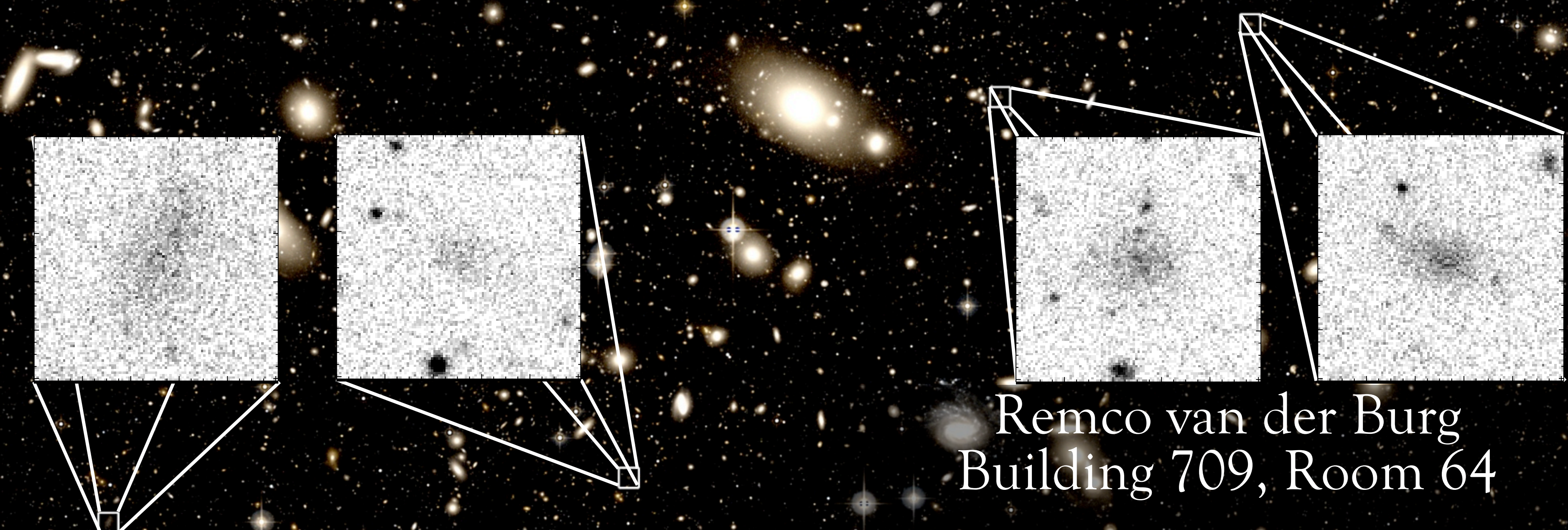
The abundance and spatial distribution of ultra-diffuse galaxies in nearby galaxy clusters

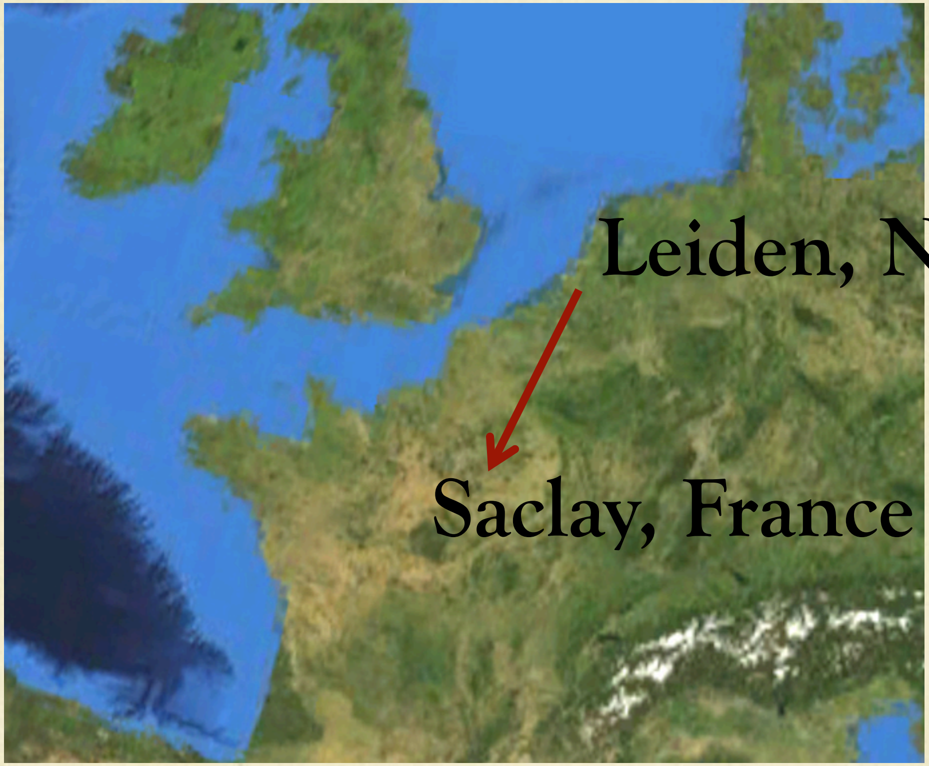


Remco van der Burg
Building 709, Room 64

A&A, 590, A20 (2016, ArXiv:1602.00002)

Adam Muzzin, Henk Hoekstra, Cristóbal Sífon

PhD Astrophysics, Leiden Observatory, May 2014
PostDoc, CEA Saclay, May 2014




Saclay, France

At the beginning of 2015...

FORTY-SEVEN MILKY WAY-SIZED, EXTREMELY DIFFUSE GALAXIES IN THE COMA CLUSTER

PIETER G. VAN DOKKUM[1], ROBERTO ABRAHAM[2], ALLISON MERRITT[1], JIELAI ZHANG[2], MARLA GEHA[1], AND CHARLIE CONROY[3]

