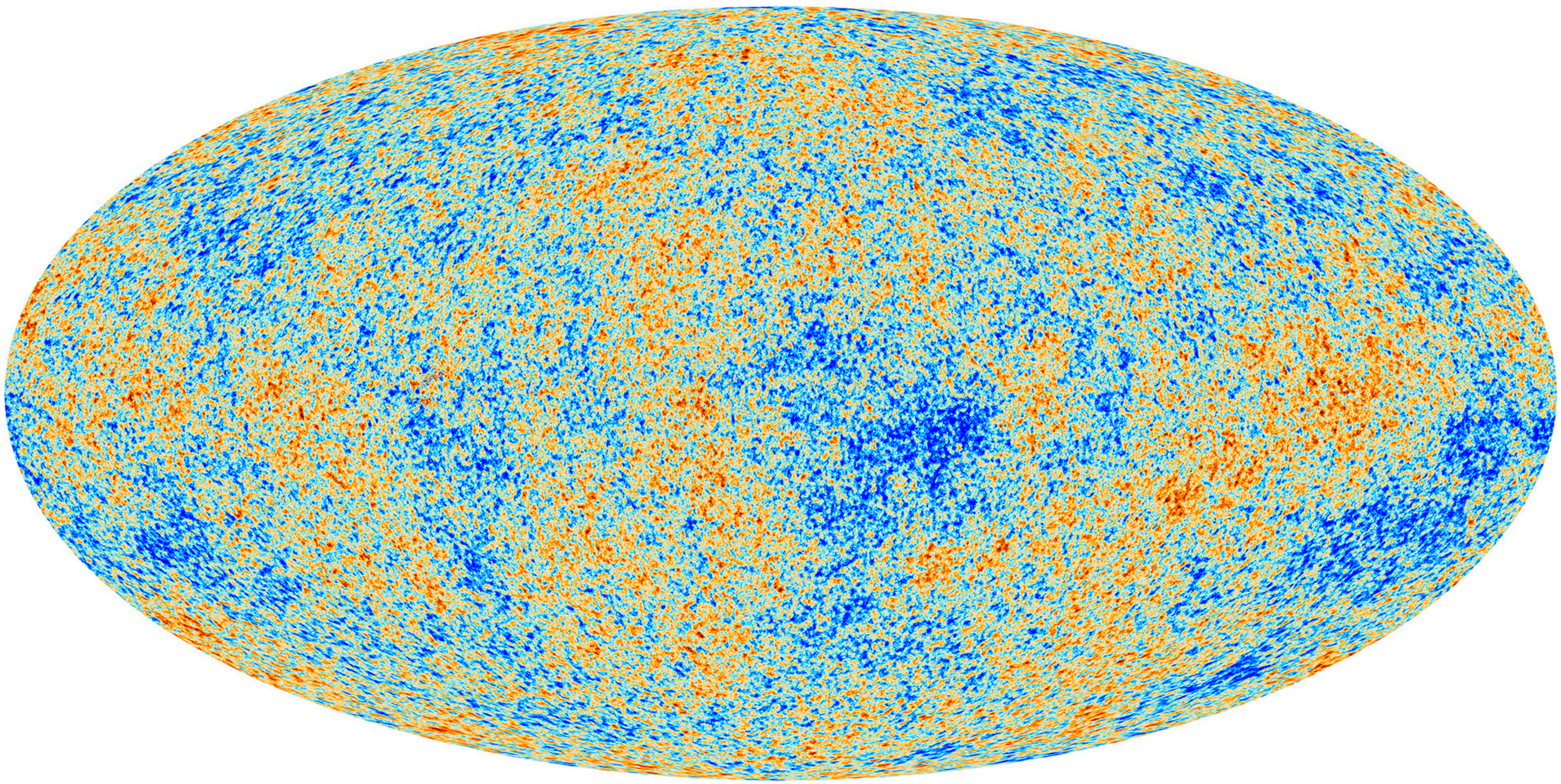
Small-scale cosmology with dwarf galaxies

Oliver Müller – University of Strasbourg
SNF Fellow

Initial conditions of the Universe

Temperatur: 2.7 Kelvin (red/blue: 0.0002 Kelvin difference)

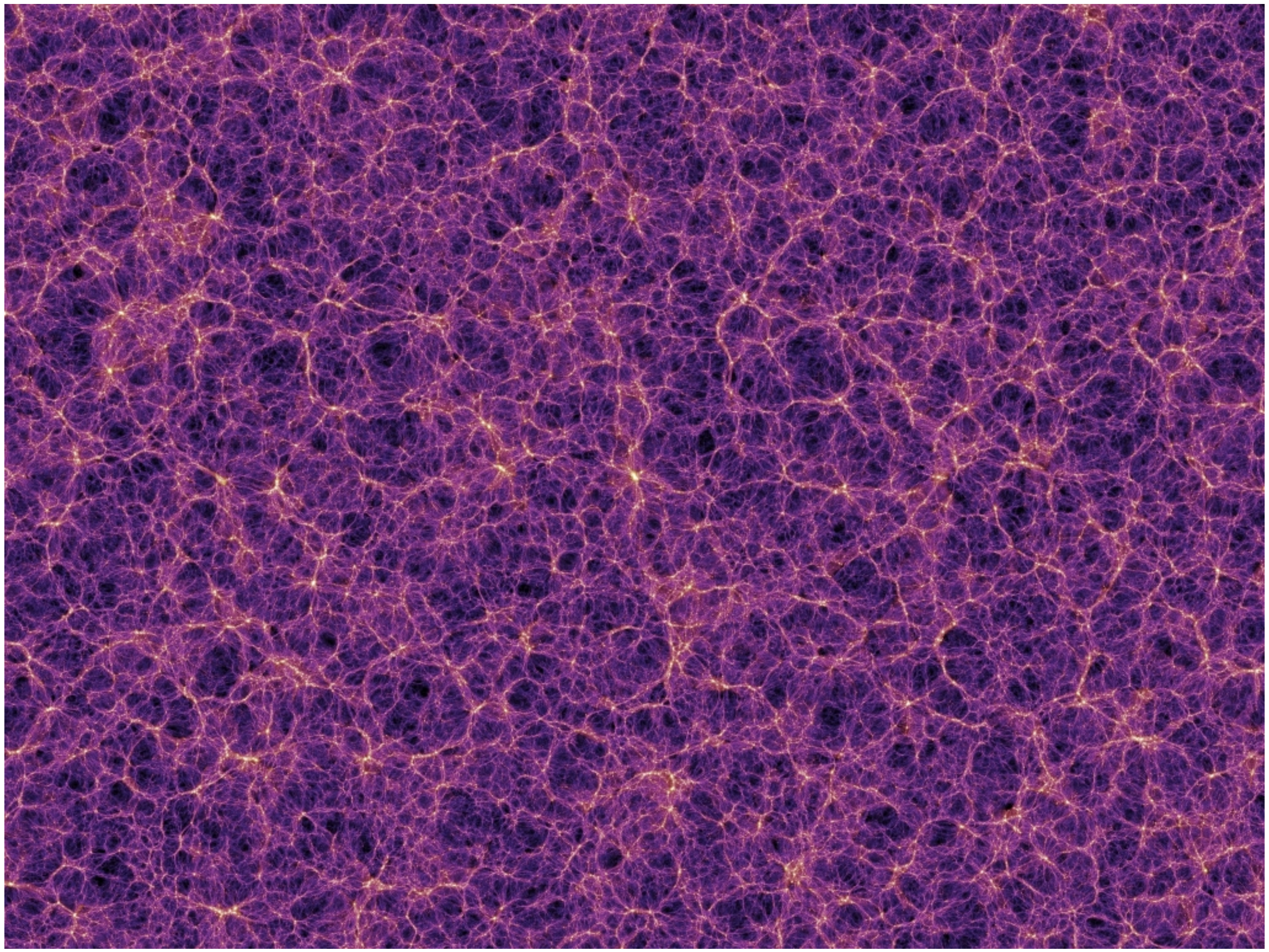


Traces the initial mass/energy distribution of the Universe

Credit: Planck

The Cosmic Web of Dark Matter

Filamentary large-scale structure of the Universe.

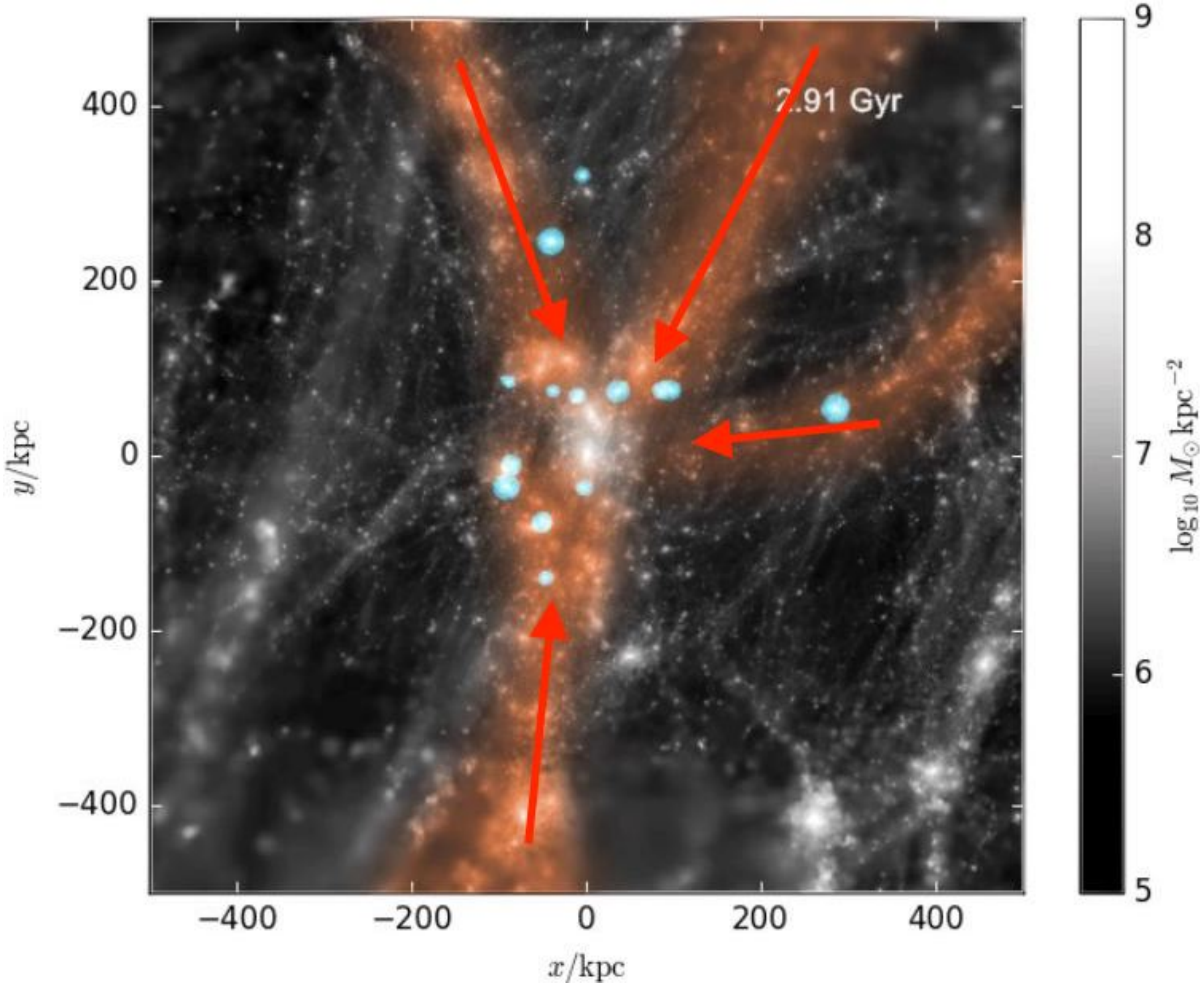


- Filaments and voids
- Baryons follow DM distribution

Credit: Millenium Simulation Project

Dark Matter accretion

Accretion of dark matter subhalos through filaments.

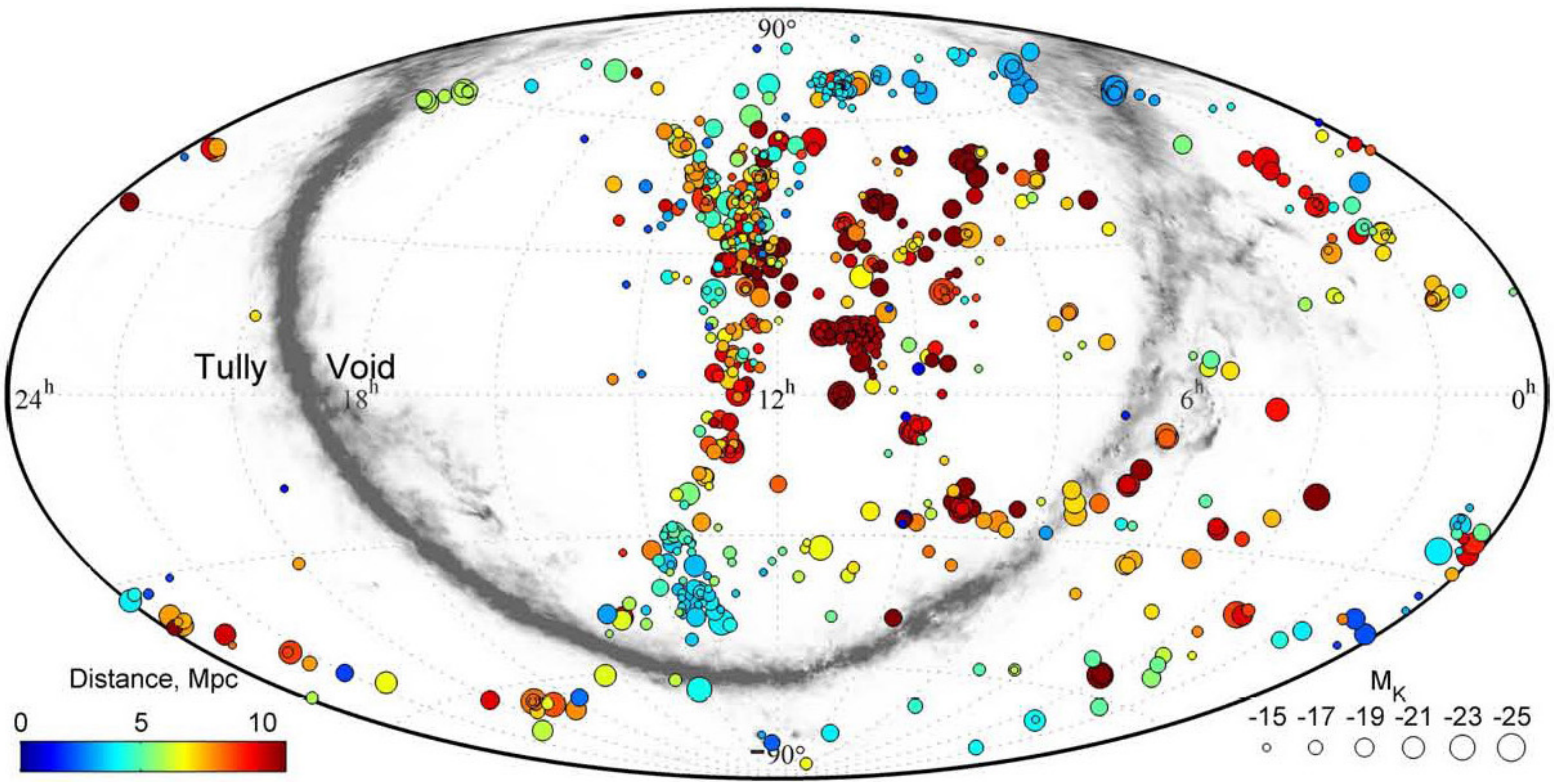


Dwarf galaxies are the building blocks of the Universe!

Adopted from Ahmed et al. (2017).

The Local Volume

Galaxies within 10 Mpc represent the nearby Universe.



https://www.sao.ru/lv/lvgdb/introduction.php, Karachentsev et al. (2013)

Challenges to CDM

An *incomplete* list of tension between predictions and observations on small-scales, all observed in the Local Group:

- Cusp/Core problem (e.g. de Blok 2010).
- Too-Big-To-Fail problem (Boylan-Kolchin et al. 2011) .
- Missing satellite problem (Moore et al. 1999).
- Bulge – number of satellites relation (Lopez-Corredoira & Kroupa 2016).
- Radial Accelaration Relation (Lelli et al. 2017).
- Planes-of-satellites problem (Kroupa et al. 2005).

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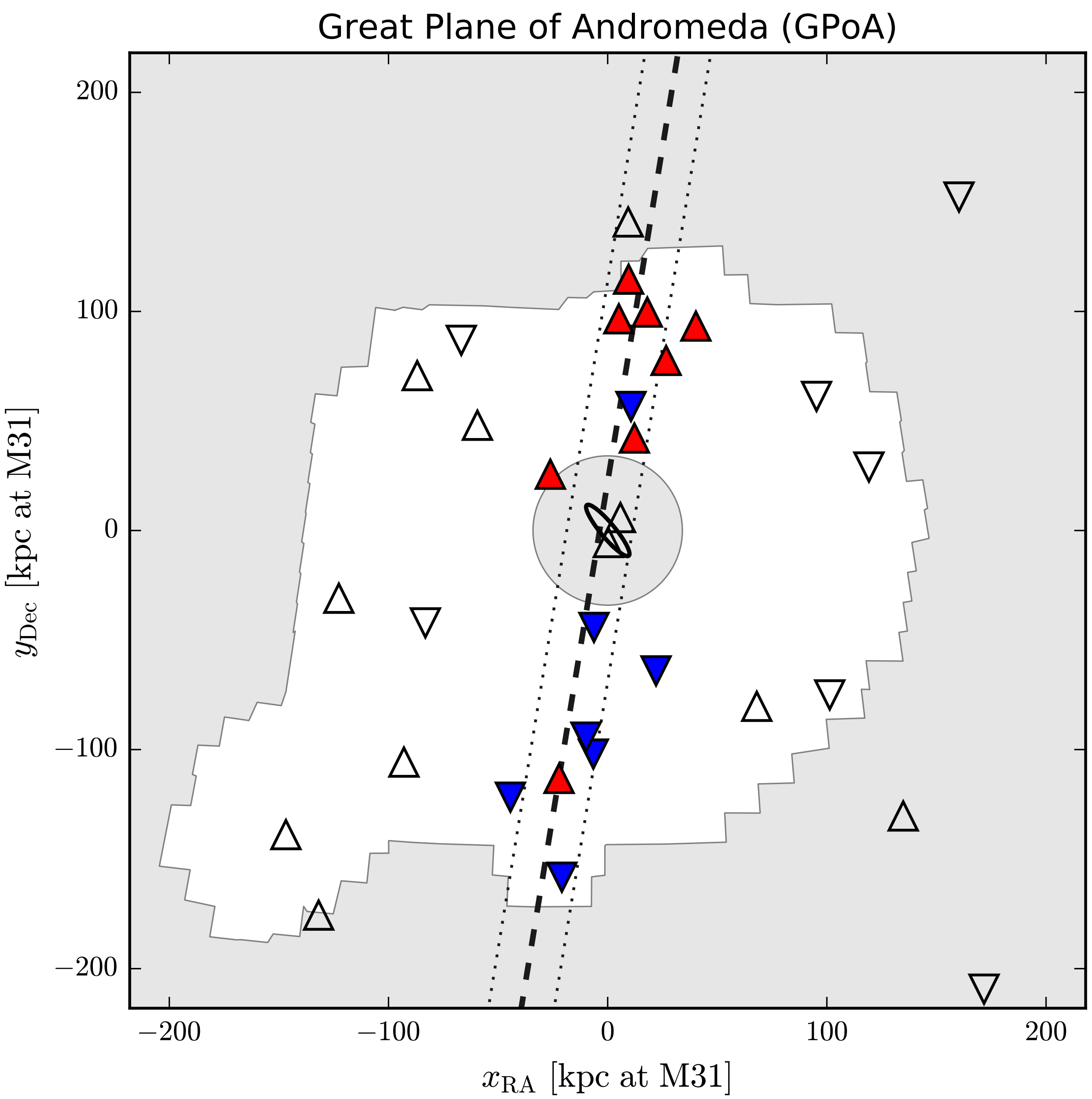
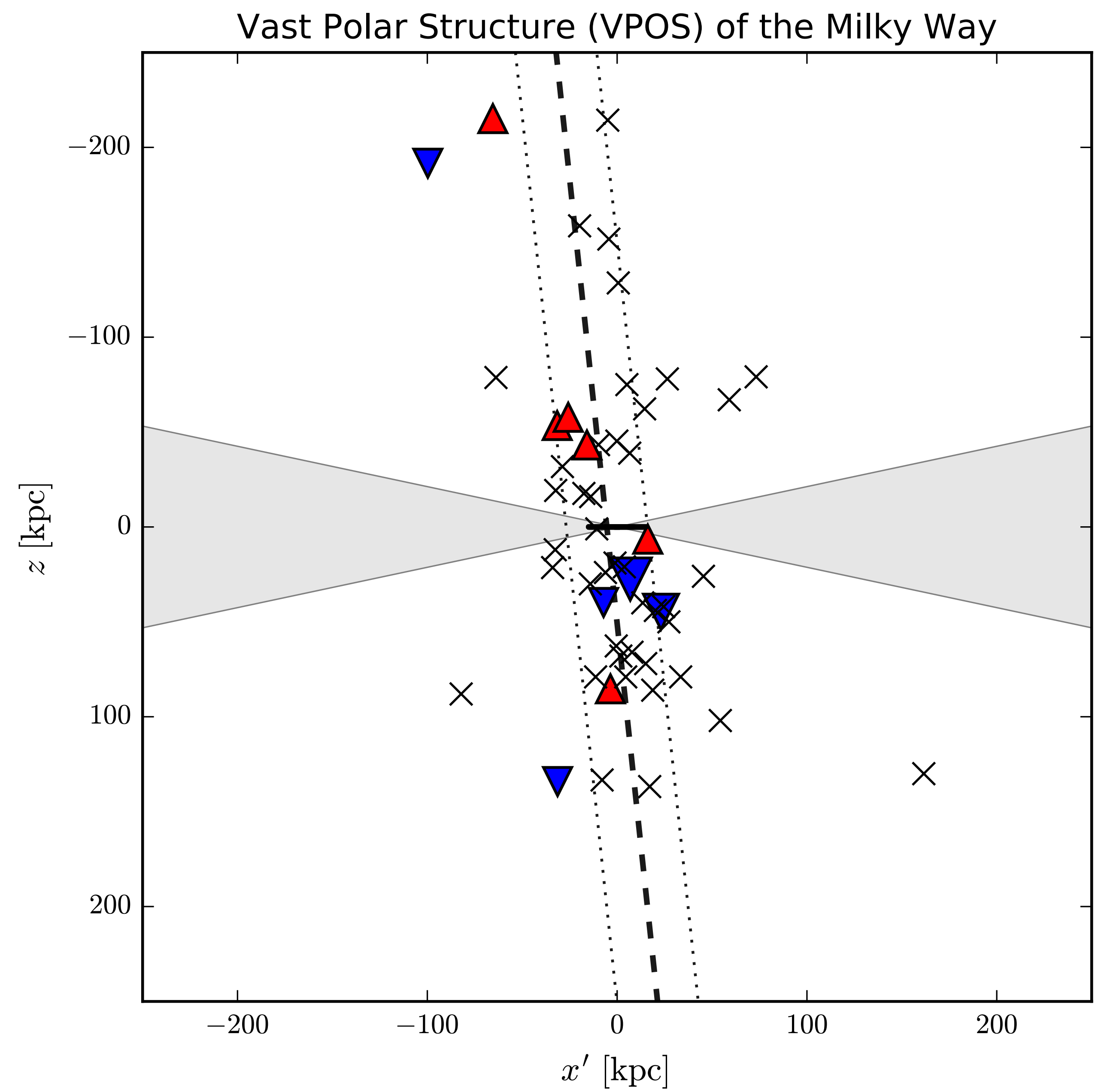
Andromeda and MW

