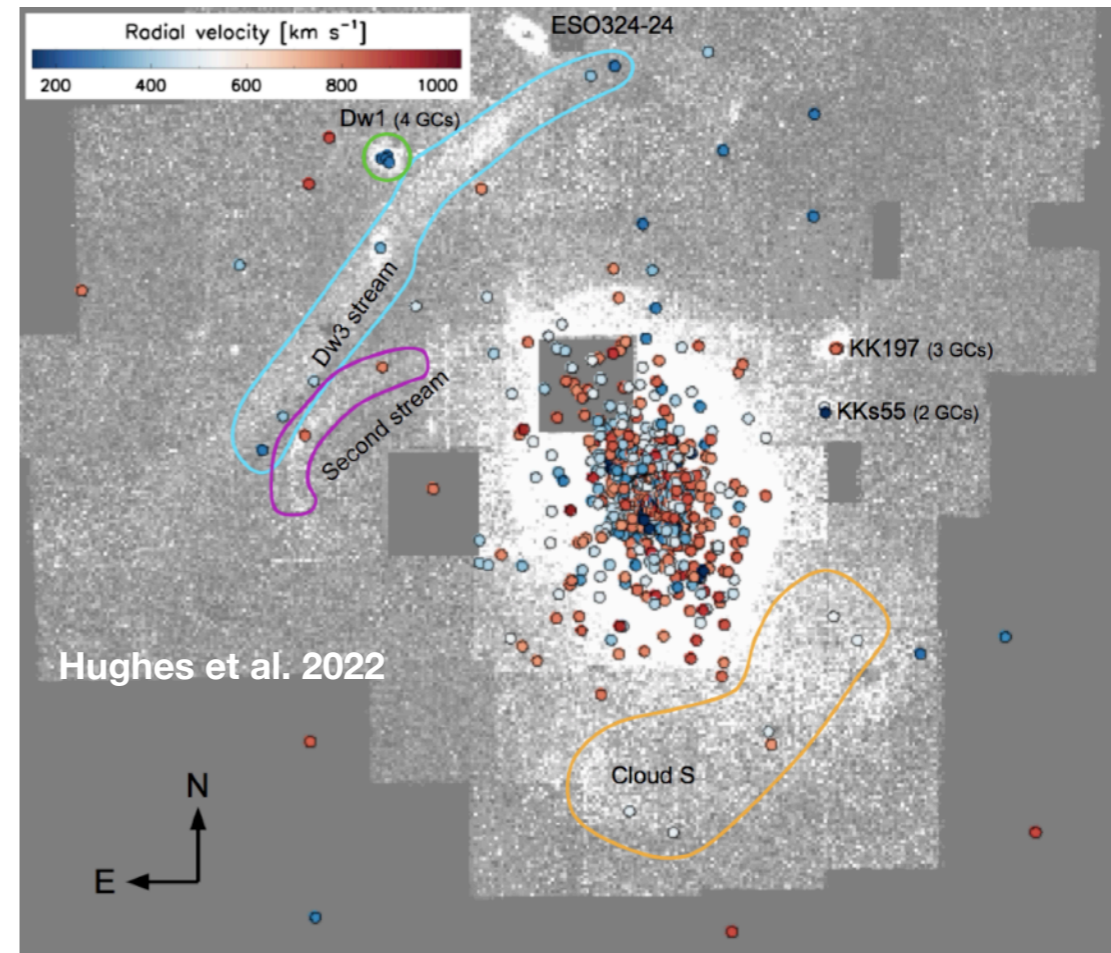
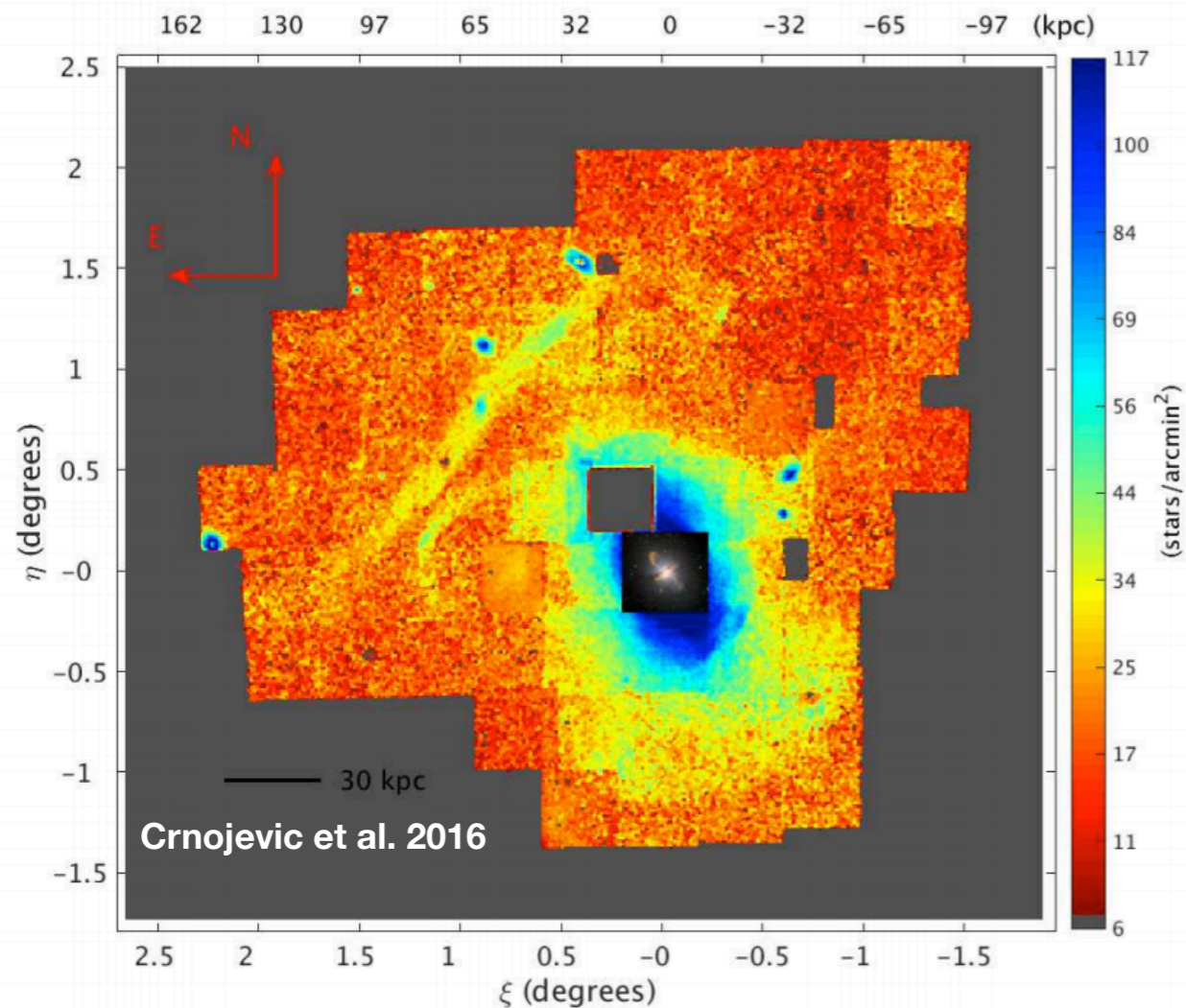


USING DECAM AND GAIA TO IDENTIFY GLOBULAR CLUSTERS IN THE LOCAL UNIVERSE: SUBSTRUCTURE AND MASS OF CENTAURUS A



D. Sand & Allie Hughes (U of Arizona)

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

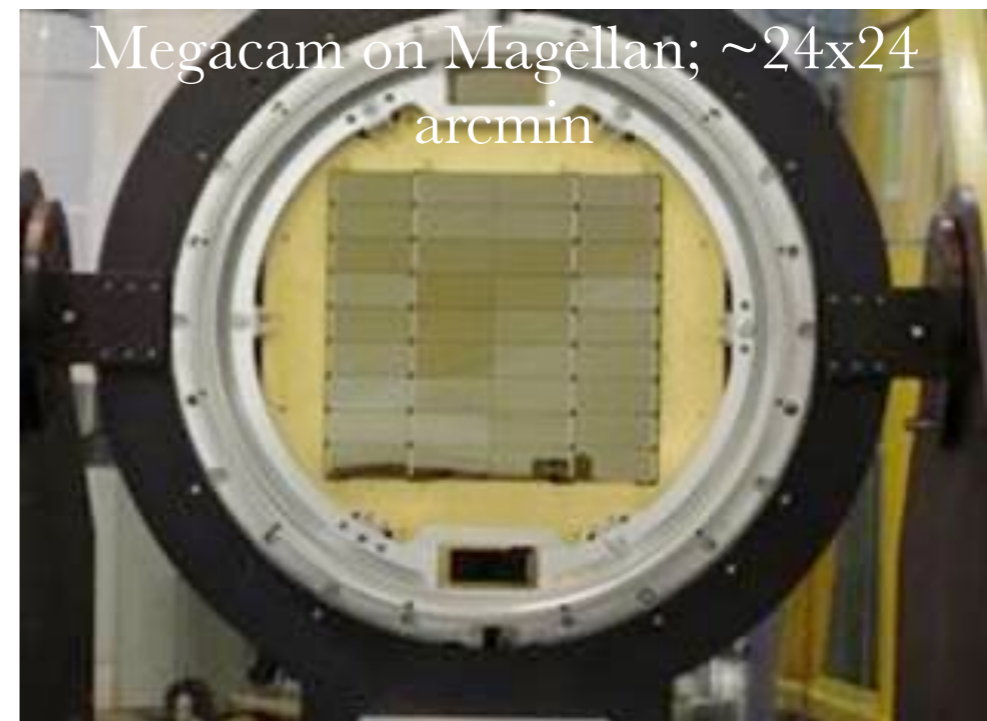
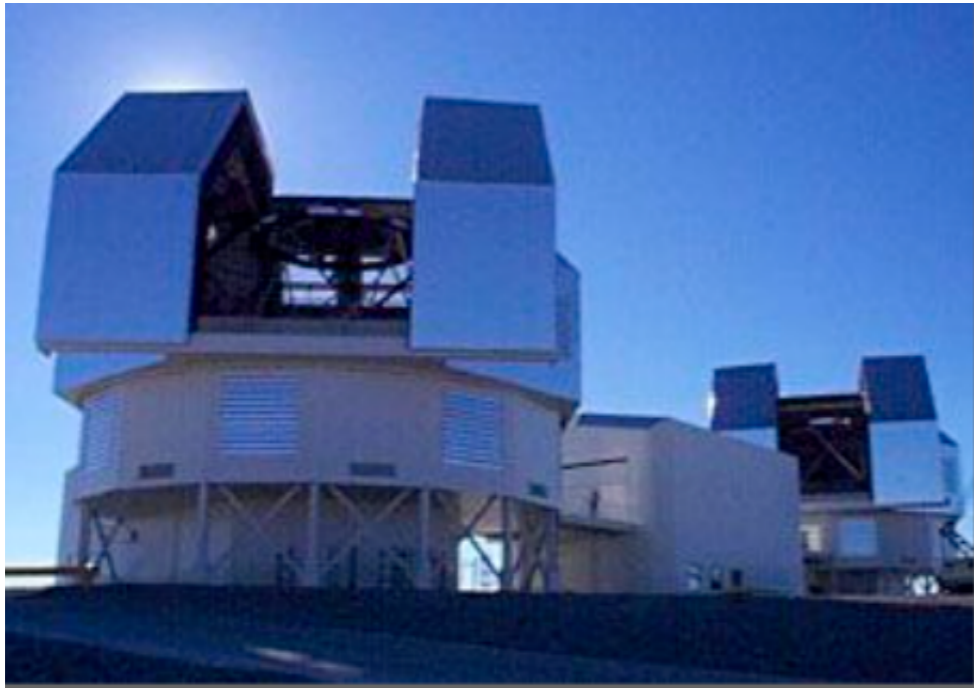
DECam at 10 years — Sep 2022



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

- A new globular cluster identification technique that combines high-res ground-based data + DECam multi-band data + 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 (SEE TALKS YESTERDAY)

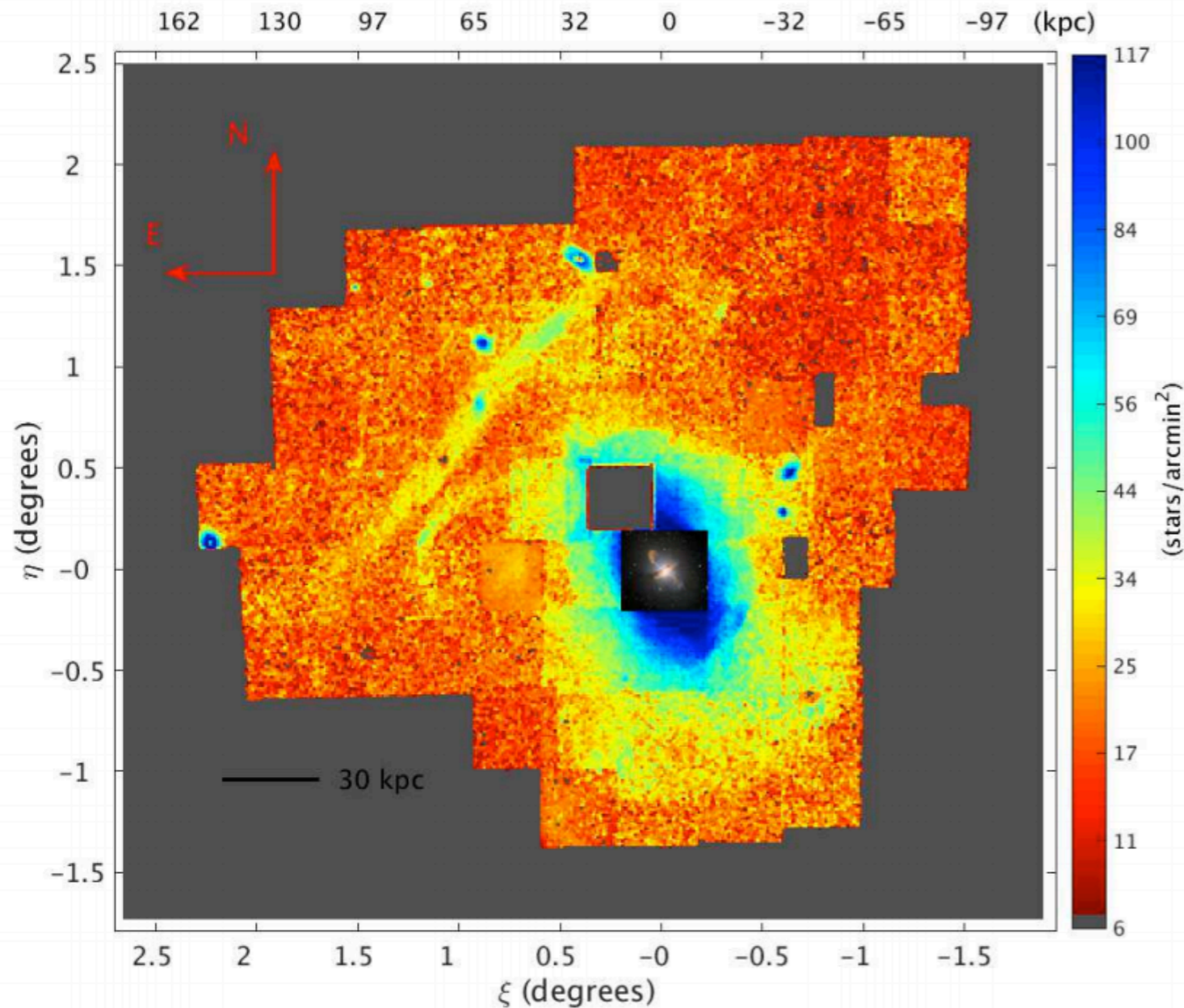


THE PANORAMIC IMAGING SURVEY OF CENTAURUS AND SCULPTOR (PISCES)

- Deep imaging ($r \sim 26$) 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

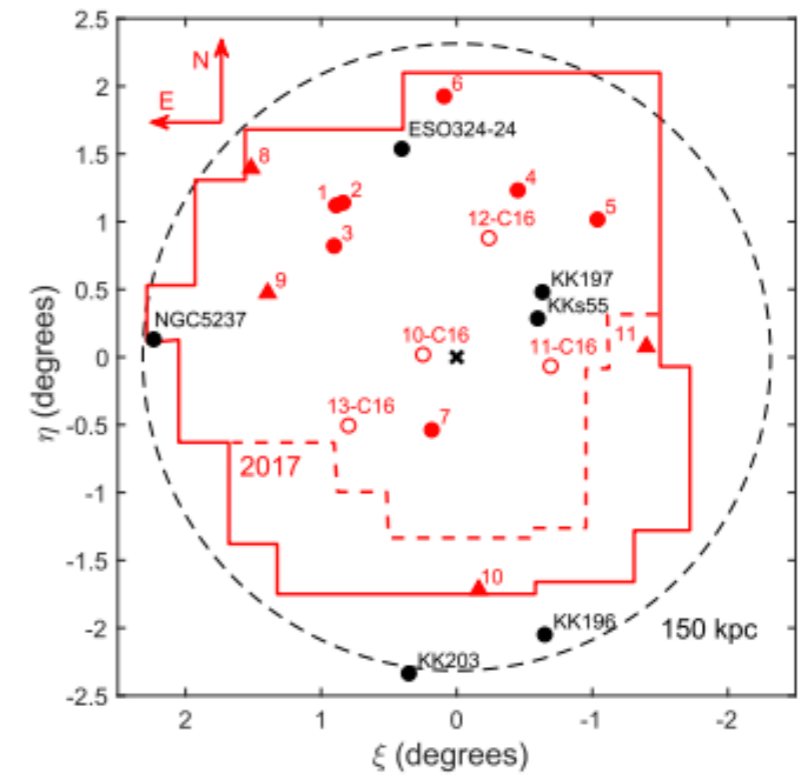
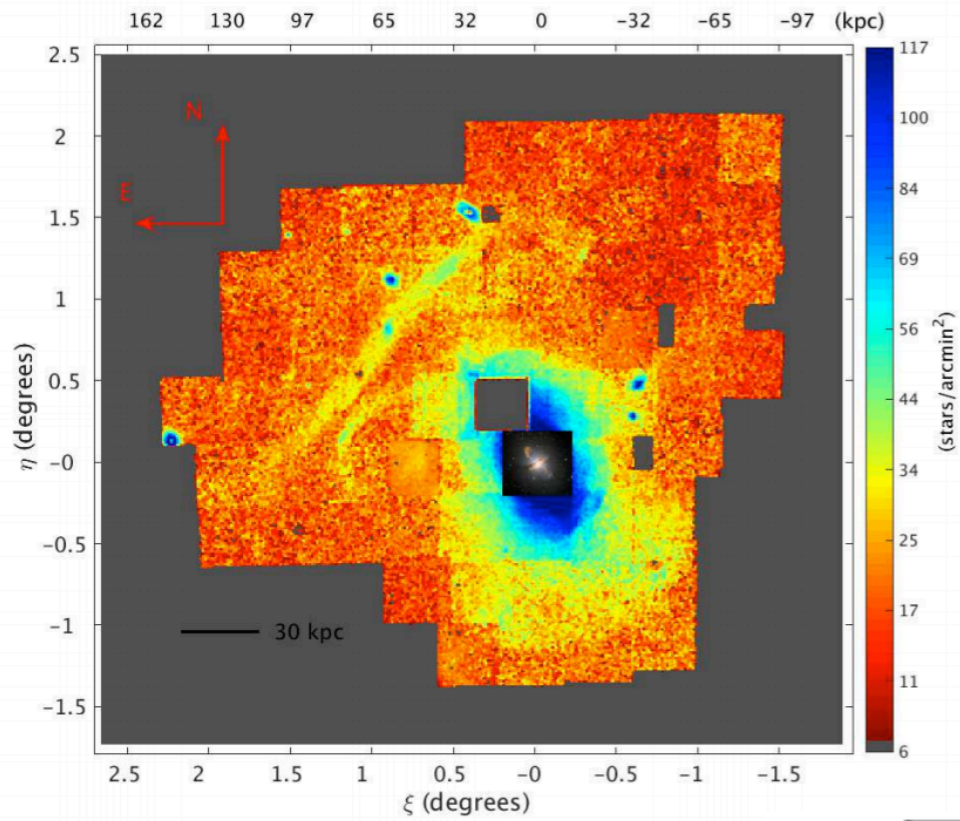


A clearly disrupting dwarf galaxy -- detected not by low surface brightness measurements but in individual resolved stars!

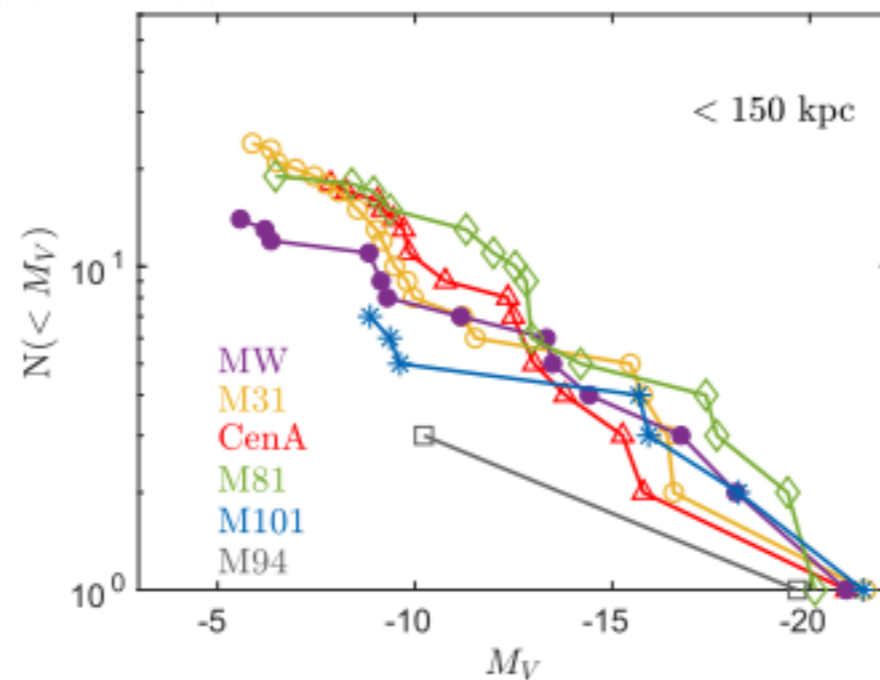
There are clearly other streams emerging.

All in resolved RGB stars

ELEVEN NEW CENA DWARFS DOWN TO $M_V \sim -7.5$ MAG



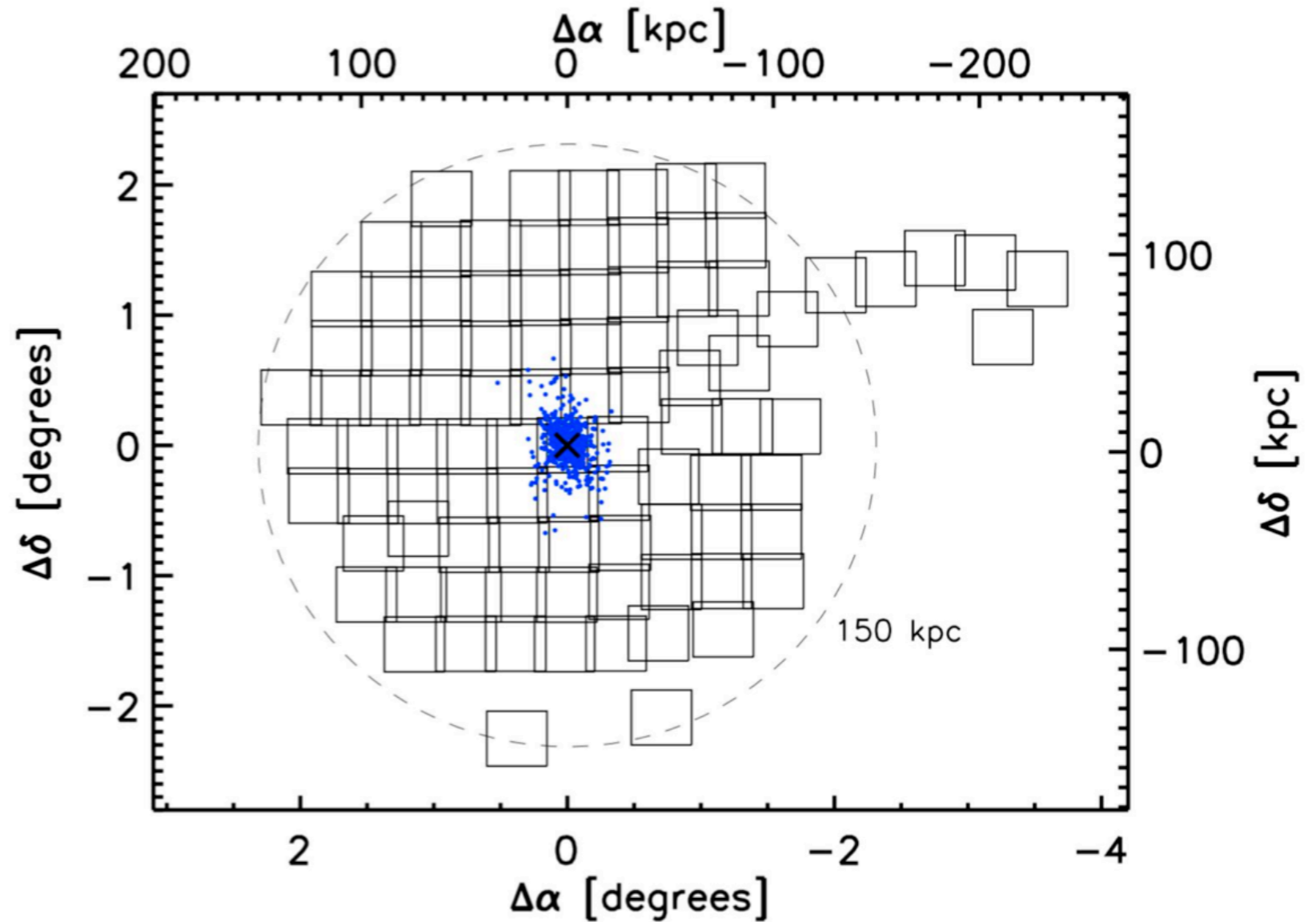
Satellite luminosity function comparable to M81 and M31



CENA GC STATUS (AS OF LAST YEAR)