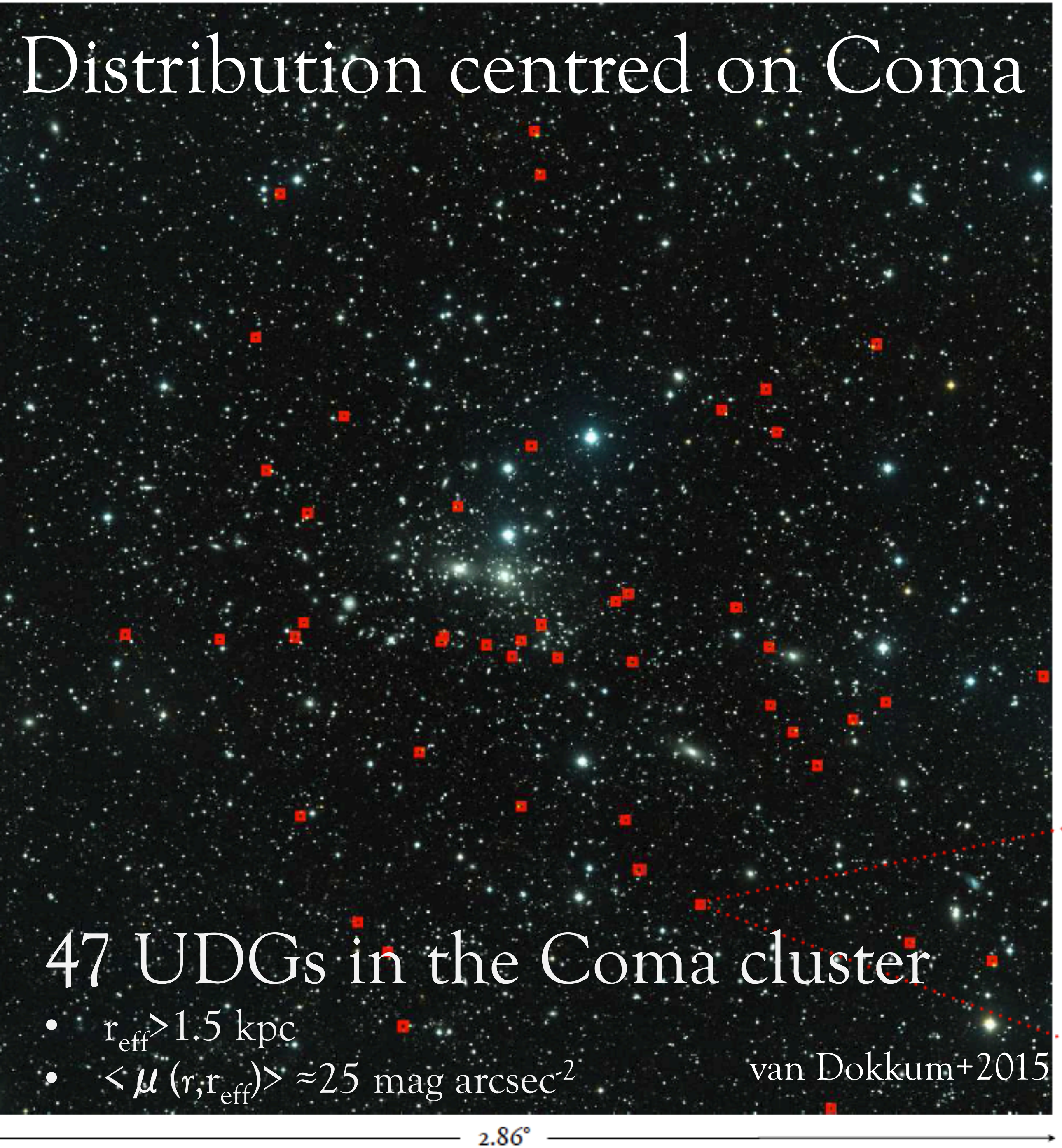
ABSTRACT

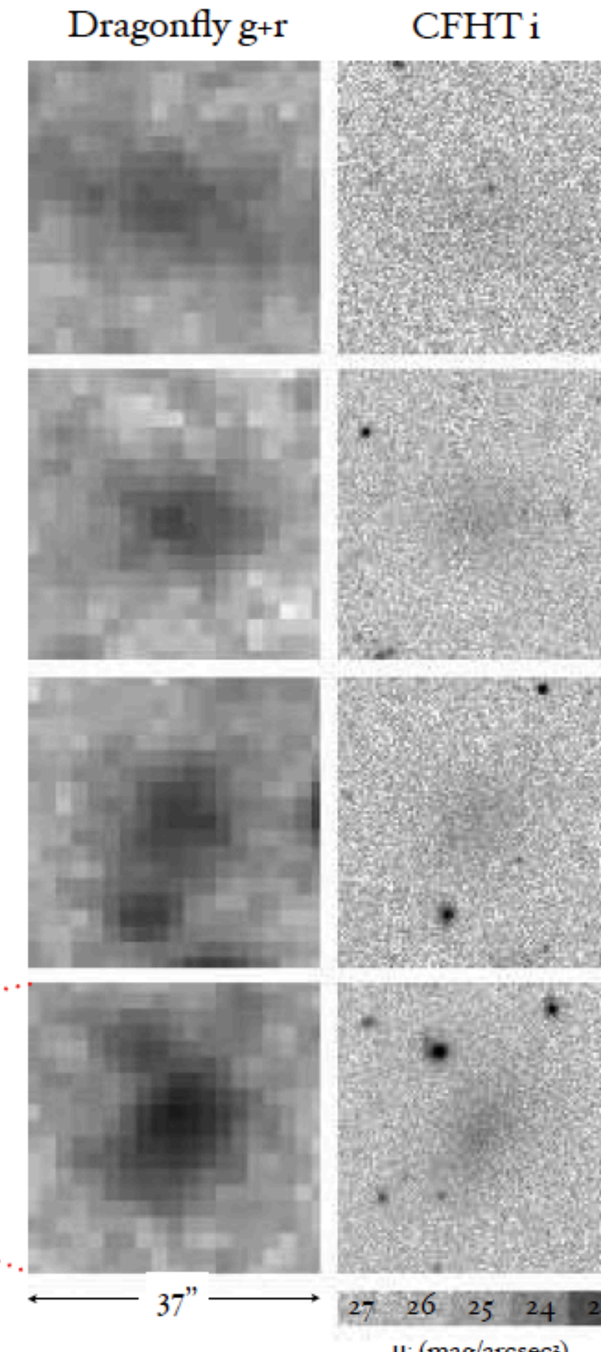
We report the discovery of 47 low surface brightness objects in deep images of a $3° \times 3°$ field centered on the Coma cluster, obtained with the Dragonfly Telephoto Array. The objects have central surface brightness $\mu(g,0)$ ranging from $24 - 26$ mag arcsec^{-2} and effective radii $r_{\rm eff} = 3'' - 10''$, as measured from archival Canada France Hawaii Telescope images. From their spatial distribution we infer that most or all of the objects are galaxies in the Coma cluster. This relatively large distance is surprising as it implies that the galaxies are very large: with $r_{\rm eff} = 1.5\,{\rm kpc} - 4.6\,{\rm kpc}$ their sizes are similar to those of L_* galaxies even though their median stellar mass is only $\sim 6 \times 10^7\,M_\odot$. The galaxies are relatively red and round, with $\langle g-i \rangle = 0.8$ and $\langle b/a \rangle = 0.74$. One of the 47 galaxies is fortuitously cover
a large spheroidal object wit
an effective radius of 7″, co
stars, consistent with expect
(UDGs) may have lost their

Keywords: galaxies: clusters

Dragonfly Camera array
Abraham & van Dokkum
2014

Distribution centred on Coma





In the following months:

SPECTROSCOPIC CONFIRMATION OF THE EXISTENCE OF LARGE, DIFFUSE GALAXIES IN THE COMA CLUSTER

Pieter G. van Dokkum[1], Aaron J. Romanowsky[2,3], Roberto Abraham[4], Jean P. Brodie[3], Charlie Conroy[5], Marla Geha[1], Allison Merritt[1], Alexa Villaume[3], and Jielai Zhang[4]

GALAXIES AT THE EXTREMES: ULTRA-DIFFUSE GALAXIES IN THE VIRGO CLUSTER

J. Christopher Mihos[1], Patrick R. Durrell[2], Laura Ferrarese[3], John J. Feldmeier[2], Patrick Côté[3], Eric W. Peng[4,5], Paul Harding[1], Chengze Liu[6,7], Stephen Gwyn[3], and Jean-Charles Cuillandre[8]

APPROXIMATELY A THOUSAND ULTRA DIFFUSE GALAXIES IN THE COMA CLUSTER

Jin Koda[1], Masafumi Yagi[2,3], Hitomi Yamanoi[2], Yutaka Komiyama[2,4]