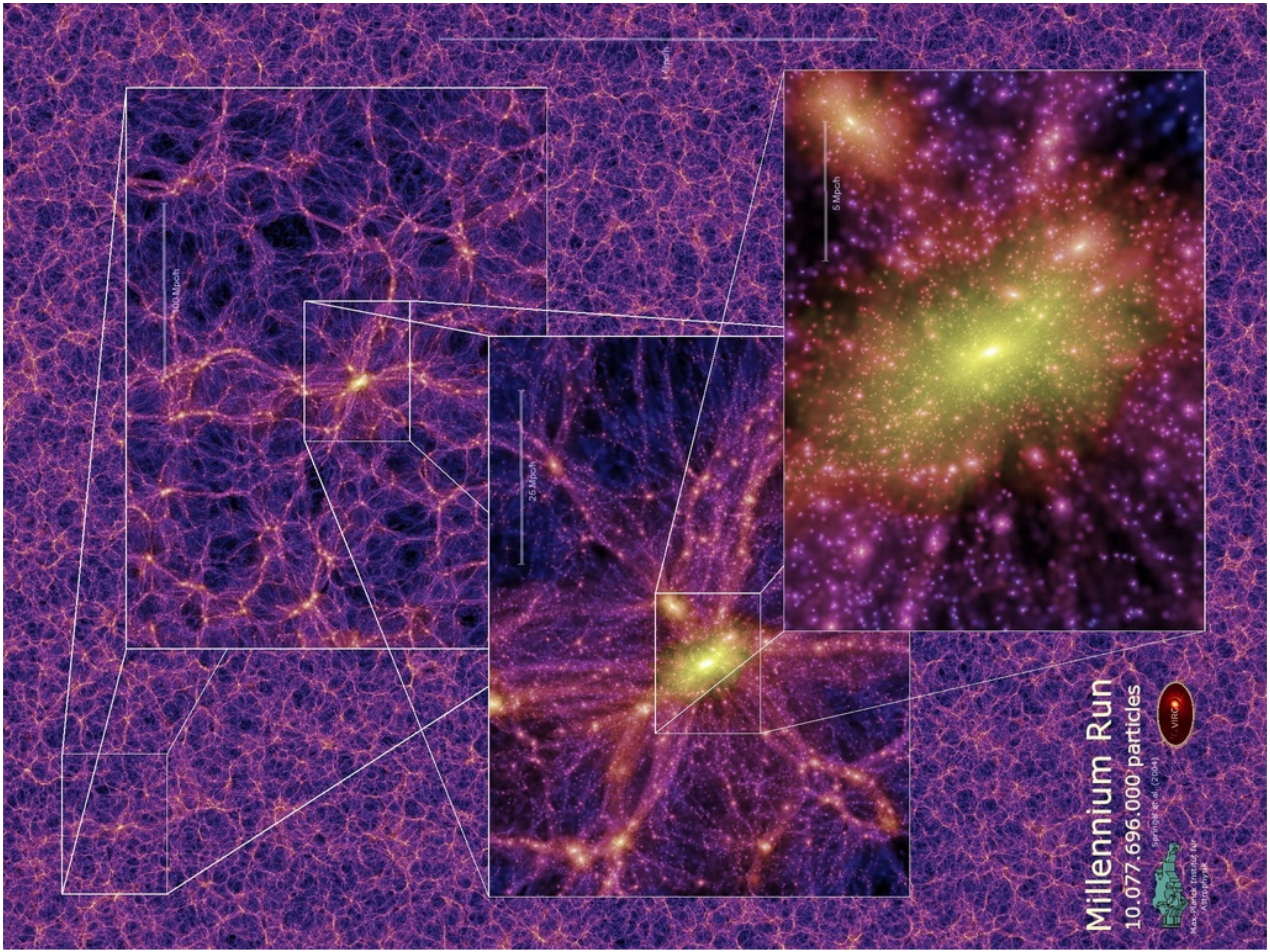
Planar structures





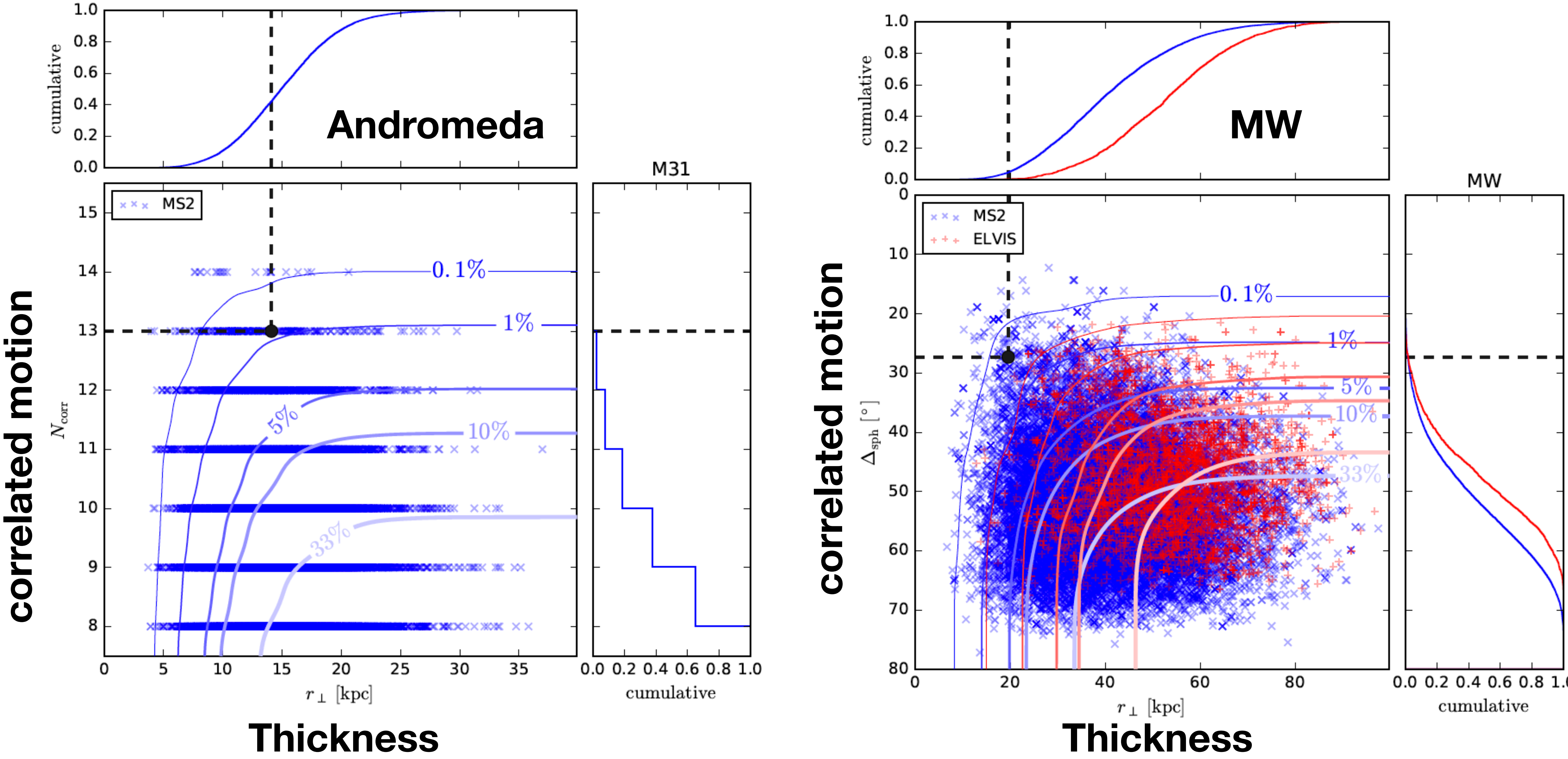
Pawlowski (2018)

Planar structures



Pawlowski (2018)

Comparison to simulations



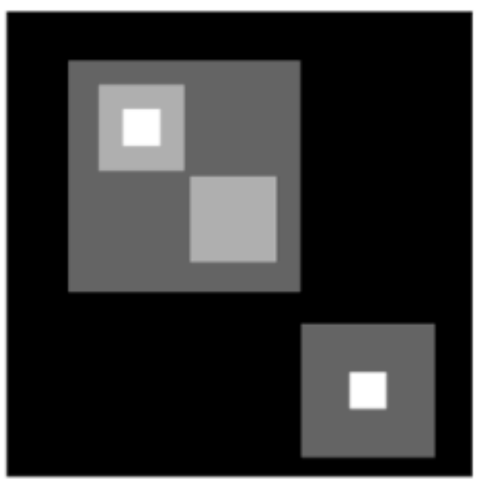
Pawlowski (2018)

Is the Local Group unique?

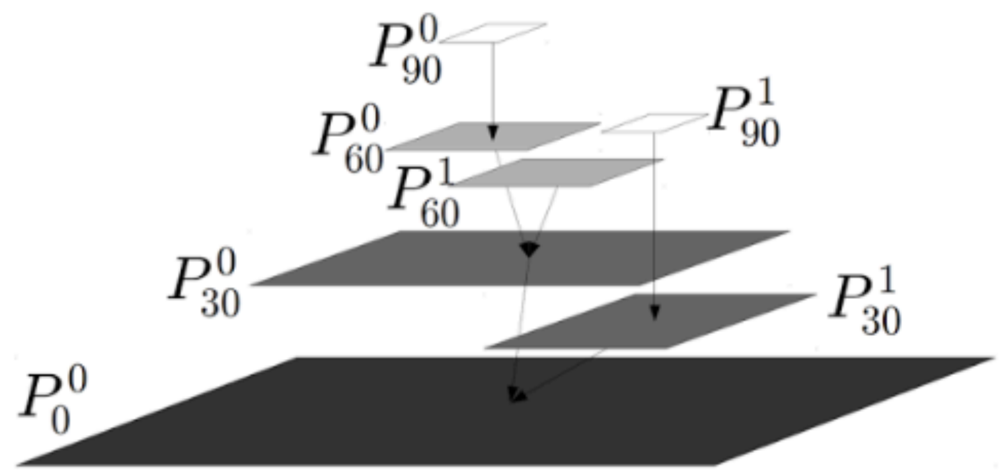
Three major tasks

- Find dwarf galaxies
- Measure their distances and velocities
- Compare to cosmological simulations

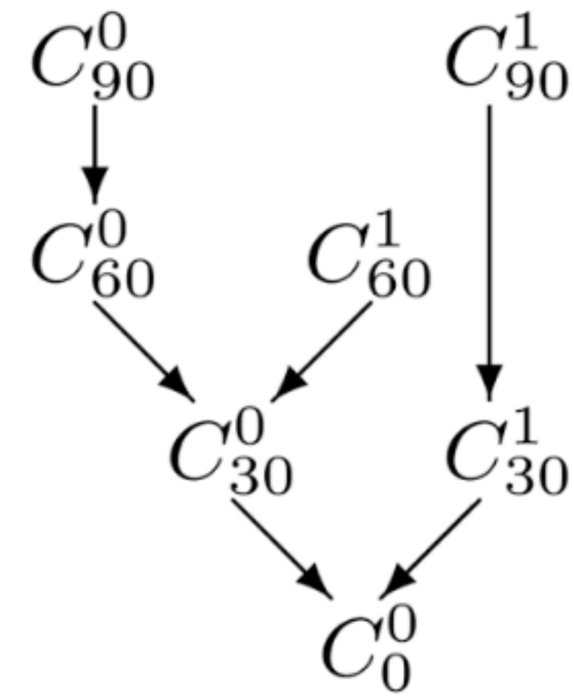
Automatic dwarf galaxy detection – MTO



(a) 2D image



(b) Peak components



(c) Max-Tree

Teeninga+2016

Automatic dwarf galaxy detection – MTO

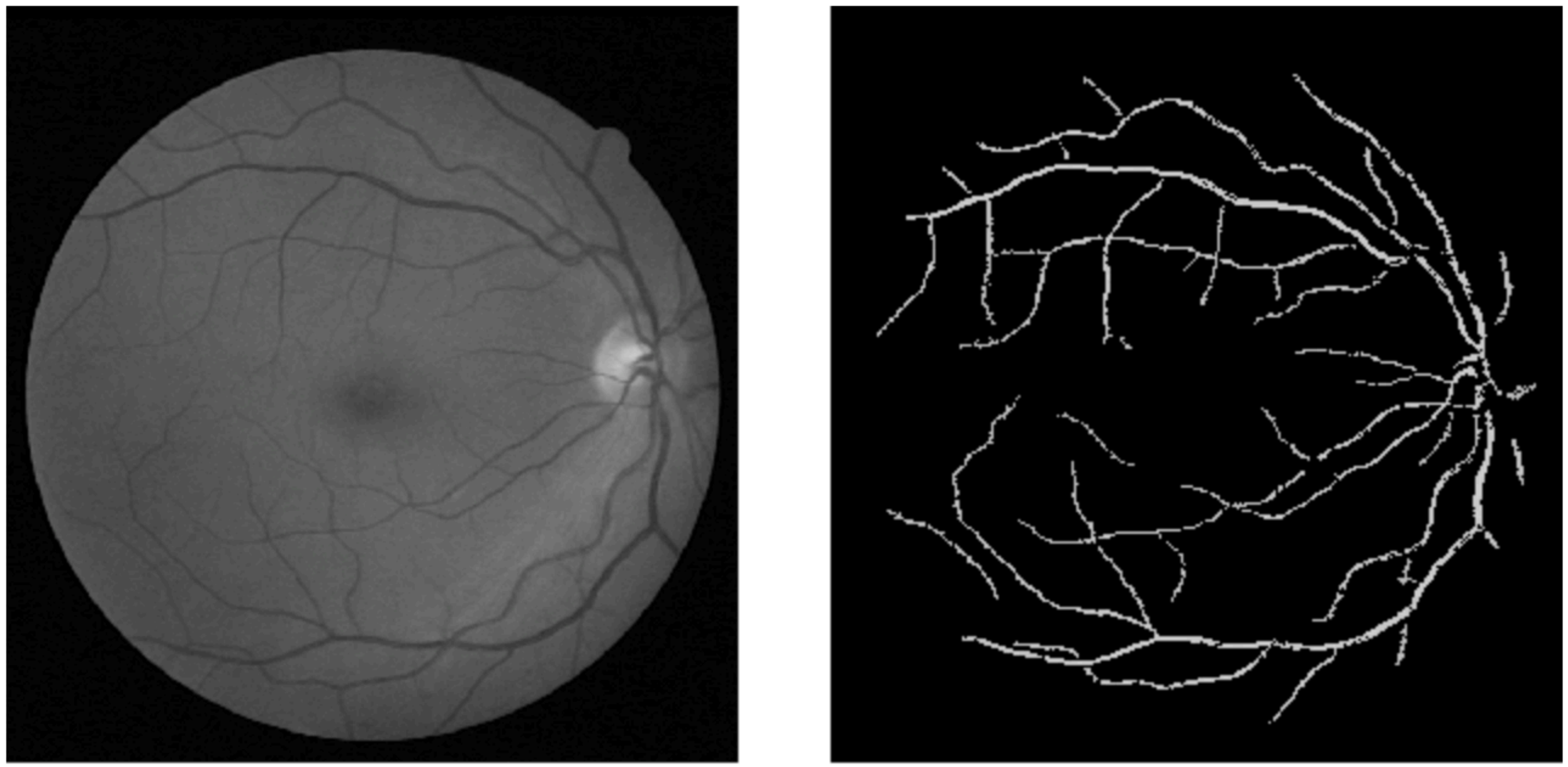
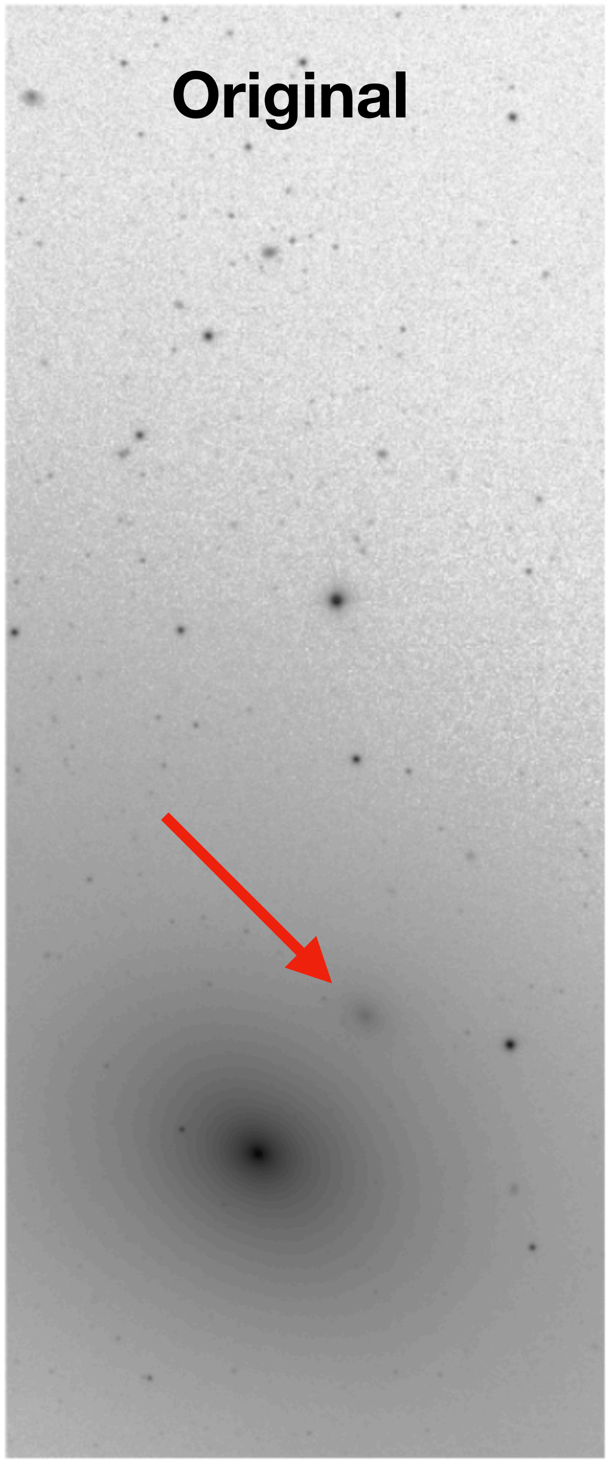


Fig. 11. (a) Retinal image and (b) max-tree segmentation result.

Teeninga+2016

MTO (Teeninga et al. 2013)



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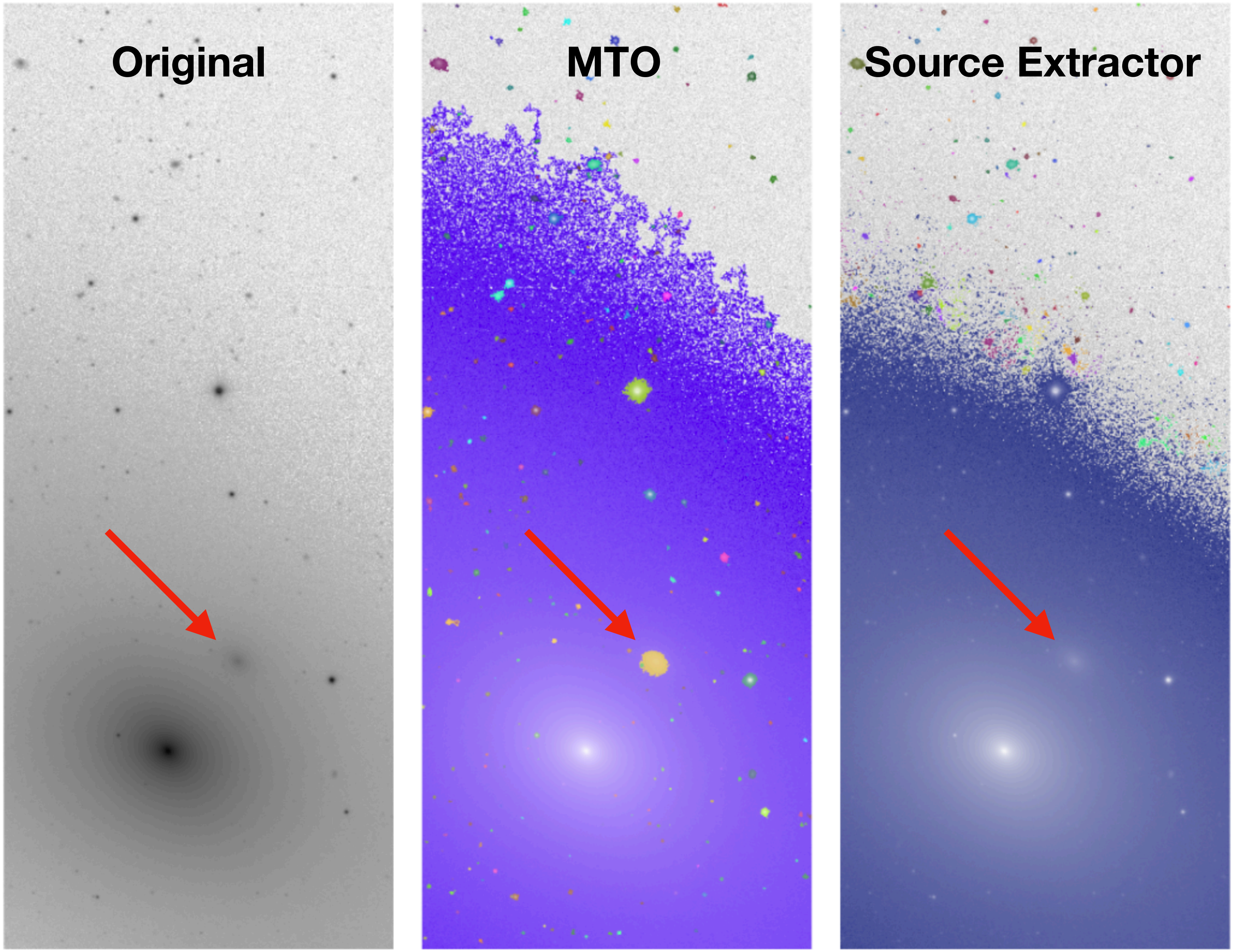
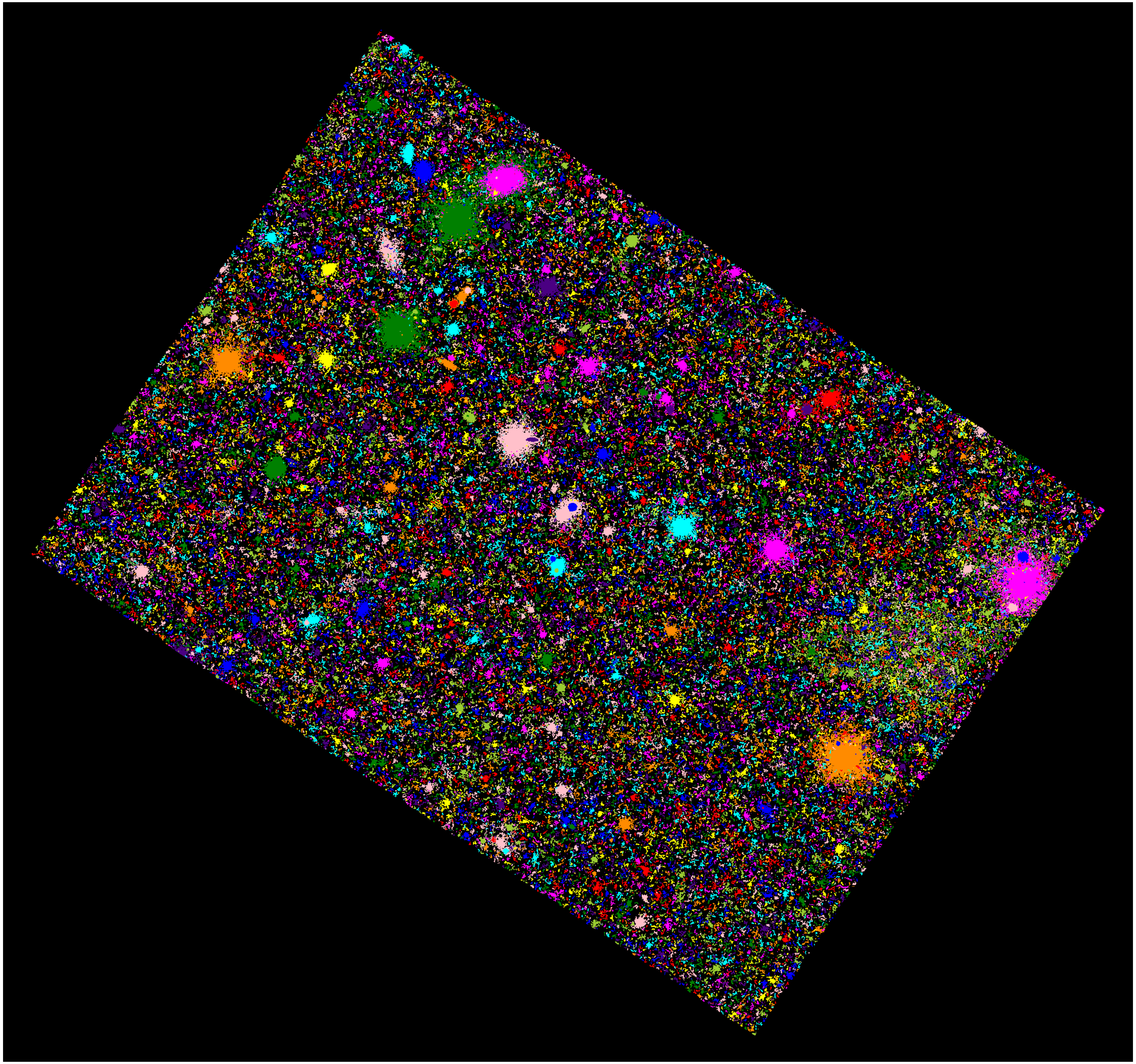
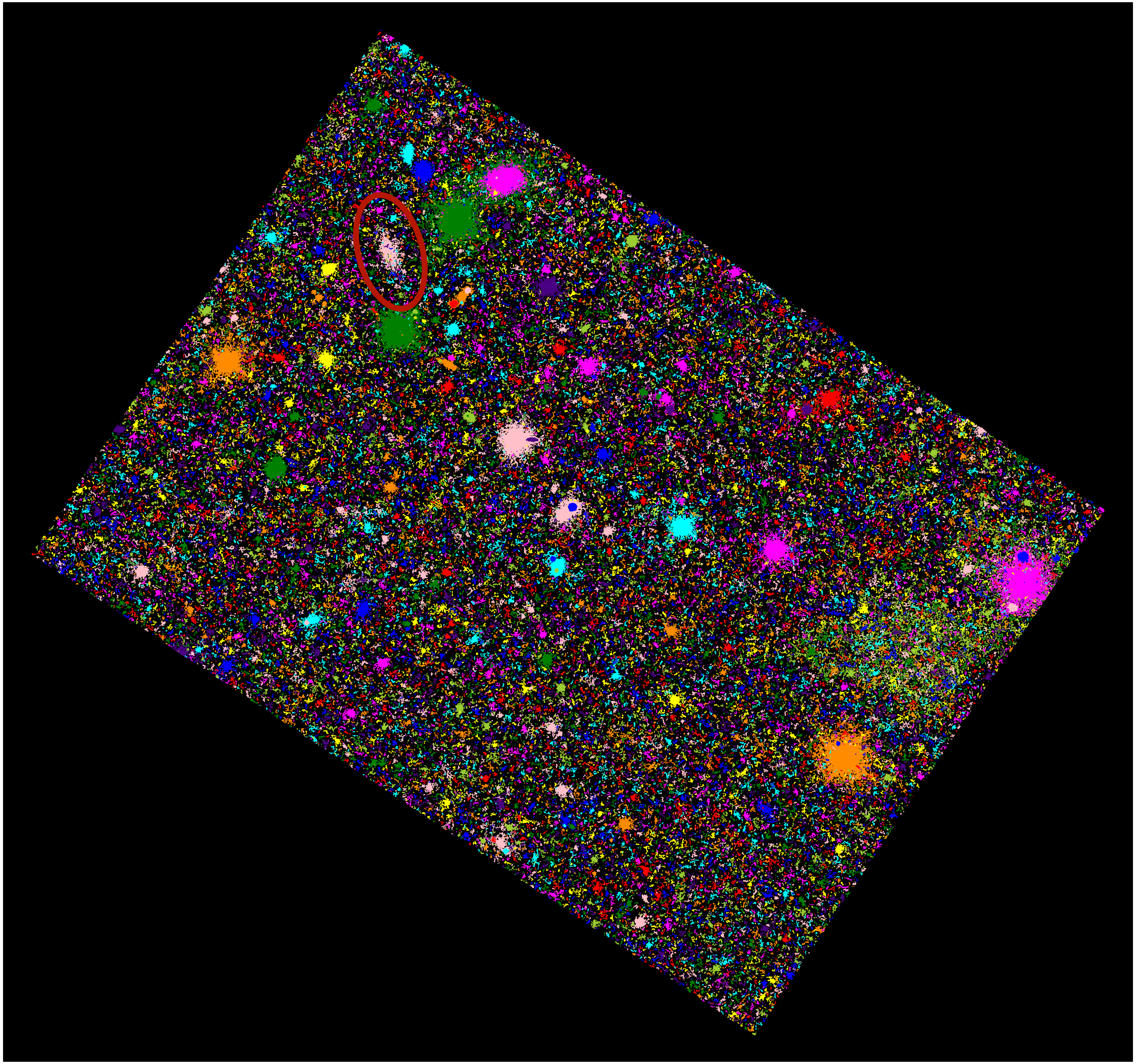



