Small-scale cosmology with dwarf galaxies

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** (ESO, Garching)

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Motivation to study dwarf galaxies

ΛCDM: Building blocks of galaxies.

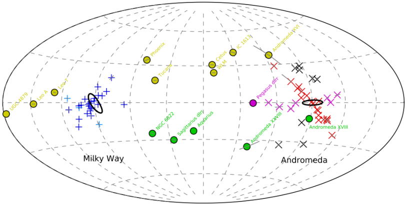
Most Dark Matter dominated objects in the Universe (Walker 2013).

Dwarf galaxies trace the fine structure of the large-scale structure (Binggeli 1989).

ΛCDM problems on Local Group scale:
e.g. missing satellite problem (e.g. Klypin et al. 1999),
too-big-too-fail problem (Boylan-Kolchin et al. 2011)
dwarf satellite plane problem (e.g. Pawlowski et al. 2012, Cautun & Frenk 2016).

Dwarf satellite plane problem

- vast polar structure (VPOS) - MW; Great Plane of Andromeda (GPOA) - Andromeda
- ΛCDM: isotropical and random motions.
- ΛCDM: chance of alignment $<$ **0.1%** (Pawlowski et al. 2015) or $<$**1%** (Cautun et al. 2015).



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

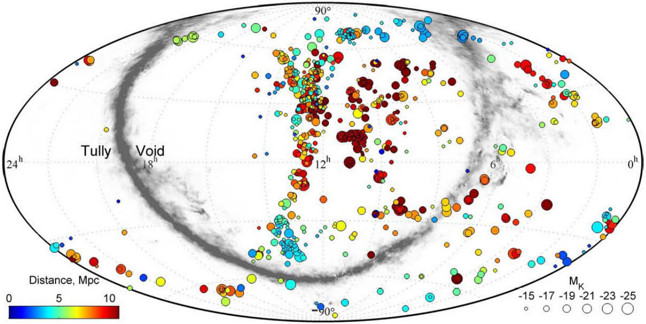
- the satellites are distributed in a highly flattened, *planar* structure in three-dimensional space,
- the *majority* of the satellites *co-orbit* in the same sense,
- and these satellites orbit *within* the plane, indicating that the plane is not just a transient alignment.

Left: Pawlowski et al. (2013), right: Pawlowski et al. (2015)

Is the Local Group unique?

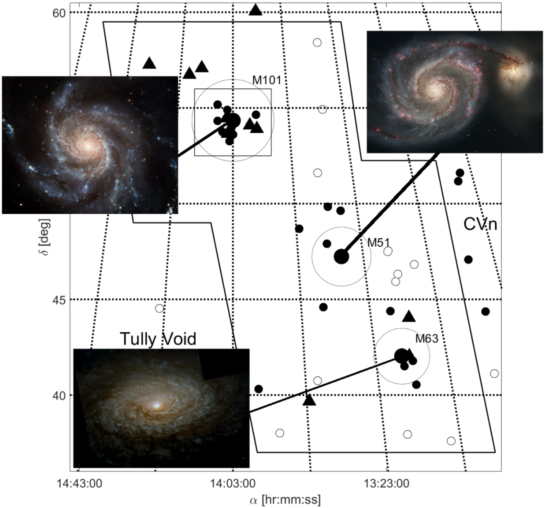
Local Volume

- The Local Volume ($D < 10\,\mathrm{Mpc}$, 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

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

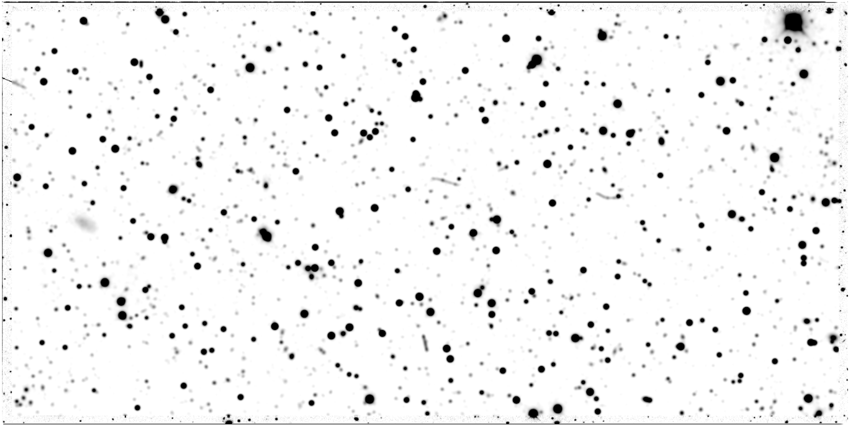
Gray rectangle: Dragonfly footprint (Merritt et al. 2014)