UNVEILING A RICH SYSTEM OF FAINT DWARF GALAXIES IN THE NEXT GENERATION FORNAX SURVEY

Roberto P. Muñoz[1], Paul Eigenthaler[1], Thomas H. Puzia[1], Matthew A. Taylor[1,2], Yasna Ordenes-Briceño[1], Karla Alamo-Martínez[1], Karen X. Ribbeck[1], Simón Ángel[1], Massimo Capaccioli[3], Patrick Côté[4], Laura Ferrarese[4], Gaspar Galaz[1], Maren Hempel[1], Michael Hilker[5], Andrés Jordán[1], Ariane Lançon[6], Steffen Mieske[2], Maurizio Paolillo[7], Tom Richtler[8], Ruben Sánchez-Janssen[4], and Hongxin Zhang[1,9,10]

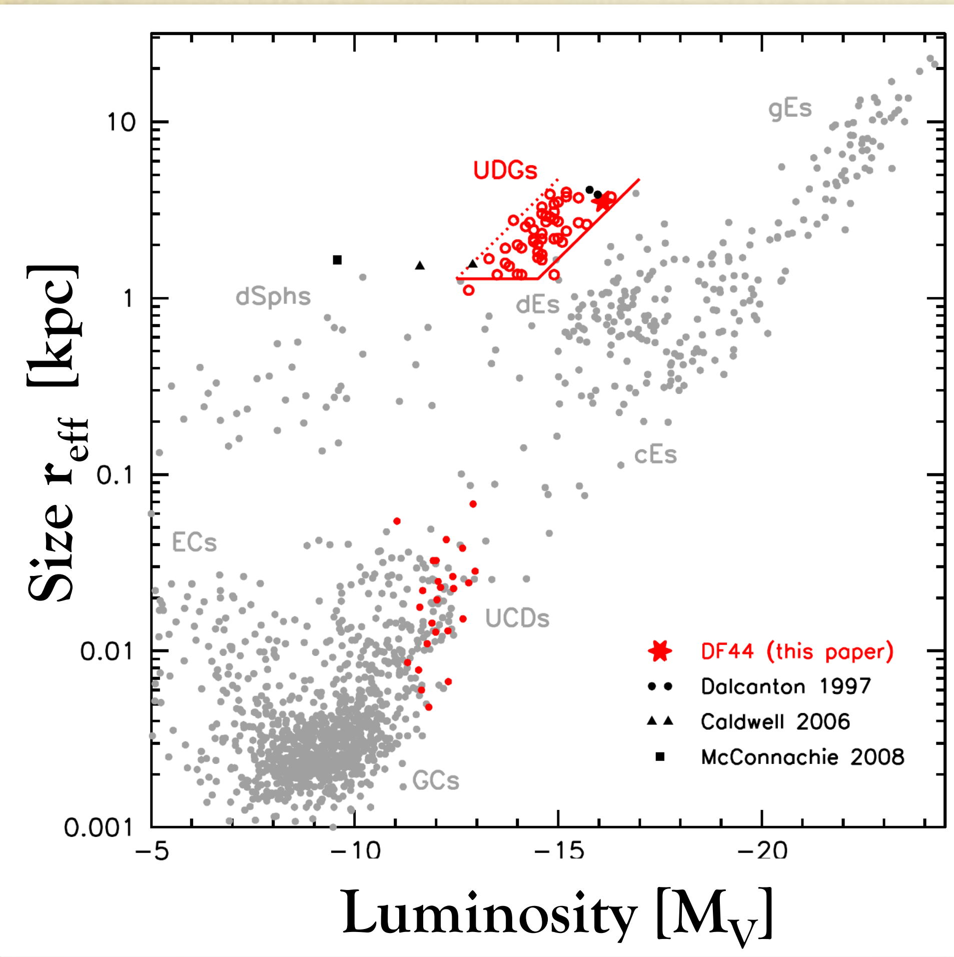
DISCOVERY OF AN ULTRA-DIFFUSE GALAXY IN THE PISCES-PERSEUS SUPERCLUSTER

David Martínez-Delgado[1,2], Ronald Läsker[2], Margarita Sharina[12], Elisa Toloba[5,13], Jürgen Fliri[3,15], Rachael Beaton[13], David Valls-Gabaud[4], Igor D. Karachentsev[12], Taylor S. Chonis[6], Eva K. Grebel[1], Duncan A. Forbes[10], Aaron J. Romanowsky[5,14], J. Gallego-Laborda[9], Karel Teuwen[8], M. A. Gómez-Flechoso[7], Jie Wang[17,11], Puragra Guhathakurta[5], Serafim Kaisin[12], Nhung Ho[16]

AN OVERMASSIVE DARK HALO AROUND AN ULTRA-DIFFUSE GALAXY IN THE VIRGO CLUSTER

Michael A. Beasley[1,2], Aaron J. Romanowsky[3,4], Vincenzo Pota[5], Ignacio Martin Navarro[1,2,4], David Martinez Delgado[6], Fabian Neyer[7], Aaron L. Deich[3]

A long history of Low Surface-Brightness galaxies…



van Dokkum et al. 2015b, after Brodie et al. 2011

- LSBs have been known before (Impey+88, Bothun+91, Turner+93, Dalcanton+97, …)
- Ultra-Diffuse Galaxies (UDGs) are extremes in the size-luminosity diagram:

r_{eff}>1.5 kpc

$< \mu\ (r, r_{eff}) > \approx 25$ mag arcsec^{-2}

How can UDGs survive the harsh dynamical environment of galaxy clusters?

Models rely on observational constraints

- Only Coma cluster studied, and some examples in Virgo and Fornax

> to perform a (mostly) objective selection with the aid of Sloan Digital Sky Survey (SDSS) and archival Canada France Hawaii Telescope (CFHT) data, as described in the next Sec-

> sition. This step left 186 objects which were inspected by eye. Of these, 139 were rejected, with most turning out to be clumps of multiple objects fainter than the $i = 22.5$ limit.

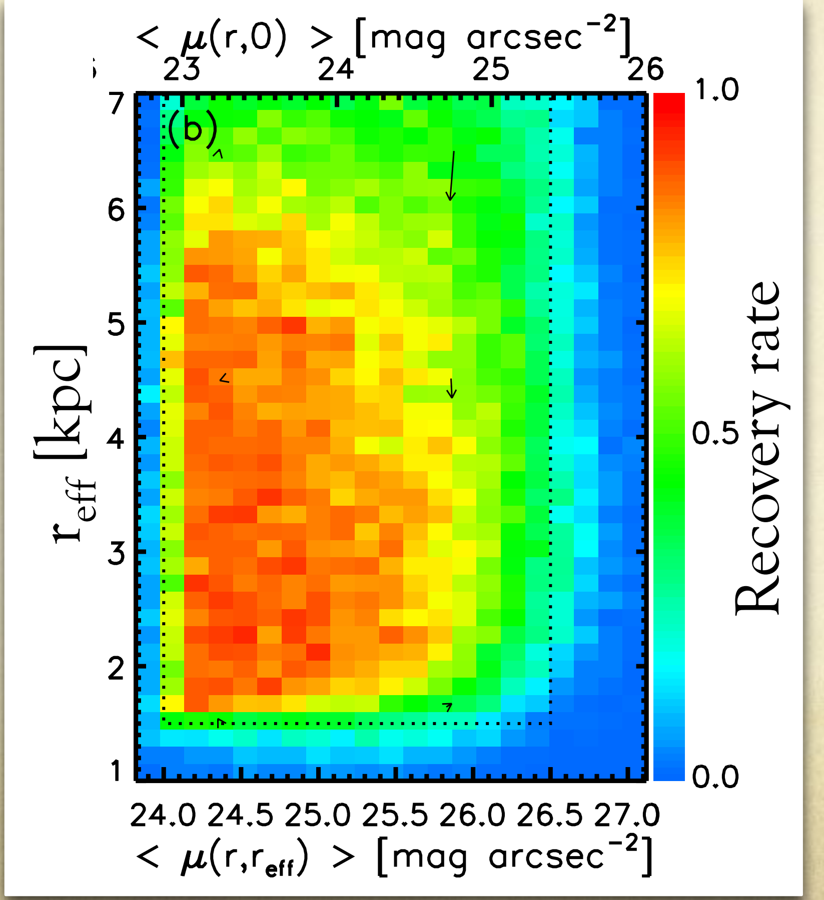
> artifacts at image edges, and optical ghosts. To minimize human error, the four authors separately went through all postage stamp images. After this step and removal of duplications based on their coordinates, 854 UDG candidates were left on which at least three of us agreed. The

