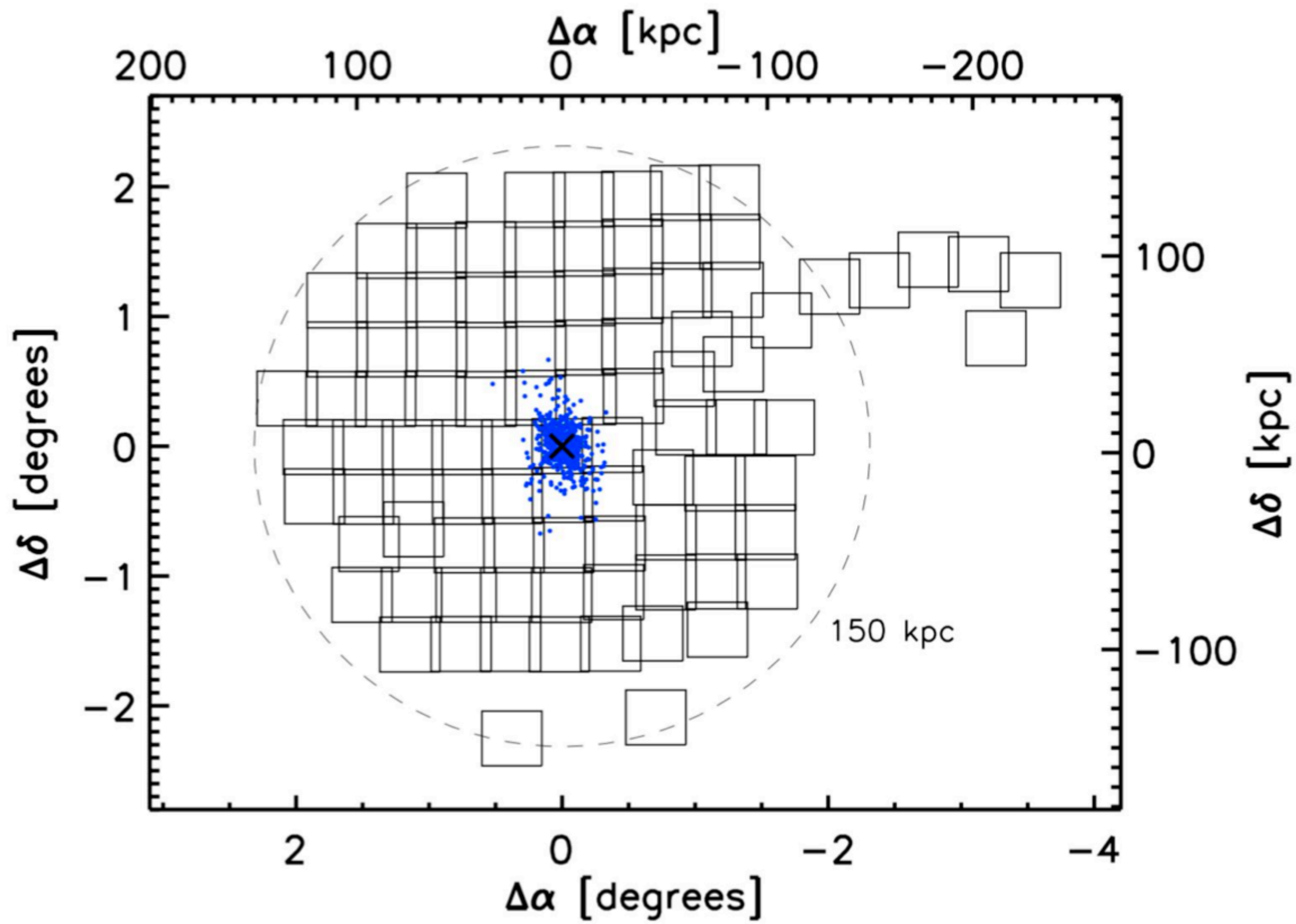


Crnojevic et al. 2019

CenA GC status (as of last year)

557 confirmed GCs in CenA, almost all within ~35 arcmin (~40 kpc)

May have up to ~1500-3000 GCs in total.

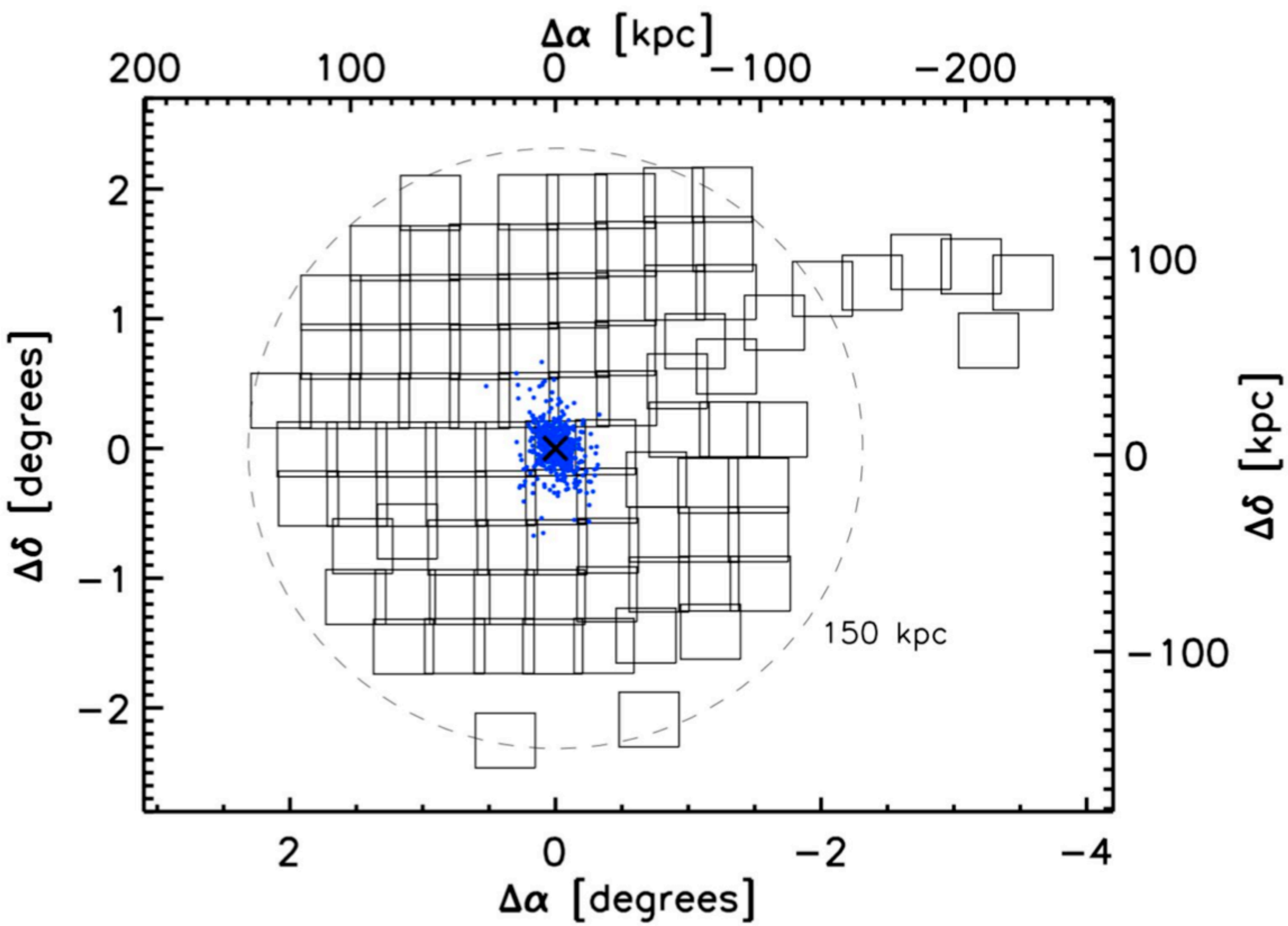


Why study extragalactic globular clusters?

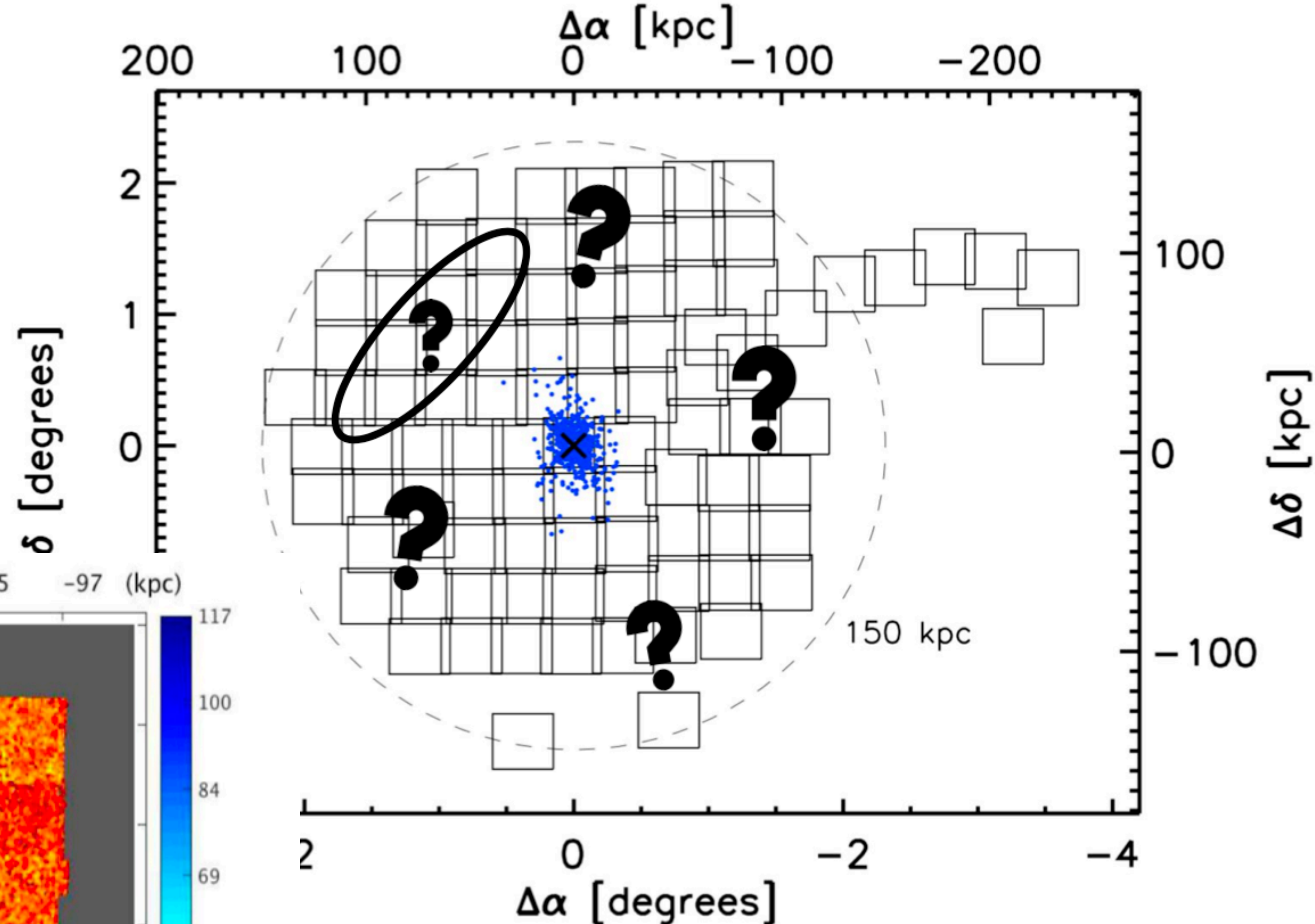
- GCs trace the underlying stellar halo — it's extent and metallicity.

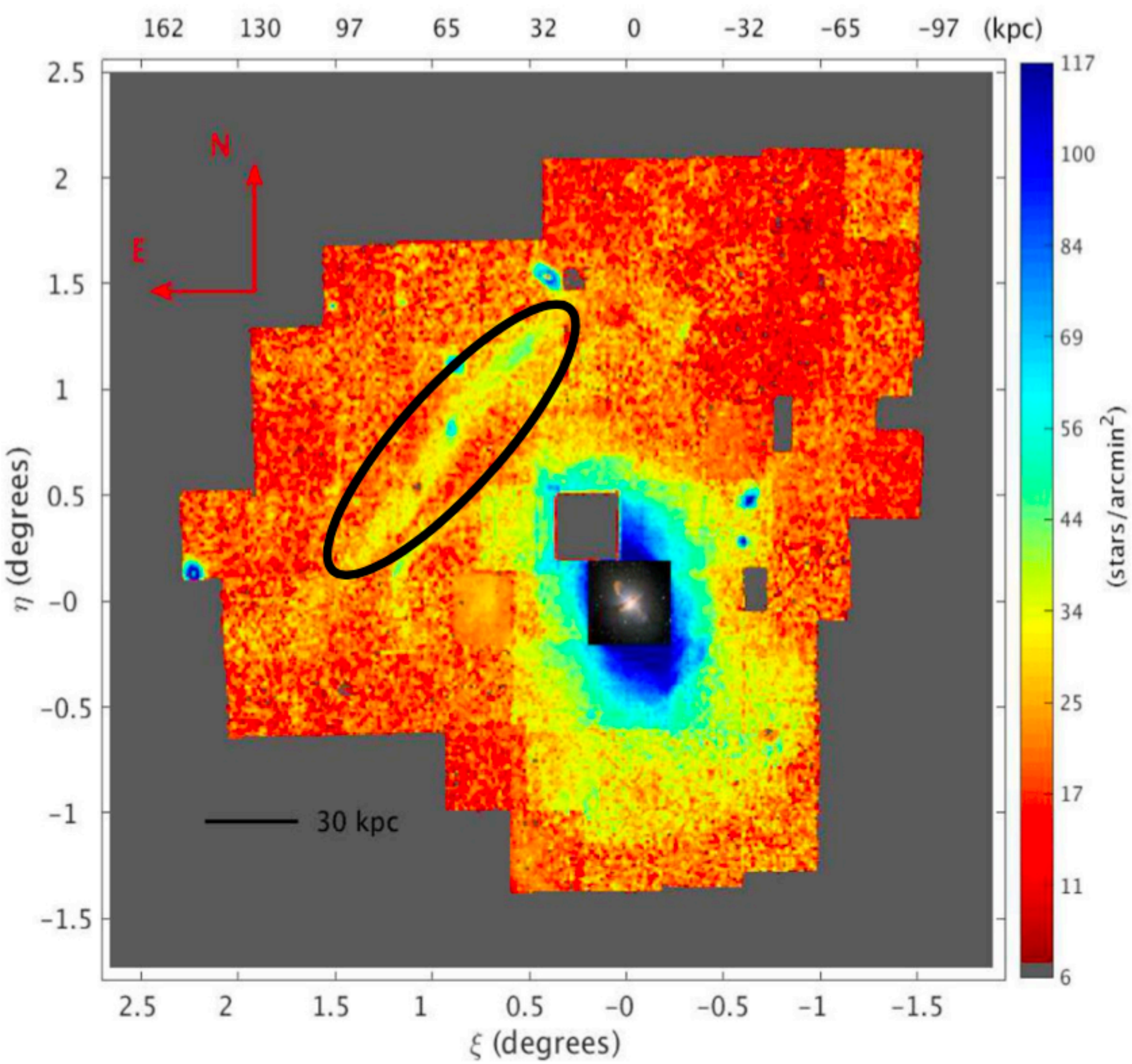
- Bright, compact <M_V>=-7. GCs are 1-20 pc in size, corresponds to ~0.1-1.1" at CenA.

- GC kinematics can be used to measure overall mass & mass profile of galaxy out to larger radii. Can test stellar mass — halo mass relation: essential test of hierarchical galaxy formation simulations.



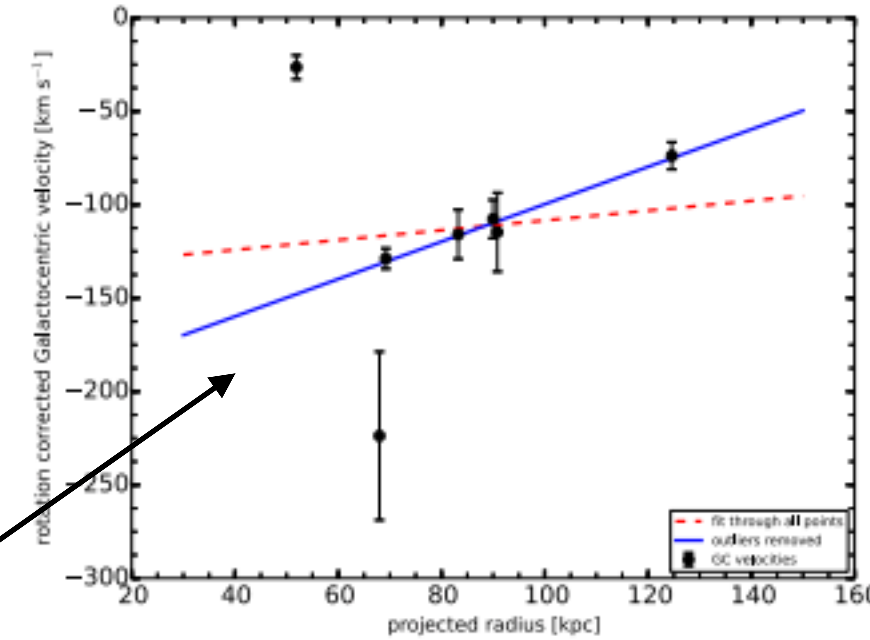
Unexplored outer Halo

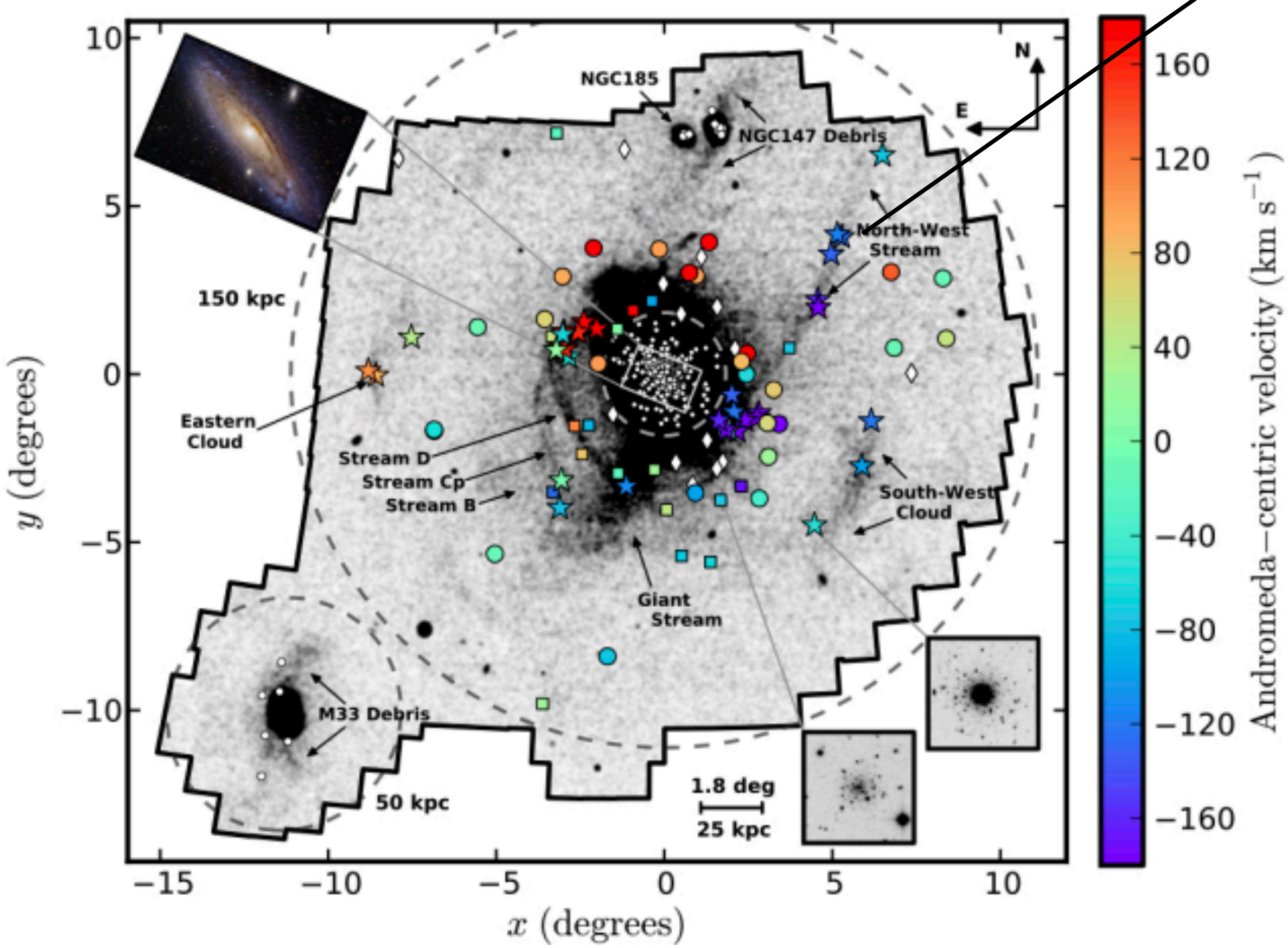


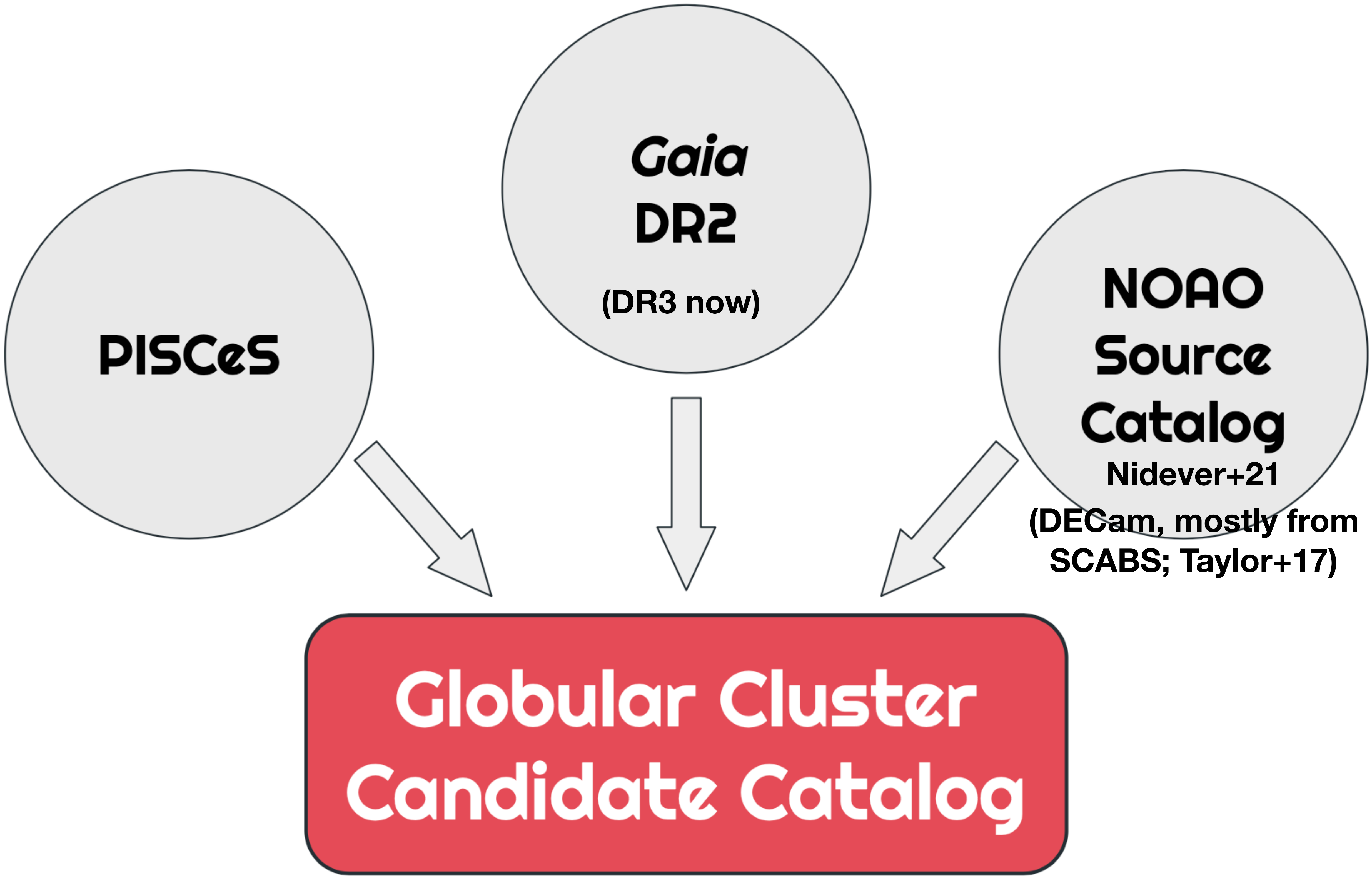


Unexplored outer Halo Compare to M31

(Veljanoski+14,Mackey+19)