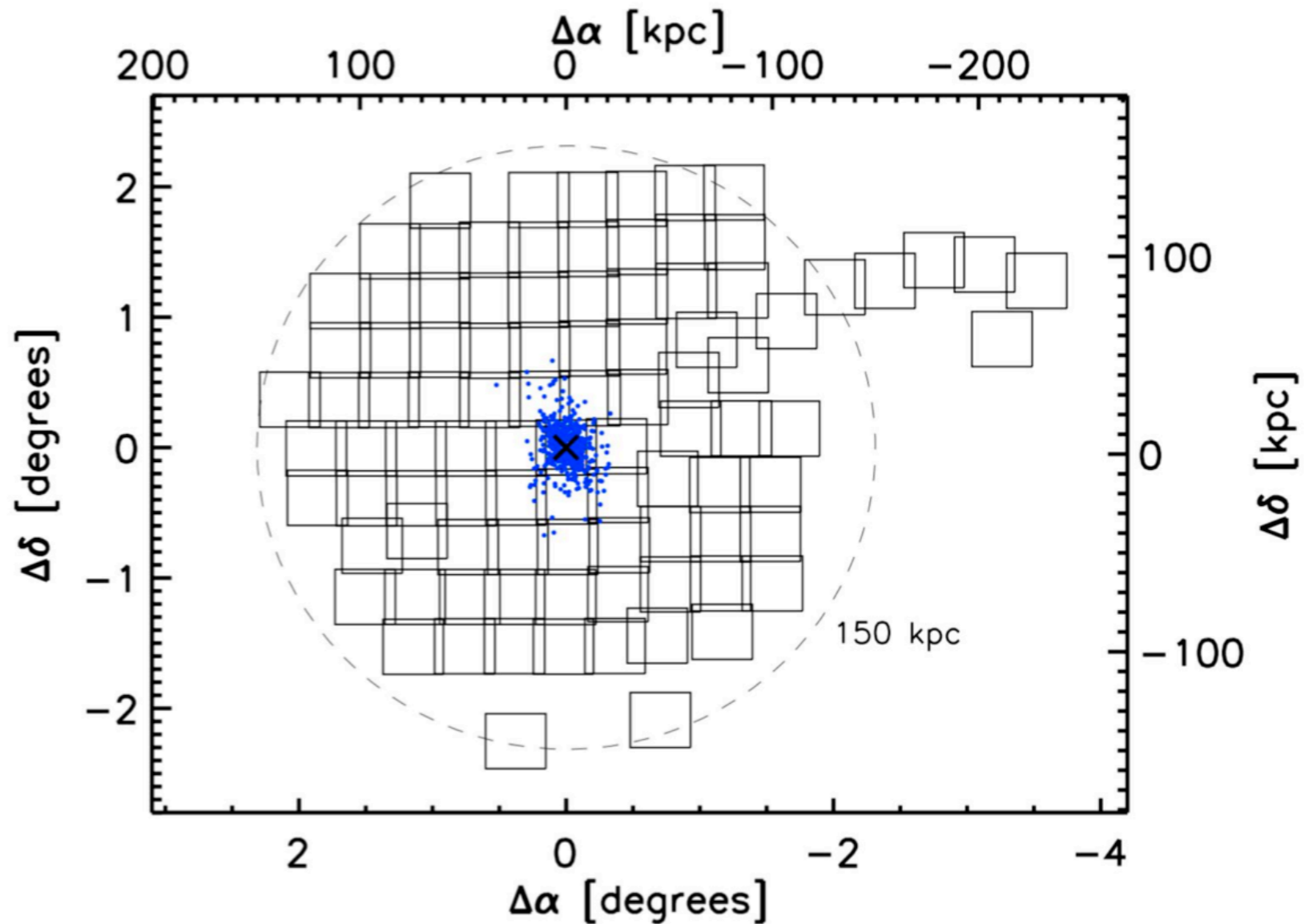
557 confirmed GCs in CenA, almost all within ~ 35 arcmin (~ 40 kpc)

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

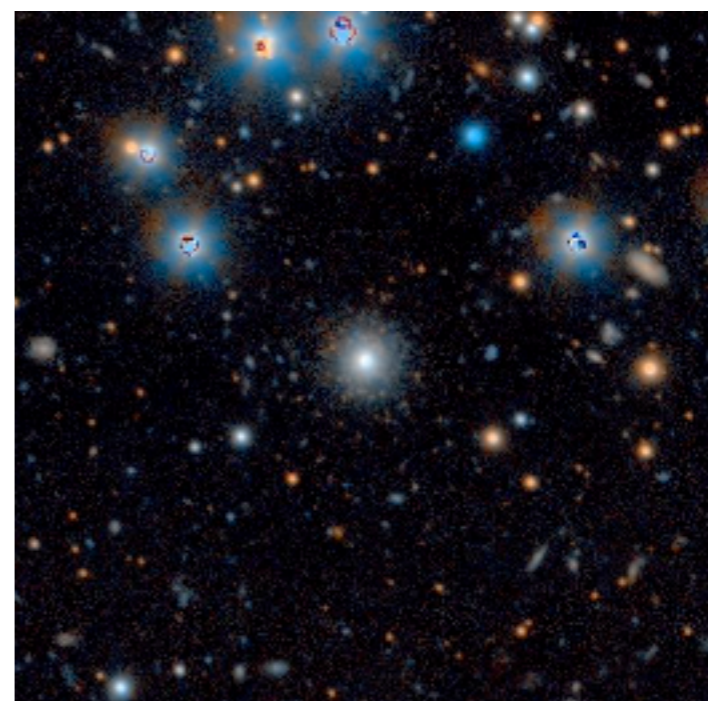
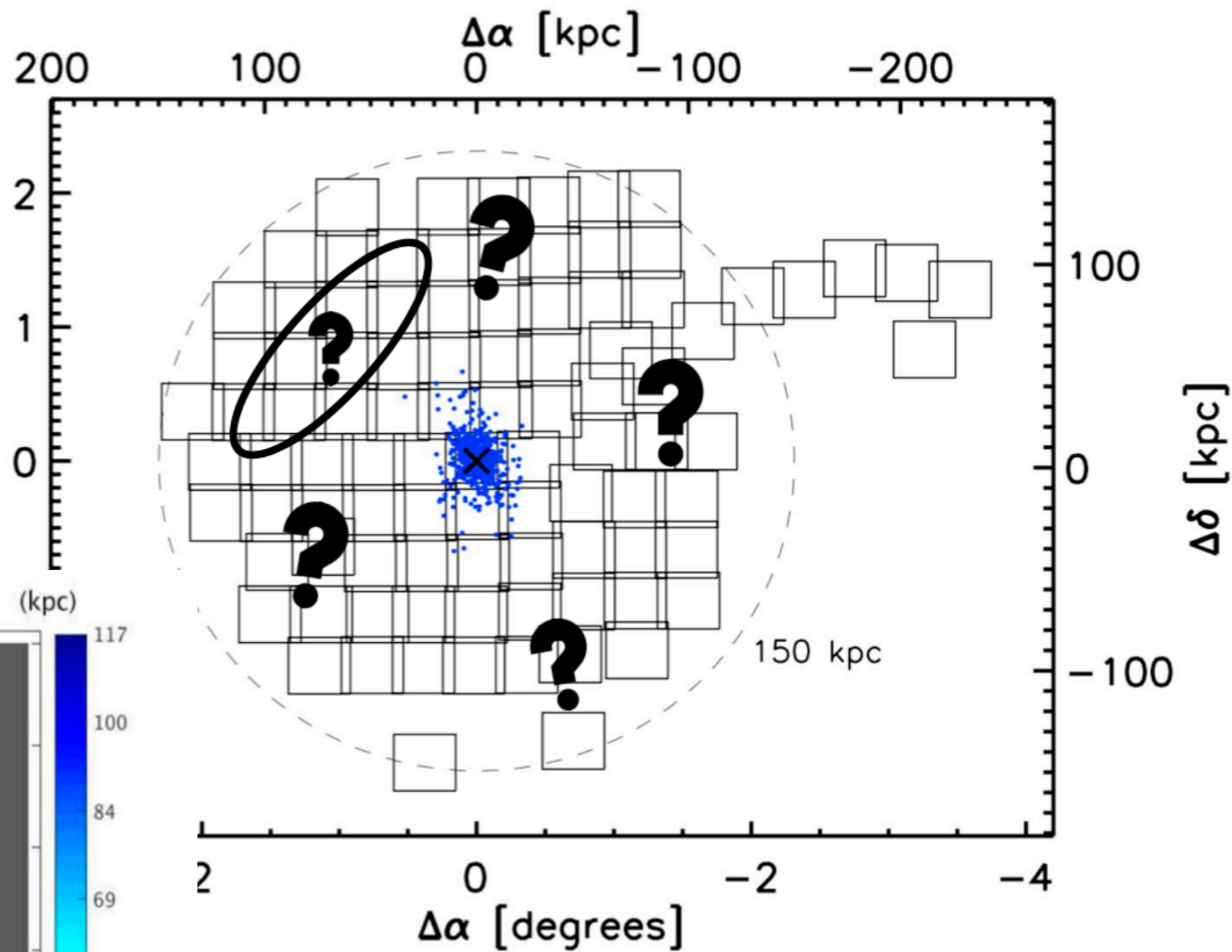
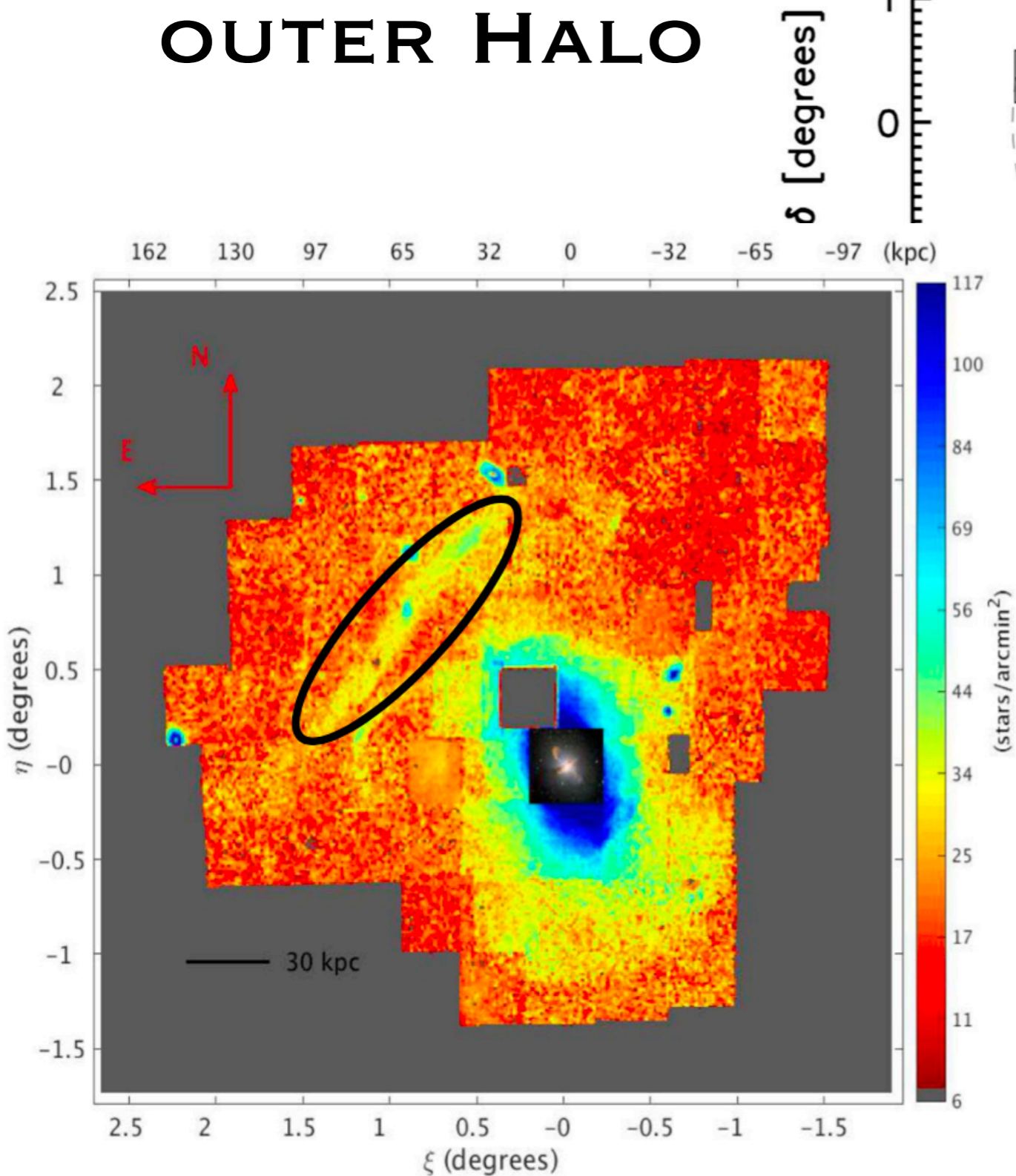


WHY STUDY EXTRAGALACTIC GLOBULAR CLUSTERS?

- Complementary probe of stellar halo
- Bright, compact $\langle M_V \rangle = -7$
- Kinematic tracer: mass, assembly history, dark matter distribution, previous accretion events.
- GCs are 1-20 pc in size, corresponds to $\sim 0.1-1.1''$ at CenA.

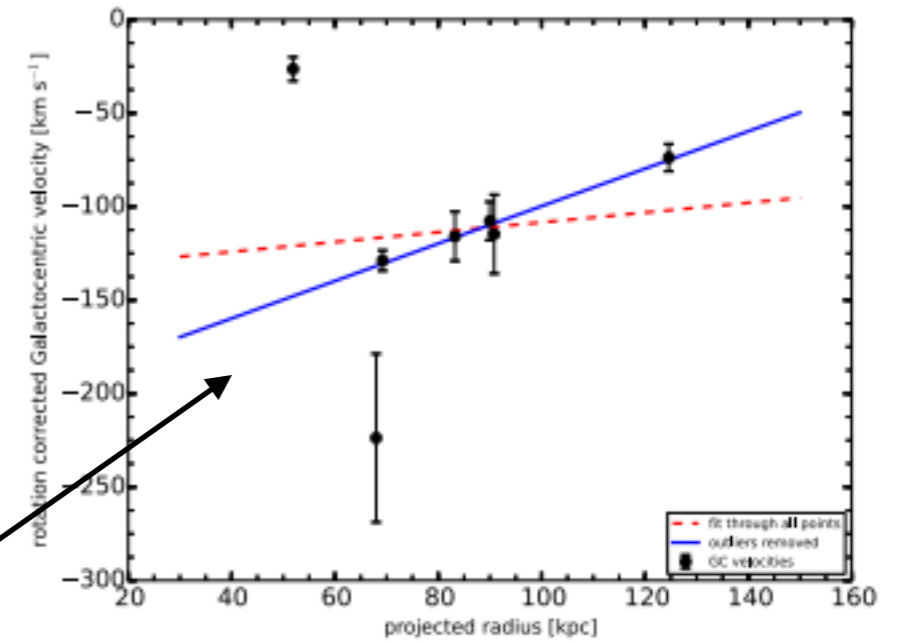
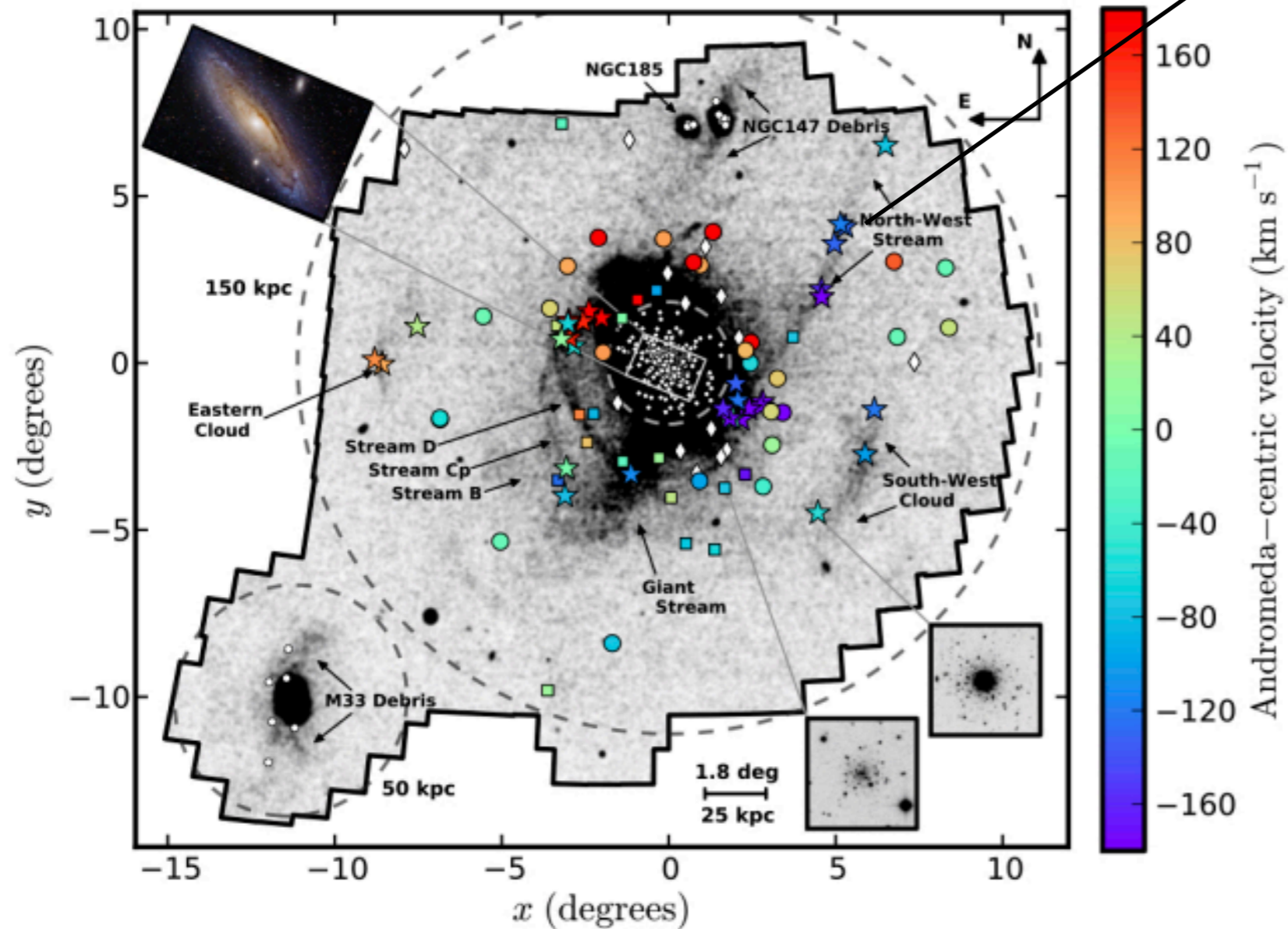


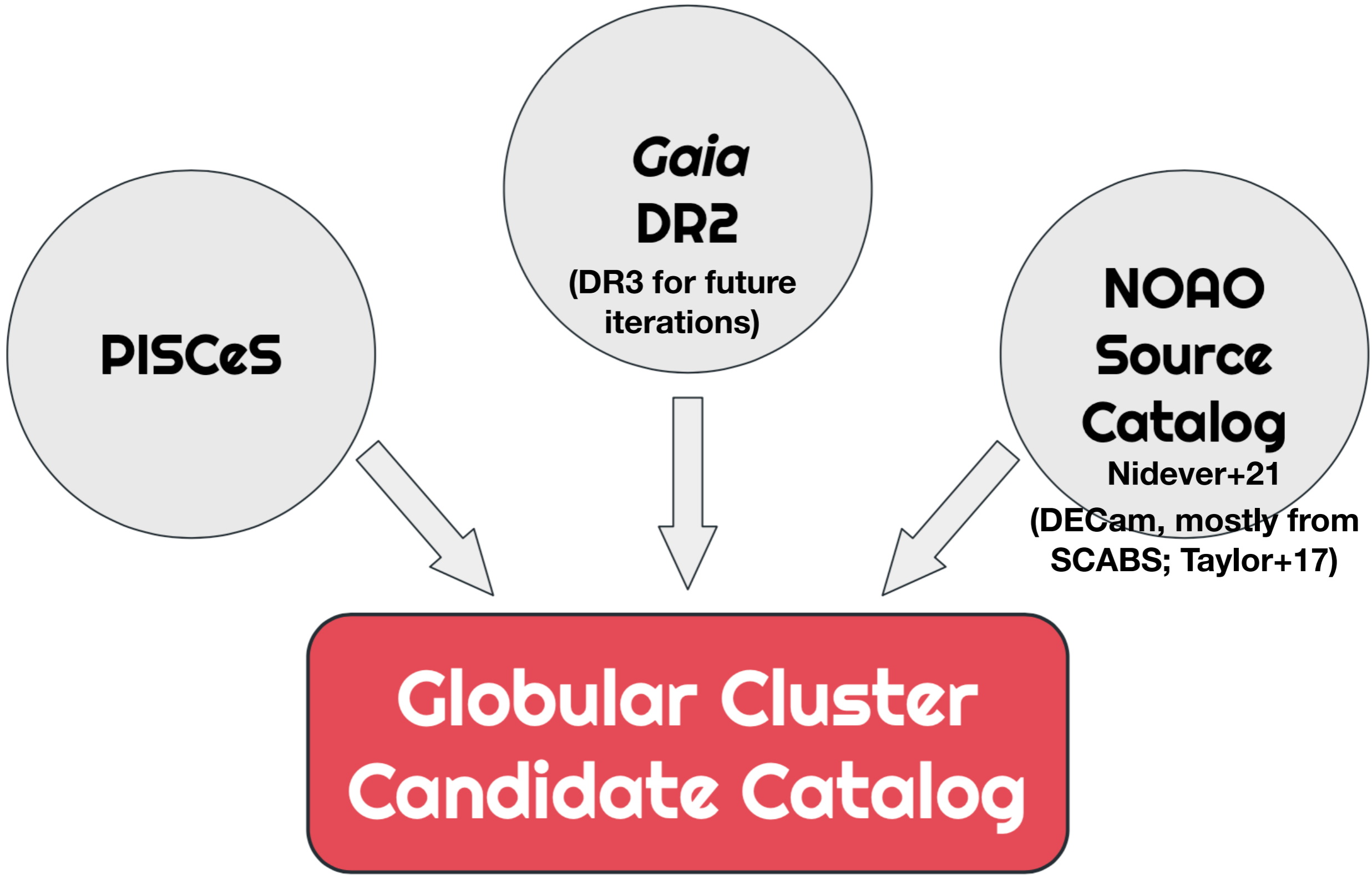
UNEXPLORED OUTER HALO



UNEXPLORED OUTER HALO COMPARE TO M31

(VELJANOSKI+14, MACKEY+19)

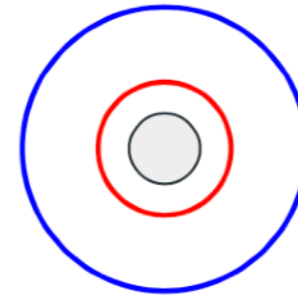




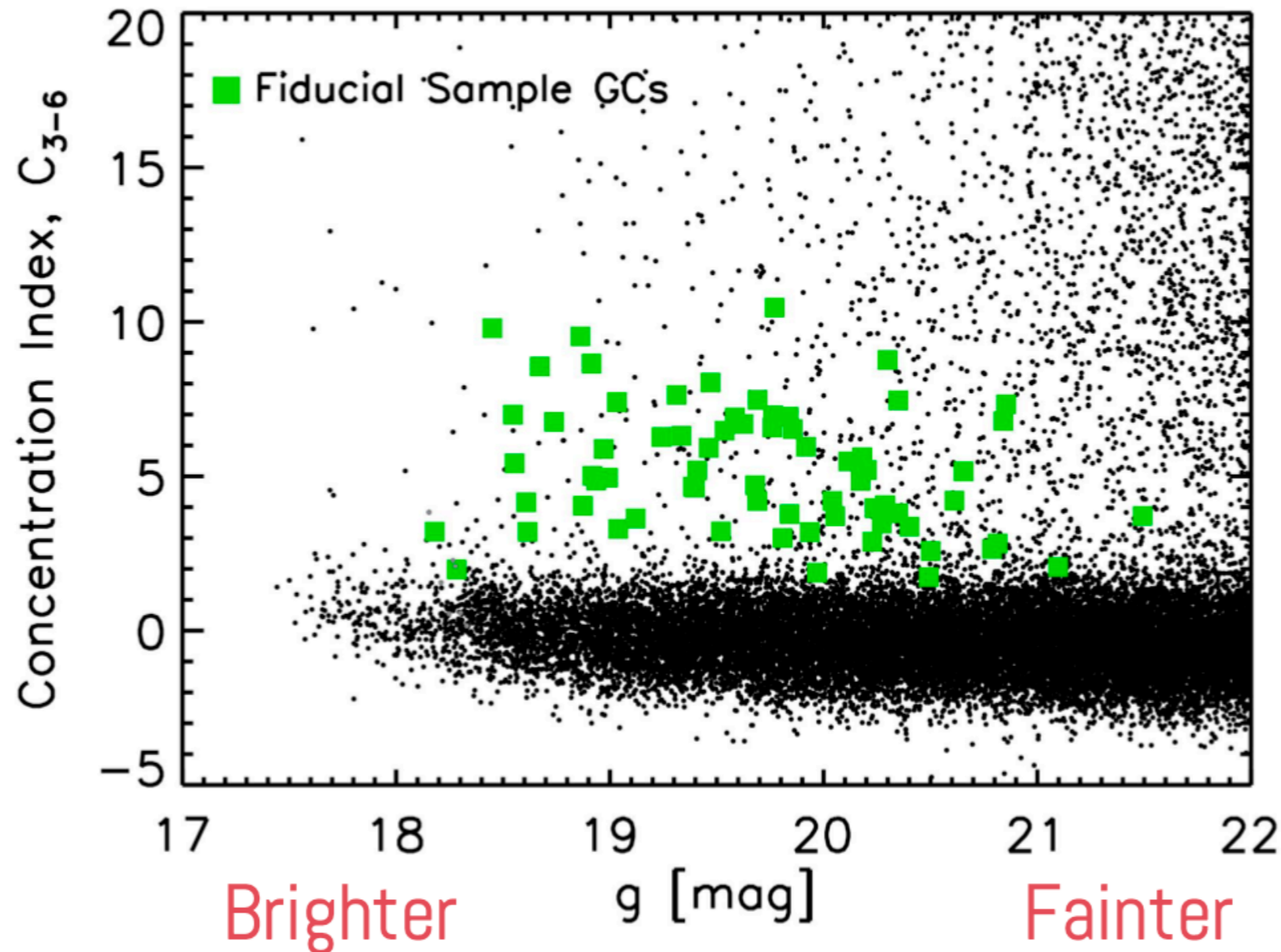
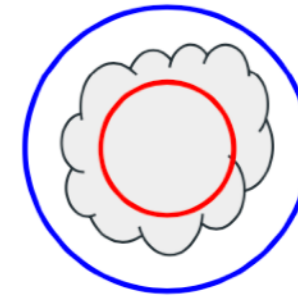
1. FIND EXTENDED SOURCES IN PISCES

Difference in magnitude between two apertures selects extended sources.