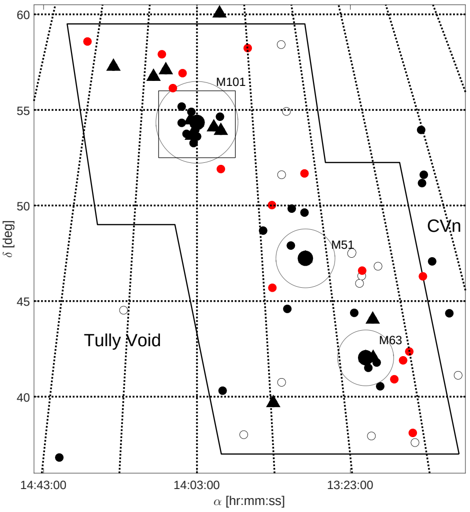
SDSS automatic detection

The reader may wonder why we did not use the SDSS data reduction pipeline directly for the detection of dwarf-like low surface brightness objects. There is indeed a tool implemented in the data reduction pipeline for the detection of extended sources. However, Kniazev et al. (2004) pointed out that galaxies are shredded by this tool, as different luminosity knots from the same source are detected and defined as separate, individual SDSS objects. Tests have shown (Kniazev et al. 2004) that the SDSS pipeline tool is unsuited for the detection of LSB objects, giving only a low detection rate of test galaxies and too many false detections. Nevertheless, we checked the SDSS database

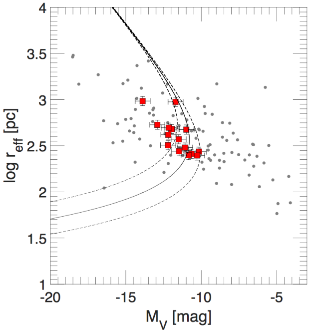
Gauss Convolution

Gauss Convolution



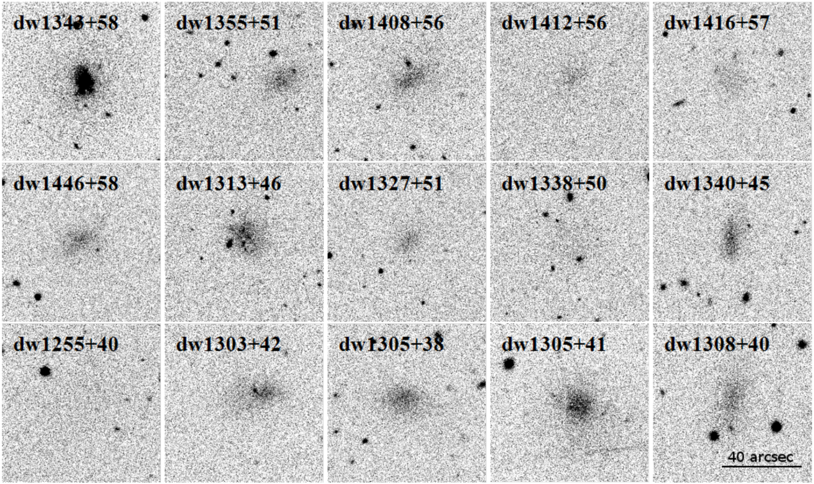


- 15 new dwarf galaxies (red points) (Müller et al. 2017b)
- **Missing satellite problem**
- Diagonal alignment