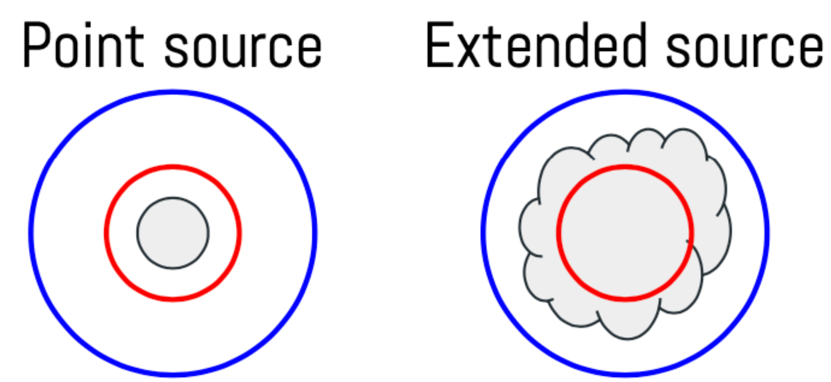


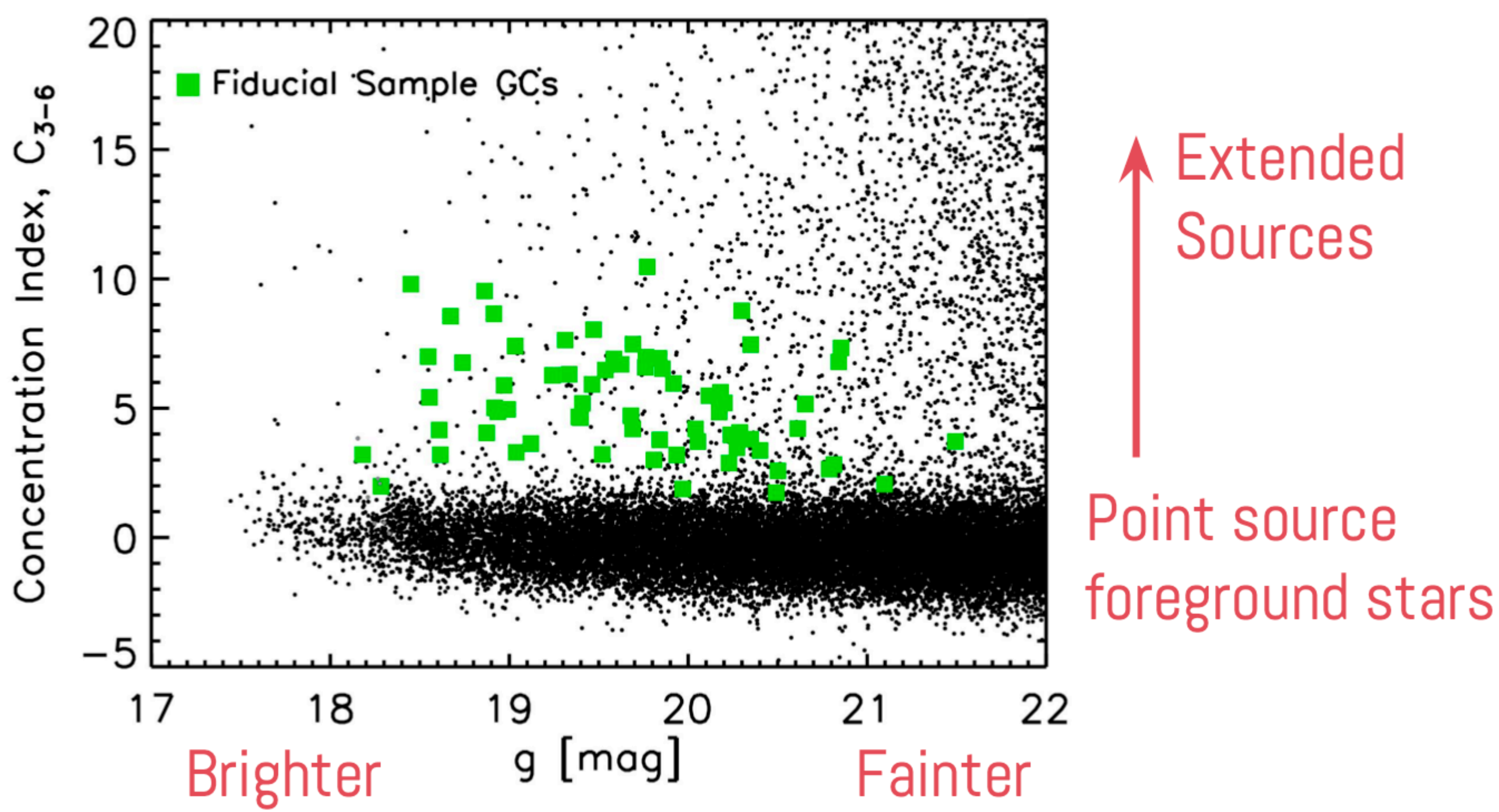



PISCeS
Gaia
DR2
(DR3 now)
NOAO
Source
Catalog
Nidever+21
(DECam, mostly from
SCABS; Taylor+17)
Globular Cluster
Candidate Catalog

1. Find extended sources in PISCeS

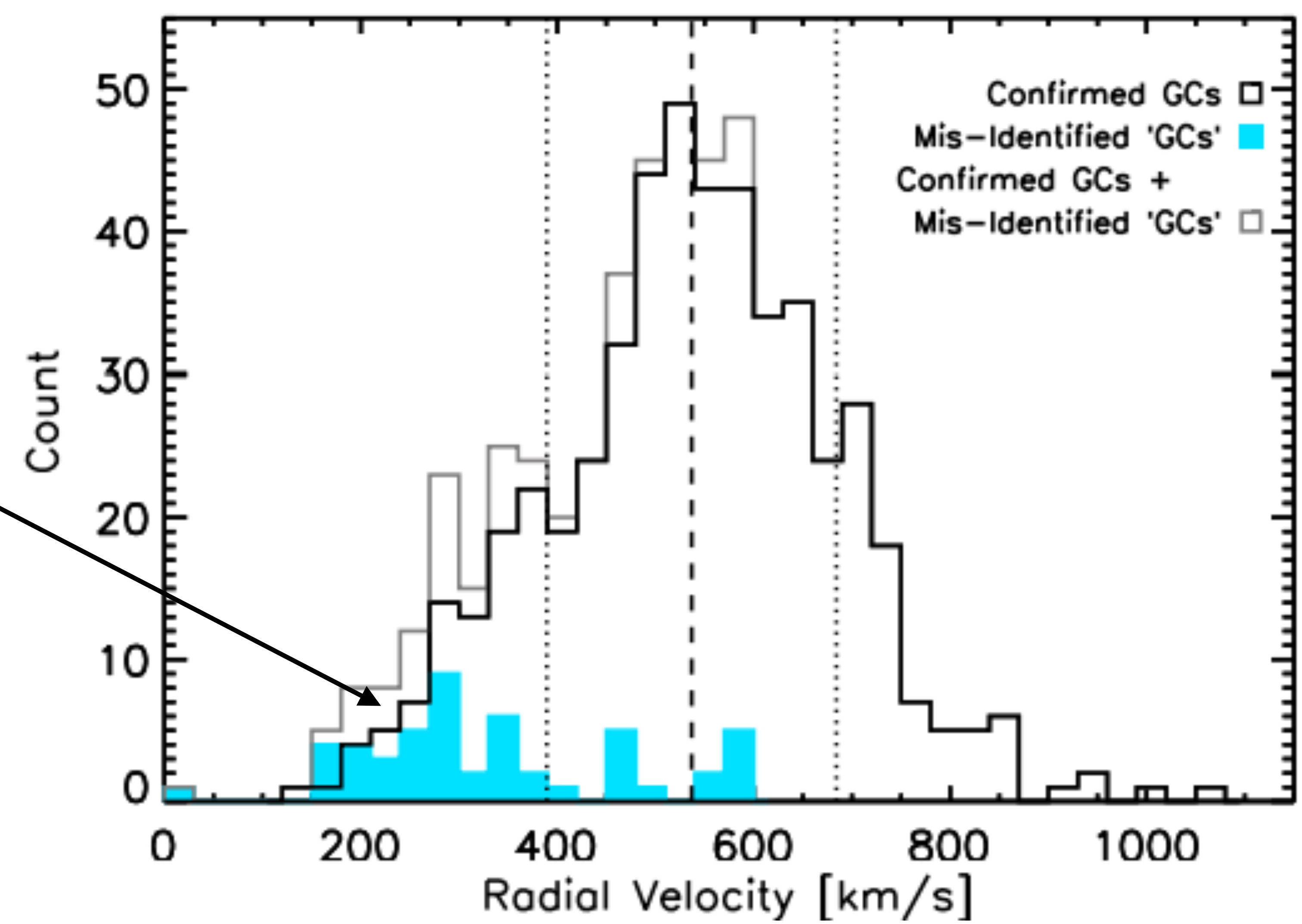
Difference in magnitude between two apertures selects extended sources.



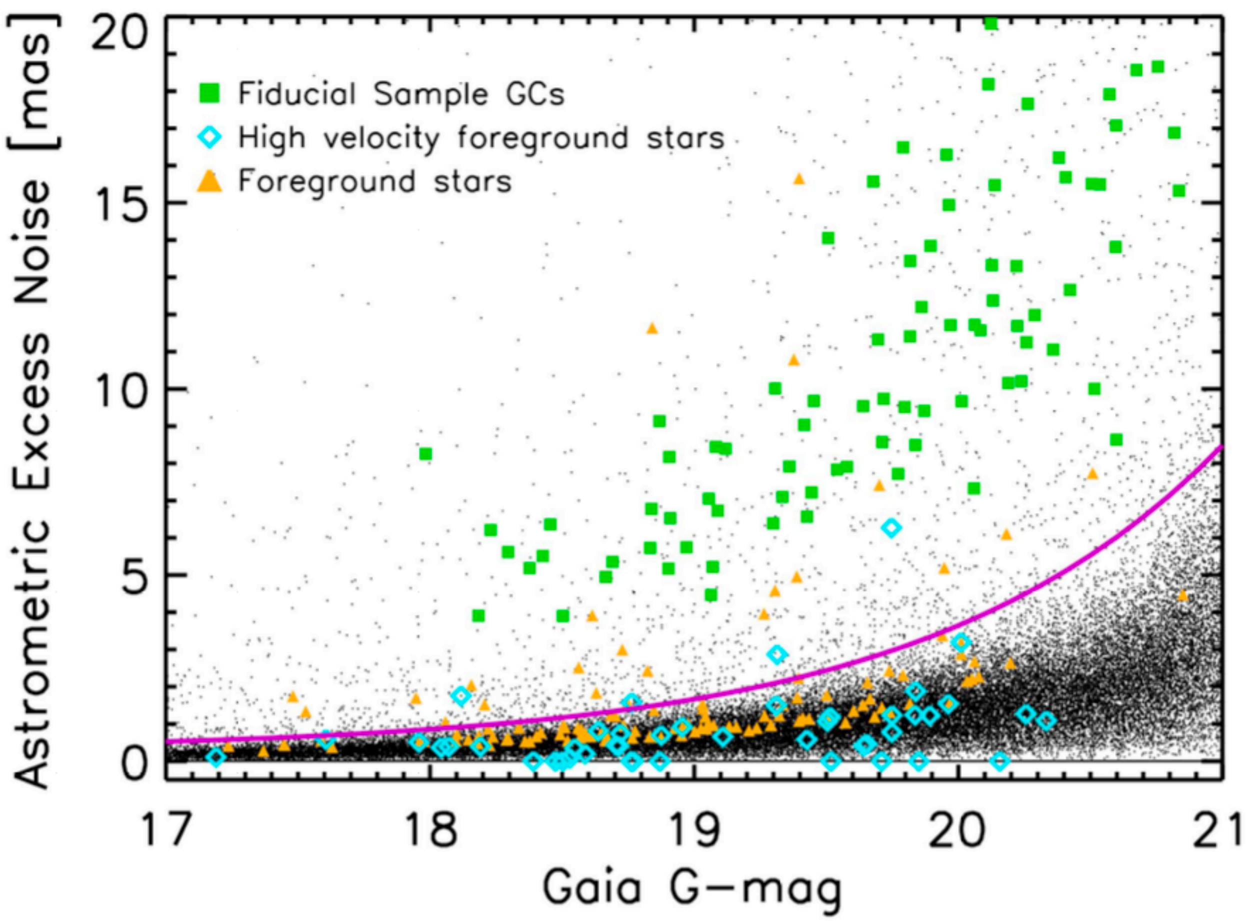


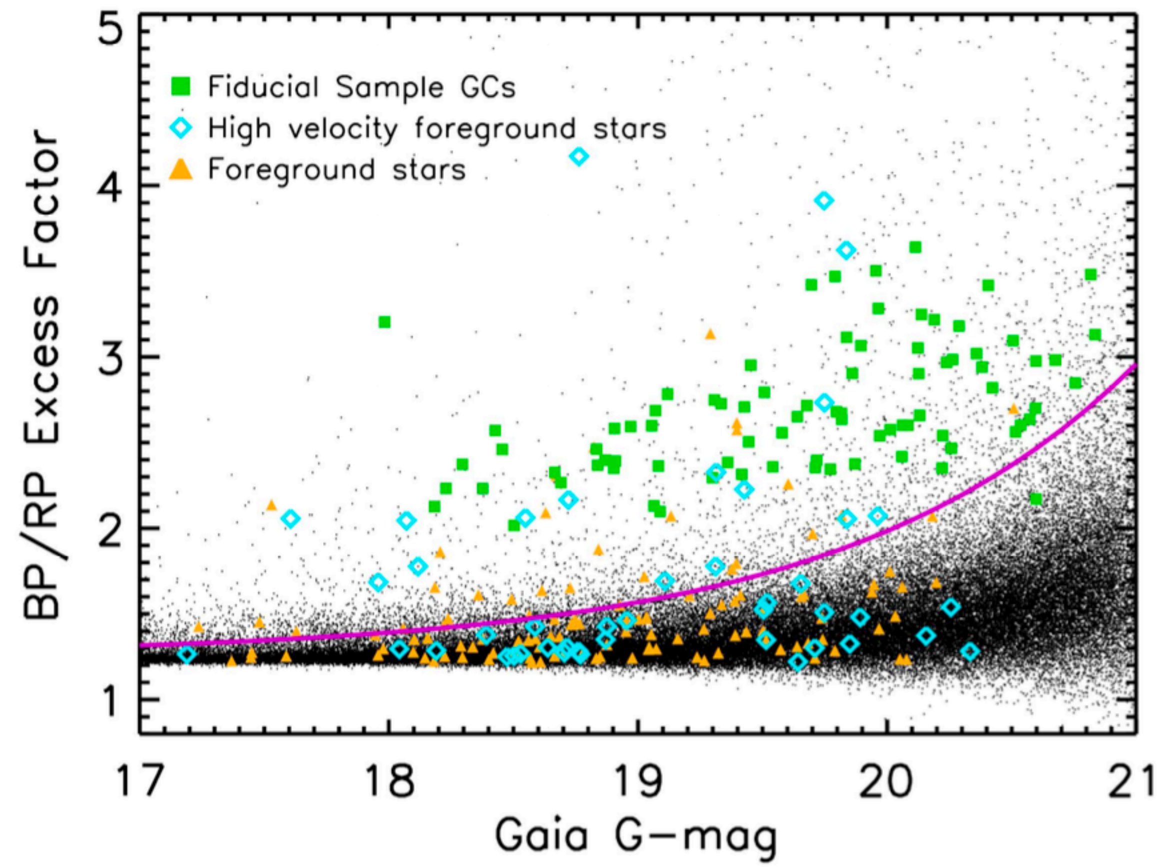
2a. Remove Candidates (and 'confirmed' GCs) with Gaia PM's and parallaxes

~50 radial velocity 'confirmed' CenA GCs have >5 sigma PM/ parallax measurements.



2b. Use Gaia to select objects that are slightly extended





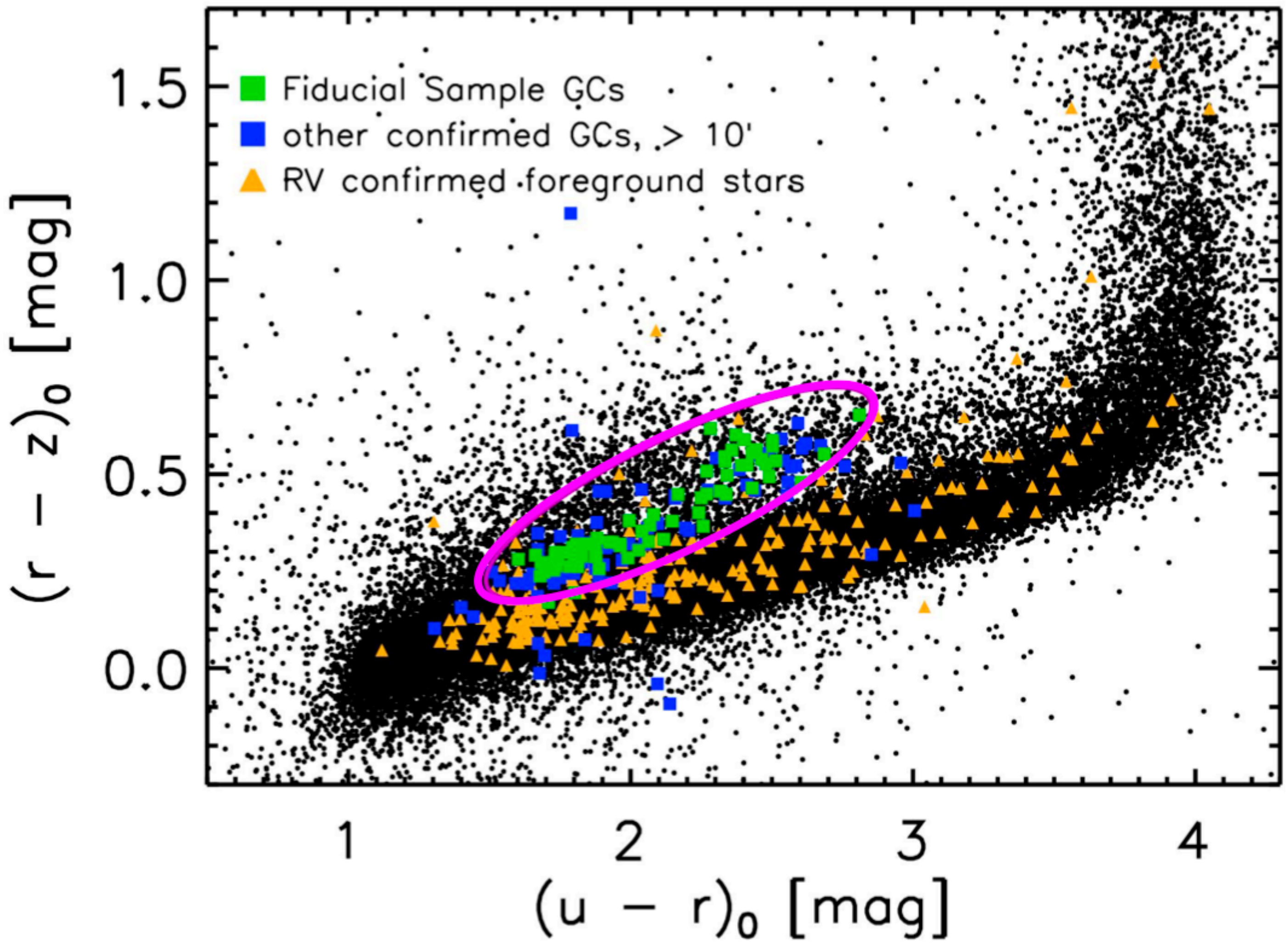
Astrometric Excess Noise: Excess noise in the model of parallax + proper motion.

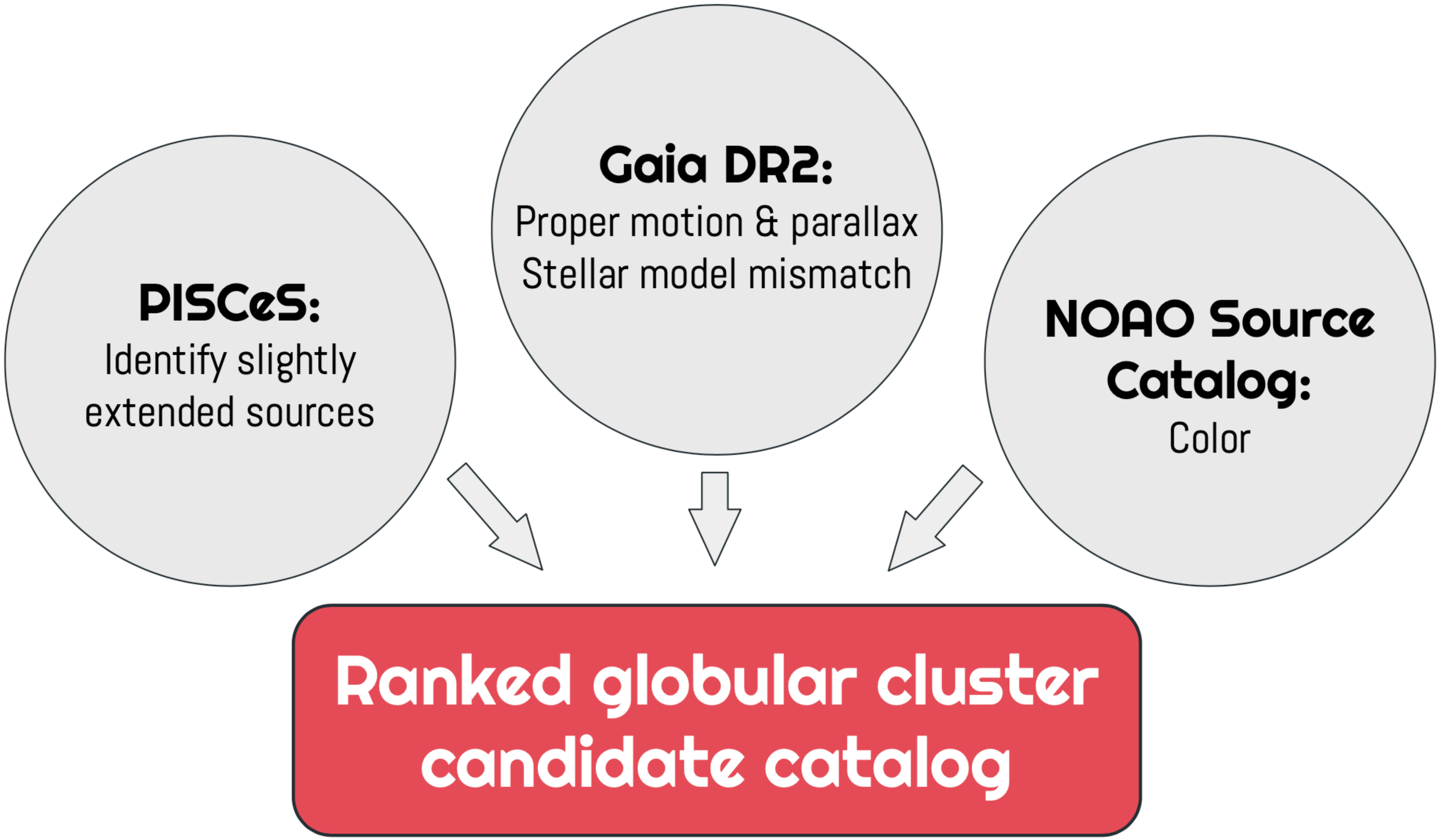
BP/RP Excess: Sum of BP+RP flux greater than G-band flux. This is a difference in aperture effect.

3. NOIRLab Source Catalog (DECam)

Appreciate uniform photometry and color information (not available from individual studies).

Proved to be a critical extra piece of information in our GC selection process.

