# Were the most compact and most diffuse stellar systems in galaxy clusters both formed by tidal stripping?

Galaxy Evolution in Groups and Clusters at 'low' Redshift:
Theory and Observations
Schloss Ringberg, December 12, 2017

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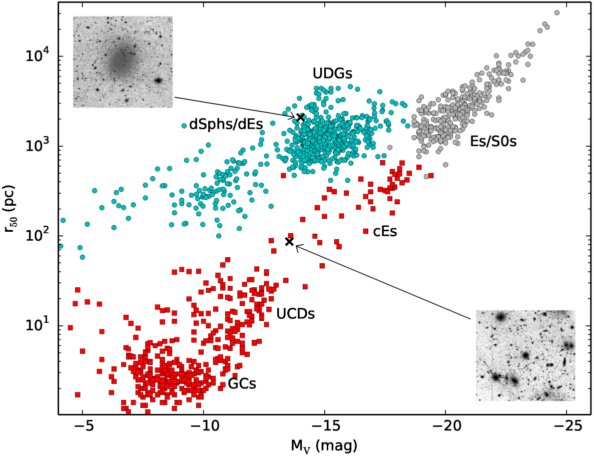
www.dwarfgalaxies.net

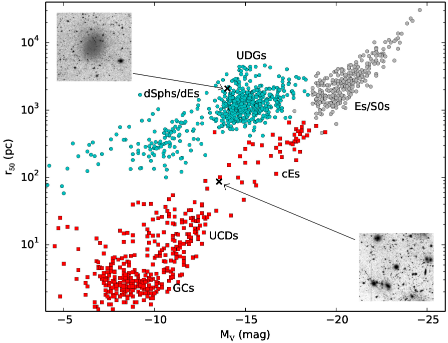
# Diffuse and compact low-mass stellar systems




Compilation from Norris et al. (2014), Lieder et al. (2012), McConnachie et al. (2012), Lisker et al. (2013, & references therein), van Dokkum et al. (2015).

# Diffuse low-mass stellar systems

**Faint low surface brightness (LSB) galaxies**




- Faint LSB galaxies with $r_{50} \gtrsim 1\,\mathrm{kpc}$ detected in galaxy clusters since the 1980s (e.g. Sandage & Binggeli et al. 1984)
- Since recently also known as "ultra-diffuse galaxies" (UDGs) (van Dokkum et al. 2015)

- Abundant populations identified in nearby galaxy clusters; some exist in lower-density environments

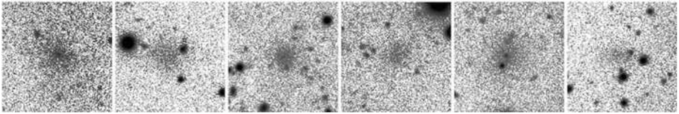
# Diffuse low-mass stellar systems

**Faint low surface brightness (LSB) galaxies**

→ How can they survive in dense galaxy clusters?

## Protected by a high dark matter content?

- Many with regular and undistorted stellar structure in Coma (van Dokkum et al. 2015; Mowla et al. 2017)
- Some have remarkably large GC systems for their luminosity (e.g. van Dokkum et al. 2017)
- High mass-to-light ratios ($M/L \sim 50 - 100$) measured for some LSB galaxies in Coma and Virgo (e.g. van Dokkum et al. 2016, Beasley et al. 2016)



# Diffuse low-mass stellar systems

**Faint low surface brightness (LSB) galaxies**

→ How can they survive in dense galaxy clusters?

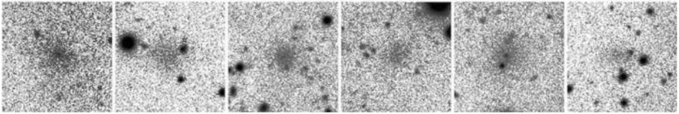
**In the process of disruption?**

- Some show signs of disruption, e.g. in Virgo and Fornax (Mihos et al. 2015, 2016; Venhola et al. 2017)