Point source

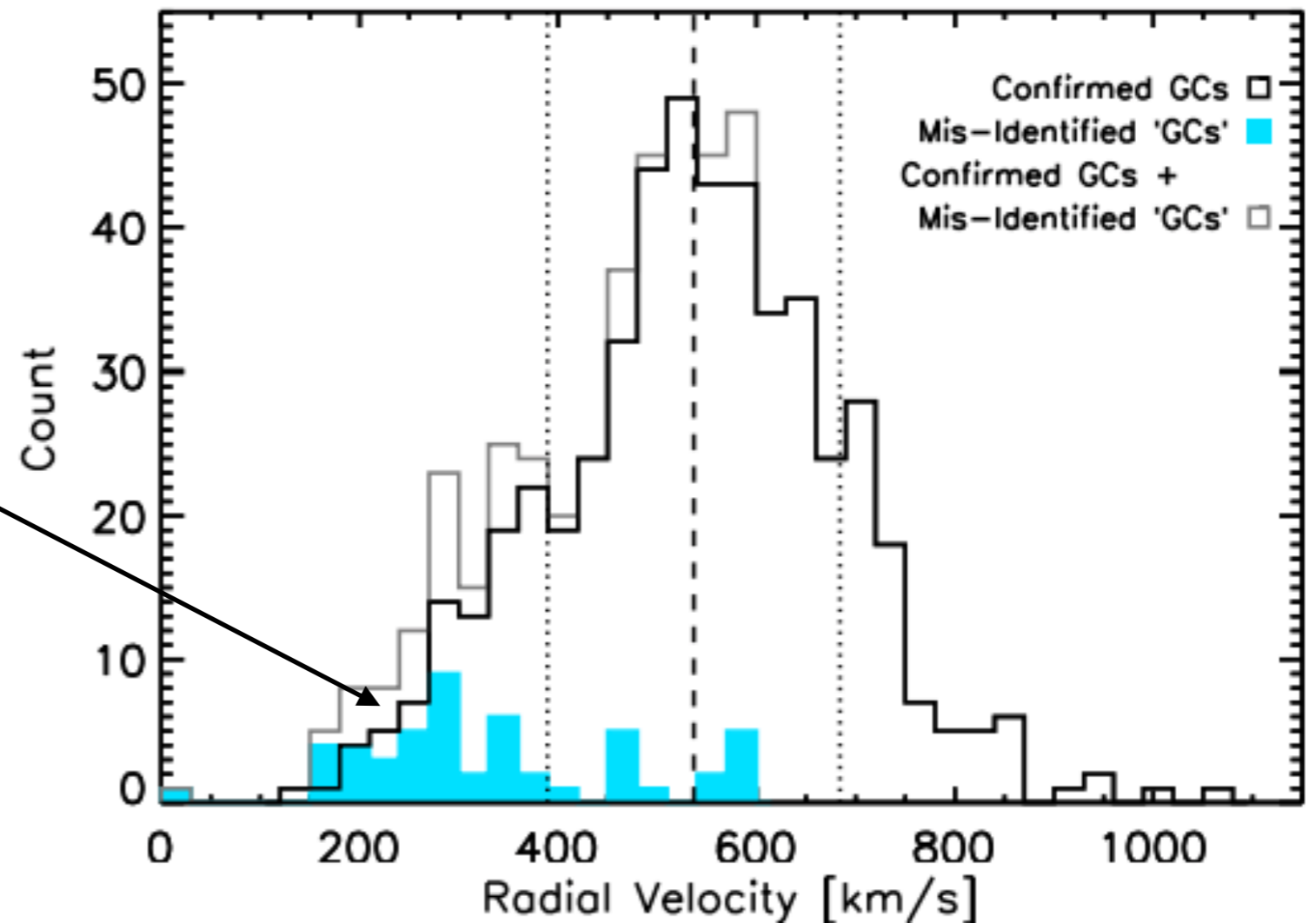


Extended source

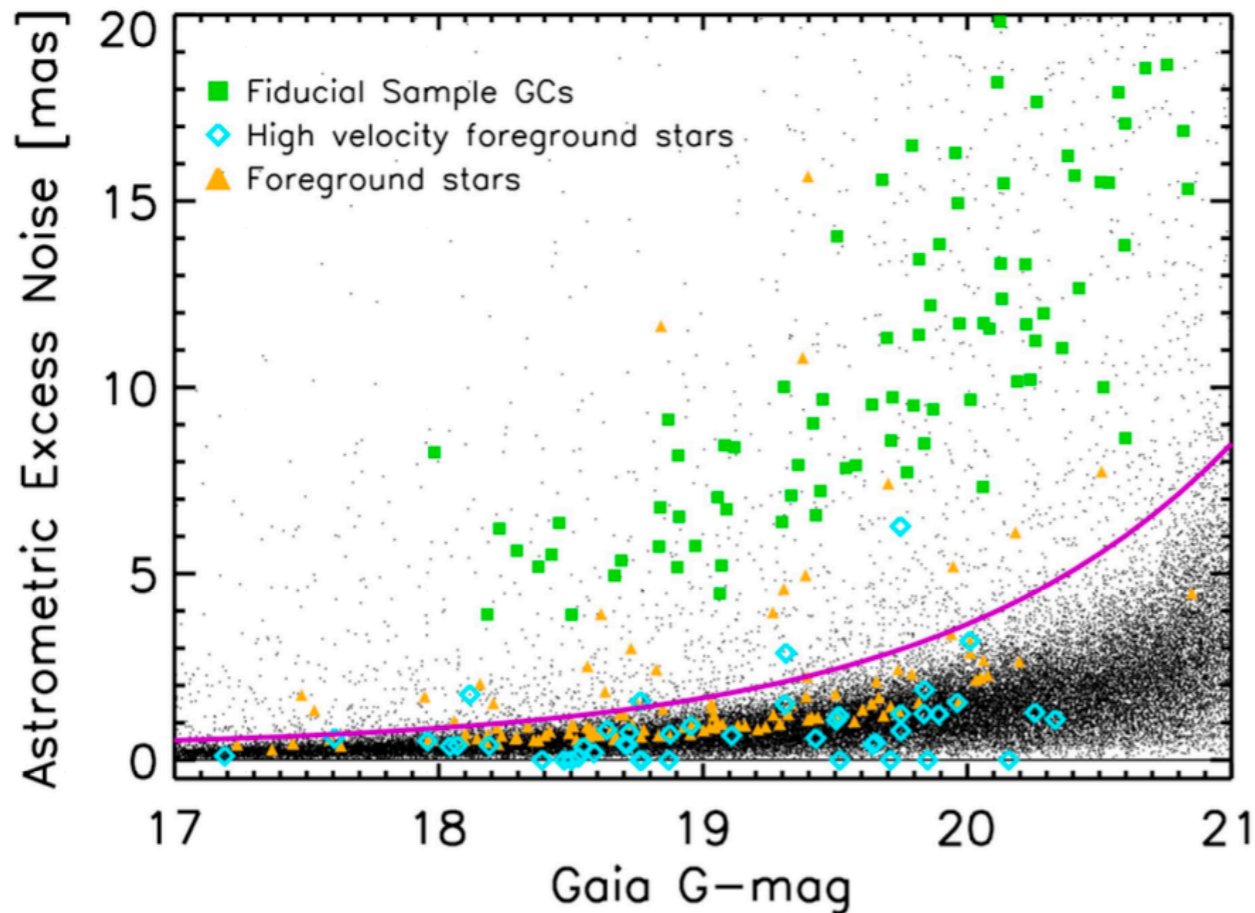


2A. REMOVE CANDIDATES (AND 'CONFIRMED' GCs) WITH GAIA PM'S AND PARALLAXES

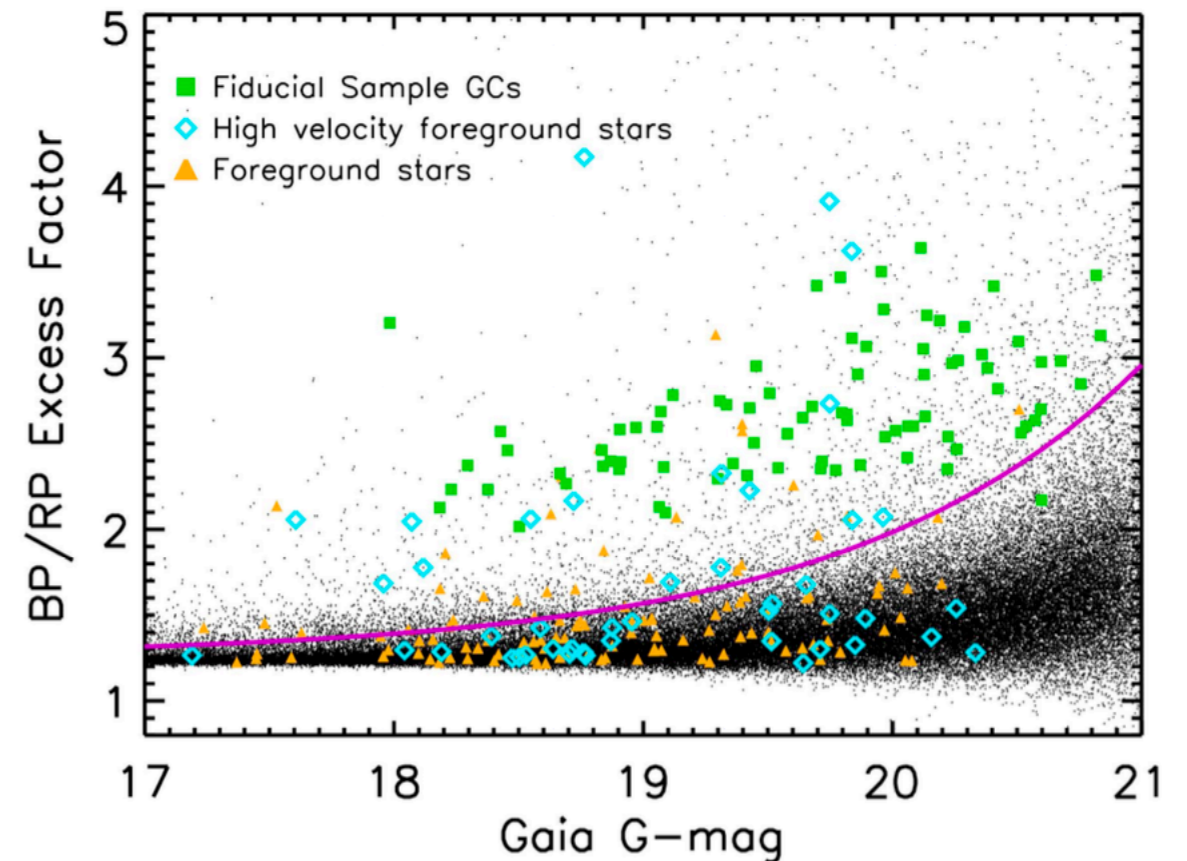
~50 radial velocity 'confirmed' CenA GCs have >5 sigma PM/parallax measurements.



2B. USE GAIA TO SELECT OBJECTS THAT ARE SLIGHTLY EXTENDED



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

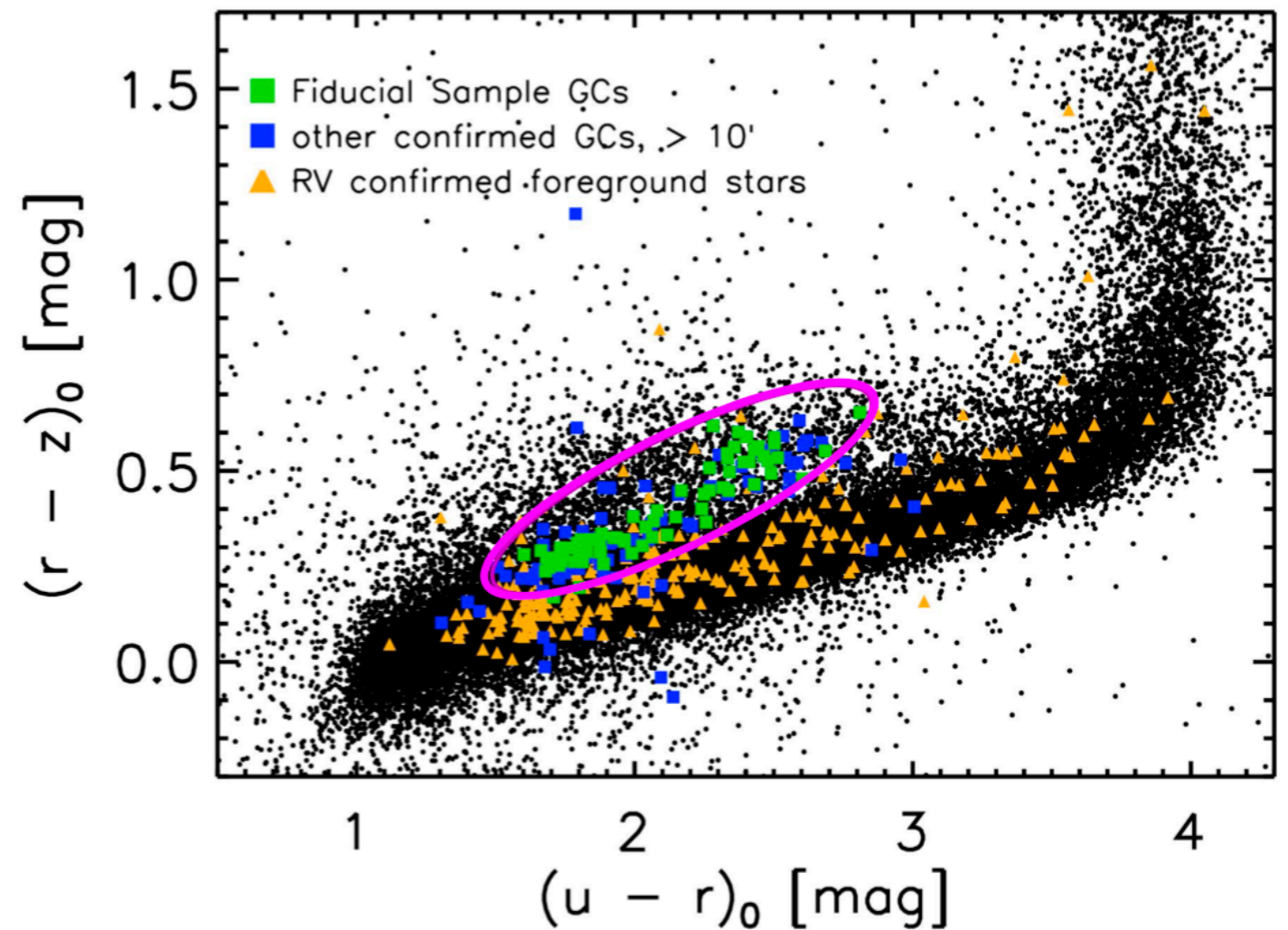


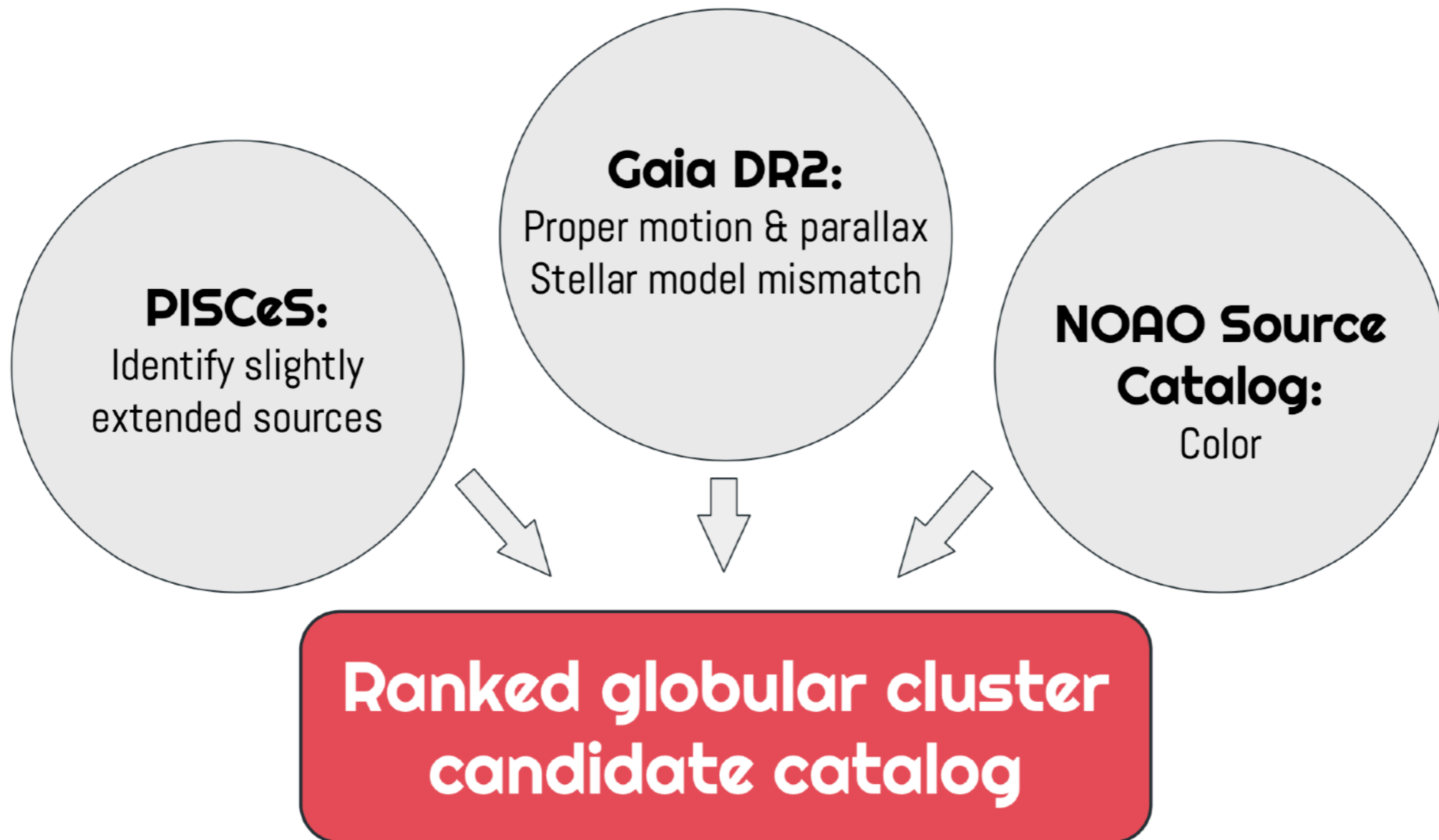
BP/RP Excess: Sum of BP+RP flux greater than G-band flux. This is a difference in aperture effect.

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.

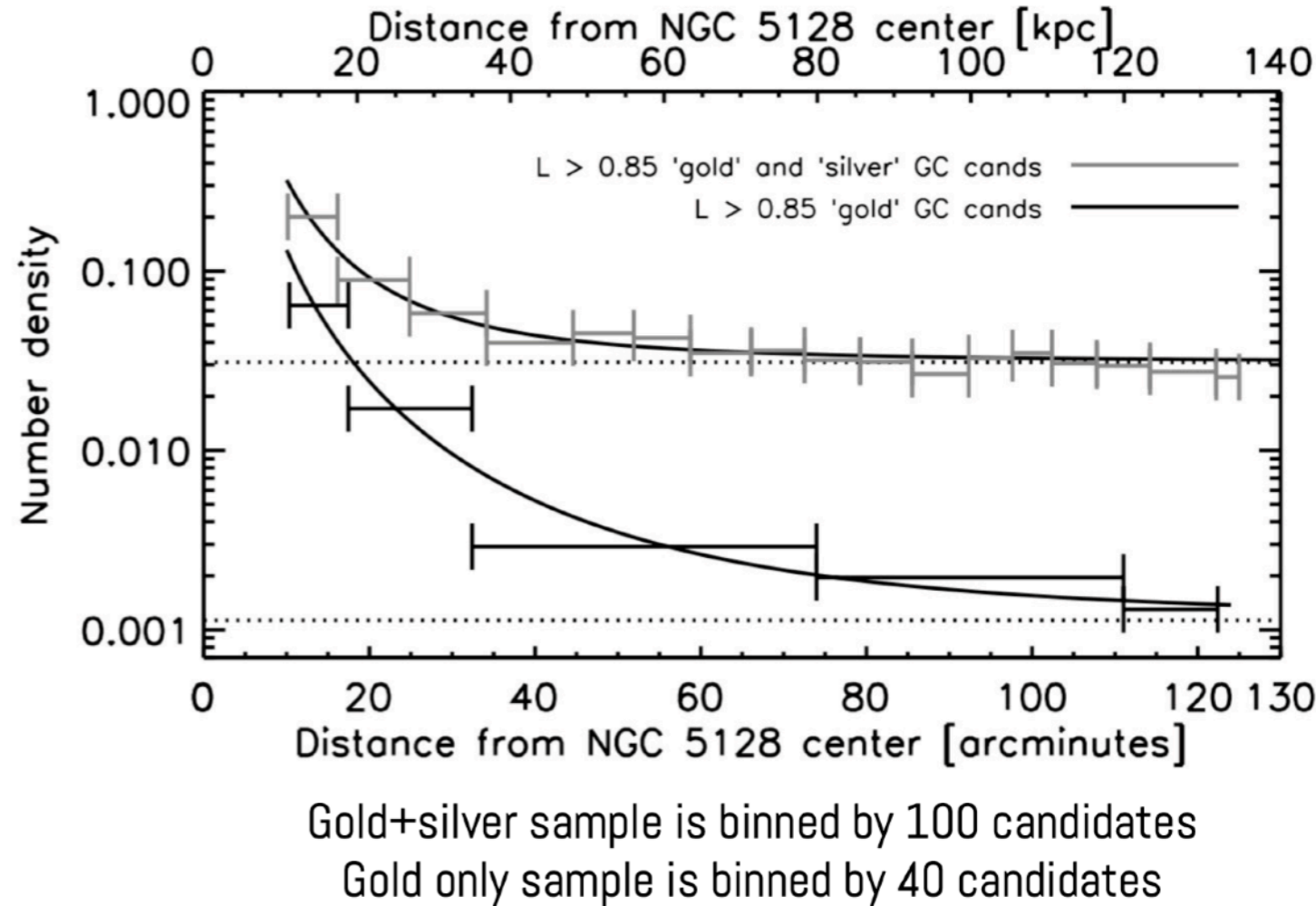
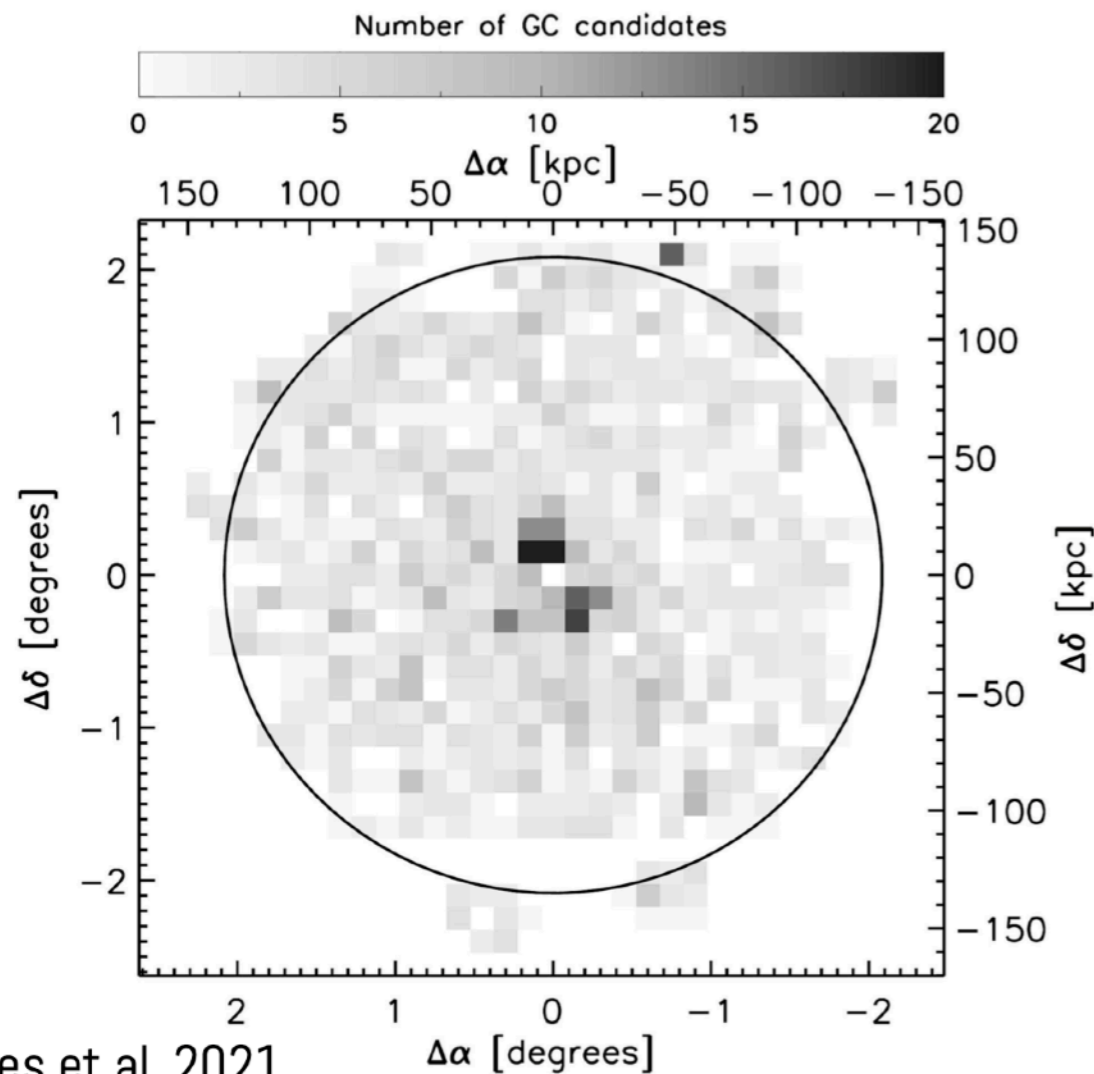