Aku Venhola





Different types of detections

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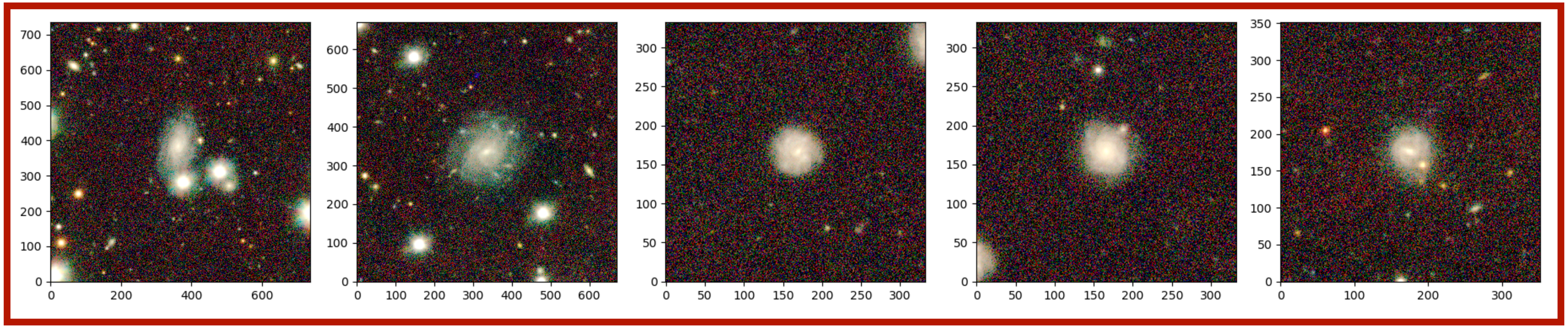

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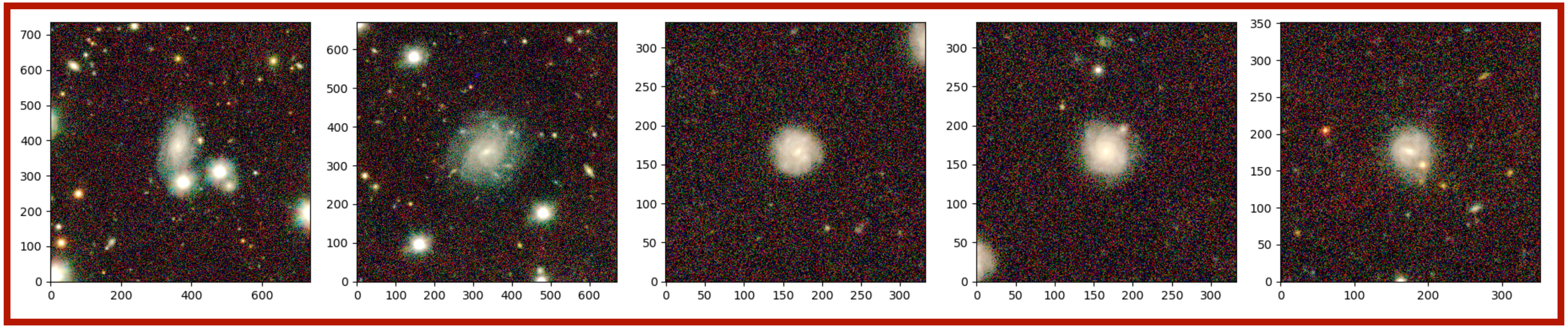

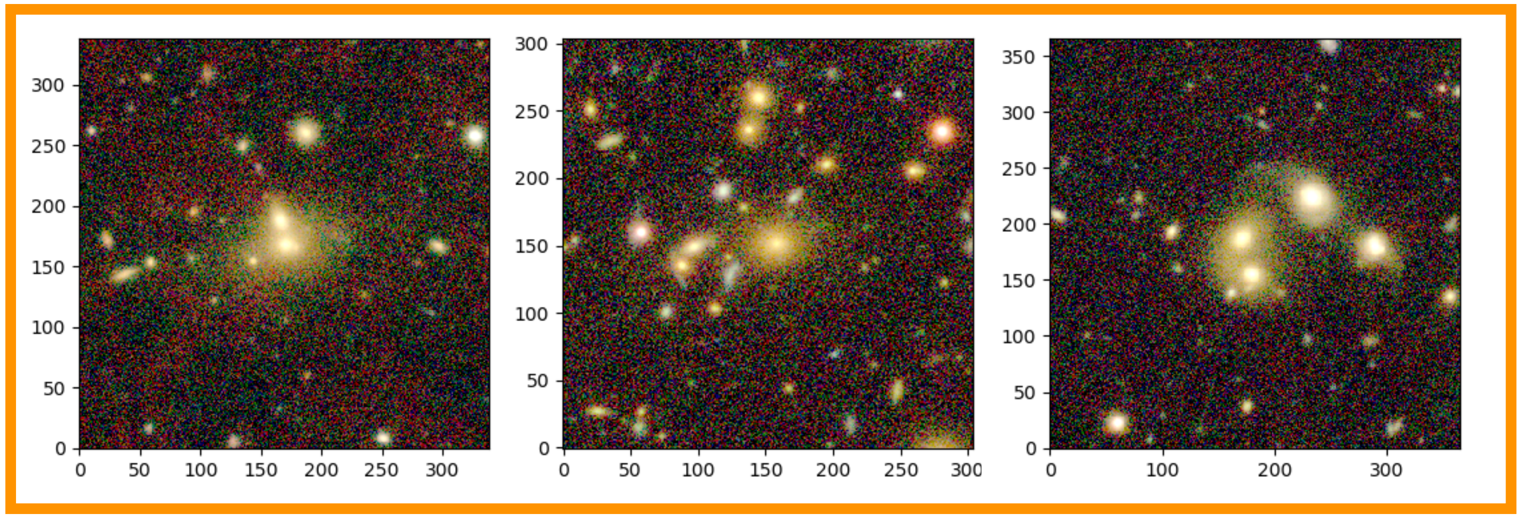

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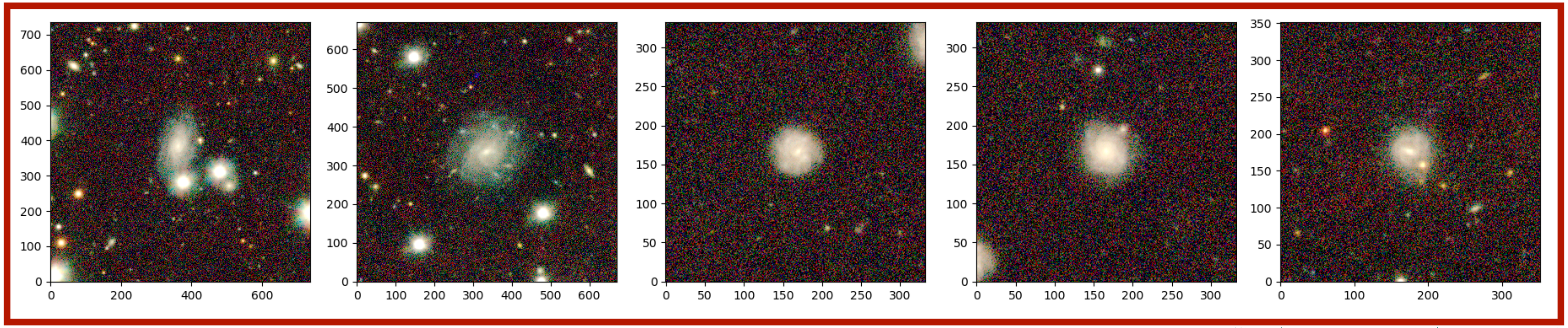

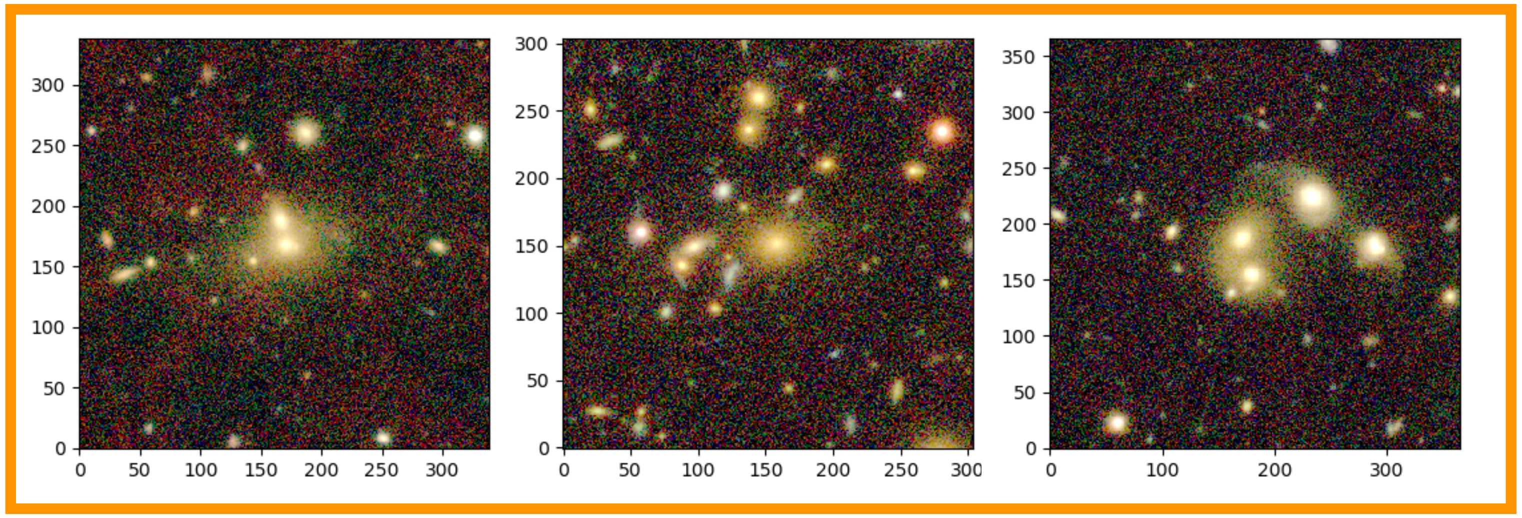

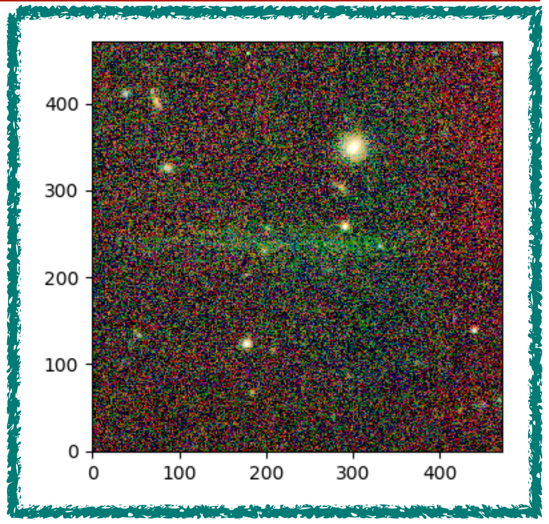

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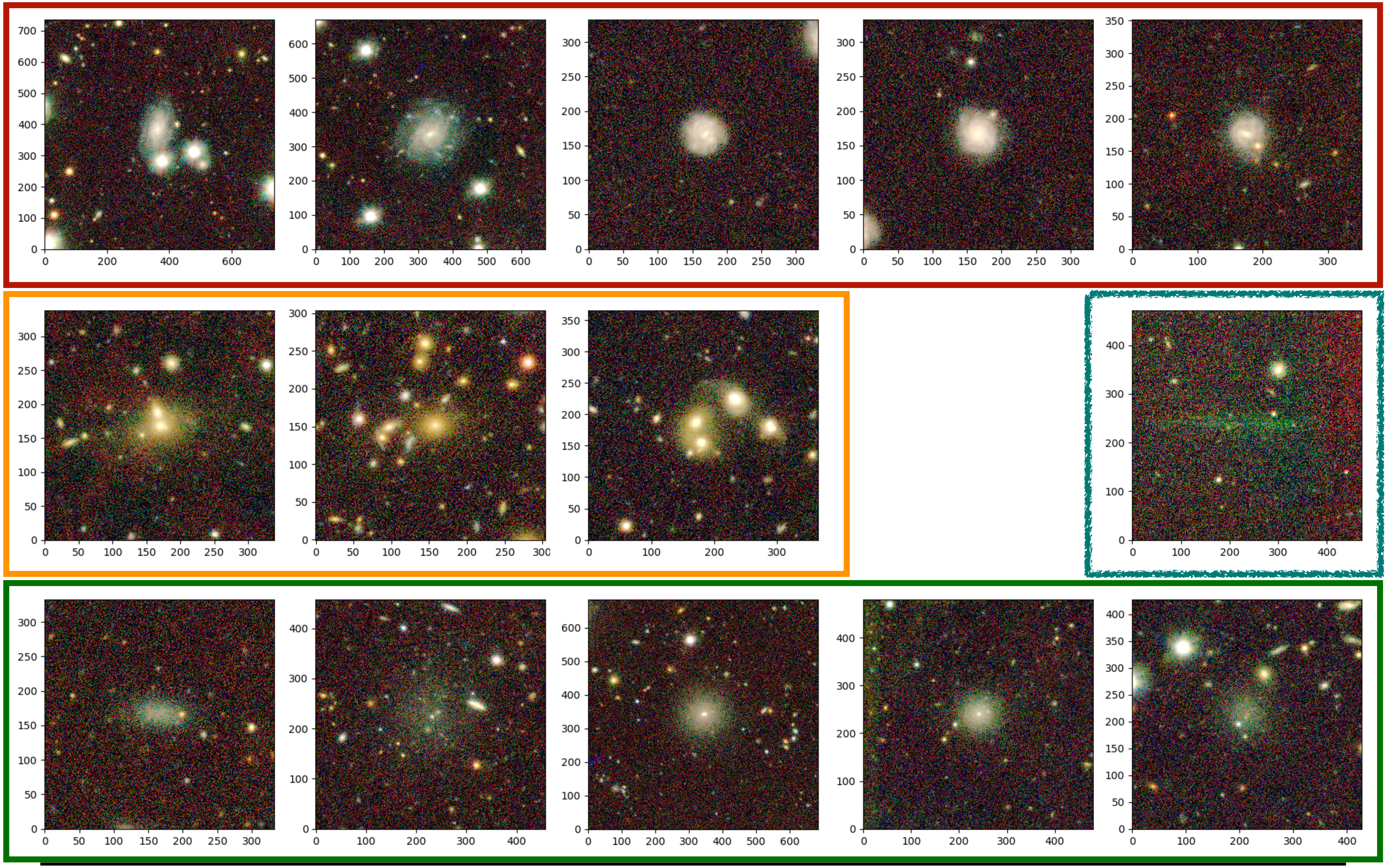

Ultra Diffuse Galaxies (UDGs)

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This study is motivated by the discovery of 47 ultra diffuse galaxies (UDGs) in the Coma cluster by van Dokkum et al. (2015a) using the Dragonfly Telescope Array (Abraham & van Dokkum 2014, hereafter Dragonfly). This unexpected discovery revealed a new populatoin of low surface brightness (SB) galaxies. Indeed, their central SBs are very low 24-26 mag arcsec^{-2} in g-band and their median stellar mass is only $\sim 6 \times 10^7 \mathrm{M}_\odot$, despite their effective radii $r_\mathrm{e} = 1.5$-4.6 kpc being as large as those of L_* galaxies (e.g., ~ 3.6 kpc for the Milky Way (MW), calculated from Rix & Bovy 2013). van Dokkum et al. (2015a) speculated that the UDGs probably have

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Recently, "ultra-diffuse galaxies" (UDGs) with larger sizes ($r_e = 1.5 - 4.5$ kpc) and lower central surface brightnesses ($\mu_{0g} > 24.0$ mag/arcsec^2) than dE/dS0s were discovered (van Dokkum et al. 2015a) in the Coma cluster. Soon after, Koda et al. (2015) and Yagi et al. (2016) identified a large population of Coma UDGs in

Ultra Diffuse Galaxies (UDGs)

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STUDIES OF THE VIRGO CLUSTER. III. A CLASSIFICATION SYSTEM AND AN ILLUSTRATED ATLAS OF VIRGO CLUSTER DWARF GALAXIES

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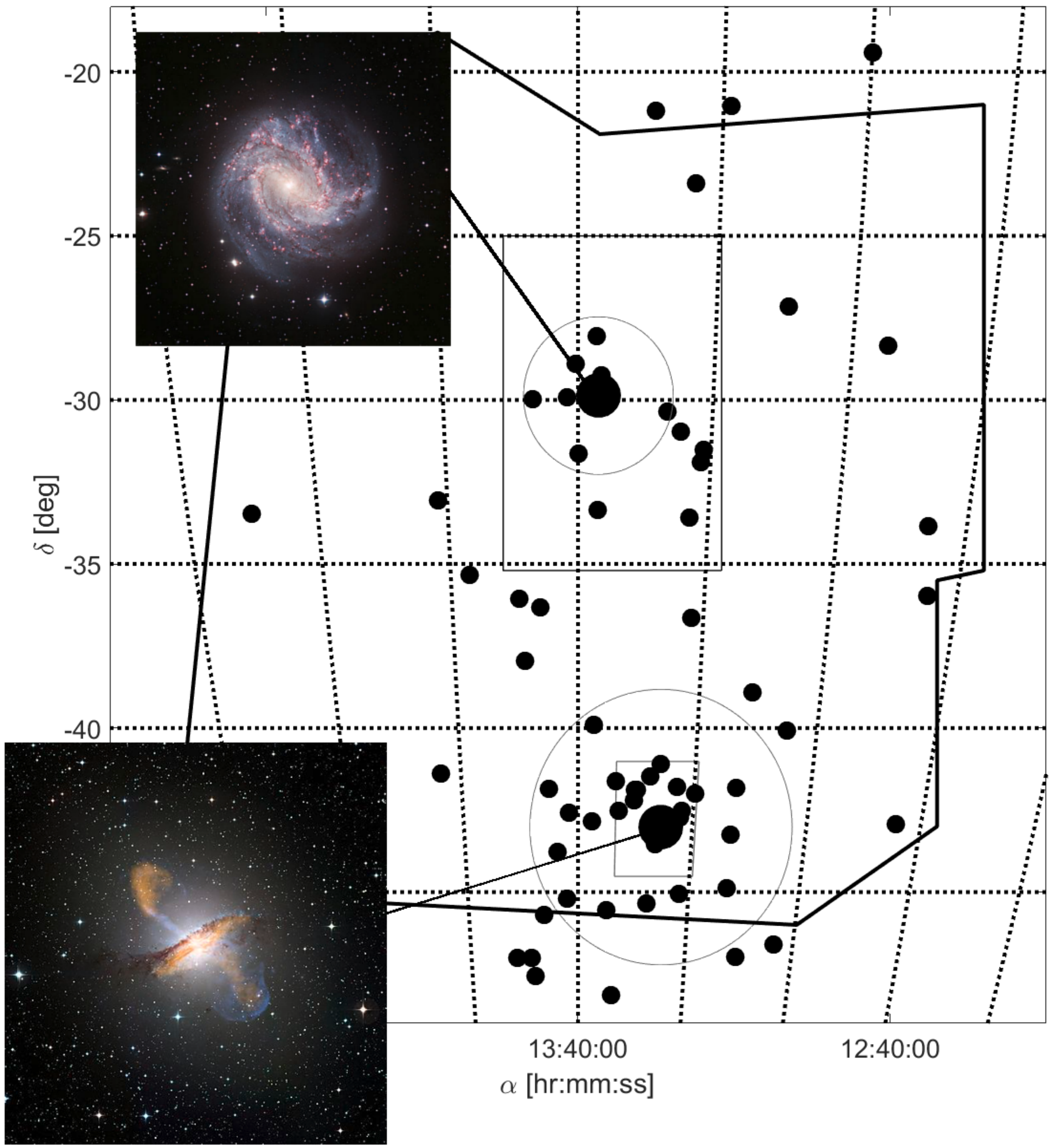
Received 3 February 1984; revised 9 April 1984

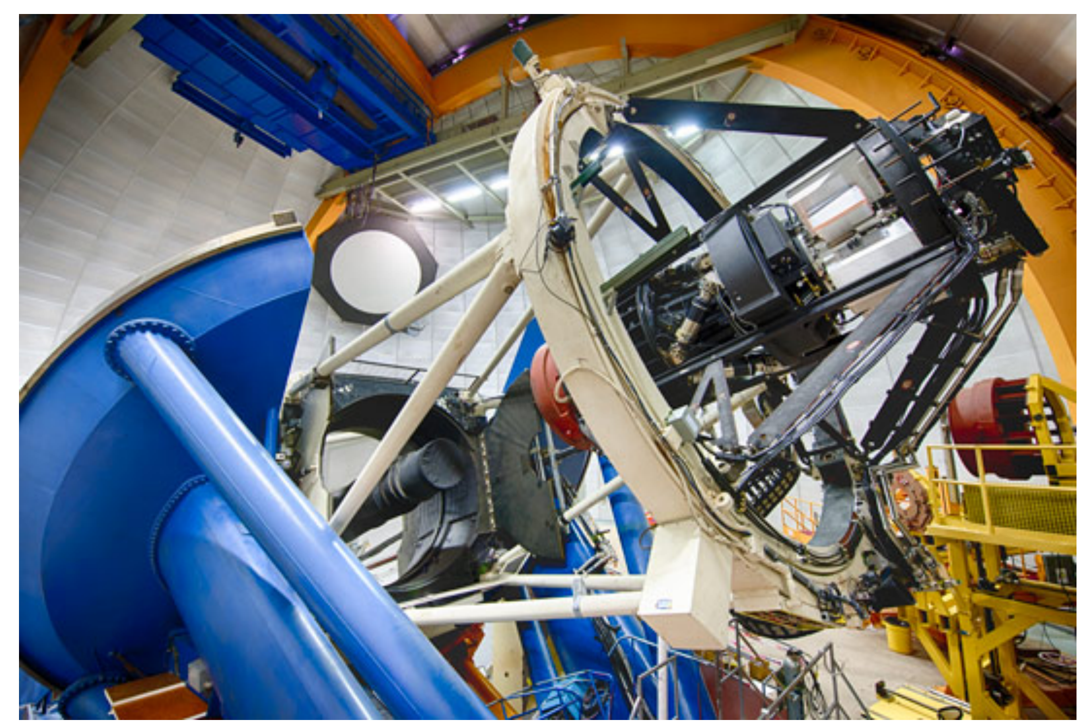
ABSTRACT

Photographs enlarged to a common scale are given for 138 dwarf galaxies in the region of the Virgo cluster. Most are cluster members, as judged either from their uniquely low surface brightness and/or morphology, or occasionally from velocity data. All known Hubble galaxy types have been found in the Virgo cluster, ranging in absolute magnitude from the brightest known giant ellipticals and spirals to all the types of dwarfs that were expected from prior knowledge of the dE, Sm, Im, and blue compact dwarfs (BCD) in the Local Group and its environs. A new type of very large diameter (10 000 pc), low central surface brightness ($\gtrsim 25$ B mag/arcsec) galaxy, that comes in both early (i.e., dE) and late (i.e., Im V) types, has been isolated, but there are, as yet, no known examples in the local neighborhood. The Atlas is organized in a way that recognizes the continuum between the giant and the dwarf ellipticals on the one hand, and the linear progression which, in order, connects the high luminosity Sc and Sd

Survey Cen A Group (DECam)

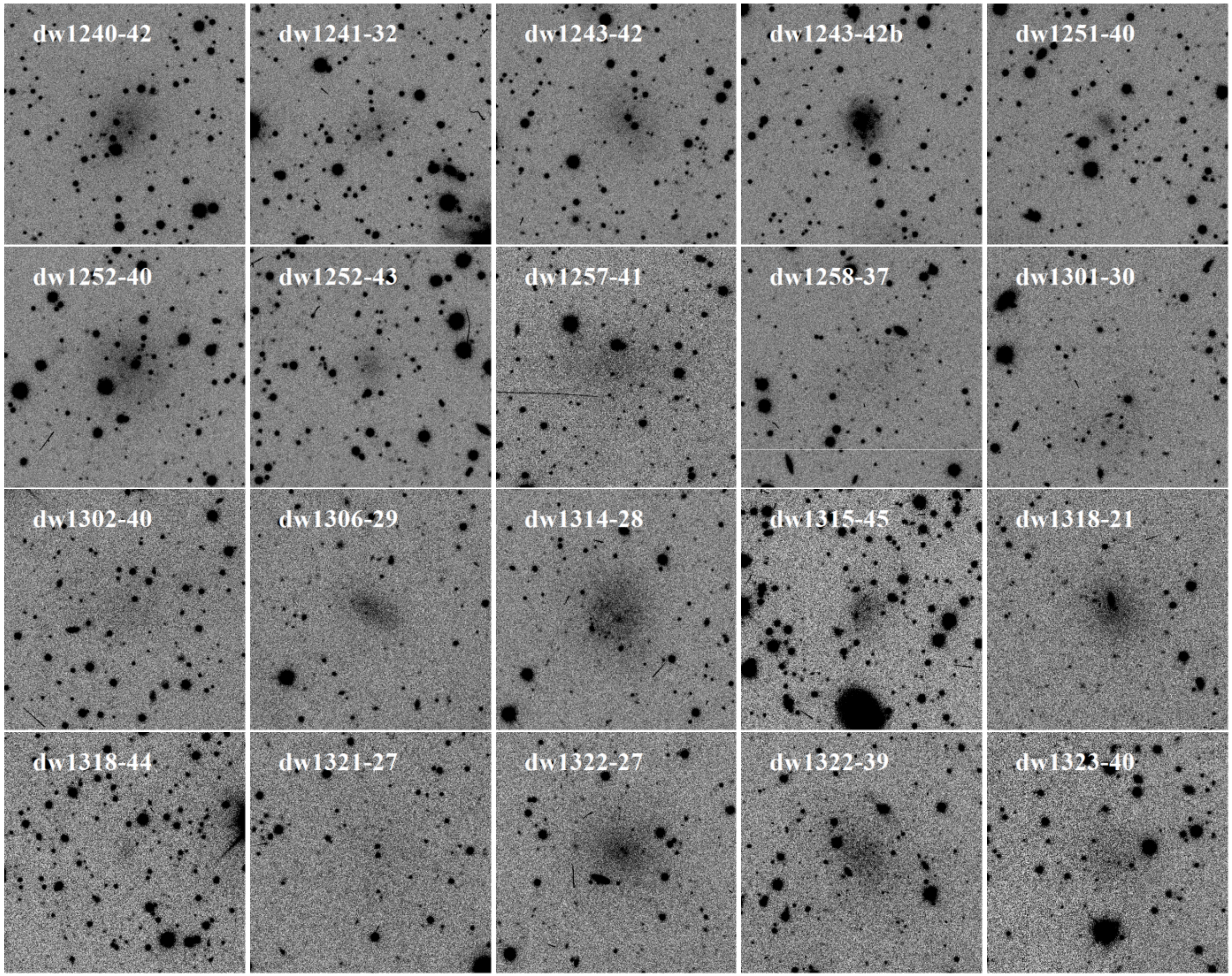


- Survey Cen A group
- Subgroups: Cen A (4 Mpc) M 83 (5 Mpc)
- 50 known group members
- 500 sq. deg field in *g* and *r*