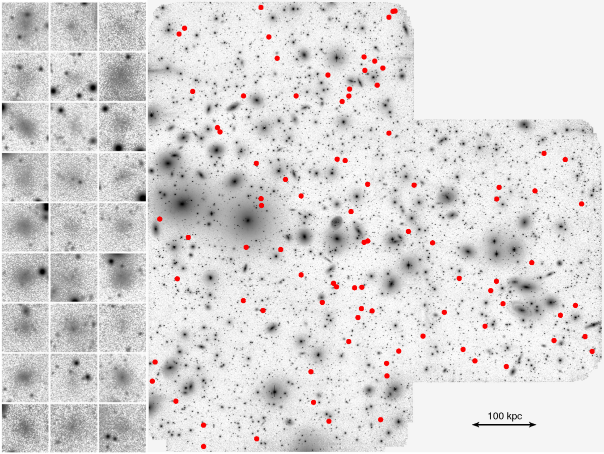
**This work:**

- Can faint LSB galaxies survive in the dense Perseus cluster core?
- Abundance? Signs of ongoing disruption?

→ Deep optical imaging!



# Faint LSB galaxy candidates in the Perseus cluster core




Deep V-band mosaic of the Perseus cluster core (WHT/PFIP). Red dots and side panels: Sample of LSB galaxy candidates. Mosaic width: 0.58 deg (0.71 Mpc). Width of the galaxy cutouts: 21 arcsec (7.1 kpc). Wittmann et al. (2017)

**The sample:**

- 89 LSB galaxy candidates
- $\langle \mu_V \rangle_{50} = 24.8$–$27.1$ mag arcsec$^2$
- $M_V = -11.8$ to $-15.5$ mag
- $r_{50} = 0.7$–$4.1$ kpc

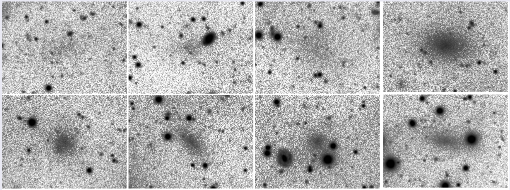
# A search for LSB galaxy candidates in Perseus

## Identification

Approach:

- Inserting LSB galaxy models into the data based on the parameter range of published galaxies (e.g. van Dokkum et al. 2015, Mihos et al. 2015)
- Systematic visual search for similarly looking objects

Examples of inserted galaxy models:



Width of one sub-panel: 1 arcmin (20 kpc)

Parameter range:

- $\langle \mu_V \rangle_{50} = 24.6$–$27.8\,\mathrm{mag\,arcsec}^2$ (Assuming $A_V = 0.5\,\mathrm{mag}$)
- $r_{50} = 1.5$–$10\,\mathrm{kpc}$
- $M_V = -13.5$ to $-16.5\,\mathrm{mag}$

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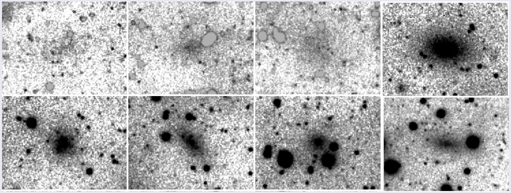

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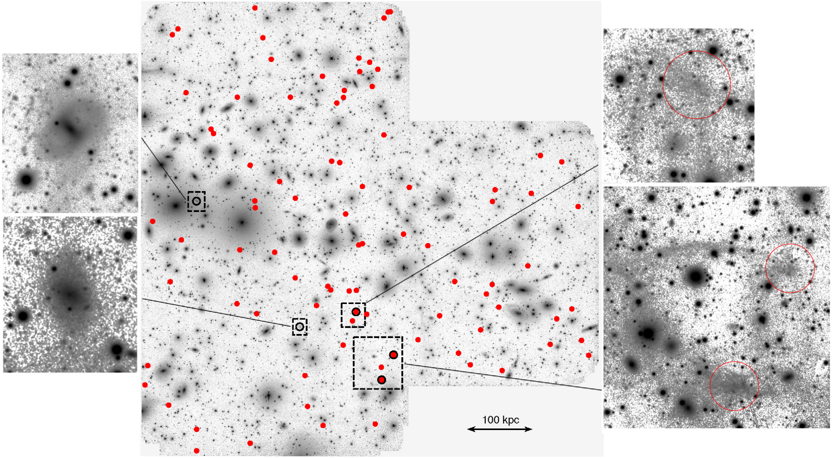
# LSB galaxy candidates with possible signs of disruption




