Co-rotating planes of dwarf galaxy satellites challenging Cold Dark Matter cosmology

Oliver Müller

University of Basel

oliver89.mueller@unibas.ch

Collaborators: Helmut Jerjen (Australian National University), Bruno Binggeli, Roberto Scalera (University of Basel), Marcel S. Pawlowski (University of California), Marina Rejkuba, Federico Lelli, Michael Hilker (ESO, Garching)

- Dwarf galaxies and cosmology
- Dwarf galaxy surveys
- Planes-of-satellites problem
- Outlook and Summary

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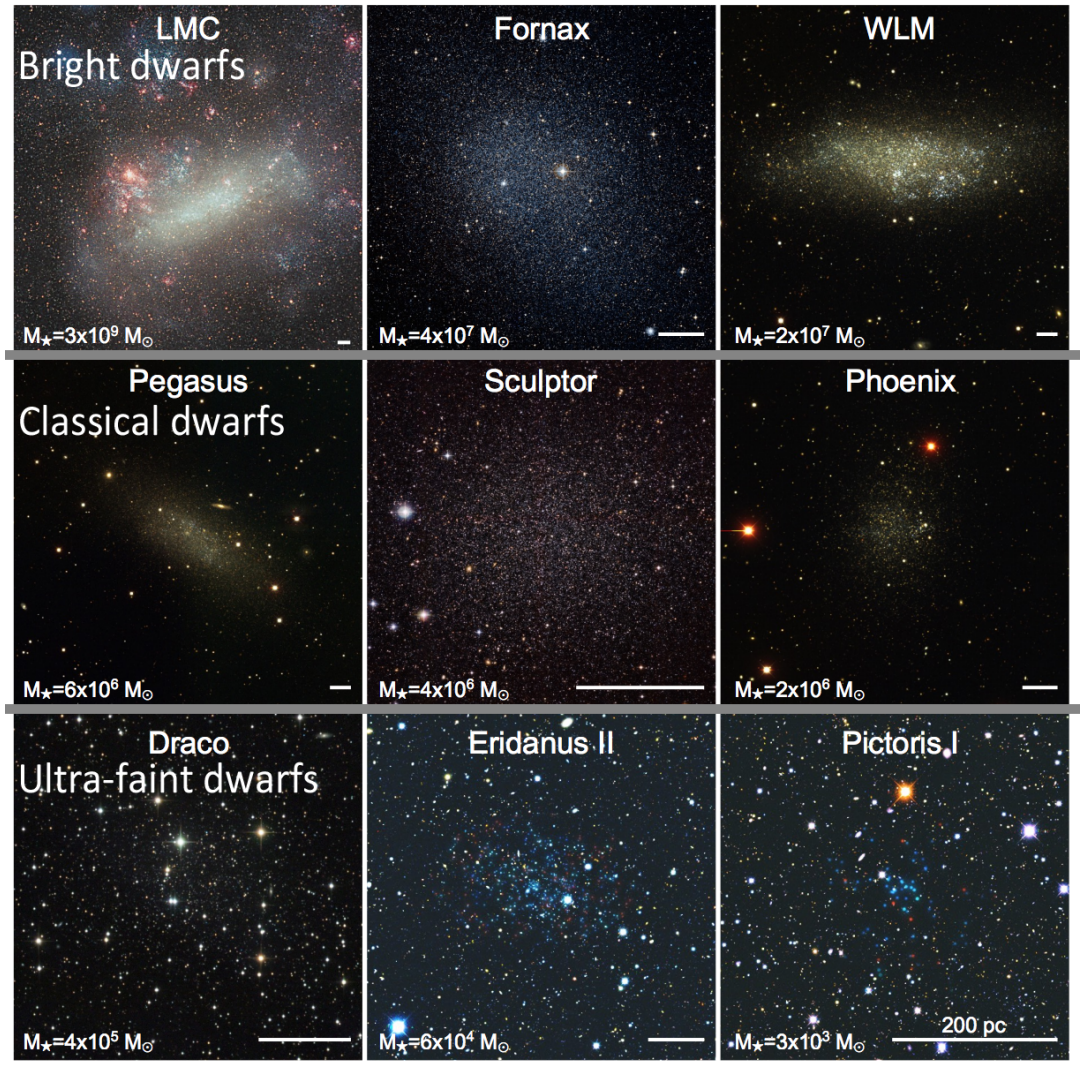
Flavors of dwarfs

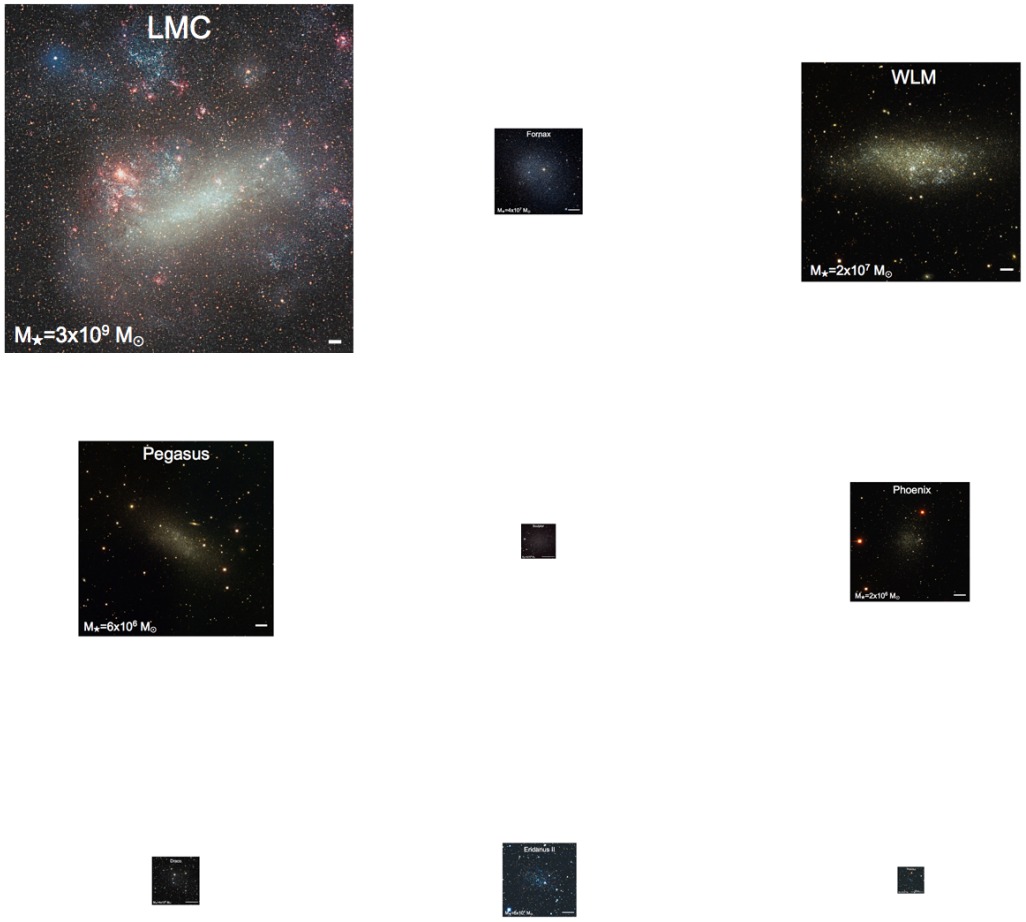
Flavors of dwarfs

Flavors of dwarf galaxies



Adopted from Bullock & Boylan-Kolchin (2017).

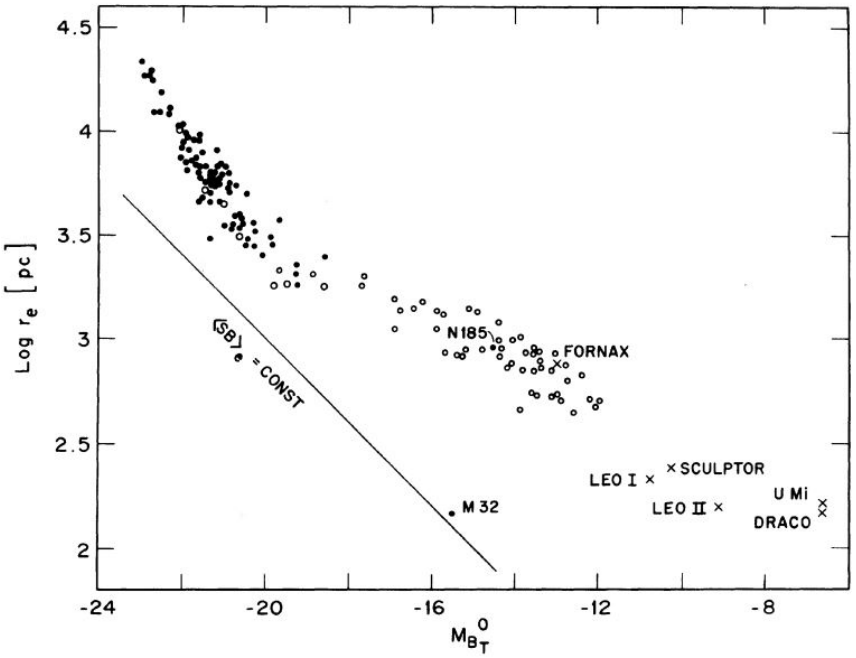
Flavors of dwarf galaxies

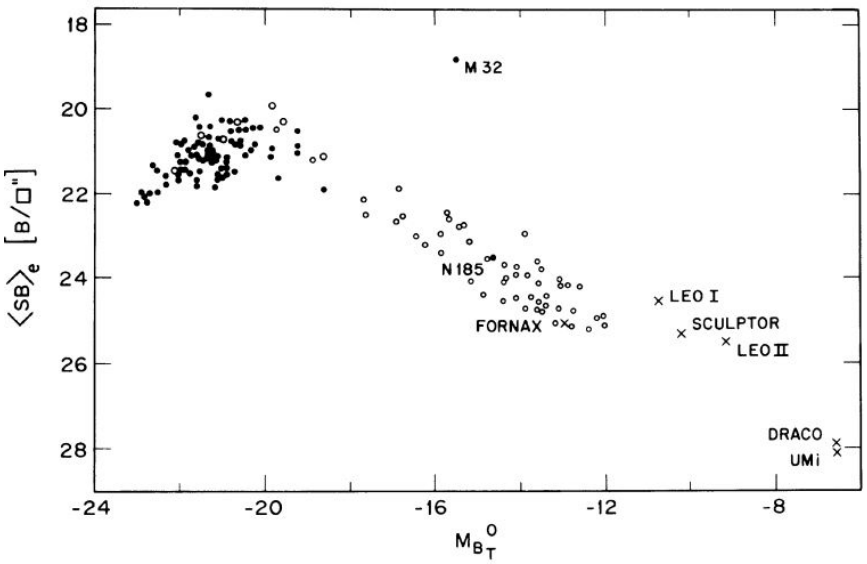


Adopted from Bullock & Boylan-Kolchin (2017).

Dwarf galaxy relations

Dwarfs follow tight photometric relations over several magnitudes.

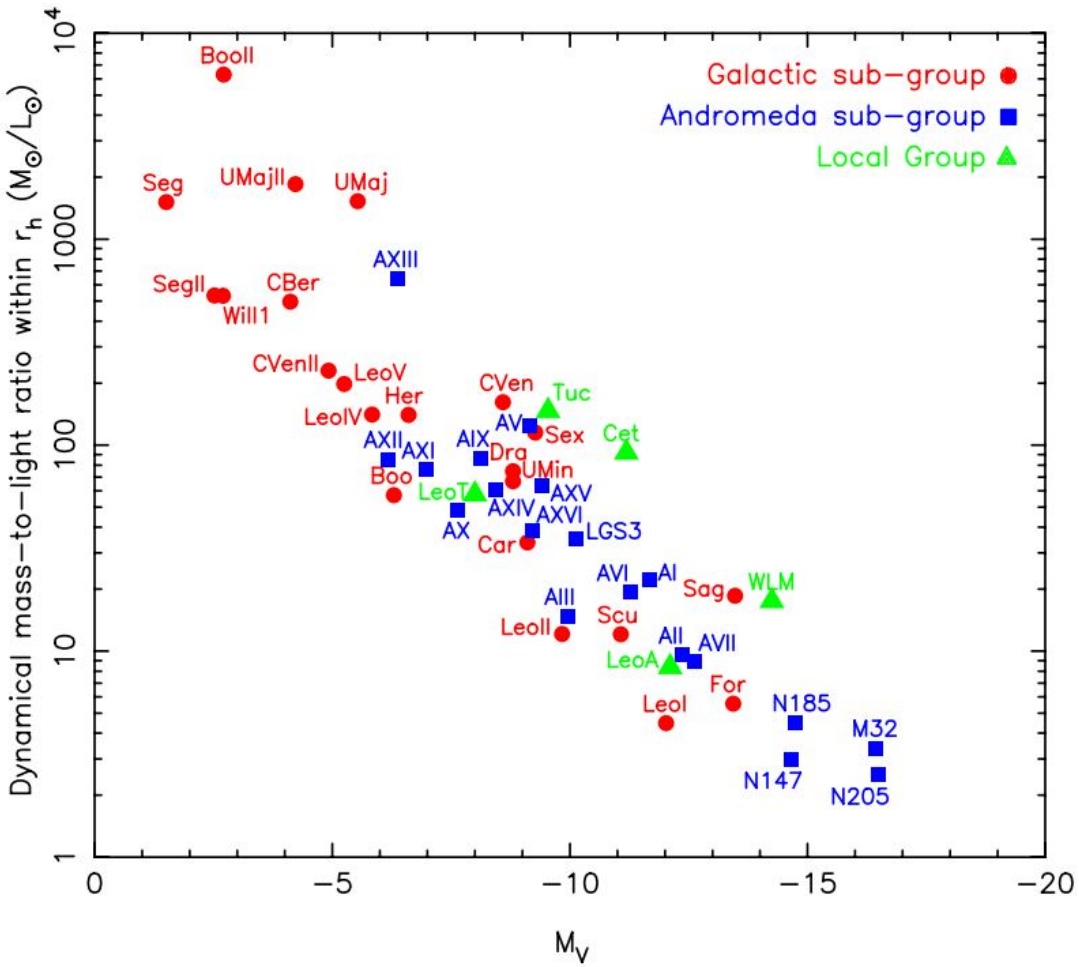




Binggeli et al. (1984)

Dwarf galaxy relations

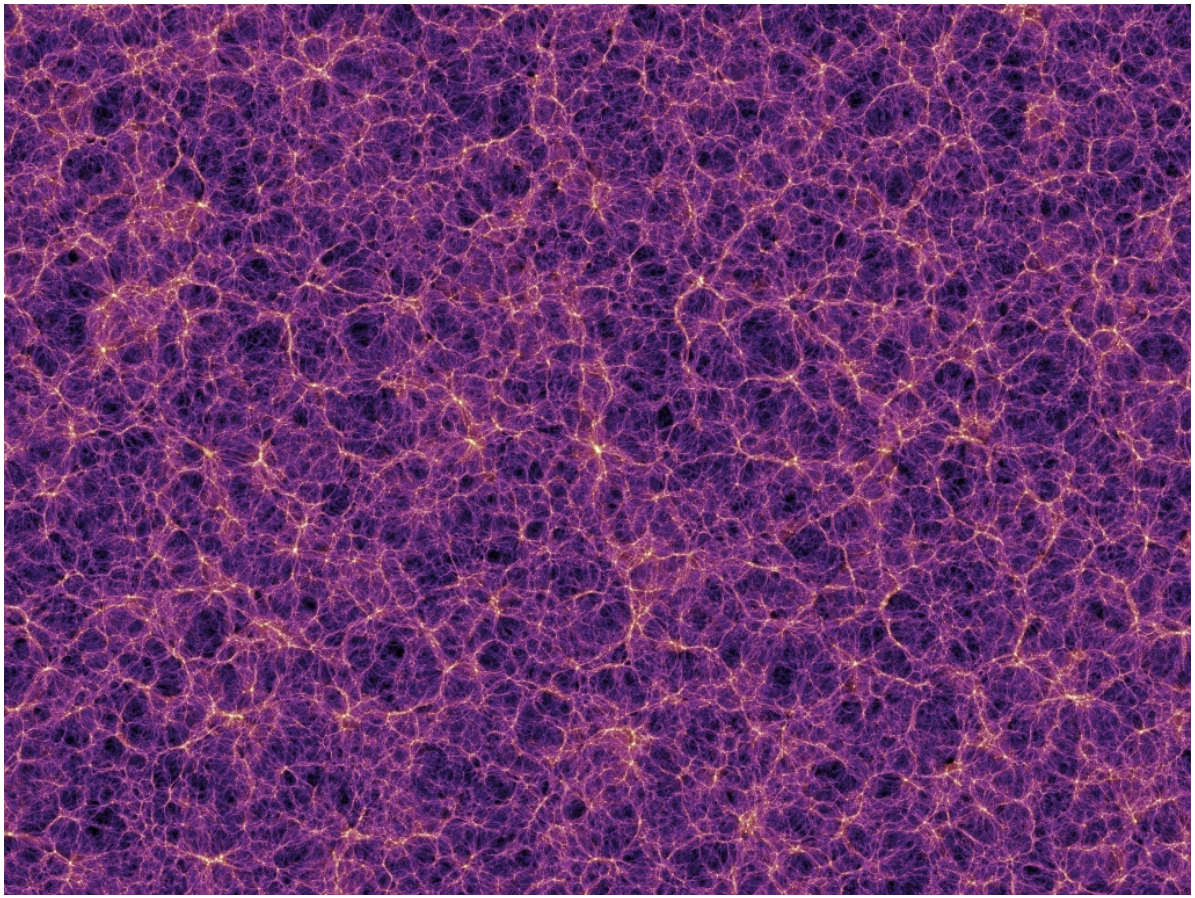
The fainter the dwarf, the more dark matter it contains.



Mcconnachie (2012)

The Cosmic Web of Dark Matter

Filamentary large-scale structure of the Universe.

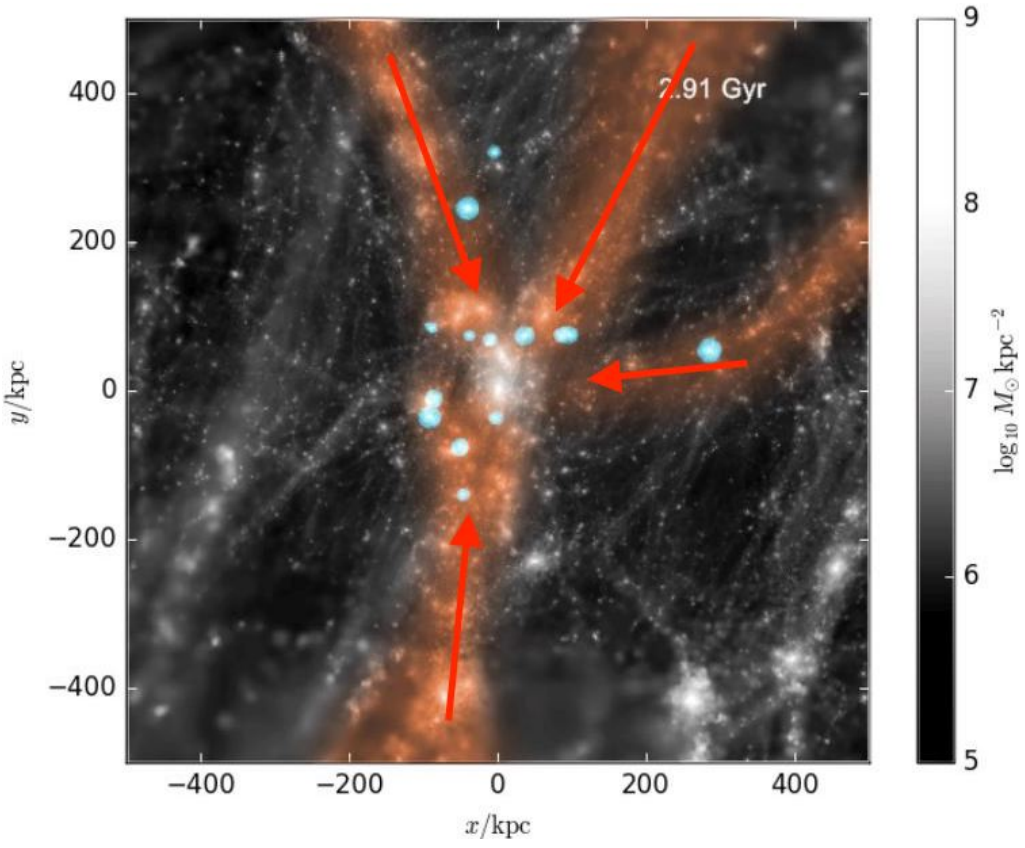


- Filaments and voids.
- Baryons follow DM distribution.
- Dwarf galaxies trace fine-structure of large scale structure (Binggeli 1989).

Credit: Millennium Simulation Project

Dark Matter accretion

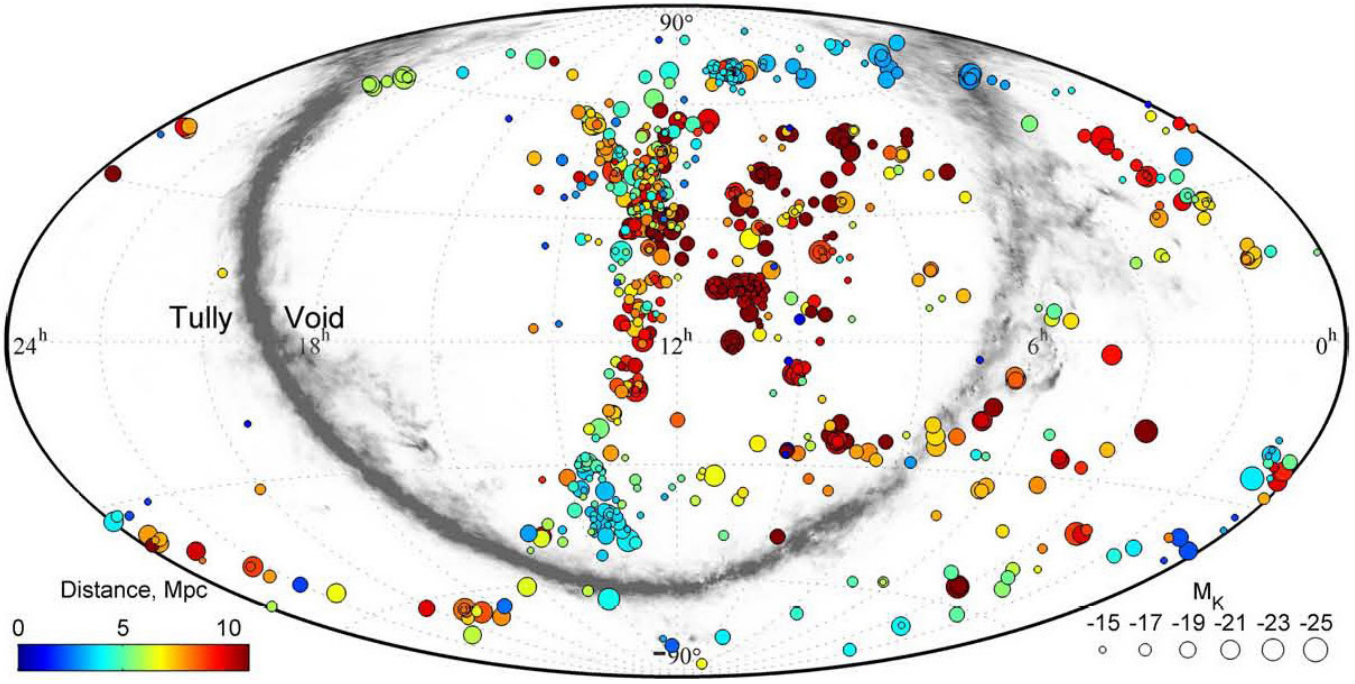
- Dark Matter subhalos accreted through filaments.
- Statistical process, i.e. there are many different mergers and formation history processes.



Adopted from Ahmed et al. (2017).