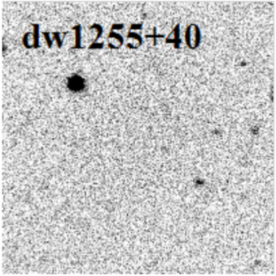
Müller et al. (2017b)

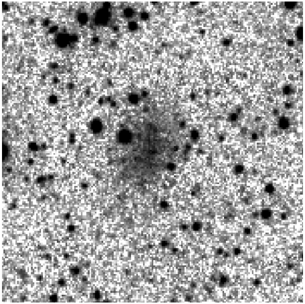
Mosaic of M101 dwarfs



dw1255+40

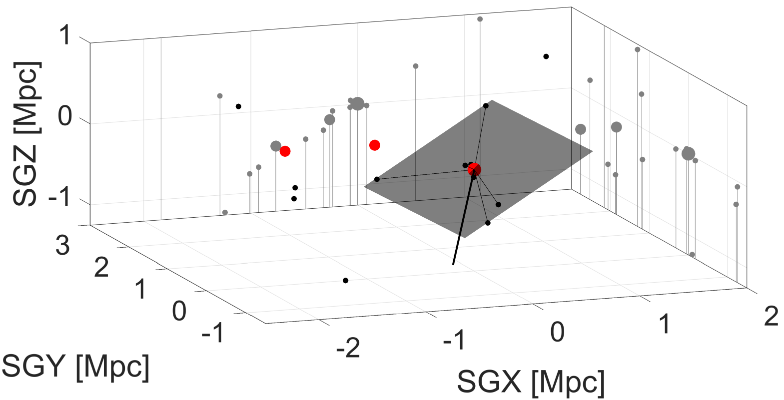
left: SDSS; right: by courtesy of Aaron Watkins and Chris Mihos





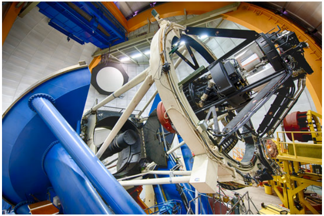
3D Distribution M 101

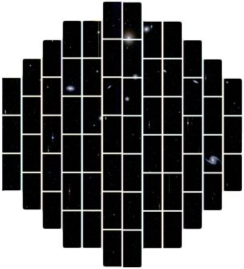
- Roughly all galaxies lie in a wall, incl. M 101, M 51, and M 63.
- Wall stretched over 3 Mpc.
- *rms* ≈ 70 kpc for whole filament, *rms* ≈ 45 kpc for M 101 vicinity. (Typical 1 Mpc in simulations)