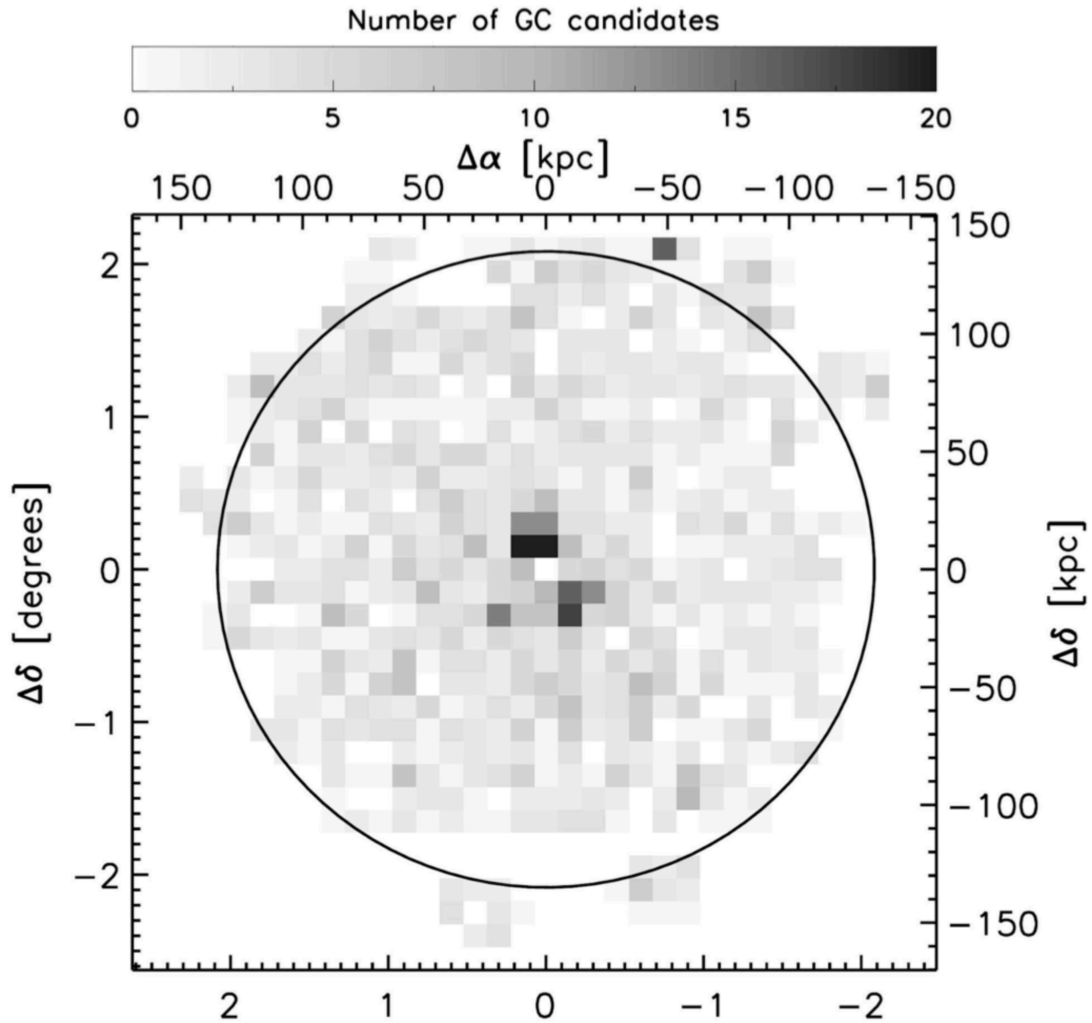




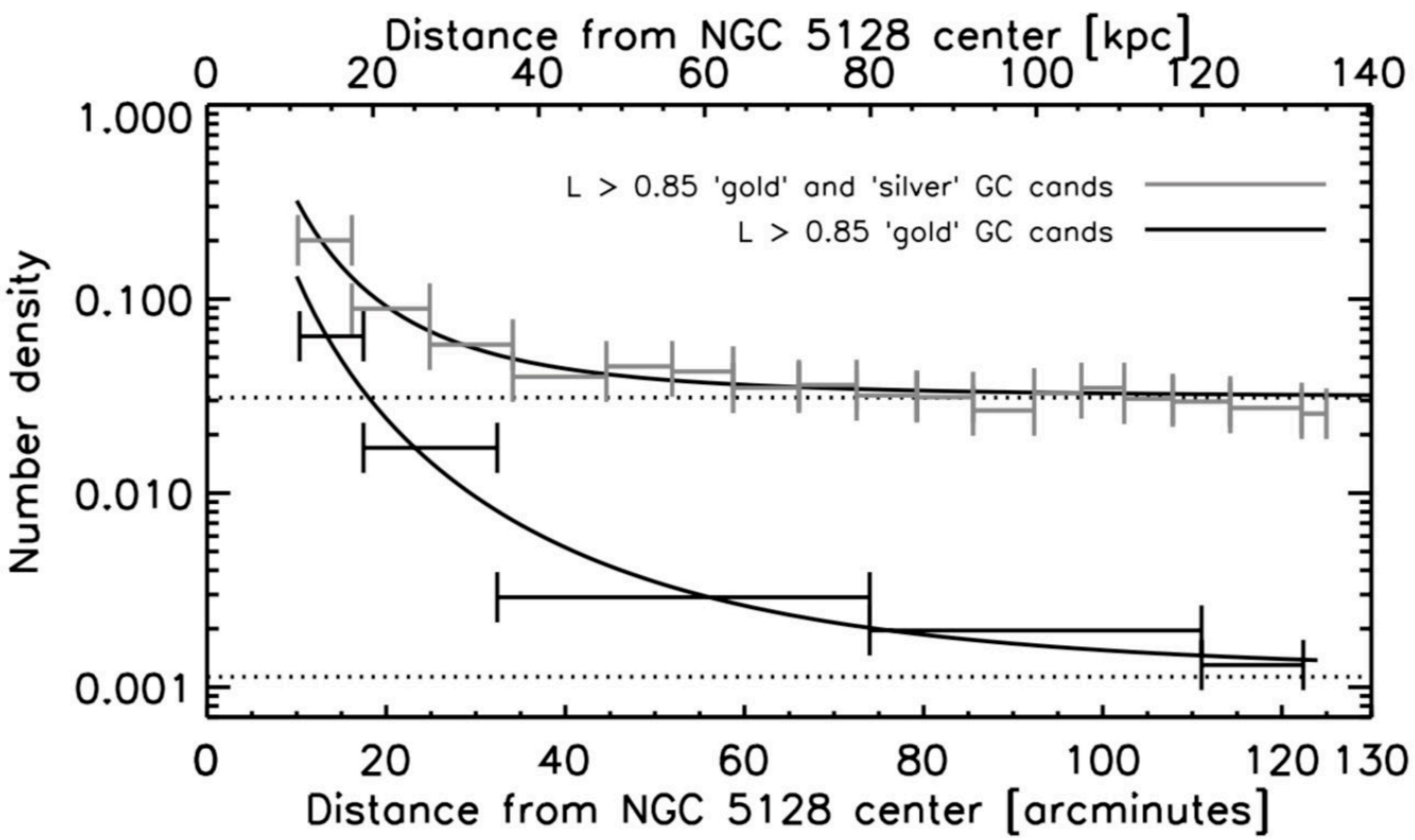
"Priority Sample"

Candidate Rank	PISCeS	*Gaia* DR2	NSC	Minimum C_{3-6}	Number of Candidates	
					Total	$\mathscr{L}_{total} > 0.85$
gold	✓	✓	✓	1.0	5763	181
silver	✓	✓	×	1.0	13793	1750
	✓	×	✓	1.0		
bronze	✓	×	×	2.0	11860	11860
copper	✓	×	×	1.0	9086	8541

Globular cluster candidate spatial distributions



Hughes et al. 2021



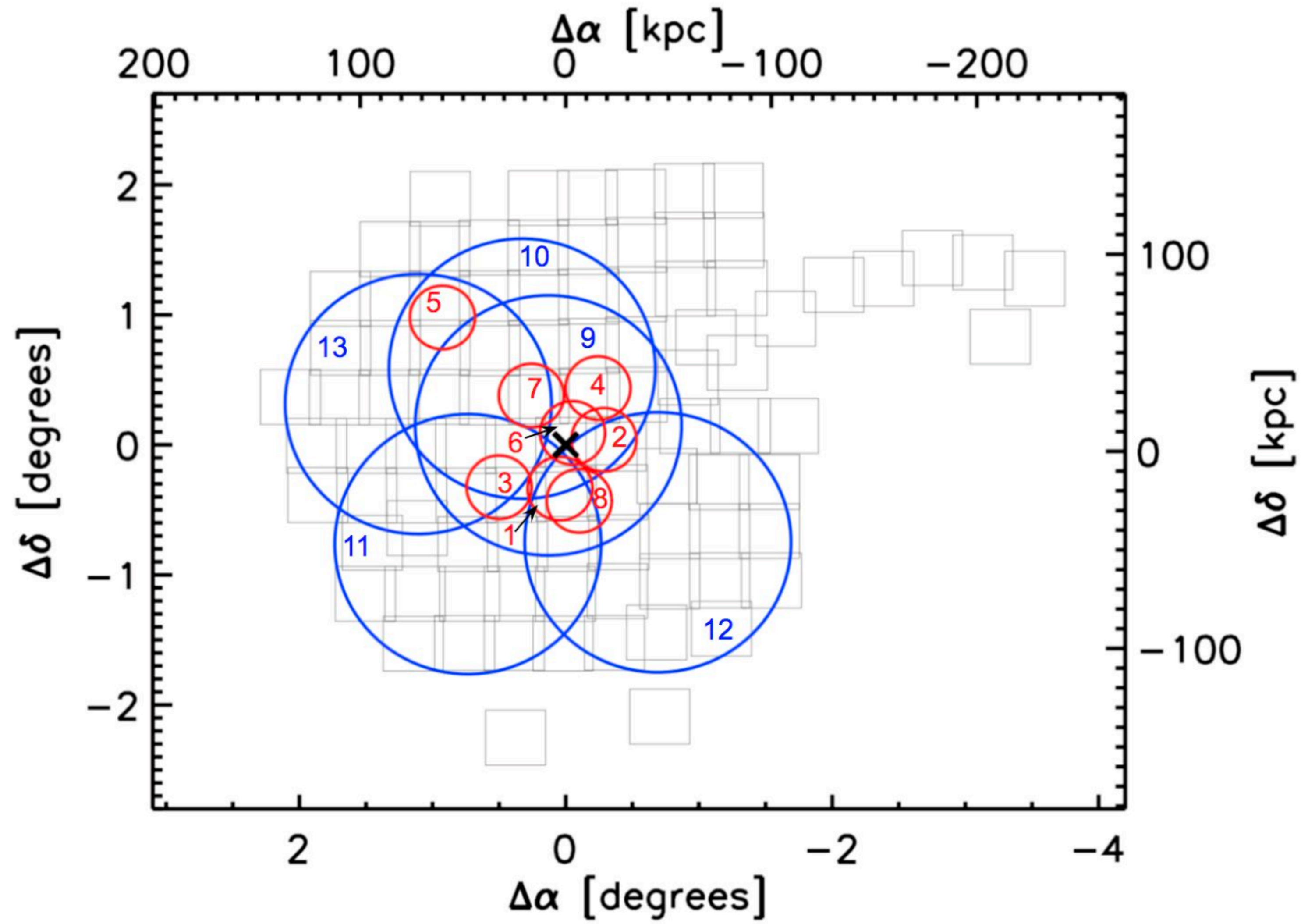
Gold+silver sample is binned by 100 candidates
Gold only sample is binned by 40 candidates

Total population estimate:
1450 +/- 160 GCs within ~150 kpc

Spectroscopic Follow-up

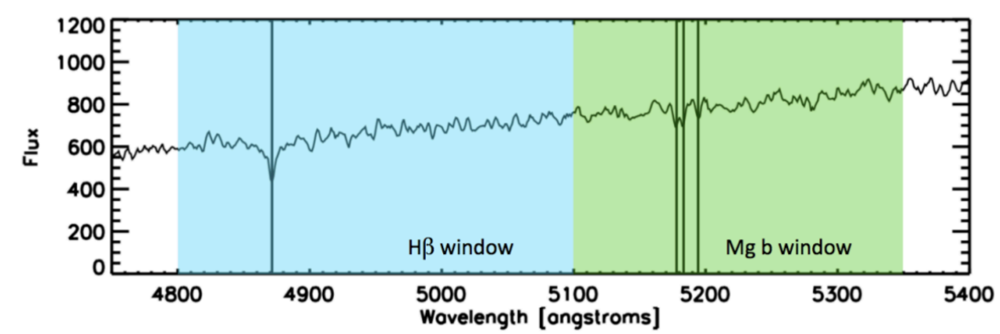
Red: Magellan/M2FS
Five observing runs; 2017 - 2019

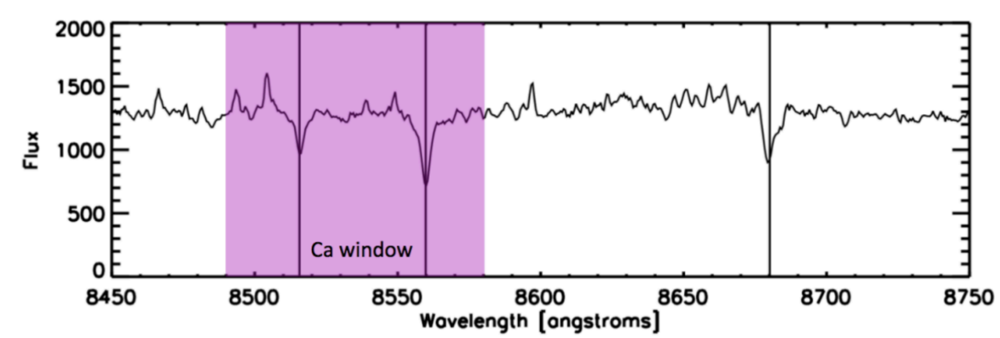
Blue: AAT/2dF
Three observing runs; 2017 - 2022



3.9 m AAT in Australia

6.5 m Magellan Clay Telescope in Chile





Updated GC sample

122+27 newly confirmed GCs (Dumont+22; Hughes+23)

645 kinematic members in total

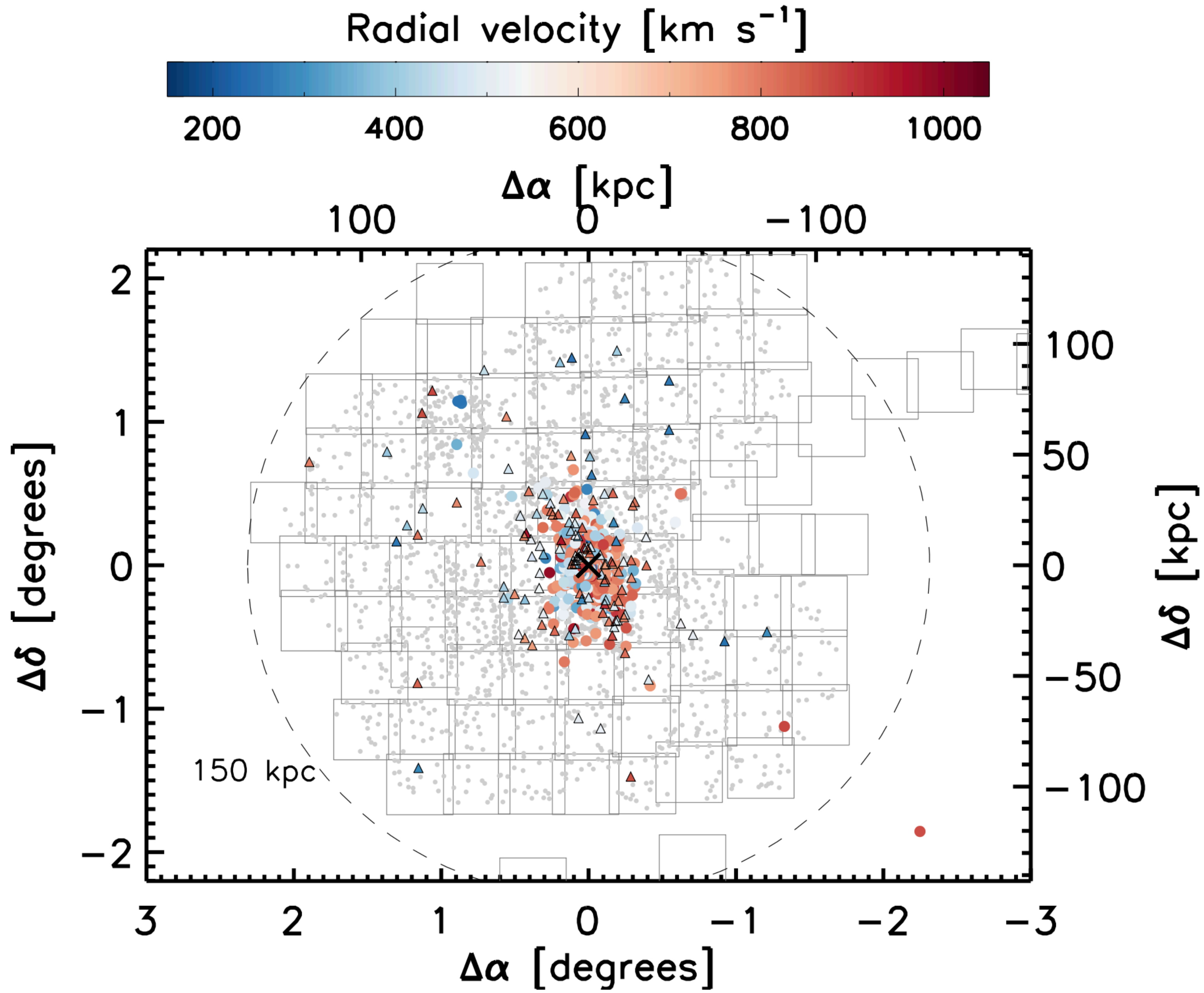
Priority sample: 35% are true GCs

68% within 30’

(7% for the not-priority sample)

28 GCs outside of 50 arcmin (55 kpc)

Most distant object at 130 kpc.



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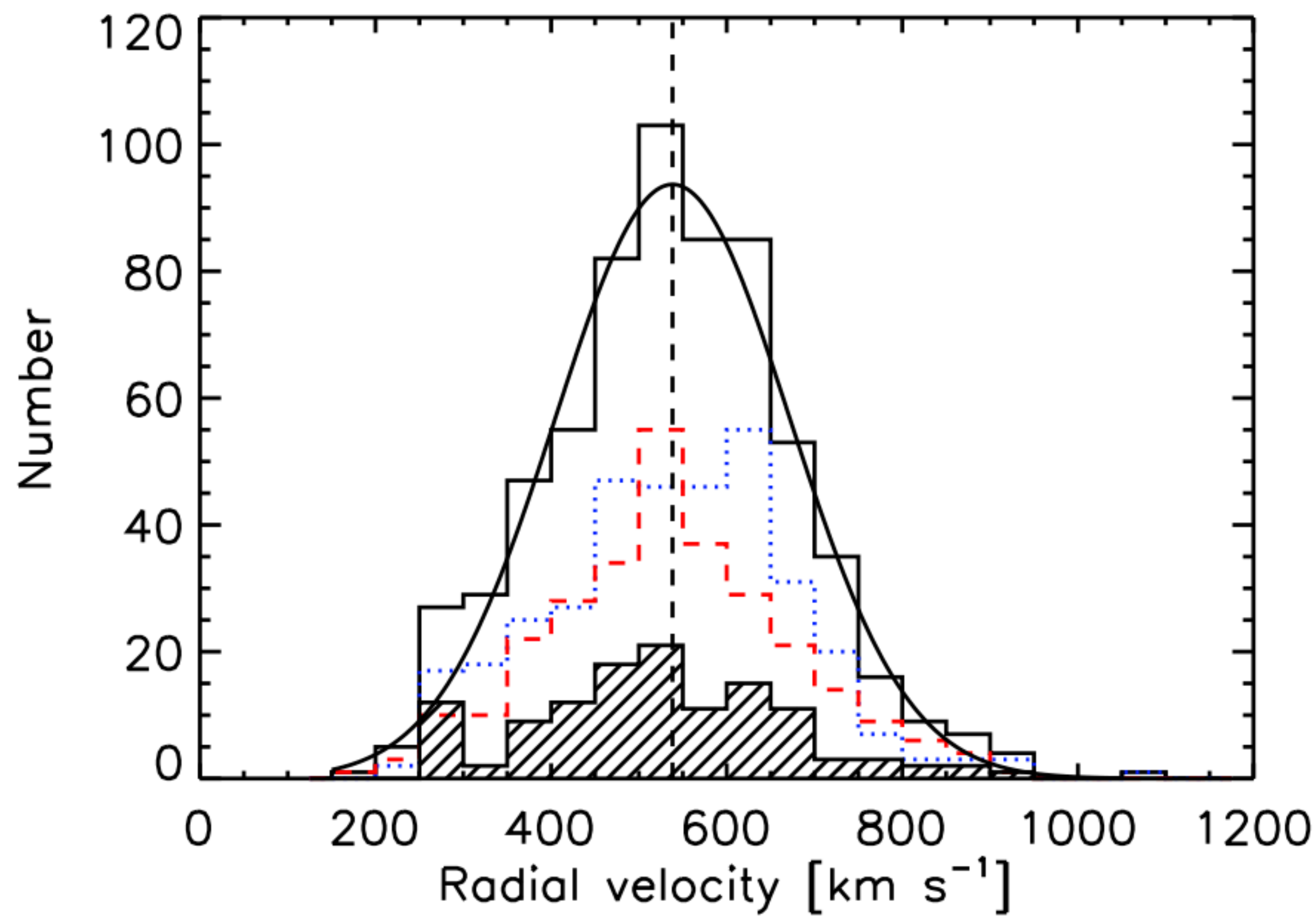
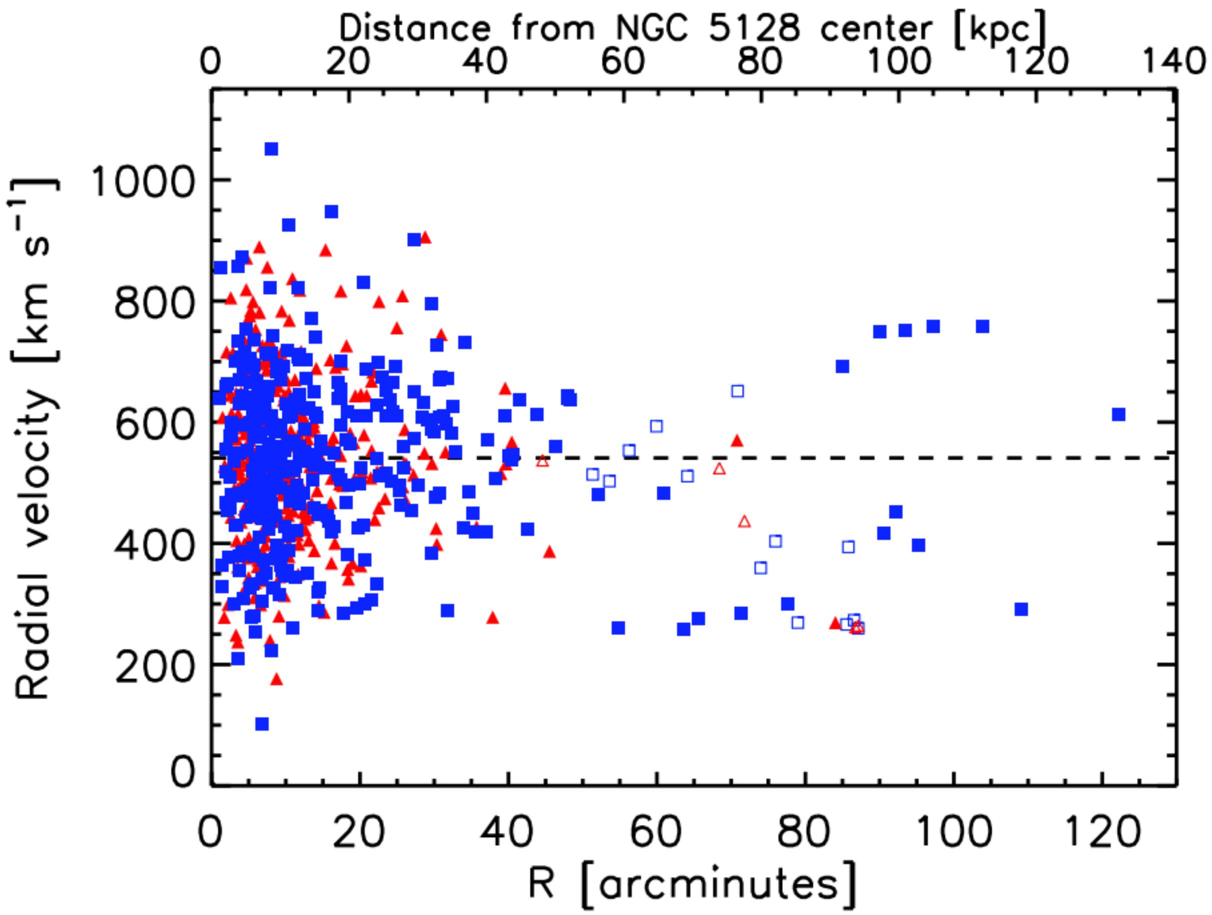
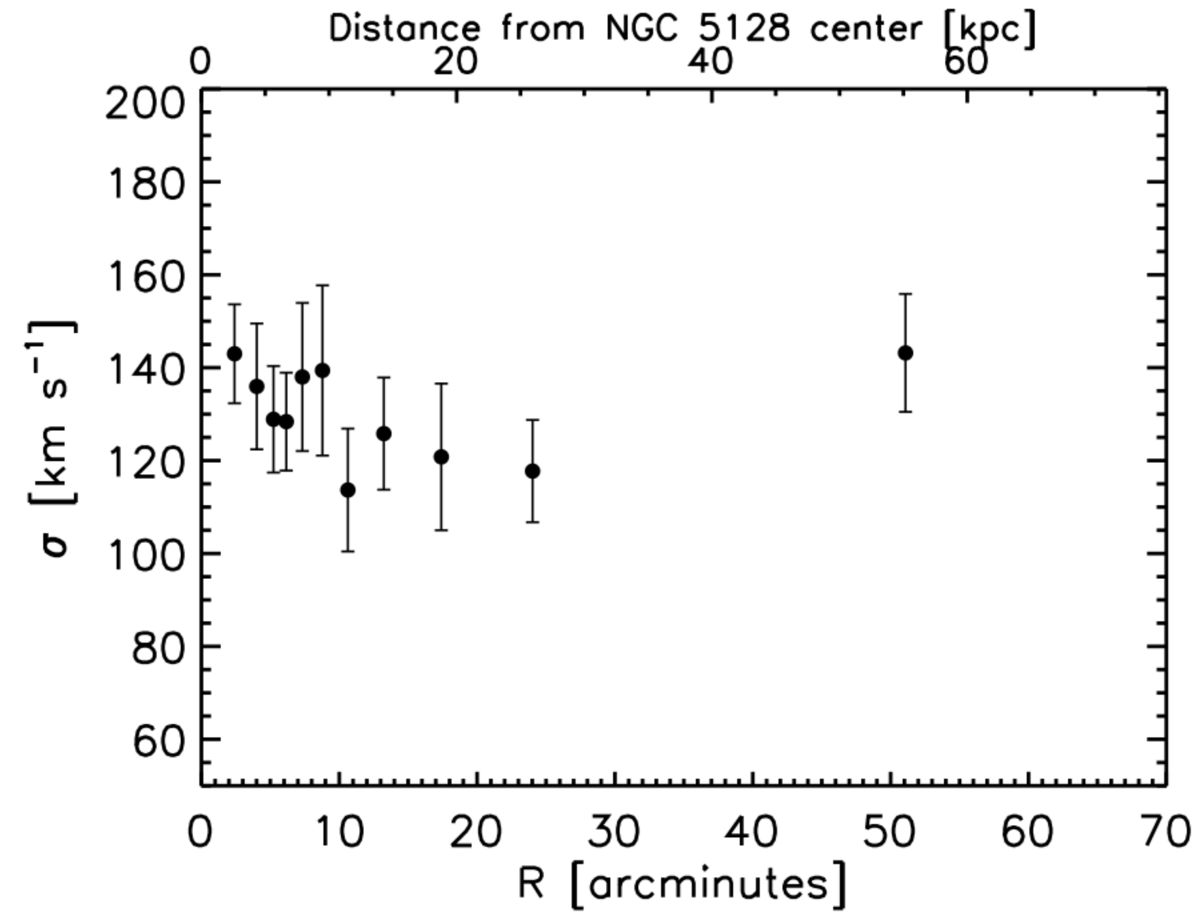