Local Volume

- The Local Volume (D $<$ 10 Mpc, Karatchentsev et al. 2013) represents nearby universe.
- $\approx$ 1000 objects, mostly dwarf galaxies
- $\approx$ 10 groups of galaxies
- Local Void, devoid of any objects

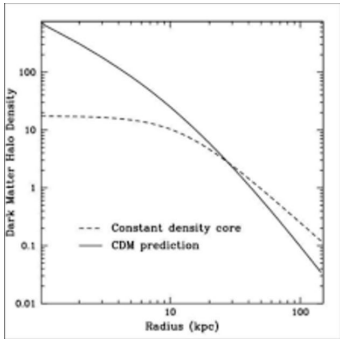


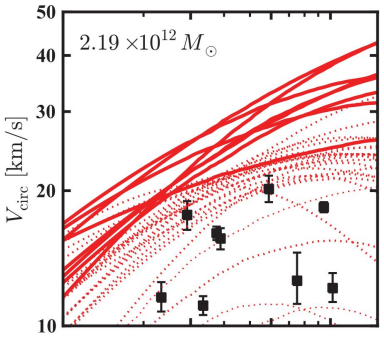
https://www.sao.ru/lv/lvgdb/introduction.php

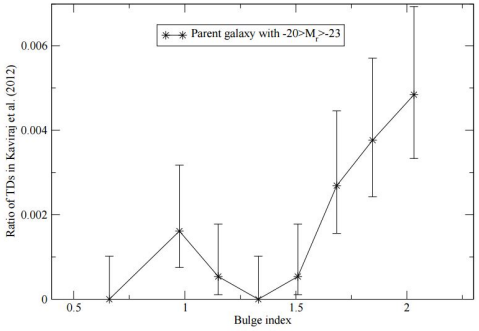
Challenges to ΛCDM

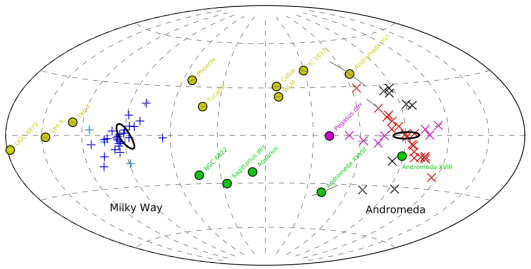
An *incomplete* list of tension between predictions and observations on small-scales, all observed in the Local Group:

- Cusp/Core problem (e.g. de Blok 2010).
- Too-big-too-fail problem (Kroupa et al. 2010, Boylan-Kolchin et al. 2011).
- Missing satellite problem (Moore et al. 1999).
- Bulge - number of satellites relation (Lopez-Corredoira & Kroupa 2016).
- Planes-of-satellites problem (Kroupa et al. 2005).









Seigar (2015) ,Boylan-Kolchin et. al (2012), Lopez-Corredoira & Kroupa 2016, Pawlowski et al. (2013)

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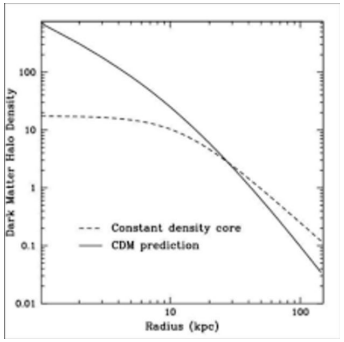
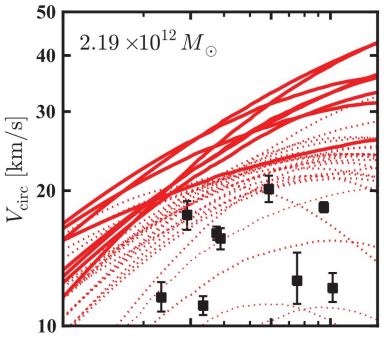
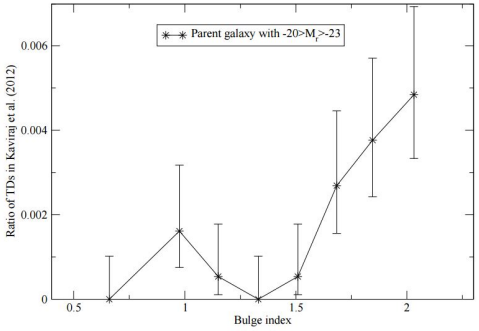
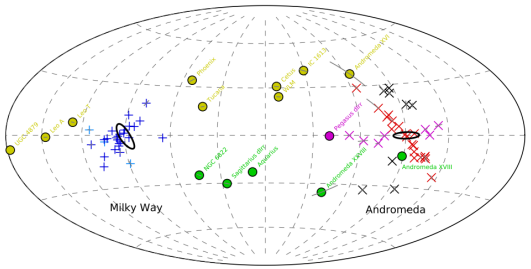




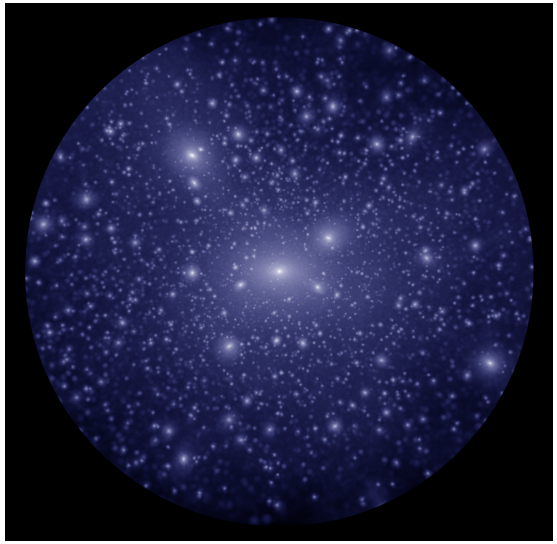


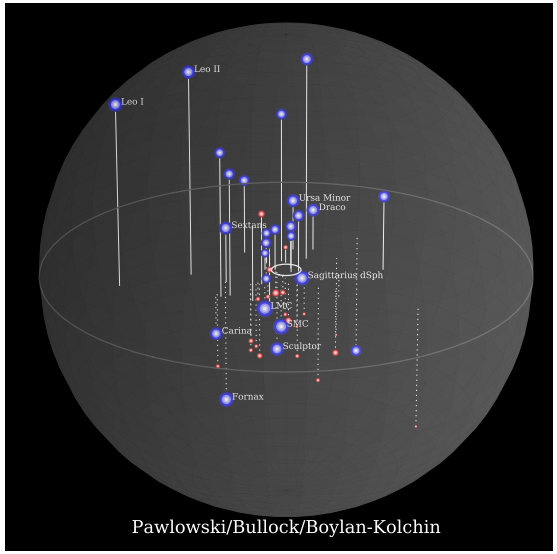


Seigar (2015), Boylan-Kolchin et. al (2012), Lopez-Corredoira & Kroupa 2016, Pawlowski et al. (2013)

Missing satellite problem

- Simulated subhaloes around giant galaxies > 1000; Measured ≈ 50
- Ultra faint dwarfs can't solve problem.
- TBTF is flavor of MS problem.
- Baryonic physics as solution? Perhaps...

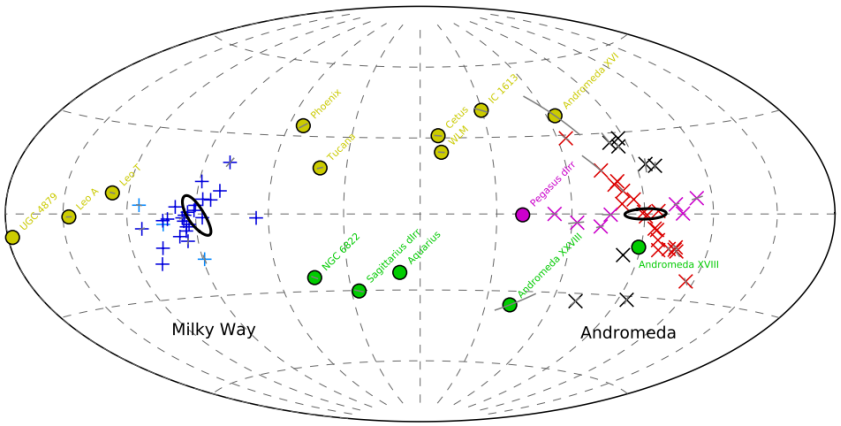




Bullock & Boylan-Kolchin (2017)

Dwarf satellite plane problem

- vast polar structure (VPOS) - MW;
  Great Plane of Andromeda (GPOA) - Andromeda
- ΛCDM: close-to isotropical and random motions.
- ΛCDM: chance of alignment $<$ **0.1%** (Pawlowski et al. 2015) or $<$**10%** (Cautun et al. 2015).



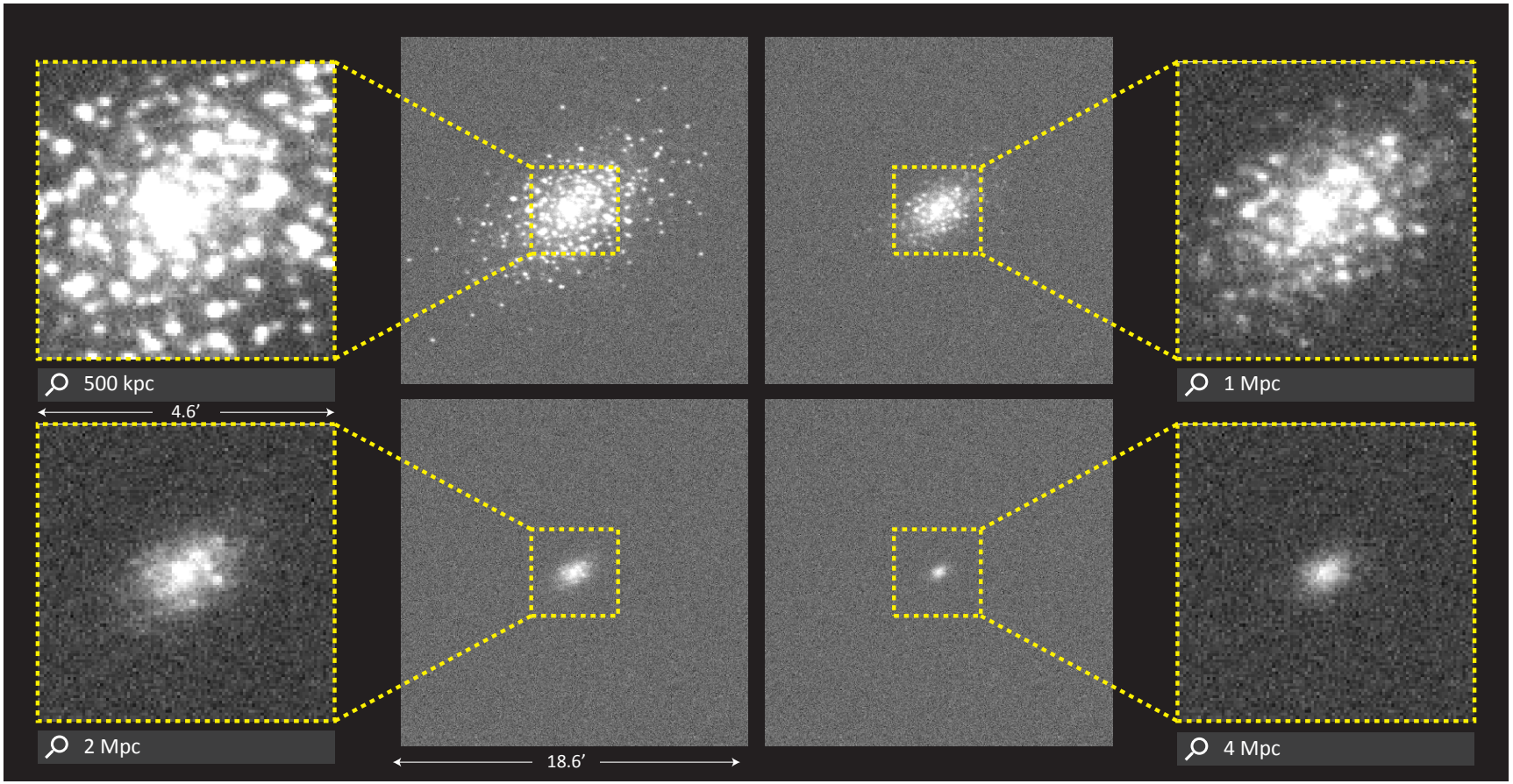
Left: Pawlowski et al. (2013)

Is the Local Group unique?

- Dwarf galaxies and cosmology
- Dwarf galaxy surveys
- Planes-of-satellites problem
- Outlook and Summary

Search for dwarfs in the Local Volume

Artificial dwarf at different distances.

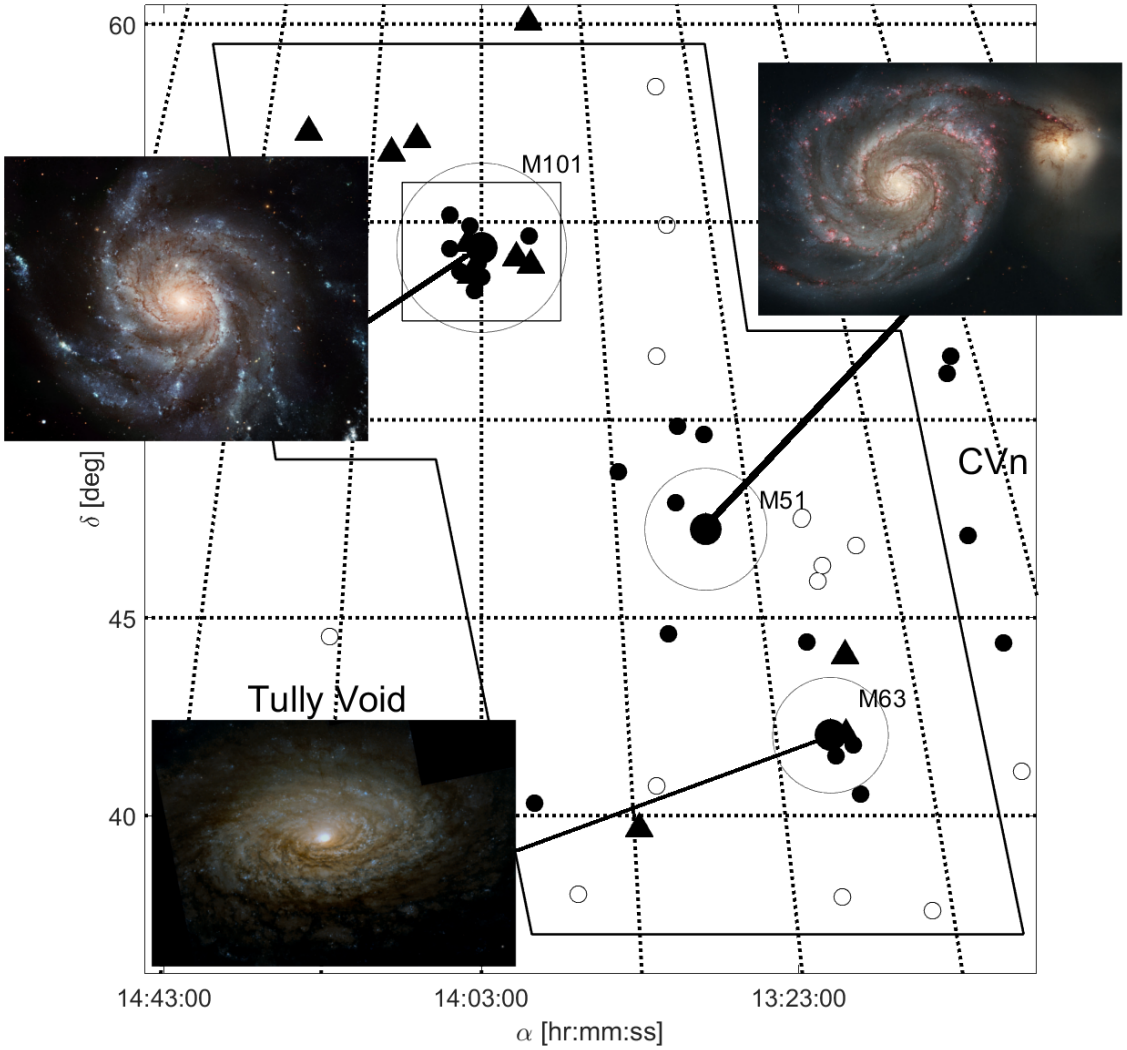


Danieli et al. (2017)

Survey M101 group complex with SDSS

—Müller et al., 2017b, Astronomy & Astrophysics, 602, 119—

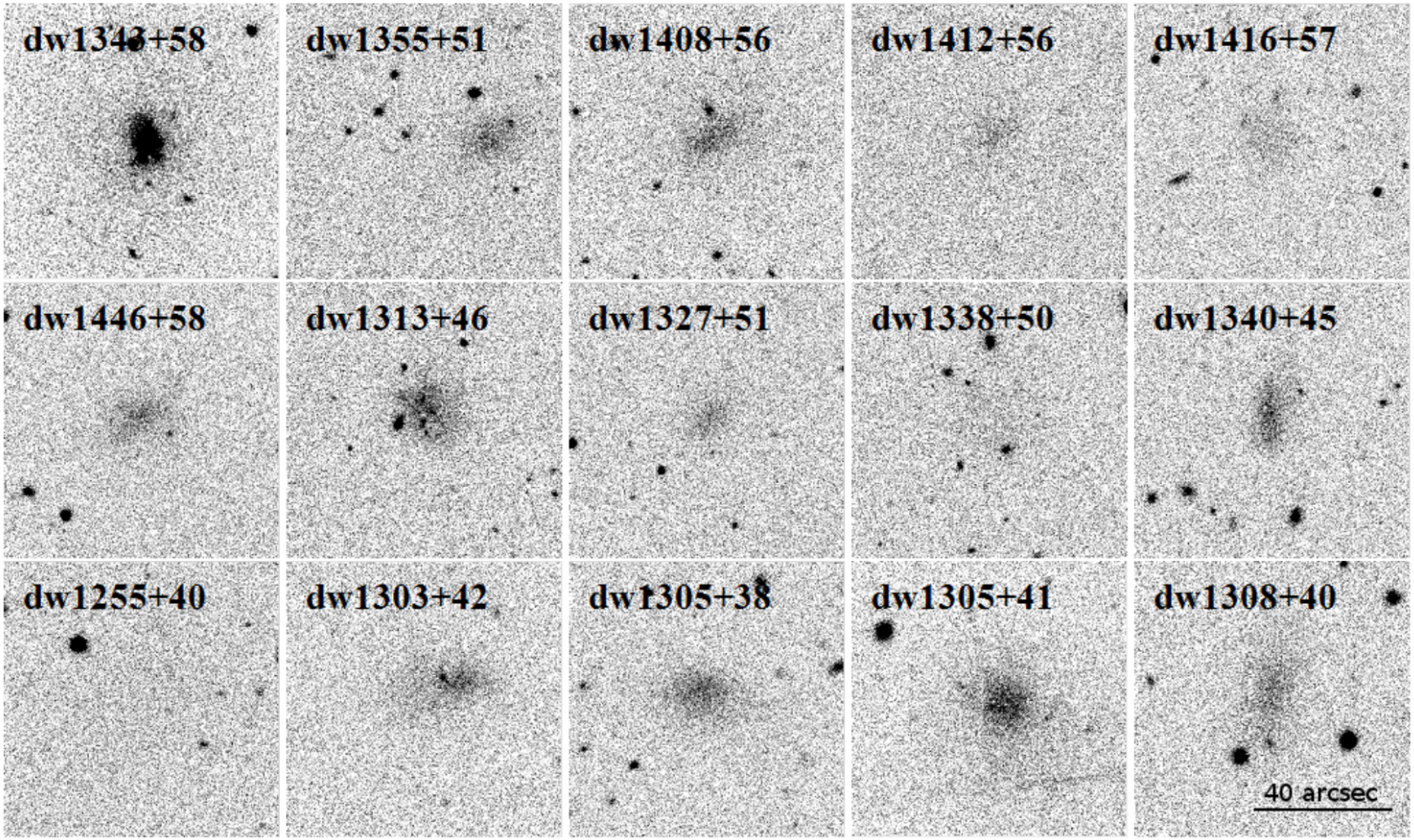
Survey M101 group complex (SDSS)



- Survey M101 group complex (SDSS)
- Subgroups:
  M 101 (7.0 Mpc),
  M 51 (8.6 Mpc),
  M 63 (9.0 Mpc)
- 28 known group members
- 330 deg^2 field, g and r band, visual search

Müller et al. (2017b) rectangle: Dragonfly footprint (Merritt et al. 2014)

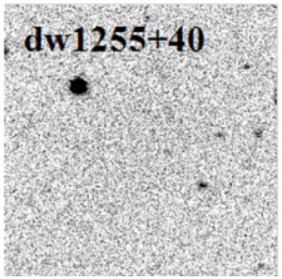
Mosaic of M101 dwarfs

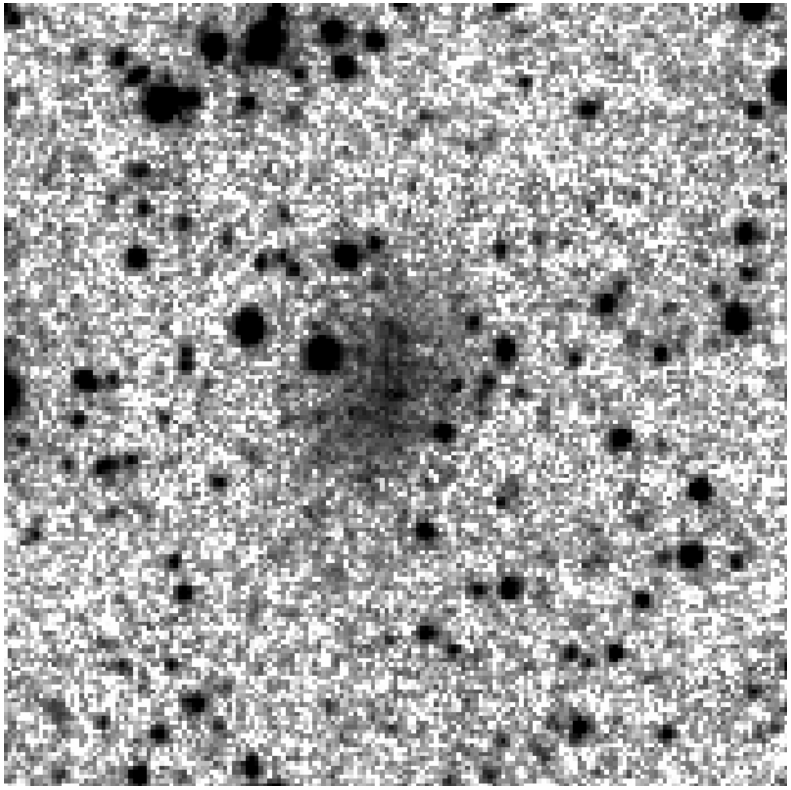


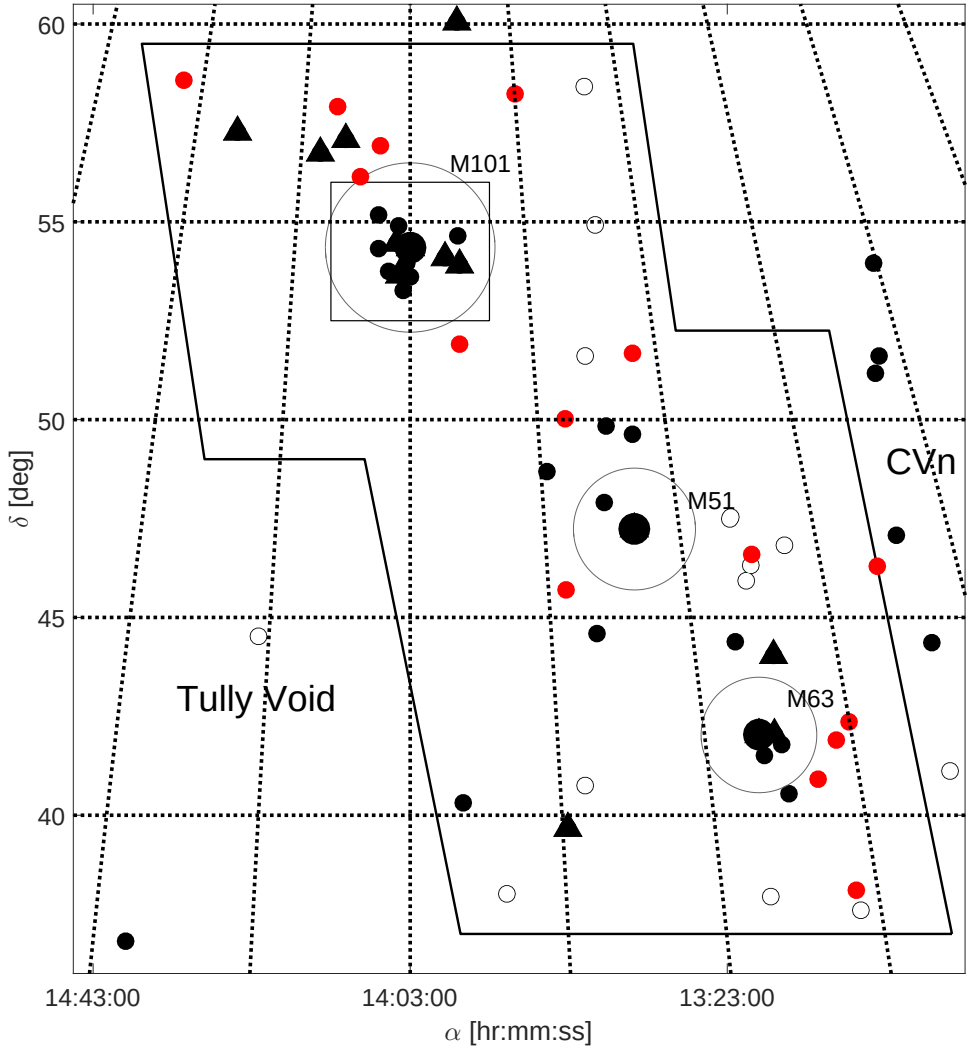
Müller et al. (2017b)

dw1255+40

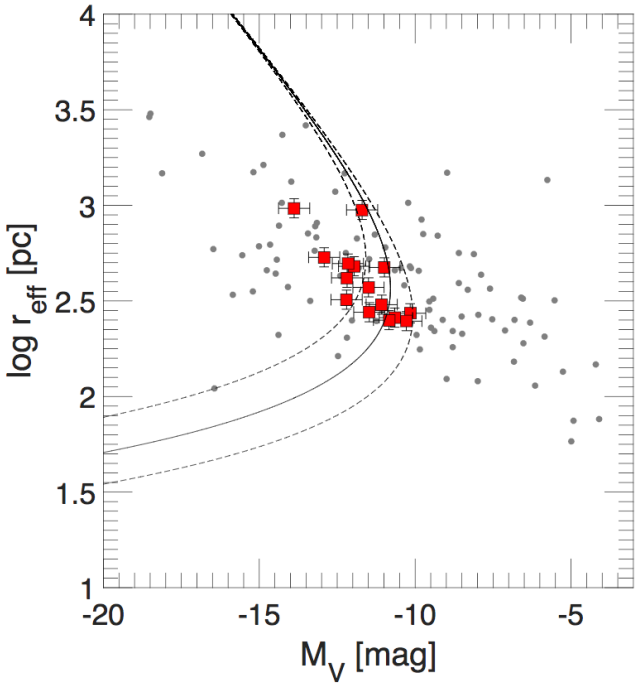
left: Müller et al. (2017b),
right: by courtesy of Aaron Watkins and Chris Mihos.