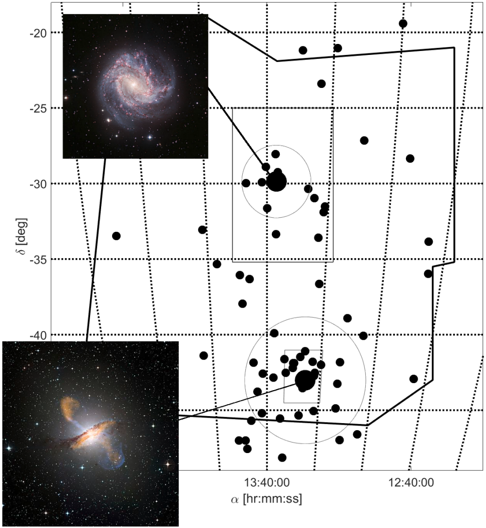
Dark Energy Camera

- 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



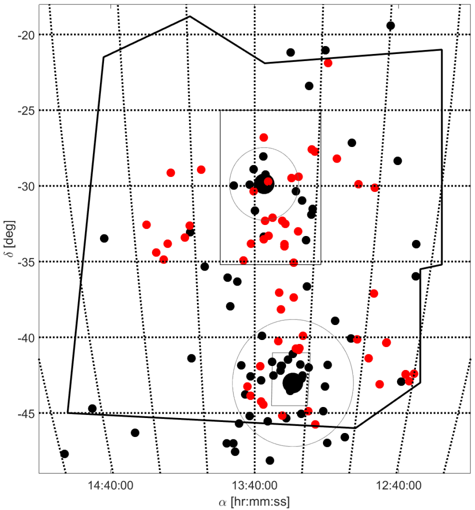


http://www.noao.edu/icarchives/all.php

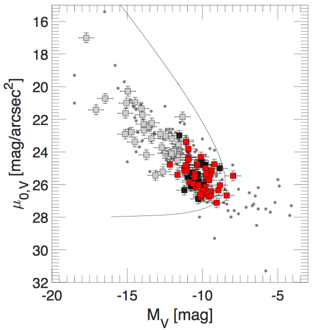


- Survey Centaurus A (DECam)
- Subgroups: Cen A (4 Mpc), M 83 (5 Mpc)
- 50 known group members
- 500 deg^2 field, g and r band
- Cen A: two parallel planes (Tully et al. 2015)

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

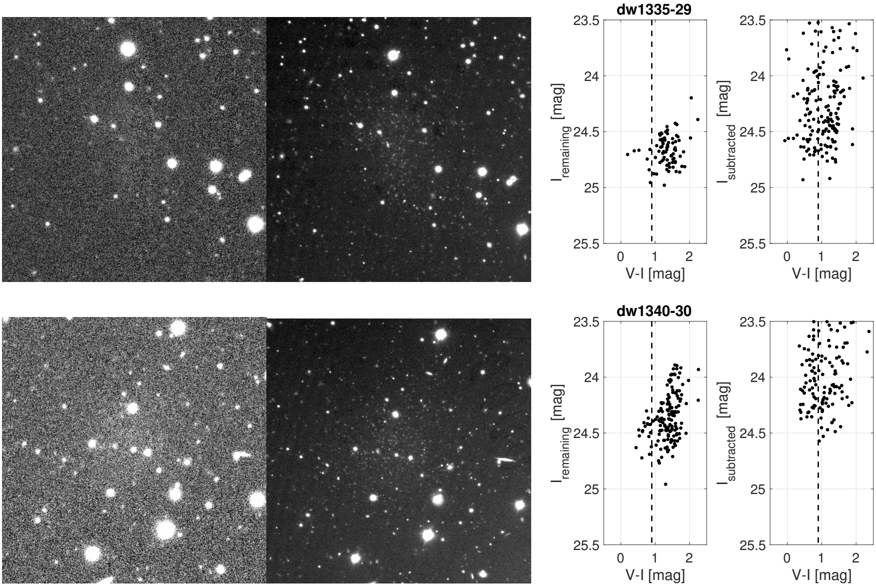


- 57 new unresolved dwarf galaxies (red points), doubling current dwarf population
- Lopsided distribution



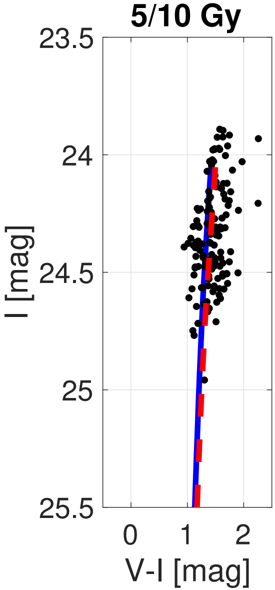
Müller et al. (2017a)

VLT FORS2 observations (M 83 subgroup ≈ 5 Mpc)



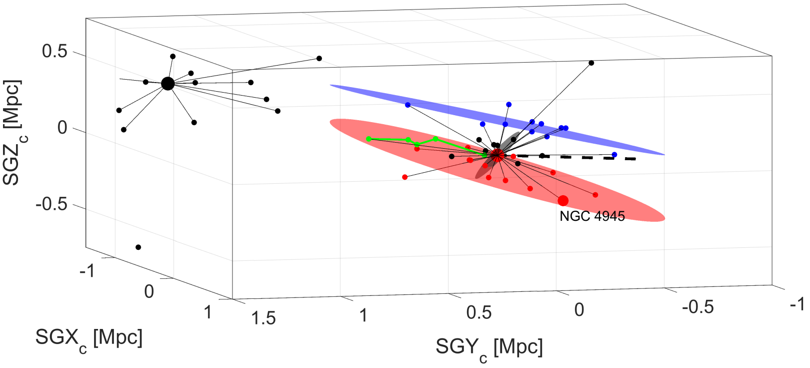
Paper in preparation

James Schombert talk: 5 Gyr old dE?