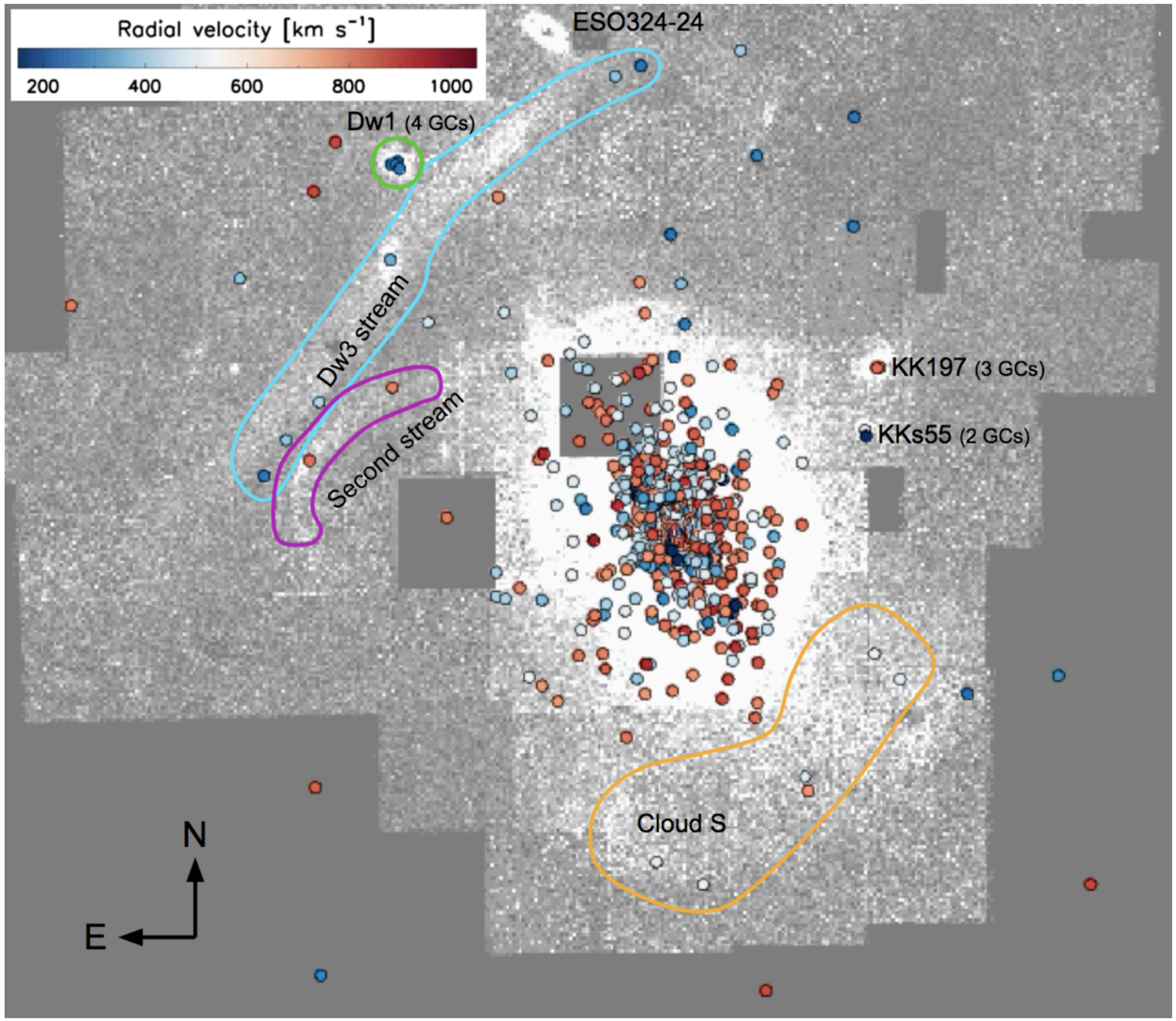
Velocity histogram including new objects (hatched), and blue and red samples

Radial Velocity distribution





Identifying GCs in Substructures



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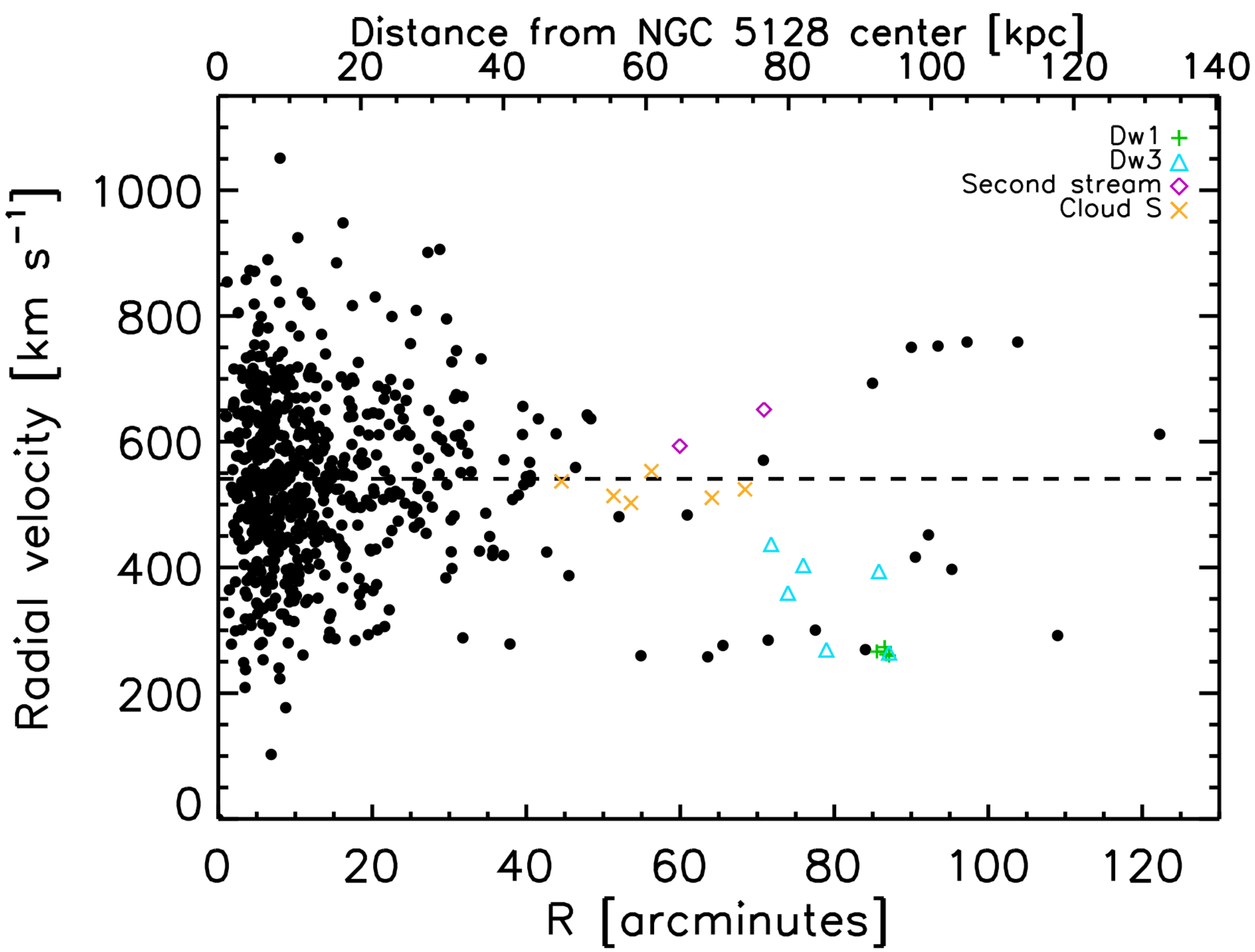
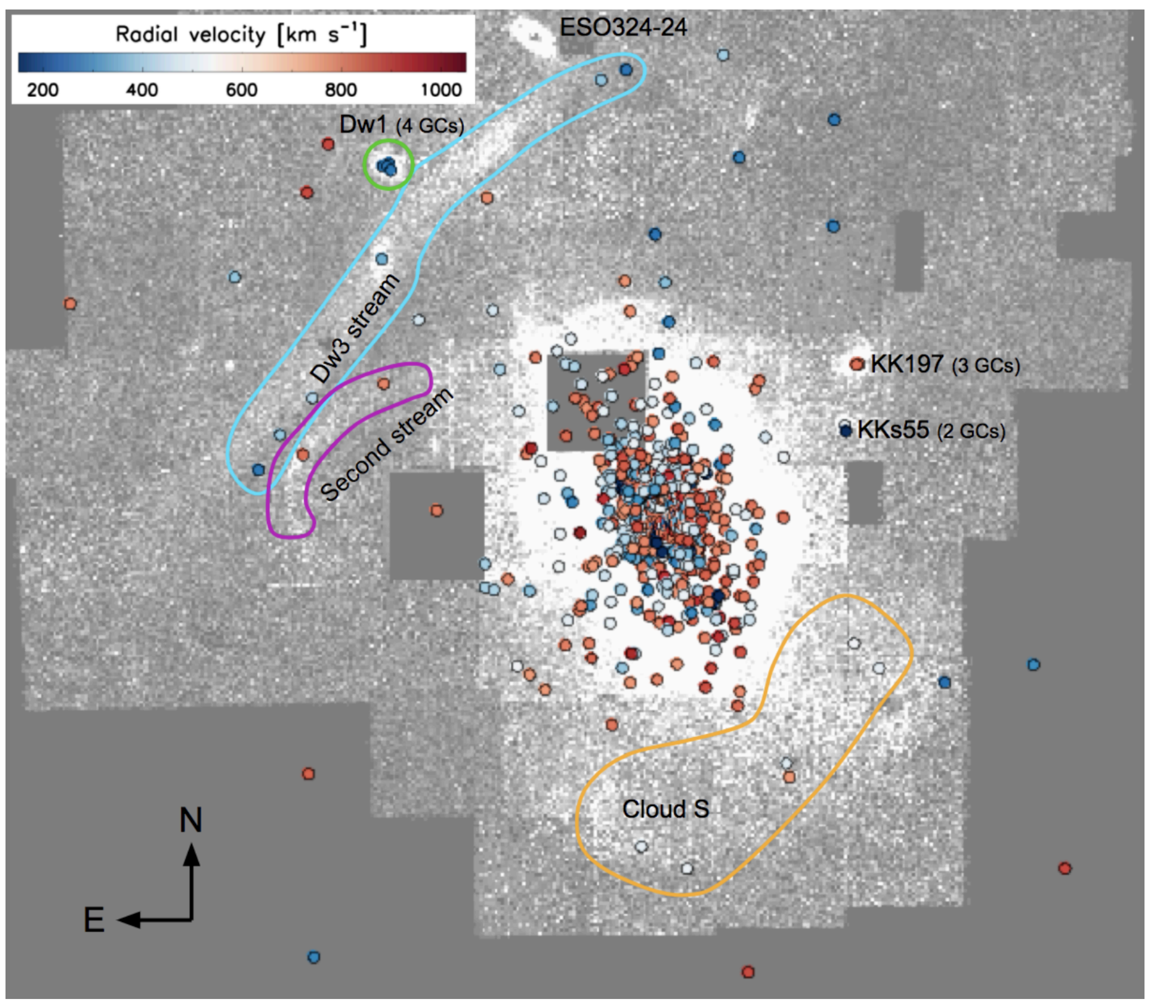
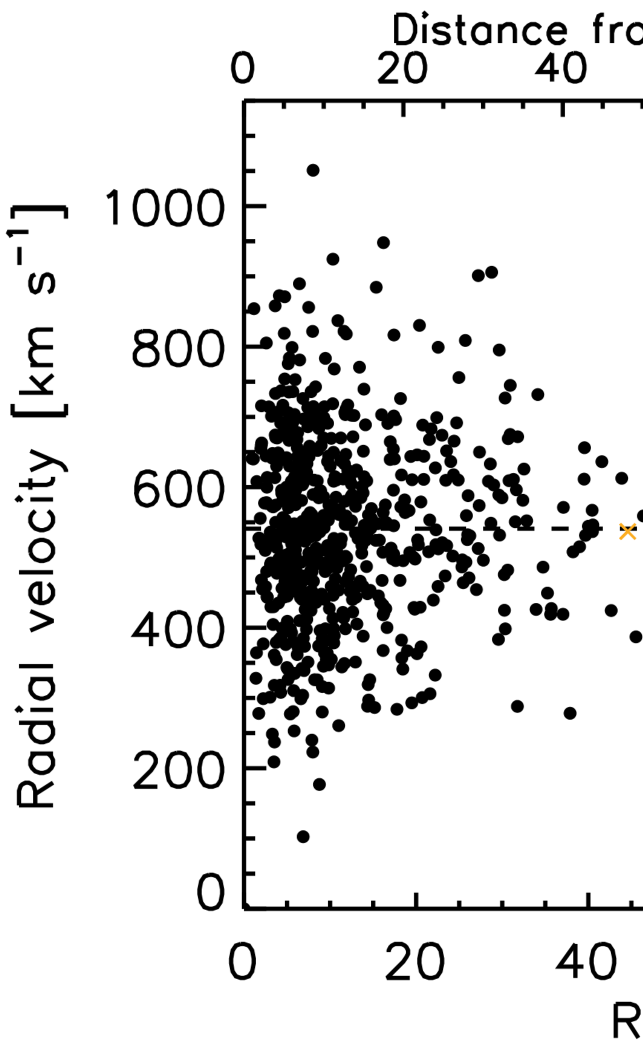


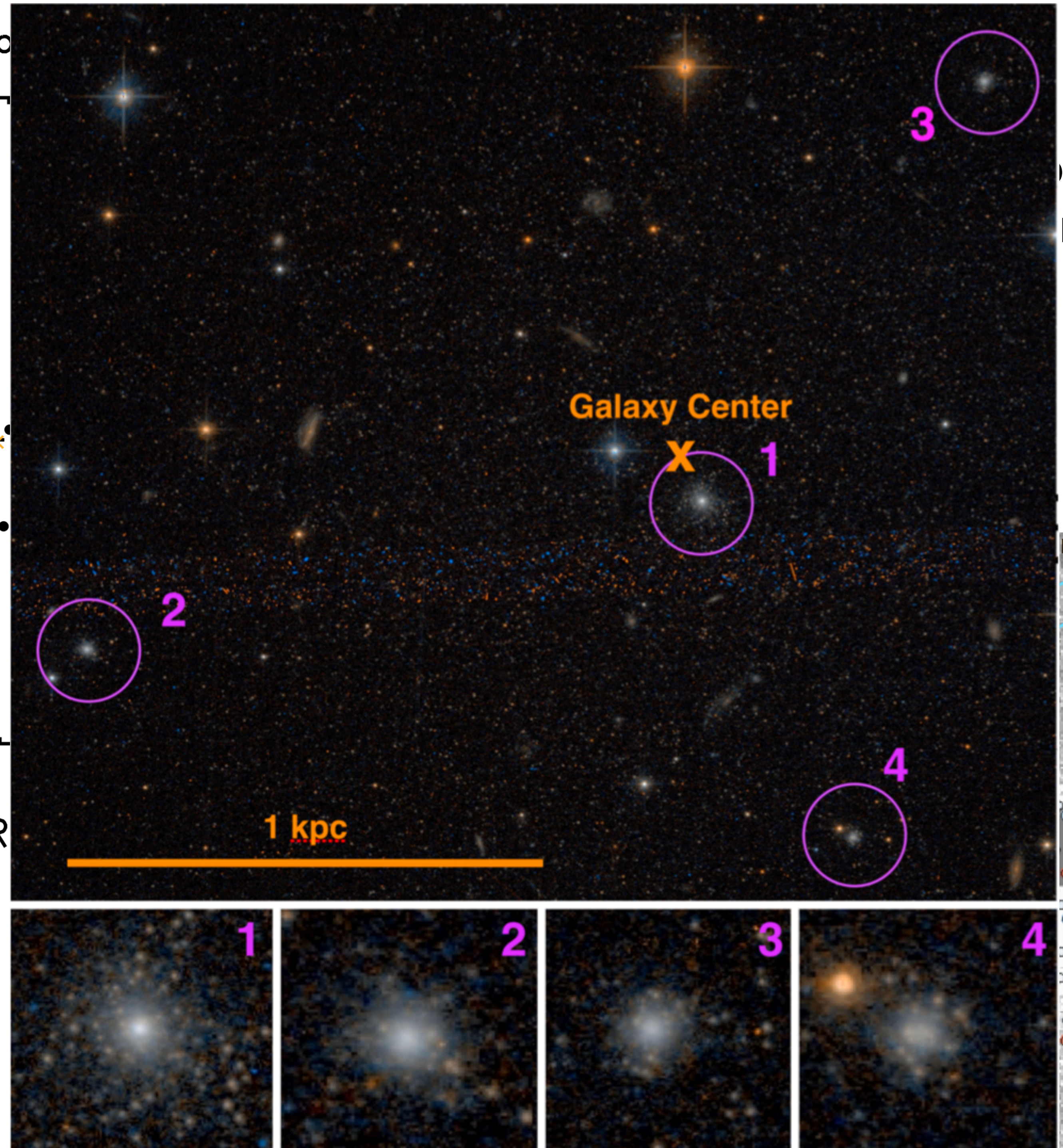
In some cases, correlation with stellar substructure is very clear (Dw1, Cloud S).

In others, there is clear halo GC contamination.