- Early studies not systematic, nor objective/reproducible

This study

vdBurg+16b
A&A, 590, A20
ArXiv:1602.00002

- 8 clusters at $z \approx 0.05$ with deep *g*, *r*-band imaging with MegaCam@CFHT
- Image simulations to quantify completeness
- Tightened selection criteria (SExtractor & GALFIT) to keep purity high



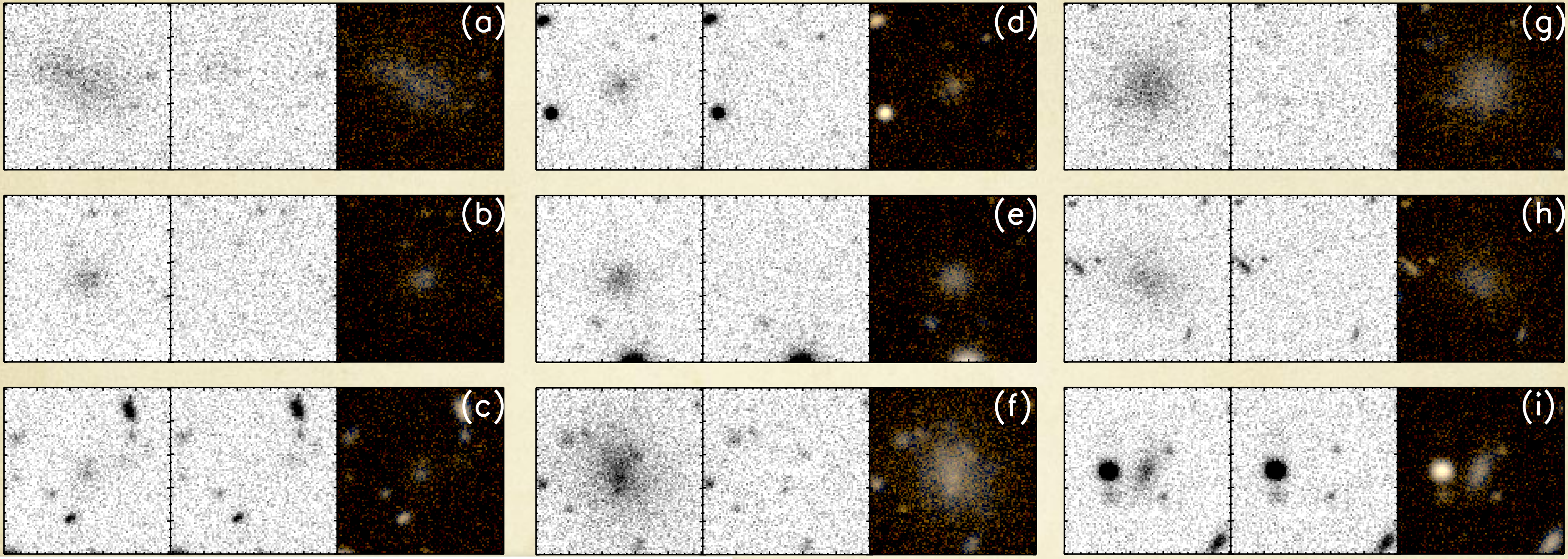
This study

vdBurg+16b
A&A, 590, A20
ArXiv:1602.00002

- 8 clusters at z≈0.05 with deep g, r-band imaging with MegaCam@CFHT
- Image simulations to quantify completeness
- Tightened selection criteria (SExtractor & GALFIT) to keep purity high
- Estimate background statistically using "empty" fields

Cluster	z_{spec}	RA J2000	Dec J2000	b_{Gal} [°]	M^{a}_{200} [10^{14} $M_{\odot}$]	R^{a}_{200} [Mpc]
A85	0.055	00:41:50.33	-09:18:11.20	-72.0	10.0 ± 1.7	2.0 ± 0.1
A119	0.044	00:56:16.04	-01:15:18.22	-64.1	7.5 ± 1.2	1.9 ± 0.1
A133	0.056	01:02:41.68	-21:52:55.81	-84.2	5.5 ± 1.7	1.7 ± 0.2
A780	0.055	09:18:05.67	-12:05:44.02	25.1	6.2 ± 2.5	1.7 ± 0.2
A1781	0.062	13:44:52.56	29:46:15.31	78.0	0.8 ± 0.5	0.9 ± 0.2
A1795	0.063	13:48:52.58	26:35:35.81	77.2	5.2 ± 1.0	1.6 ± 0.1
A1991	0.059	14:54:31.50	18:38:32.71	60.5	1.9 ± 0.5	1.2 ± 0.1
MKW3S	0.044	15:21:51.85	07:42:31.79	49.5	2.3 ± 0.6	1.2 ± 0.1