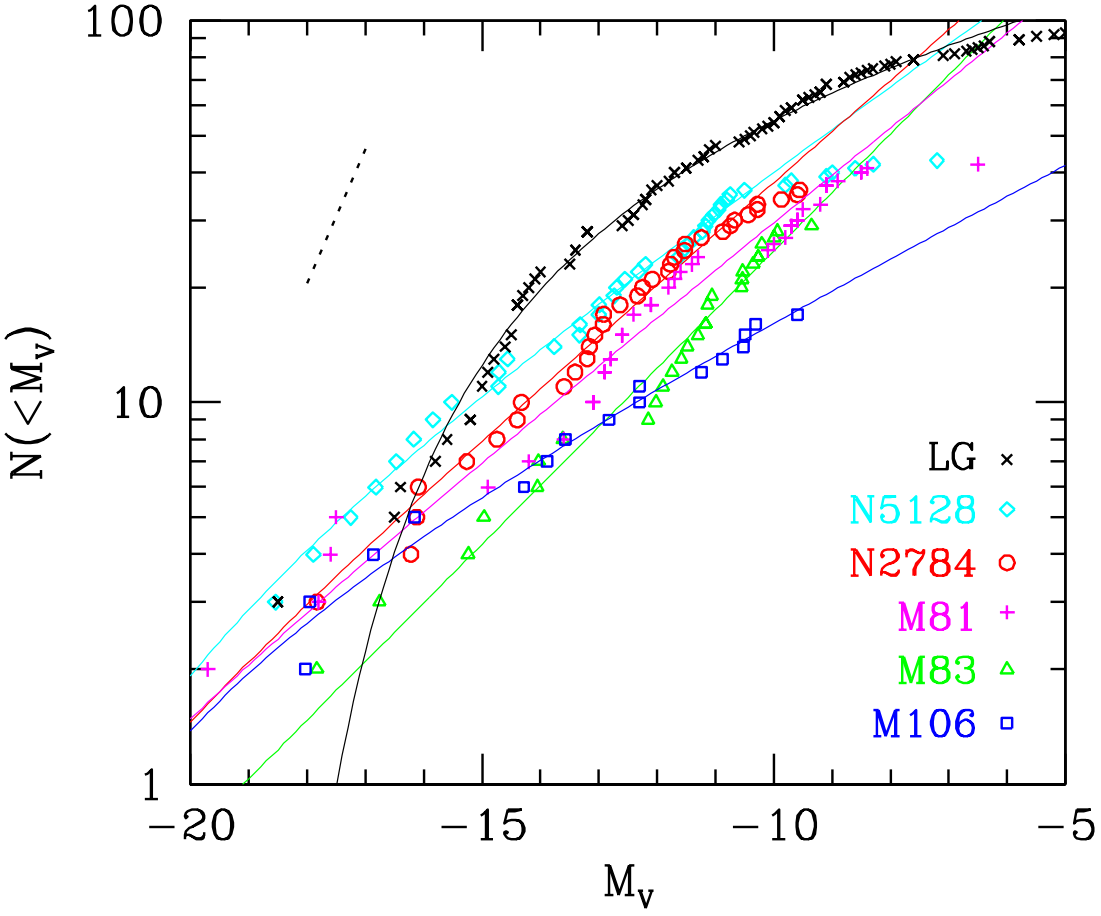


- 15 new dwarf galaxies (red points) (Müller et al. 2017b)
- **Missing satellite problem**



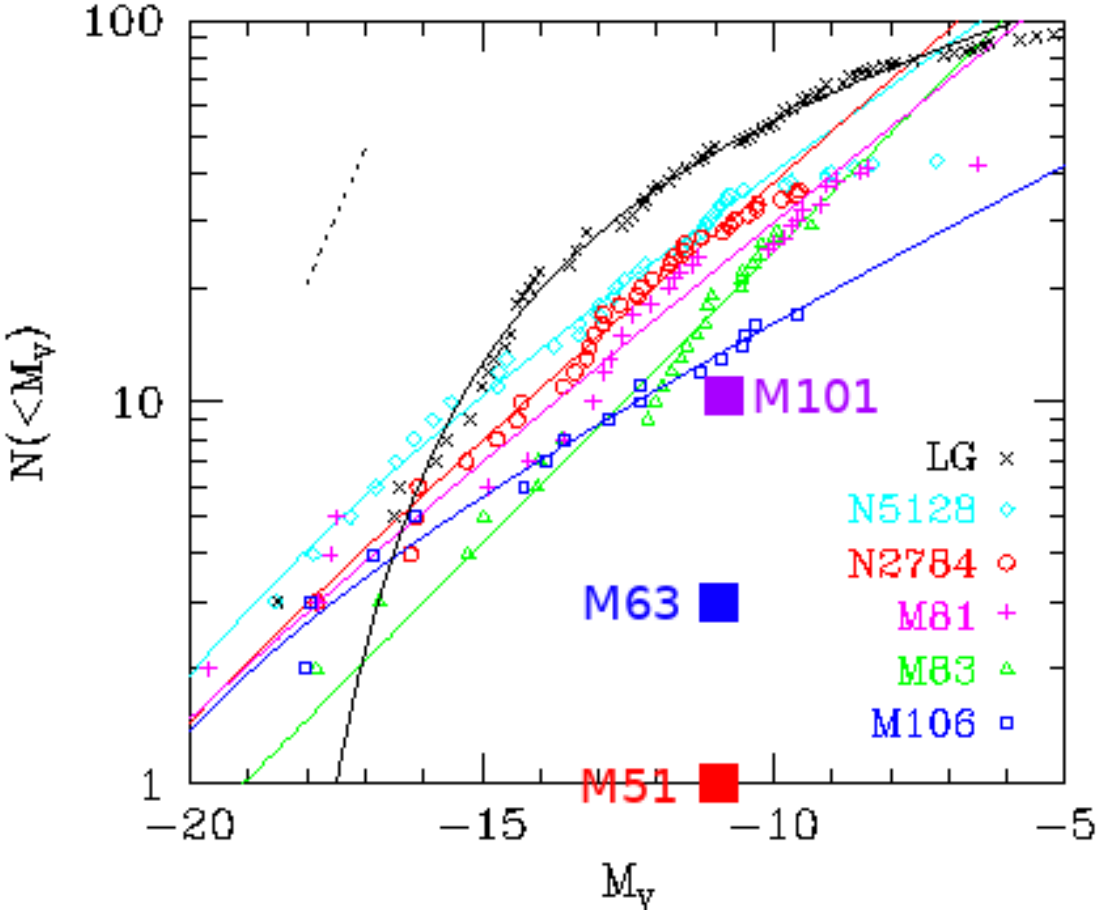
Müller et al. (2017b)

Luminosity Function



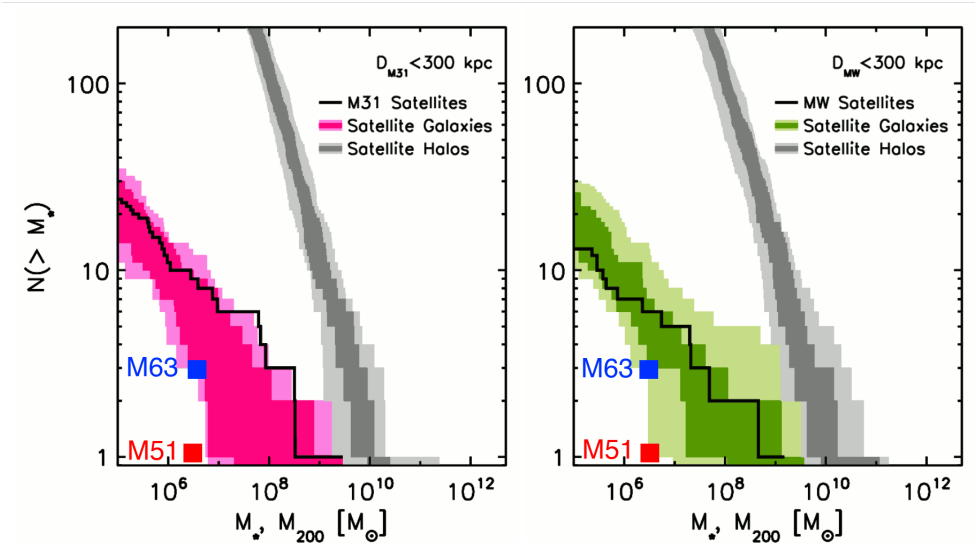
Park et al. (2017)

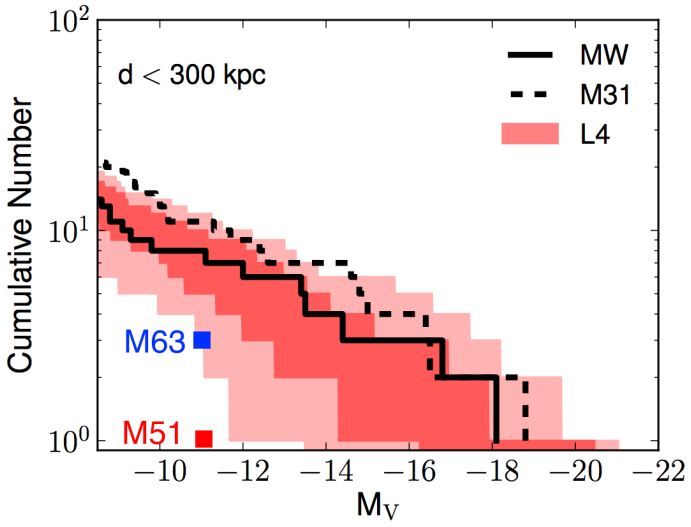
Luminosity Function with the M 101 group



Park et al. (2017)

Yesterdays talks and discussion





Sawala et al. (2016), Simon et al. (2018)

Ultra missing satellite (UMS) problem?

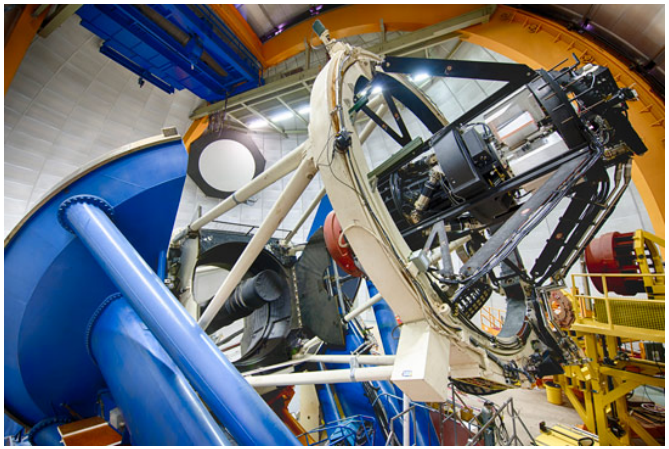
Ultra faint dwarfs (UFD), ultra diffuse galaxies (UDG), ultra compact dwarfs (UCD), ultra red galaxies (URG), ultra dark galaxies (UDG), ultra super saiyajin (USS)...

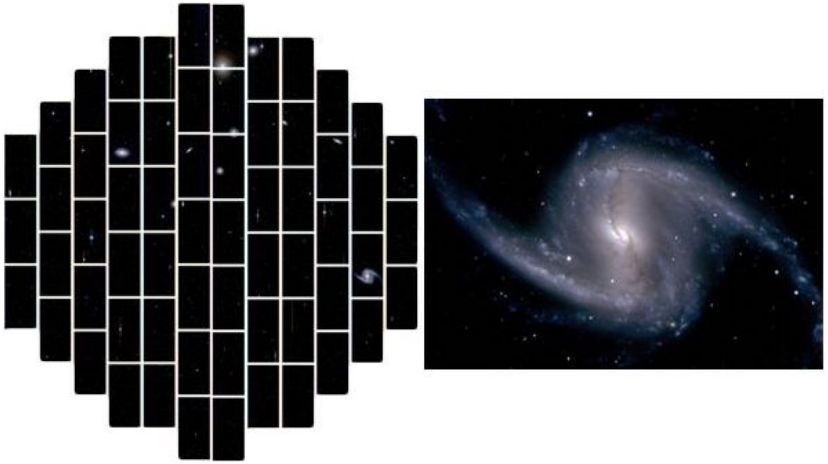
Survey Centaurus group with Dark Energy Camera

—Müller et al., 2015, Astronomy & Astrophysics, 583, 79—
—Müller et al., 2017a, Astronomy & Astrophysics, 597, 7—
—Müller et al., 2018b, Astronomy & Astrophysics, accepted—

Dark Energy Camera

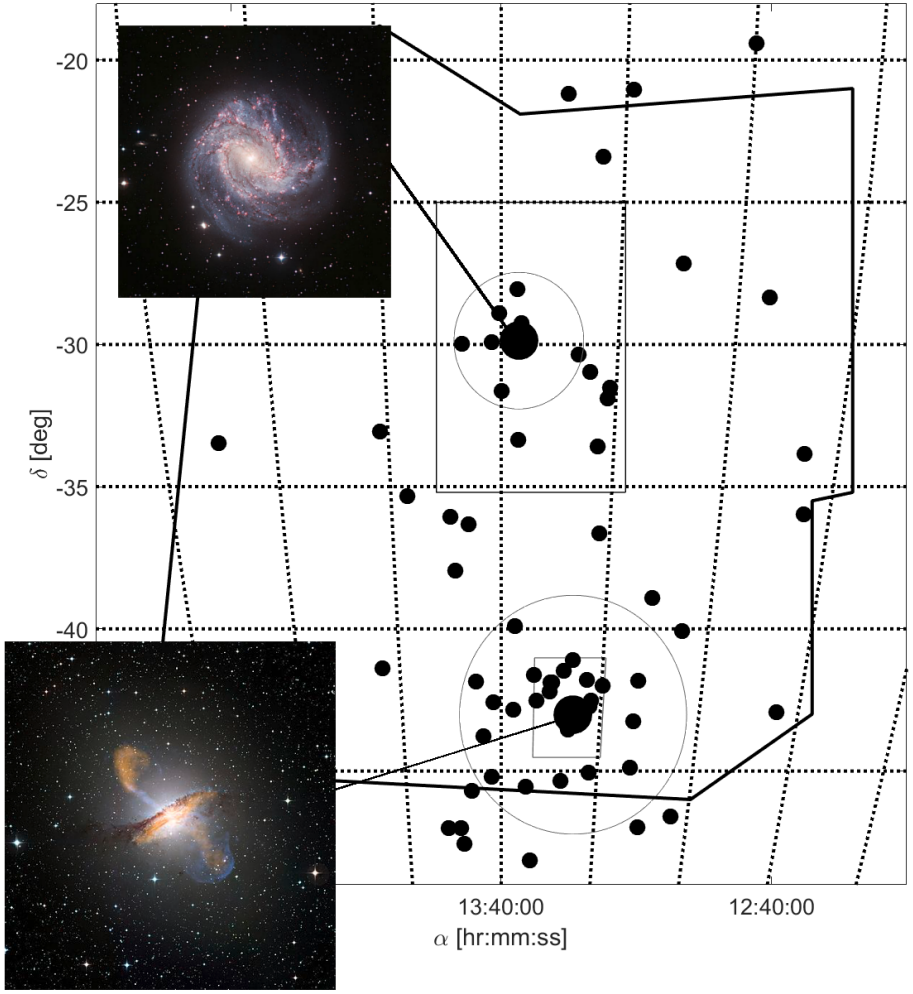
- Dedicated Cen A survey in 2014,2015
- Blanco 4-m telescope at CTIO
- 520 megapixels (3 deg^2), 62x 2048x4096 CCDs
- 0.263"/px resolution





http://www.noao.edu/icarchives/all.php

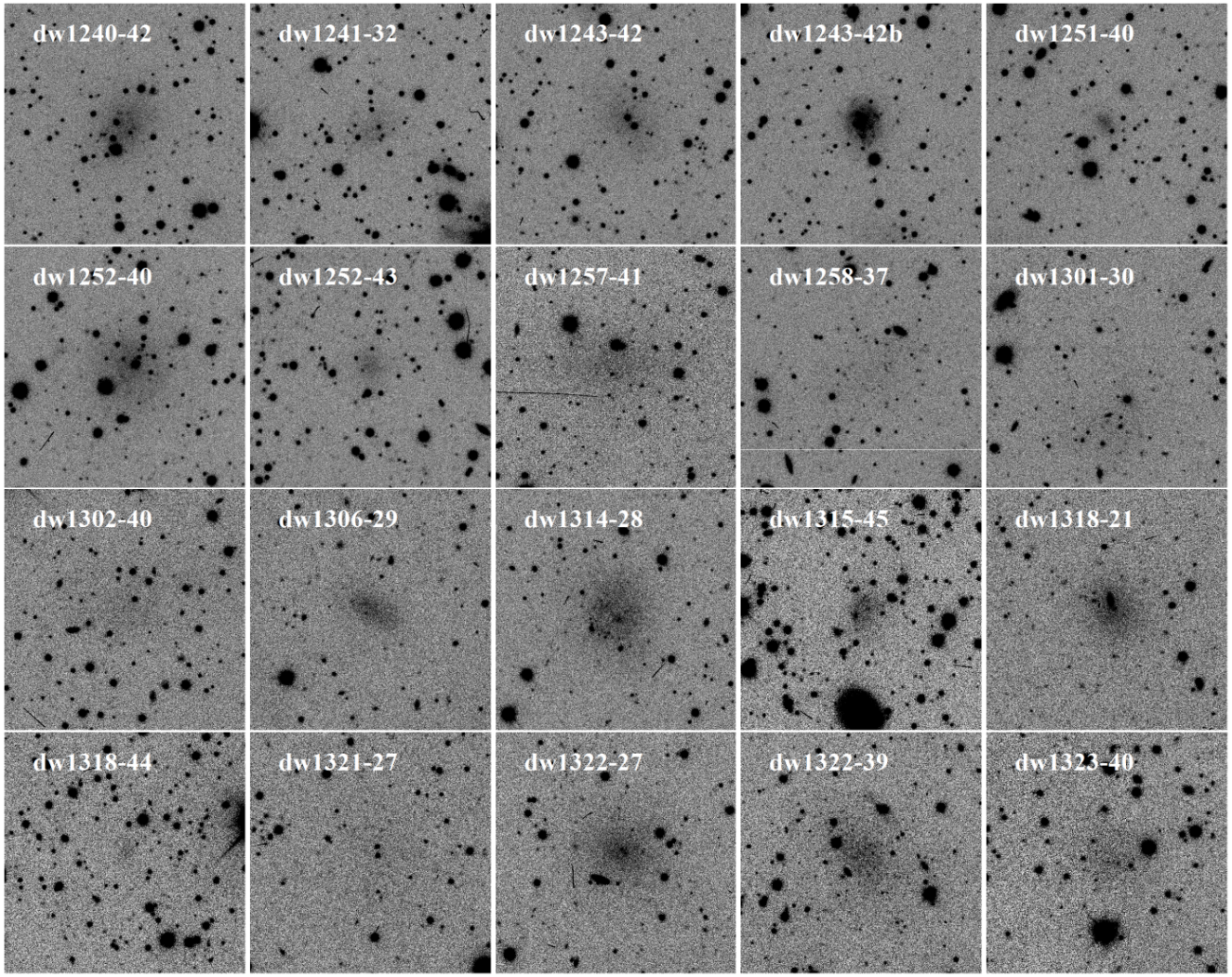
Survey Cen A group (DECam)



- Survey Centaurus A (DECam)
- Subgroups: Cen A (4 Mpc), M 83 (5 Mpc)
- 50 known group members
- 500 deg^2 field, g and r band
- Cen A: two parallel planes (Tully et al. 2015)

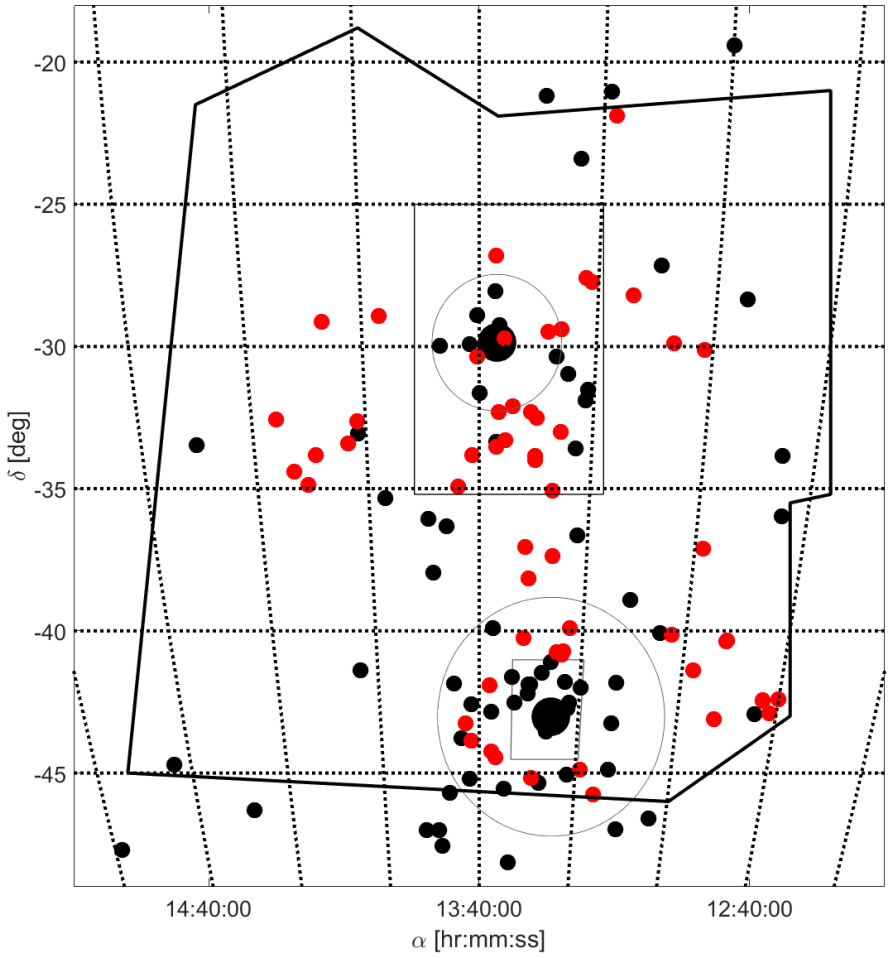
Gray rectangle: PiSCES footprint (Crnojevic et al. 2015, Sand et al. 2014)

Mosaic of some Cen A dwarfs

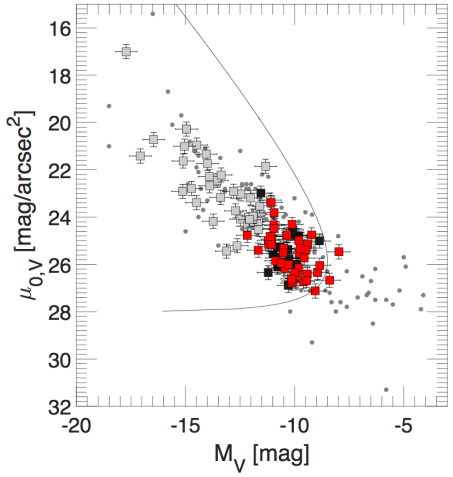


20 out of 36 dwarf candidates from Müller et al. (2017a)

Survey Cen A group (DECam)