"Priority Sample"

Candidate Rank	PISCeS	Gaia DR2	NSC	Minimum C_{3-6}	Number of Candidates	
					Total	$\mathcal{L}_{total} > 0.85$
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



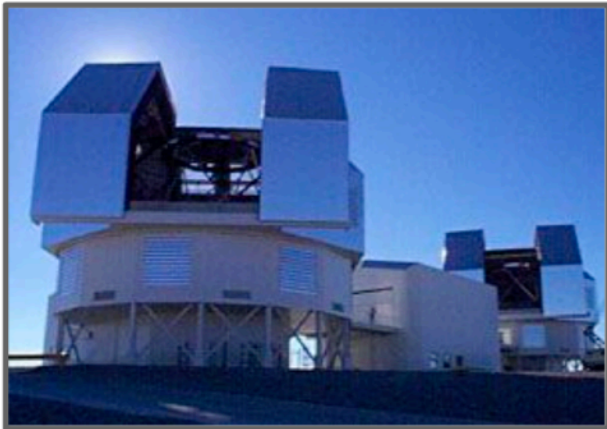
Total population estimate:
1450 +/- 160 GCs within ~150 kpc

SPECTROSCOPIC FOLLOW-UP

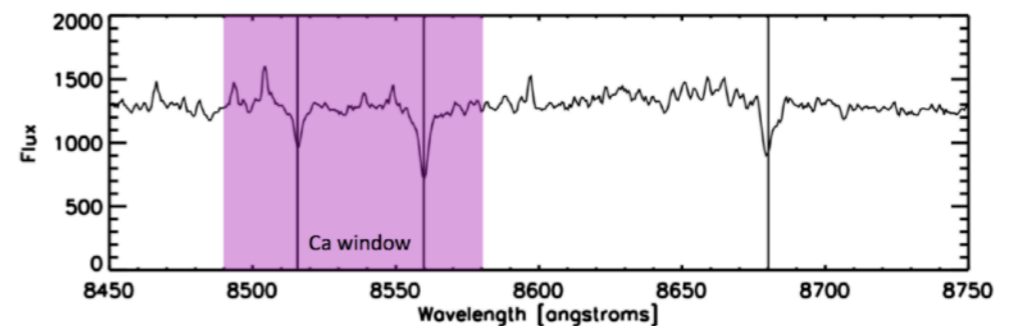
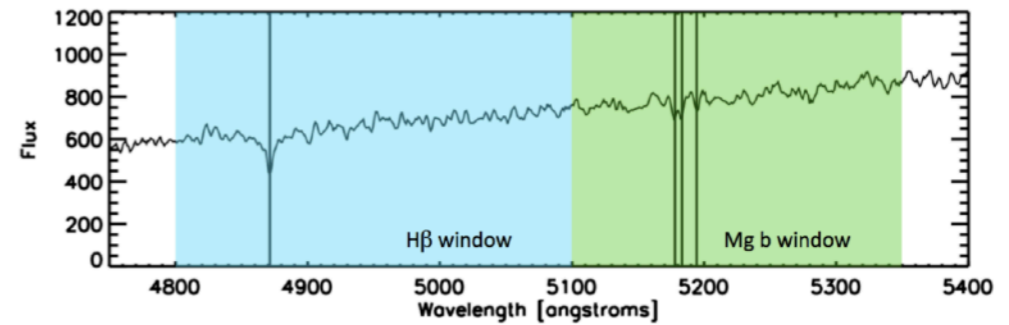
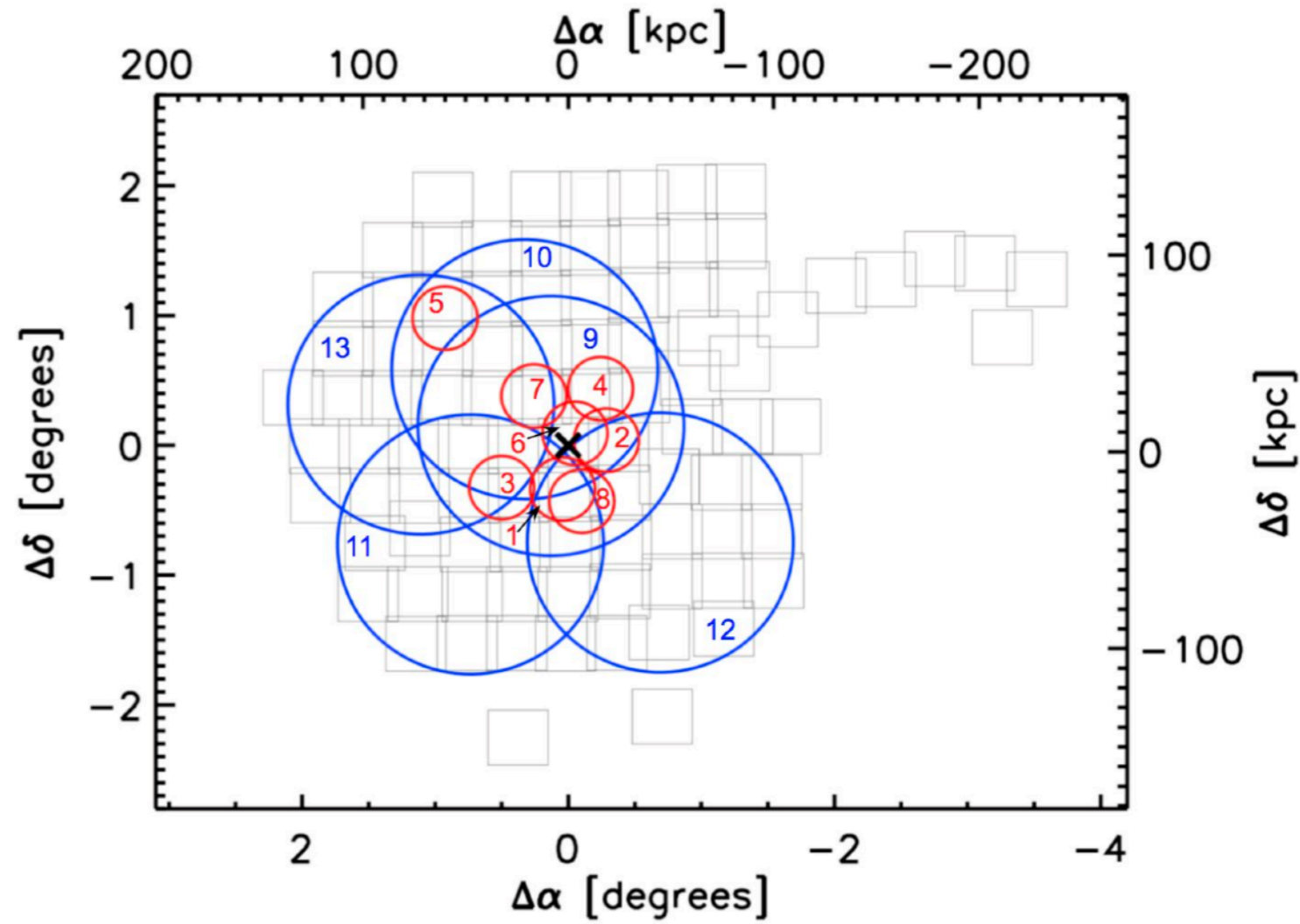
Red: Magellan/M2FS
Five observing runs; 2017 - 2019

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

6.5 m Magellan Clay
Telescope in Chile



3.9 m AAT in Australia



UPDATED GC SAMPLE

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

645 kinematic members in total

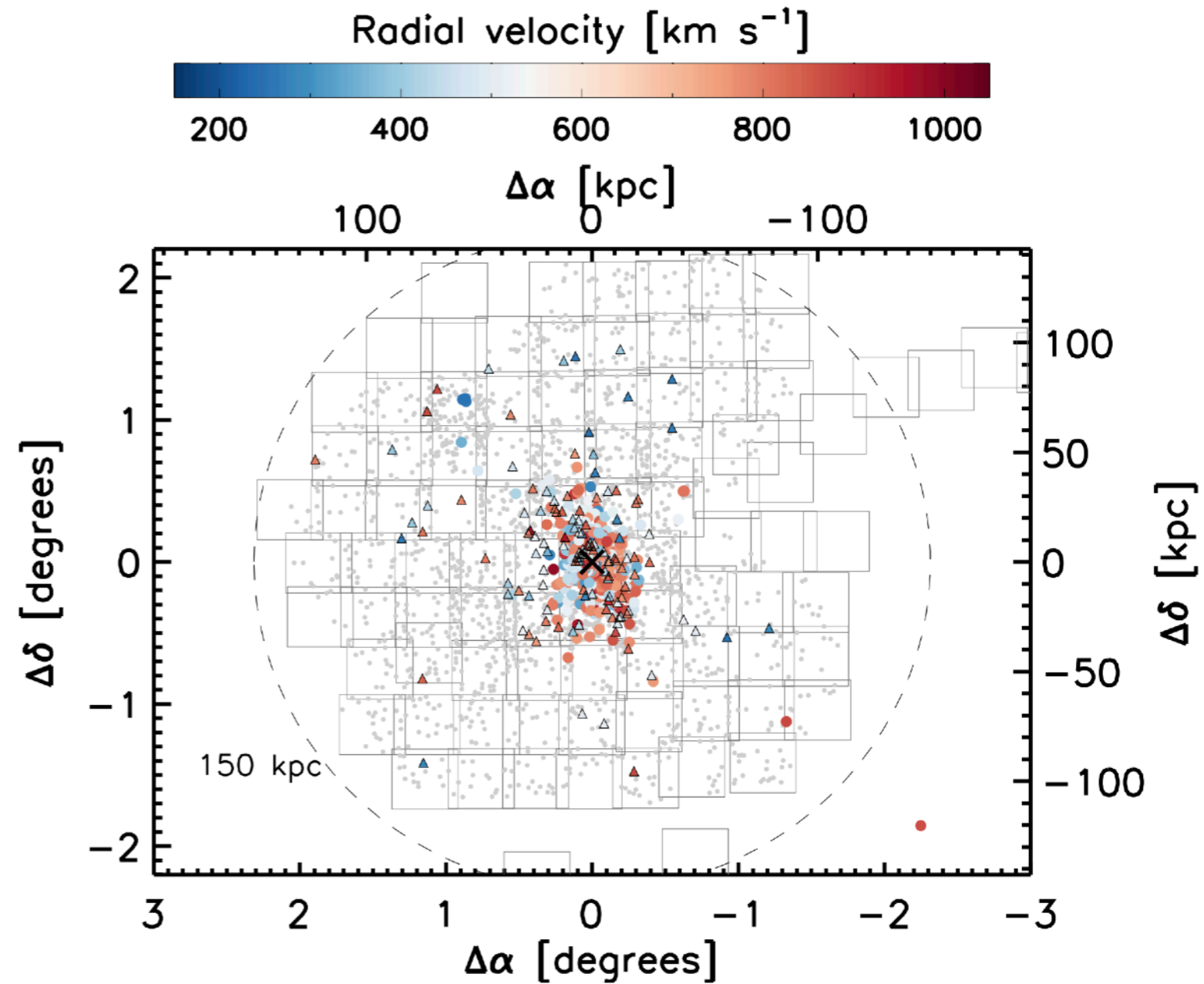
Priority sample: 35% are true GCs

68% within 30'

(7% for the not-priority sample)

**28 GCs outside of 50 arcmin (55
kpc)**

Most distance object at 130 kpc.



UPDATED GC SAMPLE

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

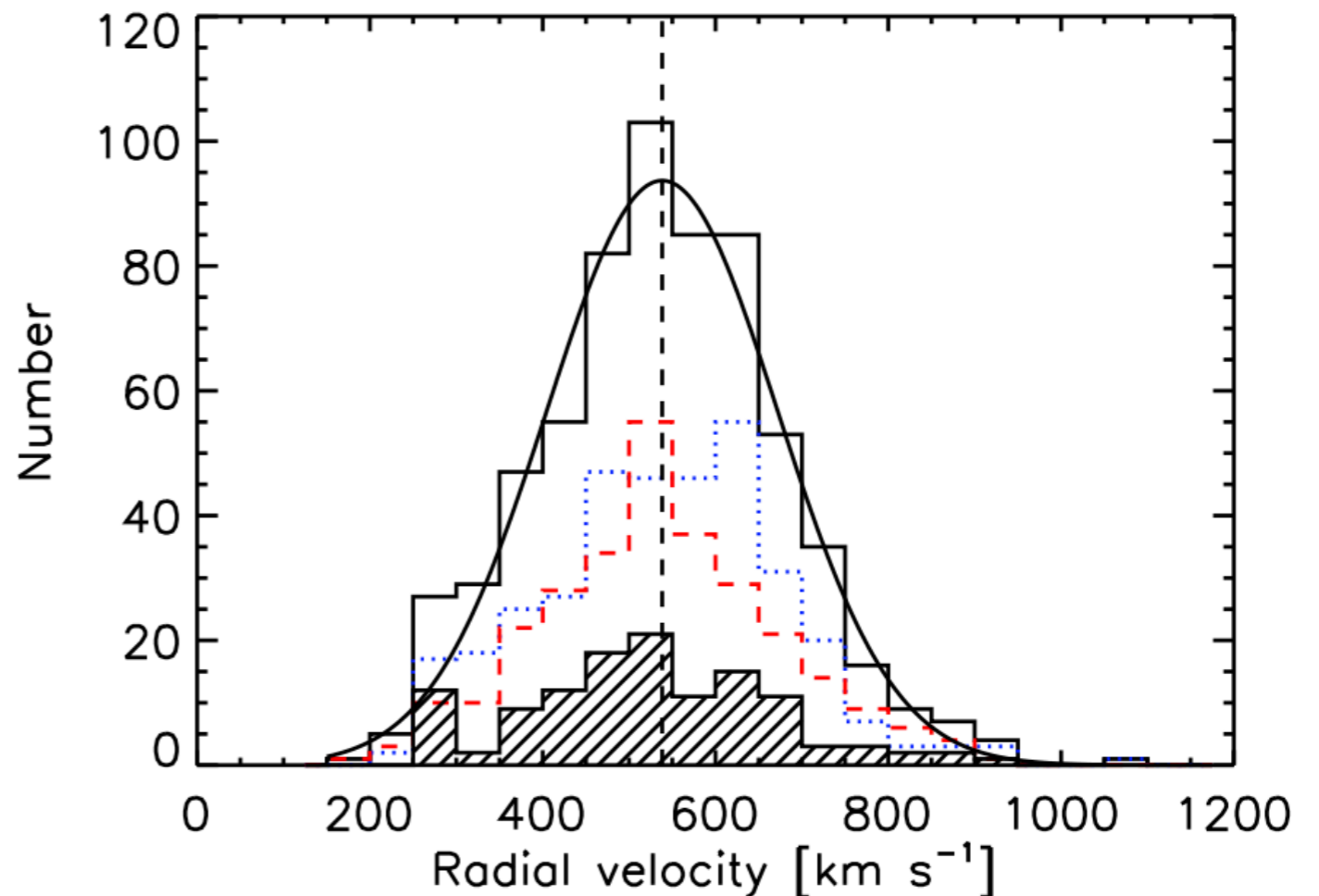
645 kinematic members in total

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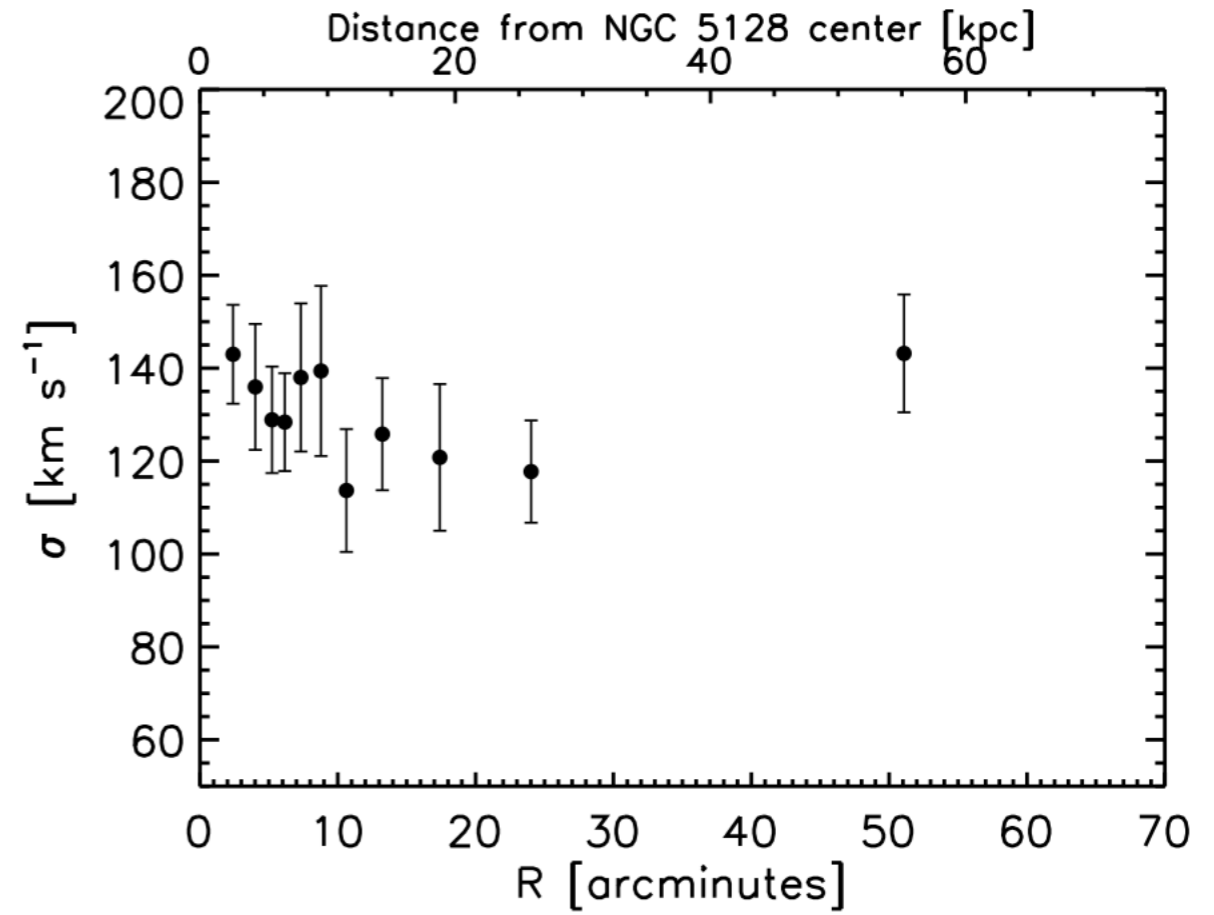
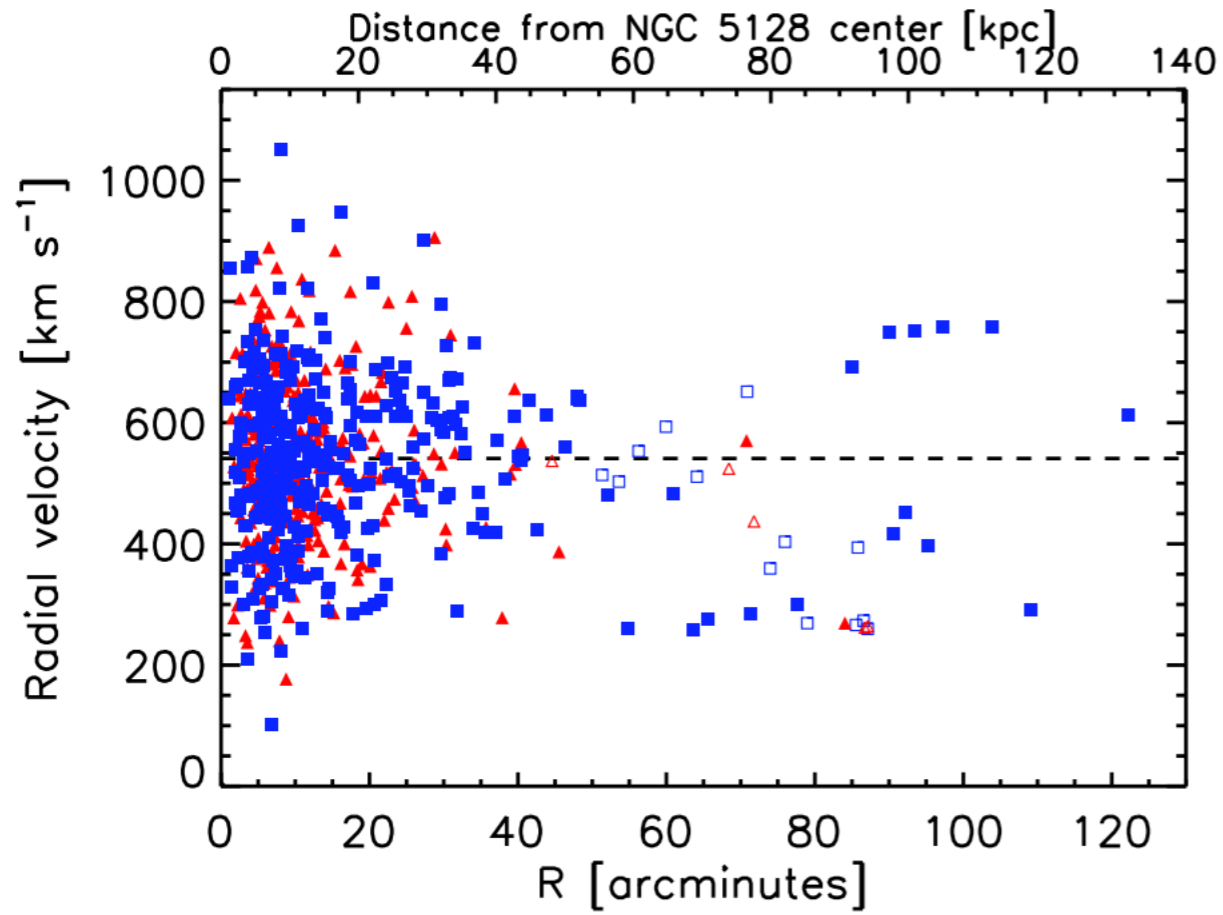
(7% for the not-priority sample)