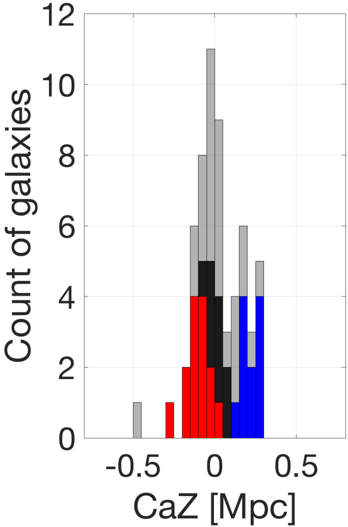


3D Distribution Cen A (Müller et al. 2016)

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



One plane only



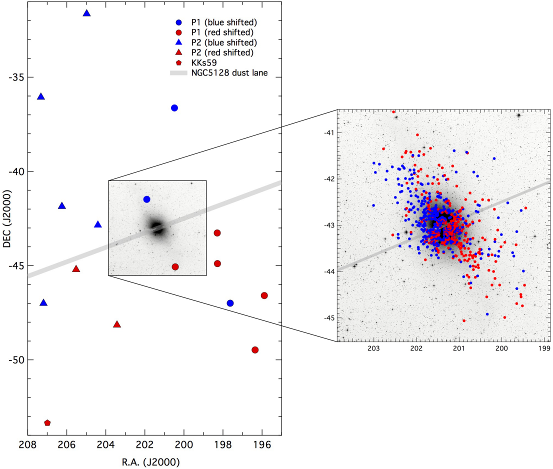
Cen A dwarf satellite plane problem?

Plane problem:

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

Plane is seen edge-on

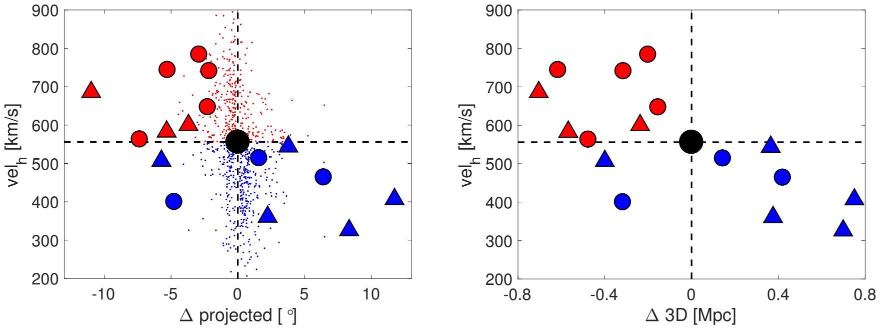
Coherent movement



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

circles: plane 1; triangles: plane 2; color: red or blueshifted in respect to Cen A; dots: PNe.
In collaboration with **Marcel Pawlowski** and **Federico Lelli**, paper in preparation.

Coherent movement (paper in preparation)

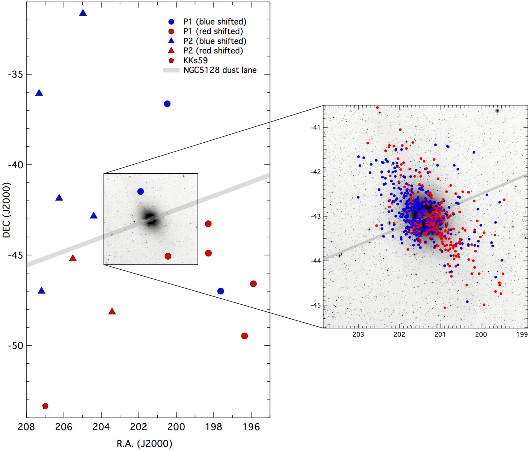


- Statistical significant correlation (3σ signal)
- PNe have different orbital time but follow same trend
- Millenium-II comparison: 2 out of 2220 Cen A-like systems

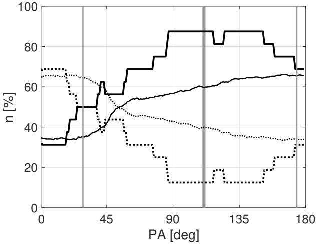
Plane problem:

- 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



circles: plane 1; triangles: plane 2; color: red or blueshifted in respect to Cen A; dots: PNe

Cen A dwarf satellite plane problem?