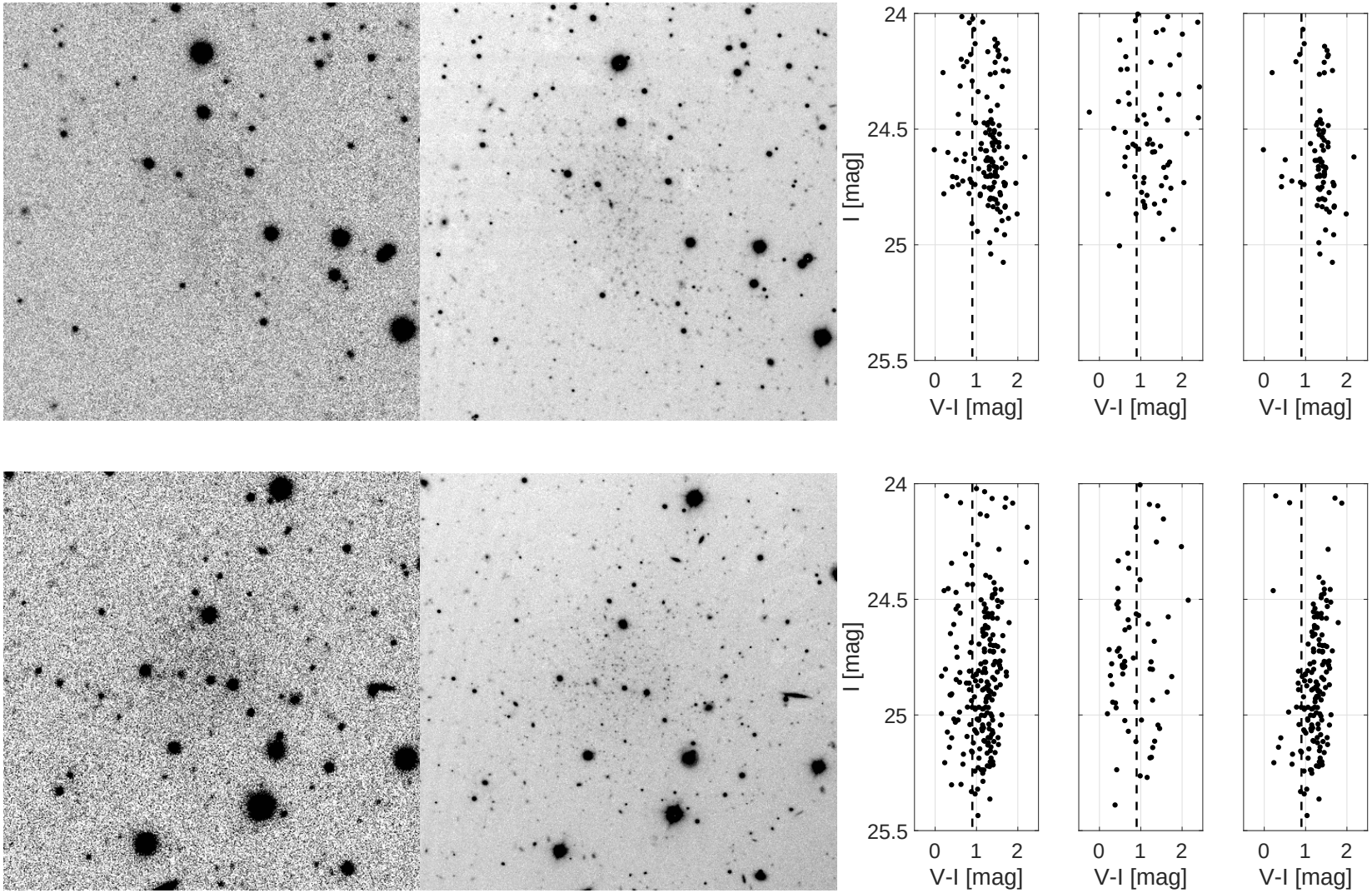


- 57 new unresolved dwarf galaxies (red points), doubling current dwarf population
- Lopsided distribution (Libeskind et al. 2016, Pawlowski et al. 2017)



Müller et al. (2015, 2017a)

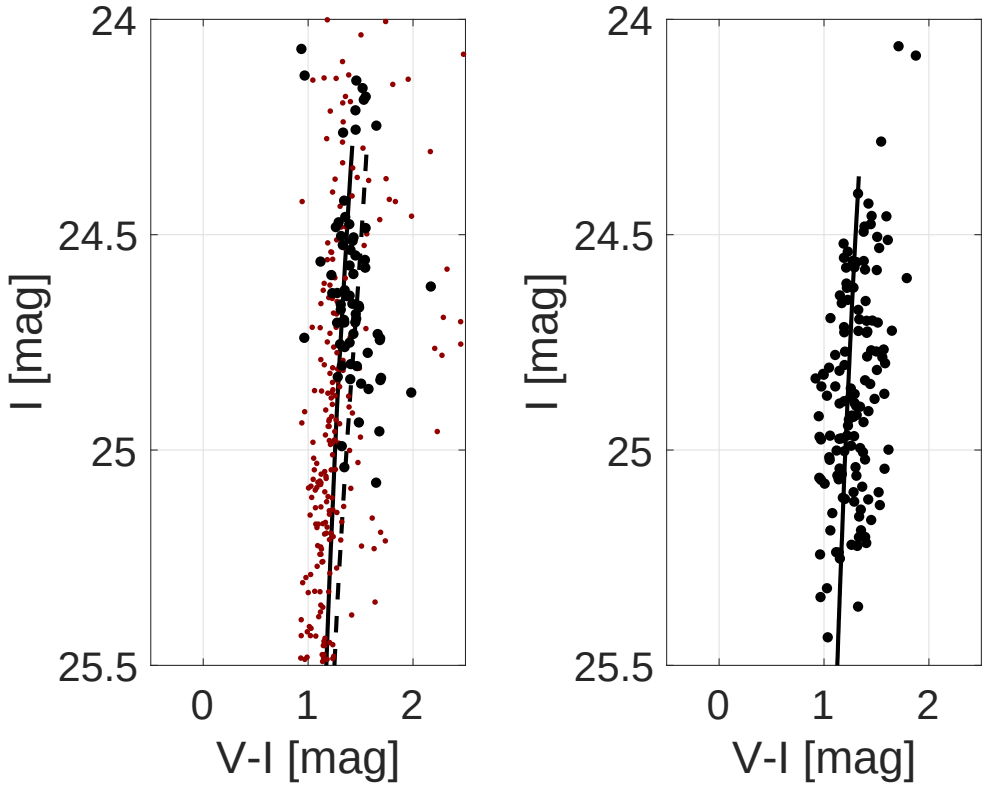
VLT FORS2 observations (M 83 subgroup)

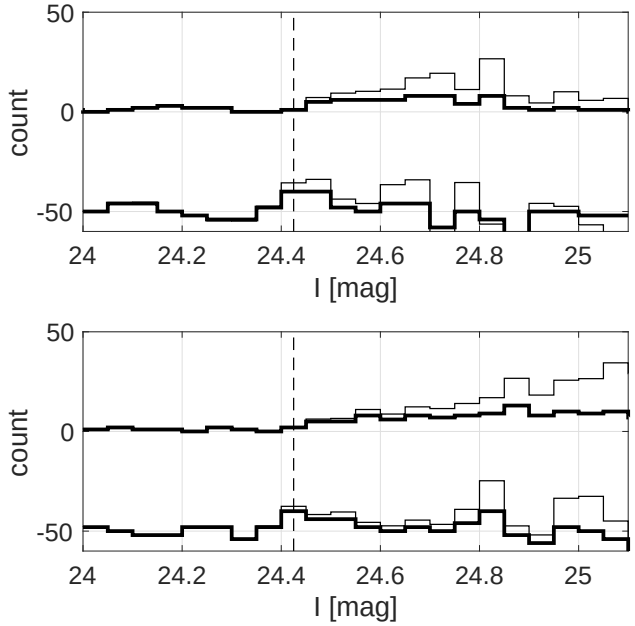


Müller et al. (2018b)

Distance and metallicity

Left: Isochrones (in red HST data from Carrillo et al. 2017), right: Luminosity function.





D=5.03 Mpc (HST: 5.01 Mpc Carrillo et al. 2017), D=5.06 Mpc

[Fe/H]=-1.8 dex, [Fe/H]=-2.2 dex

Müller et al. (2018b)

- Dwarf galaxies and cosmology
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- Planes-of-satellites problem
- Outlook and Summary

Dwarf satellite plane problem

Therefore, the defining characteristics of the satellite plane problem are that:

- the satellites are distributed in a highly flattened, *planar* structure in three-dimensional space,
- the *majority* of the satellites *co-orbit* in the same sense,
- and these satellites orbit *within* the plane, indicating that the plane is not just a transient alignment.

Definition:

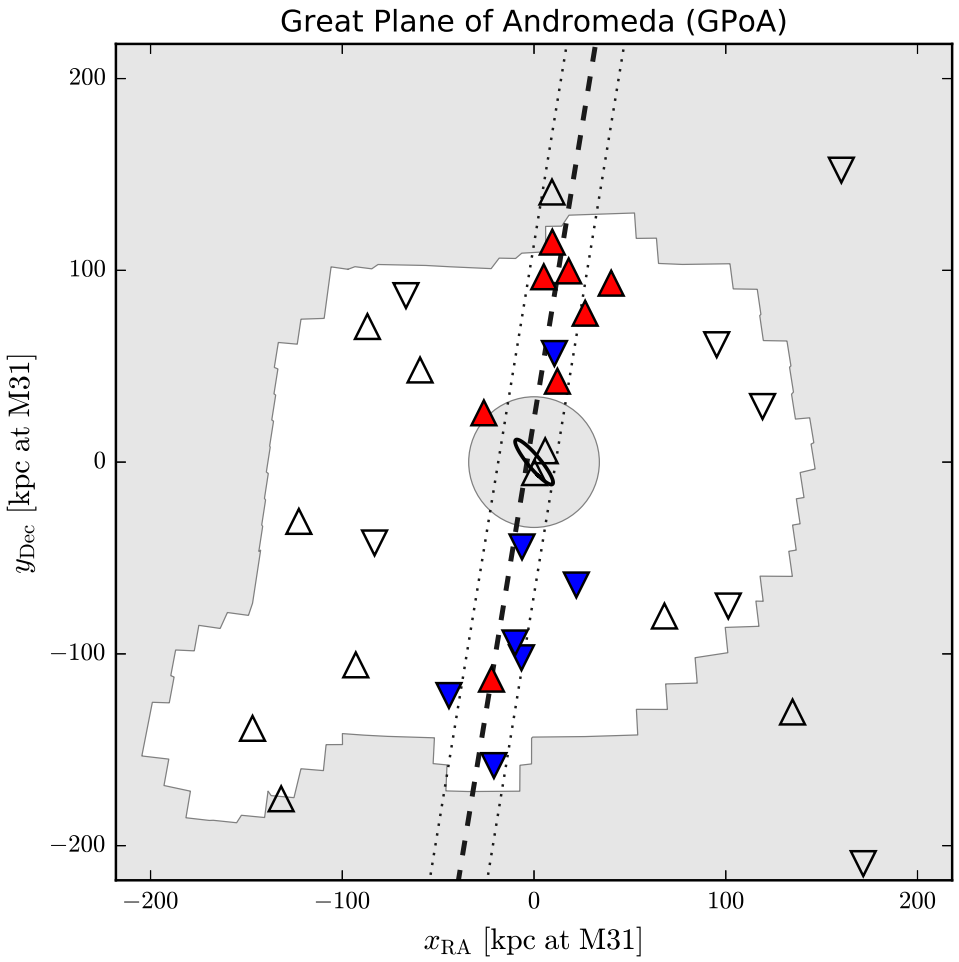
phase-space correlated flattened structure =: plane-of-satellites

Pawlowski et al. (2015)

GPoA around the Andromeda galaxy

Ibata et al. (2013); Image credit: Adam Evans

GPoA around the Andromeda galaxy

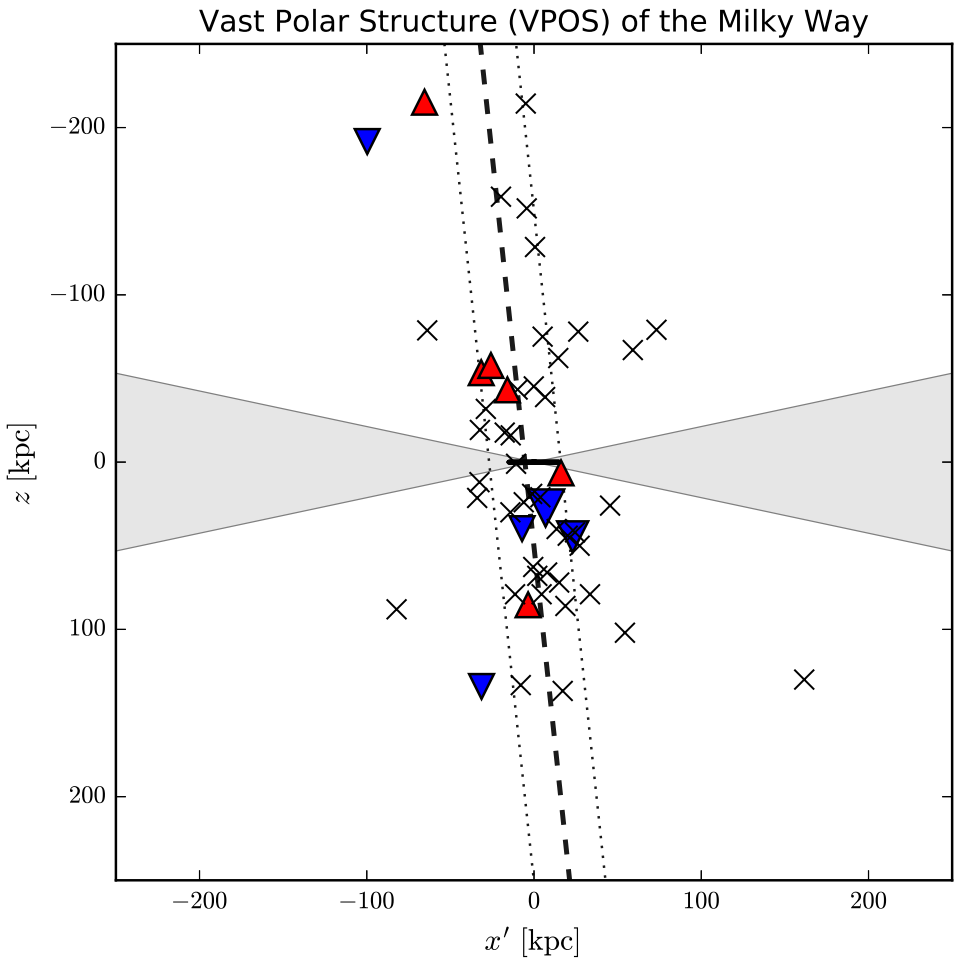


Pawlowski (2018)

VPOS around the Milky Way

Pawlowski et al. (2012); Image credit: ESO

VPOS around the Milky Way



Pawlowski (2018)

Centaurus system

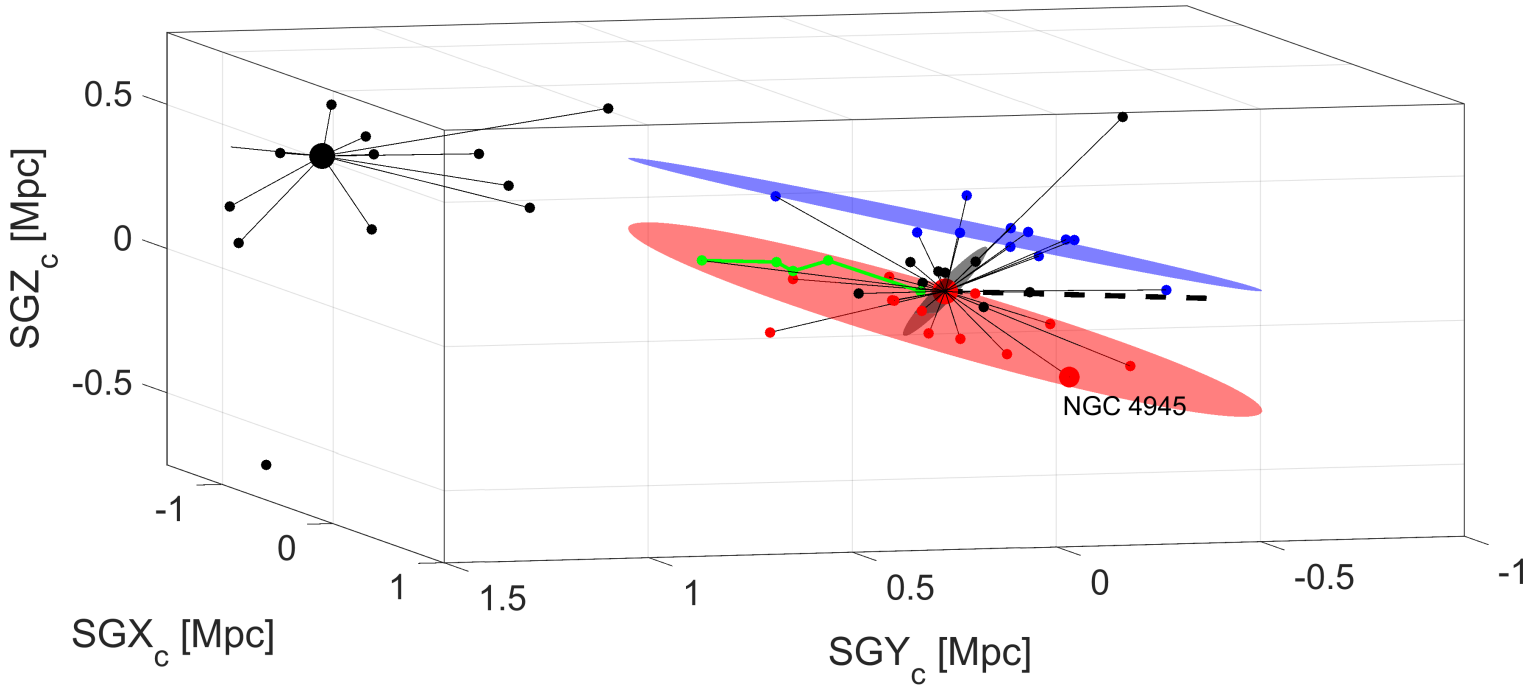
—Müller et al., 2016, Astronomy & Astrophysics, 595, 119—
—Müller (incl. Lelli) et al., 2018a, Science, 359, 534—

Centaurus A

Müller et al. (2018a); Image credit: ESO

3D Distribution Cen A

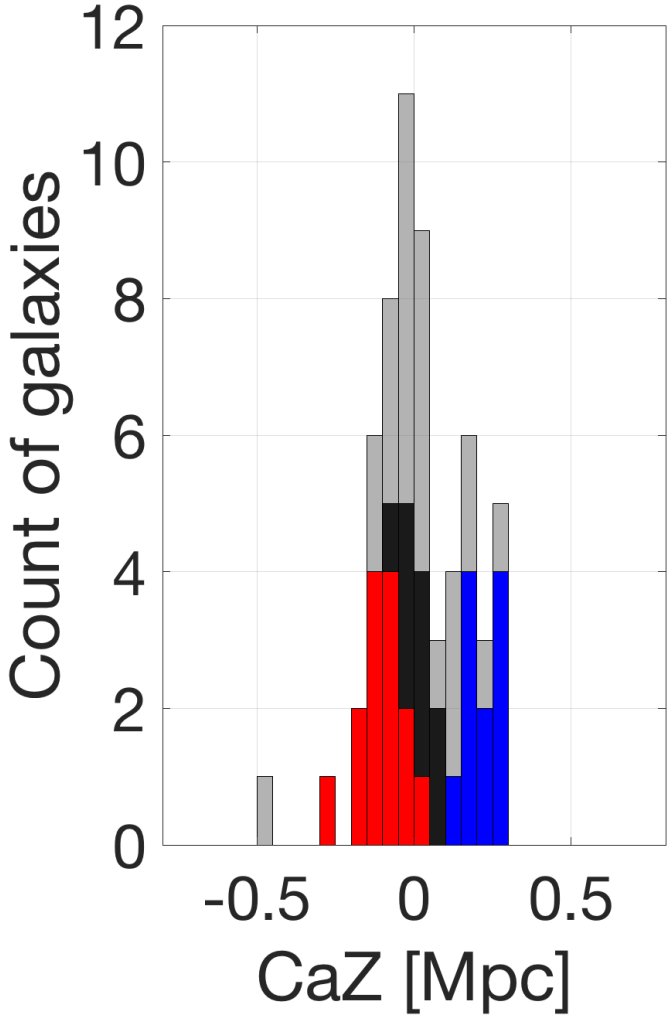
- Planes perpendicular to Cen A disc (like VPOS)
- Tidal dwarf PISCeS-dw3 parallel to planes (like VPOS)
- Planes pointing towards M 83 subgroup (like GPoA)



Müller, et al. (2016)

One plane only

New satellites by:
Müller et al. (2015, 2017a) (gray)
and Crnojevic et al. (2016) (black).



Müller, et al. (2016)

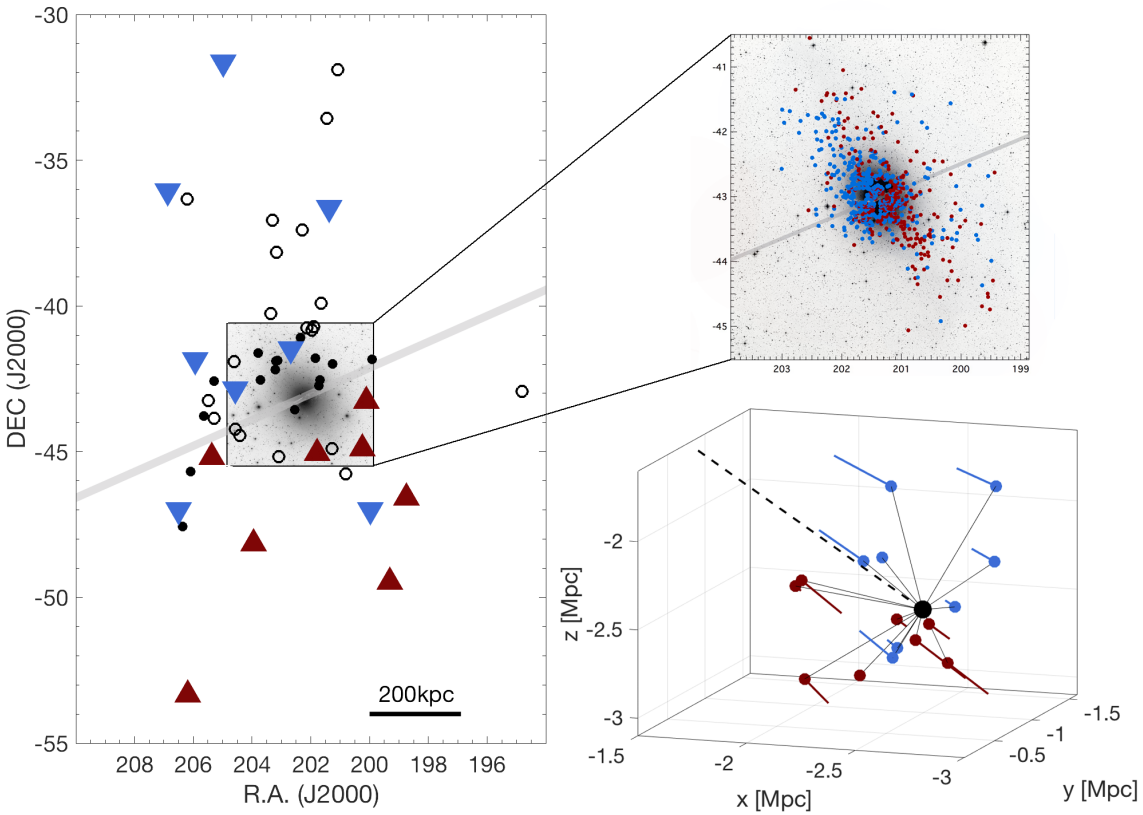
Cen A dwarf satellite plane problem?

Plane problem:

- planar distrubtion ✓
- coherent movement?
- co-orbiting *within* plane?