Some examples in the data



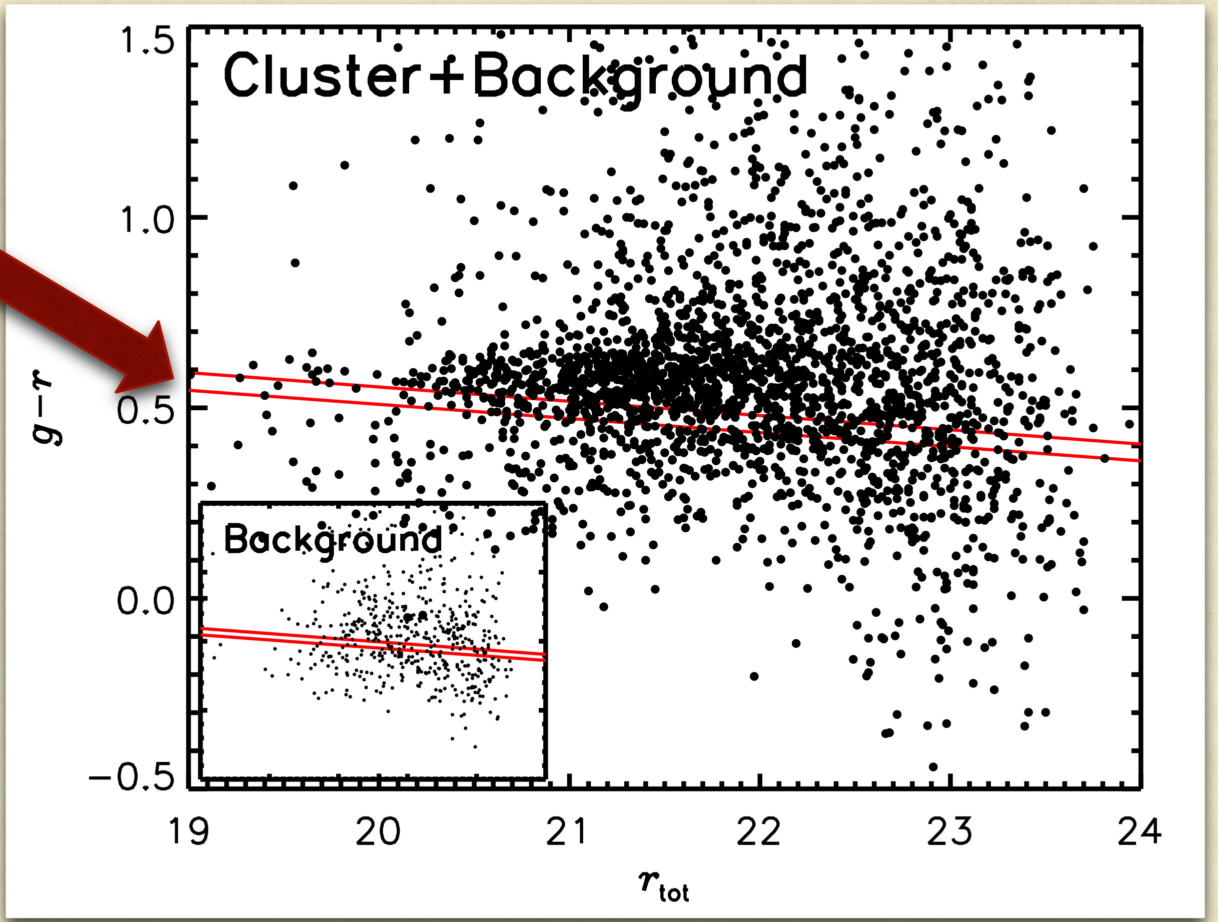
	r_{eff} [kpc]	$\langle\mu(r, r_{eff})\rangle$ [mag arcsec^{-2}]	Sérsic n	$g - r$
(a)	4.28	25.75	0.76	0.46
(b)	2.47	25.62	1.19	0.50
(c)	1.56	25.67	1.15	0.48
(d)	1.52	25.18	0.89	0.83
(e)	1.72	25.13	0.96	0.50
(f)	5.42	25.32	1.22	0.61
(g)	2.96	25.22	0.72	0.59
(h)	3.33	25.62	0.76	0.65
(i)	2.26	25.06	1.33	0.75

- 2456 selected in 8 cluster fields
- ~600 selected in 4 reference fields

What are their physical properties?

Colour-magnitude distribution

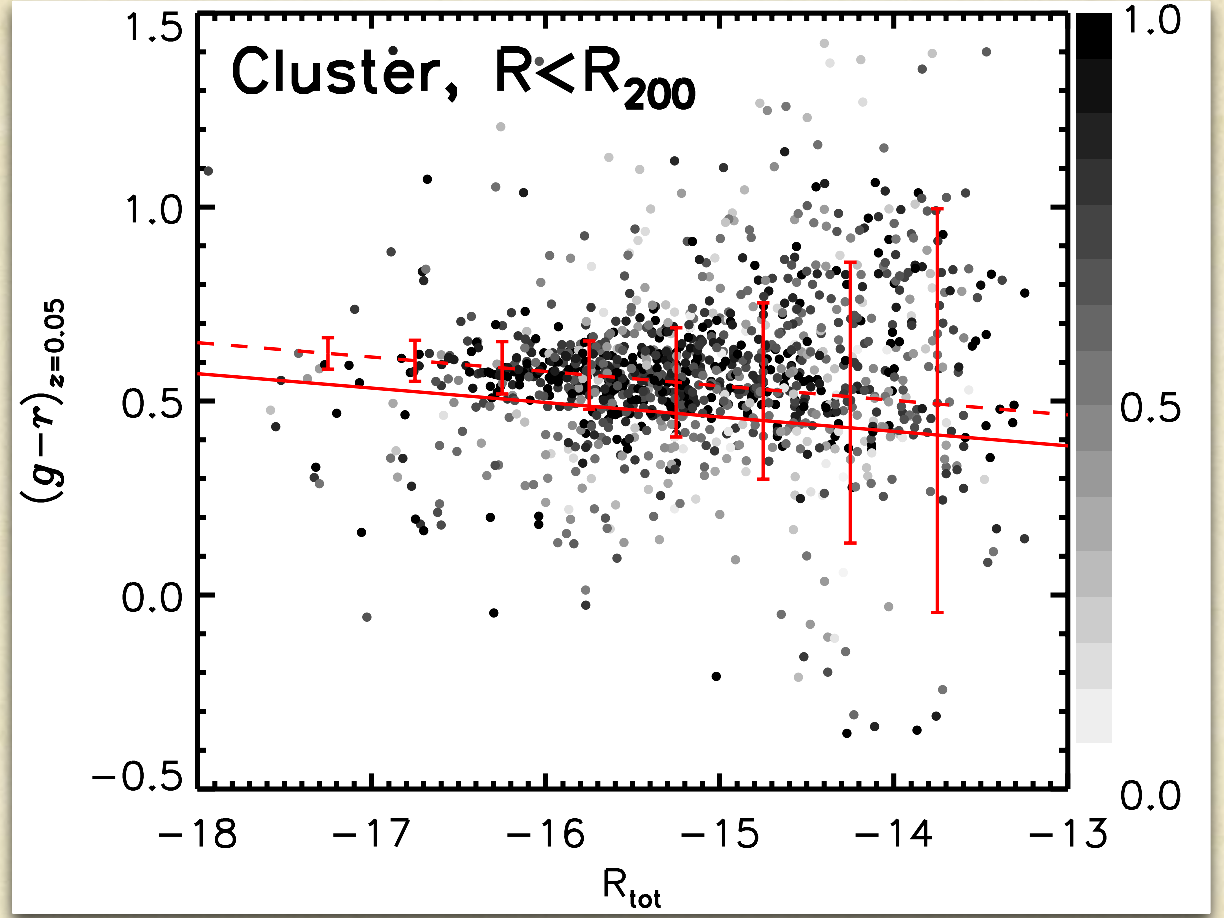
vdBurg+15



- Selection based only on morphology
- All on the red sequence -> old stellar populations