Identifying GCs in Substructures

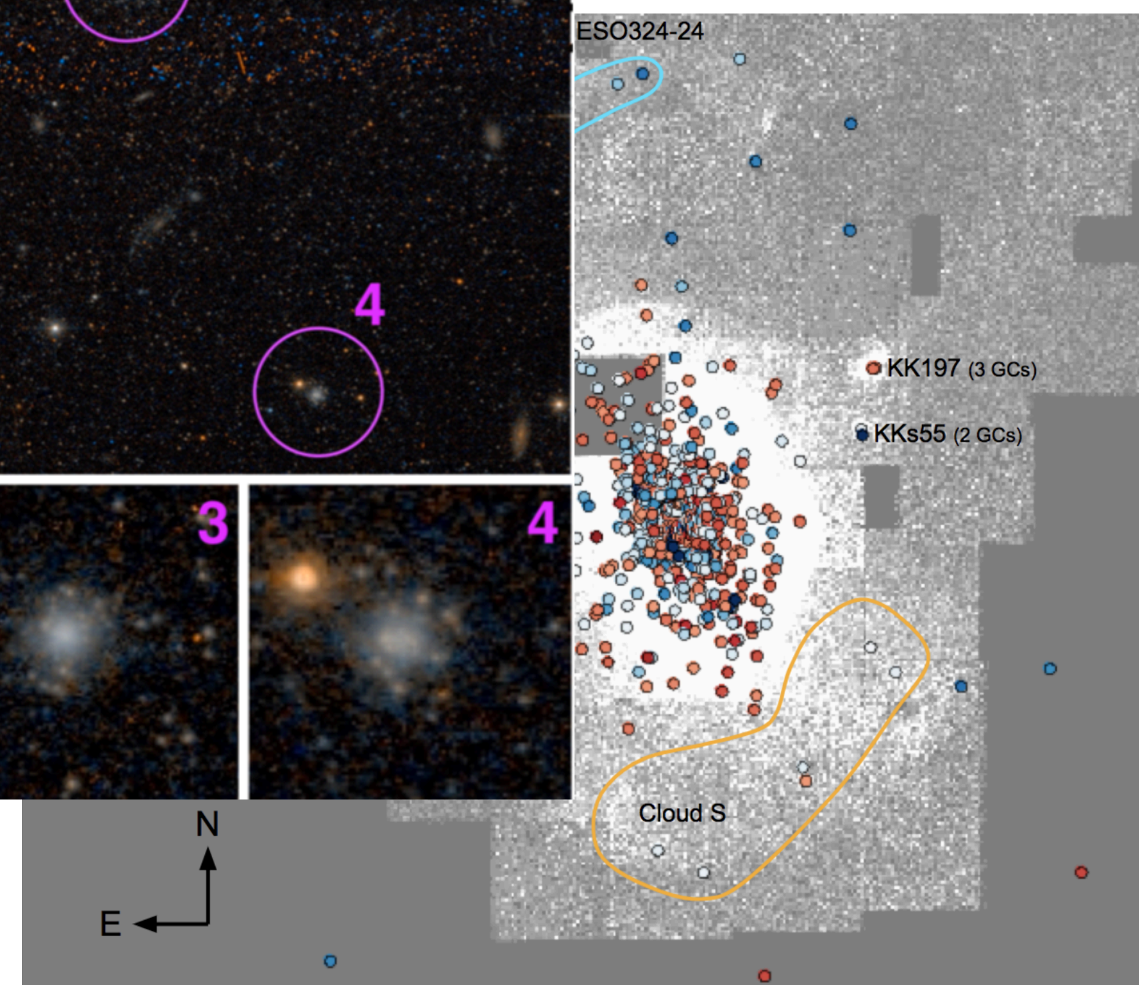




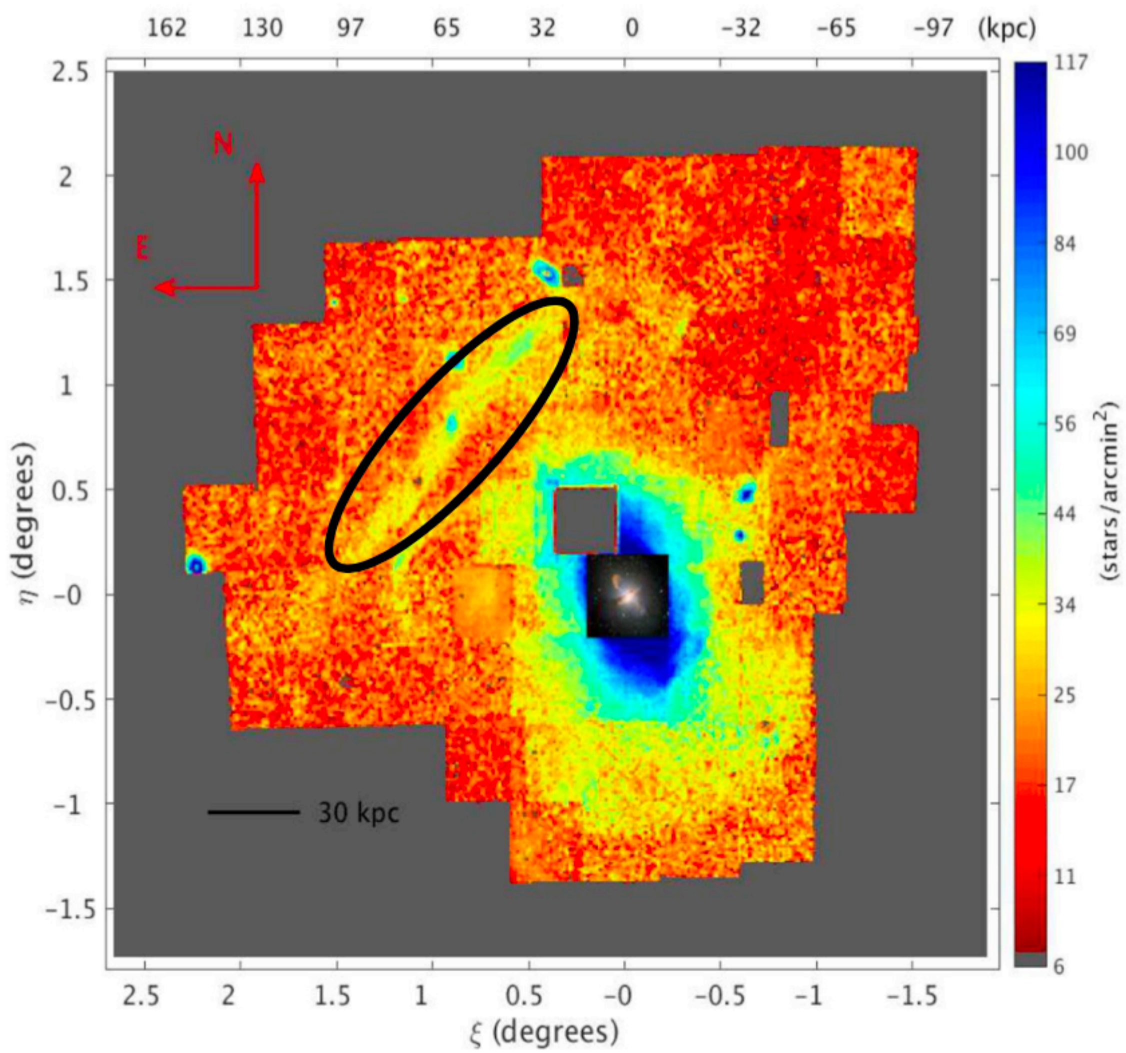
rrelation with stellar

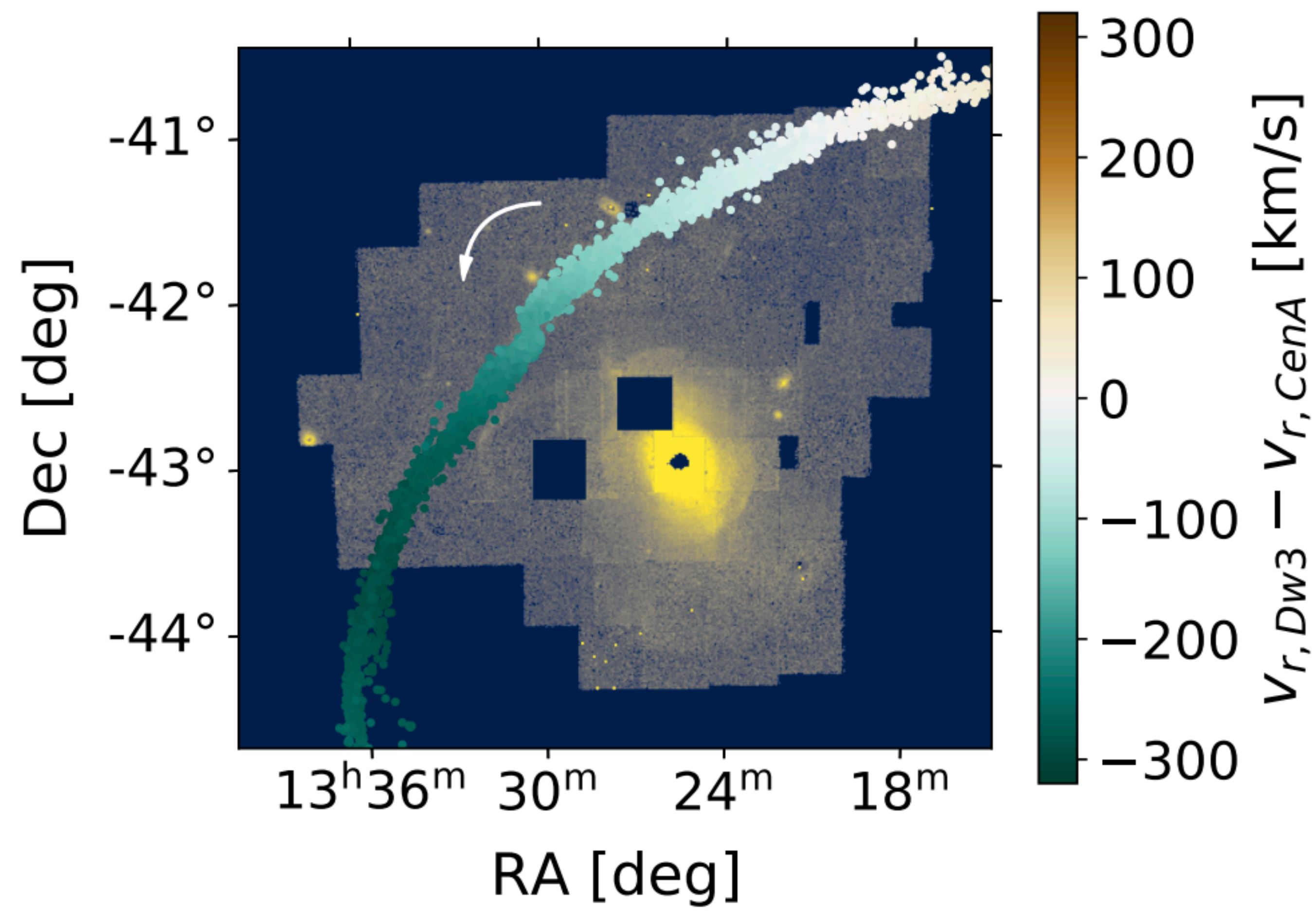
ry clear (Dw1, Cloud S).

clear halo GC



Stream modeling with stars + GC kinematics (Pearson+22)





Can reproduce Dw3 stellar stream morphology, including the nuclear star cluster morphology with reasonable CenA mass, Dw3 mass, etc.

To break degeneracies, we need velocities along the stream.

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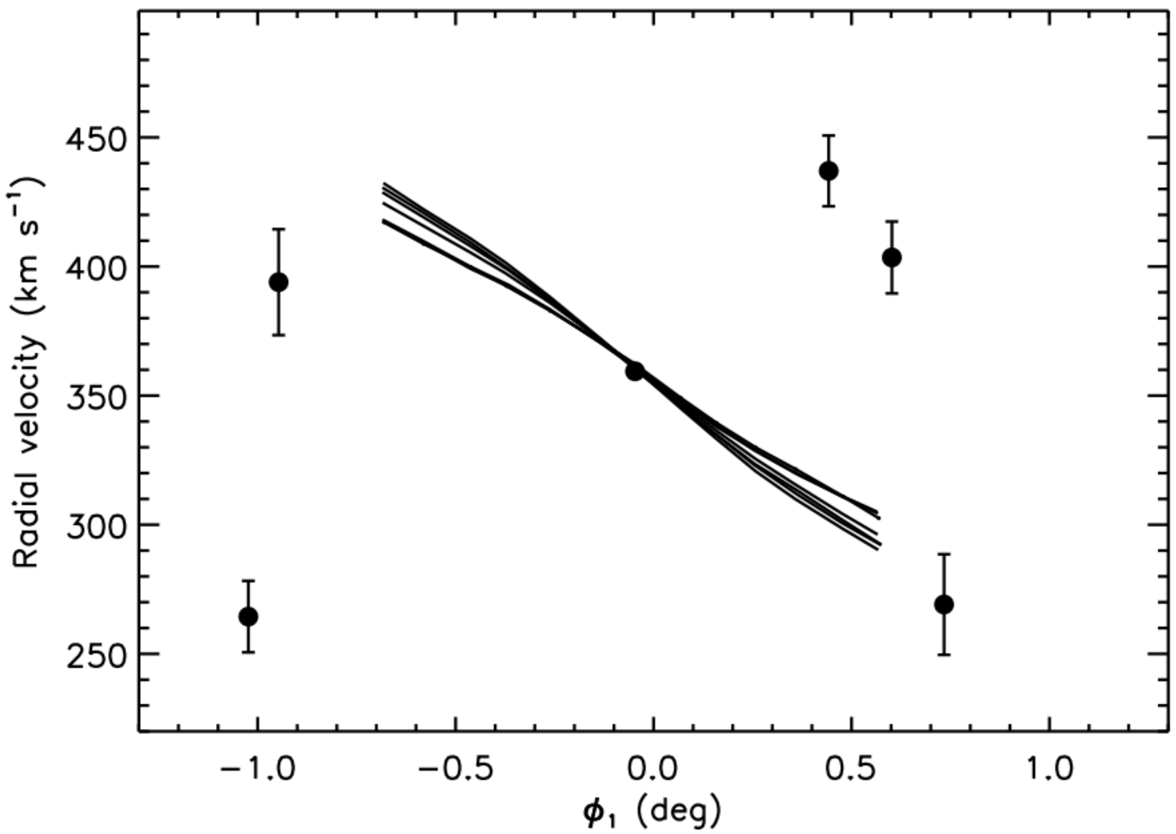

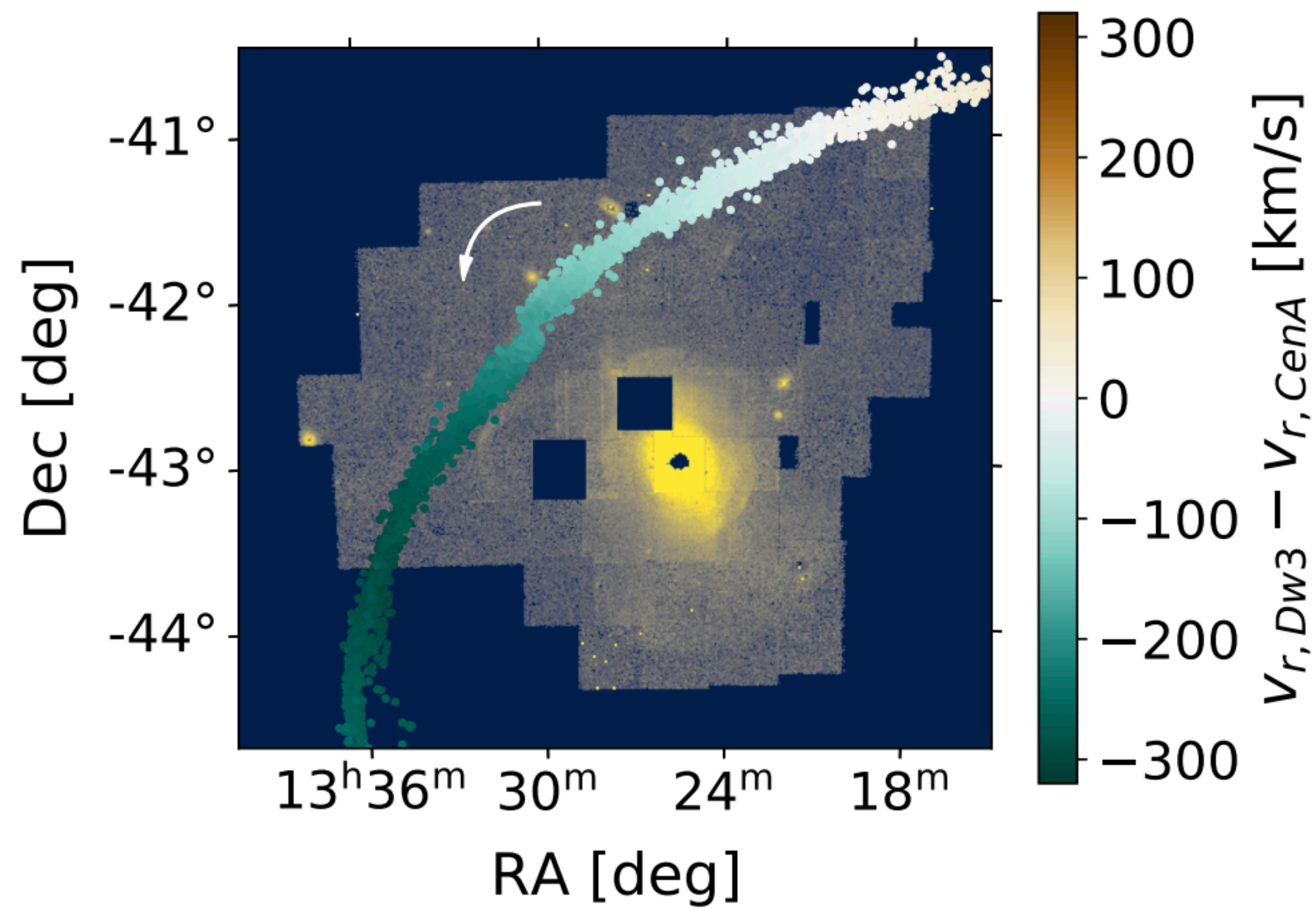

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Last Thing: total Mass Profile Tracer Mass Estimator Technique

(Evans+03)

$$M_{tot} = M_p + M_r$$

$$M_p = \frac{C}{GN} \sum_i (v_{f_i} - v_{sys})^2 R_i$$

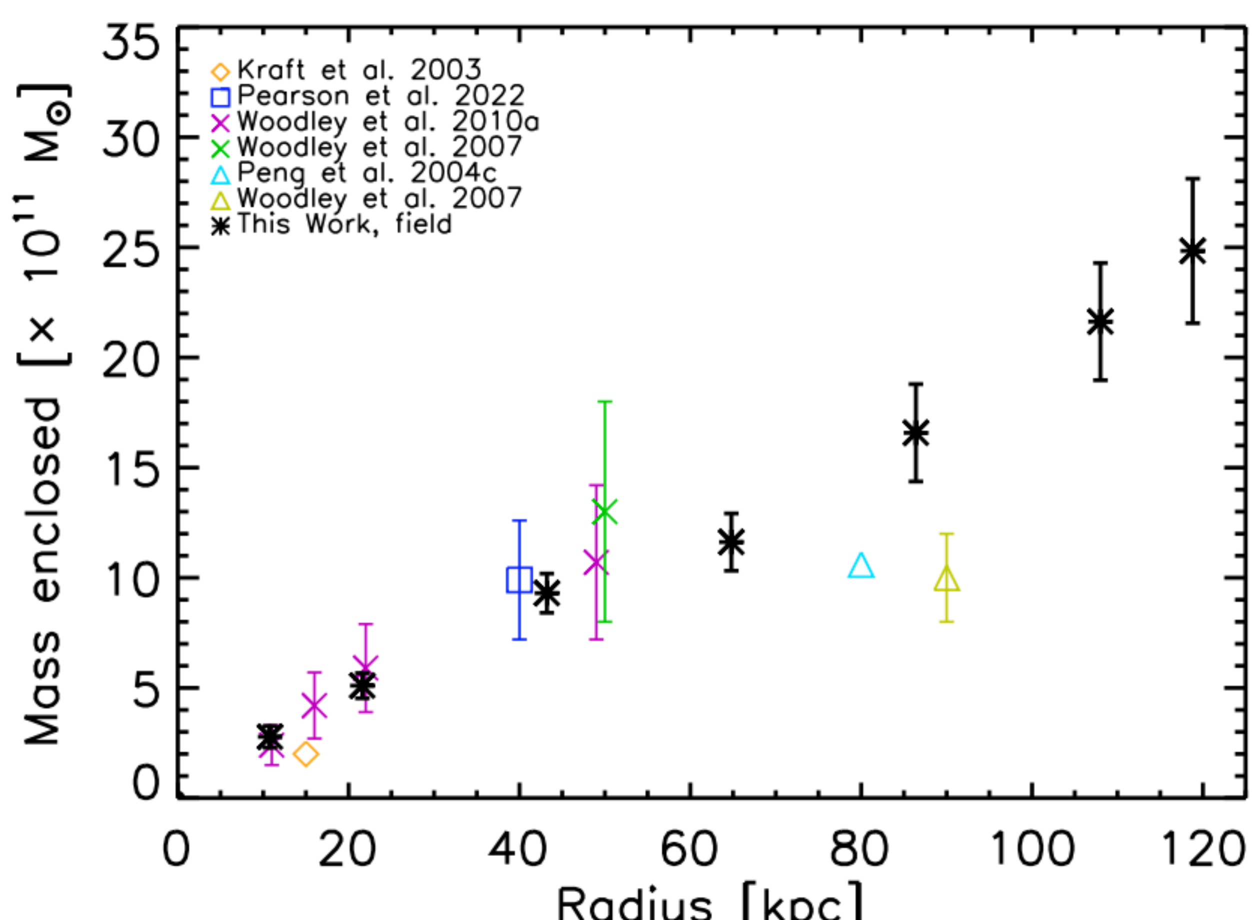
$$M_r = \frac{R_{out} v_{max}^2}{G}$$

systemic velocity

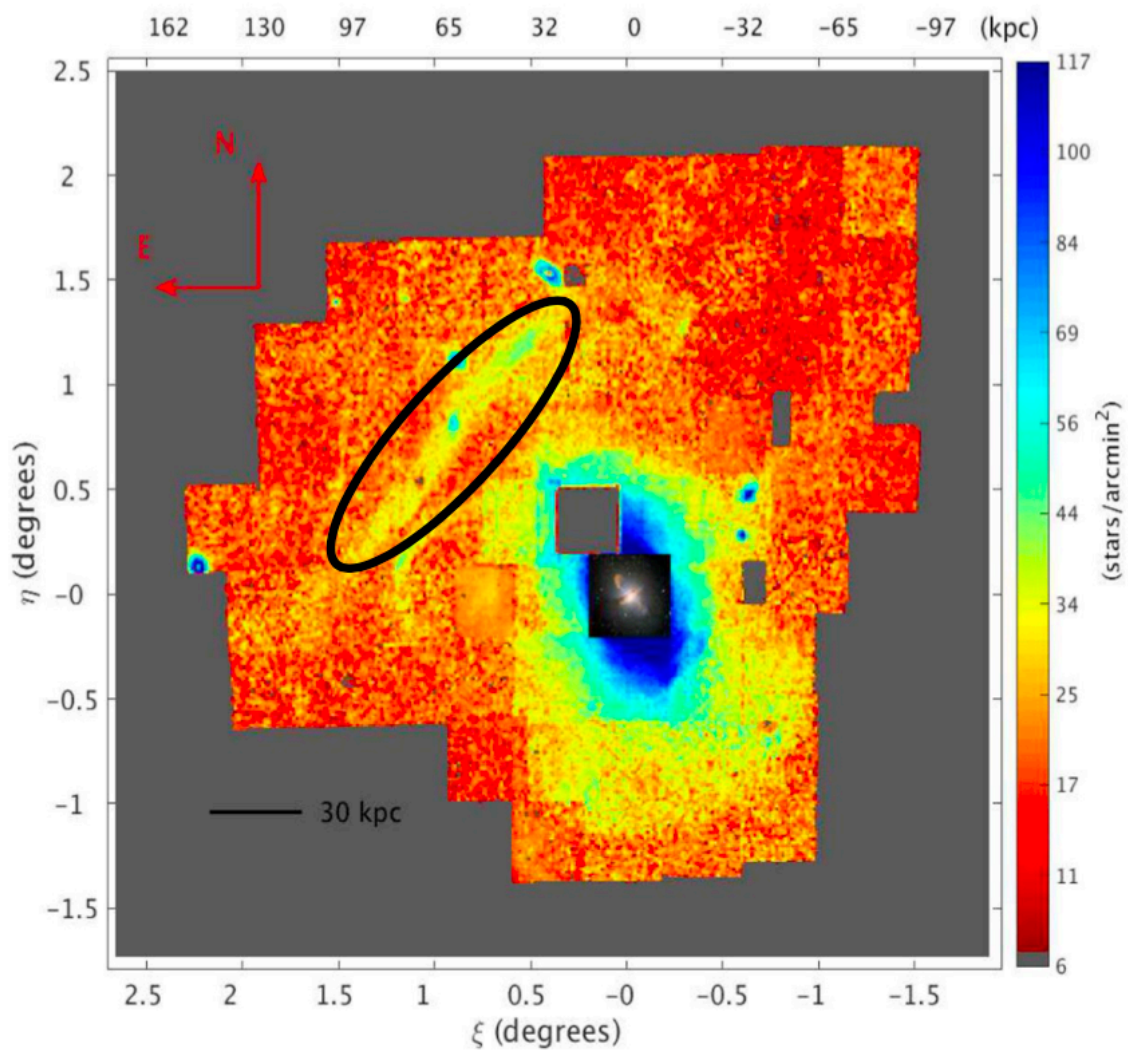
measured radial velocity minus rotation amplitude

rotation amplitude

-Include both dispersion and rotational component.
-Total mass consistent with previous measurements.
-Some discrepancy at large radii.
-We removed GCs associated with stellar substructures.
-Detailed mass DM+light profile including inner and outer DM slope. (Dumont+23)