Plane is seen edge-on

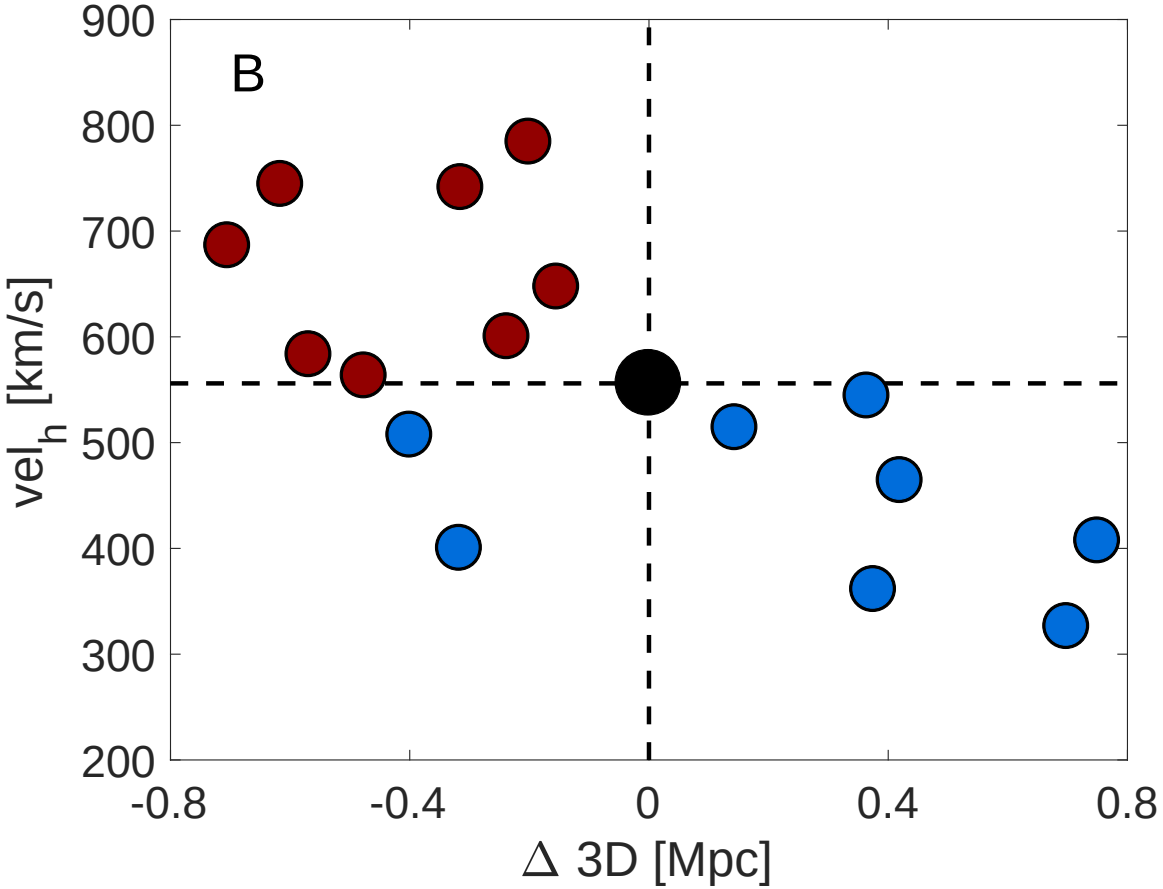
Coherent movement



- 16 (out of ≈ 30) satellites have measured heliocentric velocities
- 14 out of 16 satellites share coherent movement
- Oddity: 1200 planetary nebula velocities – share same trend (Walsh et al. 2015)

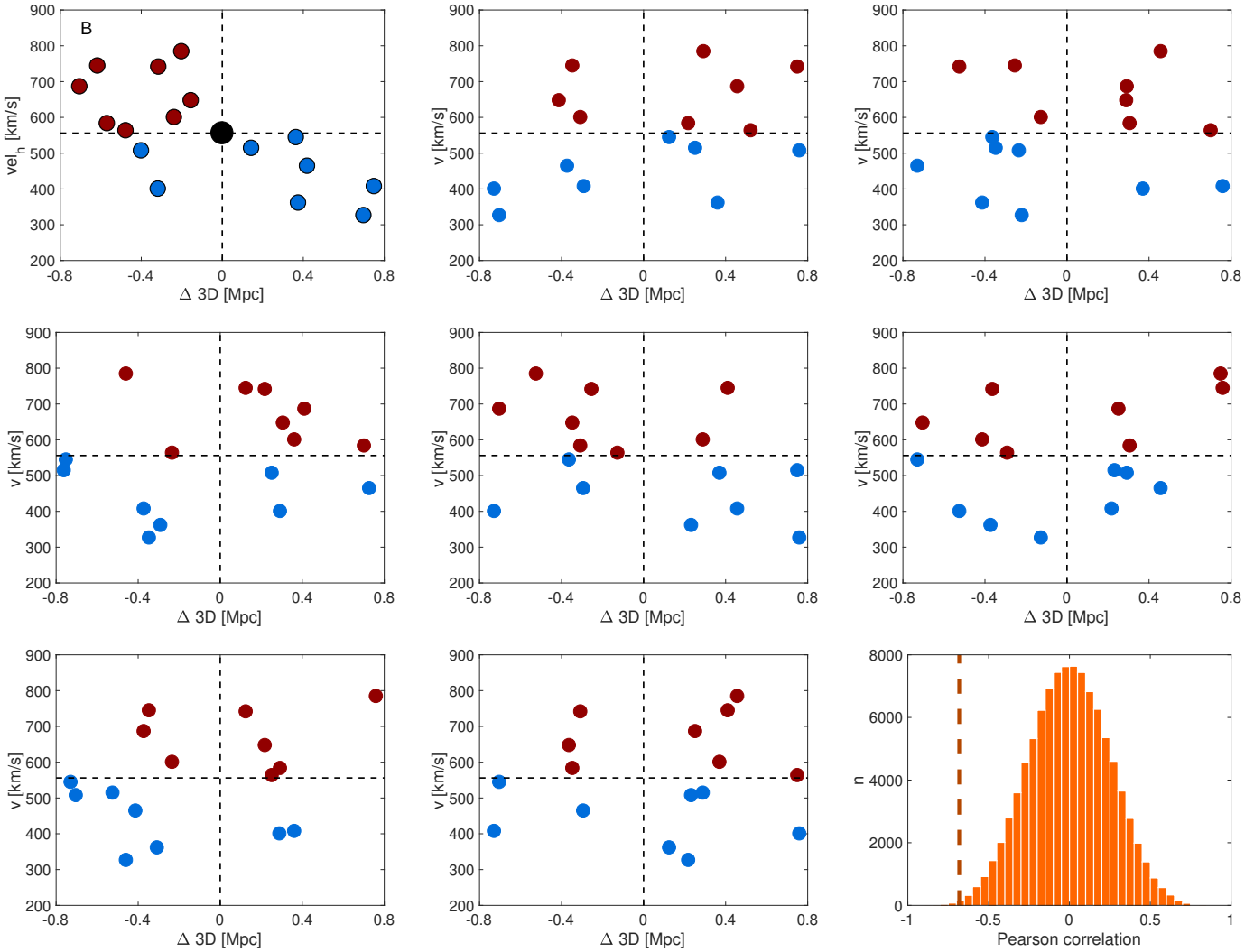
Müller, et al. 2018a, Science 359, 534

Coherent movement



Müller, et al. 2018a, Science 359, 534

Coherent movement (randomized)



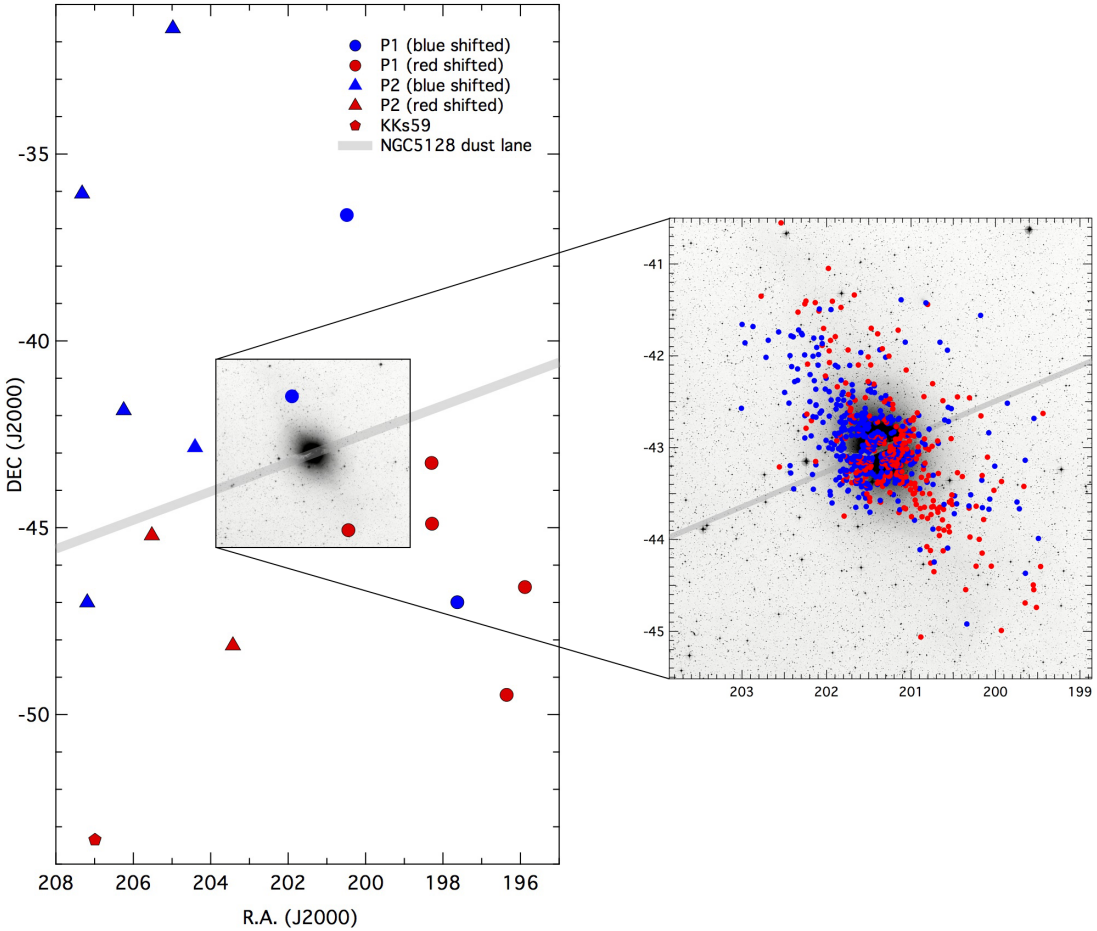
Müller, et al. 2018a, Science 359, 534

Cen A dwarf satellite plane problem?

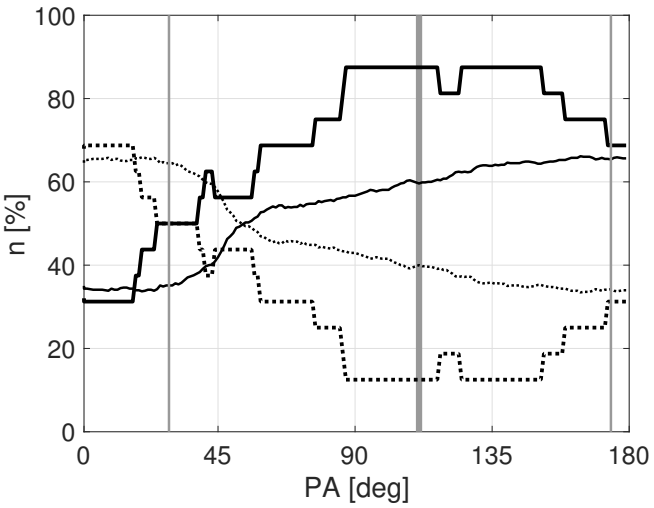
Plane problem:

- planar distrubtion ✓
- coherent movement ✓
- co-orbiting *within* plane?

Co-orbiting within plane



- Movement of satellites aligned with planes
- Movement of PNe (almost) aligned with planes



Müller, et al. 2018a, Science 359, 534

Cen A dwarf satellite plane problem?

Plane problem:

- planar distrubtion ✓
- coherent movement ✓
- co-orbiting *within* plane ✓

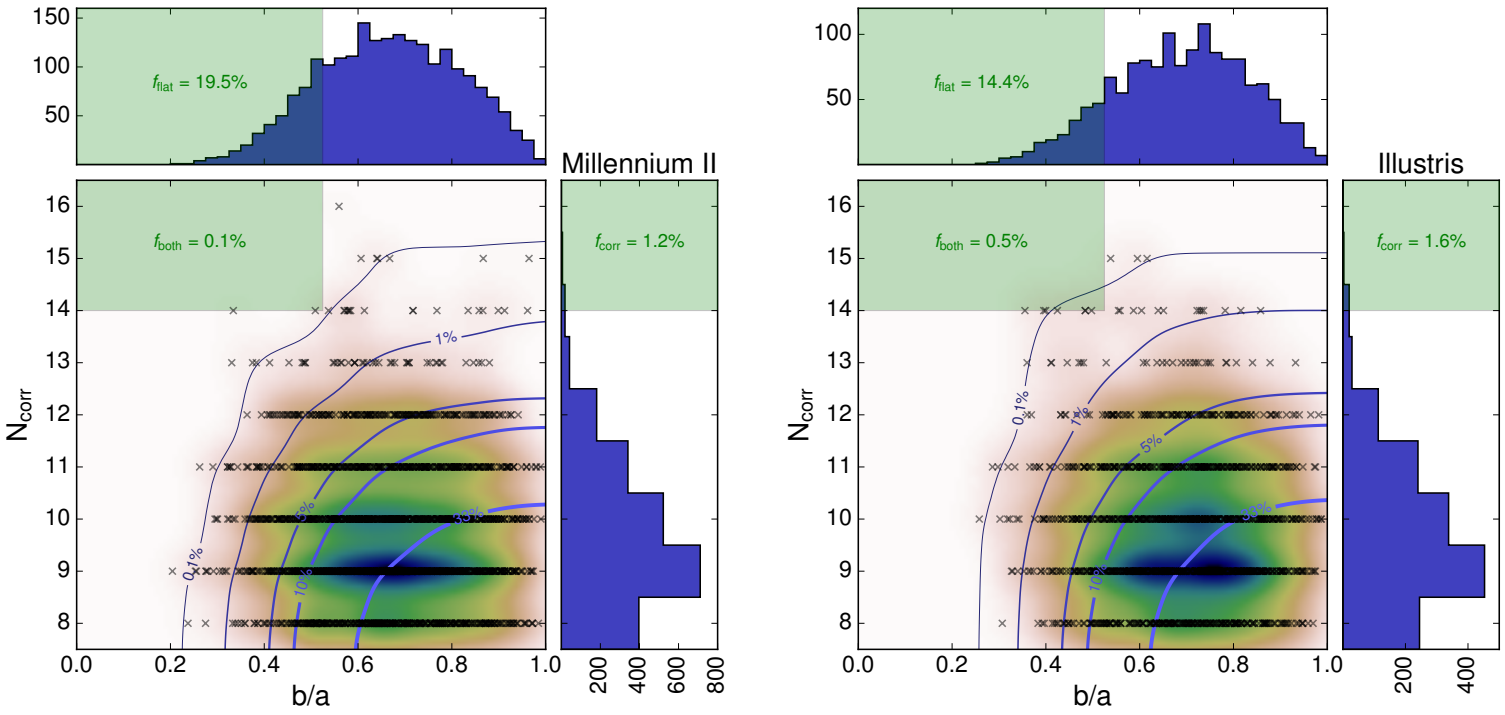
The Local Group is not unique!

Towards new cosmology?

Remember (for MW and M31):
$<1\%$ chance in ΛCDM.

Comparison to ΛCDM (Müller, et al. 2018a)

Measured around Cen A: b/a=0.52 and $N_{corr} = 14$.
Millenium-II (DM-only): 2 out of 2220 Cen A-like realizations.
Illustris (incl. baryons): 7 out of 1441 Cen A-like realizations.

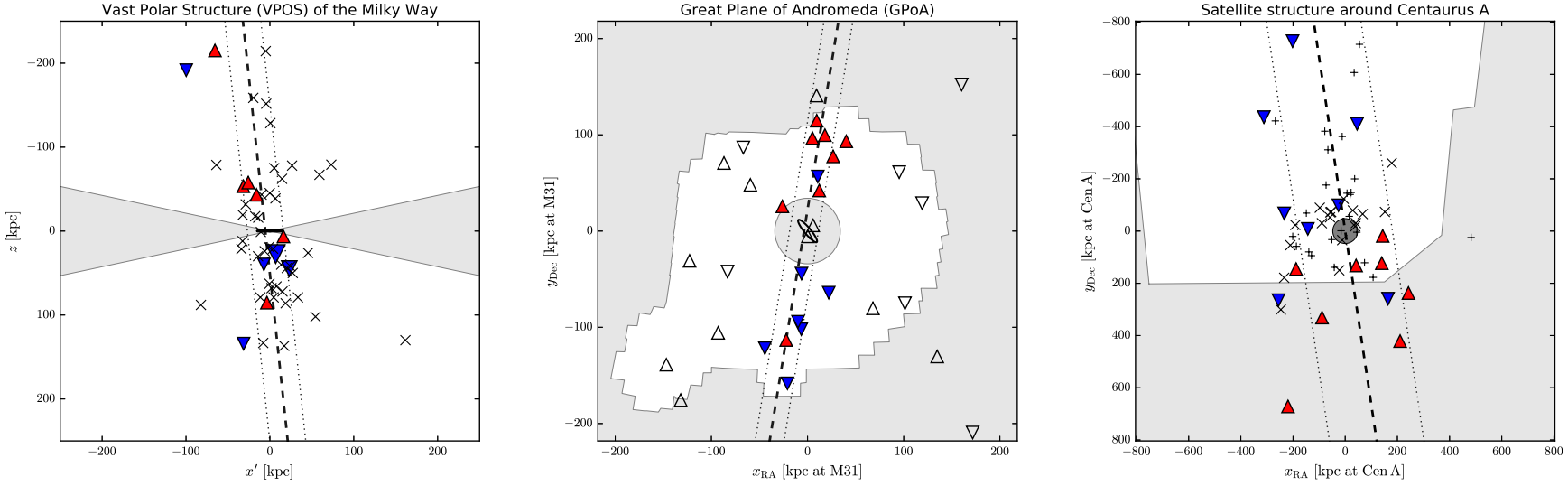


Müller, et al. 2018a, Science 359, 534

Known co-rotating planes in the universe

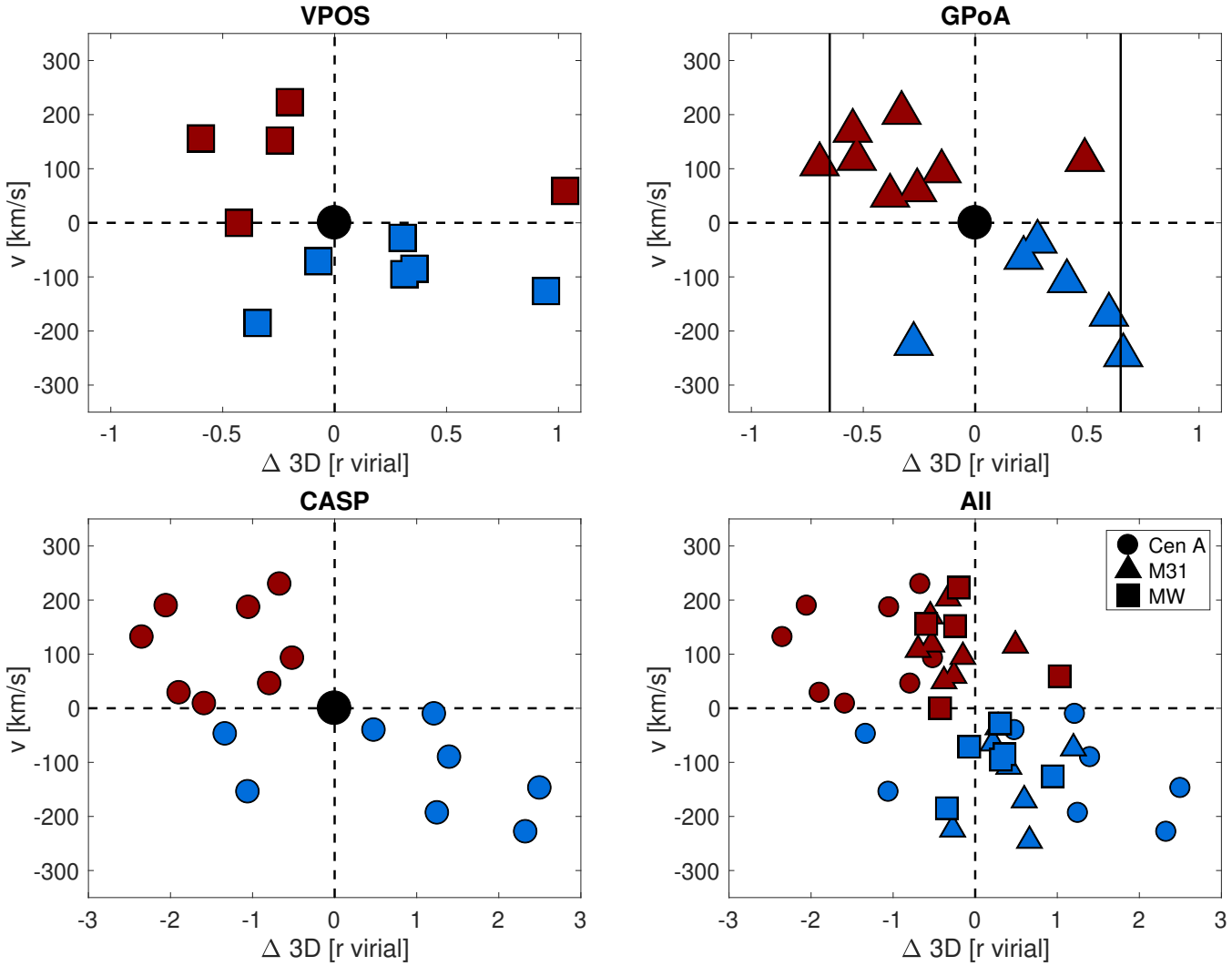
Number of co-rotating satellites:

- VPOS: 8/11 satellites (Pawlowski et al. 2012).
- GPoA: 13/15 satellites (Ibata et al. 2013).
- CASP: 14/16 satellites (Müller et al. 2018a).



Pawlowski (2018)

Known co-rotating planes in the universe



3 out of 5 nearest hosts contain planes-of-satellites

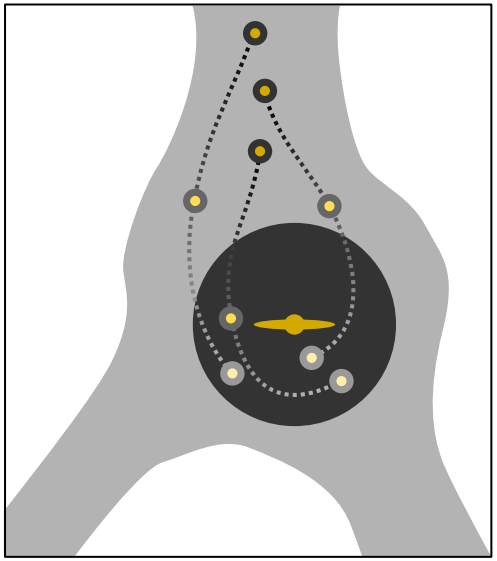
vs.

3 out of 200'000'000 nearest hosts should contain the VPOS, GPoA, and the CASP.

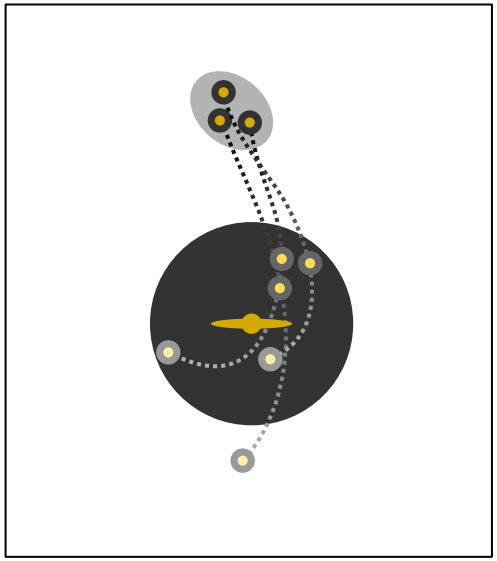
Formation of planar structures?