Plane problem:

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

Towards new cosmology?

Remember: 1% chance in ΛCDM.
Three out of four studied systems show coherent movement.

Panel discussion: How do we accomodate this in ΛCDM.

The Local Group is not unique!

Planes of dwarf galaxies

M 101 filament has no comparable filament in the LV.

Name	*rms* [kpc]	radius [kpc]	members	Ref.
MW, VPOS	$\sim$20	$\sim$250	25	(1)
M 31, GPoA	$\sim$15	$\sim$270	19	(1)
LG plane 1	$\sim$60	$\sim$1000	9	(1)
LG plane 2	$\sim$70	$\sim$500	5	(1)
M 81 group	?	$\sim$300	$\sim$20	(2)
Cen A plane 1	$\sim$70	$\sim$500	14	(3)
M101 complex	($\sim$50) $\sim$70	$\sim$1500	(8) 12	(4)

Main difference: Luminosity range of dwarf galaxies.

(1) Pawlowski et al. (2013), (2) Chiboucas et al. (2013) (3) Müller et al. (2016), (4) Müller et al. (2017b)

Twitter et al. (yesterday)

Twitter et al. (yesterday)

Noam Libeskind @satellitegalaxy · 6h

1 1 3

Oliver Müller
@VoltarCH

Replying to @satellitegalaxy @MBKplus @8minutesold

LIKE
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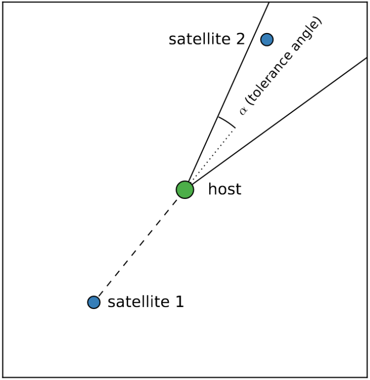
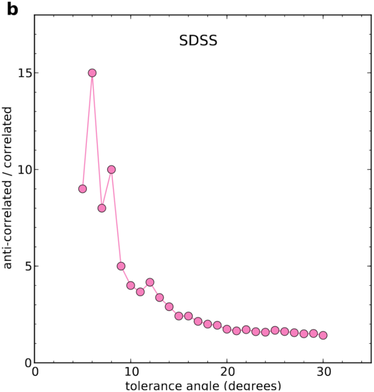
6:03 PM - 7 Jun 2017

1

Correlated velocity pairs (Ibata et al. 2014)

Corotating satellites are common in in nearby universe.





Summary

Surveys of the Centaurus Group and M 101 complex; detected around 57 and 15 candidates, respectively.

Missing-satellite problem in M 101 complex.

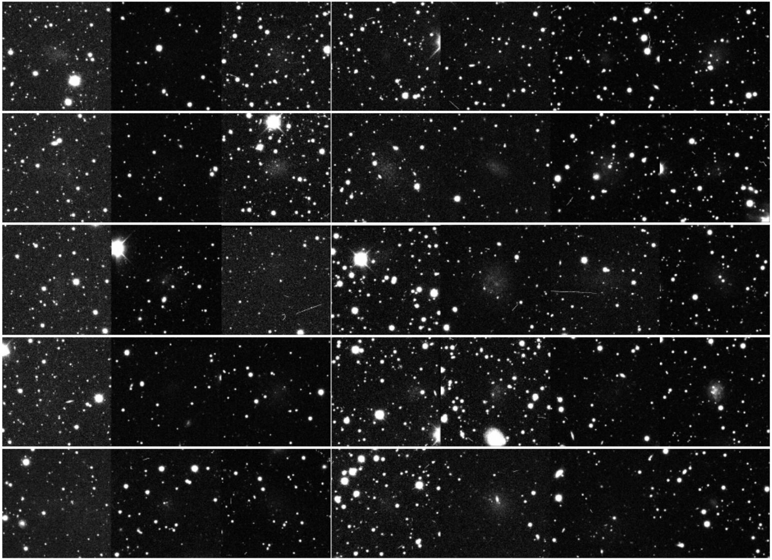
Astonishingly thin filament in M 101 complex.