Future Directions



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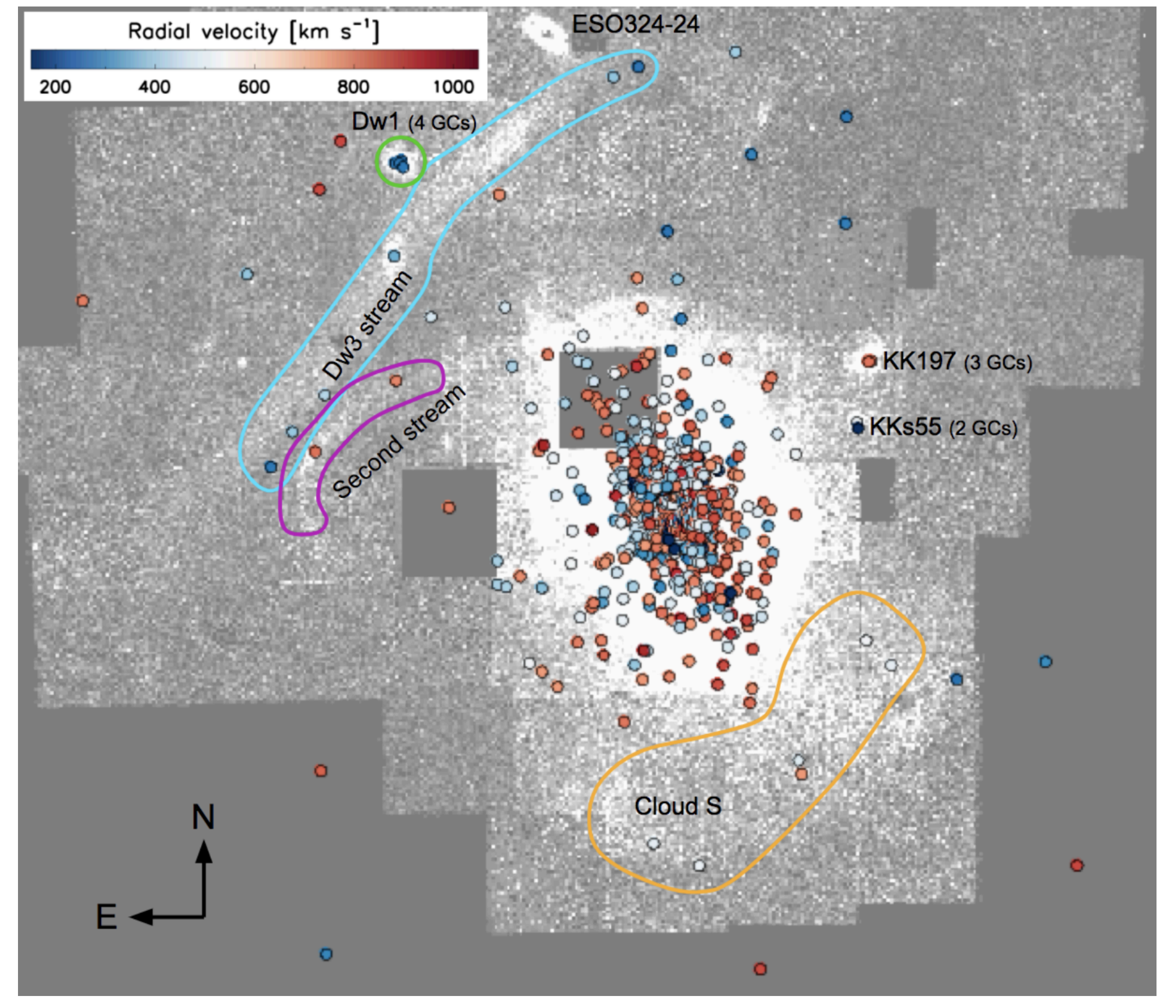
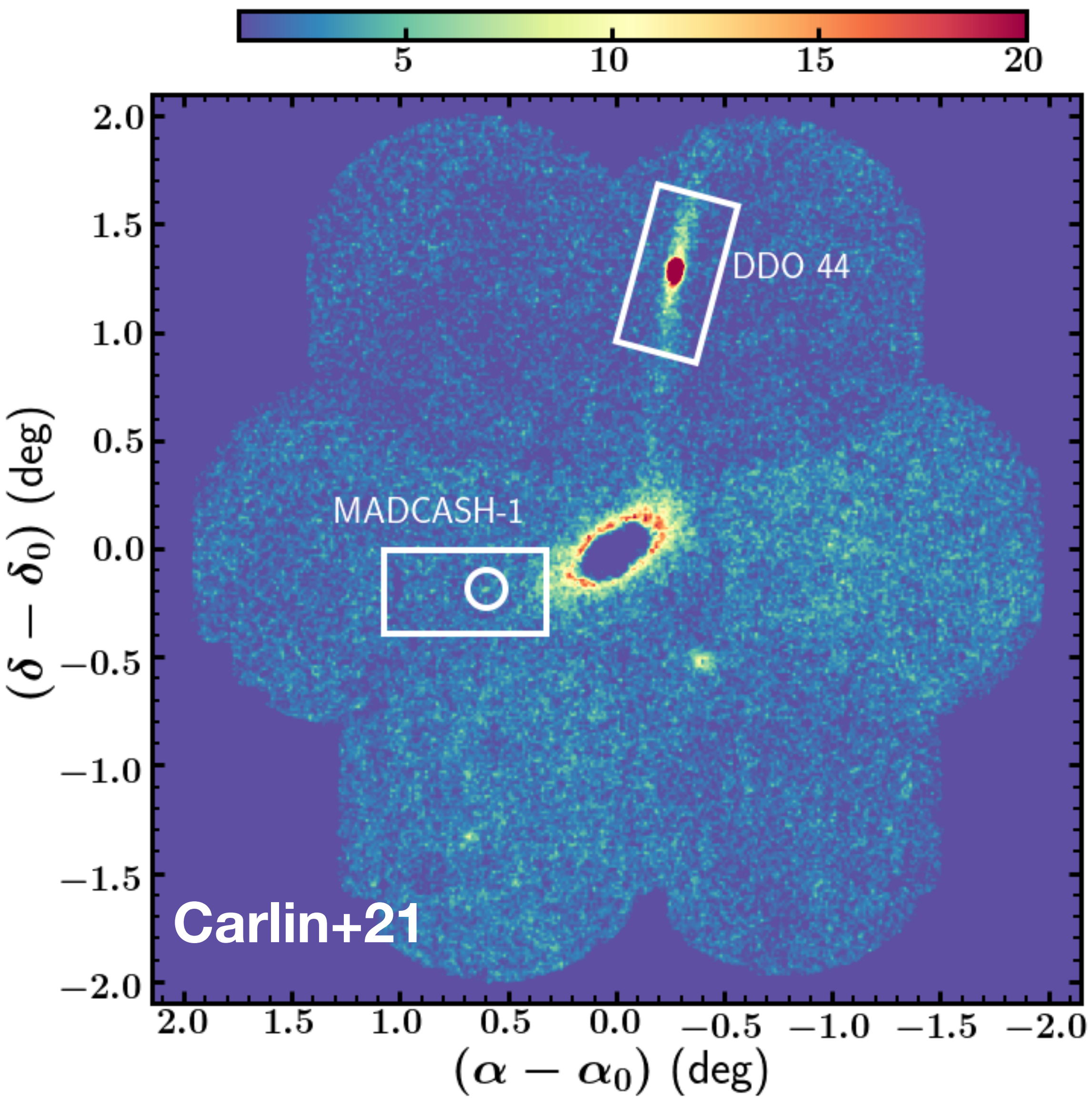


Similar results can be had throughout the D<5 Mpc Universe.

Future Directions



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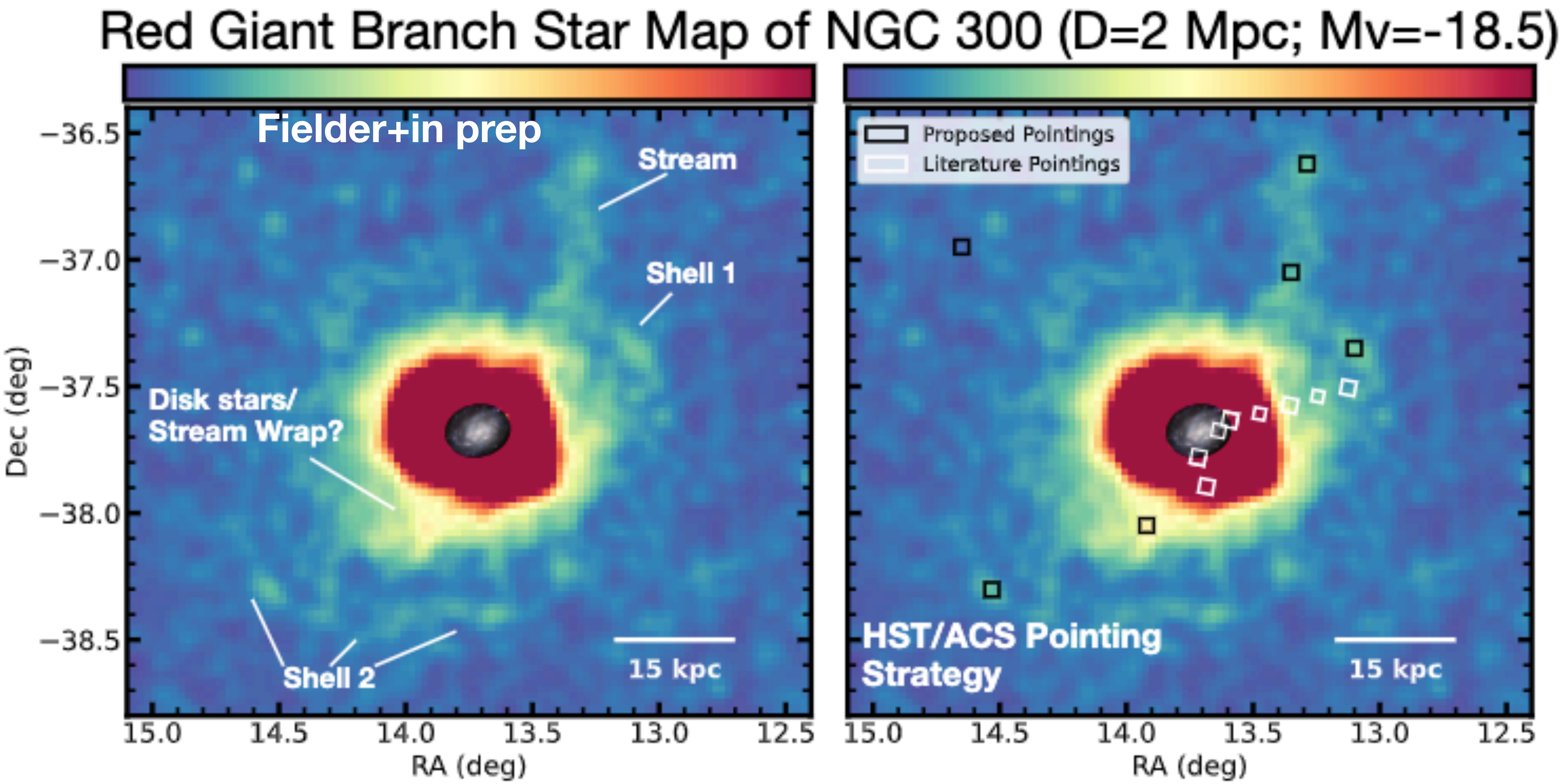

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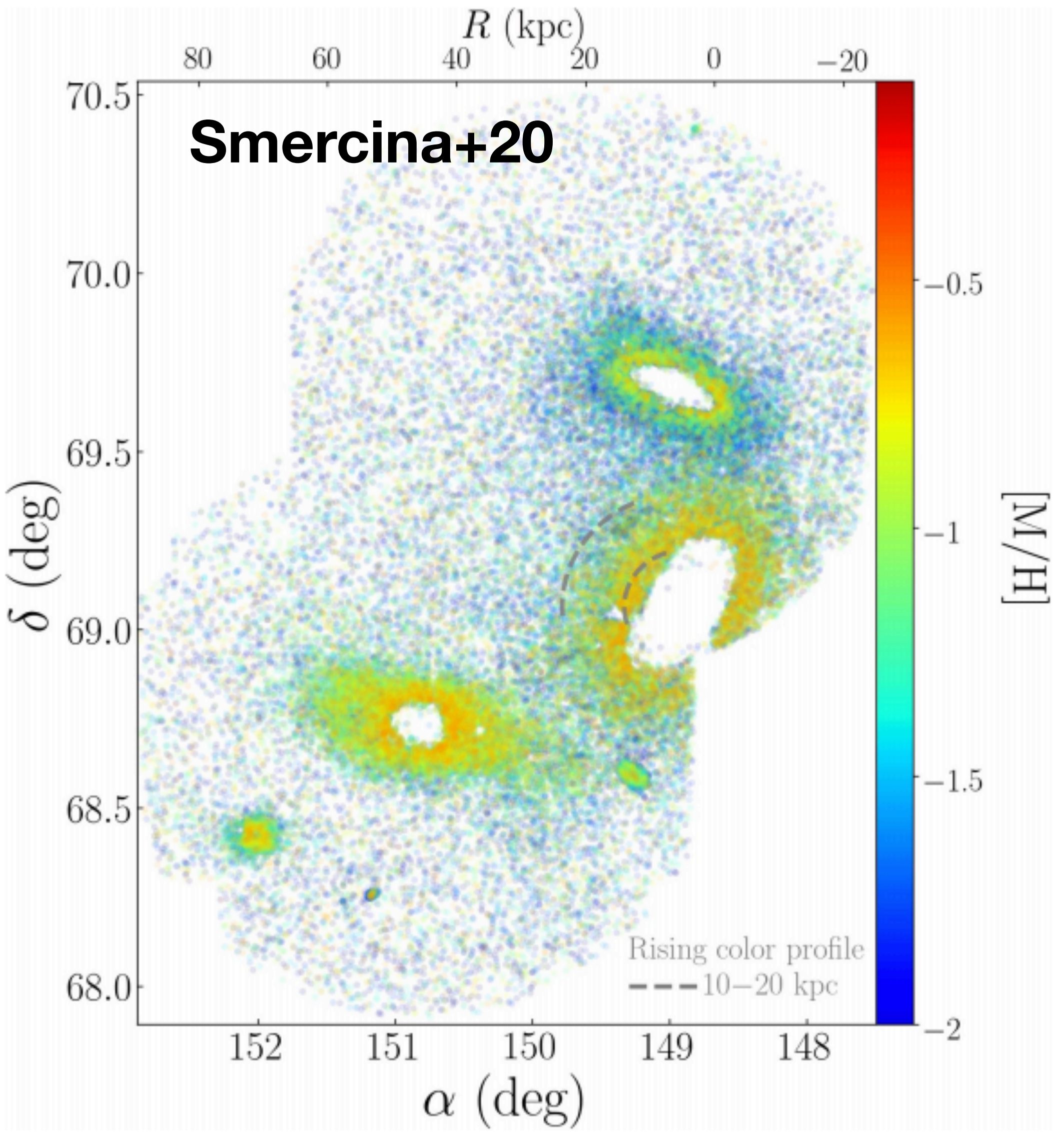

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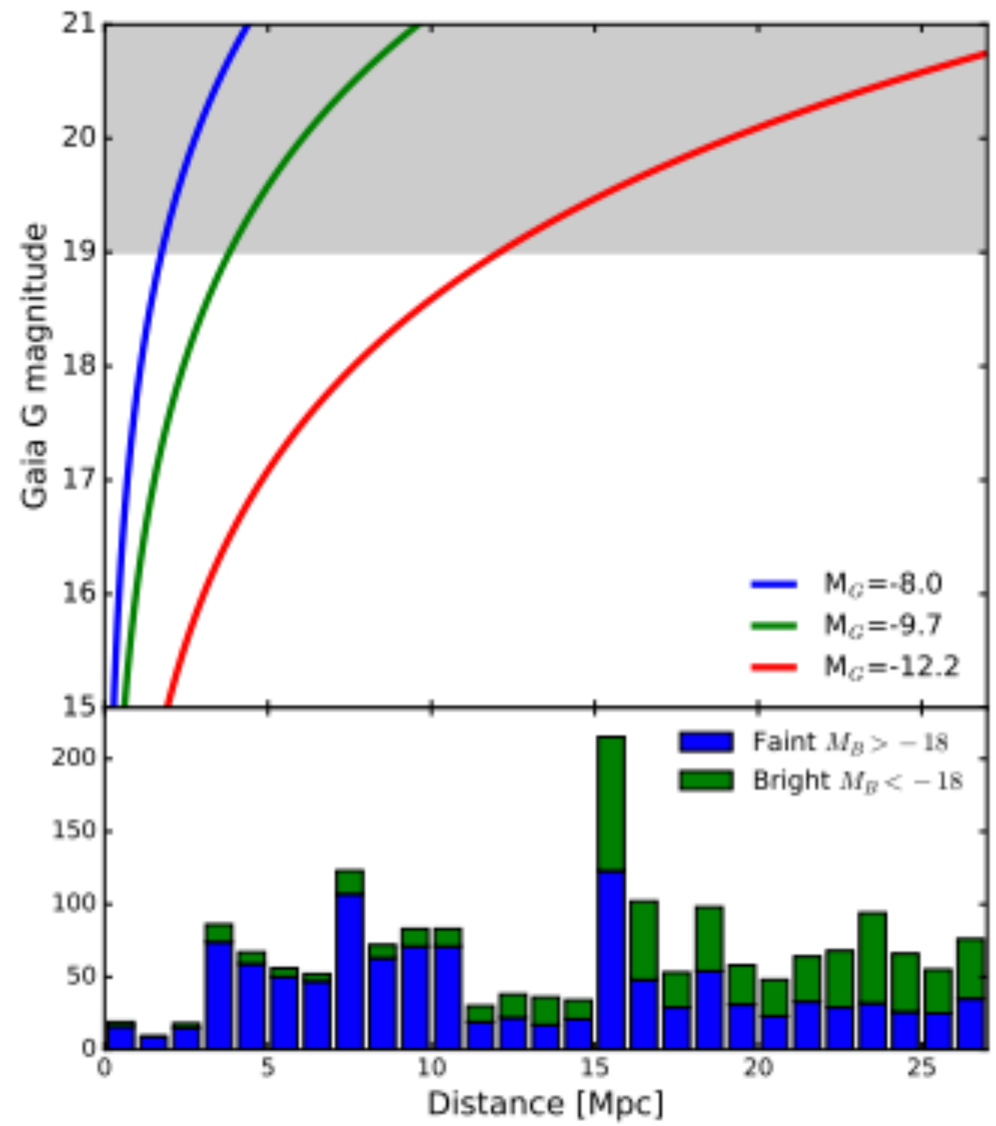
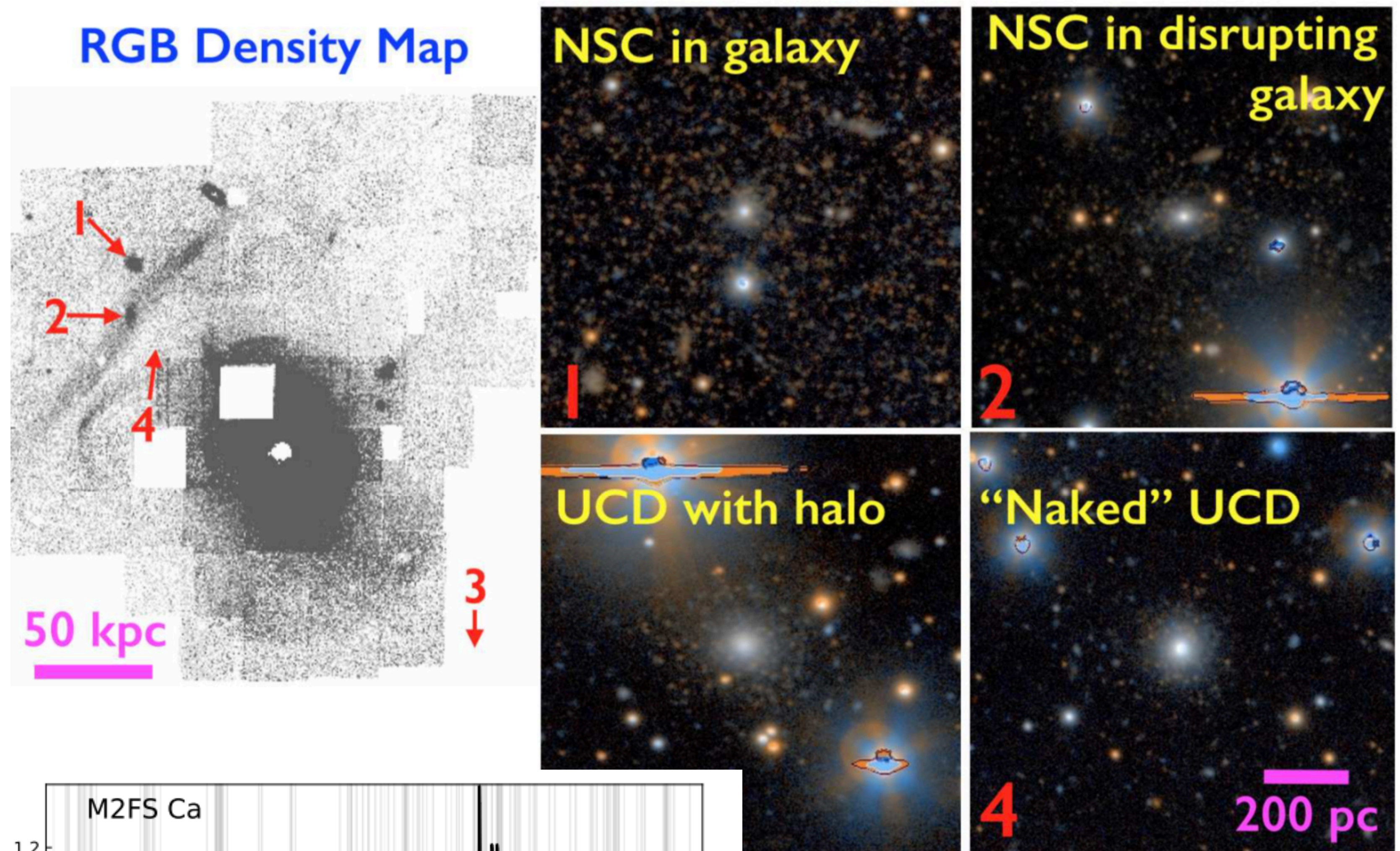
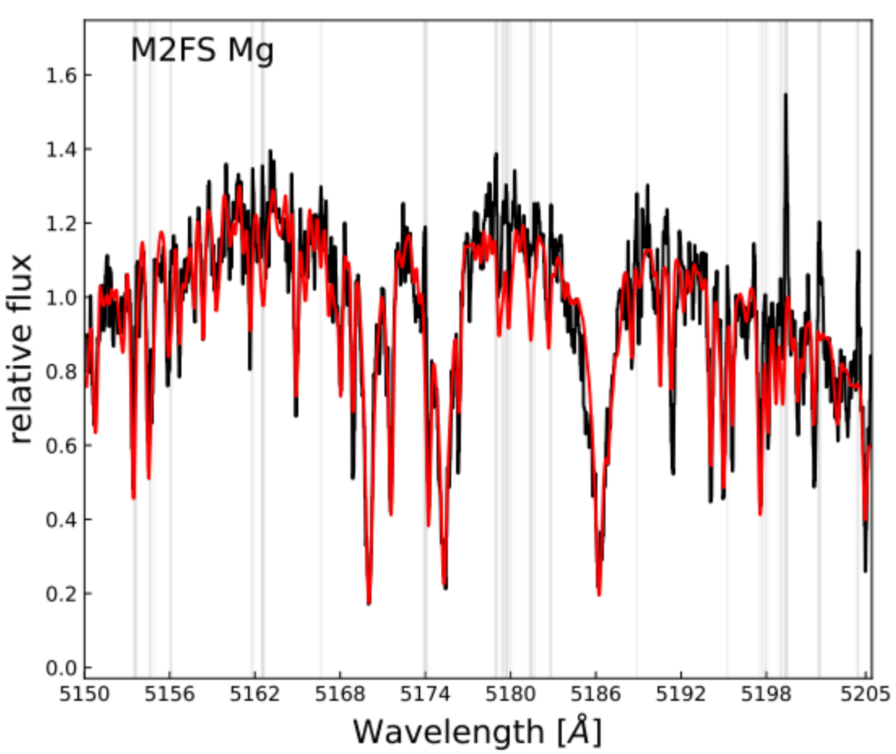


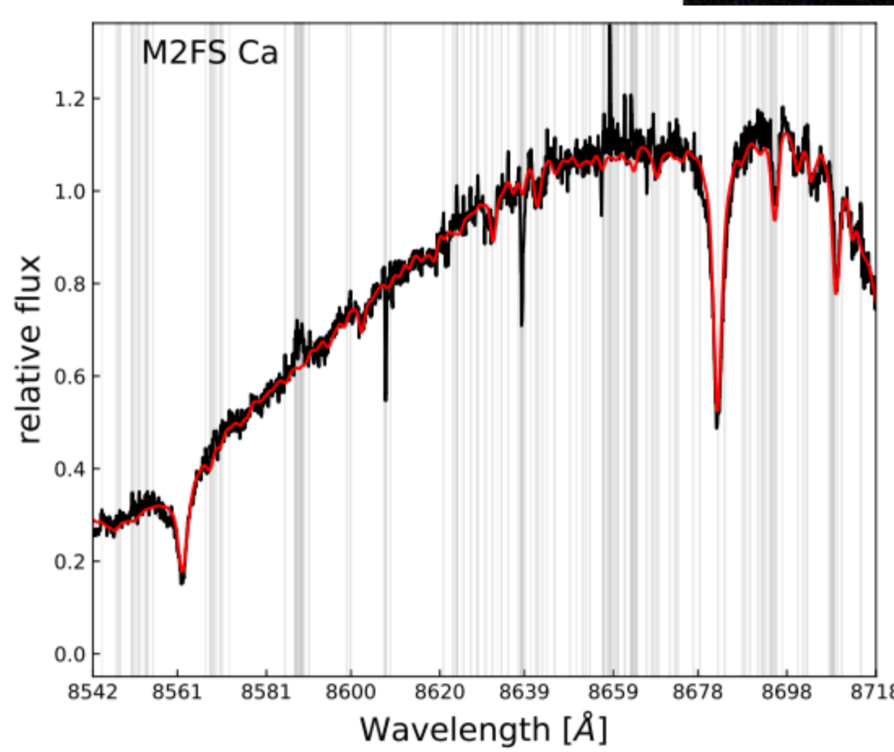
Can push out to ~20 Mpc for the very brightest GC and ultra-compact dwarfs.
Pilot survey around major galaxies out to D~10 Mpc is underway.