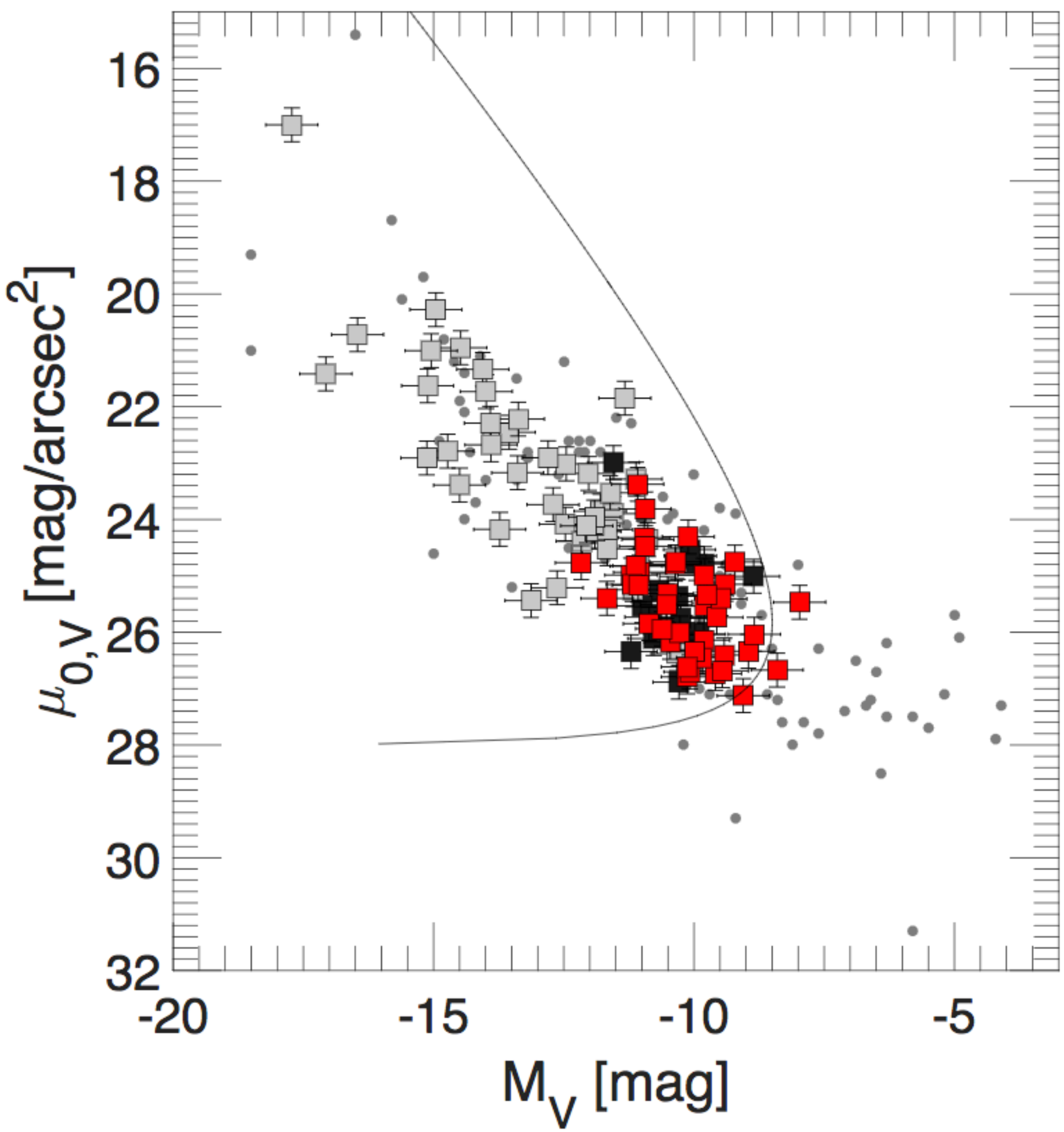
Gray rectangle: PiSCES footprint (Crnojevic et al. 2015, Sand et al. 2014)

Mugshots



Müller et al. (2017a)

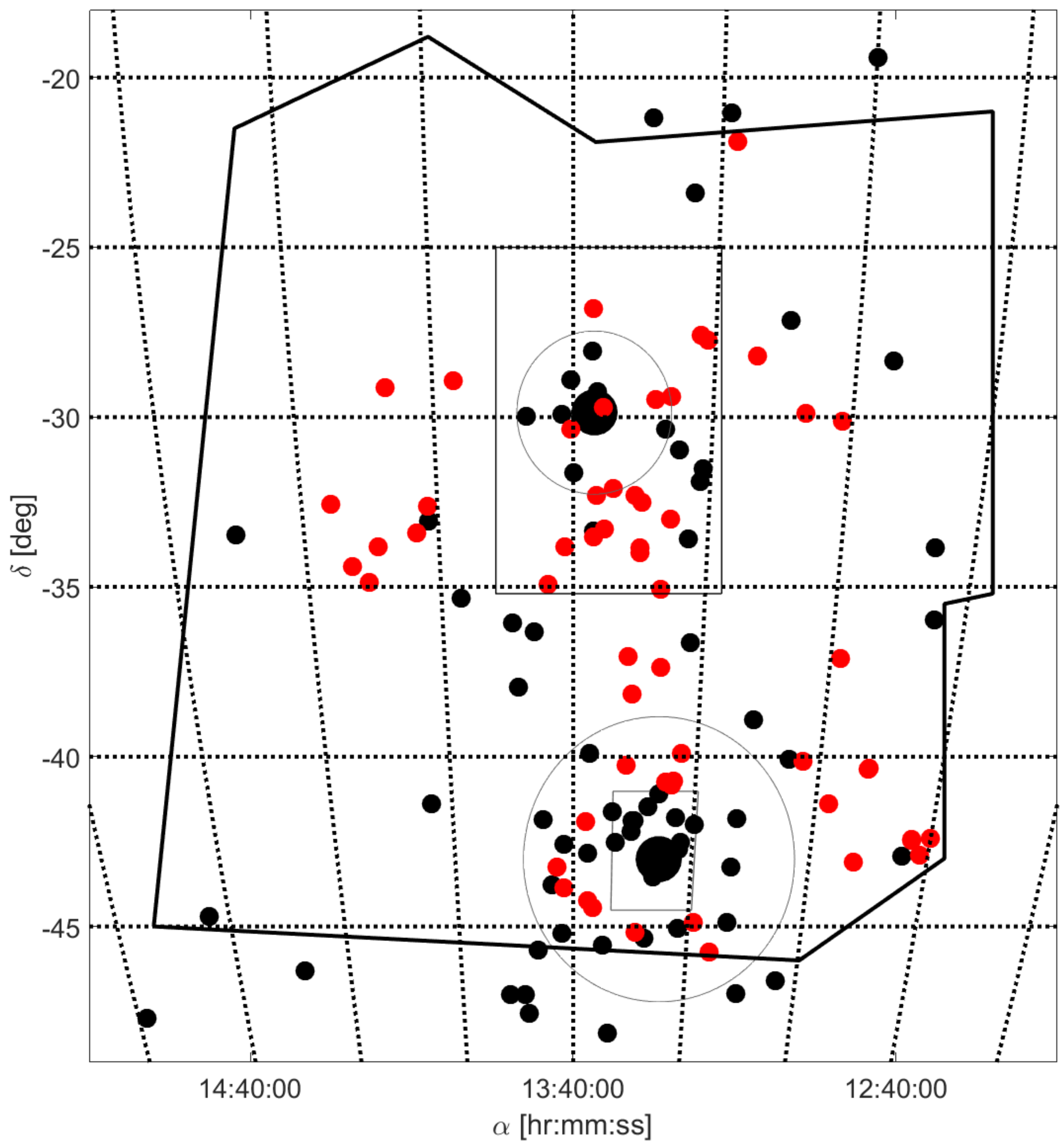
Photometric relations



- gray dots: LG dwarfs
- gray squares: known Cen A dwarfs
- red/black squares: new Cen A dwarfs

Müller et al. (2017a)

Survey Cen A Group (DECam)



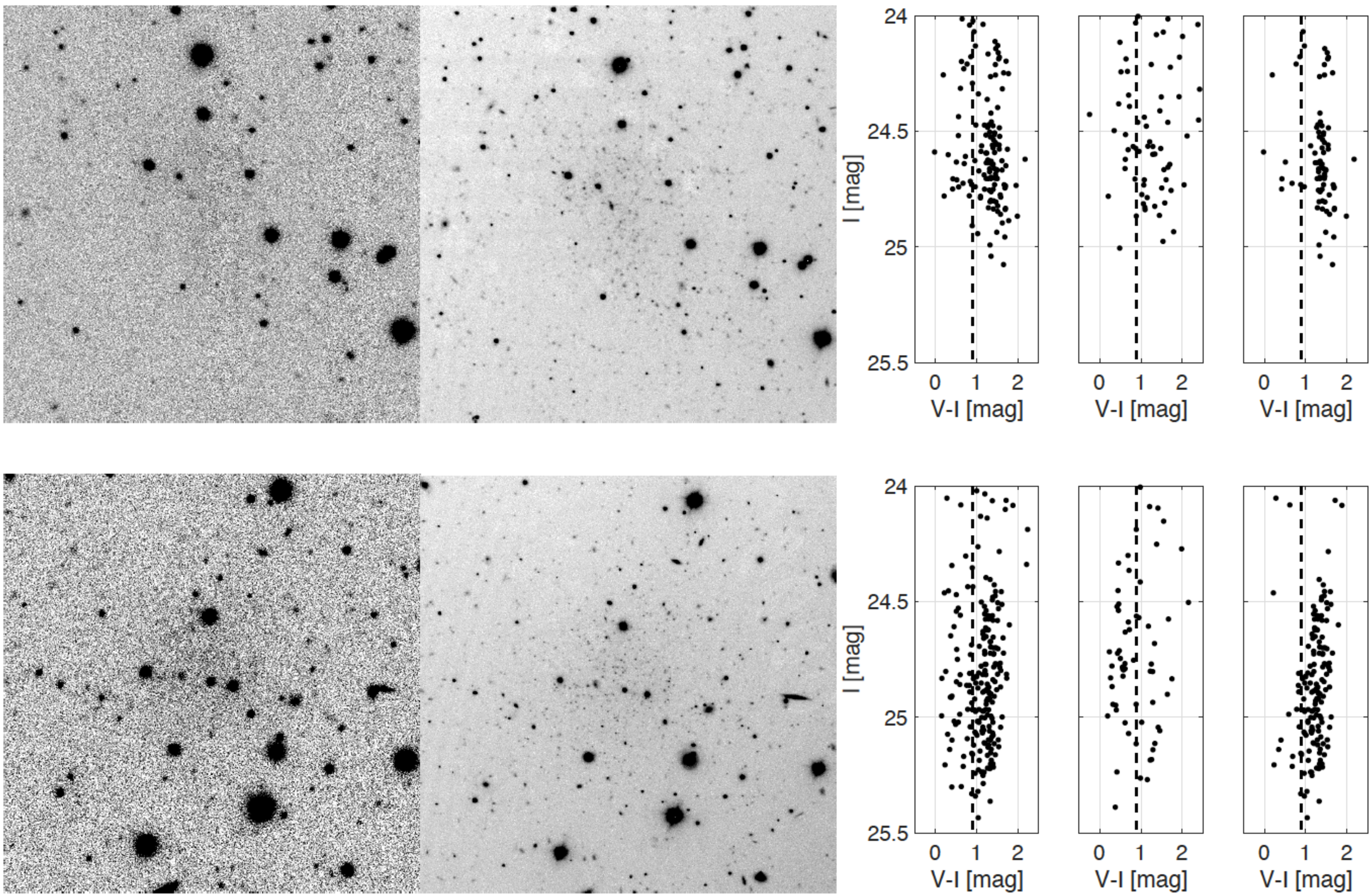
Müller et al. (2017a)

VLT follow-ups

- 2 hrs observations in VI bands with FORS2
- Excellent seeing required (< 0.6 arcsec)

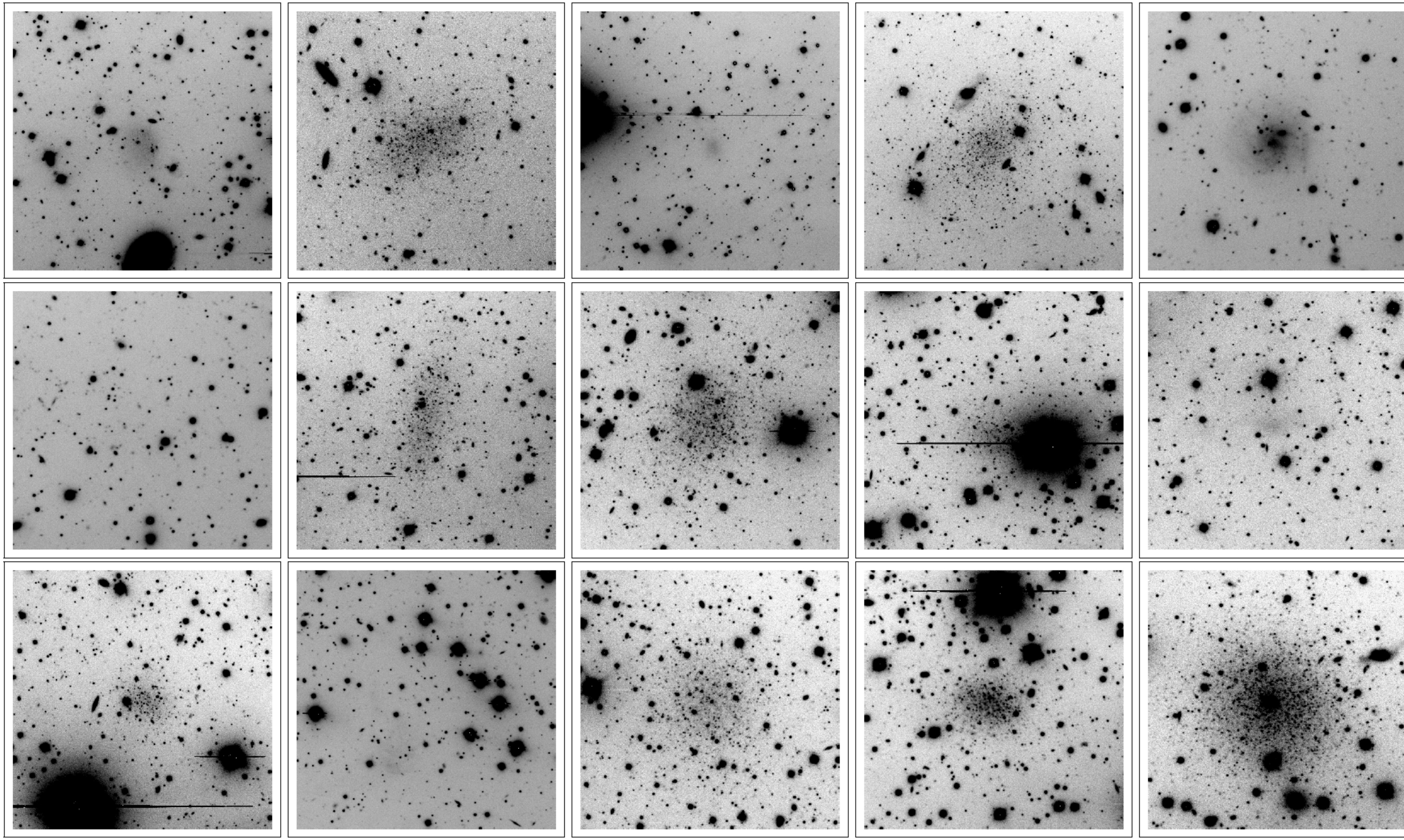
Credit: ESO

VLT follow-ups



Müller et al. (2018b)

VLT follow-ups



Müller et al. (2019)

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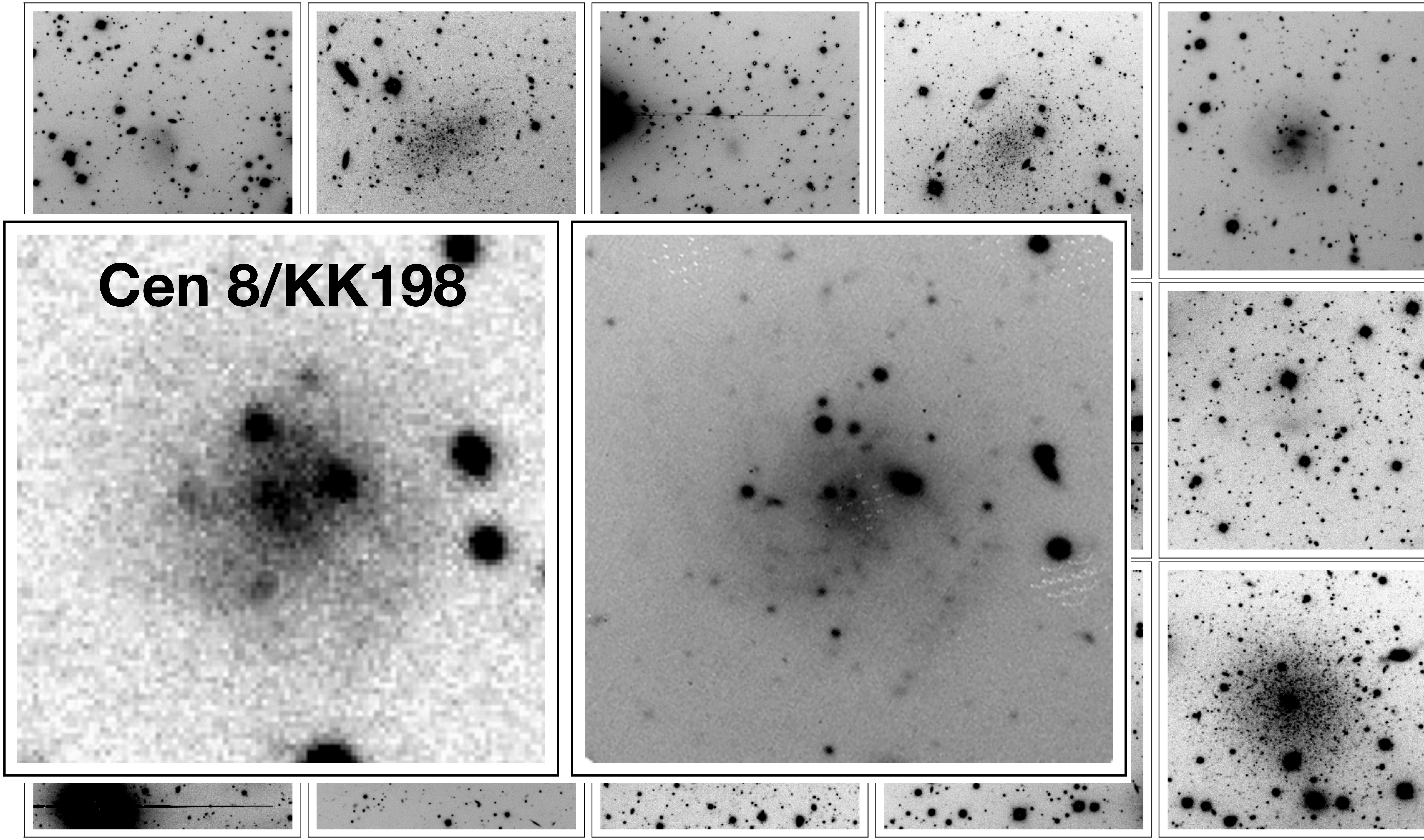

Müller et al. (2019)

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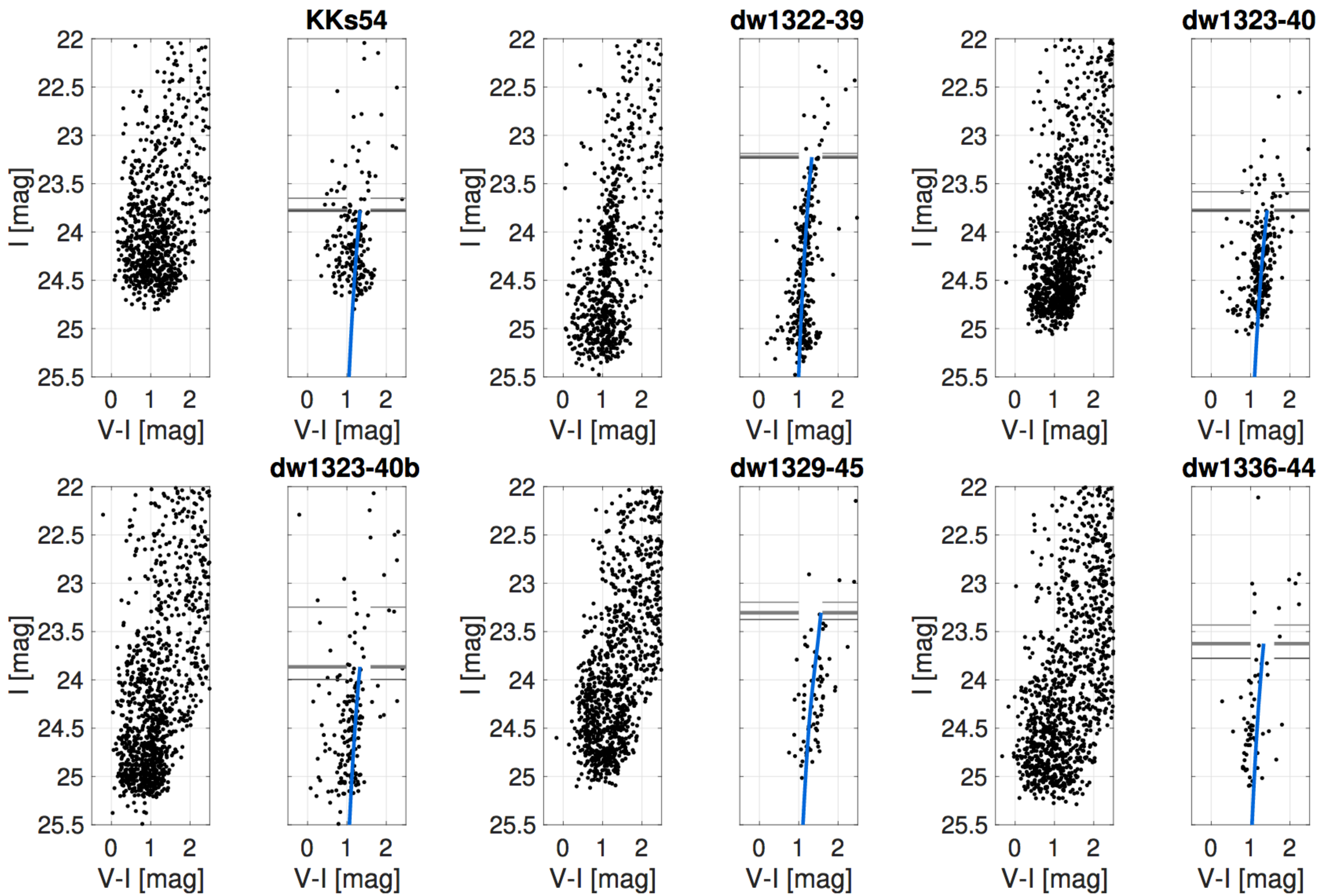

Müller et al. (2019c)