Centre image: Spatial distribution of LSB galaxy candidates in the Perseus cluster core. Image with: 0.58 deg (0.71 Mpc). Side-panels: LSB galaxy candidates with possible signs of disruption. Wittmann et al. (2017)

**...signs of tidal disruption?**

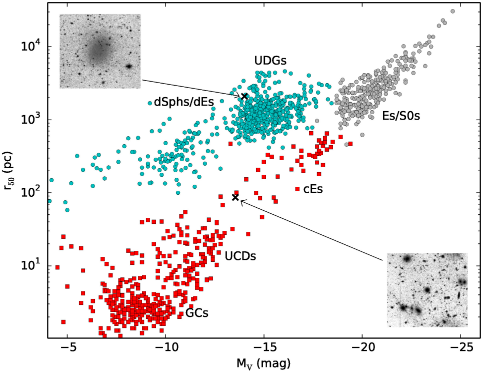
- Majority of our sample: no obvious signs of ongoing disruption!
- But: All LSB candidates except one have $r_{50} \lesssim 3\,\mathrm{kpc}$
  $\rightarrow$ Apparent upper size limit induced by the Perseus cluster tidal field?

**Rough estimate of the mass-to-light ratio:**

- Consider a typical LSB galaxy with $M_V = -14\,\mathrm{mag}$ and $r_{50} = 3\,\mathrm{kpc}$, located at $R_{peri} = 300\,\mathrm{kpc}$
- Assume that it is unperturbed within $2\,r_{50}$, i.e. $r_{tidal} = 6\,\mathrm{kpc}$

$$\rightarrow M_{obj} = 3 \times 10^9\,\mathrm{M}_\odot \quad \left[ R_{tidal} = R_{peri} \left( \frac{M_{obj}}{M_{cl}(R_{peri})(3+e)} \right)^{1/3} \right]$$ (King 1962)

$\Rightarrow M/L_V \sim 100$, consistent with dynamical mass measurements!



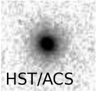

**Compact stellar systems**

- Compact objects with $r_h \lesssim 100\,\text{pc}$, $M_V = -10$ to $-14\,\text{mag}$ also known as **ultra-compact dwarf galaxies** (UCDs)
- UCDs first discovered in the Fornax cluster in 1999 (Hilker et al. 1999, Drinkwater et al. 2000a)

- Abundant populations of spectroscopically confirmed UCDs detected in nearby galaxy clusters; some known in groups and around isolated massive galaxies

# Compact low-mass stellar systems

**Ultra-compact dwarf galaxies**
→ Connected to the population of star clusters or galaxies?




## Star cluster origin?

- Appear similar to massive star clusters and share common properties (e.g. ages, metallicities, $\alpha$-element abundances)
- Statistically consistent with being the brightest members of the GC population around massive galaxies (Mieske et al. 2011)

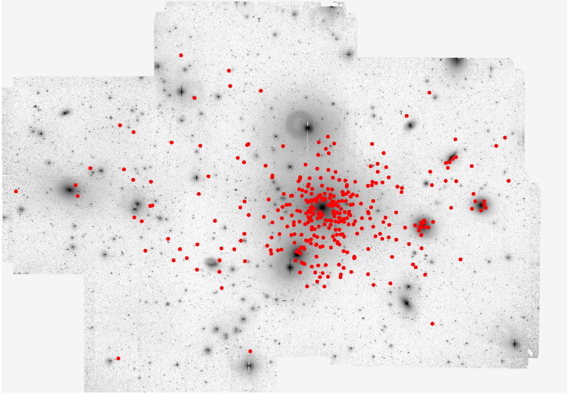
## Galaxy origin?

- Similar properties as nuclei of low-mass galaxies
  → Remnant nuclei of tidally stripped galaxies?
  (e.g. Bekki et al. 2003, Pfeffer et al. 2014)

**Current picture:** UCDs might be a "mixed bag" of objects!

# Compact stellar systems in the Fornax cluster core

...formed by tidal stripping of nucleated low-mass galaxies?