Studied 3D distribution of Cen A satellites and found strong resemblence to LG.

Found evidence for co-rotating satellites (14 out of 16 satellites).

Need accurate ($<$10%) distances for further investigations of 3D structure. Proposals submitted.
Need velocities for further investigations of rotations.

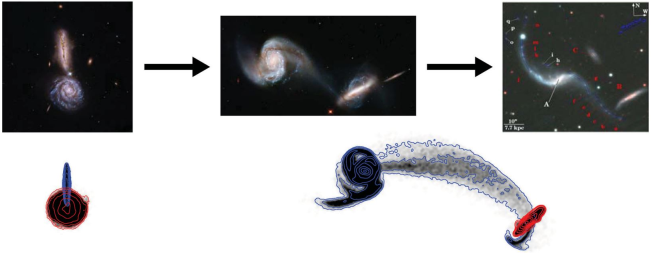
The End



Dwarf galaxies as tidal renmants (Pawlowski et al. 2012)

(Already in Joerg Dabringhausen's talk.)

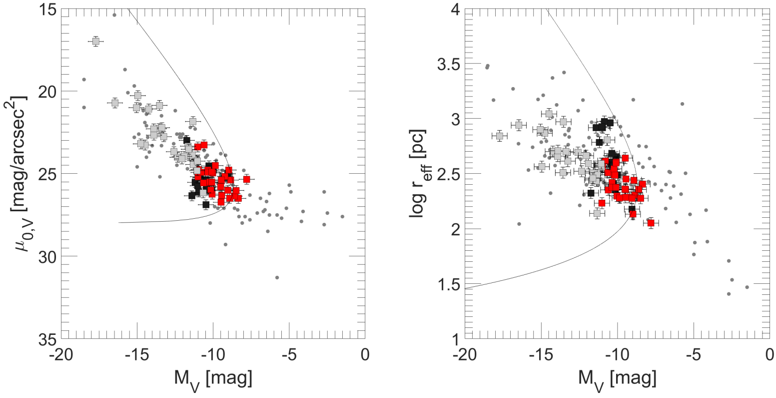
- Dwarf galaxies as TDGs (Zwicky 1956, Kroupa et al. 2010)
- TDGs form along plane of tidal interaction and inherit momentum
- Counter rotating TDGs well understood
- Dark Matter free, but show DM behavior (MOND?)



Pawlowski et al. (2012)

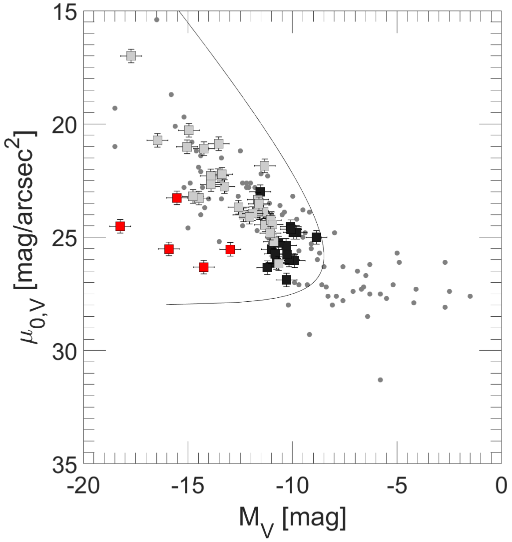
Comparison with LG Dwarfs

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



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

Background Test



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