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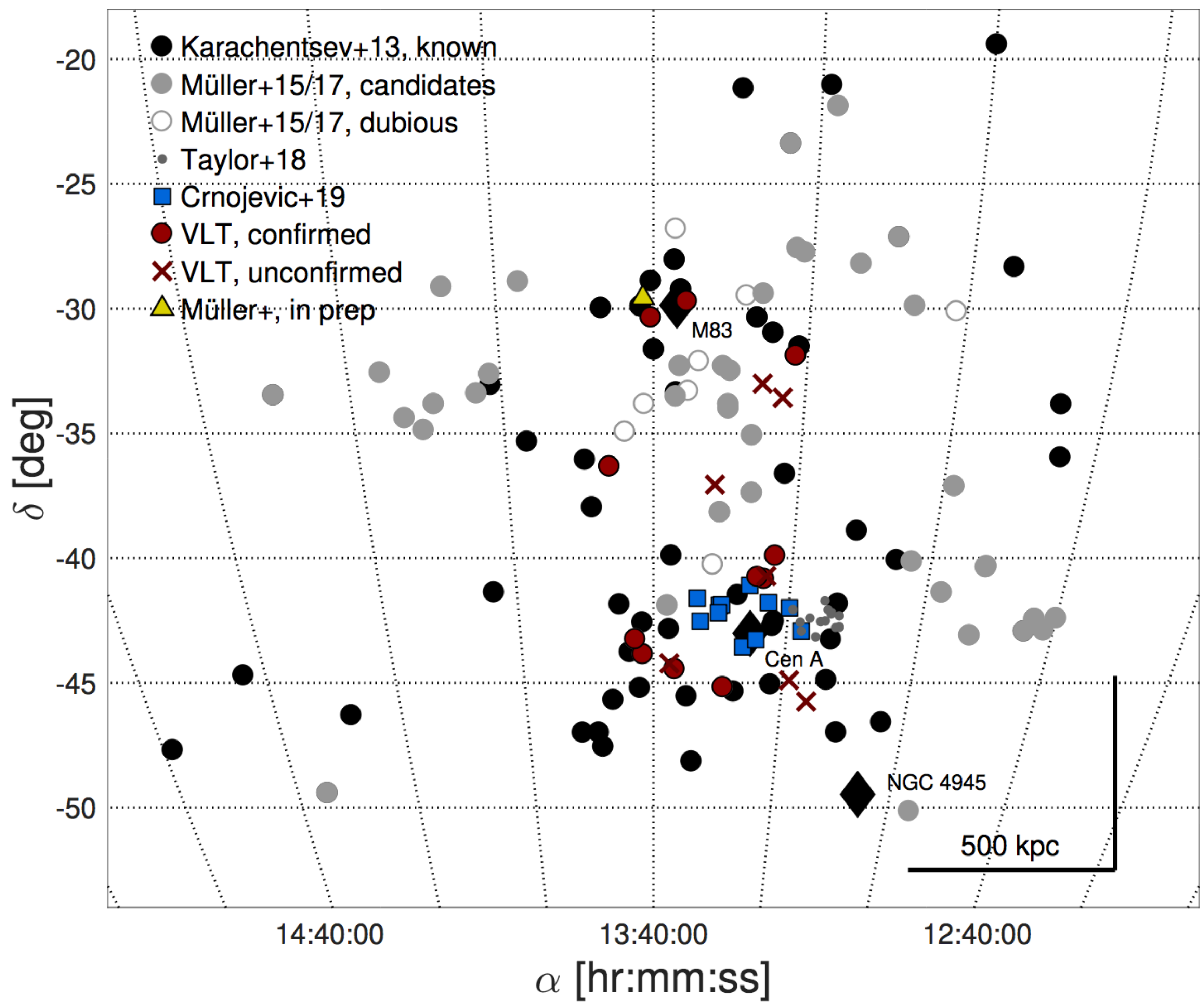
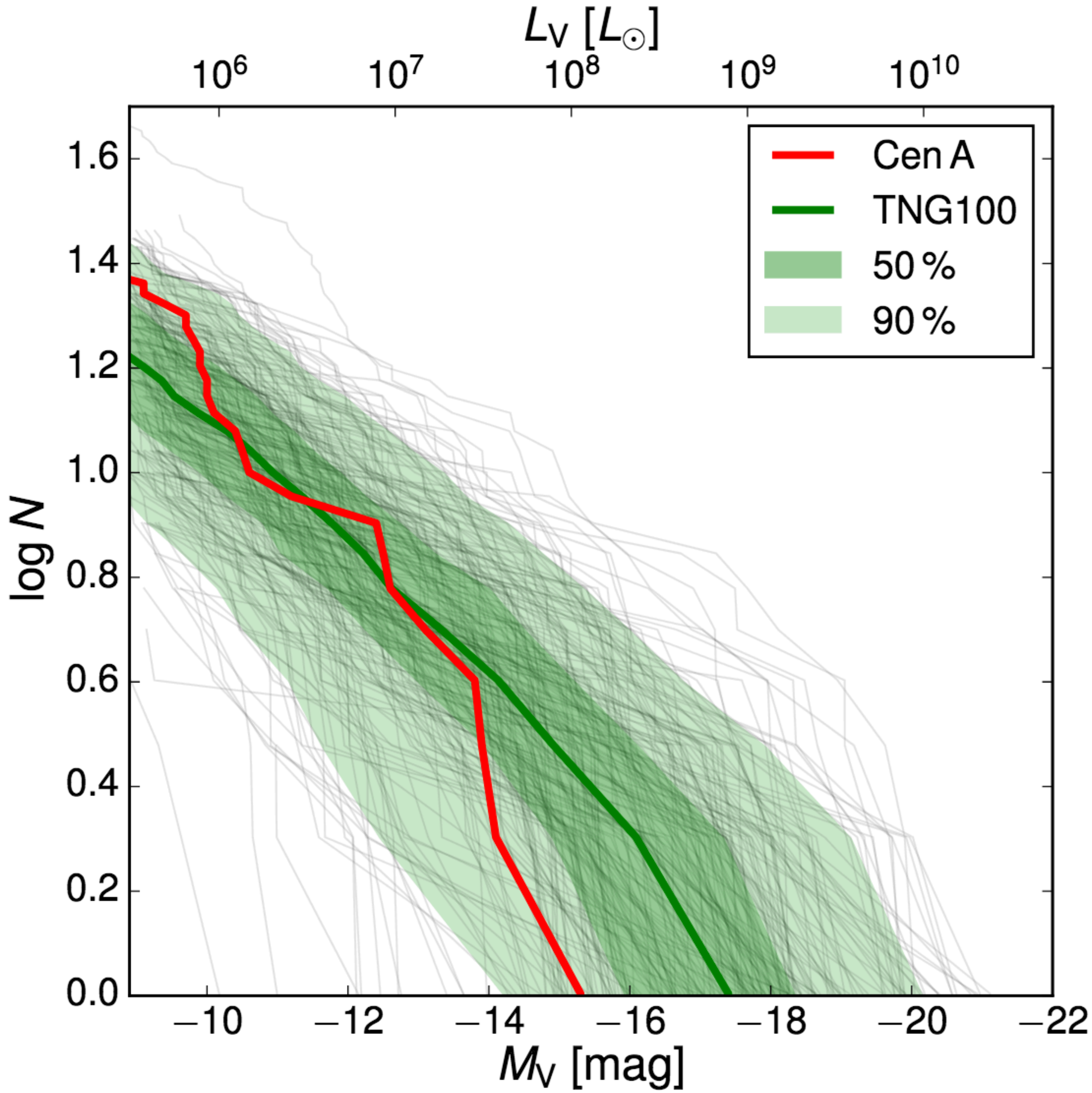


Müller et al. (2019c)

Luminosity function of Cen A in CDM



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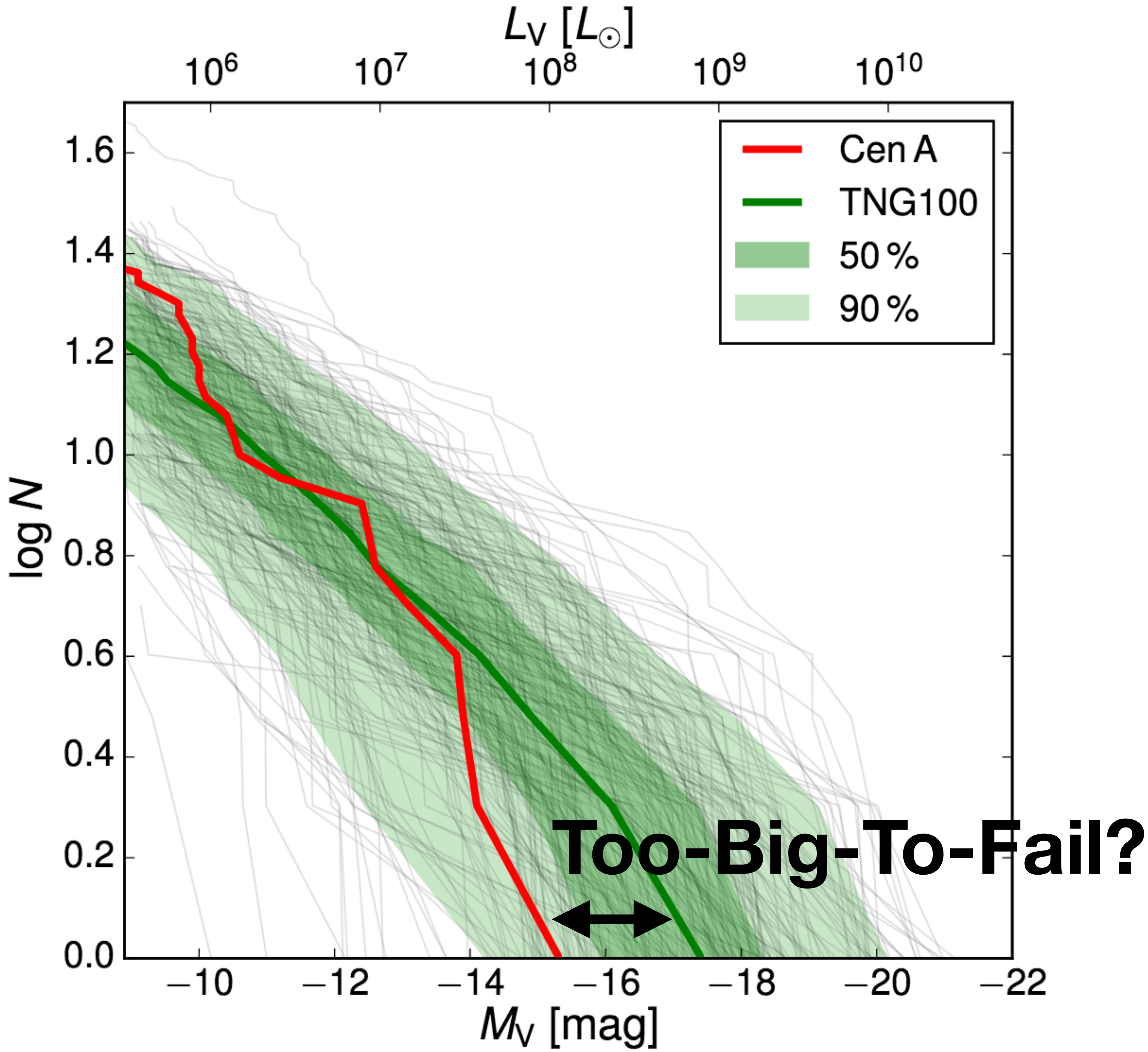

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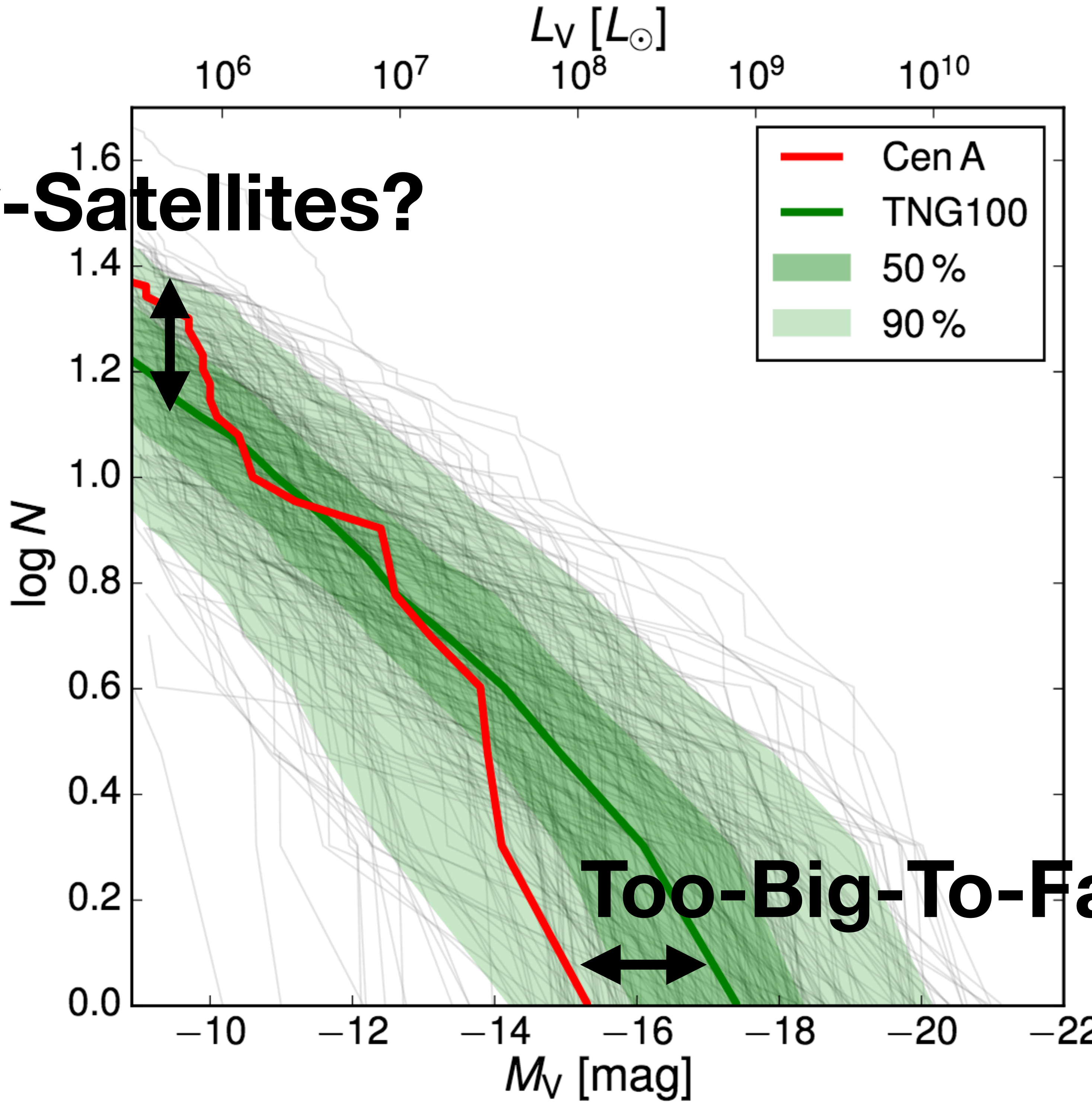
Luminosity function of Cen A in CDM

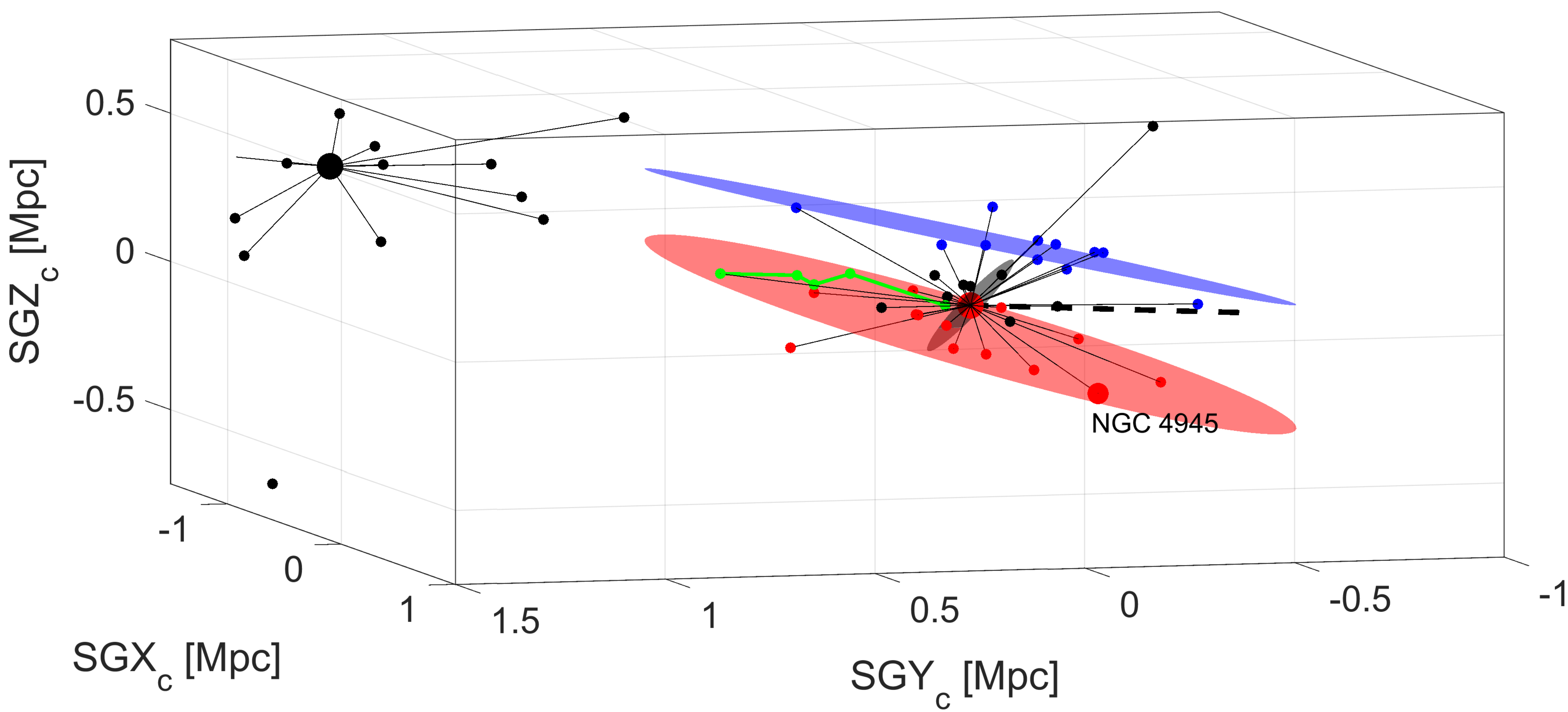
Too-Many-Satellites?



Too-Big-To-Fail?

Müller et al. (2019)

Two planes of satellites (Tully et al. 2015)



Müller et al. (2016)

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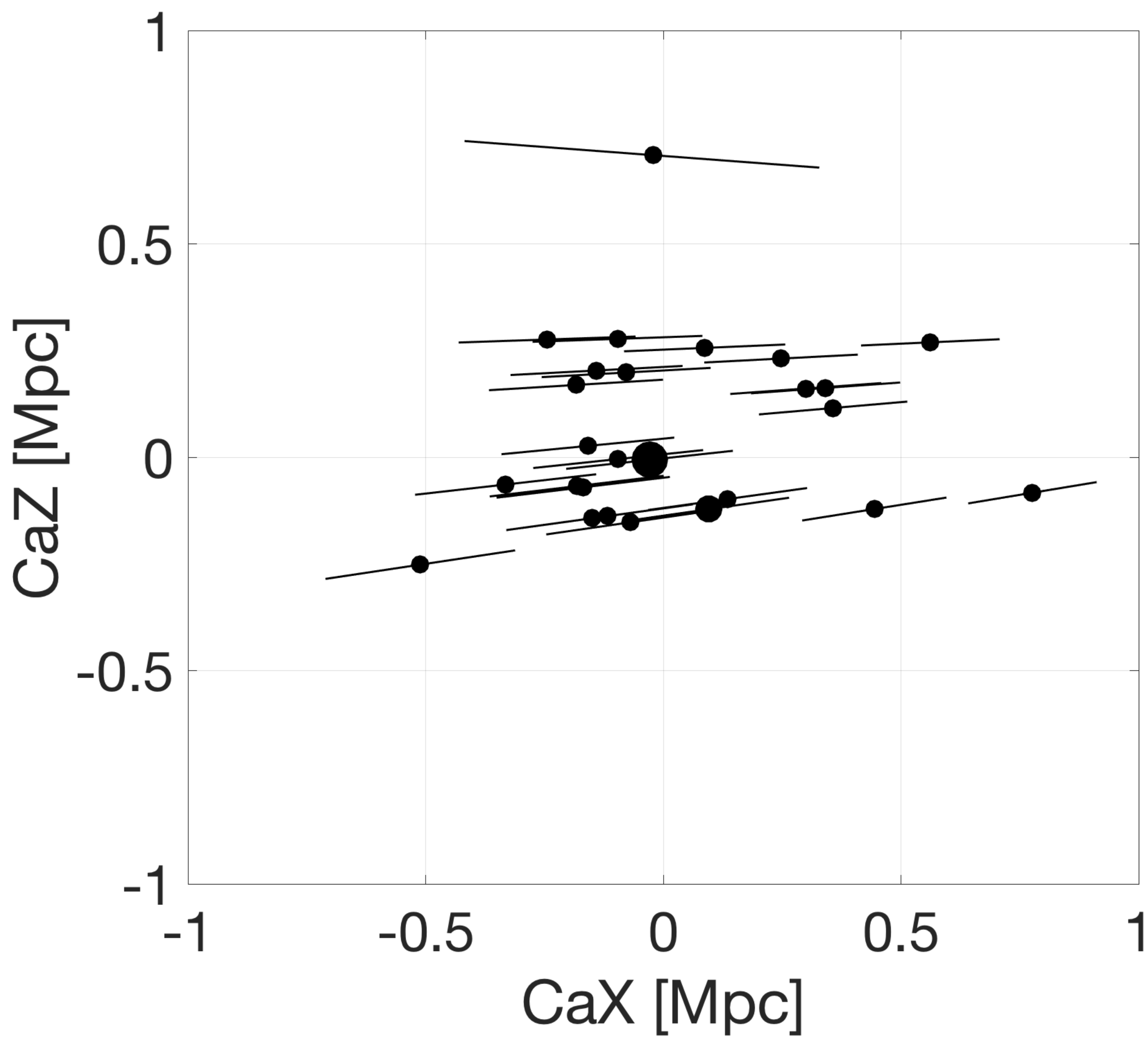

Müller et al (2016), Crnojevic et al. (2019), Müller et al. (2019c)

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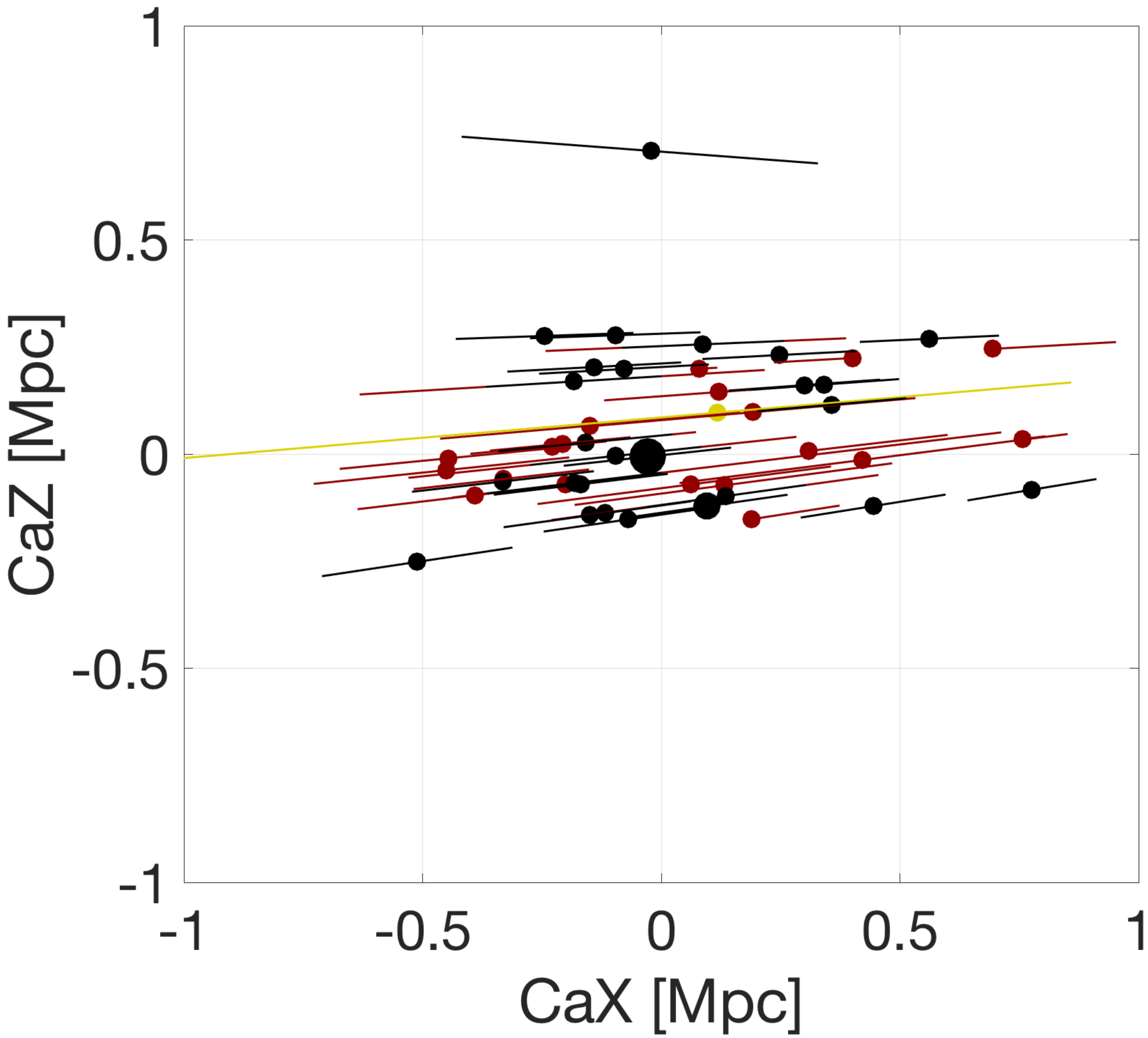

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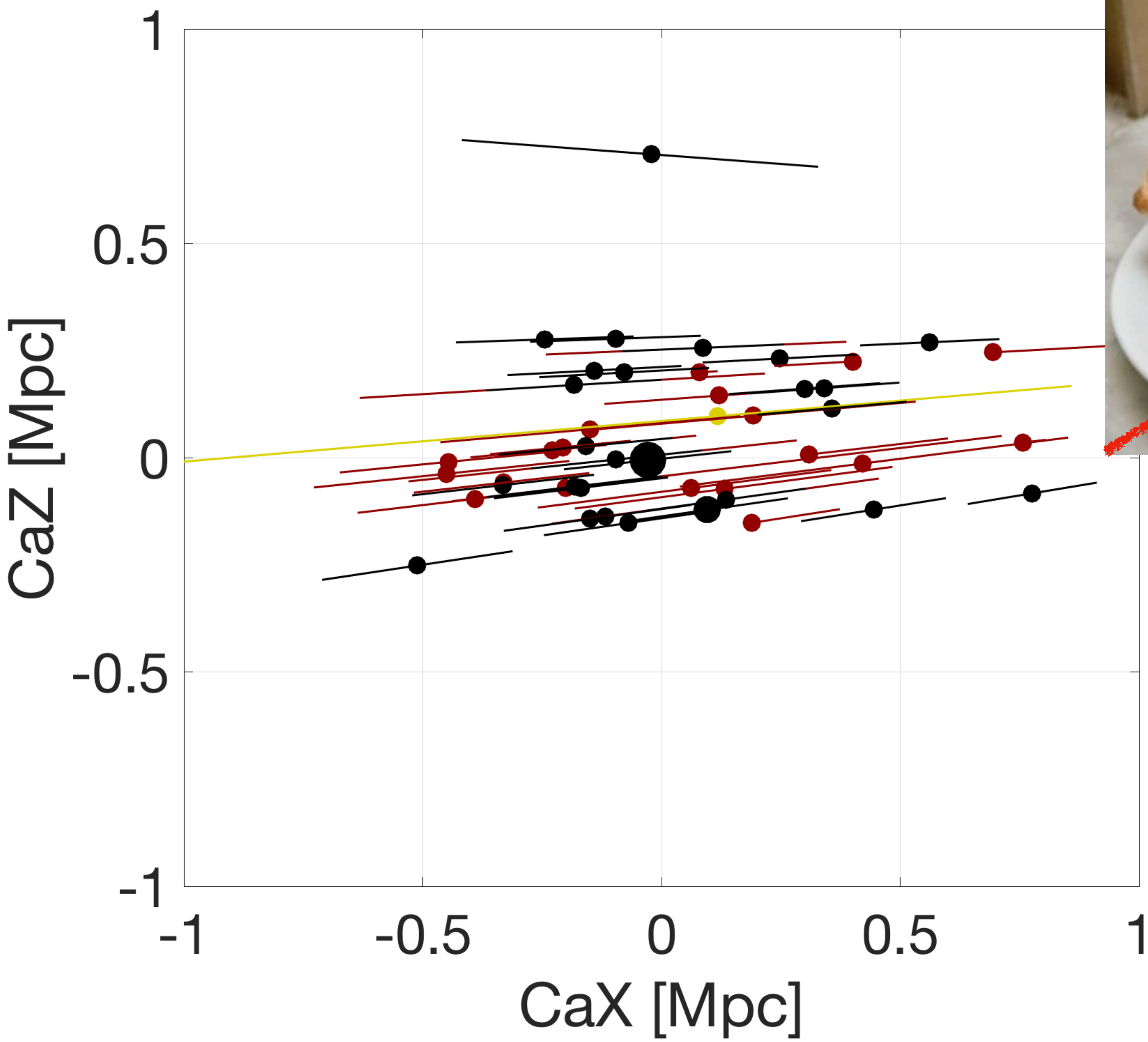
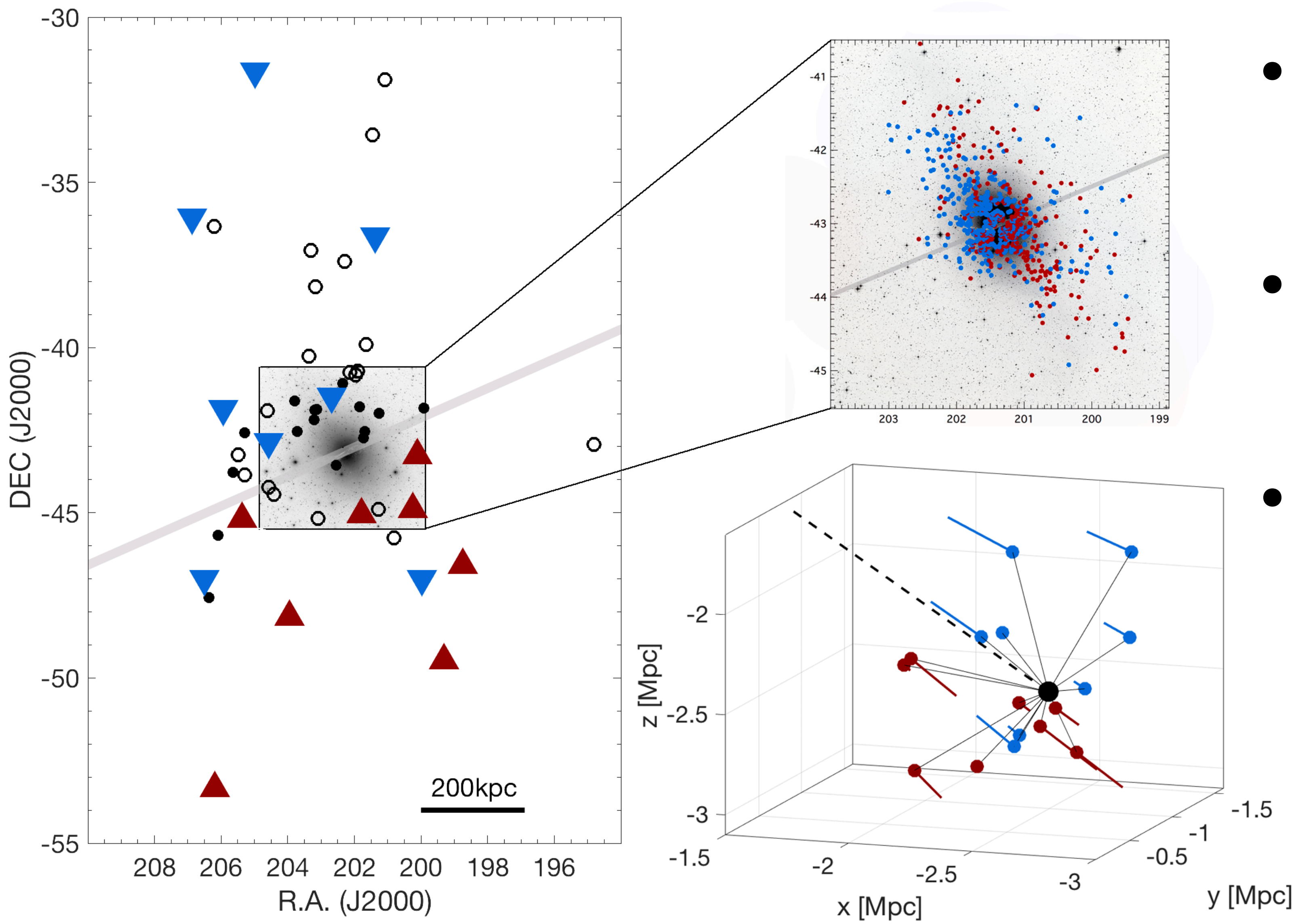


Müller et al (2016), Crnojevic et al. (2019), Müller et al. (2019c)

Group is edge-on!