Questions?

M2FS Velocity Dispersions of 50 Bright Star Clusters around CenA







Dumont et al. 2022

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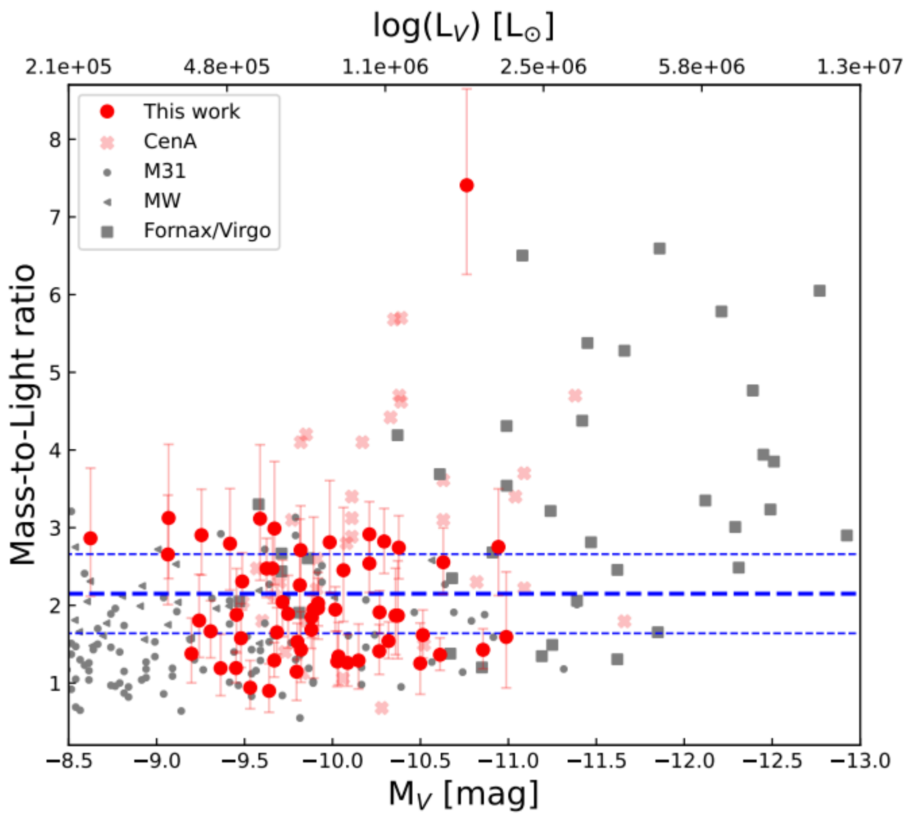
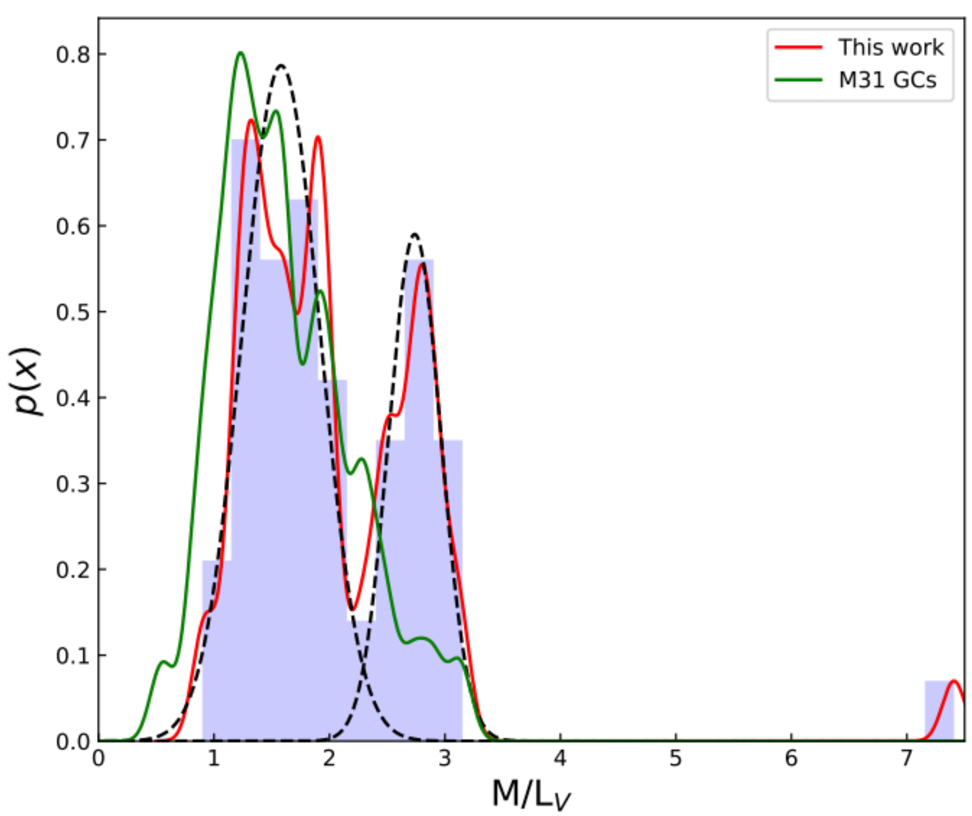
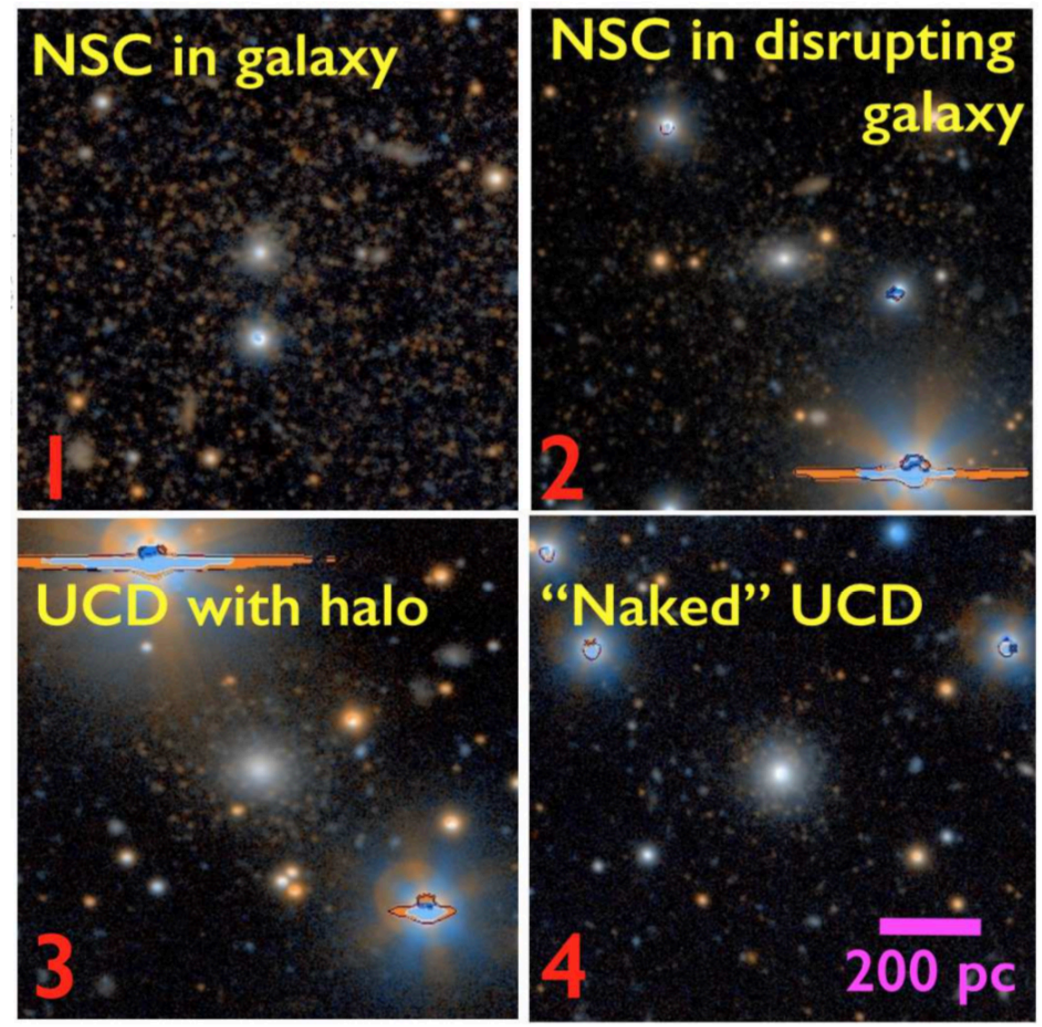






Elevated M/L may point to central supermassive black hole — allows us to distinguish between massive globular clusters and true remnant nuclear star clusters. Stay tuned.

Dumont et al. 2022

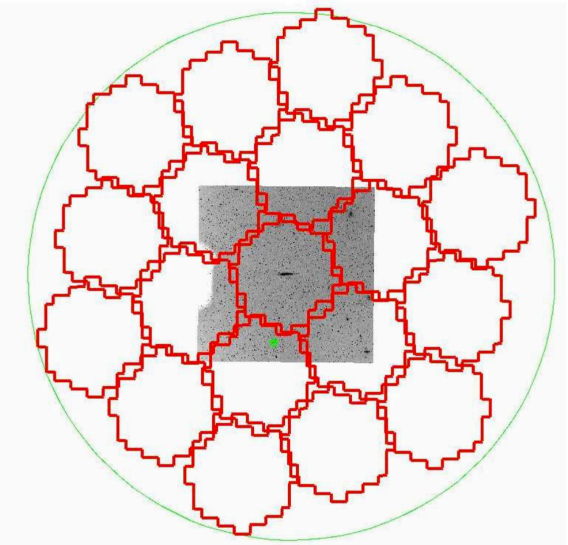
Summary

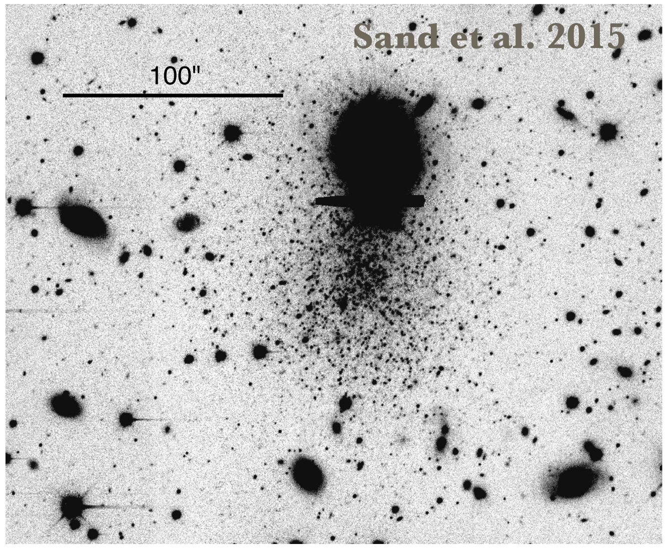
- The least massive dwarf galaxies are an excellent laboratory for testing dark matter/galaxy formation right at the intersection where astrophysics matter.

- The faintest dwarf galaxies will always be those around the Milky Way. We must understand these systems in detail as the ultimate proving ground for DM+astrophysics.

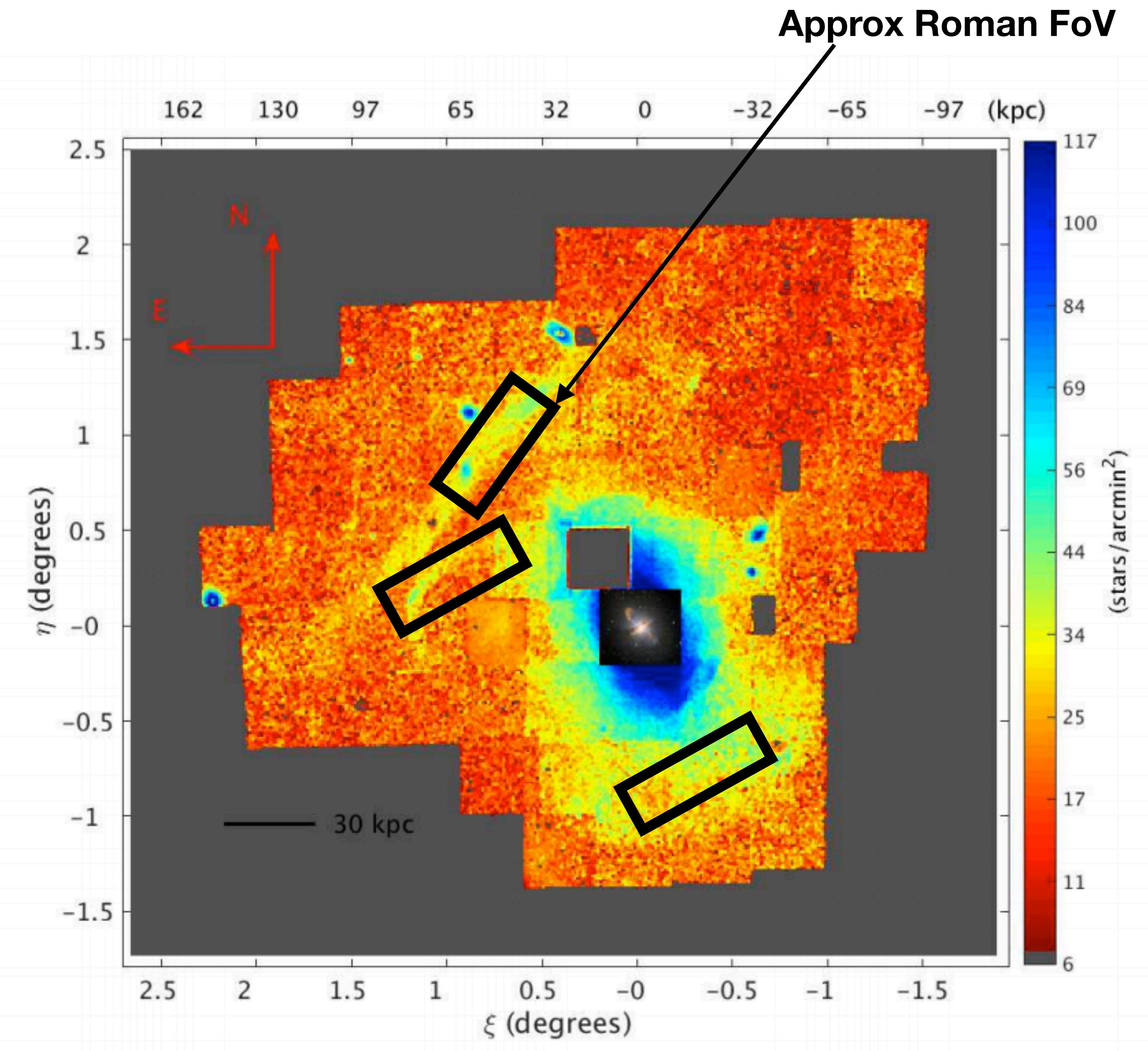
- Moving so-called 'Near Field Cosmology' beyond the Local Group is key to understanding the drivers of satellite galaxy formation and evolution. Field dwarfs are an important population to study as well.

- The next decade will be bright, with VRO, HSC and Roman all coming into their own.





The field of Streams of CenA



Crnojevic et al. 2016

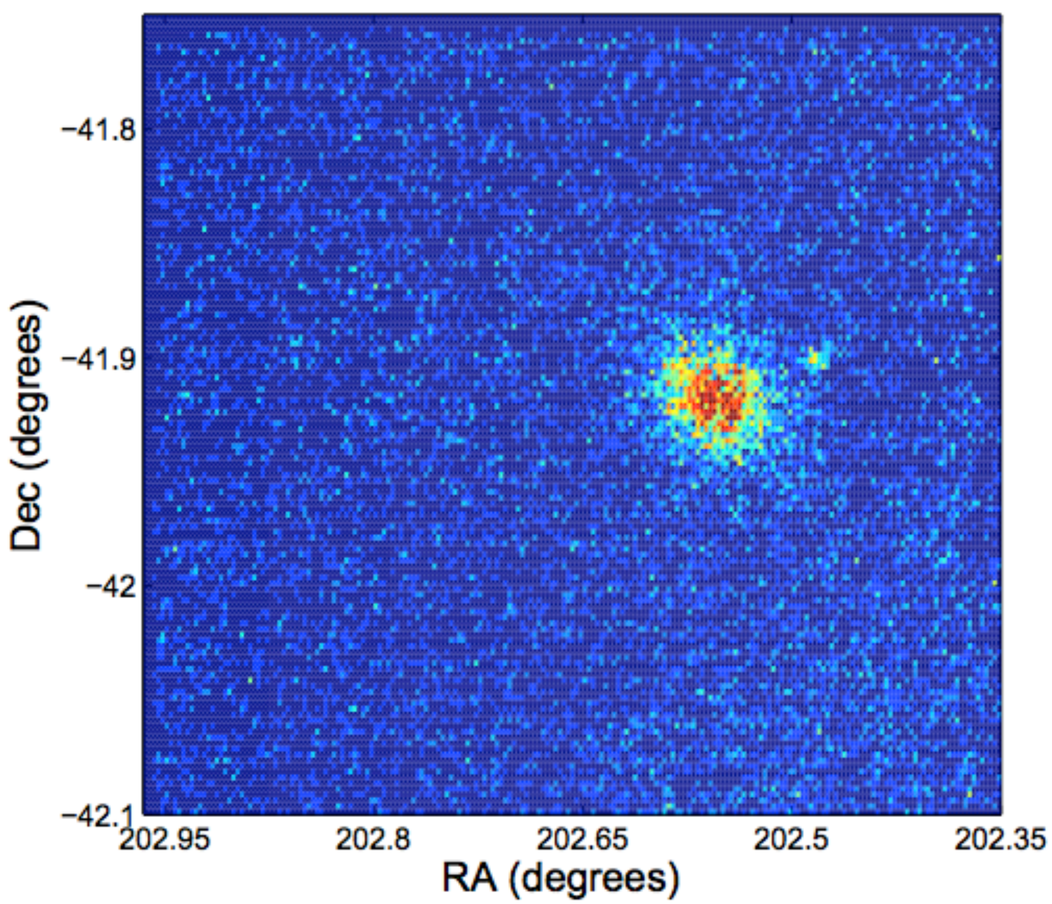
A clearly disrupting dwarf galaxy -- detected not by low surface brightness measurements but in individual resolved stars!

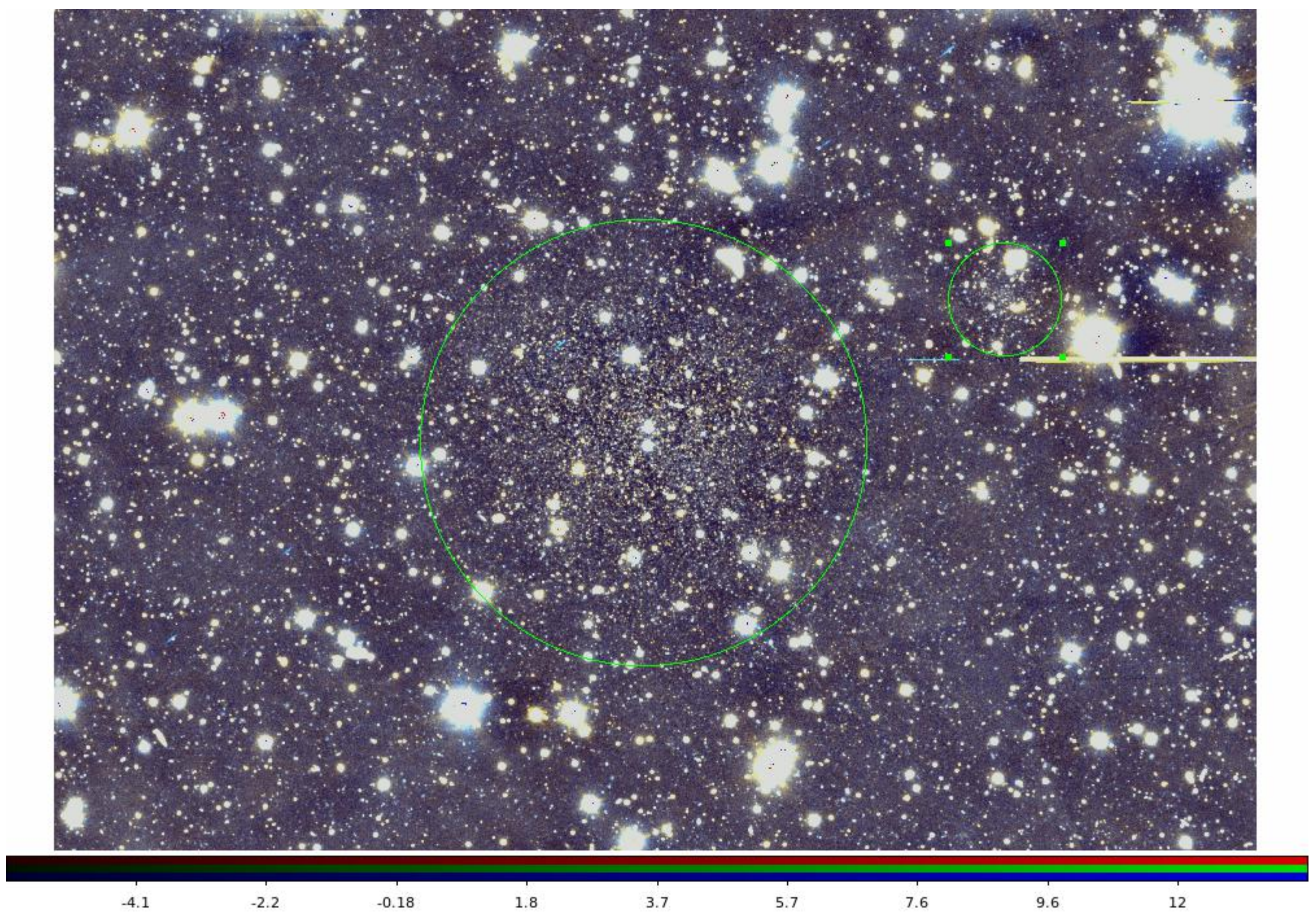
There are clearly other streams emerging.