See also:
van Dokkum+15
Koda+15

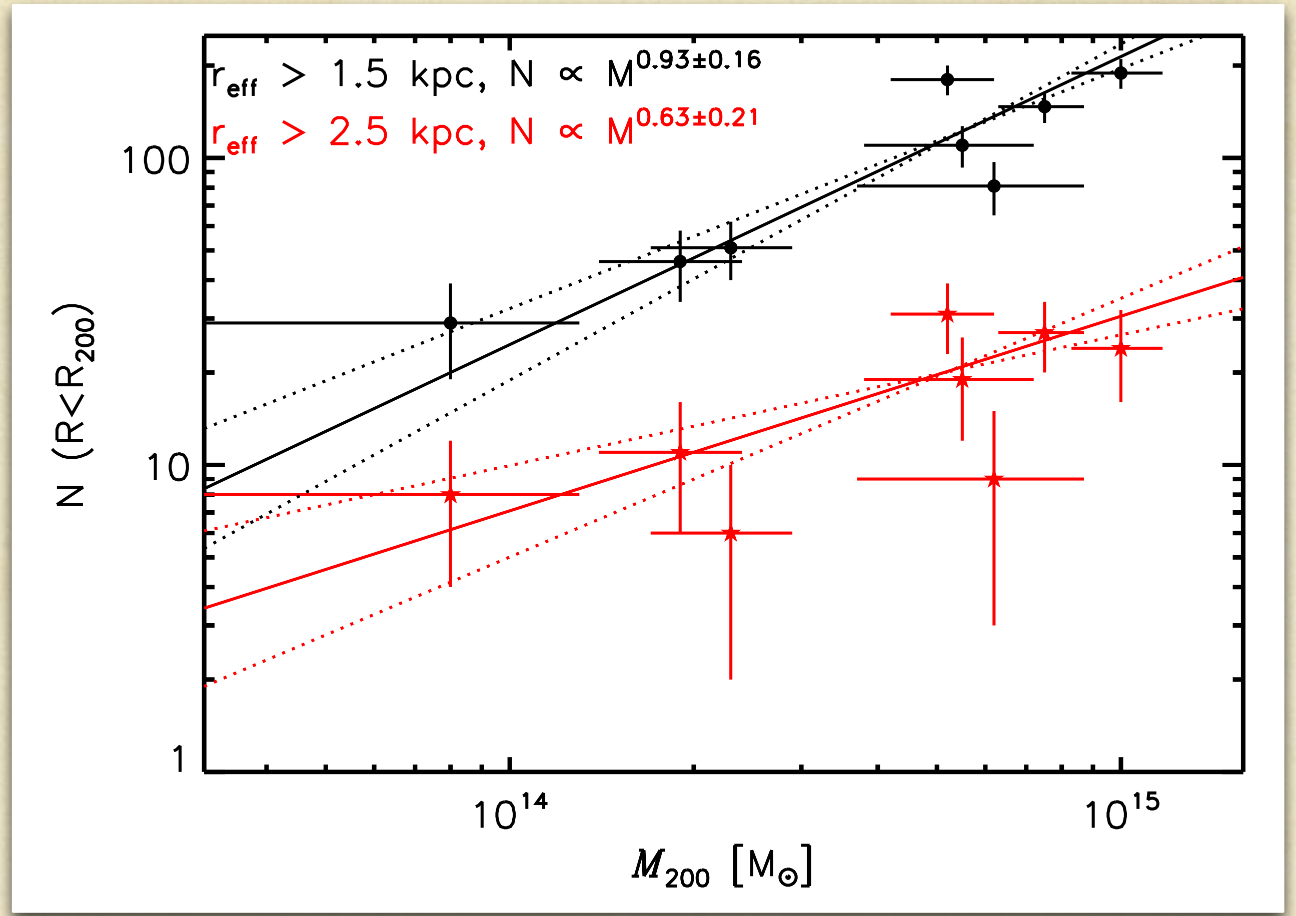
Colour-magnitude distribution



- Selection based only on morphology
- All on the red sequence -> old stellar populations
- Median stellar mass $\approx 10^8\,M_\odot$

See also:
van Dokkum+15
Koda+15

Abundance versus halo mass

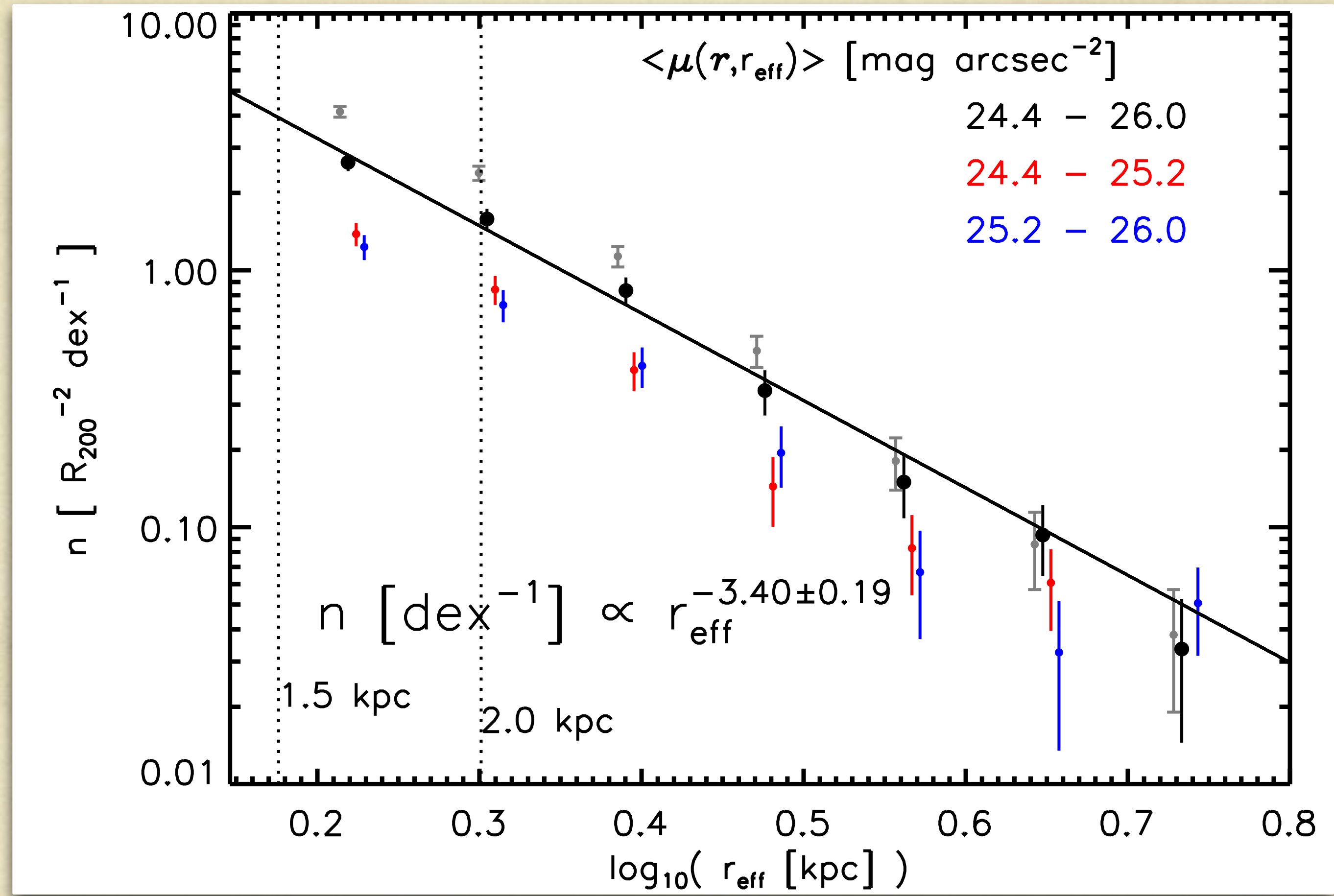


- Similar slope as mass-richness relation

Mass measurements: Sifón+15

- Total stellar mass in UDGs ≈ 0.2% of total cluster stellar mass
- Steep size distribution -> largest UDGs very rare