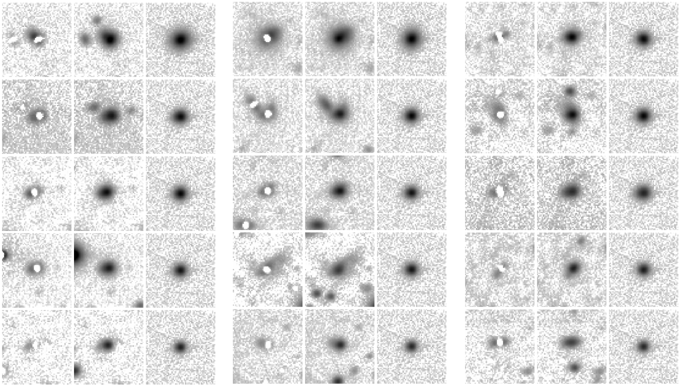
Deep mosaic of the Fornax core (WFI white-filter, ESO 2.2m telescope). Red dots: Working sample. Image: 100 × 76 arcmin$^2$ (0.58 × 0.44 Mpc$^2$). Lisker et al. (submitted)

**Sample:**

- Literature compilation of spectroscopically confirmed compact stellar systems
- Working sample: 355 compact objects with $\mathrm{M_V} <$ -10 mag

# Peculiar compact stellar systems in the Fornax cluster

Absence of long tidal streams around confirmed compact objects, but many show a distorted outer structure!



Left sub-panels: PSF-subtracted residual image. Centre sub-panels: object. Right sub-panels: artificial compact object of similar brightness, convolved with the PSF of the corresponding object. Sub-panel width: 12 arcsec (1.2 kpc). Wittmann et al. (2016)

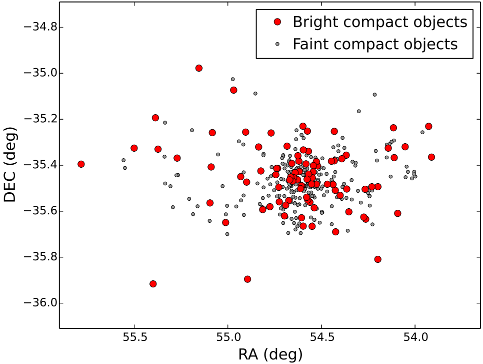
# Compact stellar systems in Fornax: Spatial distribution

Parametrization of the outer and central light distribution:

**Residual asymmetry**
Defined in analogy to the Asymmetry parameter
(Conselice et al. 2000)

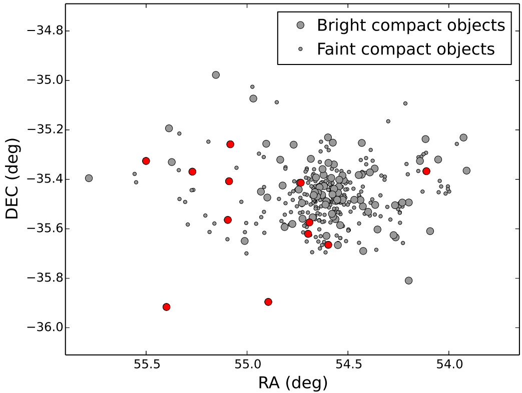
**Ellipticity**
Measured on the PSF-subtracted residual image

**Core concentration**
Mean central flux ratio of the object to the fitted PSF



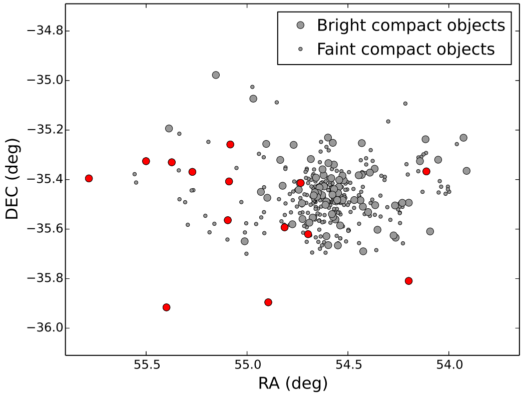

Spectroscopically confirmed compact objects in Fornax. Bright objects: $M_V < -11$ mag. Faint objects: -11 $< \mathrm{M_V} <$ -10. Wittmann et al. (2016)