All in resolved RGB stars

A close pair of satellites around Centaurus A

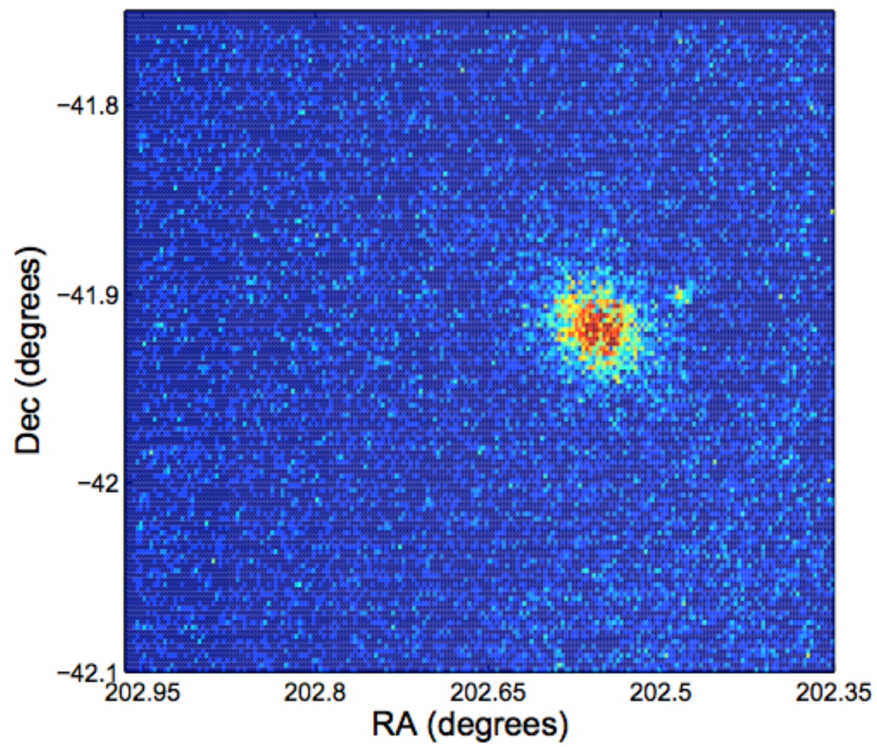
Crnojevic et al. 2014

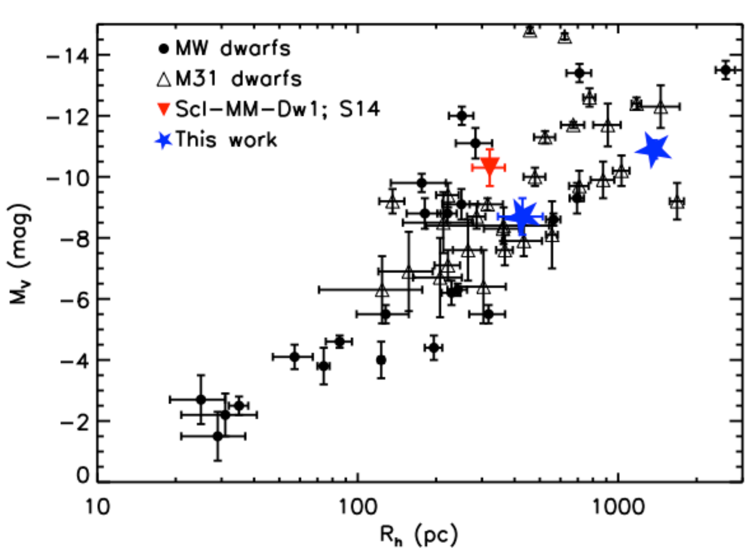


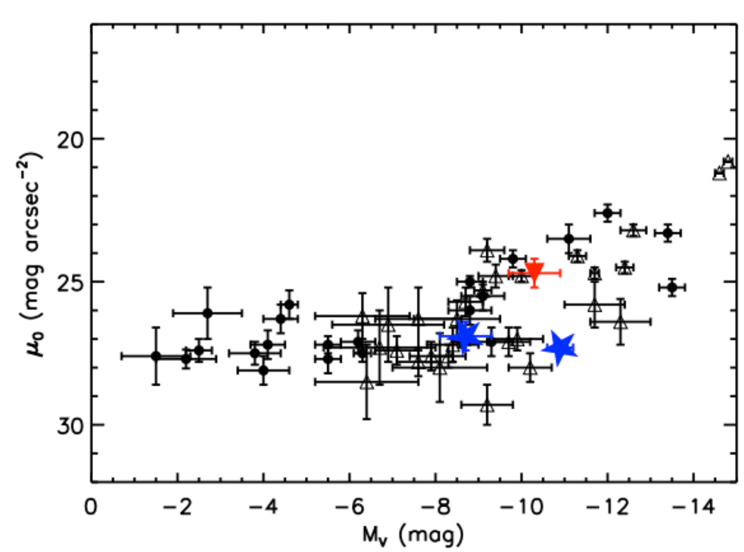


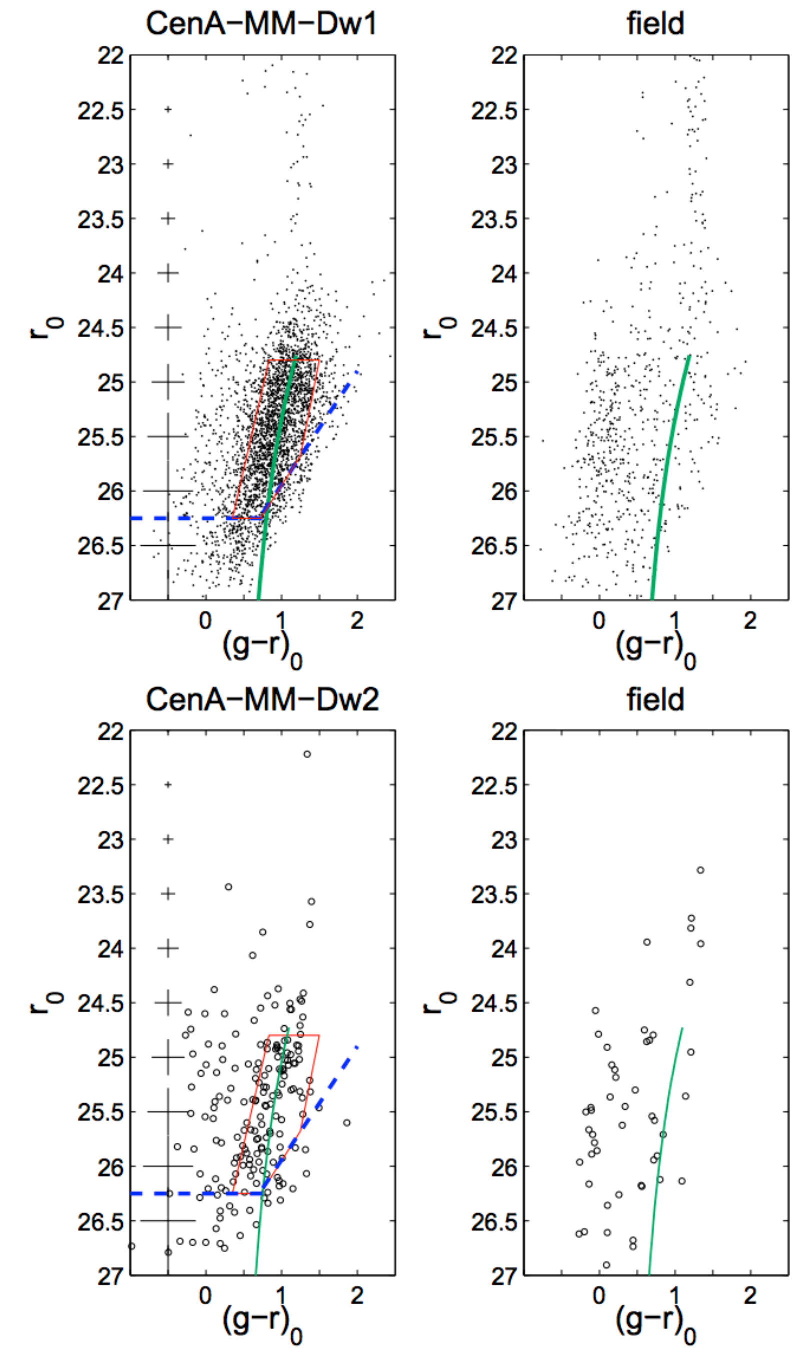
Pair is projected ~90 kpc from center of CenA.
3 kpc projected separation. Both are at D~3.6 Mpc.
A 'satellite of a satellite'? -- also a prediction of CDM.

A close pair of satellites



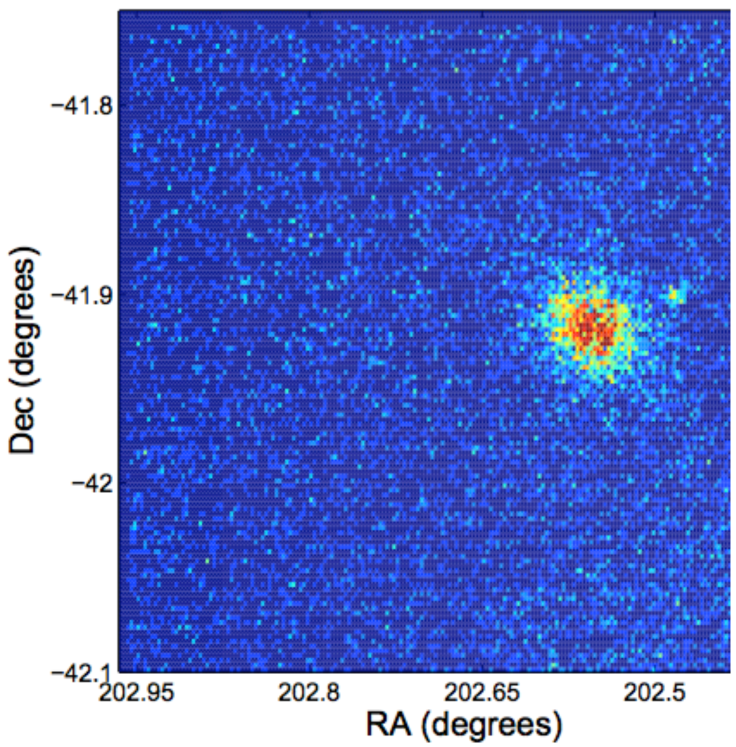


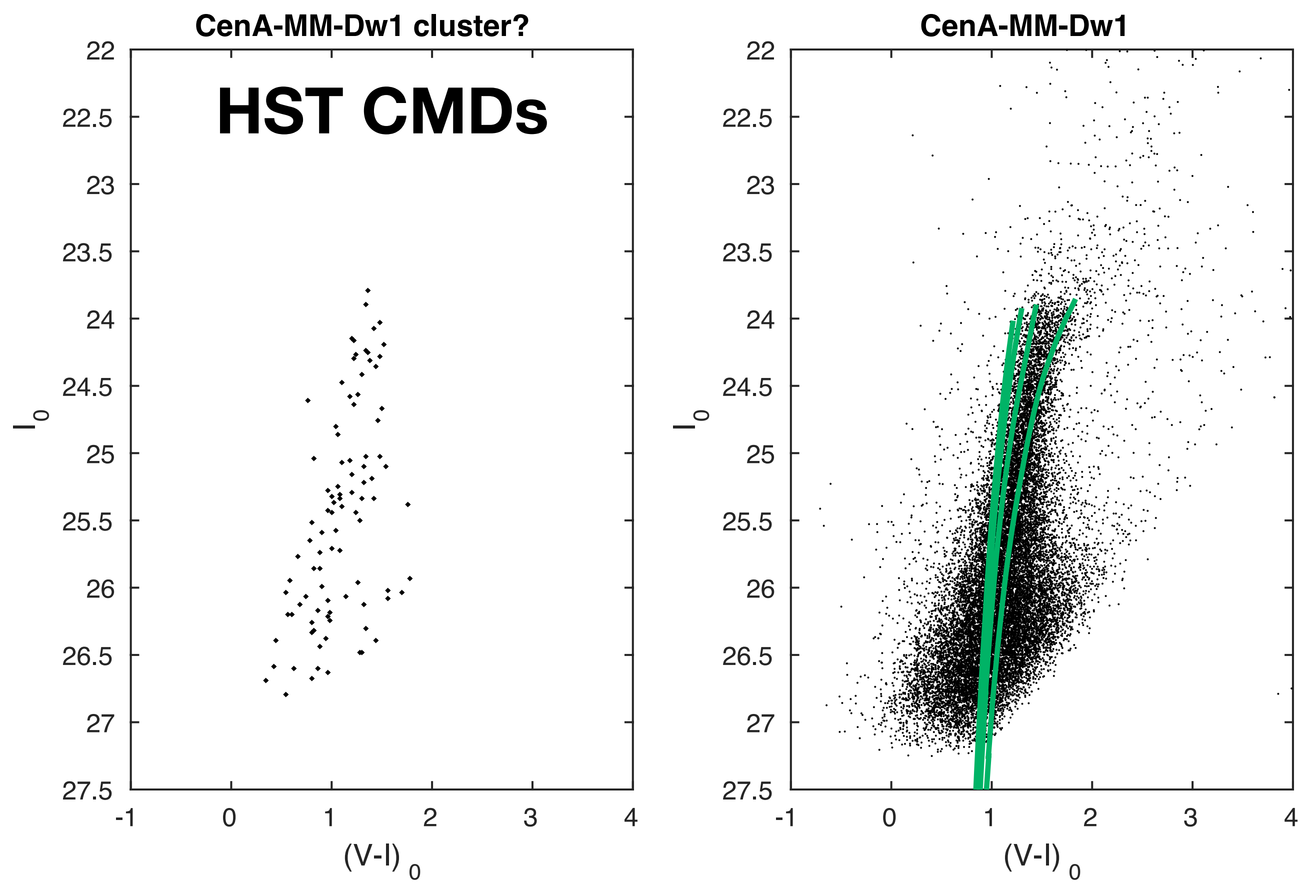


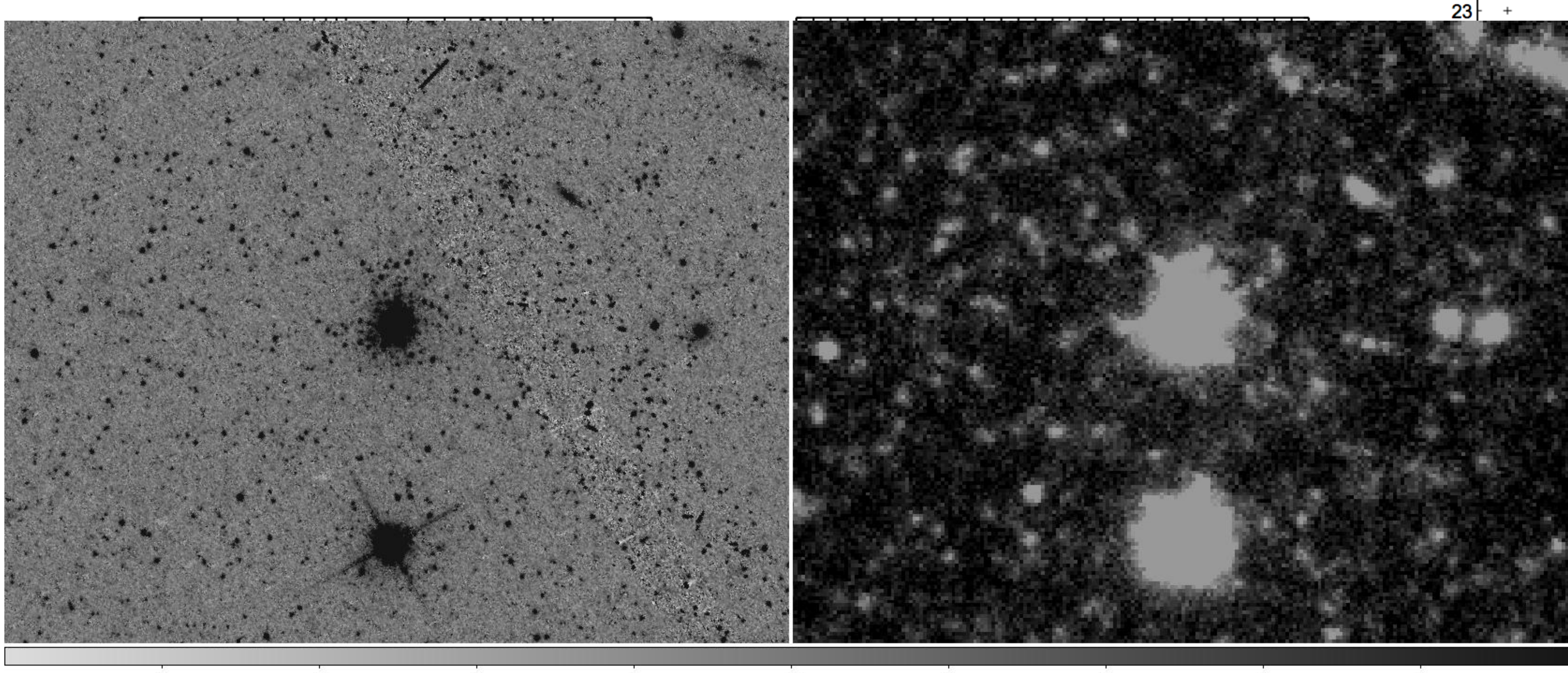


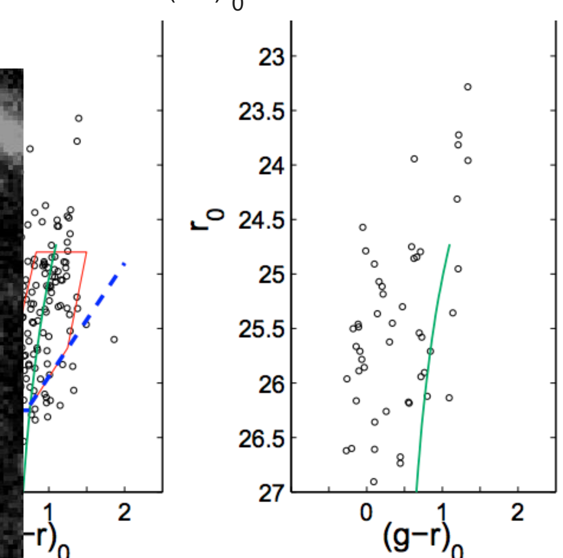
Crnojevic et al. 2014

A close pair of satellites

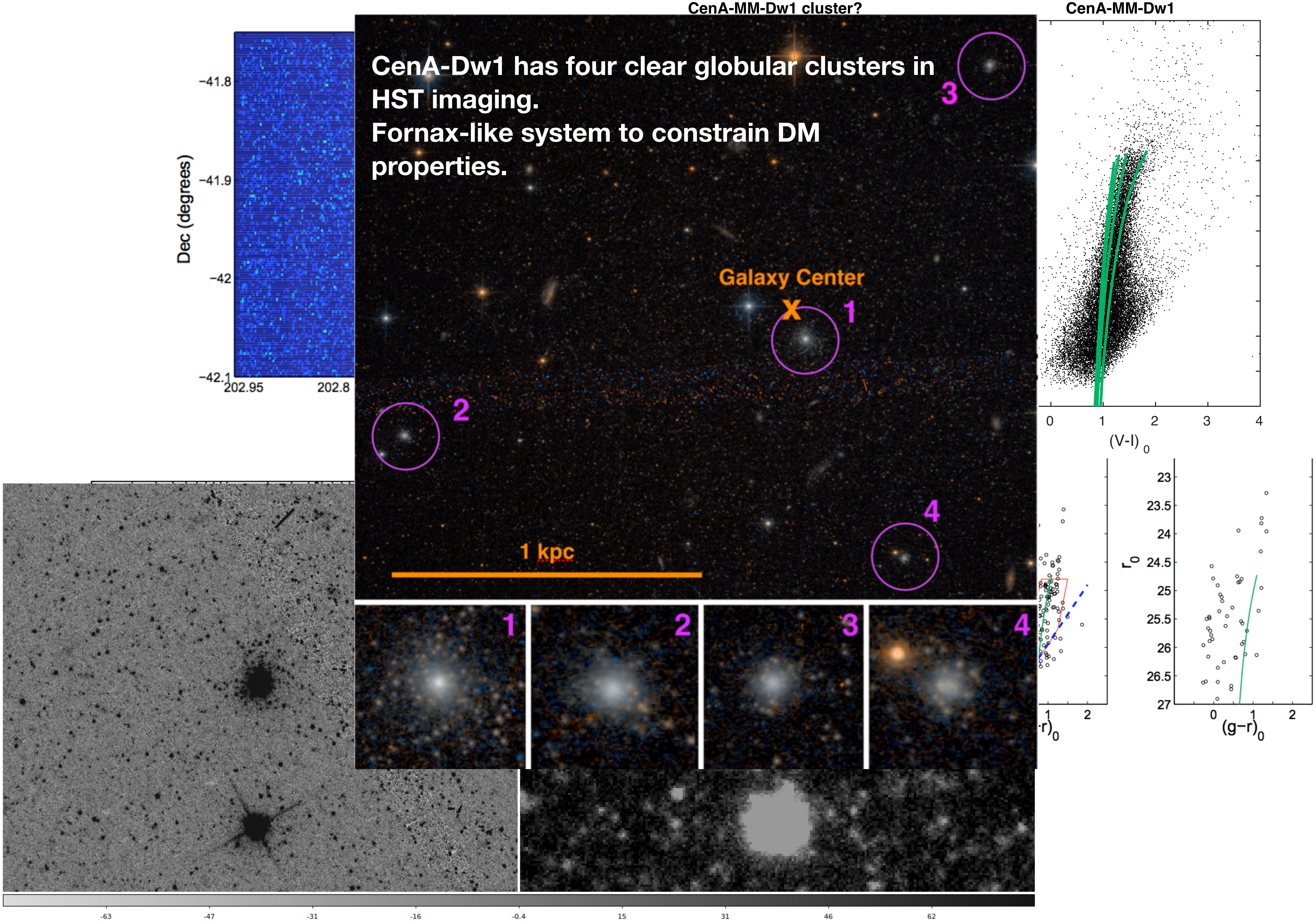






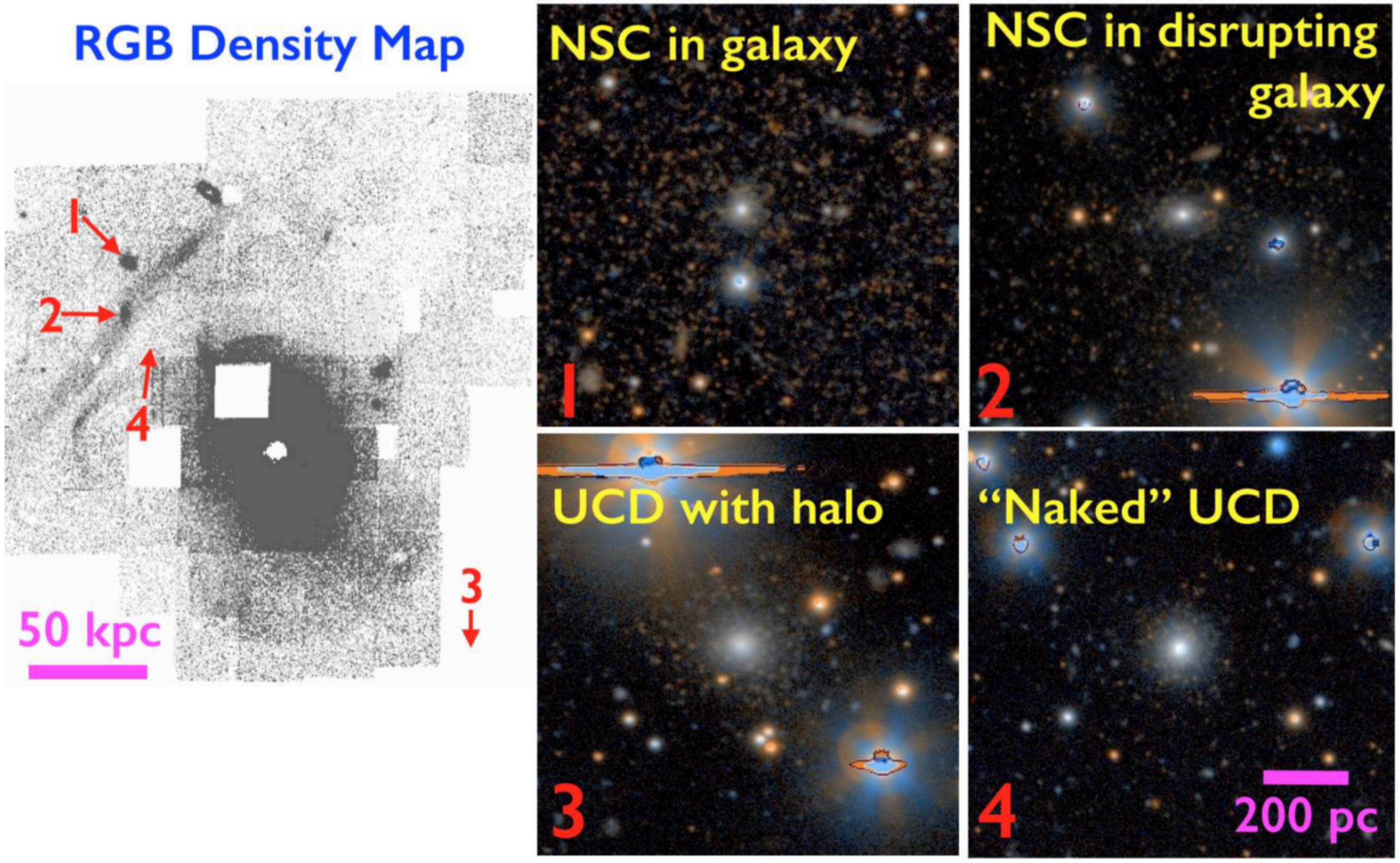


A close pair of satellites



HST followup is revealing a rich variety of star clusters

At an average M_V=-7, we can use star clusters to probe kinematics of halo substructures and DM profile of CenA, and other nearby galaxies.



Cross-check with literature Velocities