**28 GCs outside of 50 arcmin (55
kpc)**

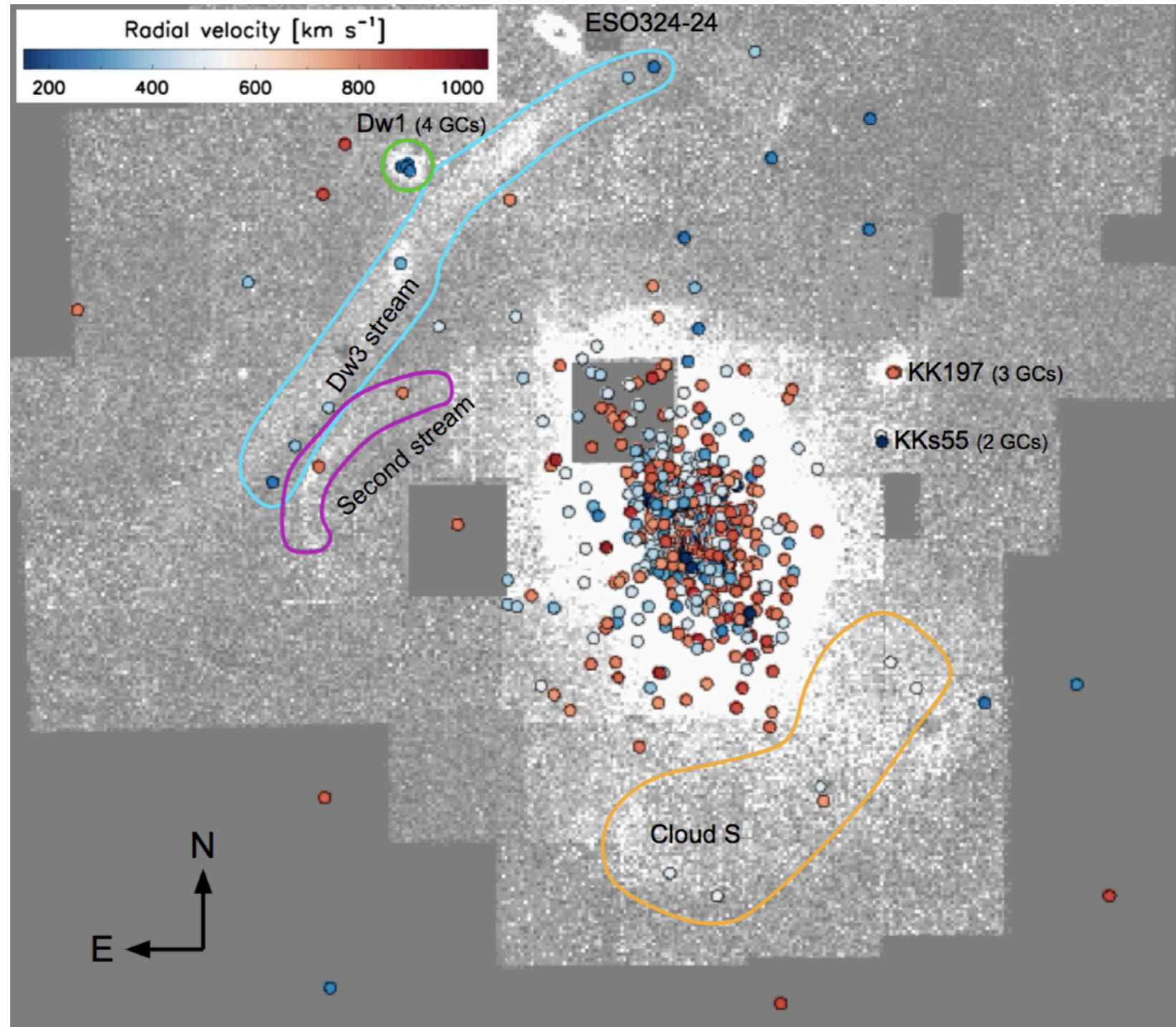


**Velocity histogram including new objects
(hatched), and blue and red samples**

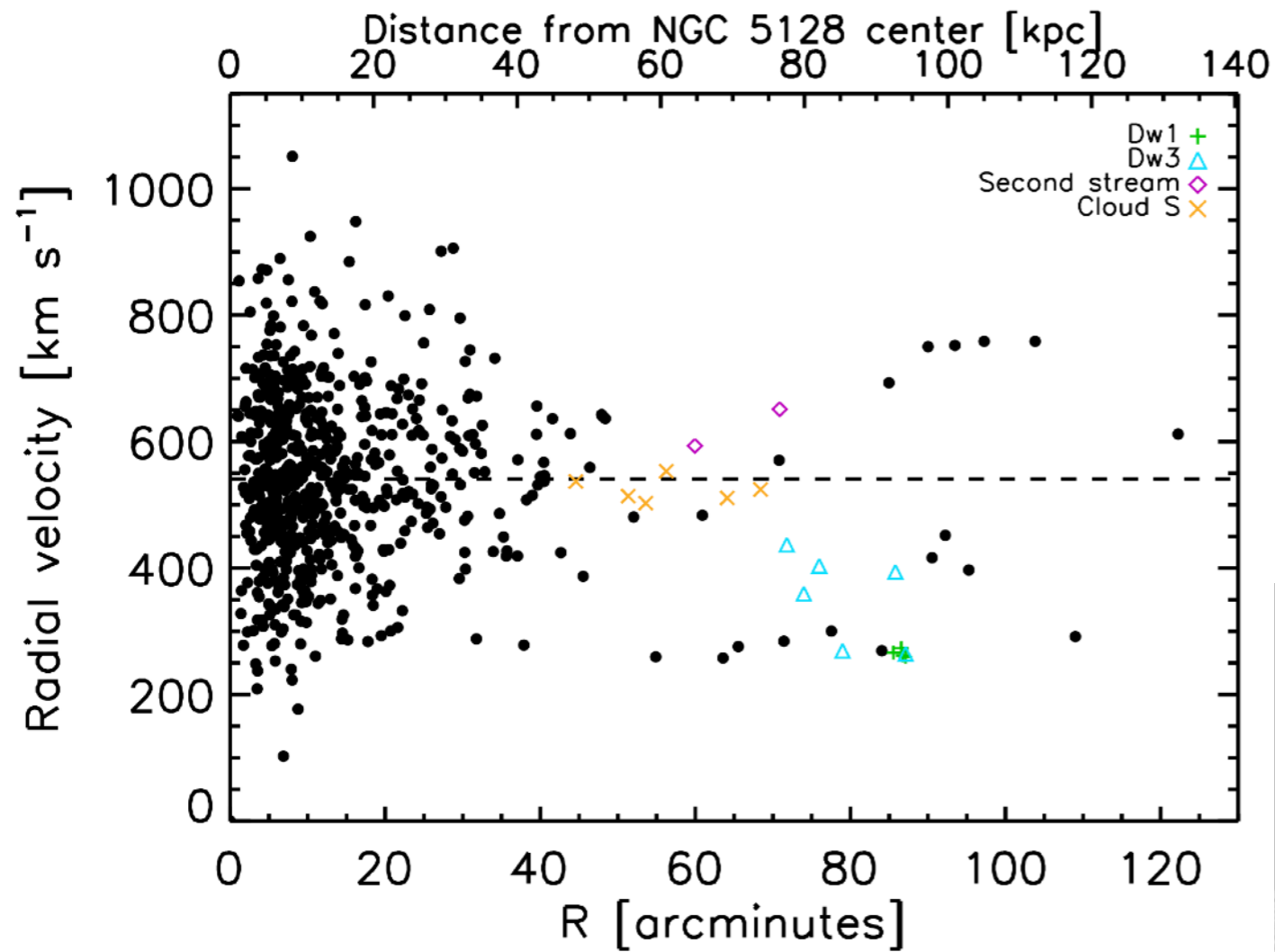
RADIAL VELOCITY DISTRIBUTION



IDENTIFYING GCs IN SUBSTRUCTURES

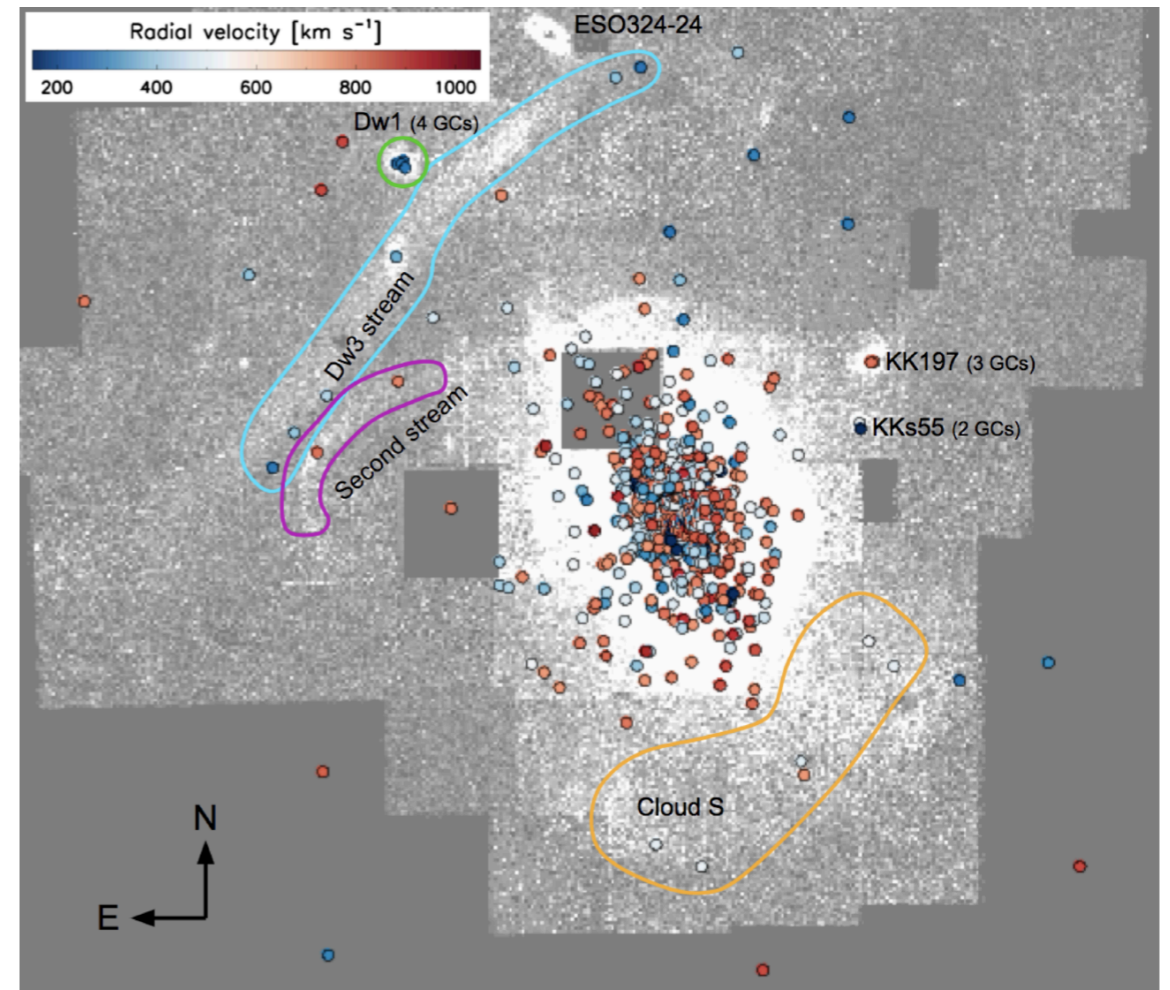


IDENTIFYING GCs IN SUBSTRUCTURES

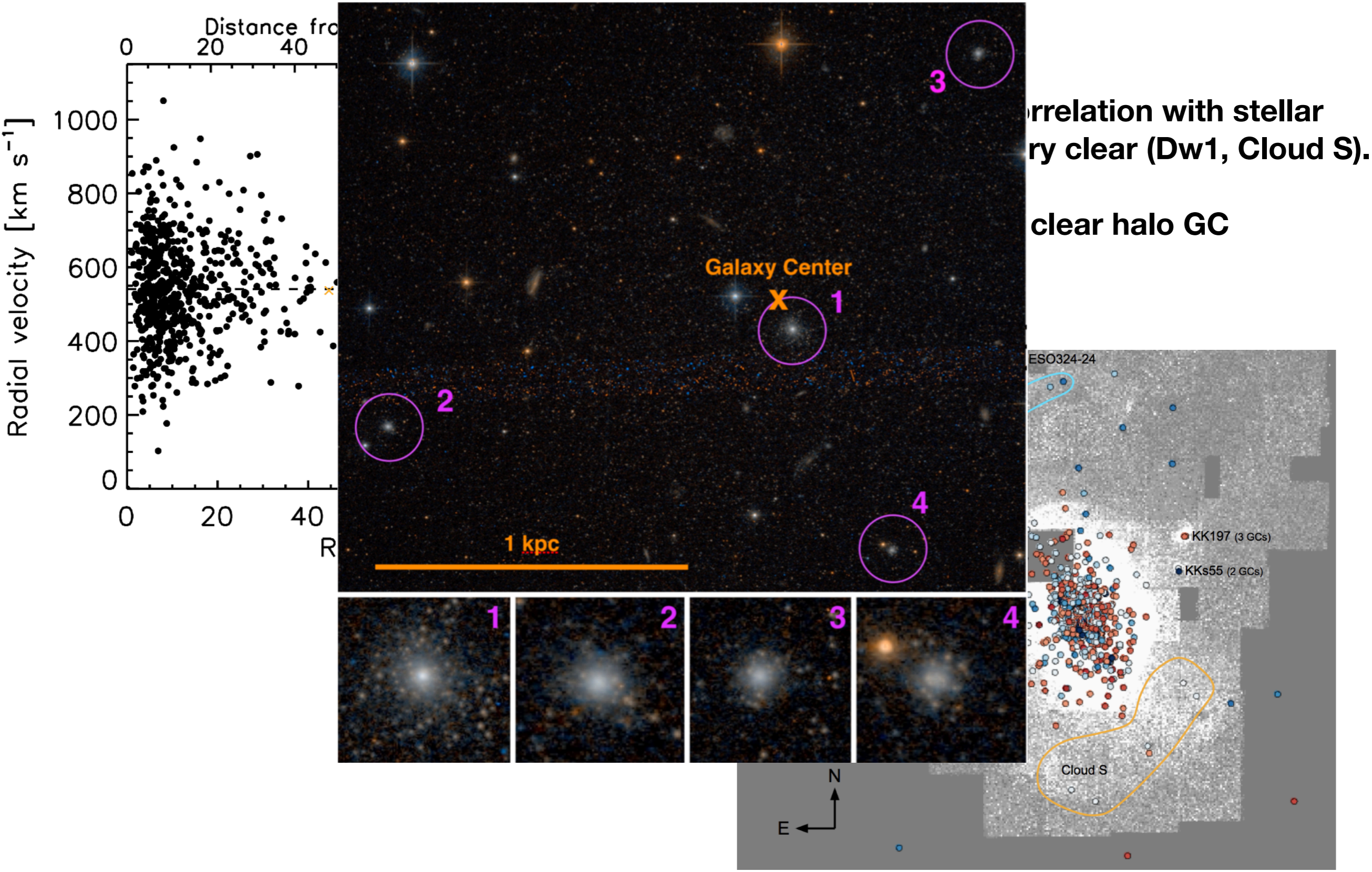


In some cases, correlation with stellar substructure is very clear (Dw1, Cloud S).

In others, there is clear halo GC contamination.

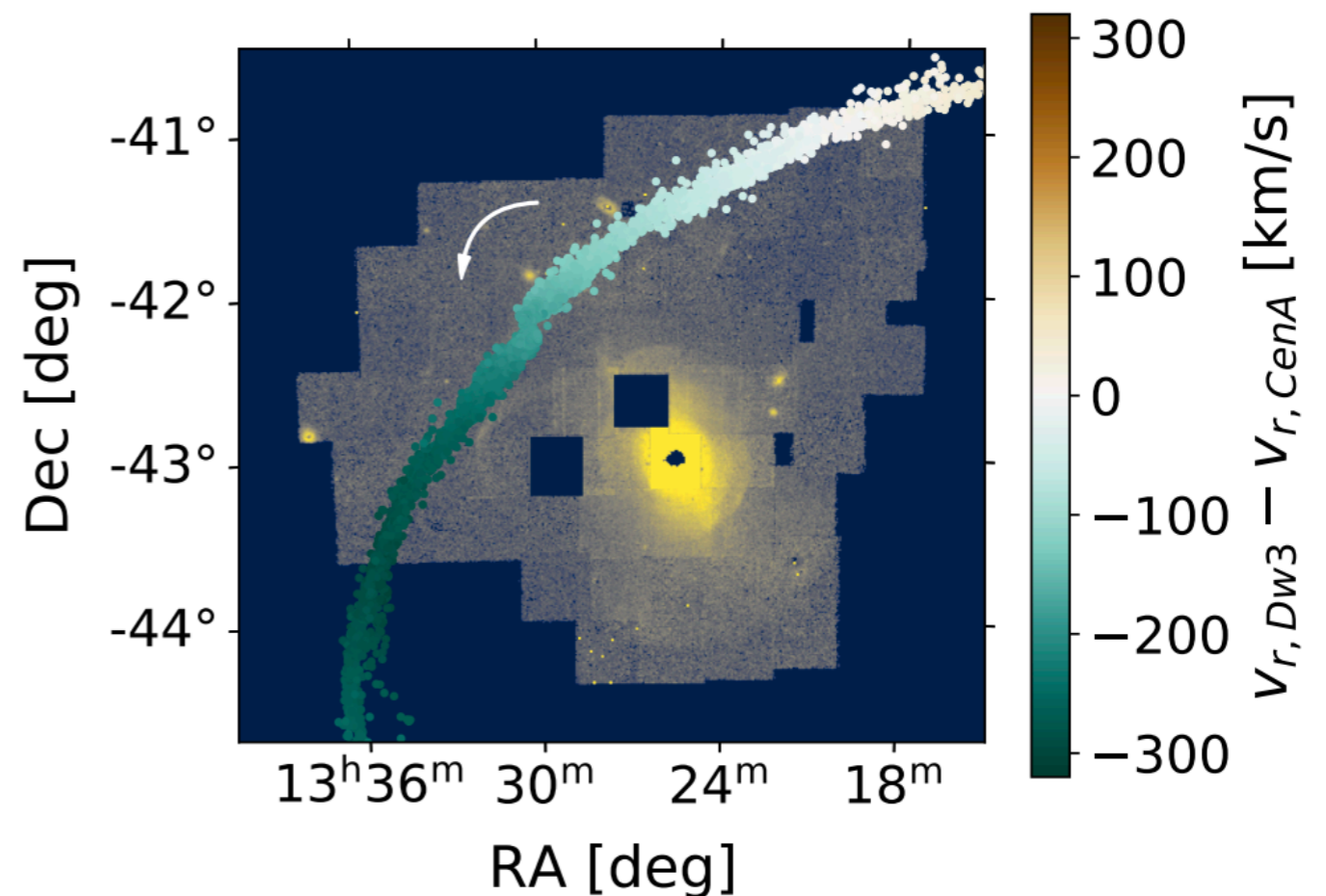
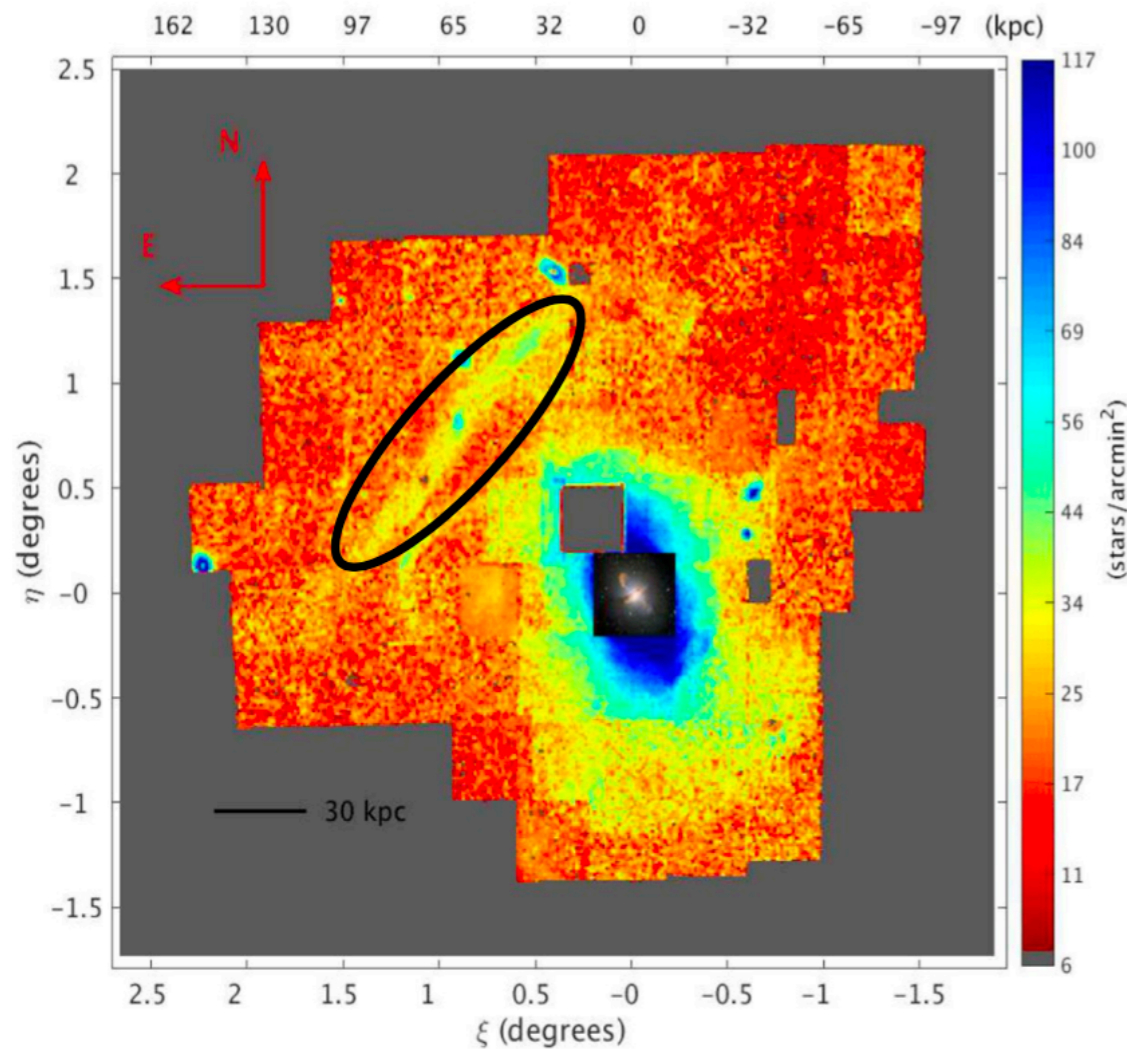


IDENTIFYING GCs IN SUBSTRUCTURES



STREAM MODELING WITH STARS + GC

KINEMATICS (PEARSON+22)

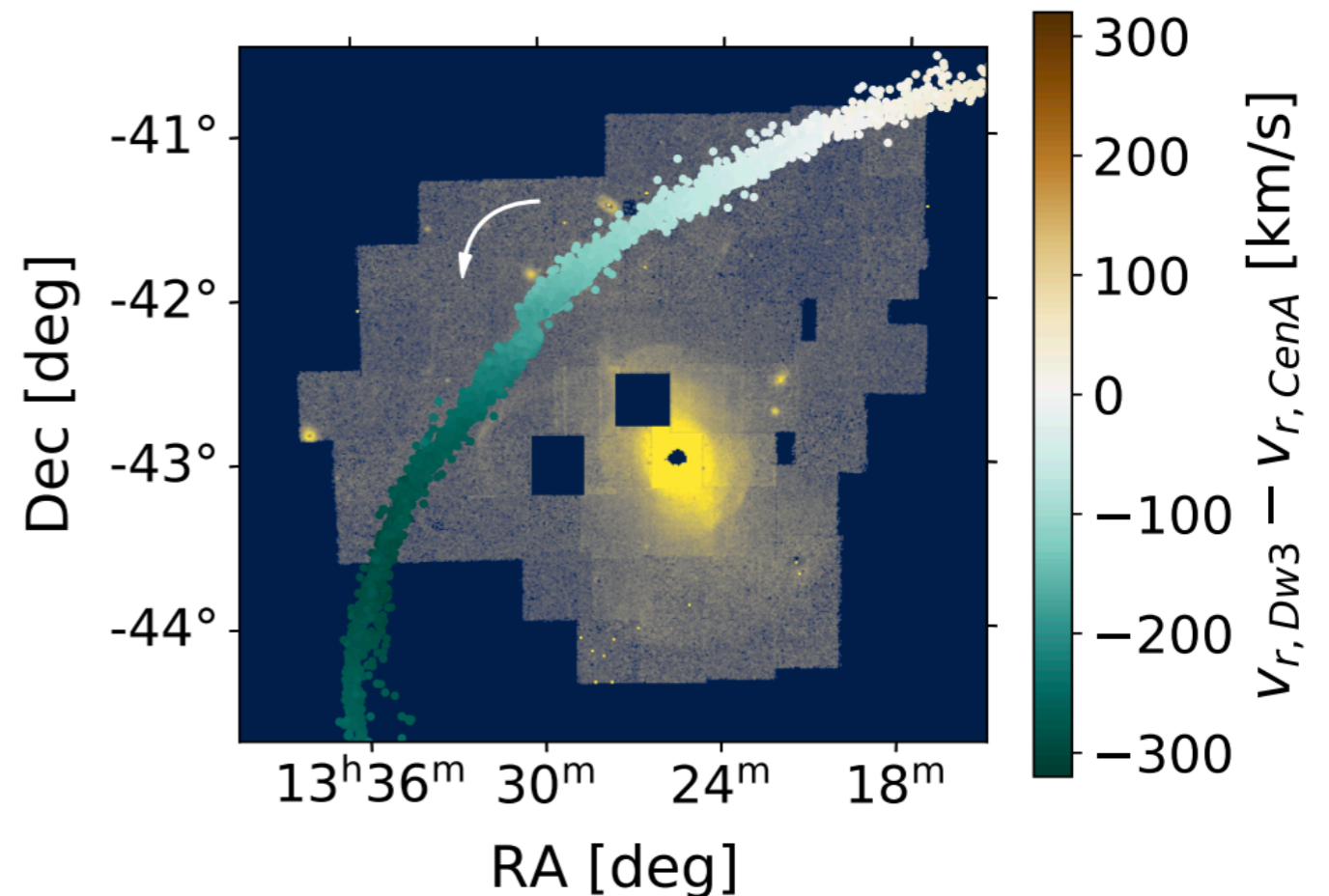
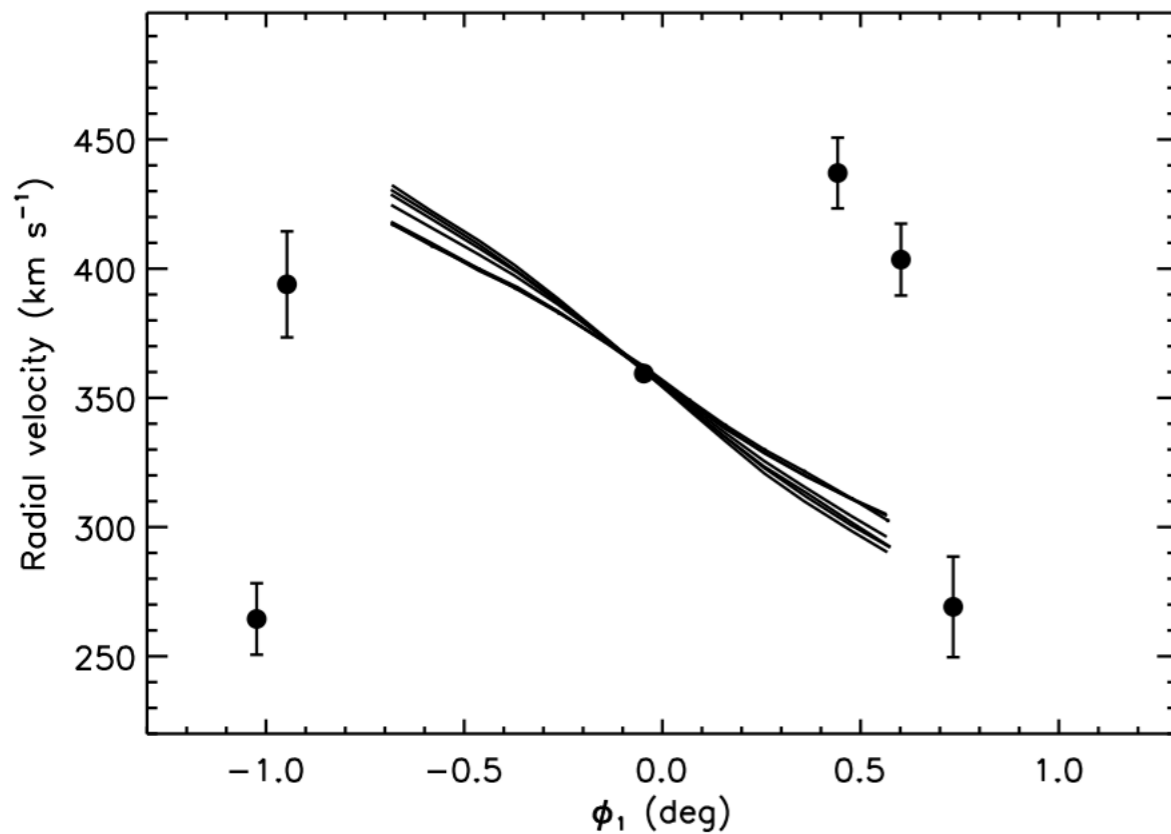


Can reproduce Dw3 stellar stream morphology, including the nuclear star cluster morphology with reasonable CenA mass, Dw3 mass, etc.

To break degeneracies, we need velocities along the stream.

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.