## Objects with high ellipticity and low core concentration



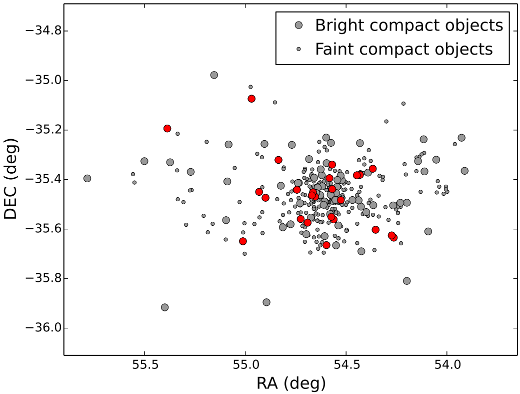

Spatial distribution of spectroscopically confirmed compact stellar systems in Fornax. Bright objects: $M_V < -11\,\mathrm{mag}$. Faint objects: -11 $< \mathrm{M_V} <$ -10. Wittmann et al. (2016)

**Objects with high residual asymmetry and low core concentration**




Spatial distribution of spectroscopically confirmed compact stellar systems in Fornax. Bright objects: $M_V < -11$ mag. Faint objects: -11 $< \mathrm{M_V} <$ -10. Wittmann et al. (2016)

## Objects with low residual asymmetry and low core concentration

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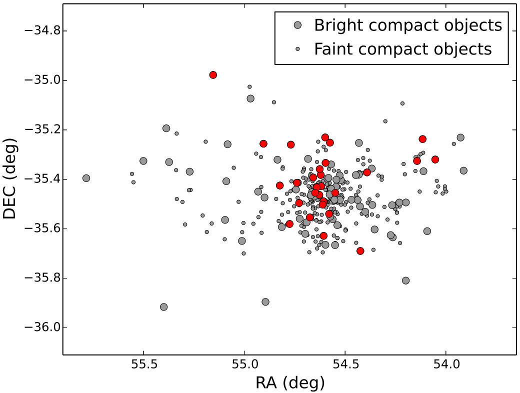
**Objects with high residual asymmetry and high core concentration**

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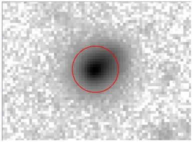
# Peculiar compact stellar systems in Fornax

...formed by tidal stripping?



**Estimate of the tidal radius:** (King 1962)
For $M_{object} \approx 10^7\ M_\odot$ at $R_{pericenter} = 20$ kpc
$\rightarrow R_{tidal} \approx 200$ pc

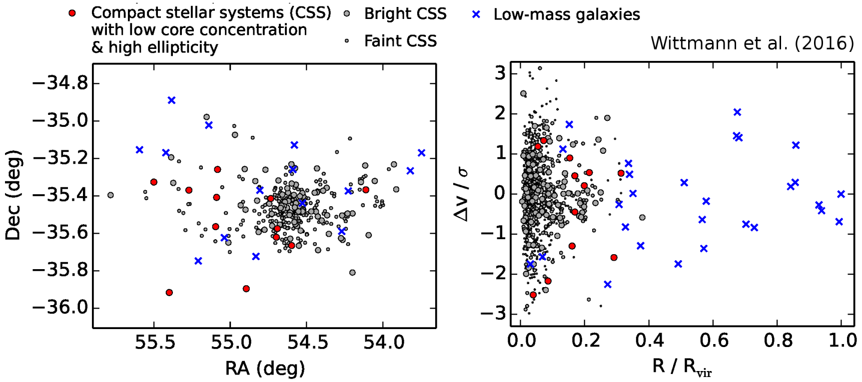
$\Rightarrow$ Disturbances of the outer structure expected for objects with close cluster centre passages

**But: Disruption signs not sufficient to discriminate between a star cluster and a galaxy origin!**

# Peculiar compact stellar systems in Fornax

...deformed star clusters or remnants of stripped galaxies?

**Compact objects with distorted outer structure and low core concentration:**




⇒ **Might be good candidates for originating from stripped galaxies!**

# Summary and conclusions

Were the most compact and most diffuse stellar systems in galaxy clusters both formed by stripping?