Size distribution



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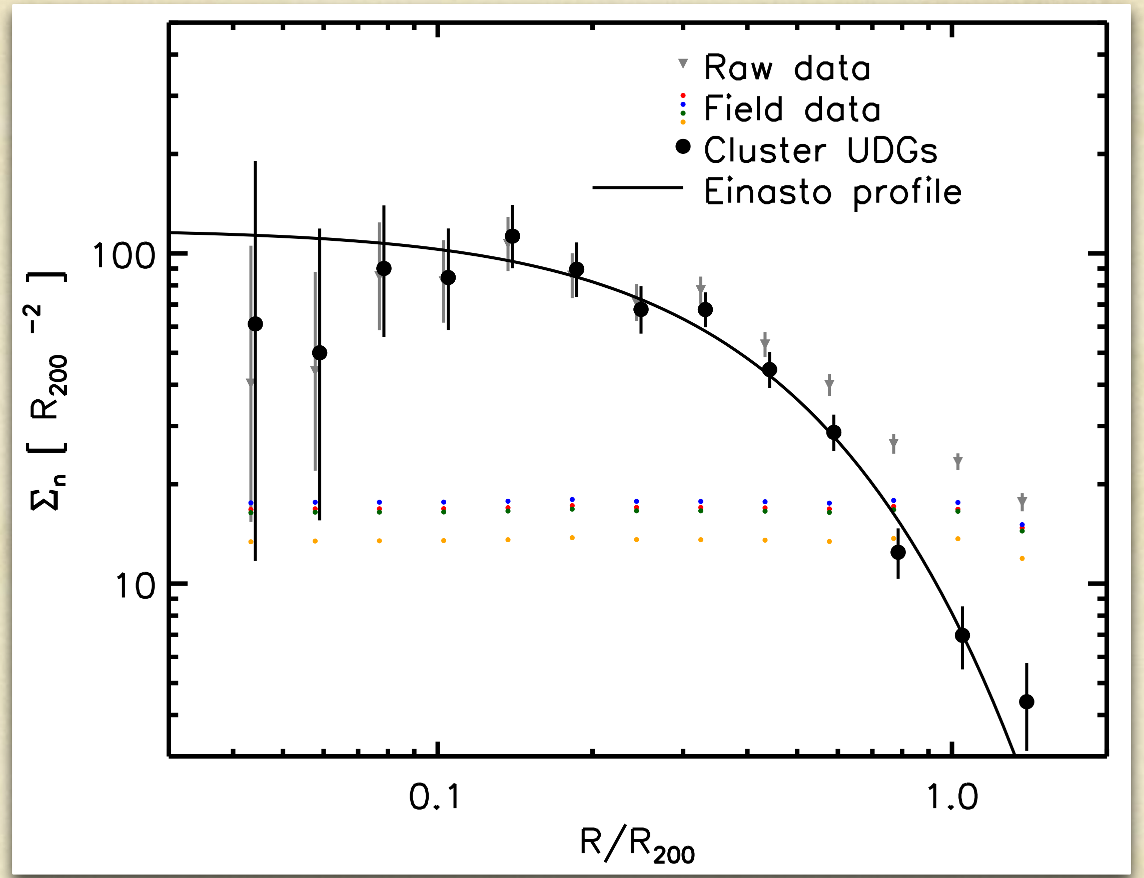
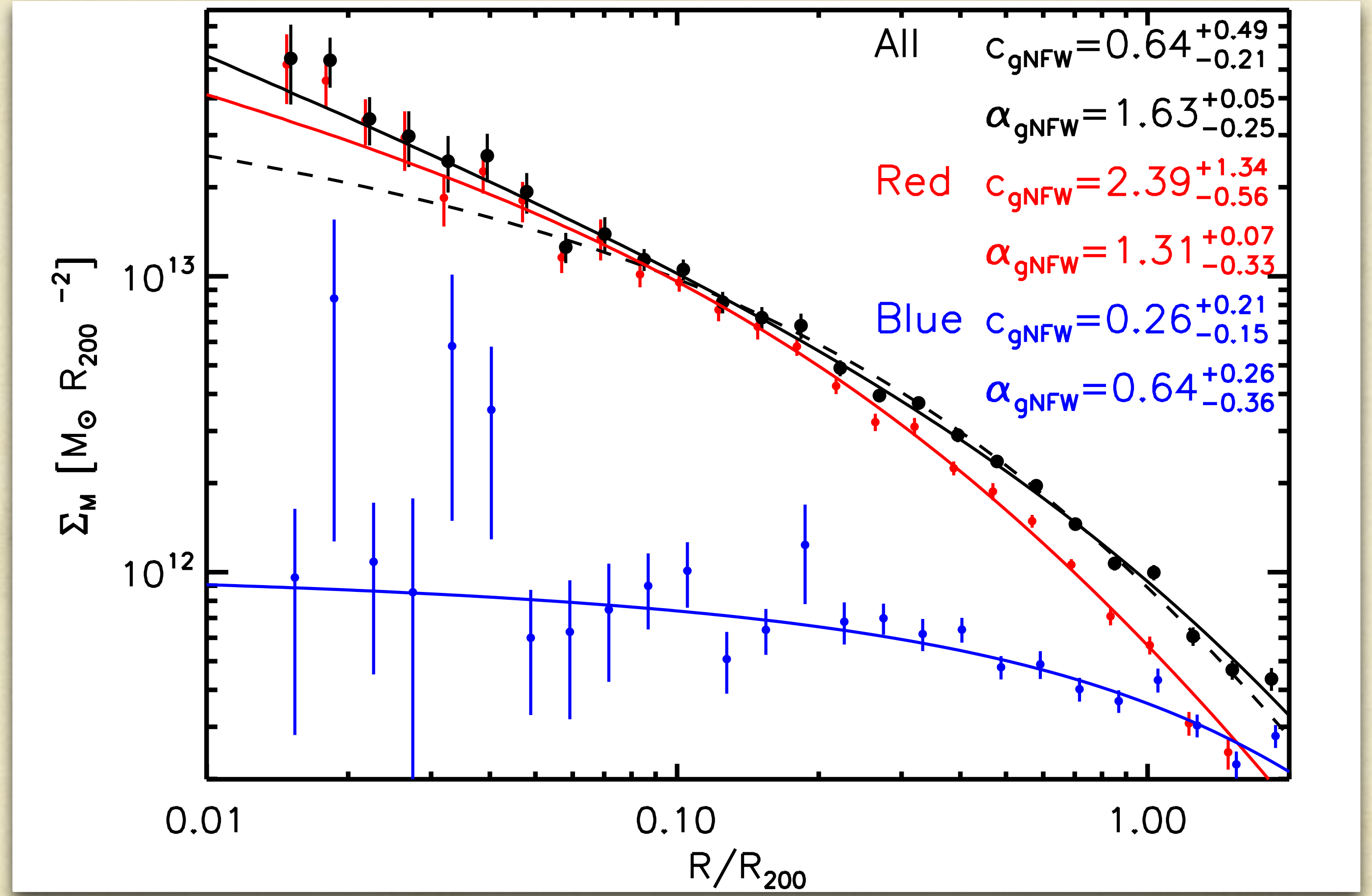
ArXiv:1602.00002

Radial distribution of UDGs



- Einasto parameters different from typical dark matter halo
- Where does this distribution originate from?