Three sugested formation scenarios

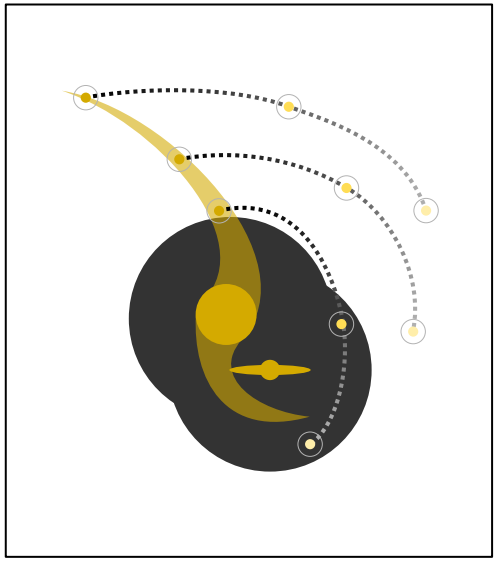
Filamentary Accretion



Group Infall



Tidal Dwarf Galaxies

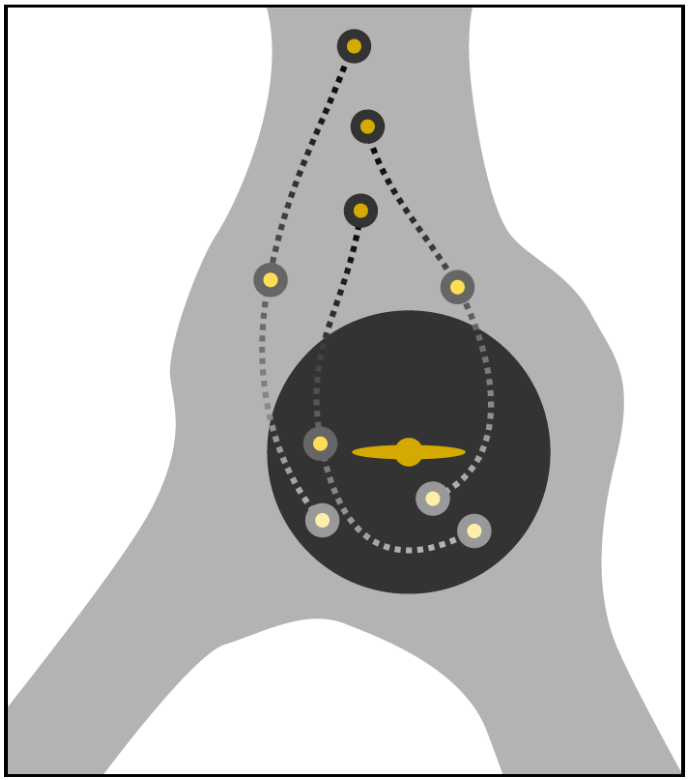


Pawlowski (2018)

Pawlowski (2018)

Filamentary accretion

Filamentary Accretion

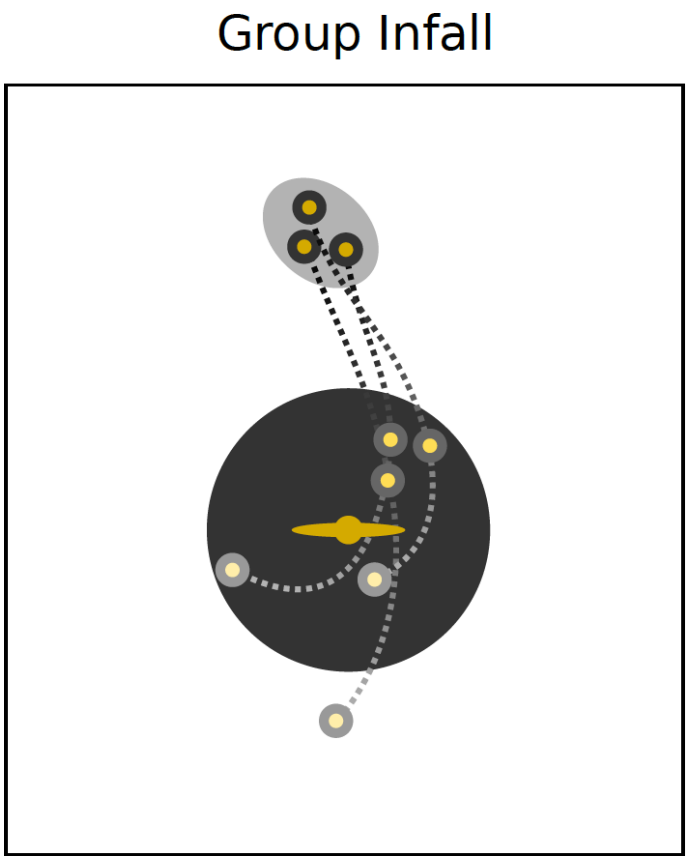


- Can produce transient planar alignments (Buck et al. 2015).
- Filaments too thick (thicker than 200 kpc).
- Better resolution: worse results.
- Baryonic physics: no change.
- Self-consistingly implemented in simulations.

Unlikely the cause!

Pawlowski (2018)

Group infall



- Dwarf association accreted in one single event.
- Need 10+ dwarfs in these associations.
- Observations: 3-4 dwarfs per association.
- Need 30 kpc extended associations.
- Observations: 200 kpc extended.
- Self-consistingly implemented in simulations.

Unlikely the cause!

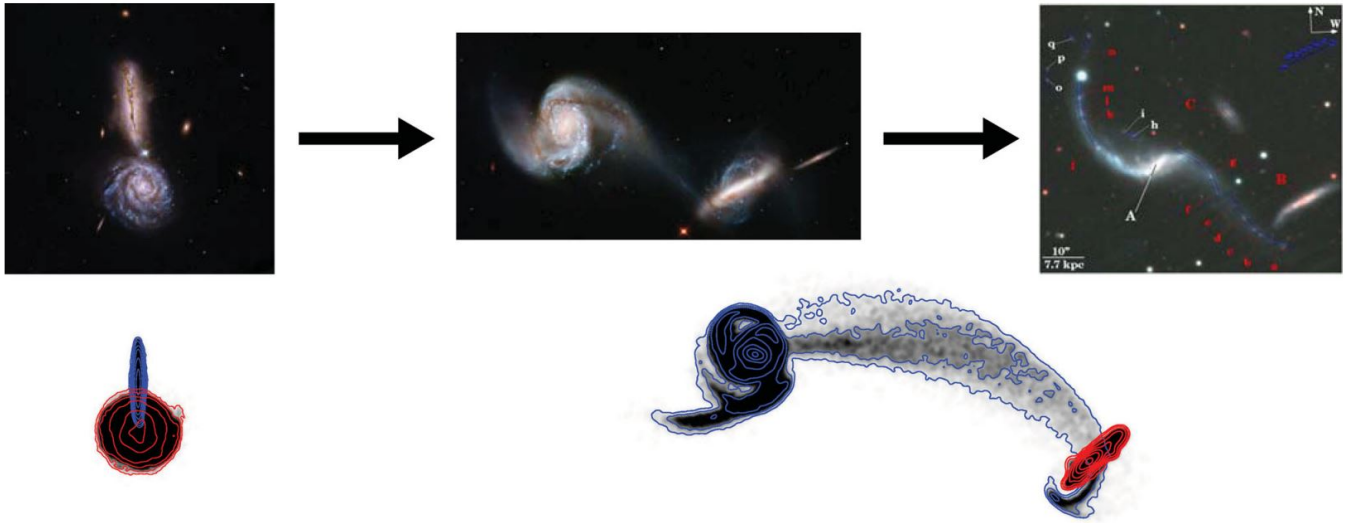
Pawlowski (2018)

Formation of planar structures?

The only way how to make real pizza

Dwarf galaxies as tidal renmants

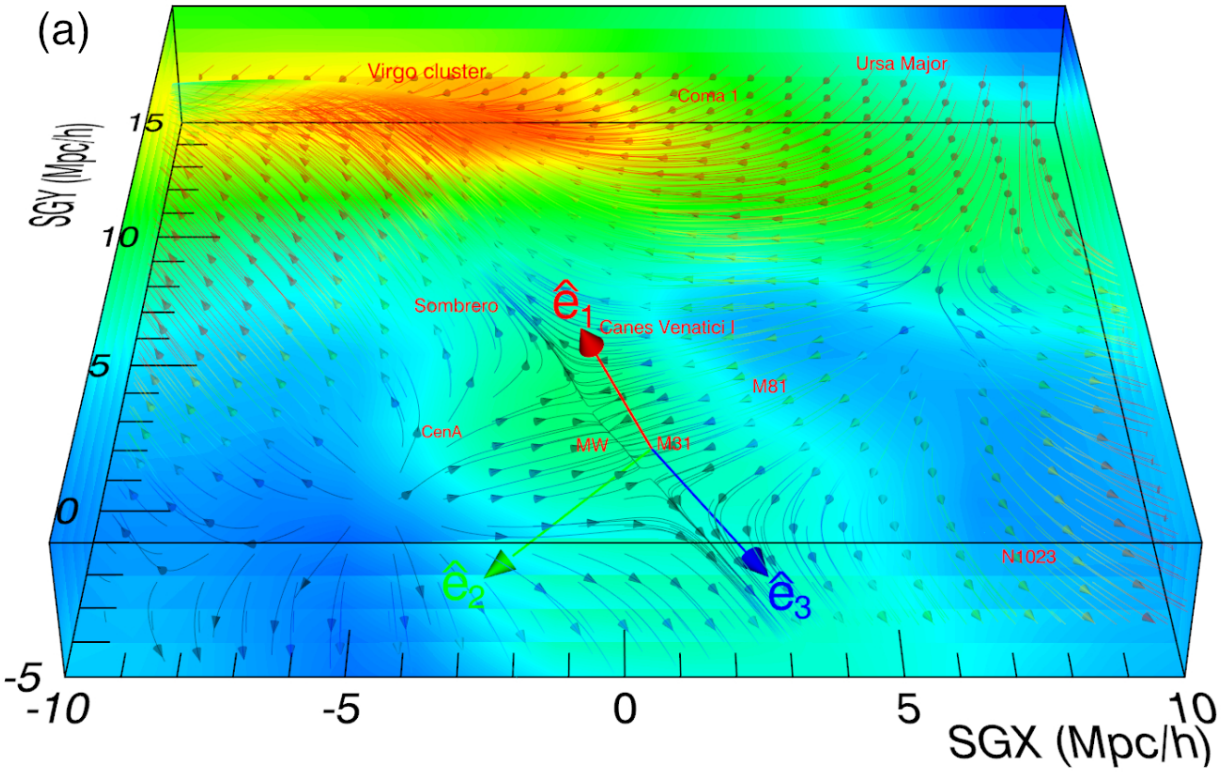
- Dwarf galaxies as TDGs (e.g. Zwicky 1956, Lynden-Bell 1976, Kroupa et al. 2010, Hammer et al. 2013, 2018a)
- TDGs form along plane of tidal interaction and inherit momentum
- Counter rotating TDGs well understood
- Dark Matter free, but show DM behavior. MOND (Milgrom 1983)? DM mass overestimated (Hammer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



Pawlowski et al. (2011, 2012)

Planes induced by LSS

- vpos, GPoA, CASP aligned with border of Local Void.
- Expansion of Local Void & pull of Virgo cluster induce planes.
- Corotation within this framework? Unclear!

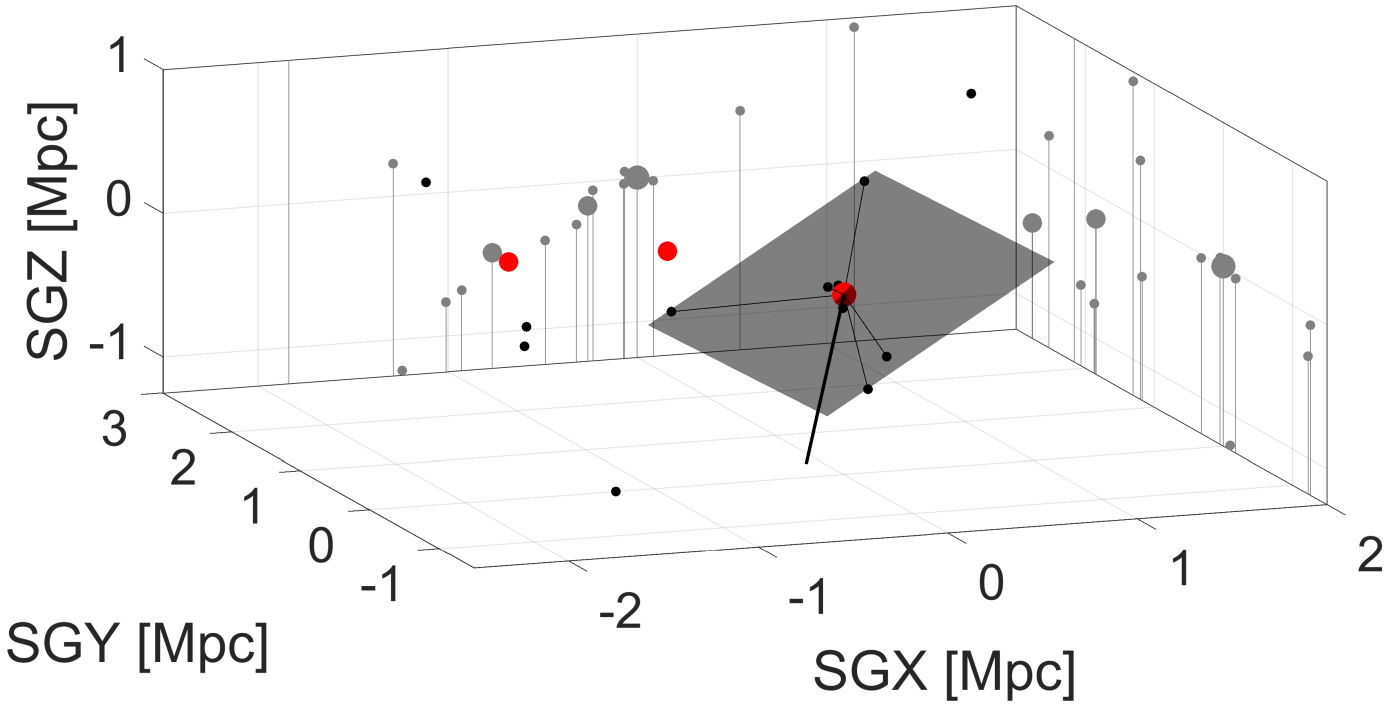


Libeskind et al. (2015)

But wait, there's more!

3D Distribution M 101

- Roughly all galaxies lie in a wall, incl. M 101, M 51, and M 63.
- Wall stretched over 3 Mpc.
- *rms* ≈ 70 kpc for whole filament, *rms* ≈ 45 kpc for M 101 vicinity. (Typical 1 Mpc in simulations)

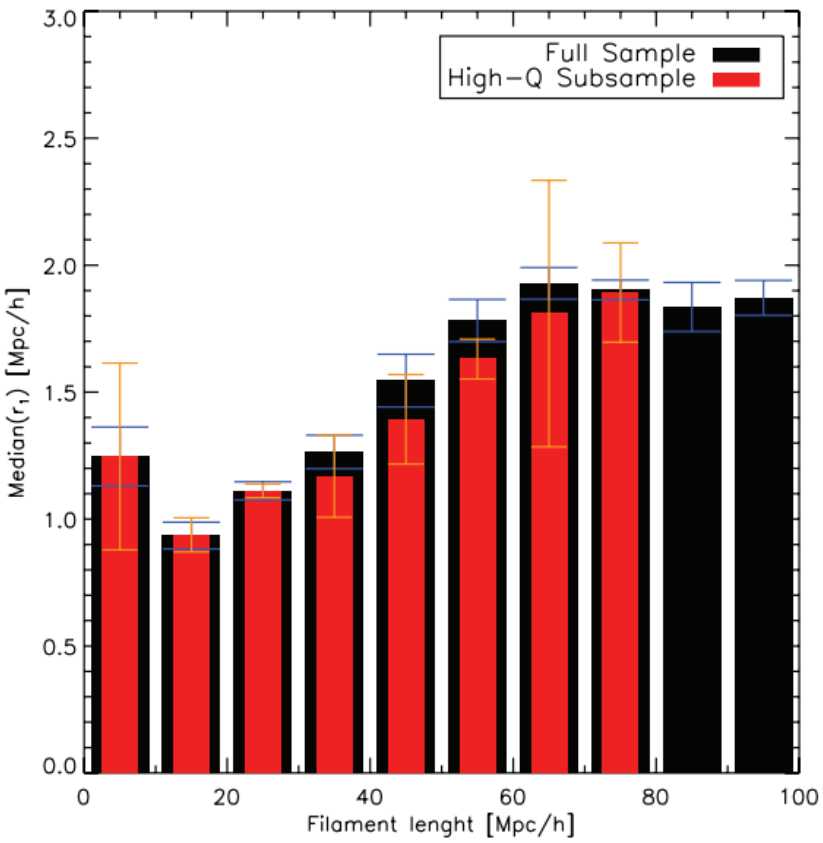


Müller et al. (2017b)

3D Distribution M 101

Thickness measurements of filaments in LSS simulations.

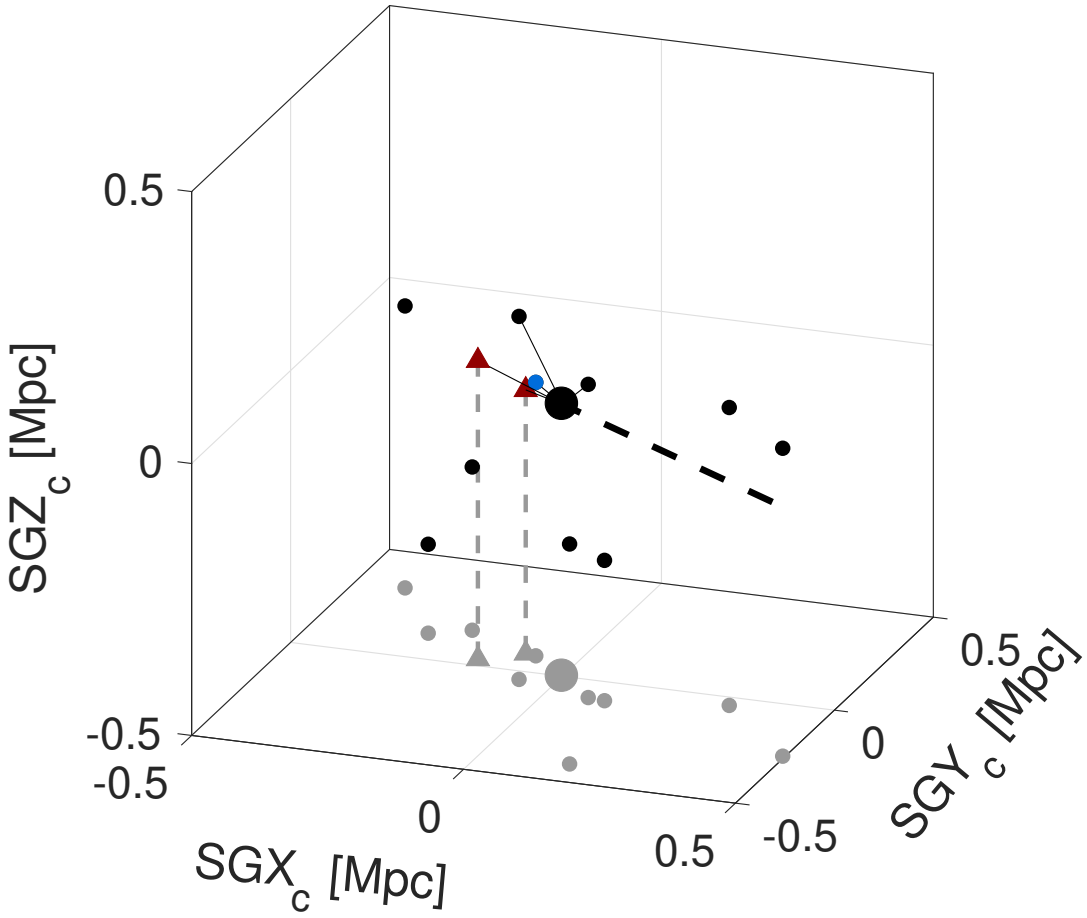
R. E. González and N. D. Padilla



Gonzales & Padilla (2010)

3D Distribution M 83

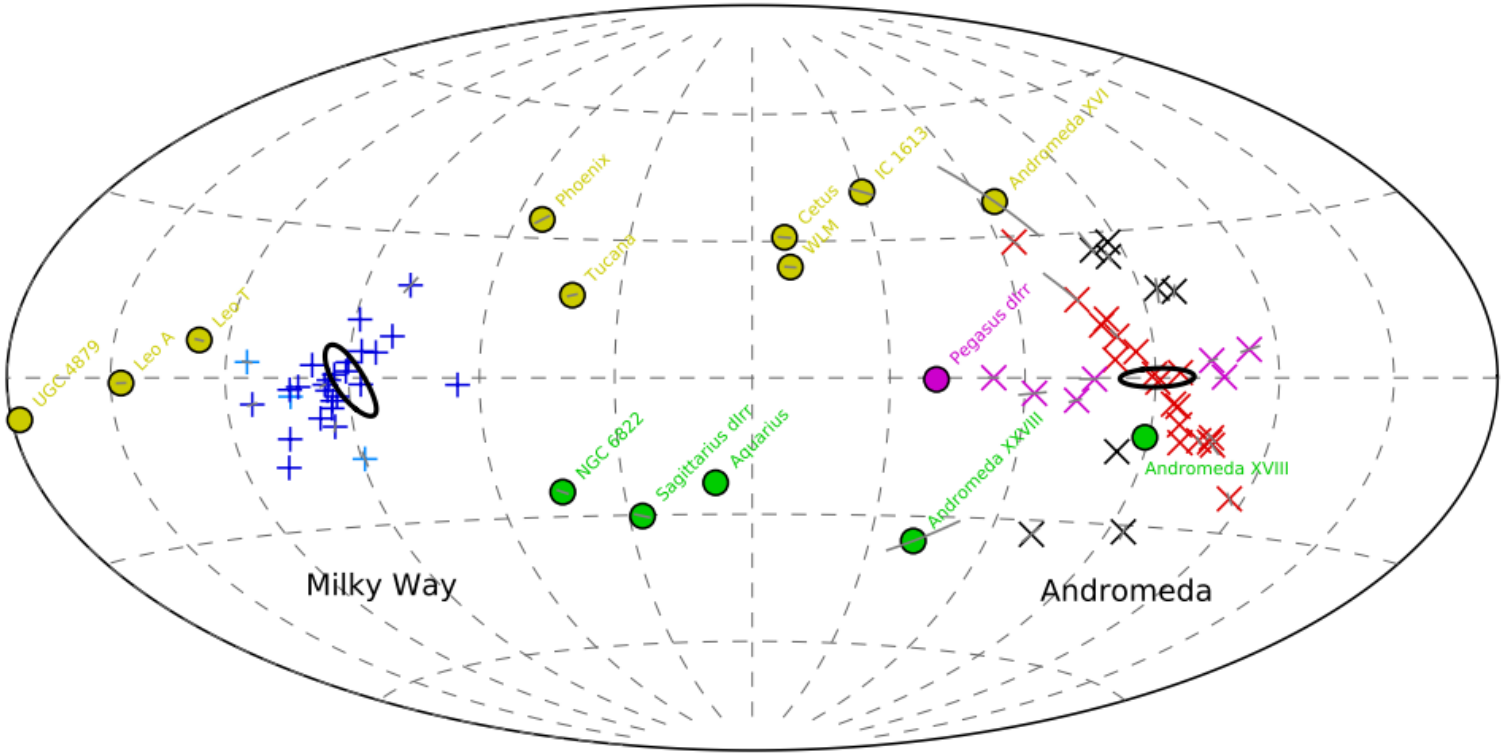
rms ≈ 20 kpc for M 83 vicinity.



Müller et al. (2018b)

Dwarf satellite planes in Local Group

Two parallel planes between MW and M31.



Pawlowski et al. (2013)

Planar structures in the Local Volume

Name	*rms* [kpc]	radius [kpc]	mem	Ref.
phase-space:				
MW, VPOS	∼20	∼250	25	Pawlowski et al. (2013)
M 31, GPoA	∼15	∼270	19	Pawlowski et al. (2013)
Cen A, CASP	∼70	∼500	∼30	Müller et al. (2016)
space:				
LG plane 1	∼60	∼1000	9	Pawlowski et al. (2013)
LG plane 2	∼70	∼500	5	Pawlowski et al. (2013)
M 81 group	?	∼300	∼20	Chiboucas et al. (2013)
M 83 plane	∼20	∼210	6	Müller et al. (2018c)
M 101 plane	∼50	∼260	8	Müller et al. (2017b)
M 101 wall	∼70	∼1500	13	Müller et al. (2017b)

ΛCDM predictions

Does inclusion of baryons change results?

yes it does:	no it doesn't:
Ahmed et al. (2017)	Pawlowski et al. (2015)
...	Garaldi et al. (2017)
...	Müller et al. (2018)
...	...

Are planes a problem for ΛCDM?

no they are not:	yes they are:
Zentner et al. (2005)	Kroupa et al. (2005)
Kang et al. (2005)	Pawlowski et al. (2012)
Cautun et al. (2015)	Cautun et al. (2015)
Bahl & Baumgardt (2014)	Ibata et al. (2014)
Buck et al. (2016)	Cautun et al. (2017)
Maji et al. (2017a,b)	Müller et al. (2018)
...	Forero-Romero & Arias (2018)

My predictions

Does inclusion of baryons change results?

yes it does:	no it doesn't:
A et al. (2019)	B et al. (2019)
C et al. (2021)	D et al. (2023)
E et al. (2025)	F et al. (2027)
...	...

Are planes a problem for ΛCDM?