**Low-surface brightness galaxy candidates in Perseus**

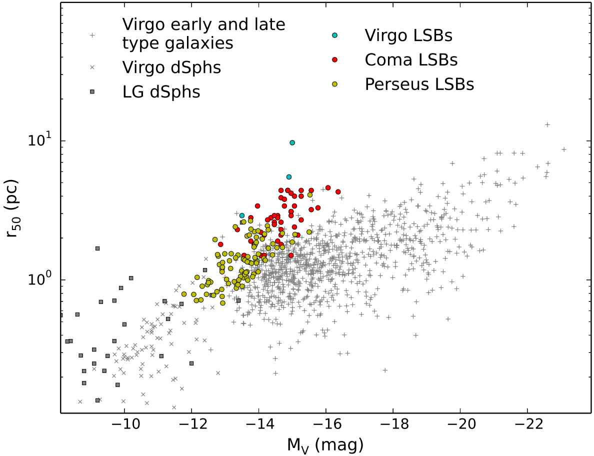
- The majority of the identified 89 LSB candidates does not show signs of recent tidal disruption
  $\rightarrow$ If (trans-)formed by tidal stripping, likely happened at earlier times
- Earlier tidal influence indicated by apparent upper size limit ($r_{50} \lesssim 3\,\mathrm{kpc}$)?

**Compact stellar systems in Fornax**

- Detection of peculiar compact objects with distorted outer structure
  $\rightarrow$ Distortions could be caused by tidal stripping
  $\rightarrow$ Not sufficient to distinguish between a star cluster/galaxy origin
- A subsample of compact objects with distorted structure and low core concentration may originate from tidally stripped galaxies based on its "galaxy-like" spatial and phase space distribution

# Faint LSB galaxy candidates in the Perseus cluster core

## Magnitude-size distribution




Virgo galaxies: Lisker et al. (2013, & references therein). Virgo dSphs: Lieder et al. (2012). LG dSphs: McConnachie et al. (2012). Coma LSBs: van Dokkum et al. (2015). Virgo LSBs: Mihos et al. (2015). Perseus LSBs: Wittmann et al. (2017).

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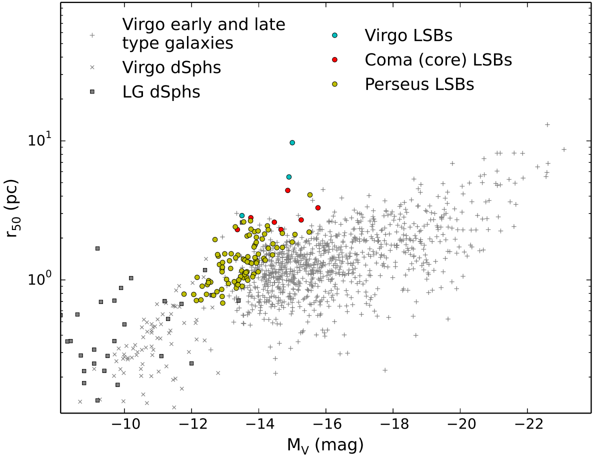
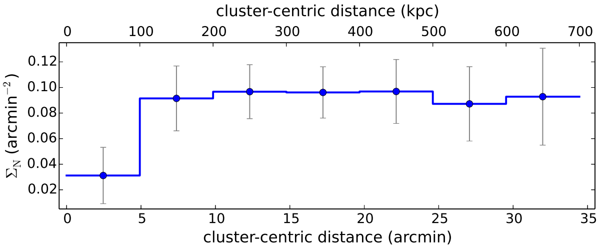



Apparent depletion of large LSB galaxy candidates with $r_{50} \gtrsim 3\,\mathrm{kpc}$ in both the Perseus and Coma cluster core!

Virgo galaxies: Lisker et al. (2013, & references therein). Virgo dSphs: Lieder et al. (2012). LG dSphs: McConnachie et al. (2012). Coma LSBs: van Dokkum et al. (2015). Virgo LSBs: Mihos et al. (2015). Perseus LSBs: Wittmann et al. (2017).

**Projected radial number density profile**




Wittmann et al. (2017)