Coherent motion



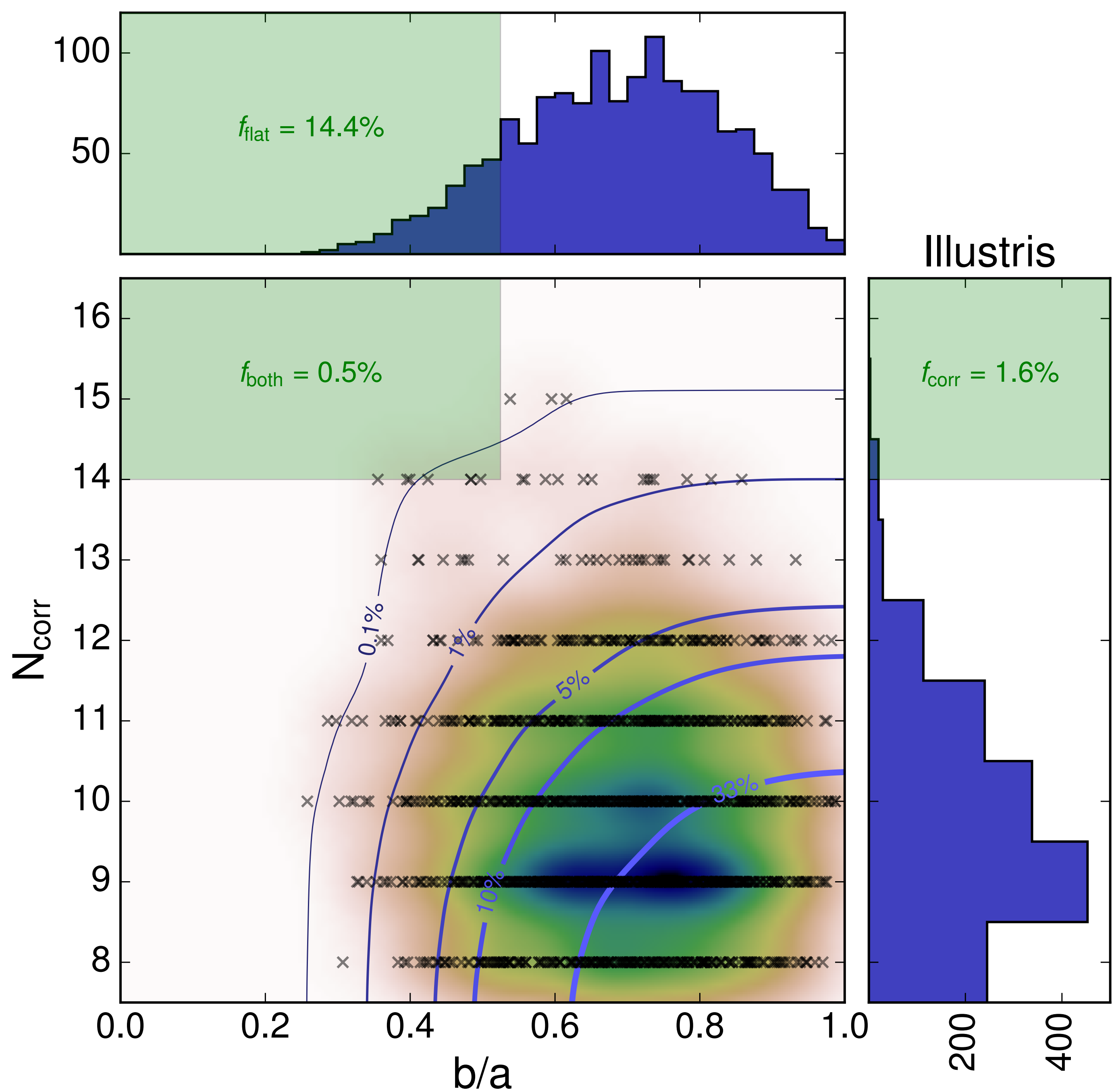
- 16 out of 30 satellites have velocity measurements
- 14 out of 16 share coherent movement
- Oddity: same signal for PNe

Müller et al. (2018a)

For the Local Group

<1% in CDM

Comparison to IllustrisTNG



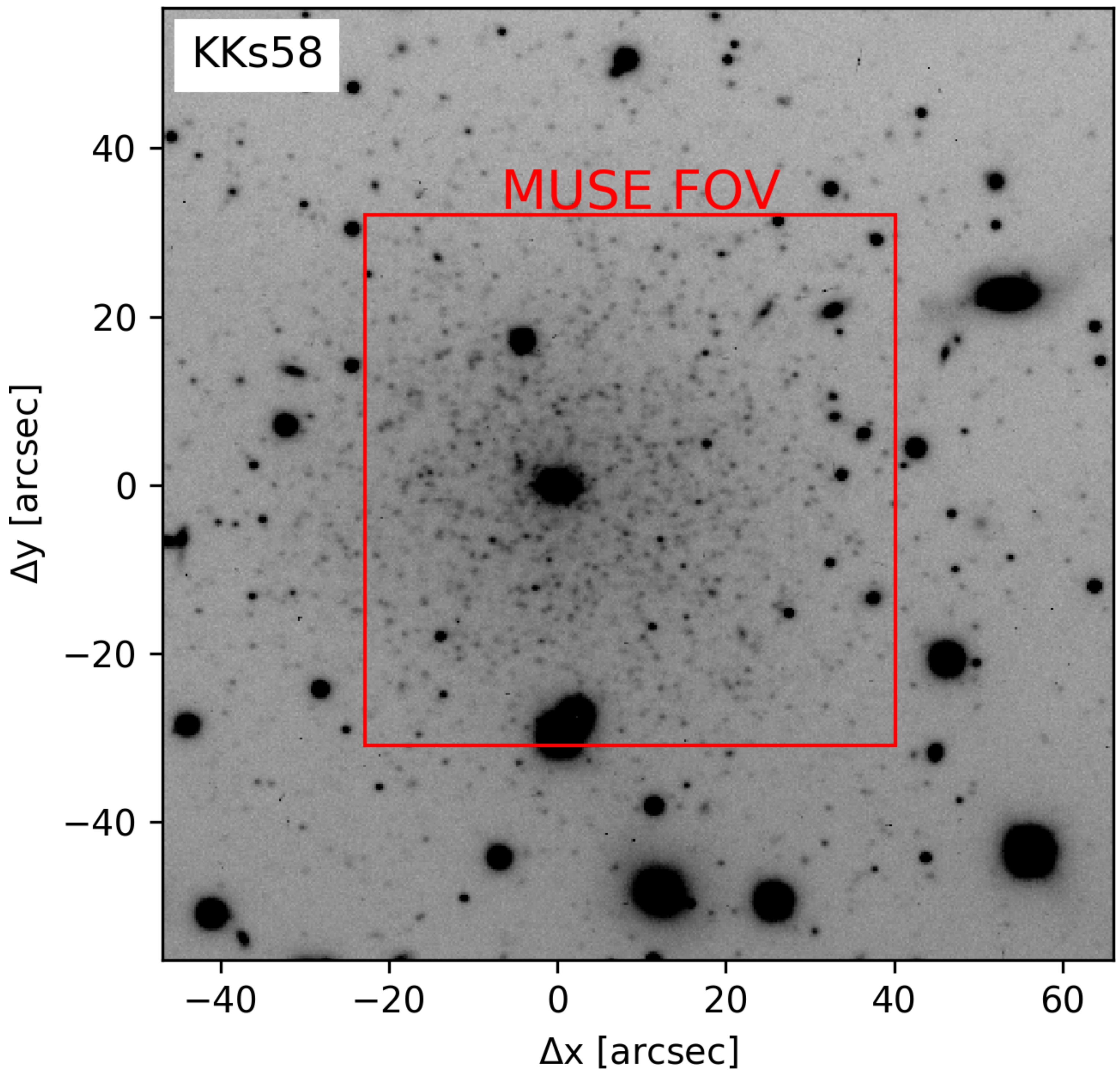
Müller et al. (2018a)

VLT follow-ups

- 2 hrs observations in VI bands with MUSE
- Bad seeing okay (> 1.0 arcsec)

Credit: ESO

VLT follow-ups



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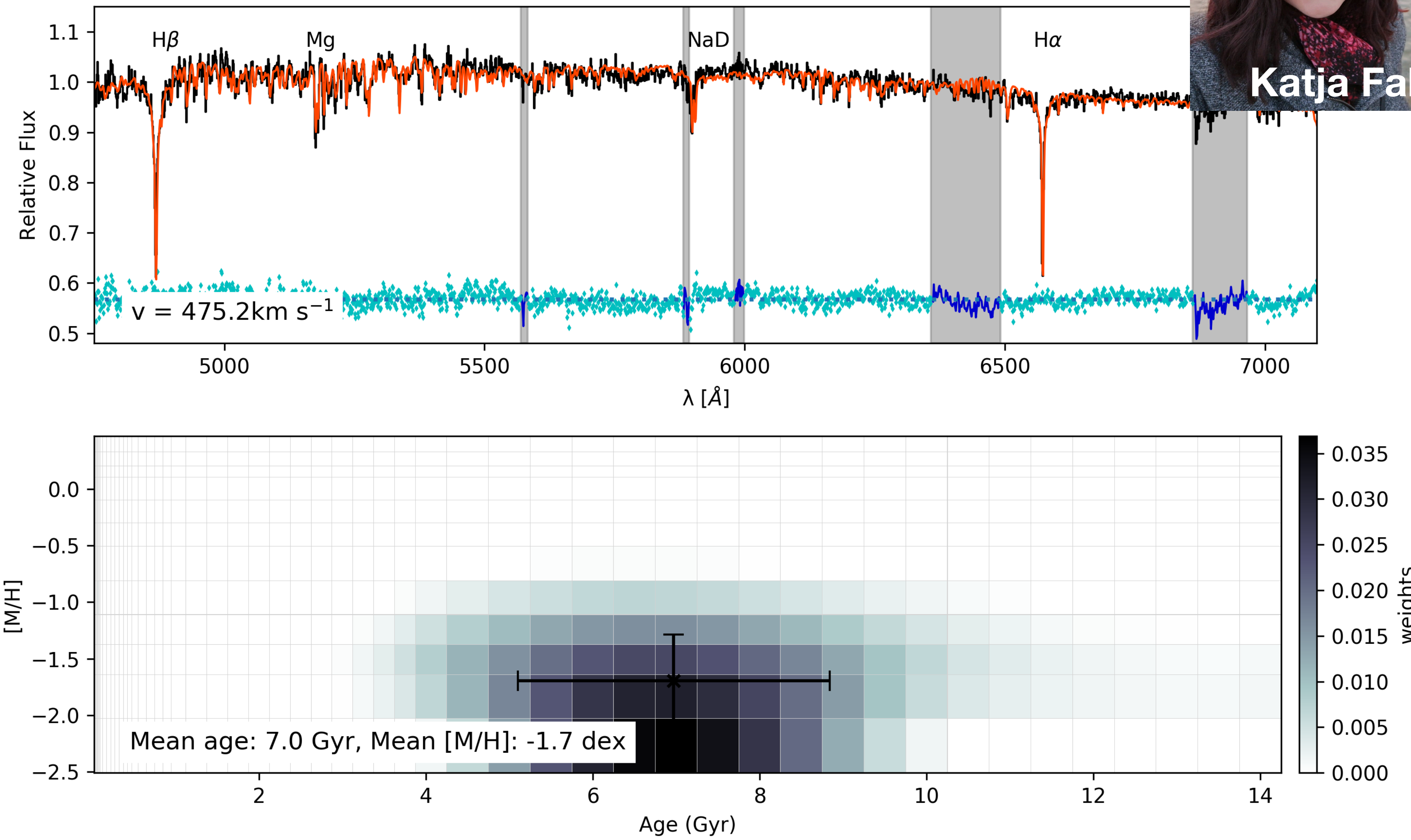

Fahrion et al. (in prep.)

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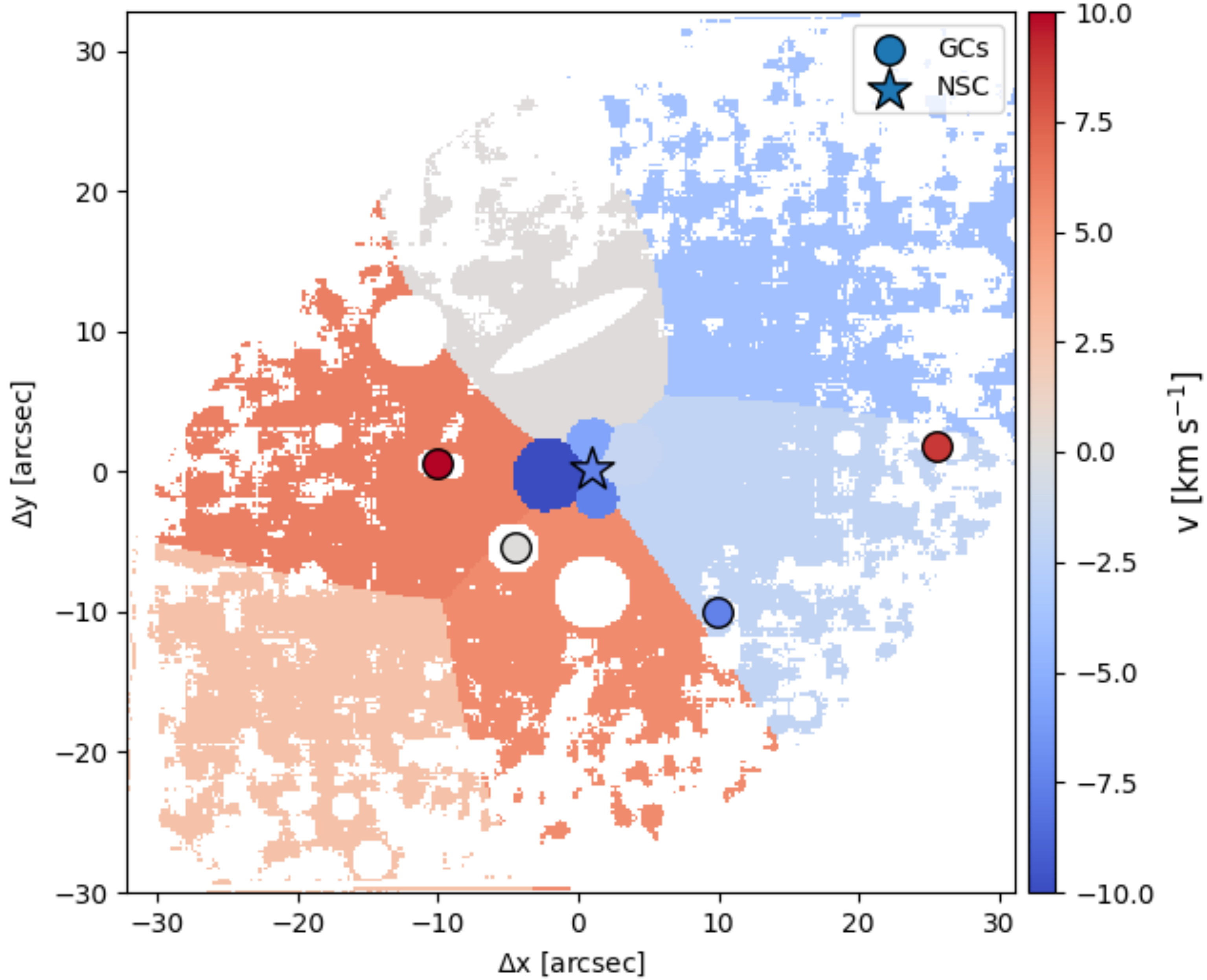

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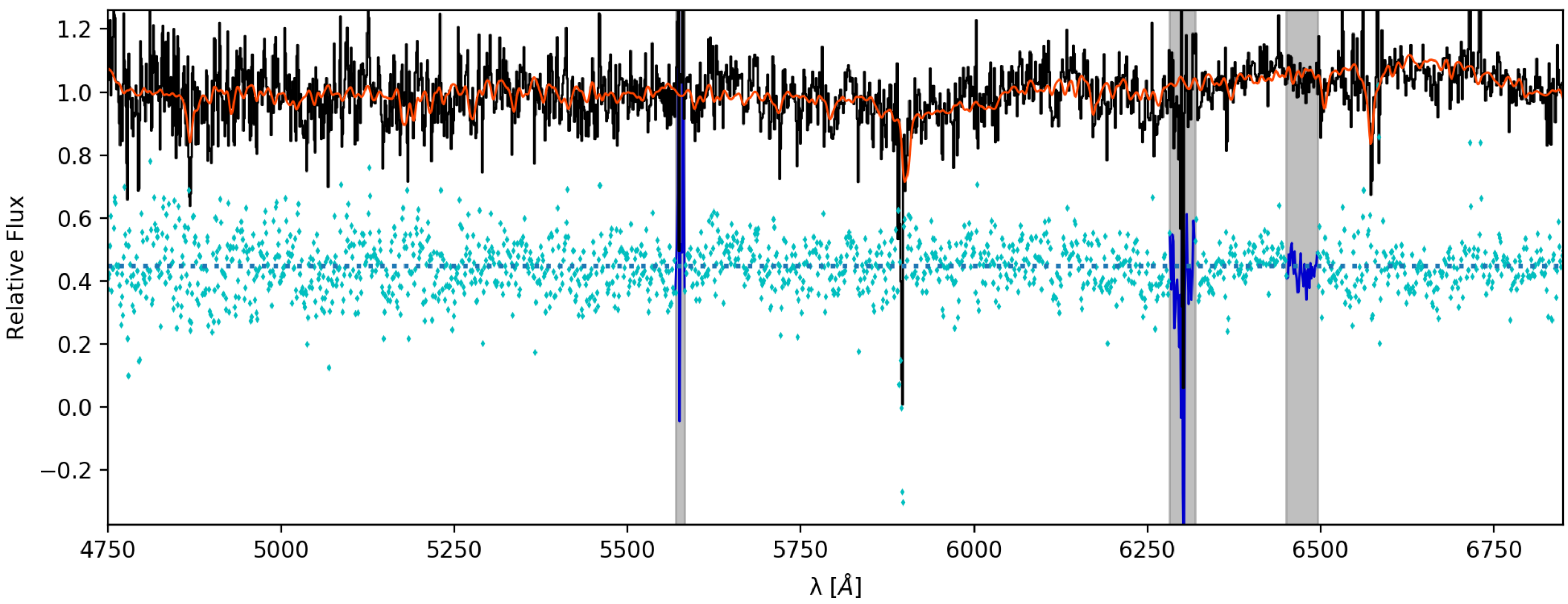
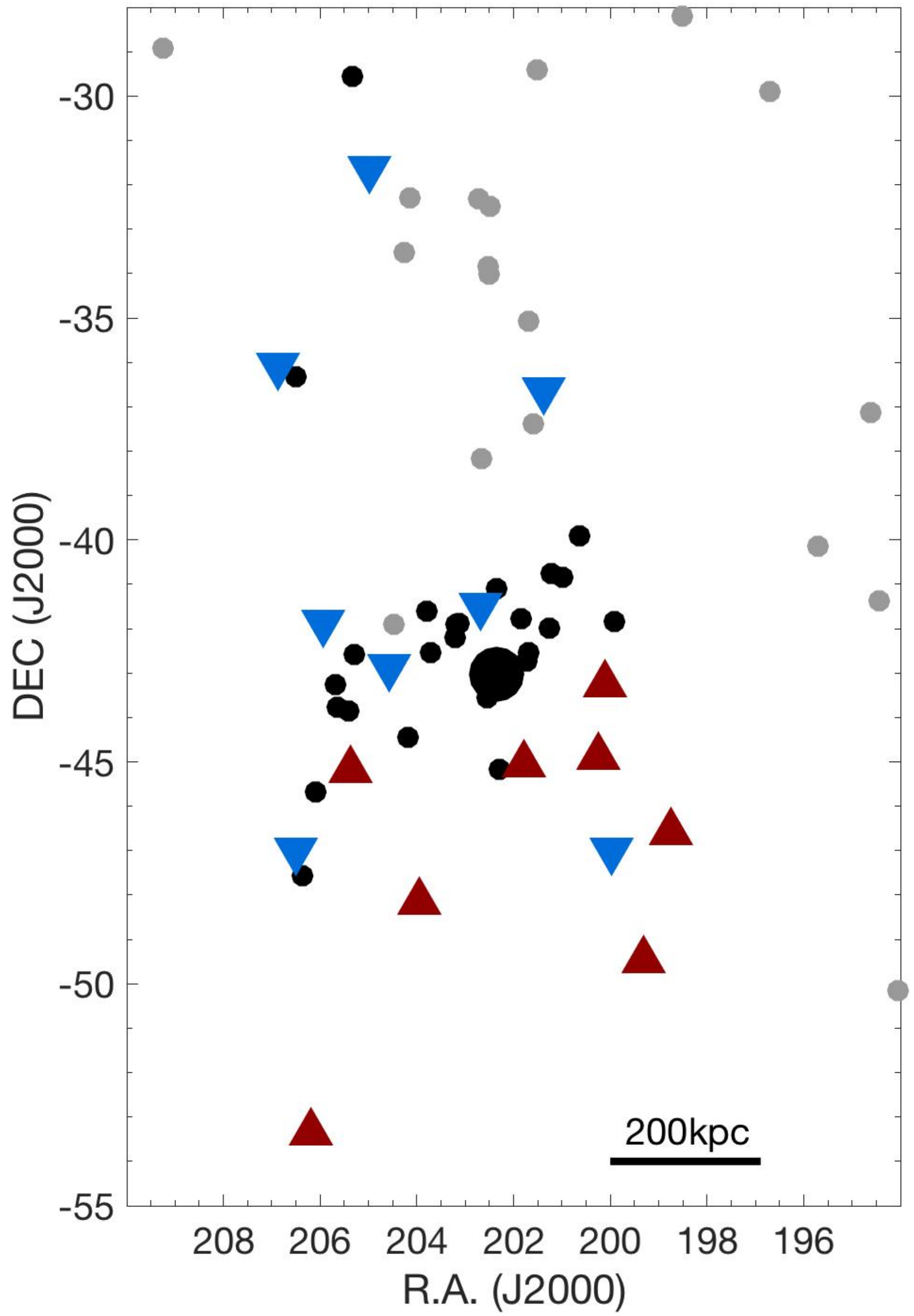