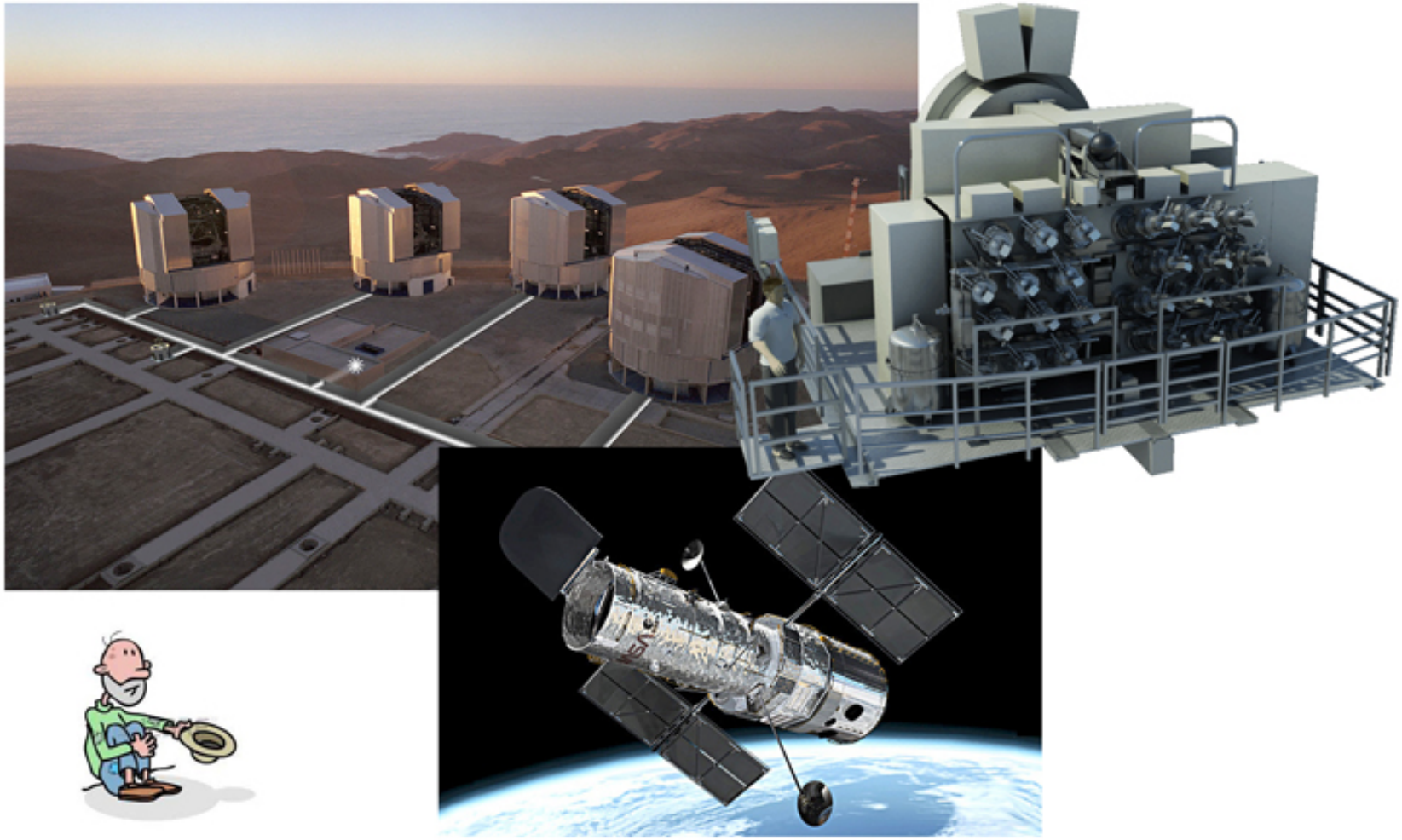
no they are not:	yes they are:
G et al. (2018)	H et al. (2018)
I et al. (2019)	J et al. (2020)
K et al. (2021)	L et al. (2022)
M &N (2024)	O et al. (2025)
P et al. (2028)	Q et al. (2030)
R et al. (2030)	S et al. (2035)
...	T & U (2099)

Sphere Of Specialness (SOS) is apparently ever-expanding!

- Dwarf galaxies and cosmology
- Dwarf galaxy surveys
- Planes-of-satellites problem
- Outlook and Summary

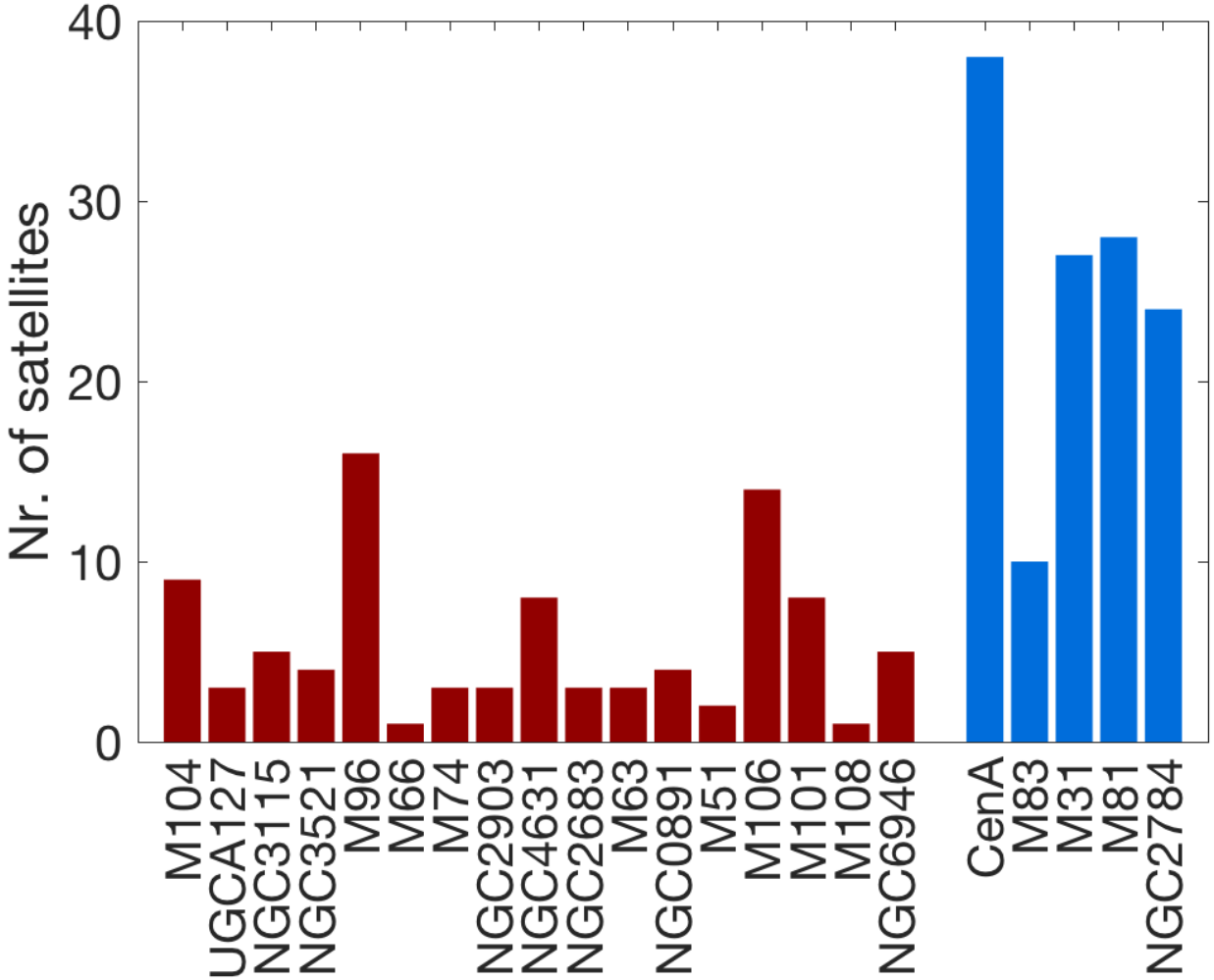
Future observations

Could increase statistical significance of plane signal up to 5σ.



Future observations

Surveys of other groups with Subaru (submitted)



Summary

Detected numerous new dwarf galaxies (Müller et al. 2015, 2017a, 2017b).

Ultra missing satellite problem in M 101 complex (Müller et al. 2017b).

Thin filament in M 101 complex (Müller et al. 2017b) and plane around M 83 (Müller et al. 2018b) .

Strong evidence for co-rotating satellites around Cen A (14 out of 16 satellites, (Müller et al. 2018a).

Need accurate ($<$5%) distances for further investigations of 3D structure.
Need velocities for further investigations of rotations.

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

MARCEL S. PAWLOWSKI*

Department of Physics and Astronomy, University of California, Irvine, CA 92697, USA
marcel.pawlowski@uci.edu

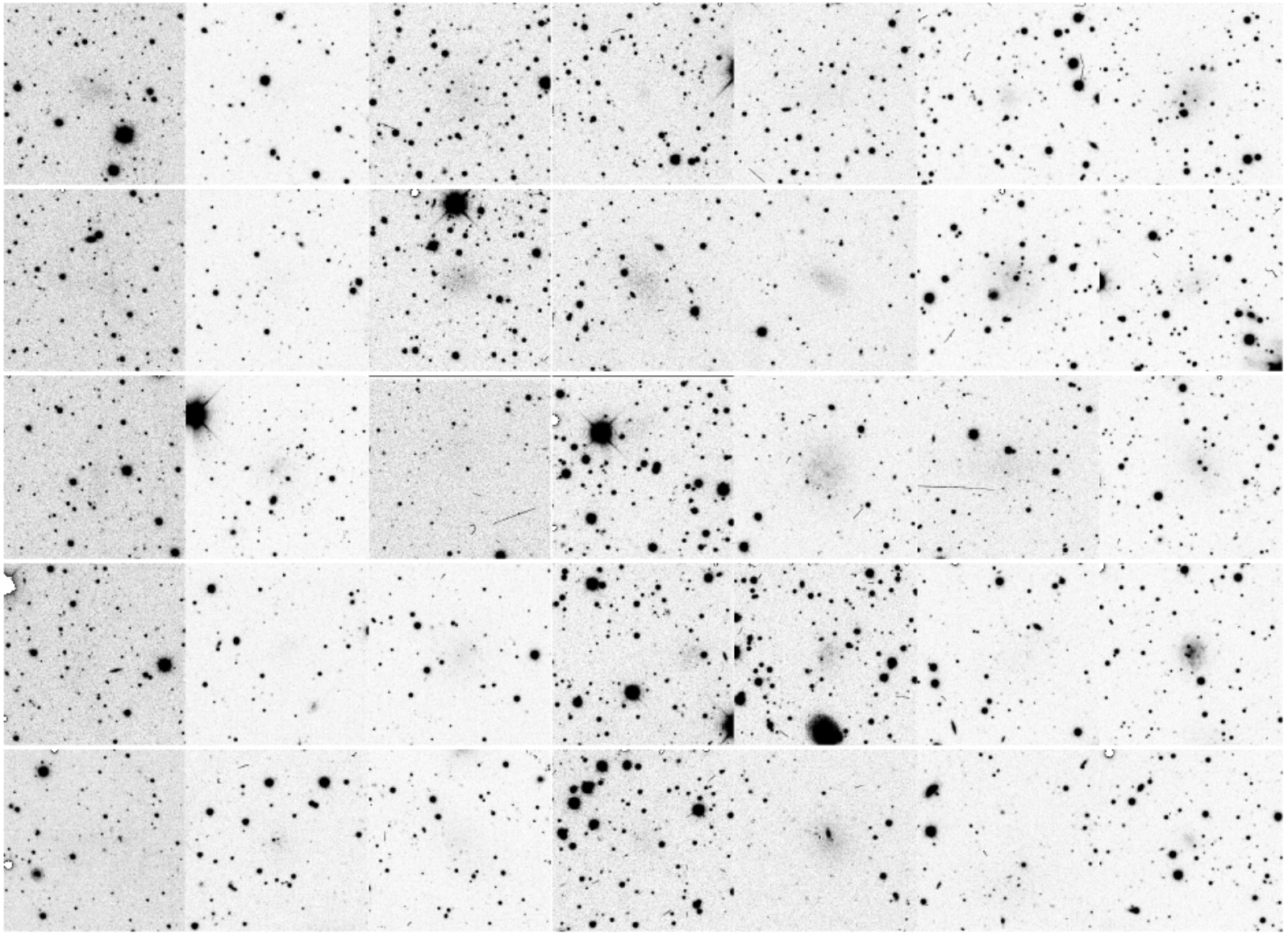
Received (Day Month Year)
Revised (Day Month Year)

Satellite galaxies of the Milky Way and of the Andromeda galaxy have been found to preferentially align in significantly flattened planes of satellite galaxies, and available velocity measurements are indicative of a preference of satellites in those structures to co-orbit. There is increasing evidence that such kinematically correlated satellite planes are also present around more distant hosts. Detailed comparisons show that similarly anisotropic phase-space distributions of sub-halos are exceedingly rare in cosmological simulations based on the ΛCDM paradigm. Analogs to the observed systems have frequencies of ≤ 0.5 per cent in such simulations. In contrast to other small-scale problems, the satellite planes issue is not strongly affected by baryonic processes because the distribution of sub-halos on scales of hundreds of kpc is dominated by gravitational effects. This makes the satellite planes one of the most serious small-scale problem for ΛCDM. This review summarizes the observational evidence for planes of satellite galaxies in the Local Group and beyond, and provides an overview of how they compare to cosmological simulations. It also discusses scenarios which aim at explaining the coherence of satellite positions and orbits, and why they all are currently unable to satisfactorily resolve the issue.

Keywords: dark matter; cosmology; dwarf galaxies; near-field cosmology.

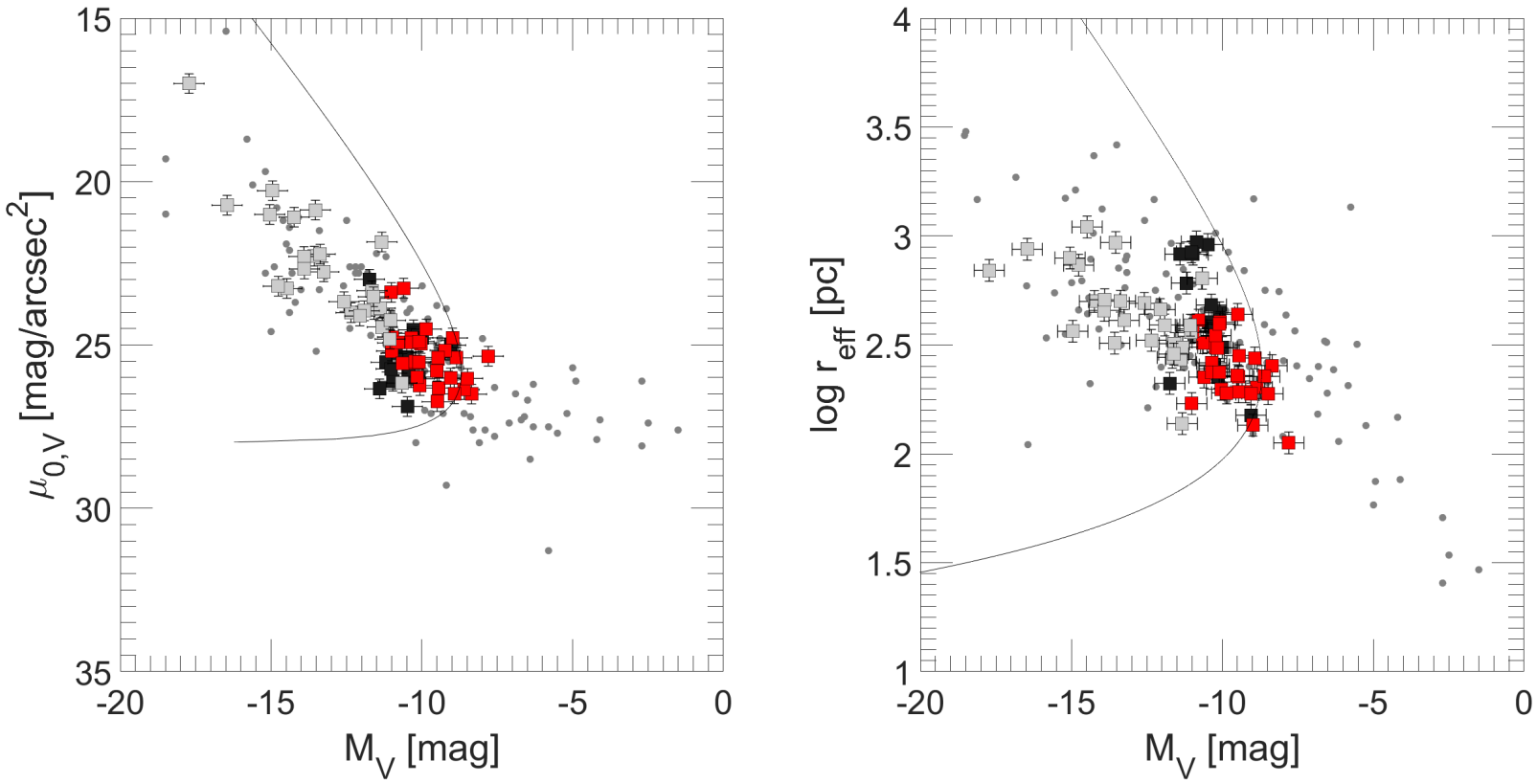
PACS Nos.: include PACS Nos.

The End



Comparison with LG Dwarfs

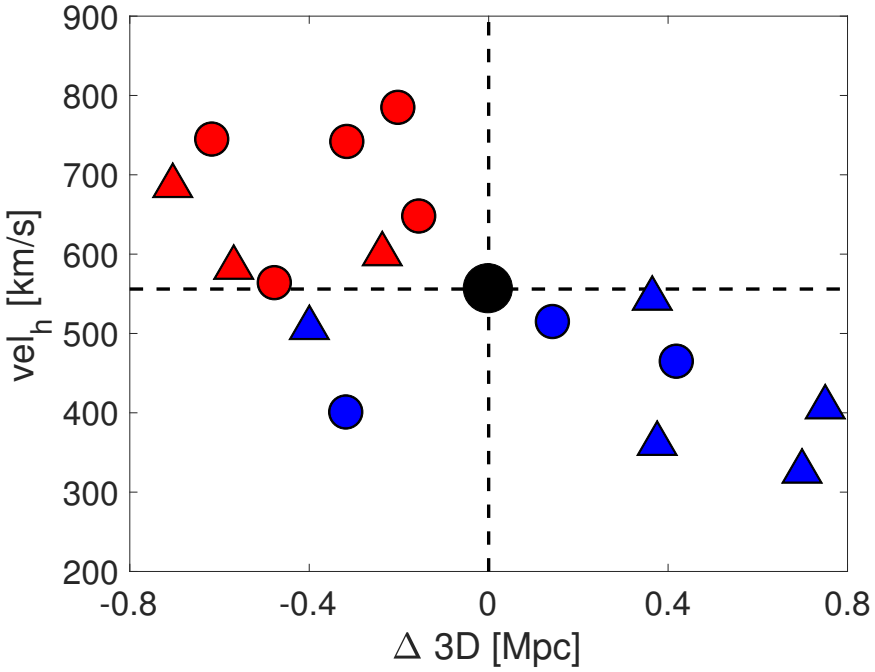
Sérsic fit: $\mu(r) = \mu_0 + 1.0857 \cdot \left(\frac{r}{r_o}\right)^n$, Distance $\approx 4.5\,\mathrm{Mpc}$

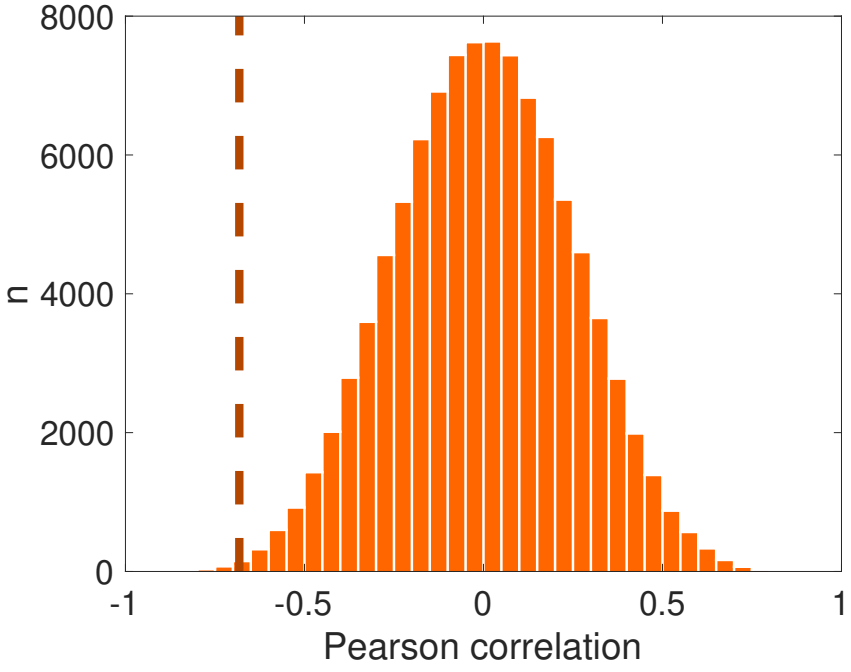


Centaurus Group - squares: Müller et al. (2015)
Local Group - gray dots: McConnachie (2012)

Coherent movement (Müller, et al. 2018a)

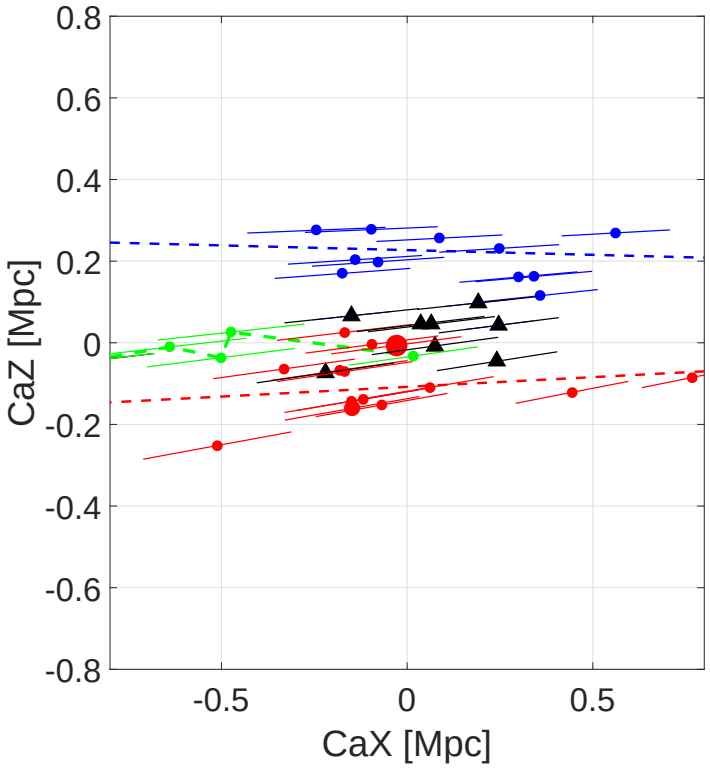
Statistical significant correlation (3σ signal)

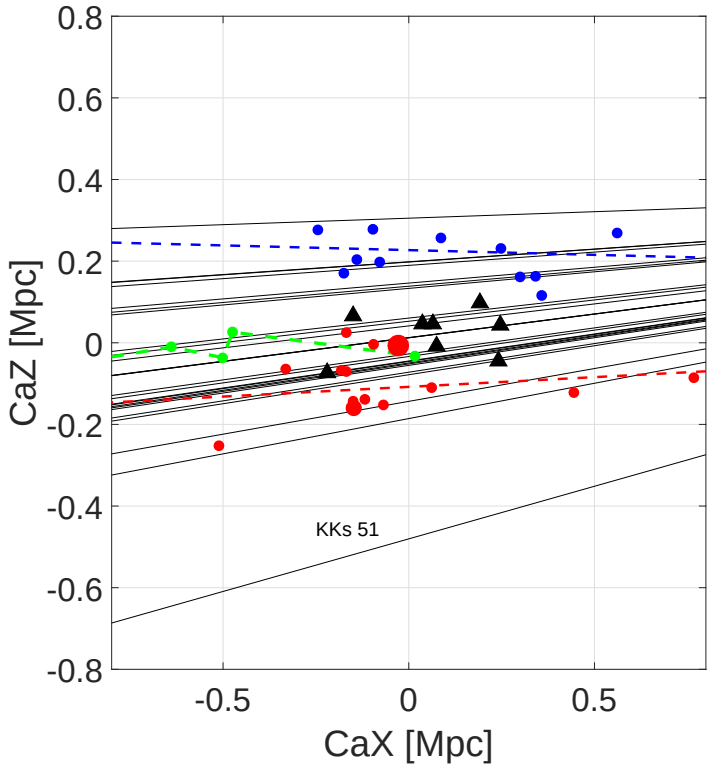




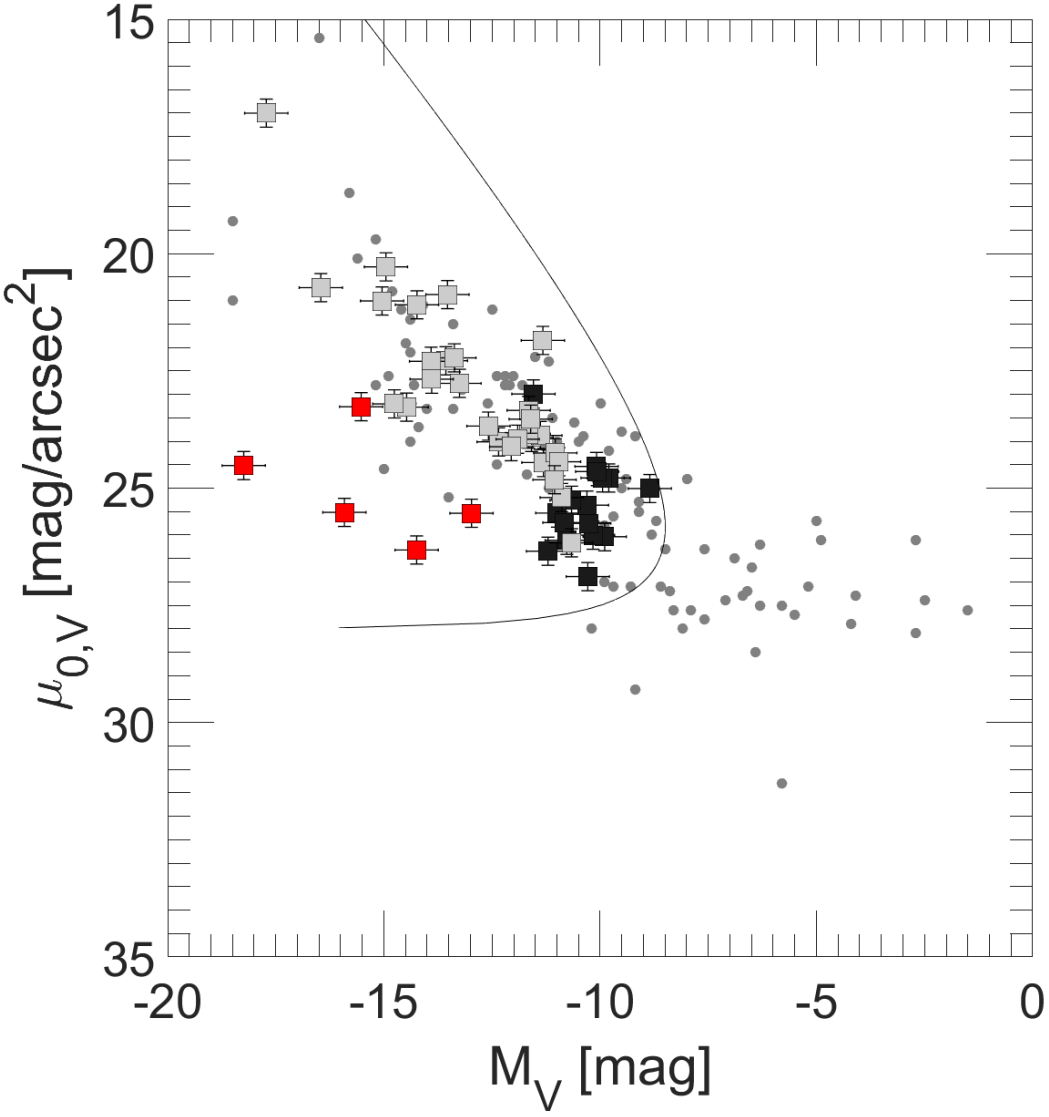
Eigenframe (Tully et al. 2015, Müller et al. 2016)