LAST THING: TOTAL MASS PROFILE TRACER MASS ESTIMATOR TECHNIQUE

(EVANS+03)

$$M_{tot} = M_p + M_r$$
$$M_p = \frac{C}{GN} \sum_i (v_{fi} - v_{sys})^2 R_i$$

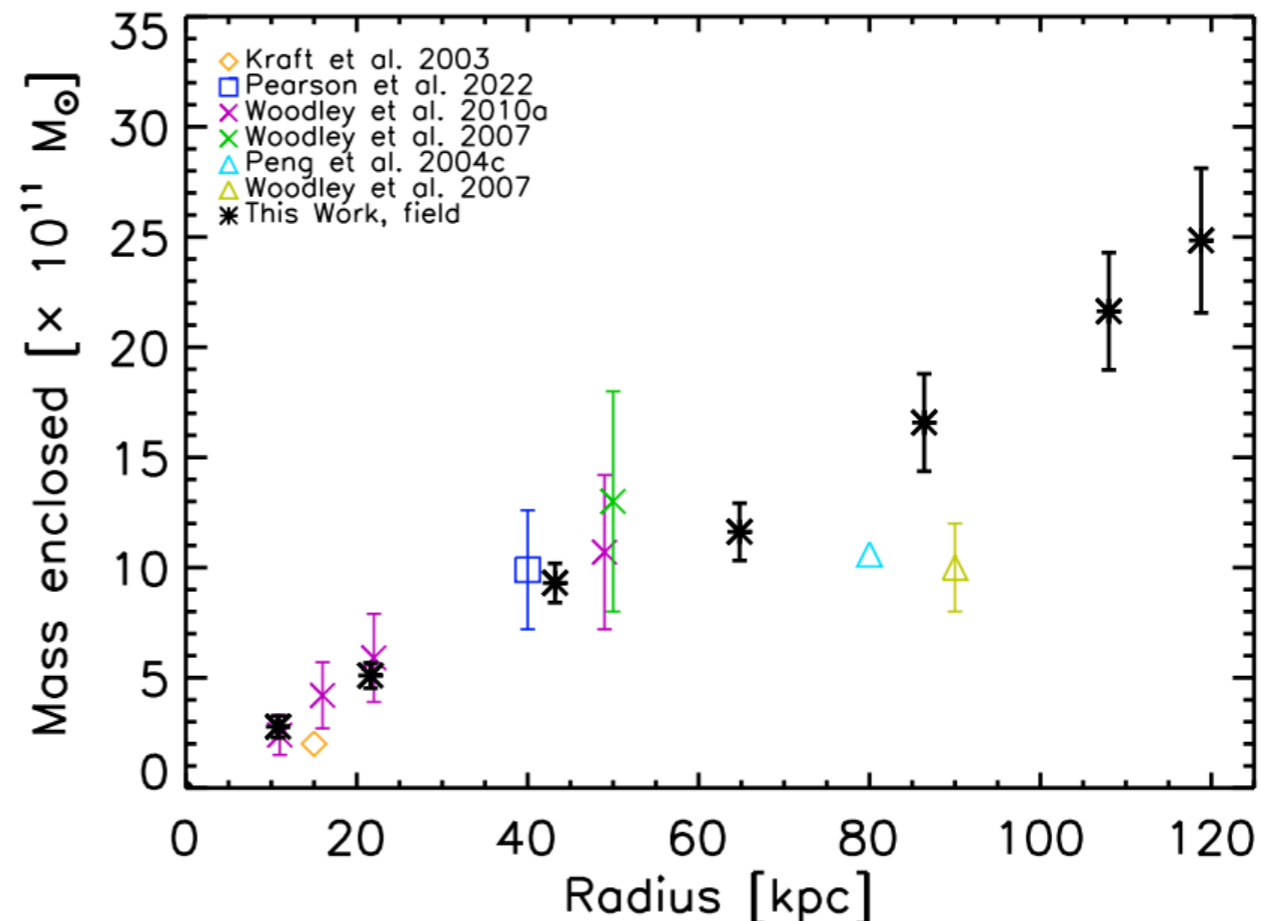
measured radial velocity minus rotation amplitude

systemic velocity

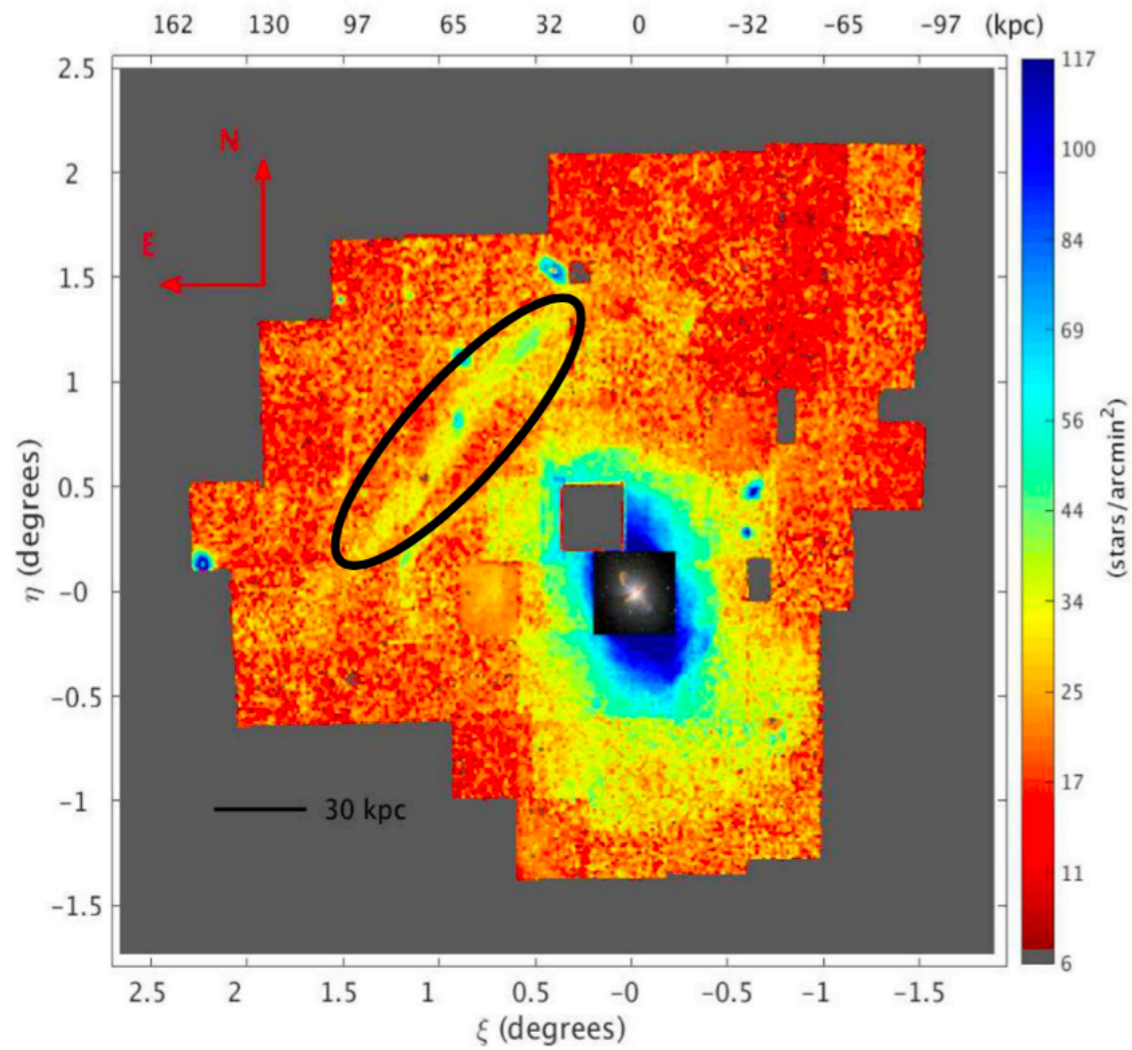
$$M_r = \frac{R_{out} v_{max}^2}{G}$$

rotation amplitude

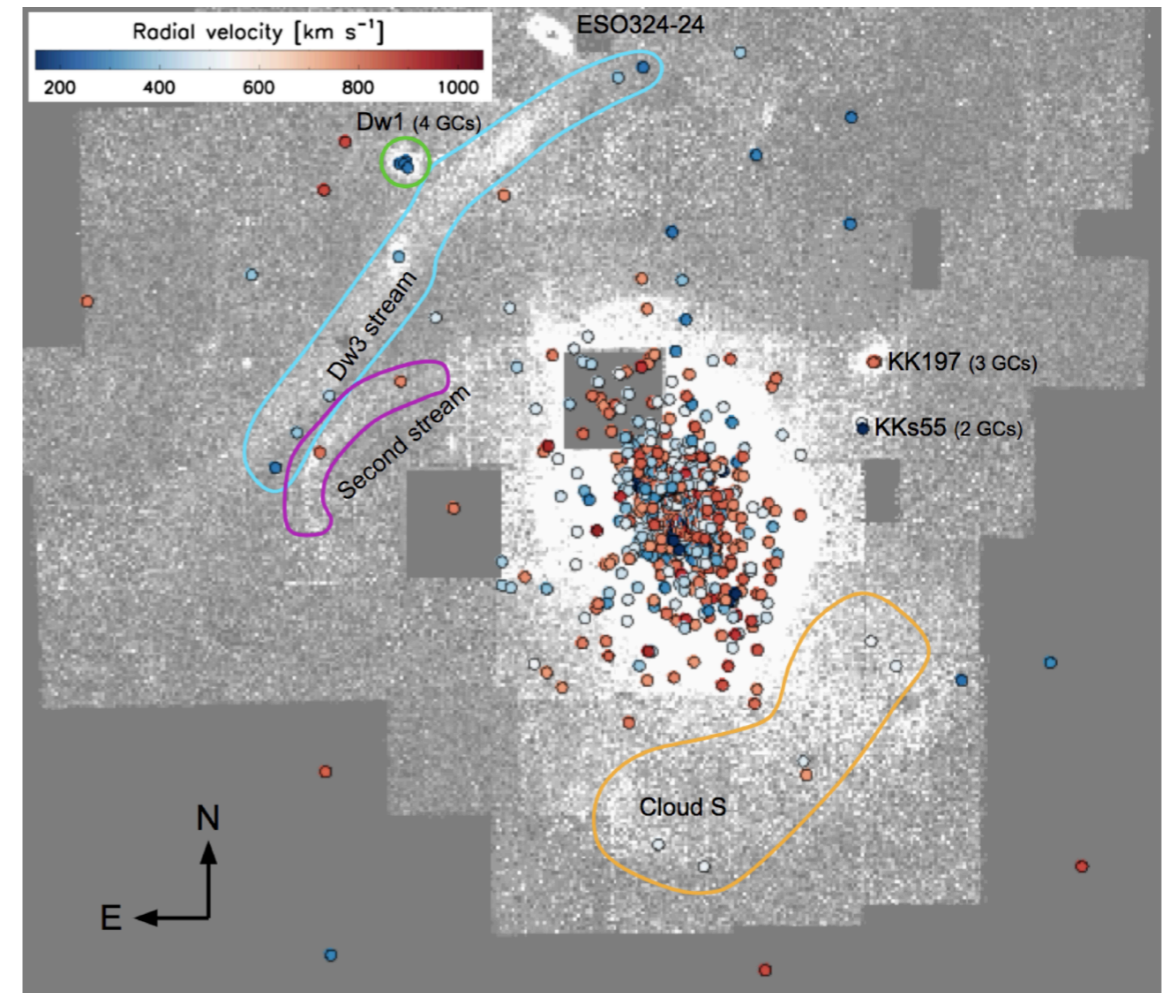
- Include both dispersion and rotational component.
- Total mass consistent with previous measurements.
- Some discrepancy at large radii.
- We removed GCs associated with stellar substructures.
- Detailed mass DM+light profile in progress, including inner and outer DM slope. (Dumont+ in prep)



FUTURE DIRECTIONS

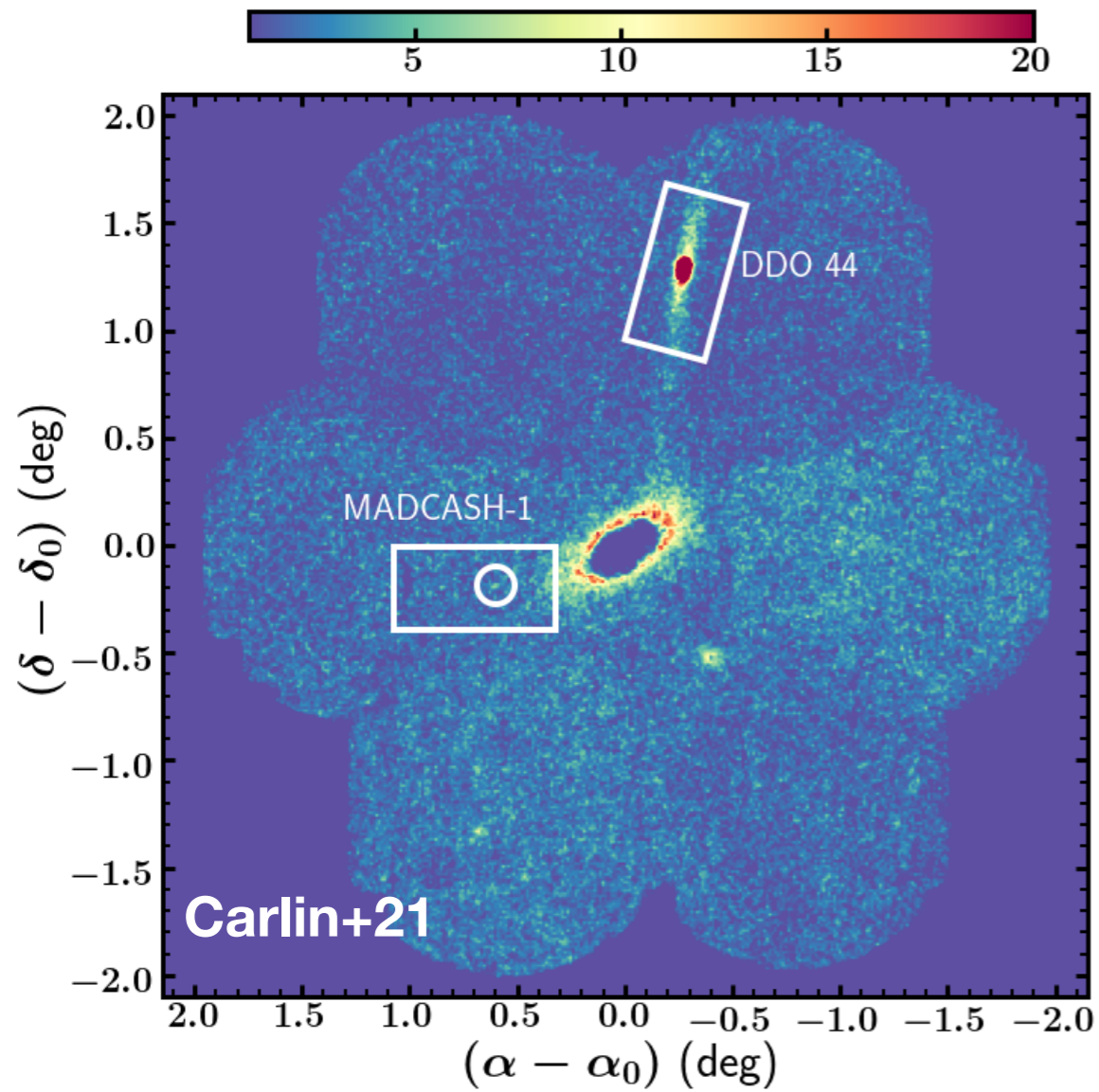


+



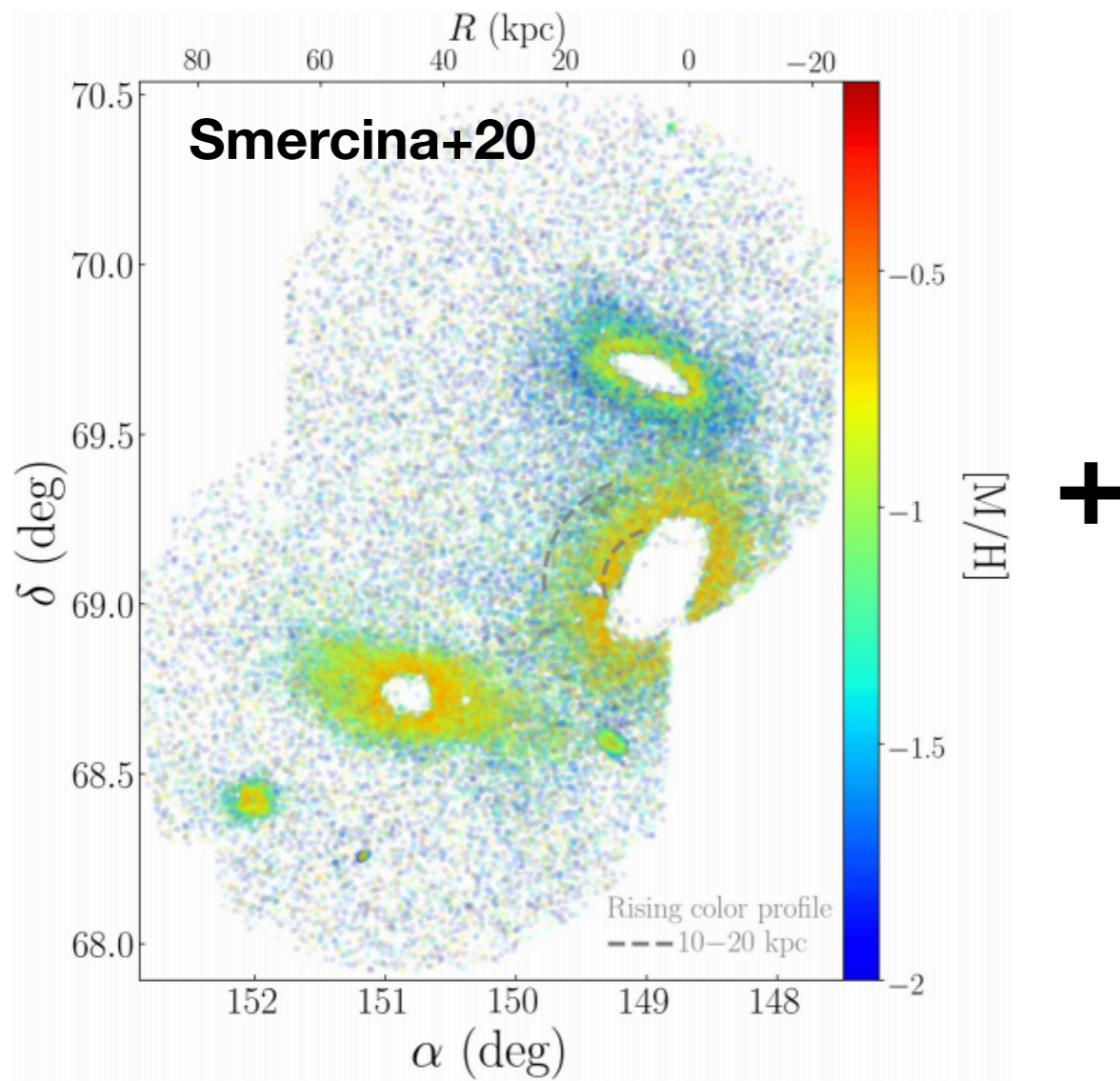
Similar results can be had throughout the $D < 5$ Mpc Universe.

FUTURE DIRECTIONS



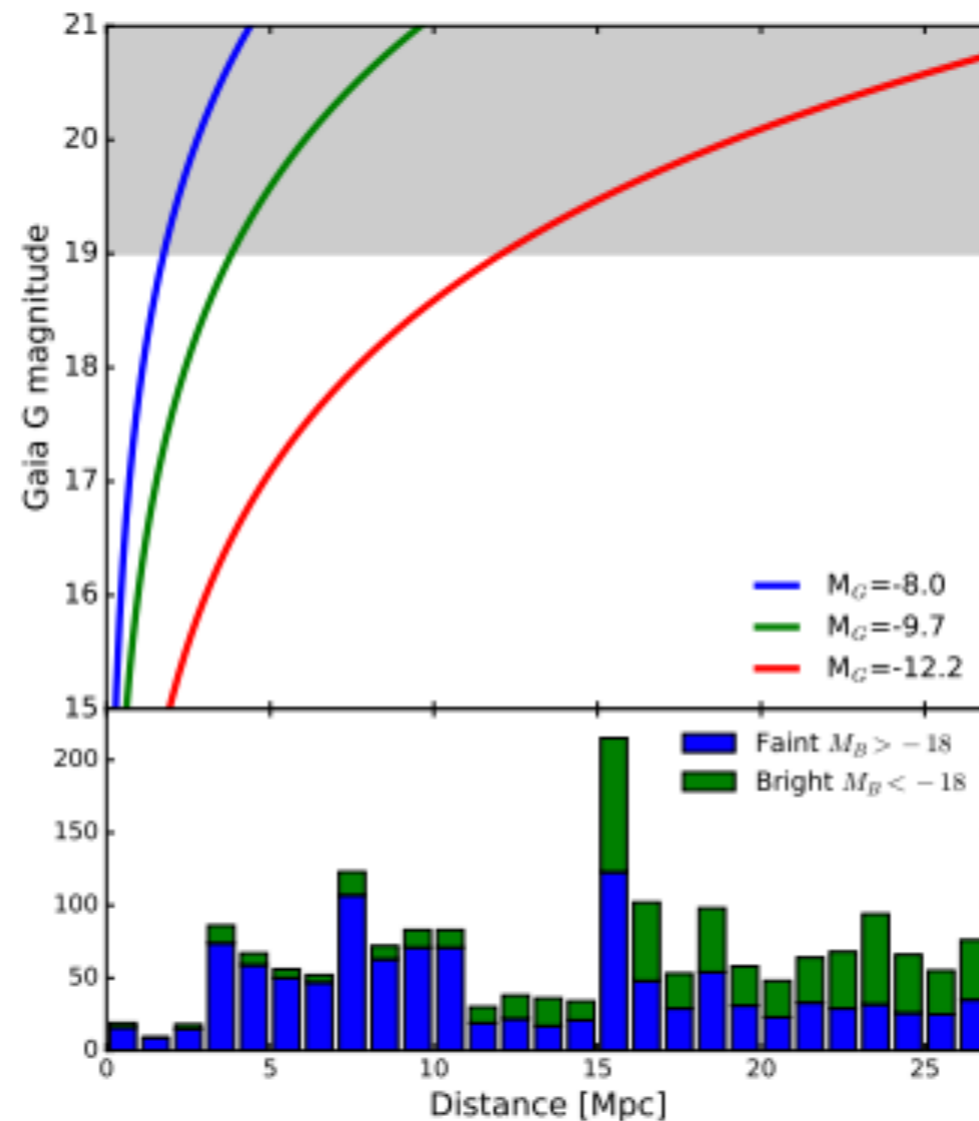
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FUTURE DIRECTIONS