Coherent motion



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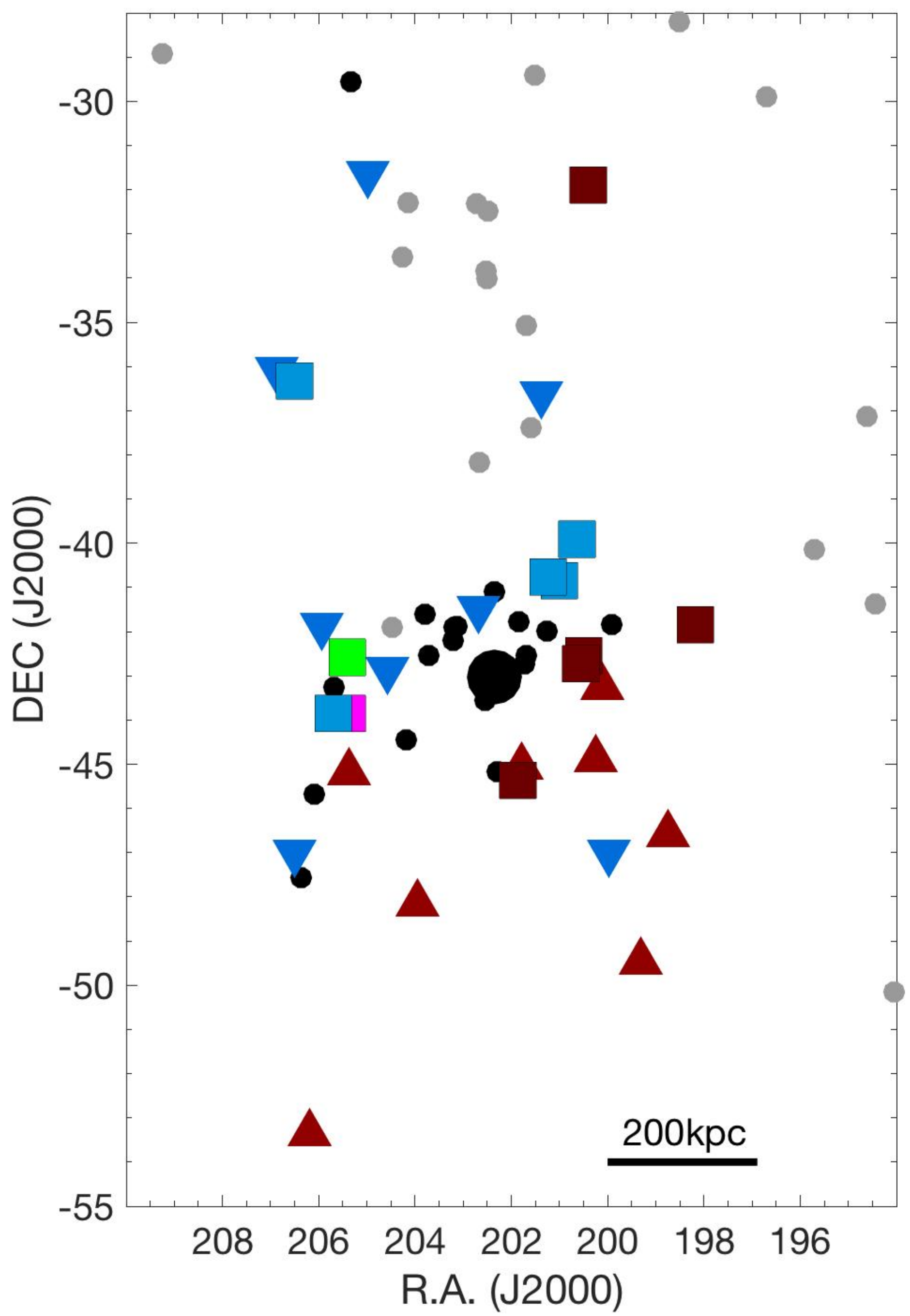

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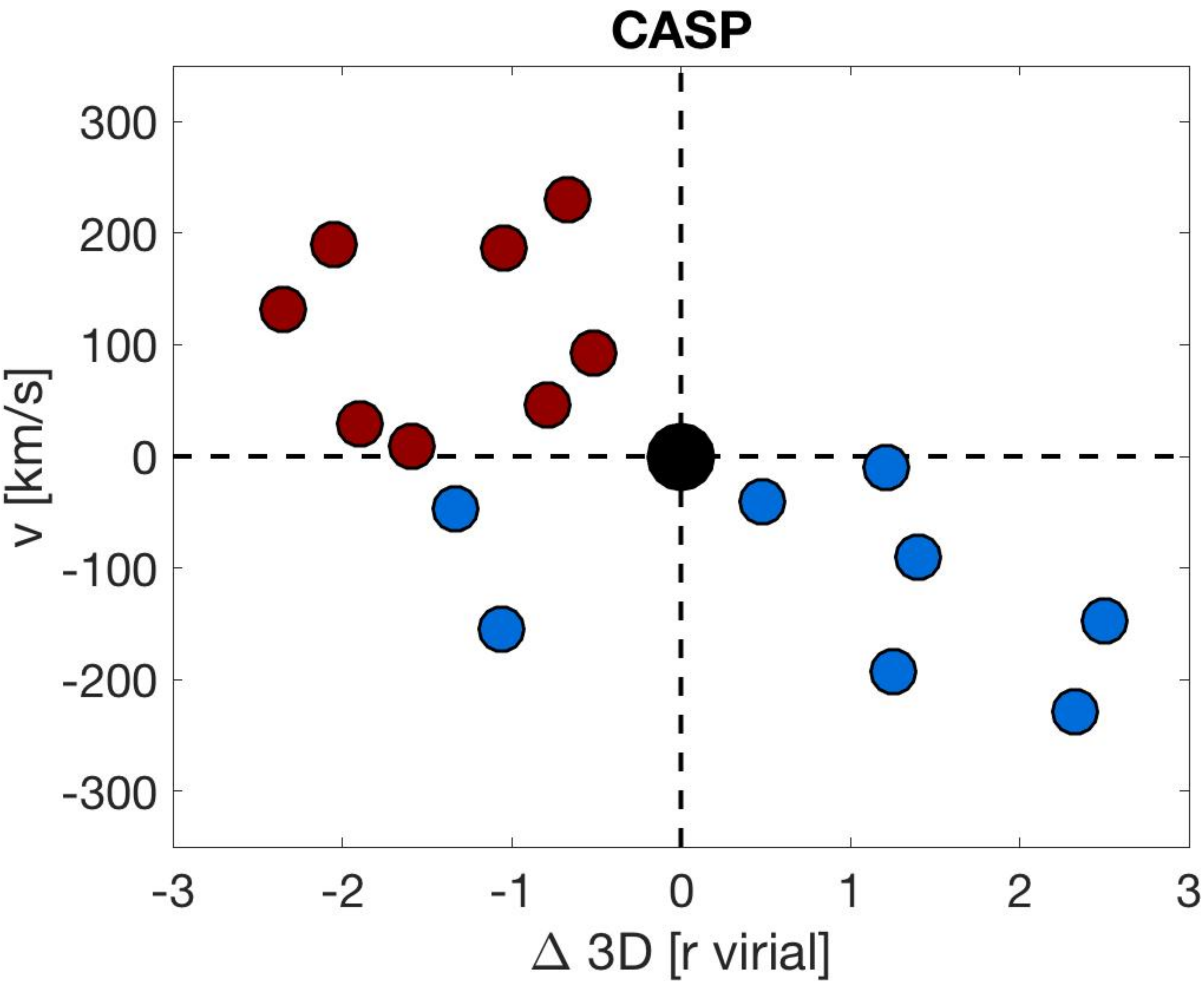

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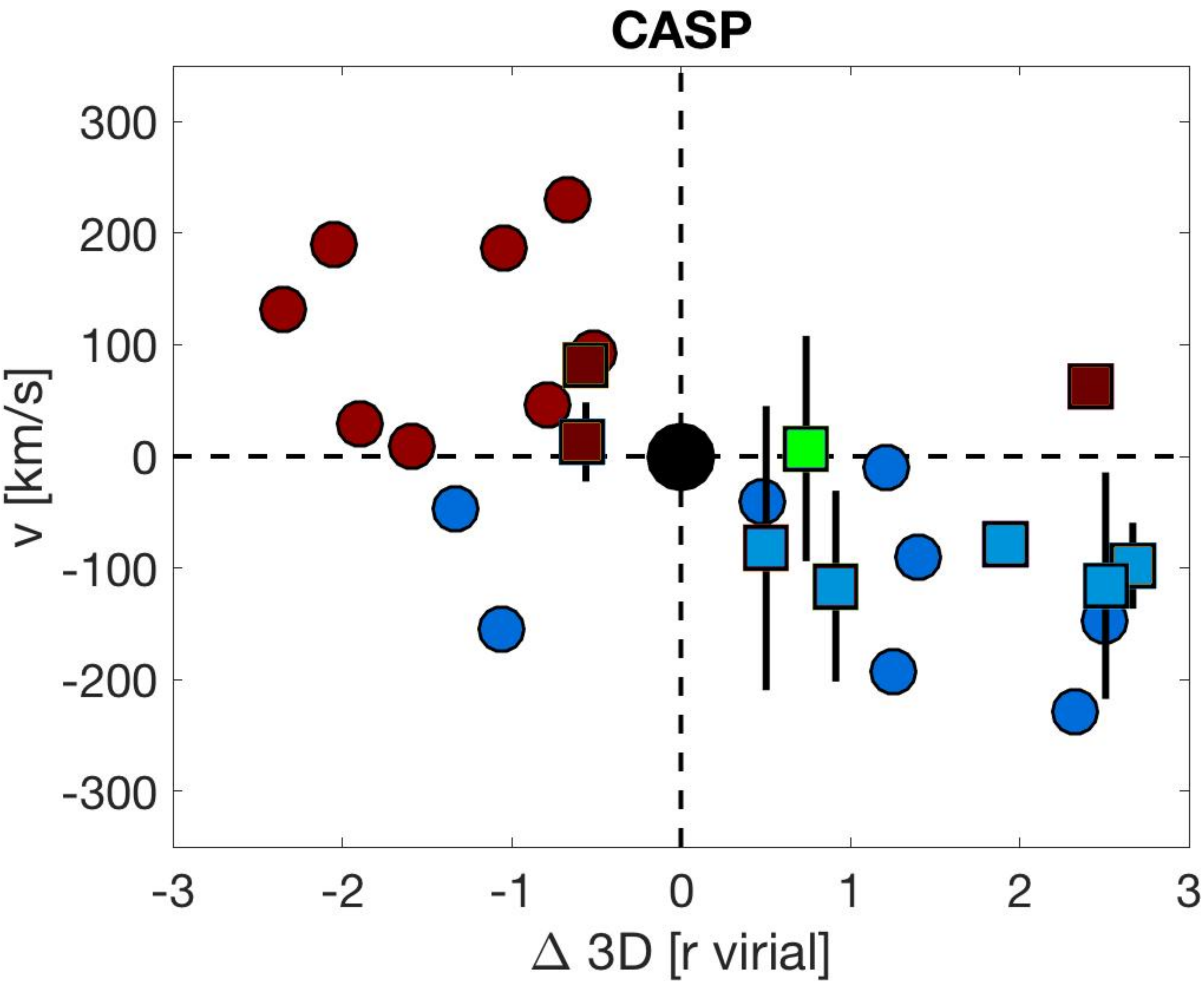
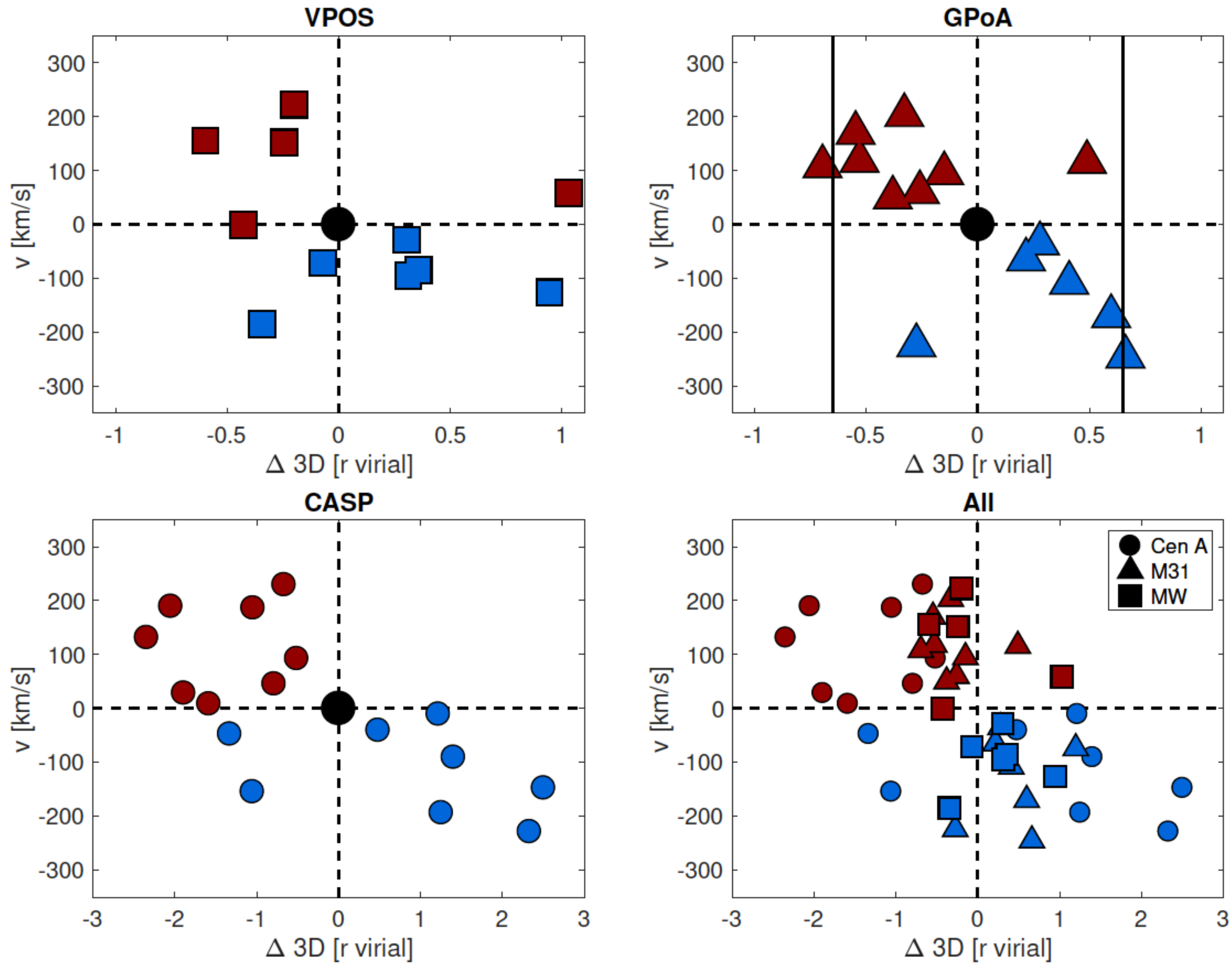


Müller et al. (in prep)

The Local Group is not unique!

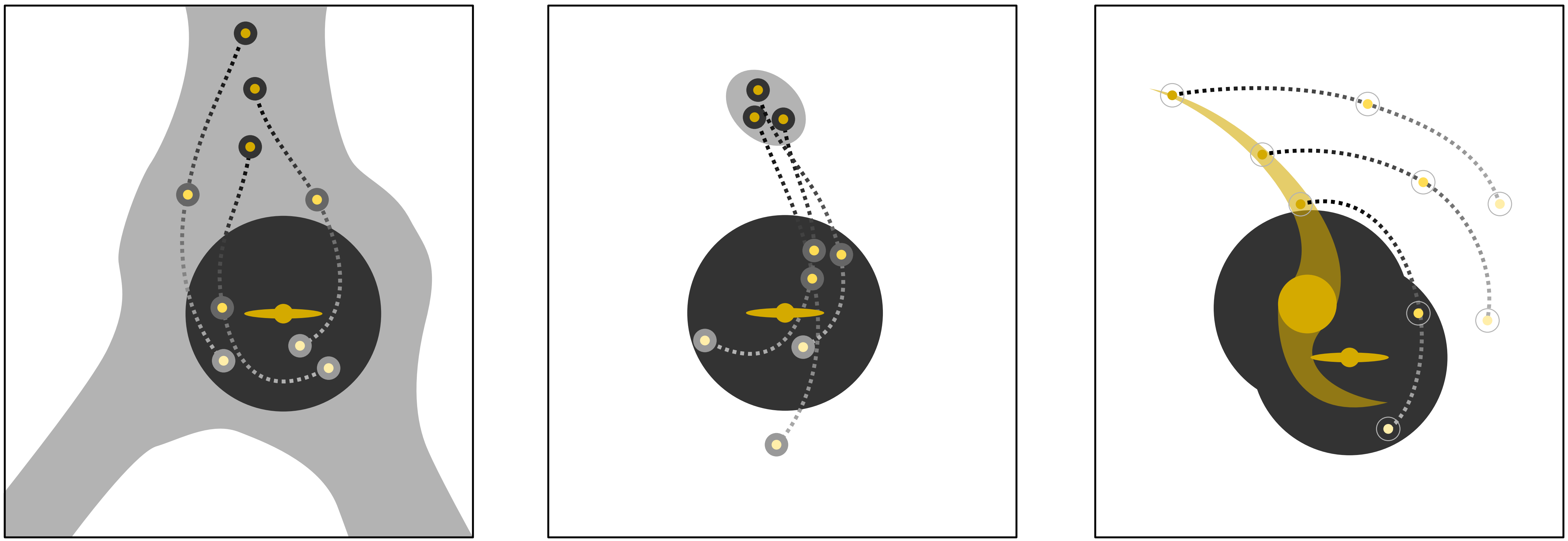
Known co-rotating systems in the Universe



Müller thesis

Three suggested formation scenarios

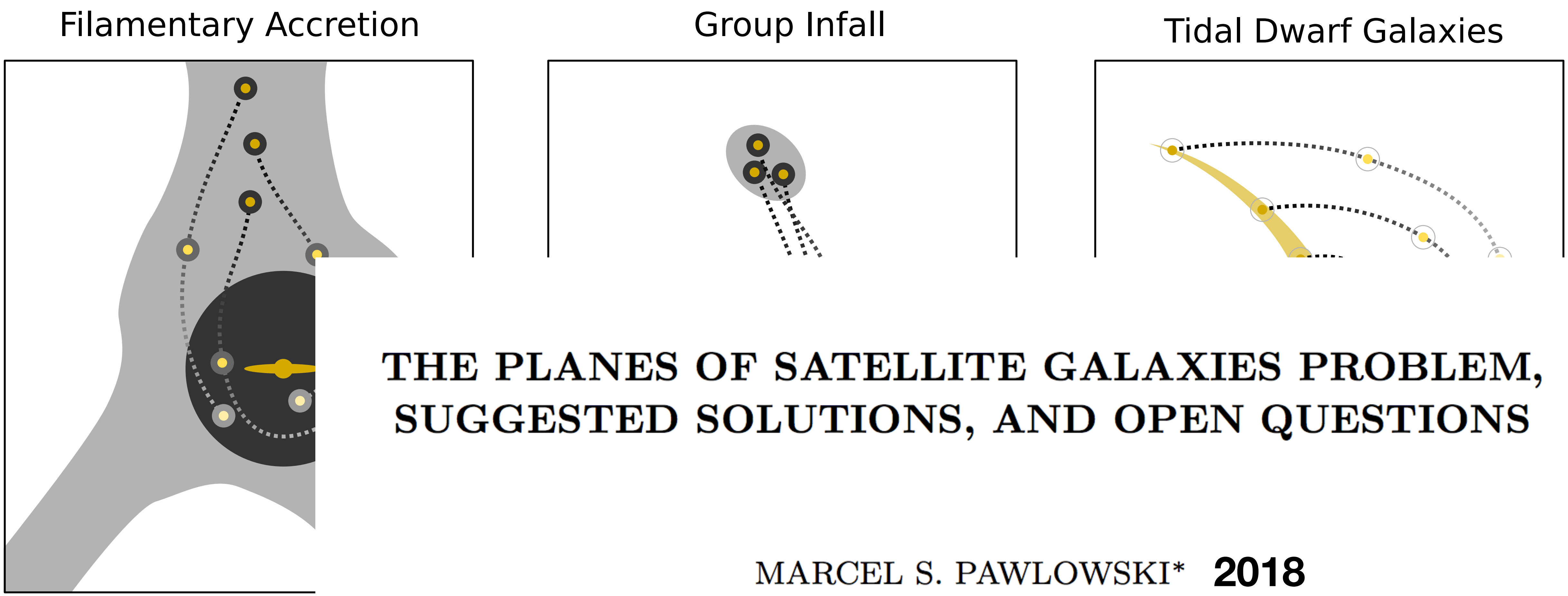
Filamentary Accretion | Group Infall | Tidal Dwarf Galaxies



Pawlowski (2018)

Pawlowski (2018)

Three suggested formation scenarios



THE PLANES OF SATELLITE GALAXIES PROBLEM, SUGGESTED SOLUTIONS, AND OPEN QUESTIONS

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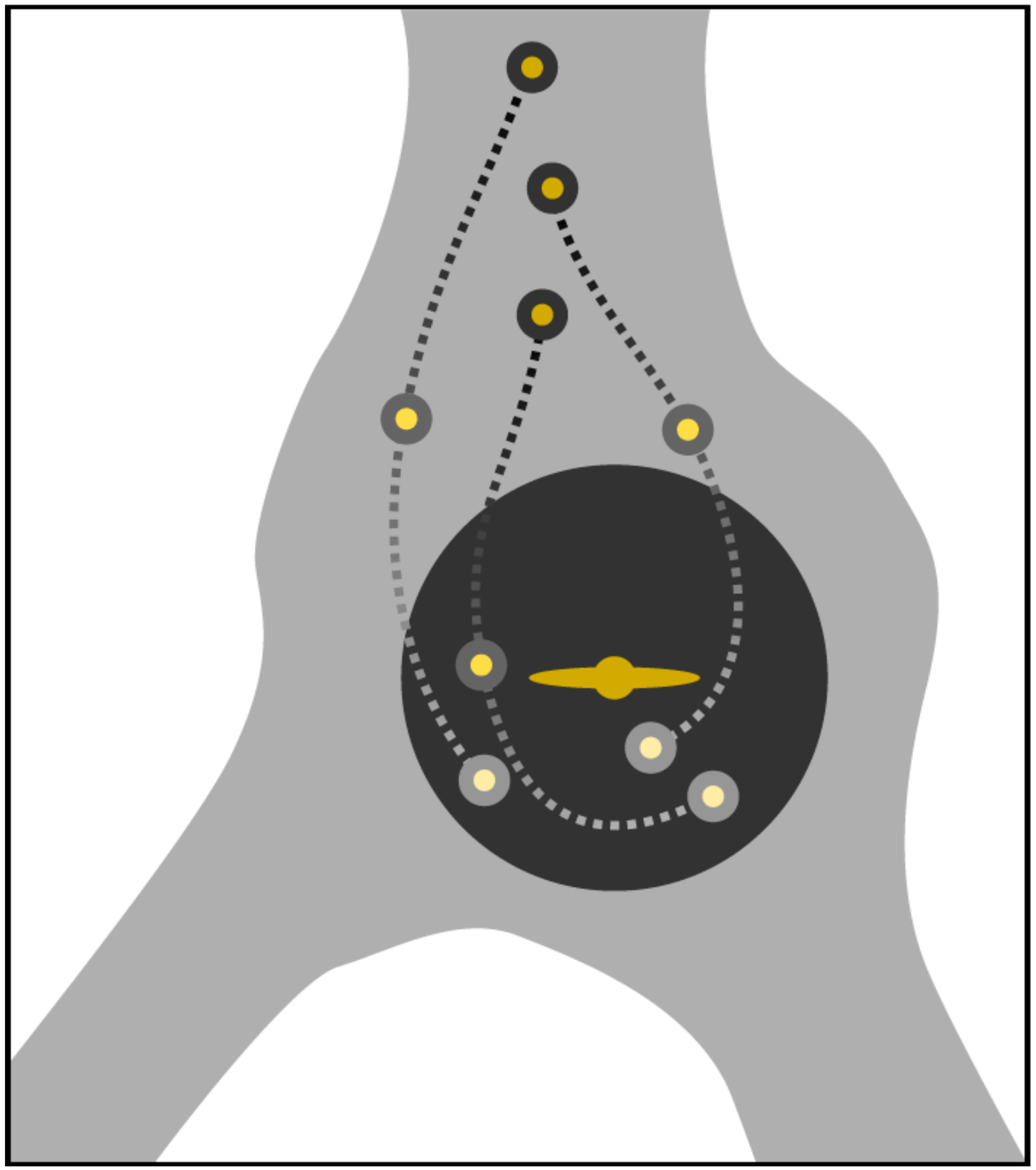
Pawlowski (2018)

Filamentary accrection

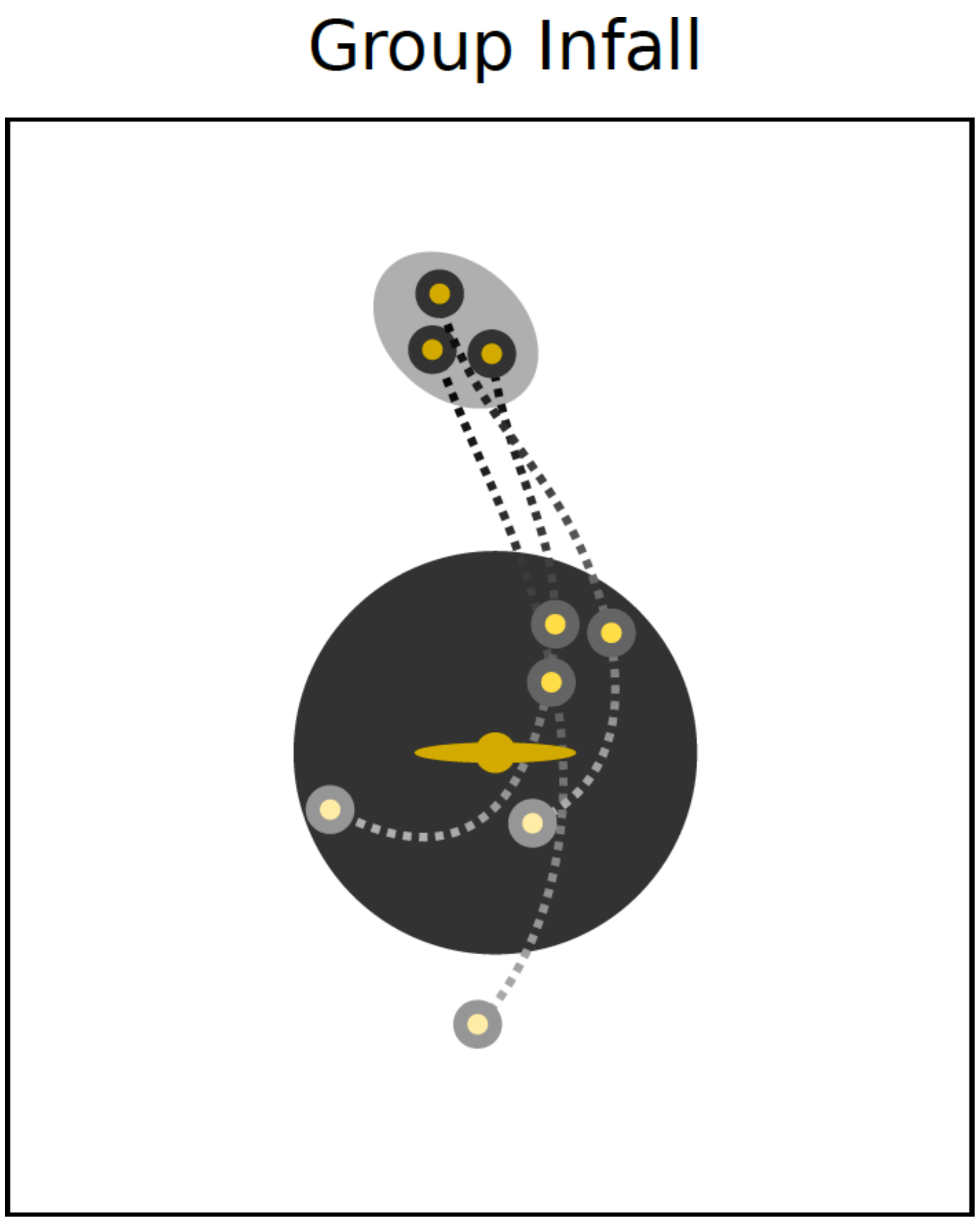
Filamentary Accretion



- Can produce transient planar structures (Buck et al. 2015)
- Filaments are too thick
- Better resolution, worse results
- Baryonic physics: no change
- Self-consistently implemented in the simulations