- Edge-on view onto the planes
- Left: Known galaxies with distances, Right: LoS of candidates
- (Almost) all LoS intercept with plane



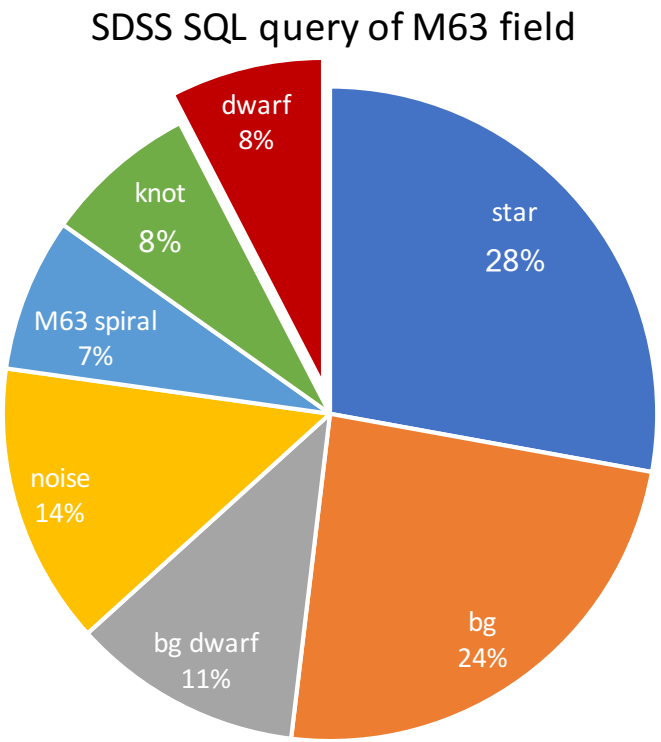


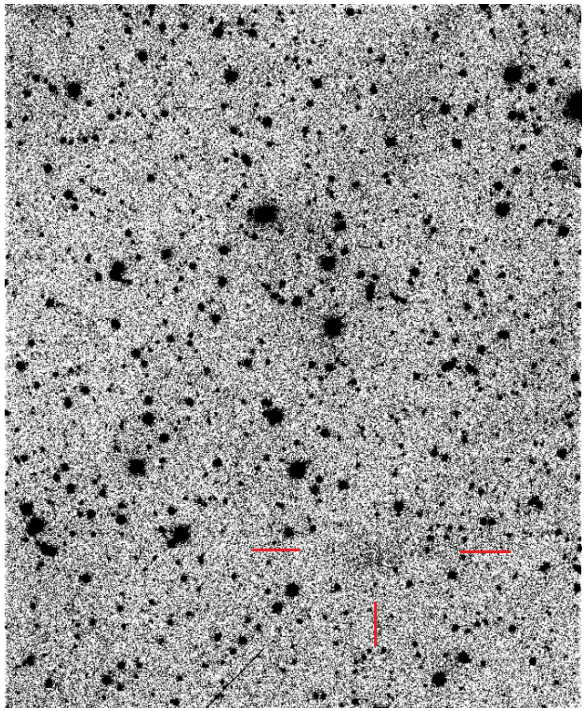
Preliminary membership test



Search for dwarfs in the Local Volume

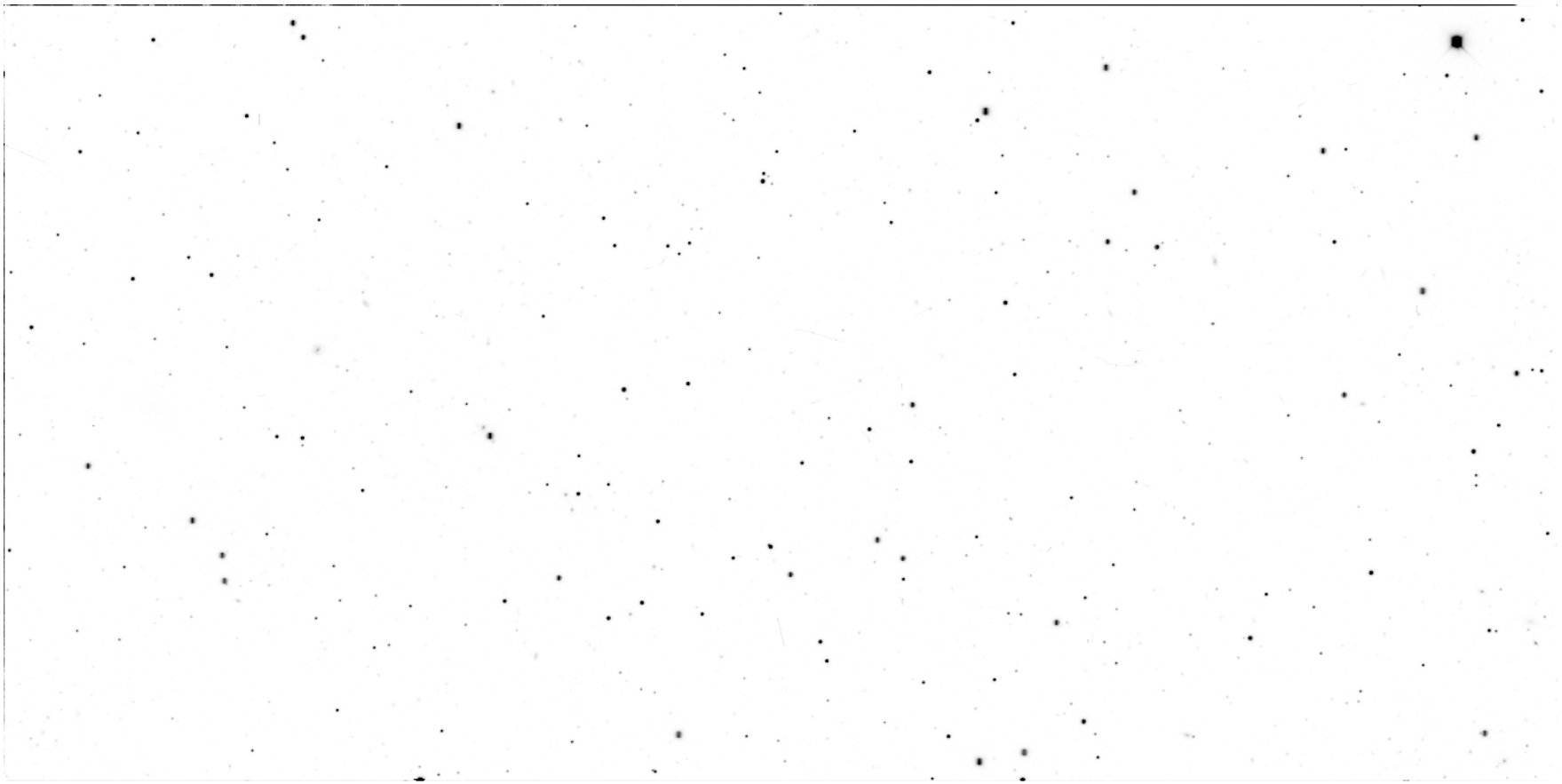
- Automatic detection extremely inefficient, e.g. with SDSS (Kniazev et al. 2004).
- Only 2 out of 9 dwarfs detected.





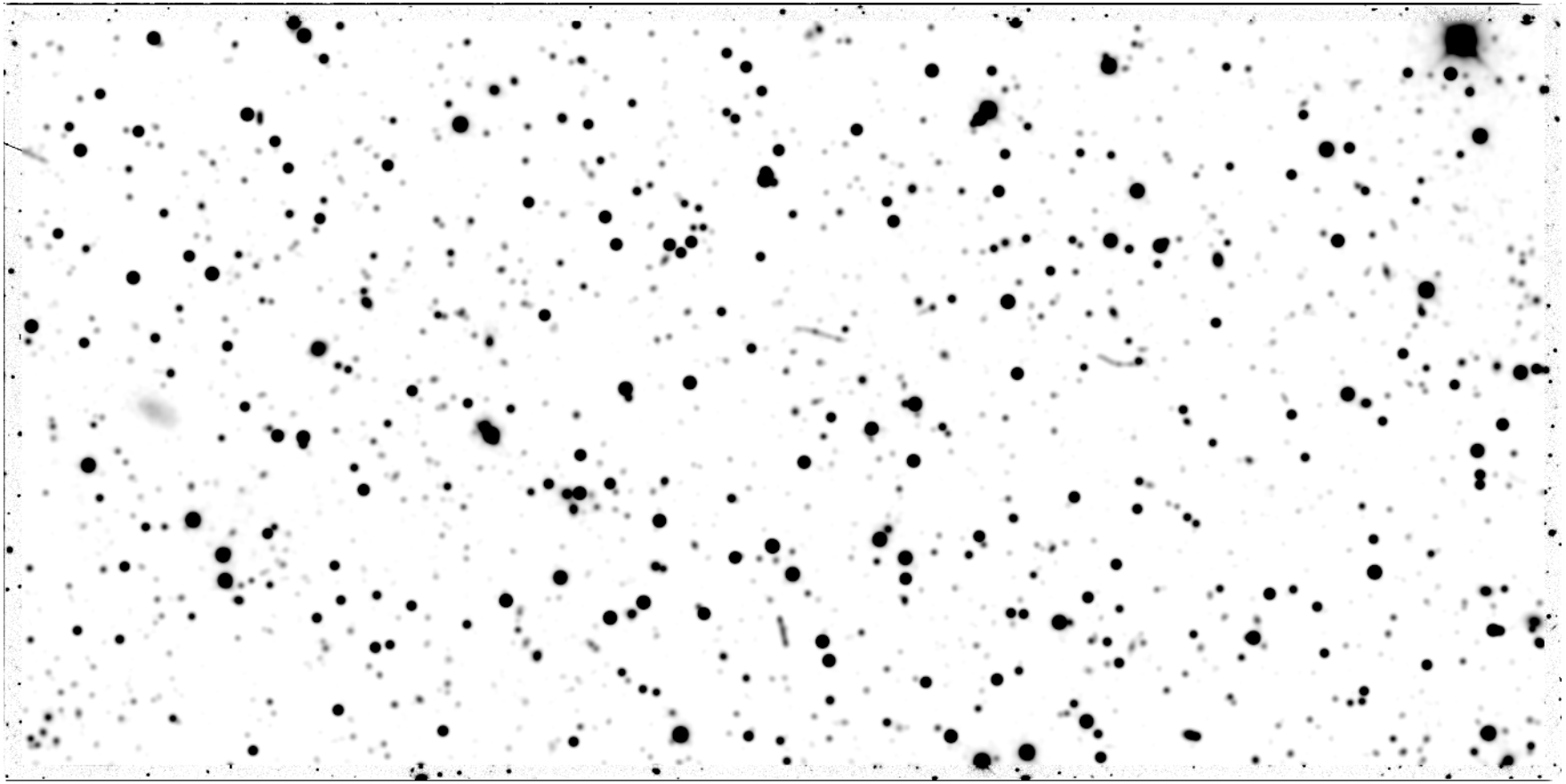
left: Müller PhD thesis, right: Müller et al. (2017a)

Gauss Convolution



DECam data, unprocessed

Gauss Convolution



DECam data, Gauss convolved

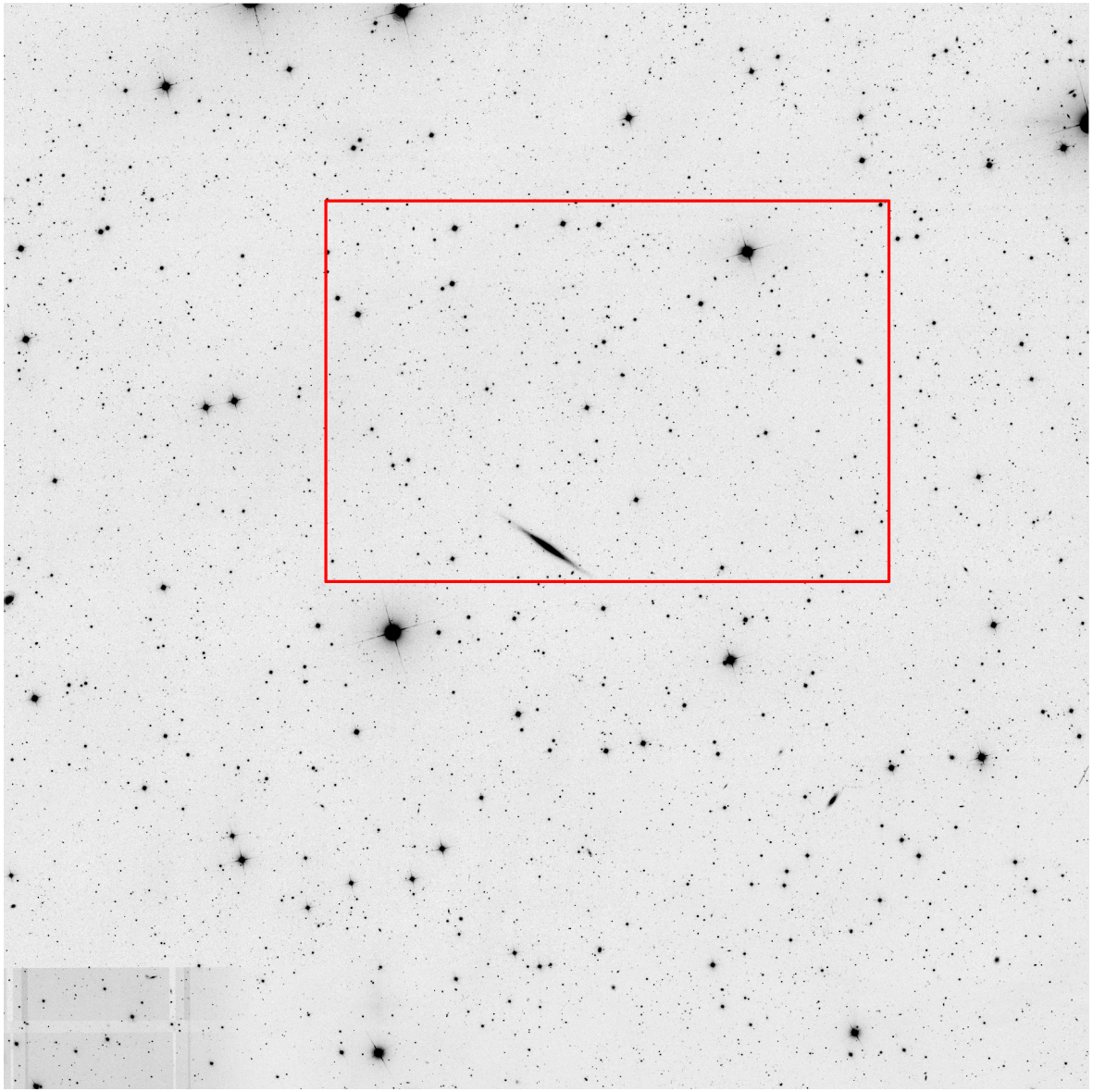
My personal workflow

- Binning 9×9 px onto 1 px
- gray scale range 1σ around background
- Apply small Gaussian smoothing
- visual inspection
- Apply large Gaussian (or other) smoothing
- re-inspection

S/N enhancement by a factor of 30 (Müller 2017b)

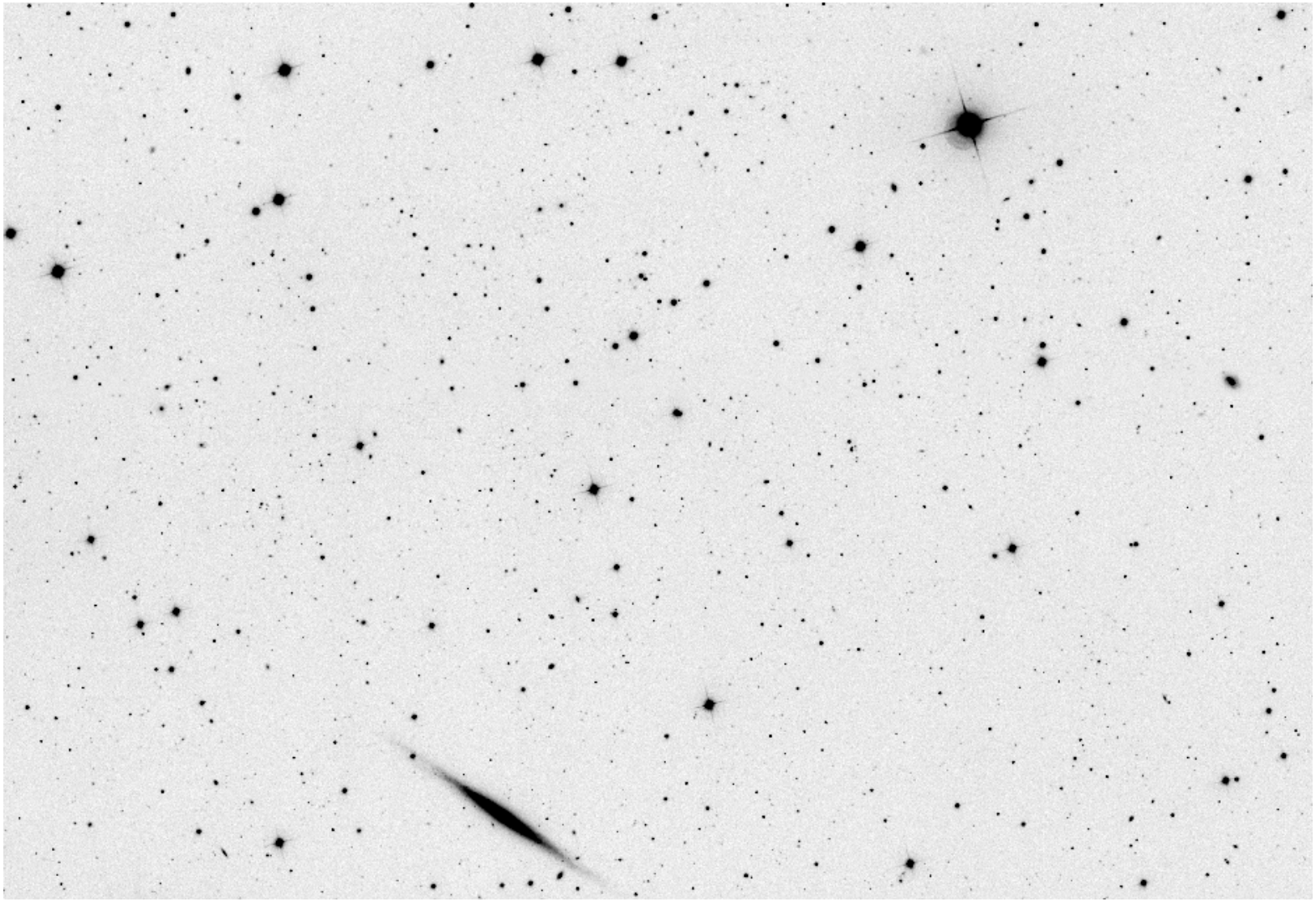
My personal workflow

SDSS 1 sq. deg field around NGC 100 in *r*-band.



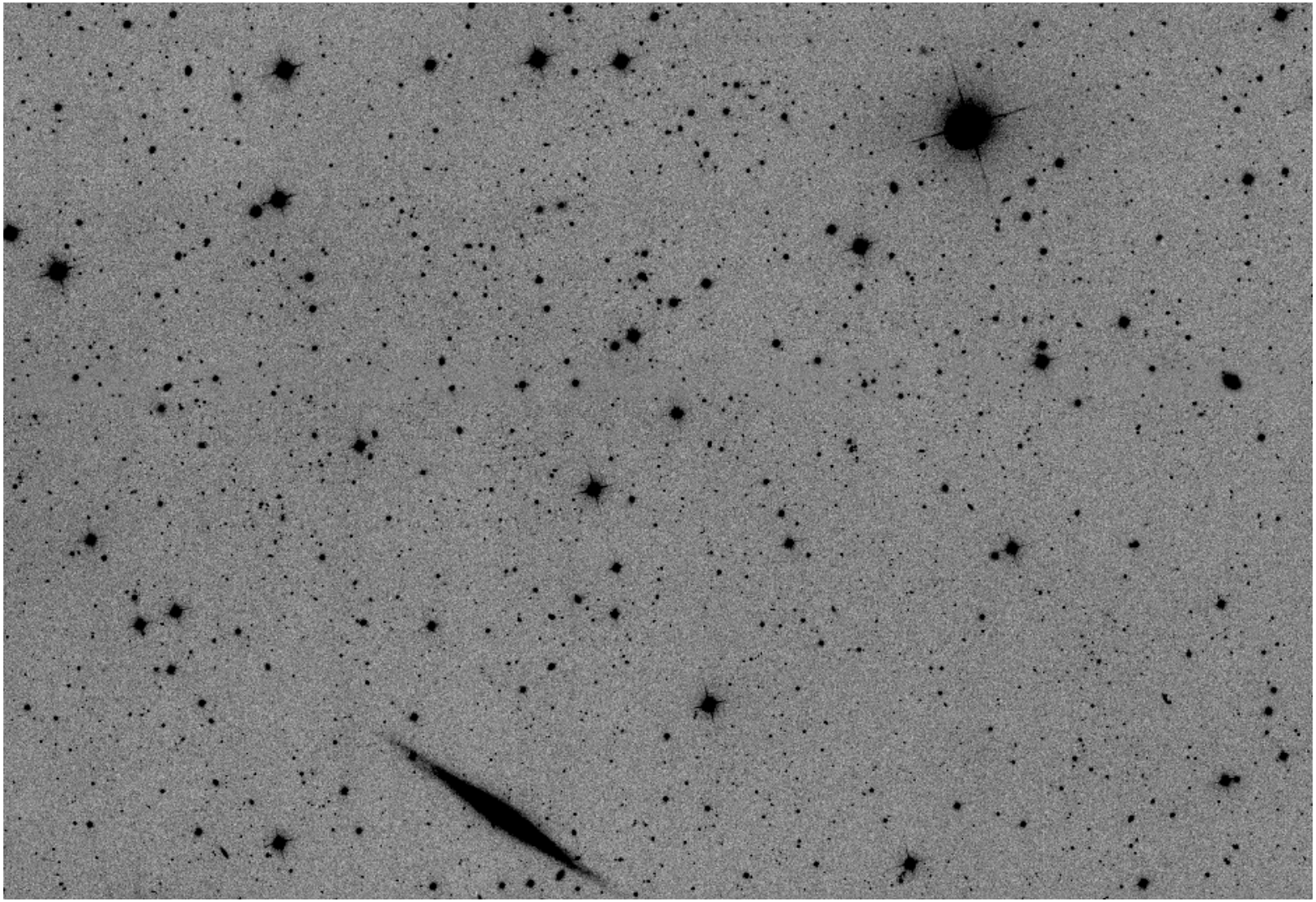
My personal workflow

Binning 9×9 px onto 1 px (= box filter).



My personal workflow

Gray scale range 1σ around background.



My personal workflow

Apply small Gaussian smoothing and visually inspect.