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FUTURE DIRECTIONS



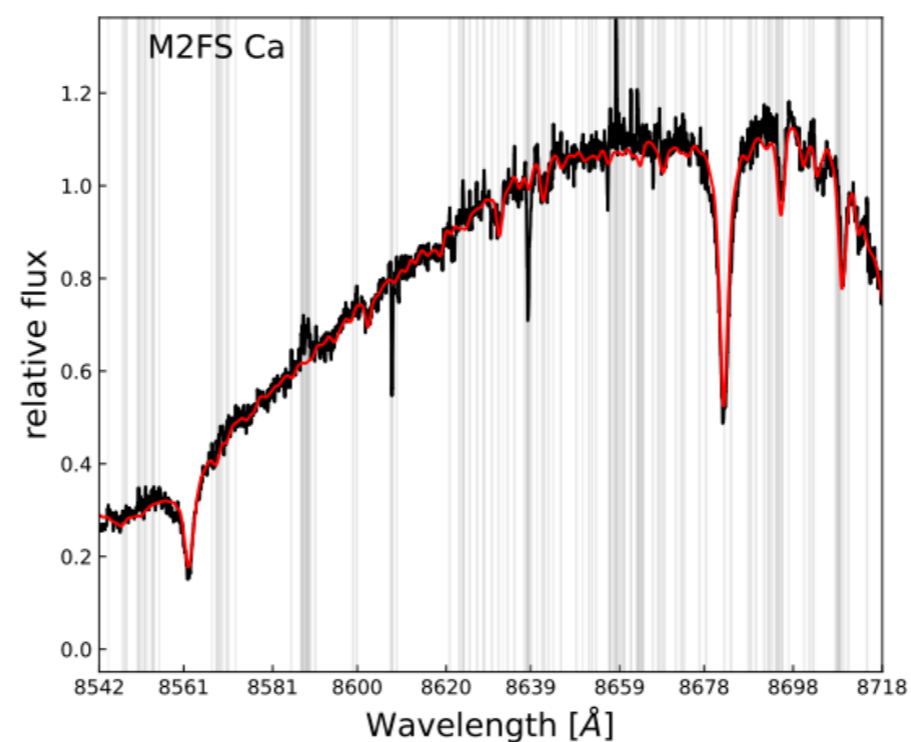
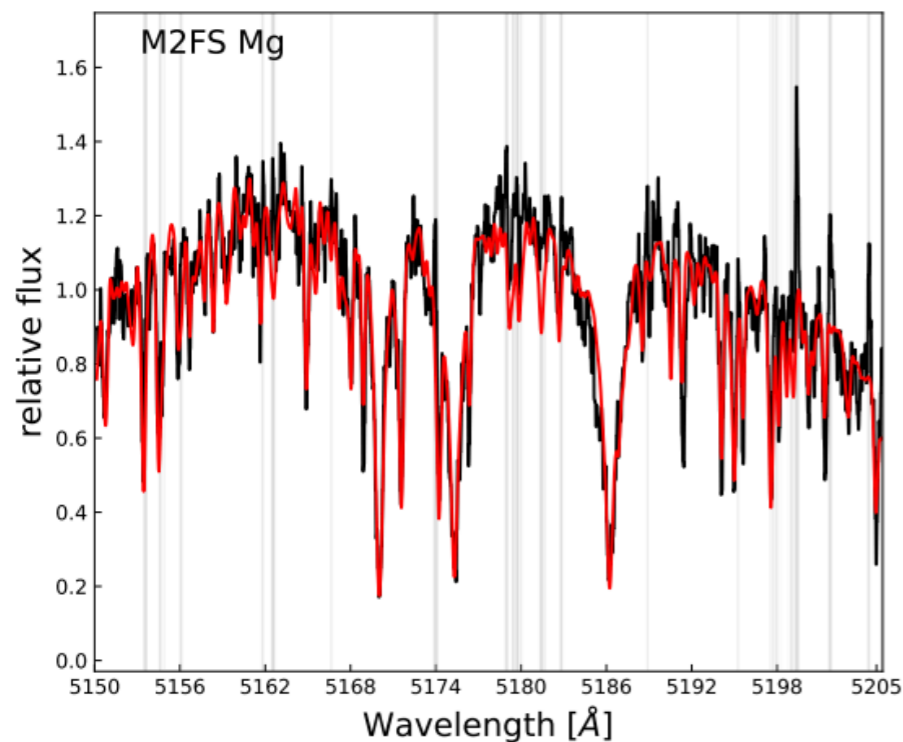
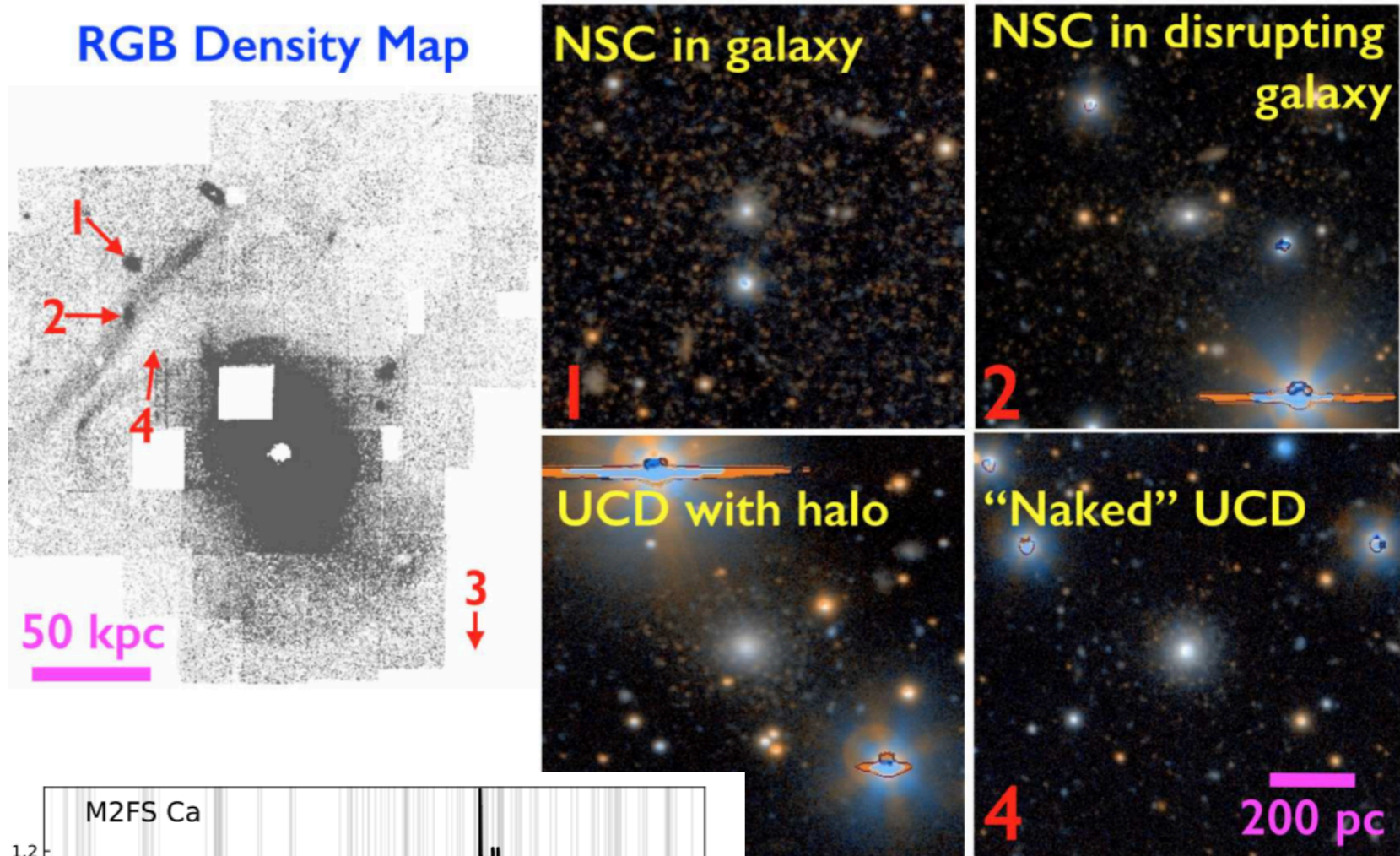
Can push out to ~20 Mpc for the very brightest GC and ultra-compact dwarfs.

Pilot survey around major galaxies out to $D \sim 10$ Mpc is underway.

Large push on NGC253 as well.

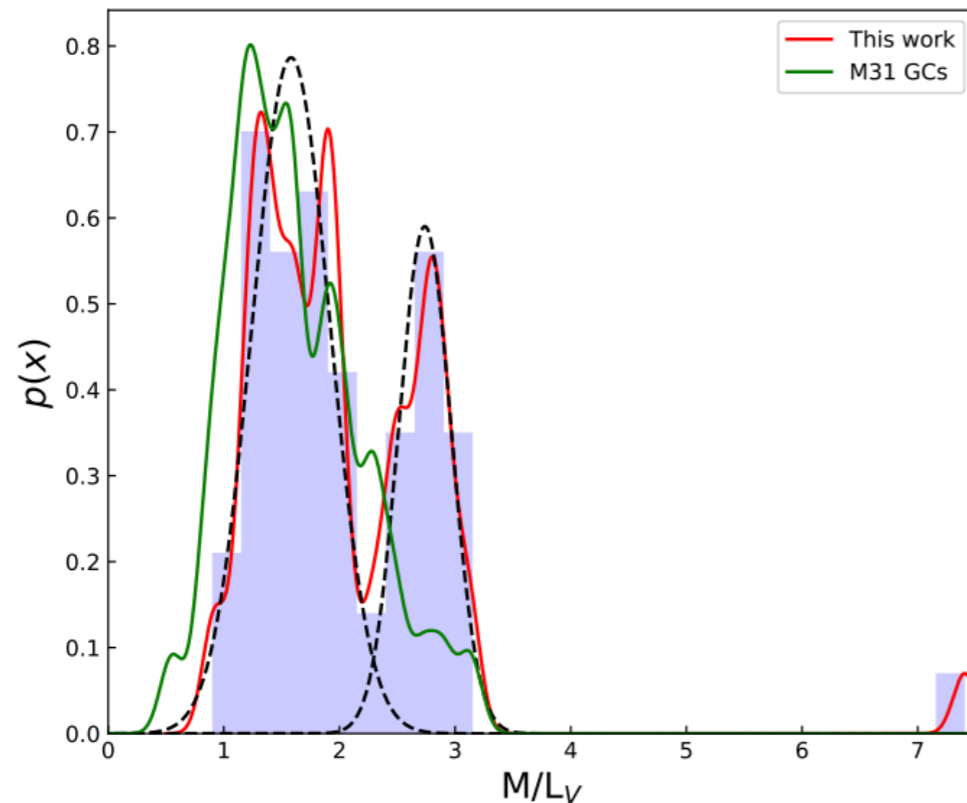
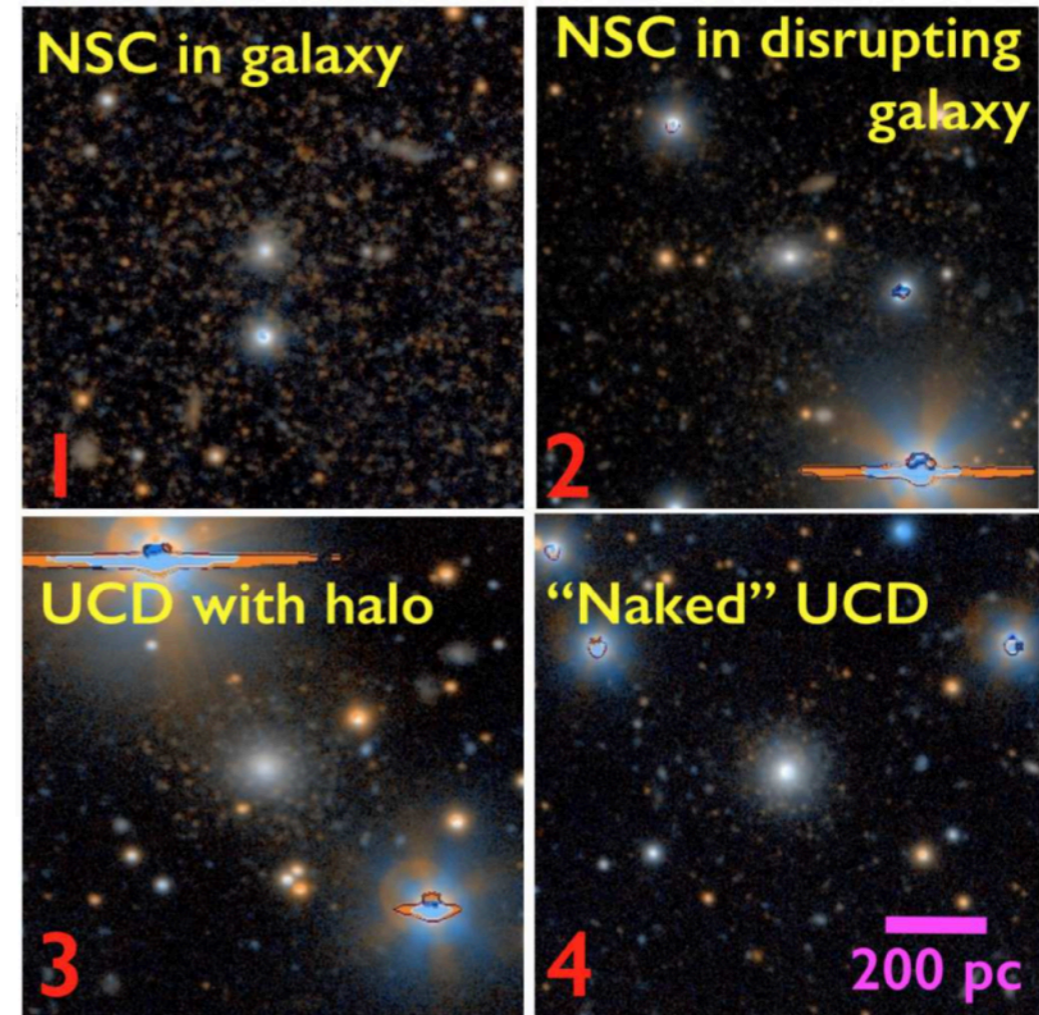
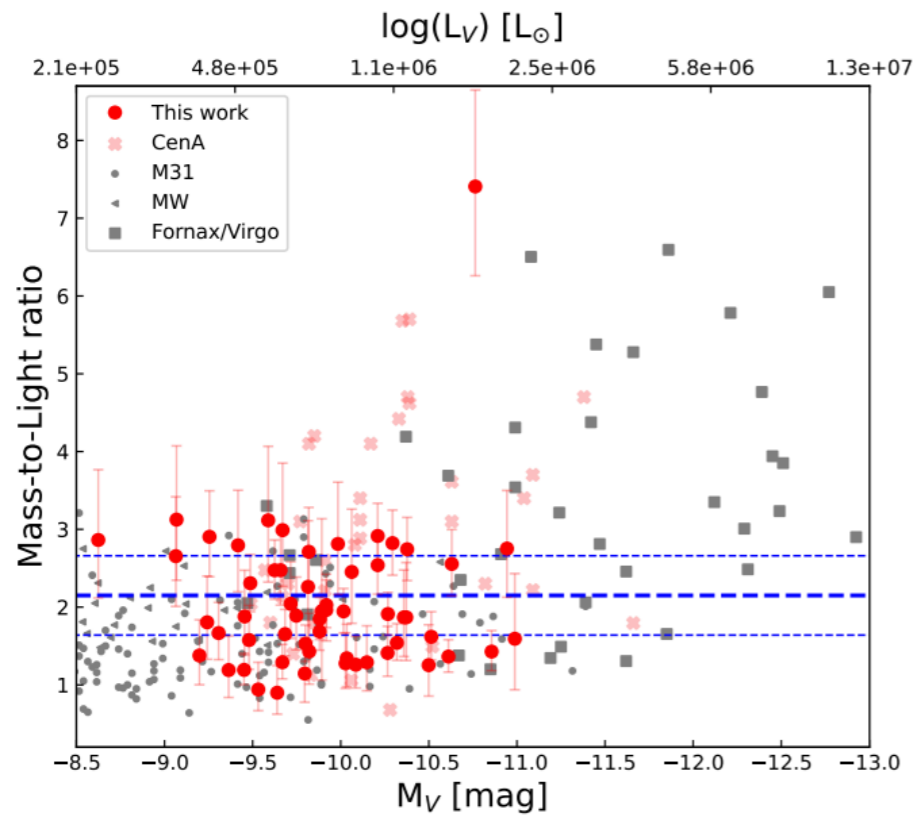
Questions?

M2FS VELOCITY DISPERSIONS OF 50 BRIGHT STAR CLUSTERS AROUND CENA



Dumont et al. 2022

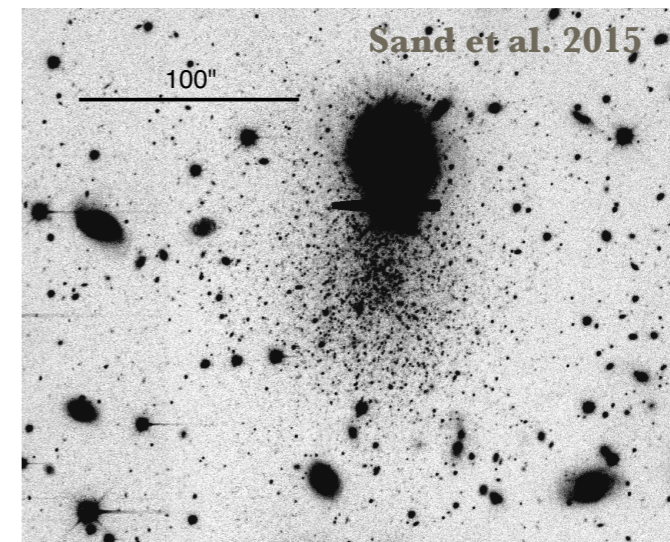
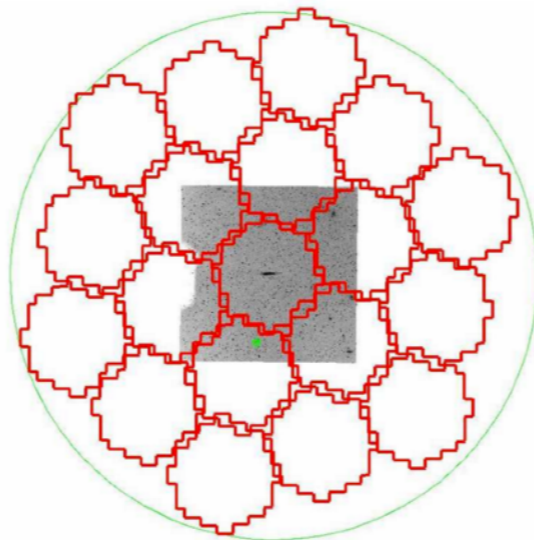
M2FS VELOCITY DISPERSIONS OF 50 BRIGHT STAR CLUSTERS AROUND CENA



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.

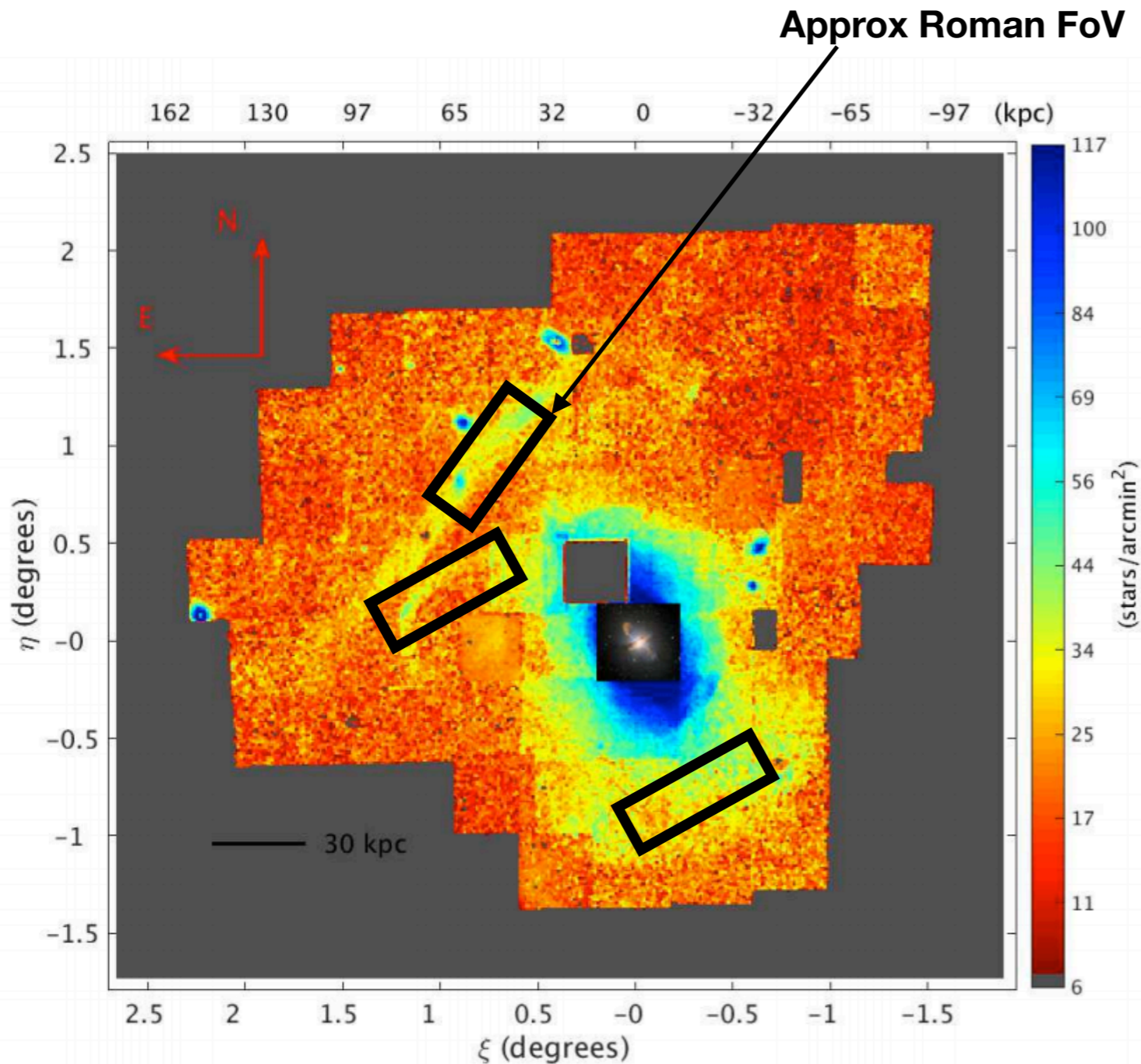
Summary

- 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



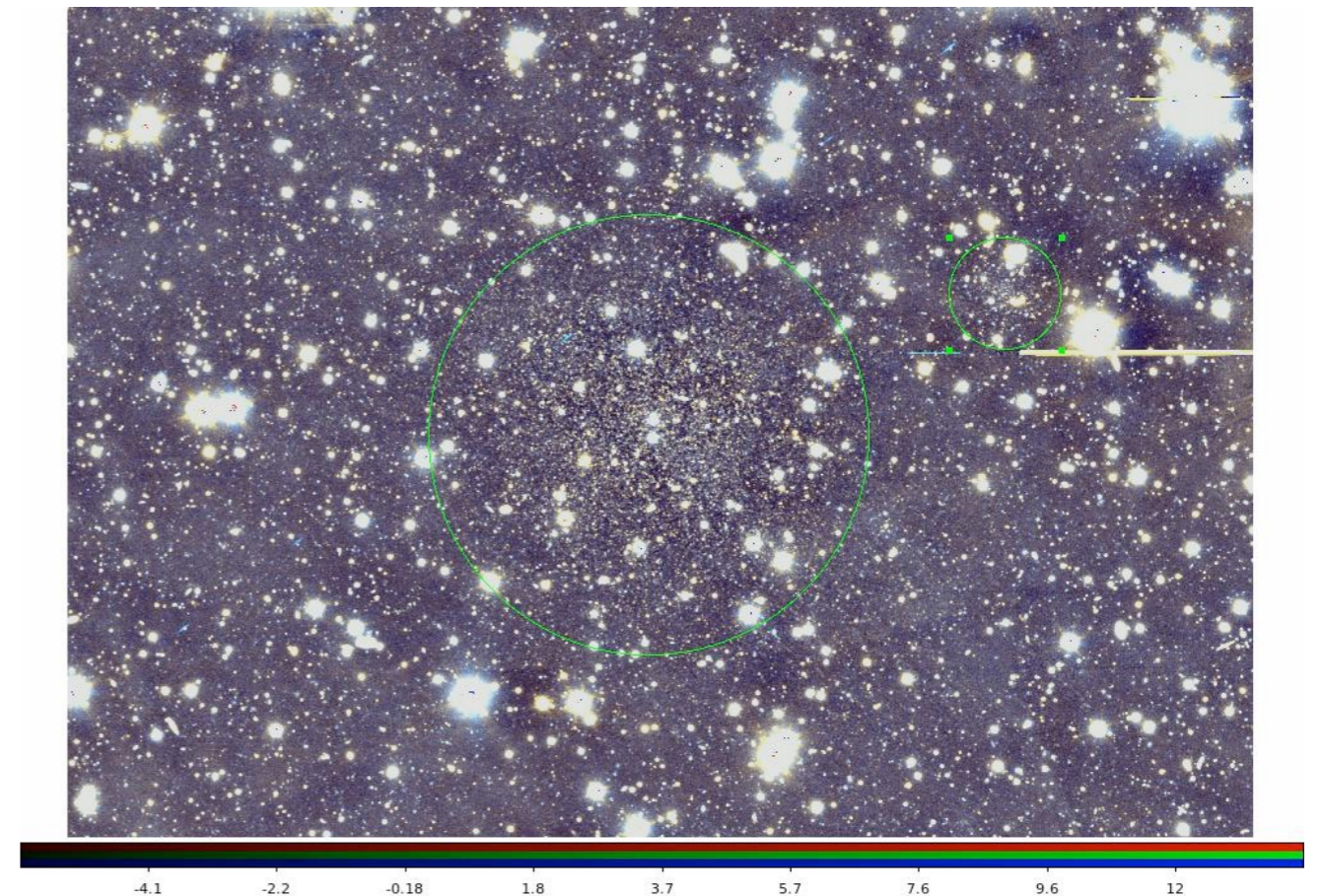
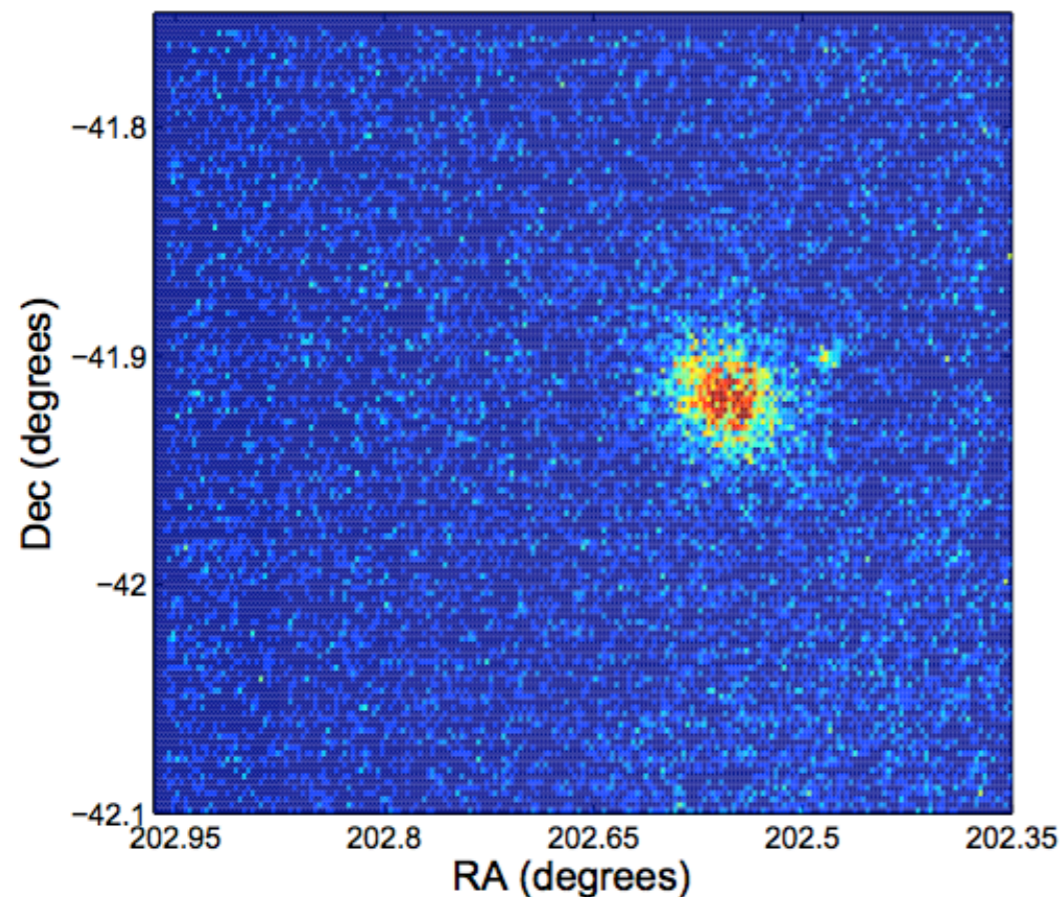
A clearly disrupting dwarf galaxy -- detected not by low surface brightness measurements but in individual resolved stars!

There are clearly other streams emerging.