Pawlowski (2018)

Group infall

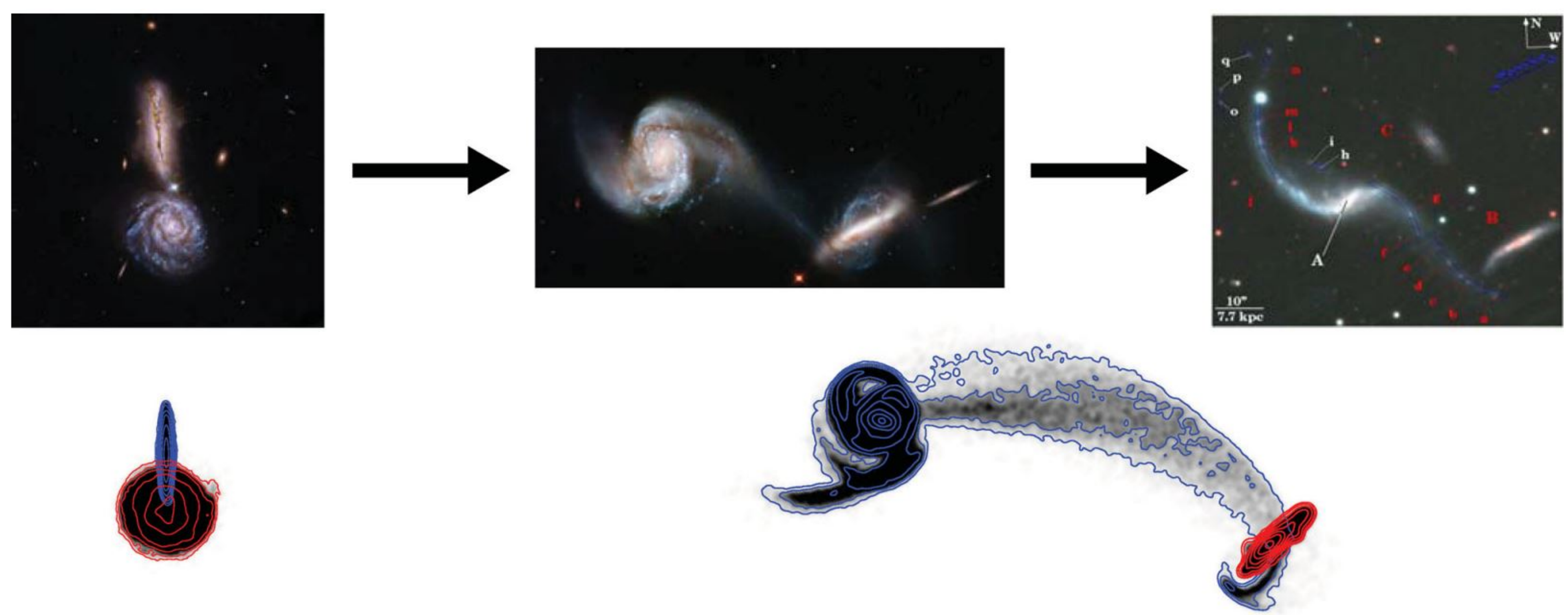


- Dwarf associations accreted in single event.
- Need 10+ dwarfs.
- Observations: 3-4 dwarfs in such groups.
- Need 30 kpc extension
- Observations: 200 kpc extended
- Self-consistently implemented in the simulations

Pawlowski (2018)

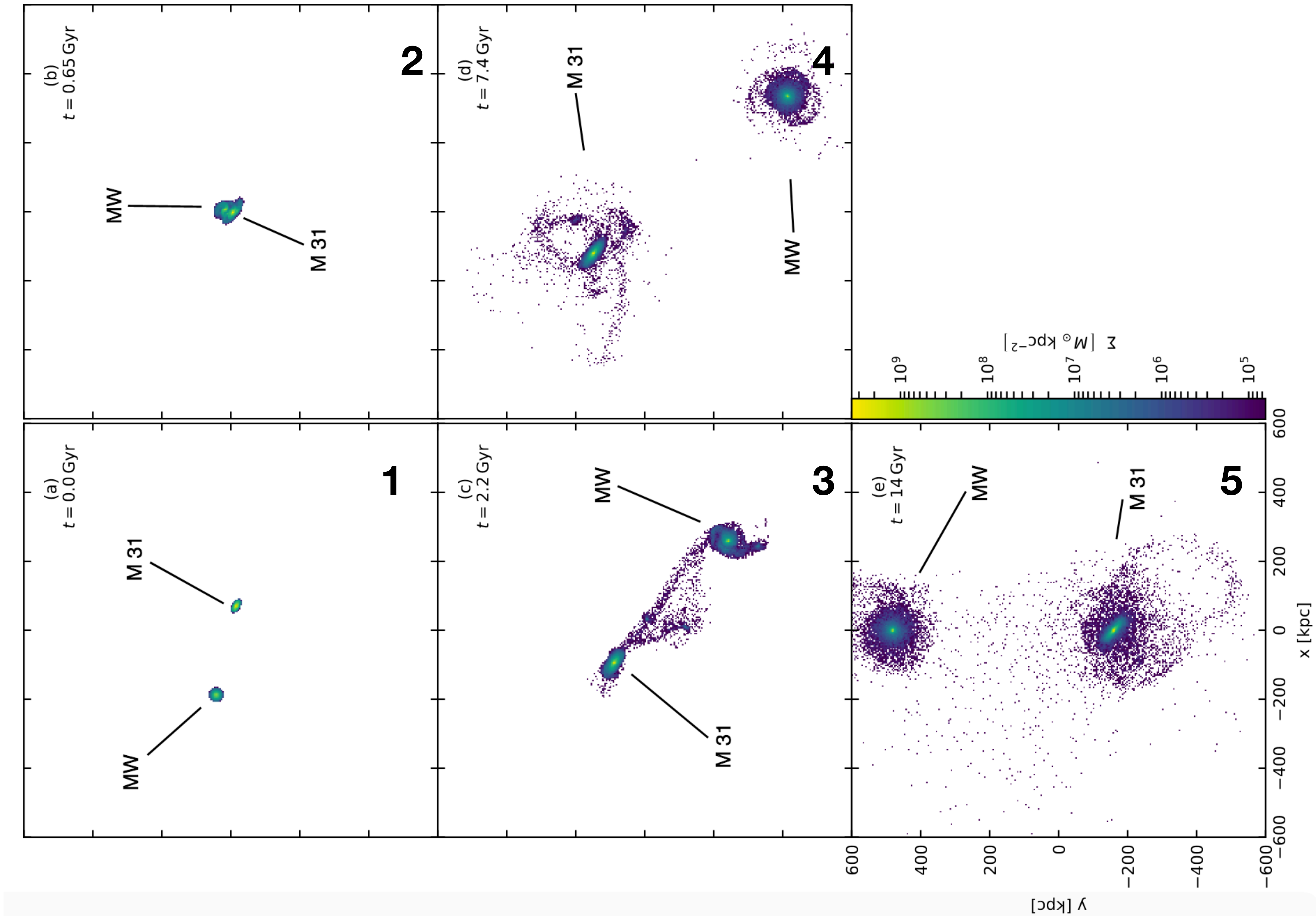
Dwarf galaxies as tidal remnants

- Dwarf galaxies as TDGs (e.g. Zwicky 1956, Lynden-Bell 1976, Kroupa et al. 2010, Hammer et al. 2013, 2018a)
- TDGs form along plane of interaction and inherit momentum
- Dark Matter free, but show DM behaviour! MOND (Milgrom 1983)? DM mass overestimated (Hammer et al. 2018b)?



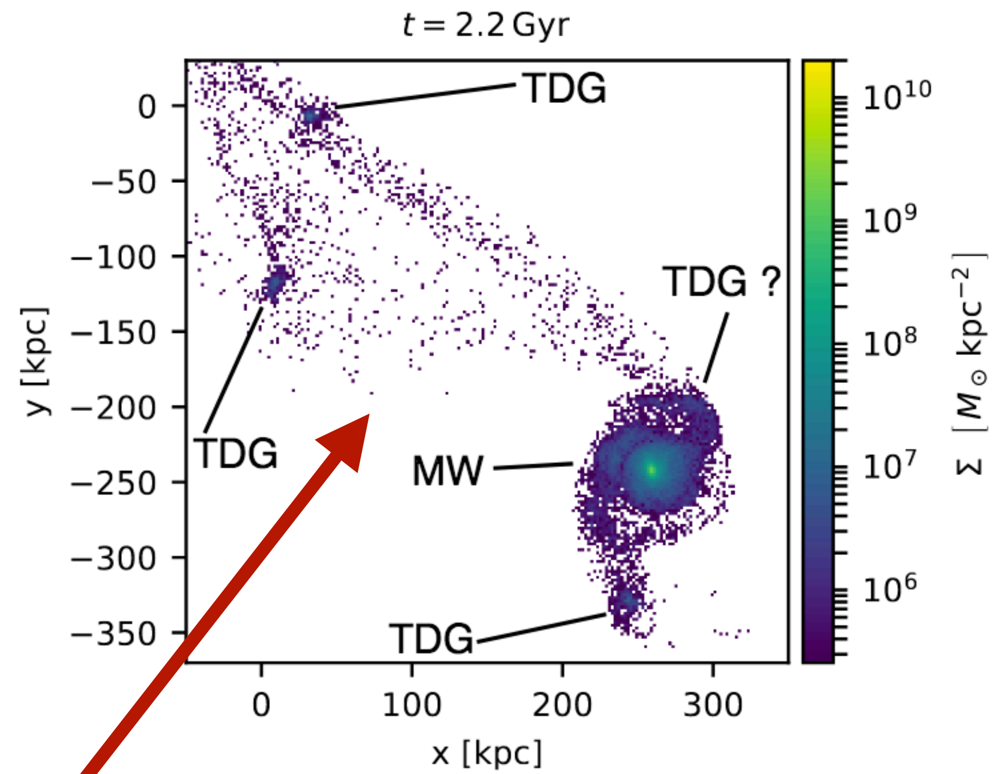
Pawlowski et al. 2011, 2012

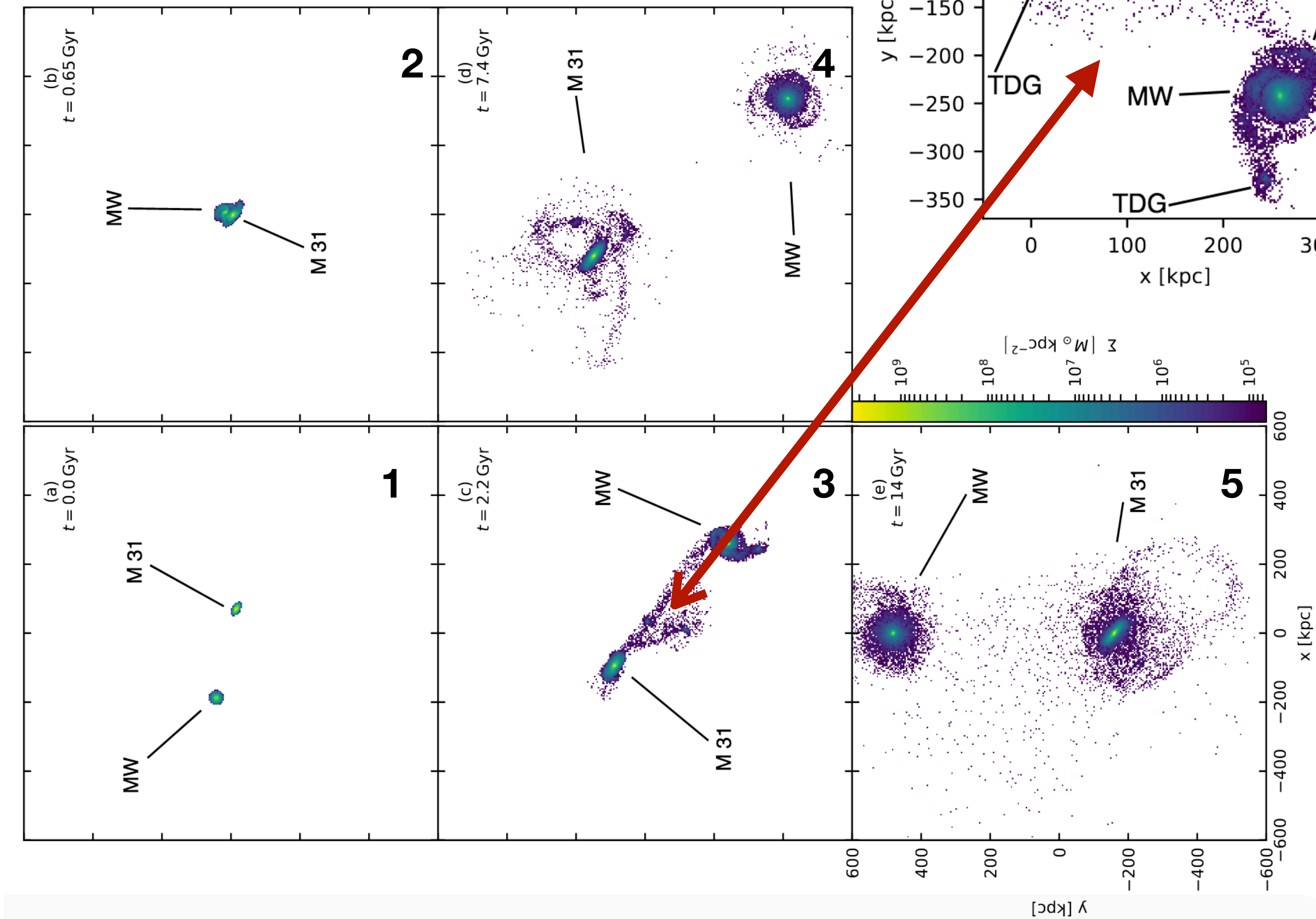
Dwarf galaxies as tidal remnants



Bilek et al. (2018)

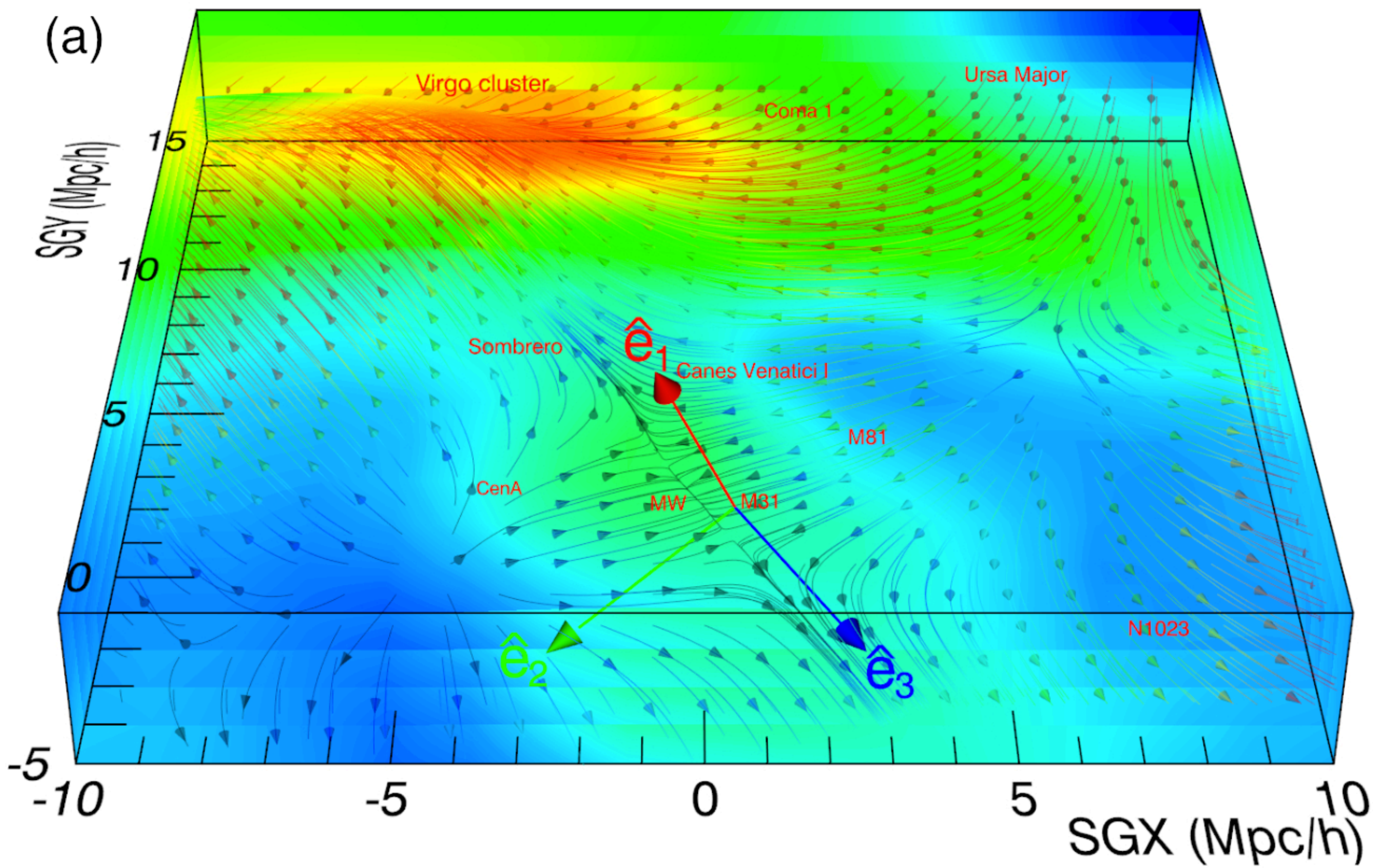
Dwarf galaxies as tidal rei





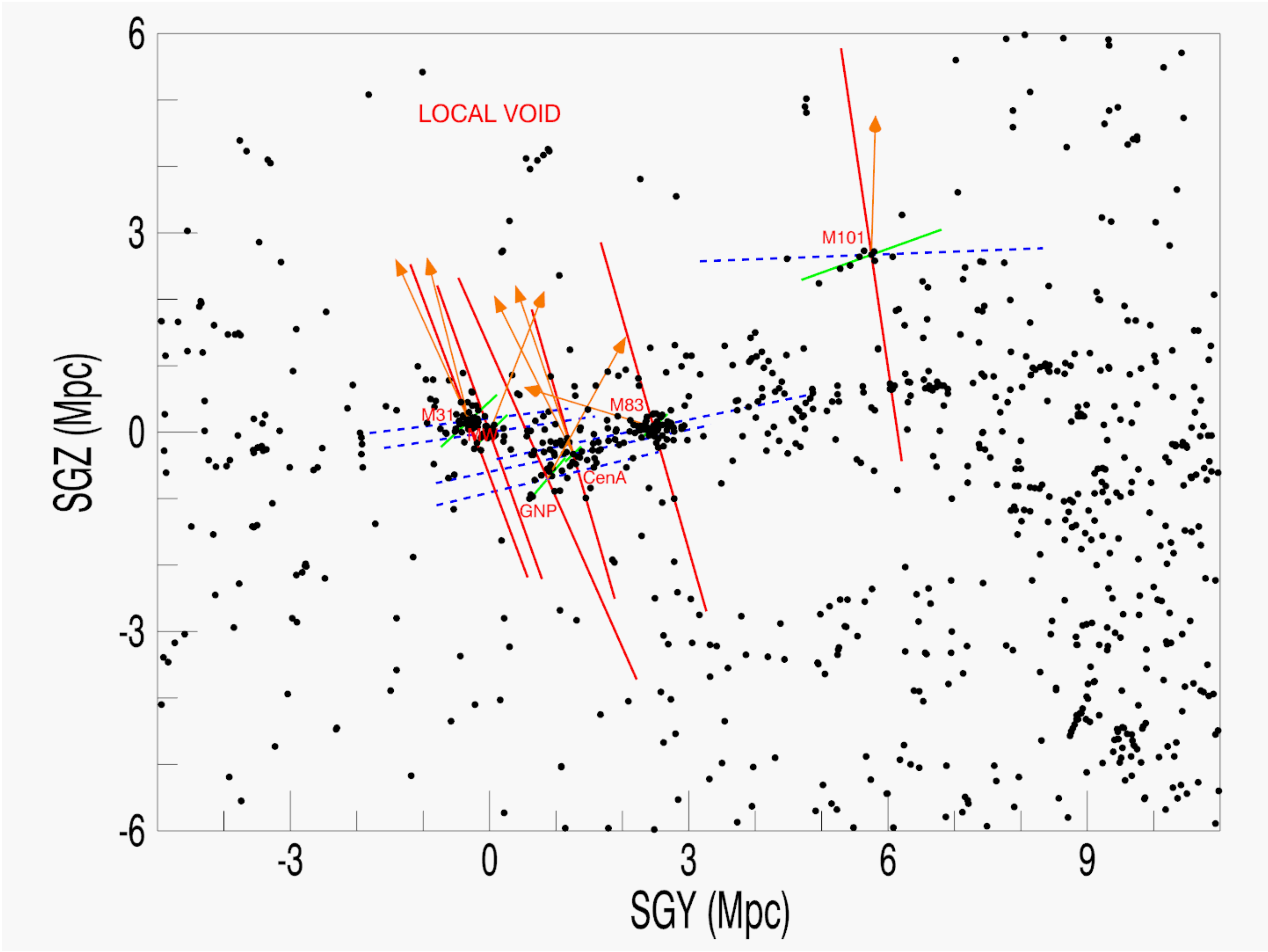
Bilek et al. (2018)

Local environment?



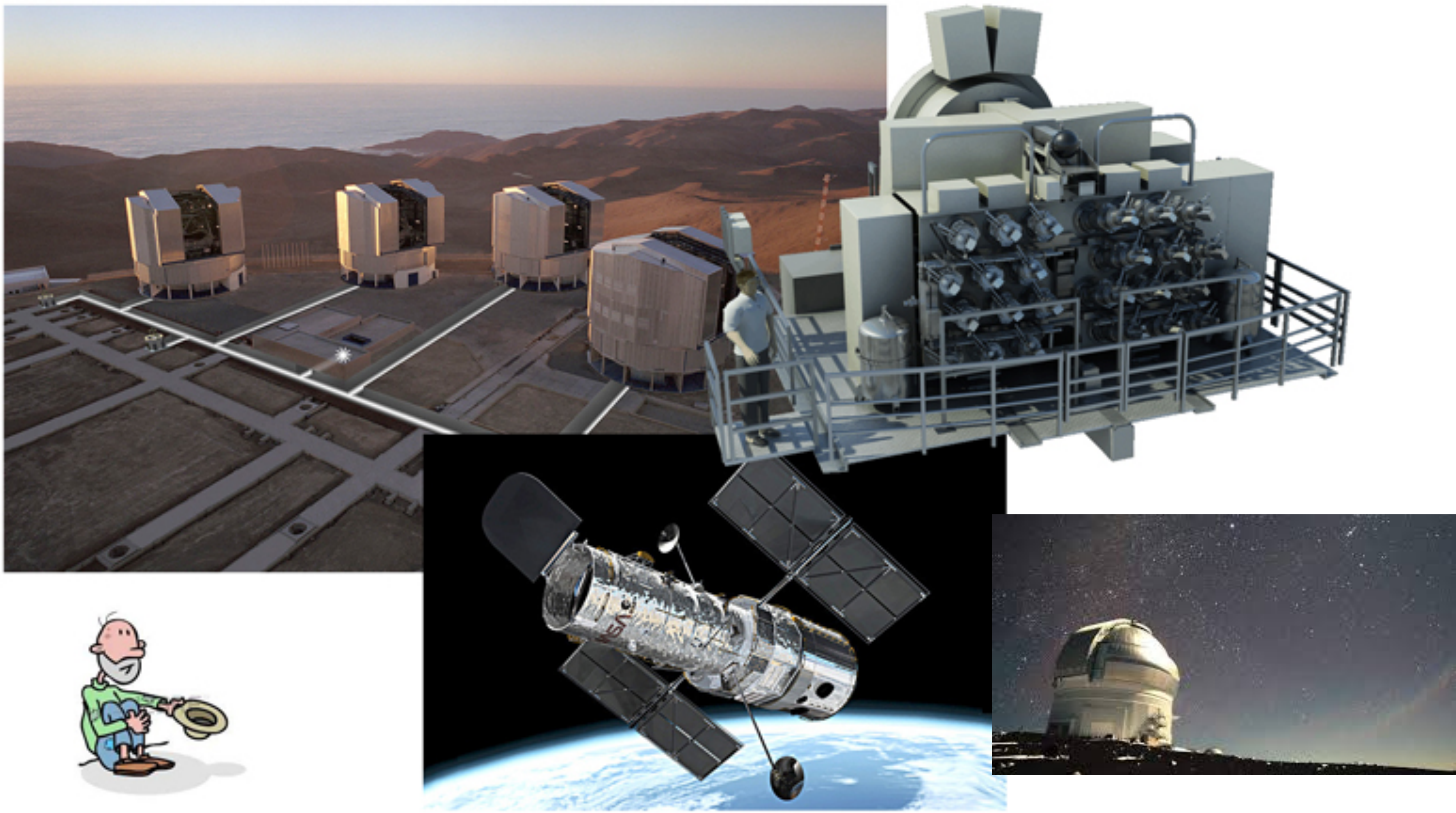
Libeskind et al. (2015)

Alignments of planes



Libeskind et al. (2019)

More observations needed



Summary

- Detected numerous dwarfs in different groups
- Automatic detection of dwarfs quite promising
- Measured distances and velocities with VLT
- Strong evidence for co-rotating plane-of-satellites around Cen A which challenges our understanding of structure formation
- Need more observational data!