All in resolved RGB stars

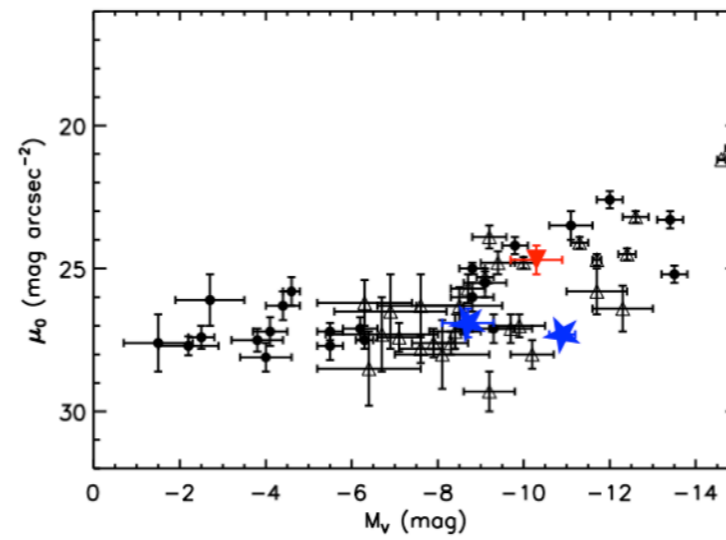
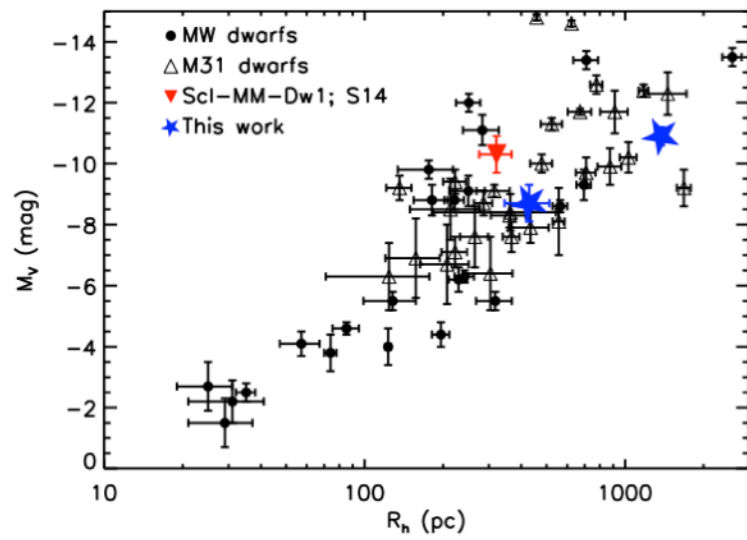
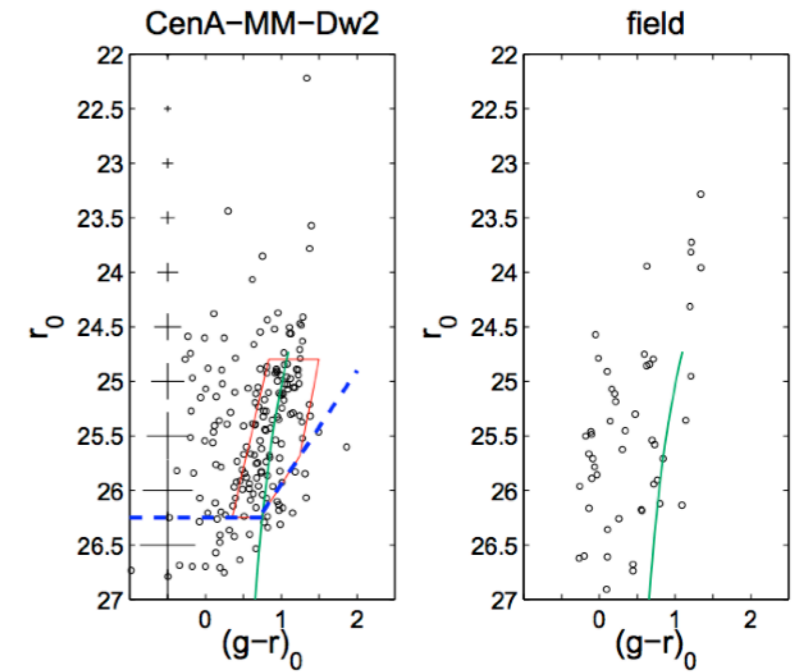
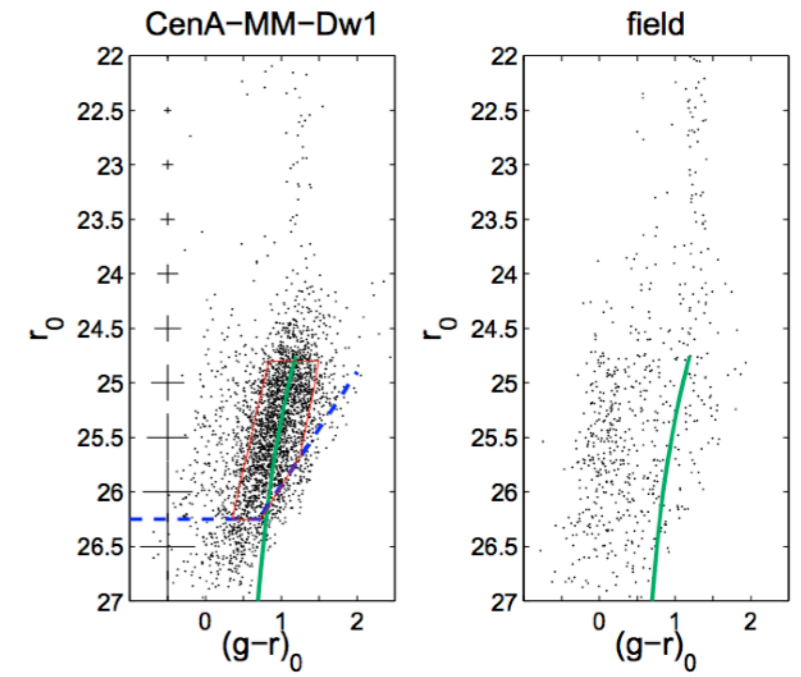
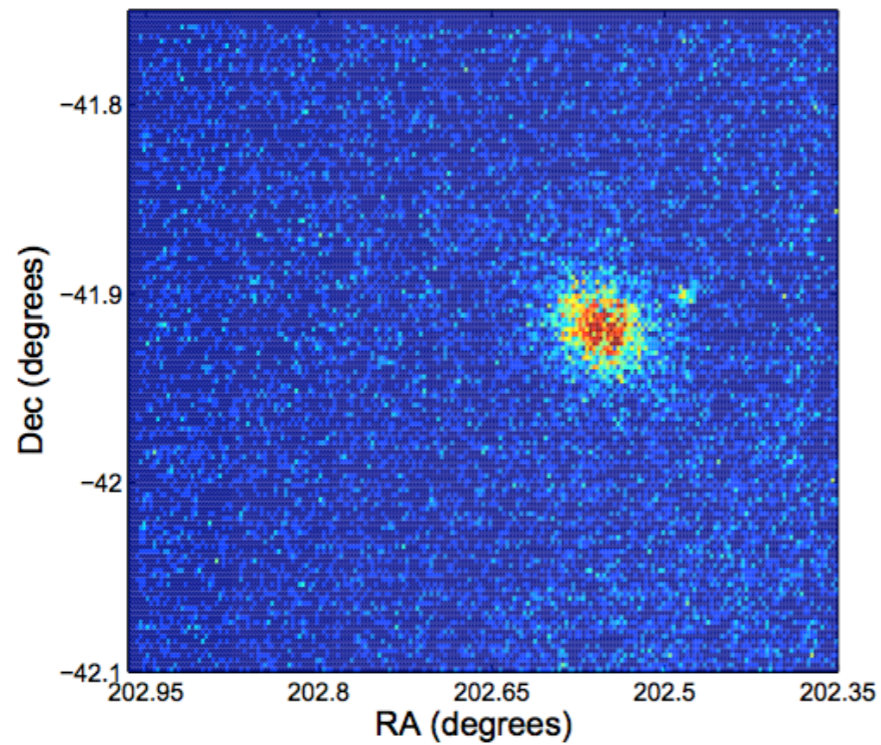
A CLOSE PAIR OF SATELLITES AROUND CENTAURUS A

Crnojevic et al. 2014

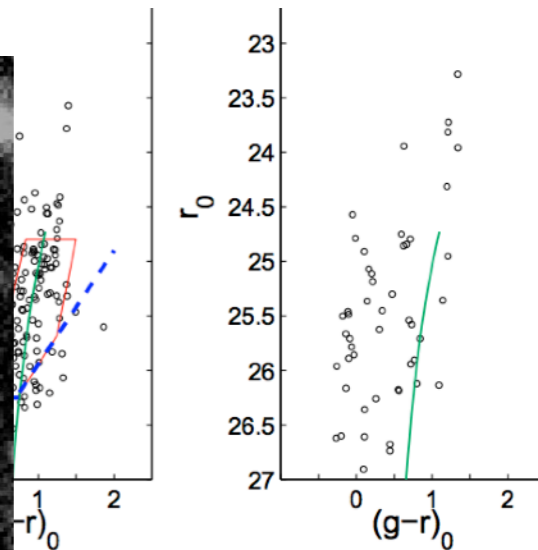
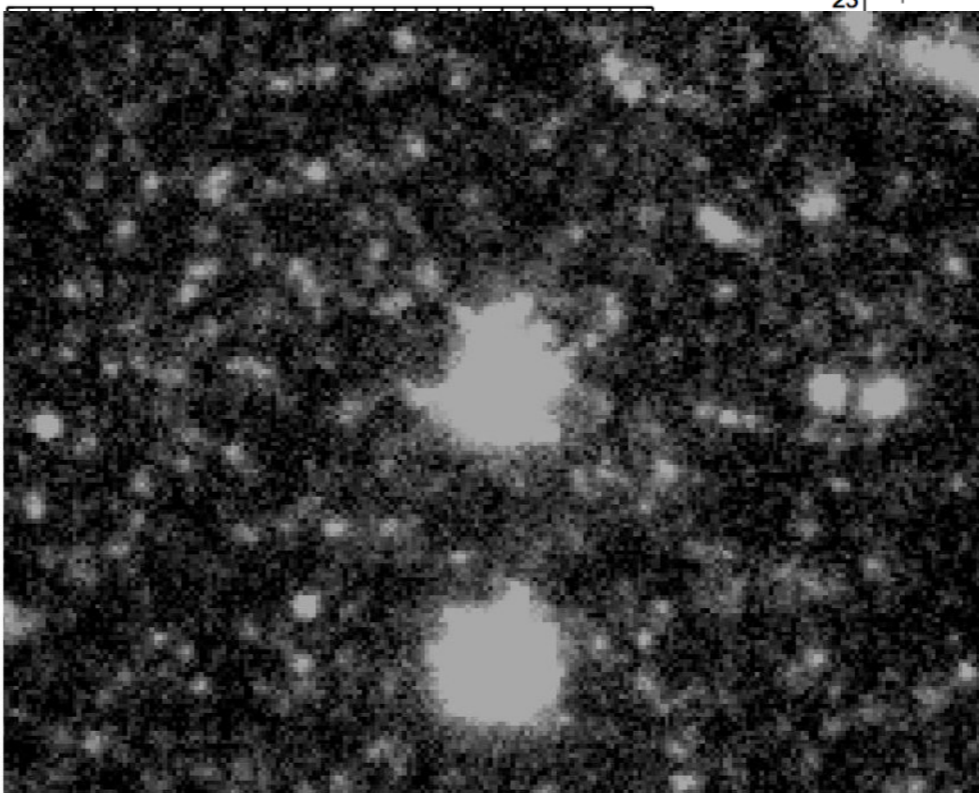
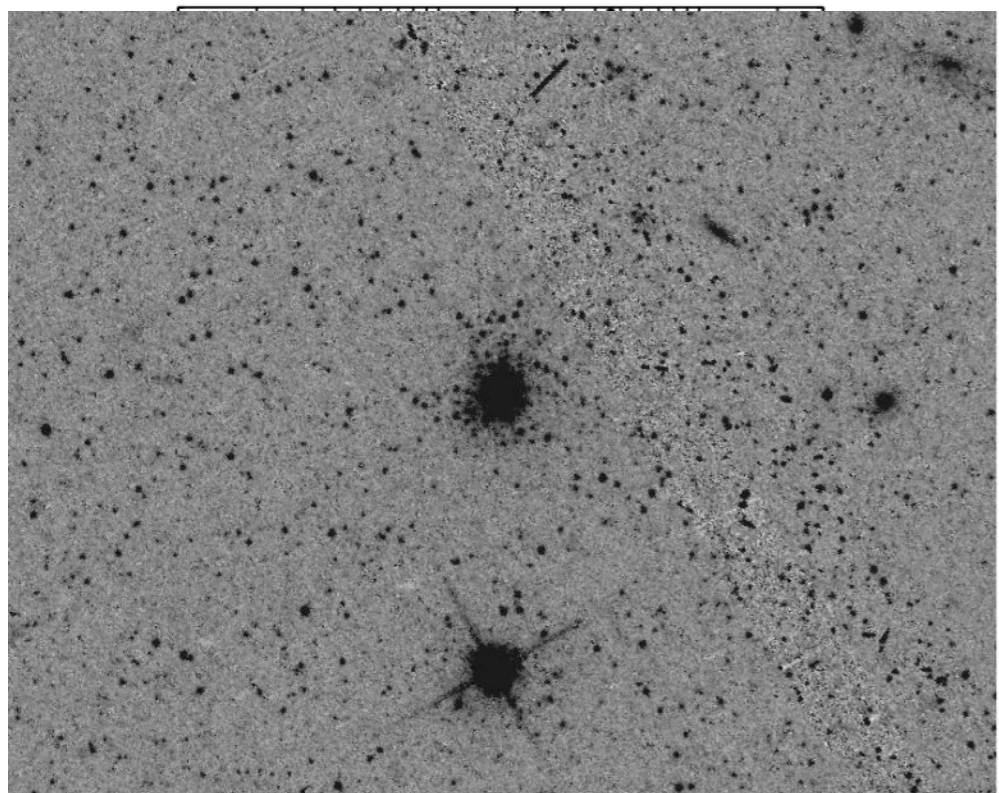
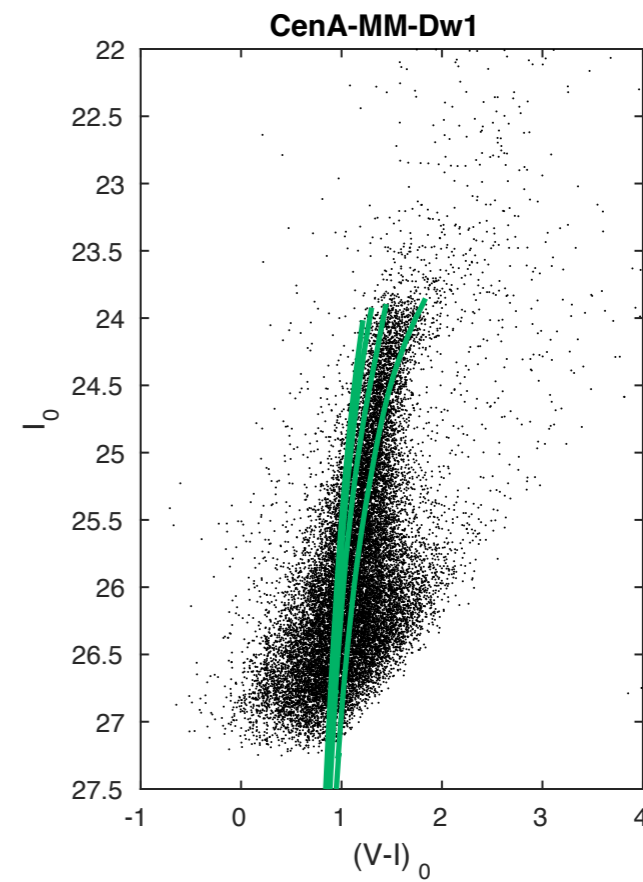
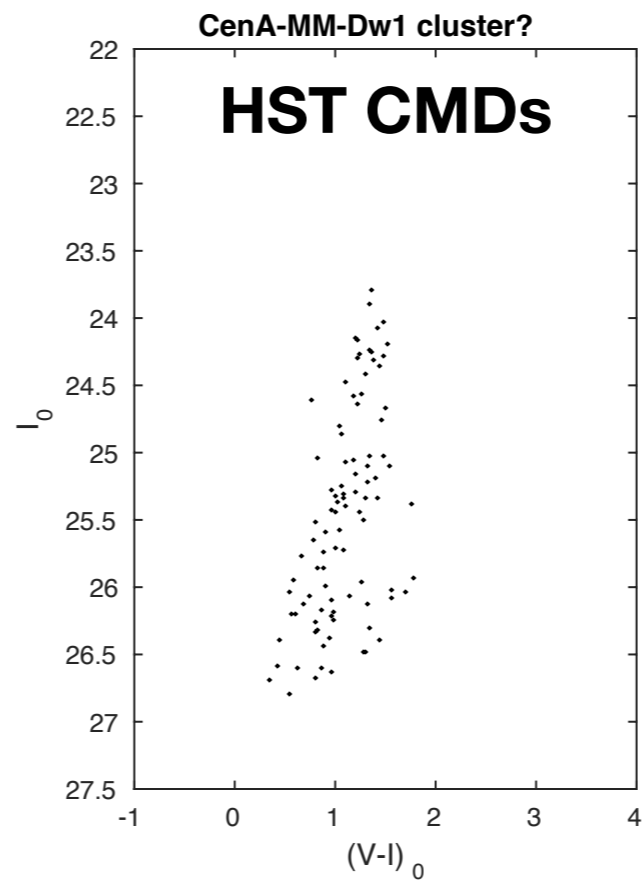
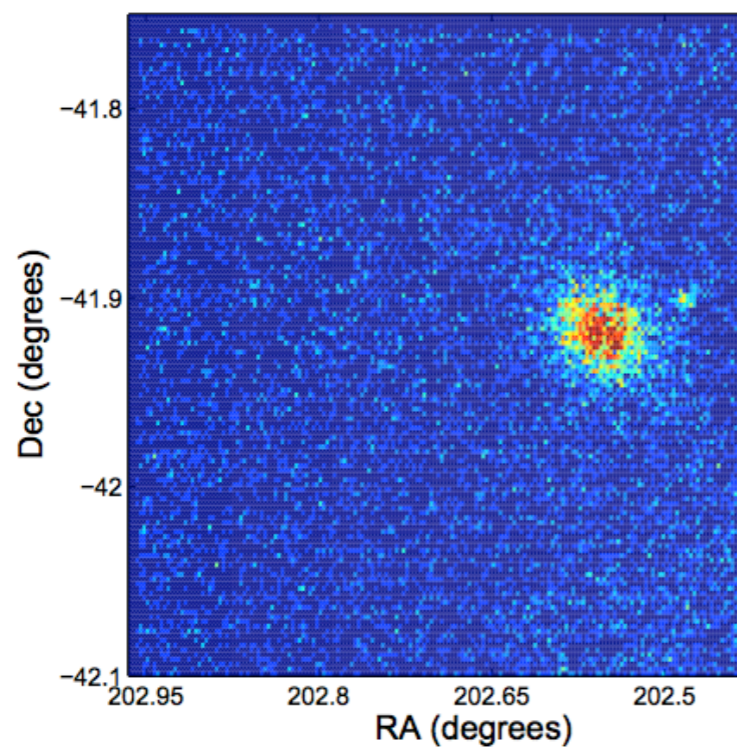


Pair is projected ~ 90 kpc from center of CenA.
3 kpc projected separation. Both are at $D \sim 3.6$ Mpc.
A 'satellite of a satellite'? -- also a prediction of CDM.

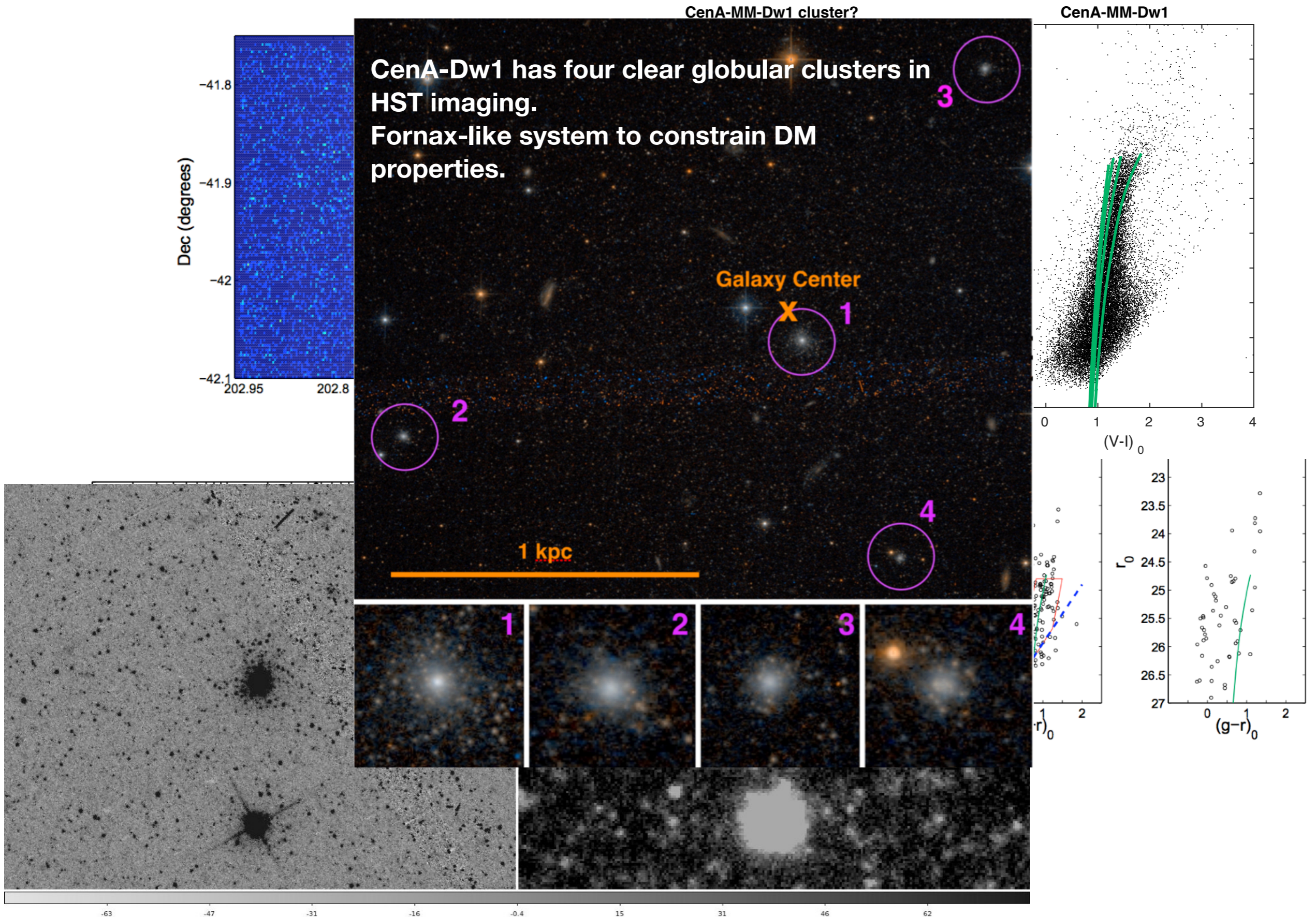
A CLOSE PAIR OF SATELLITES



A CLOSE PAIR OF SATELLITES

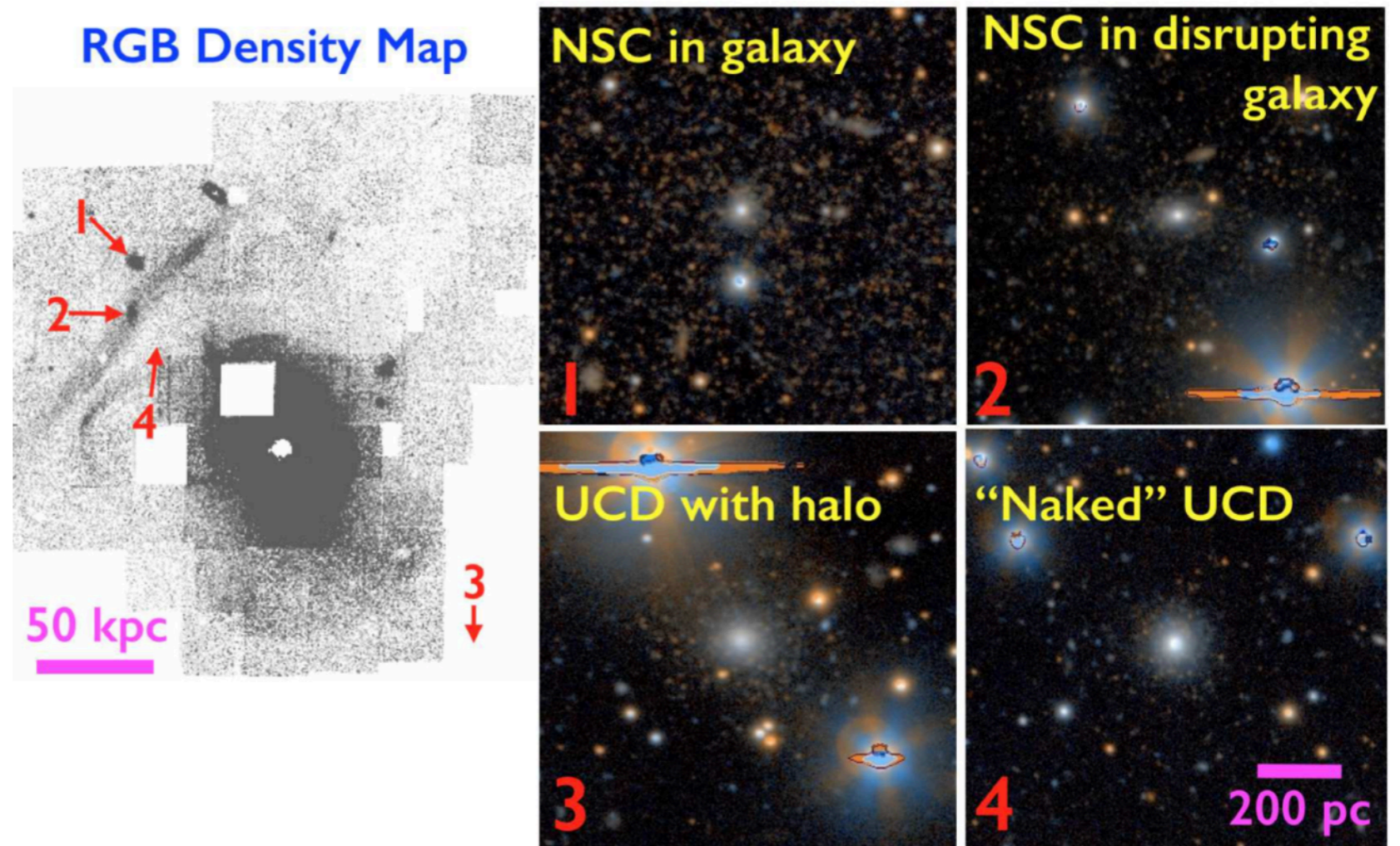


A CLOSE PAIR OF SATELLITES



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