Radial distribution of (massive) galaxies in clusters

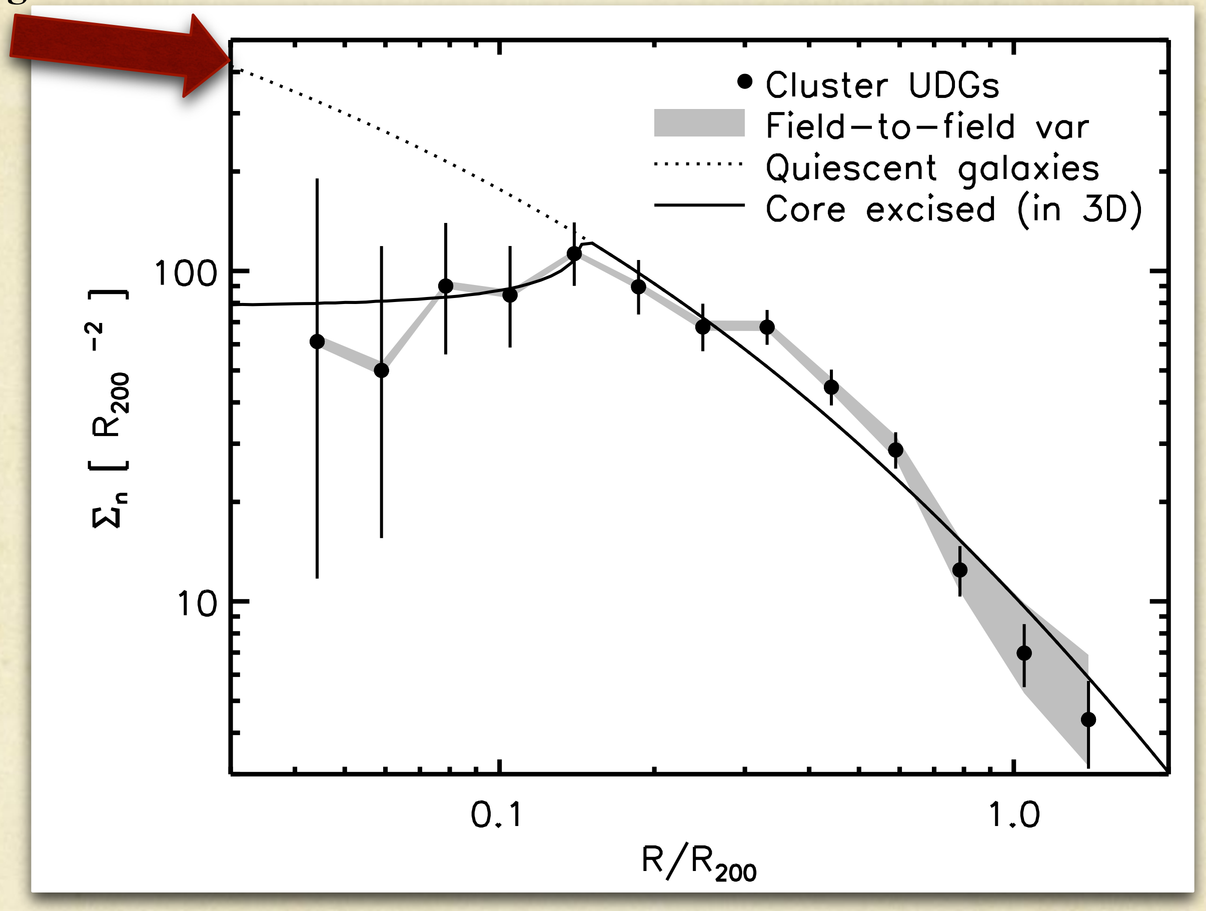


vdBurg+15

- Total galaxy distribution follows NFW profile (dashed, total mass)
- Red and blue galaxies have very different distributions

Radial distribution of UDGs

Total stellar-mass-weighted distribution of quiescent galaxies (vdBurg+15)



- Roughly follows dynamically old population in outskirts
- Complete deficit in the central 300kpc (in 3D, before projection)

How can UDGs survive down to 300kpc?

Also see van Dokkum+15

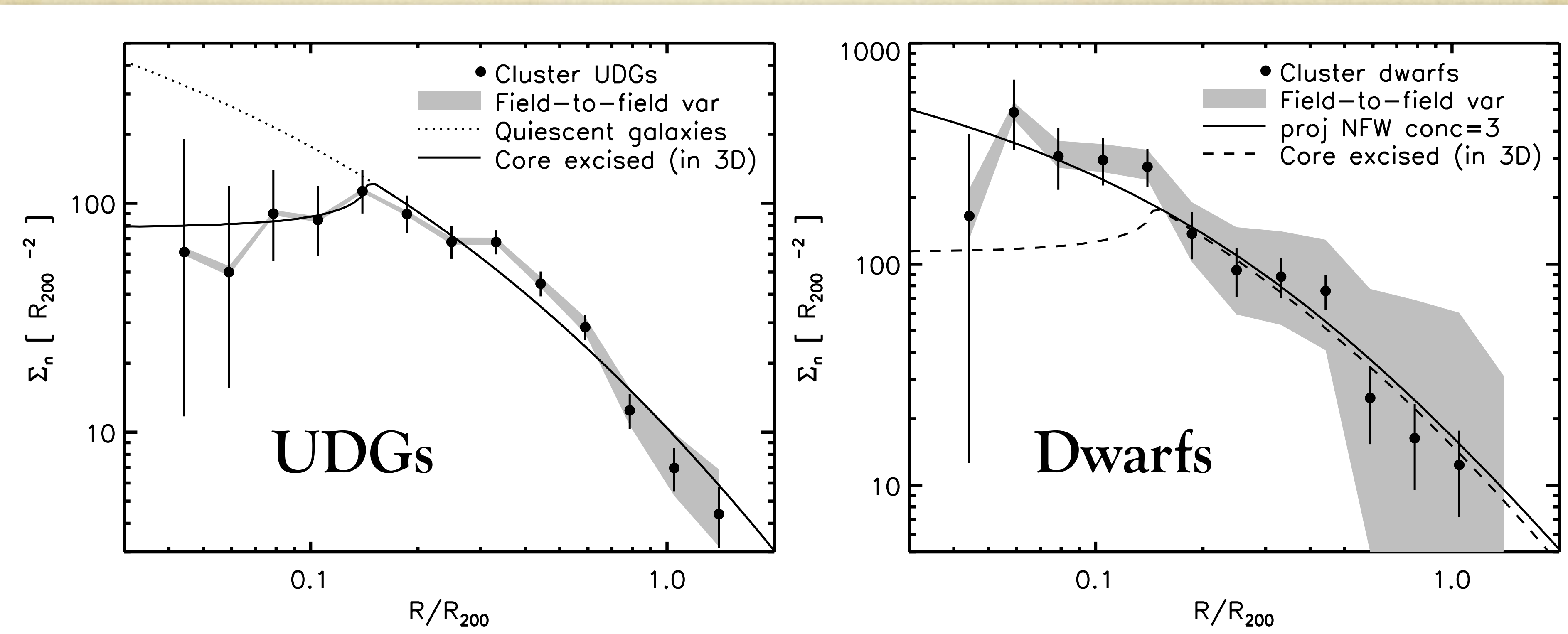
- A binding mass of $10^8\,M_\odot$ (the stellar mass) by far not enough
- Given cluster mass interior to 300kpc, one needs $2\times10^9\,M_\odot$ within a tidal disruption radius of 6kpc
  - **95% dark matter in the UDG centres**

Roche limit,
Binney & Tremaine 1987

- Within 300kpc, the tidal forces from the cluster halo exceed the binding mass of the UDGs

Are these failed Milky-Way type galaxies?

Radial distribution of "normal" dwarfs



- "Normal" dwarfs with 0.5< r_{eff} [kpc] <1.0 and same luminosities as UDGs exist down to ~100kpc from the cluster centre

Roche limit for "normal" dwarfs at 100kpc

- A comparison of UDGs and more compact dwarfs with stellar masses of $10^8\ M_\odot$
- Given cluster mass interior to 100kpc, one needs $4\times10^8\ M_\odot$ within a tidal disruption radius of 2kpc for dwarfs
- Given cluster mass interior to 300kpc, one needs $2\times10^9\ M_\odot$ within a tidal disruption radius of 6kpc for UDGs
- Two enclosed masses for 2 different populations

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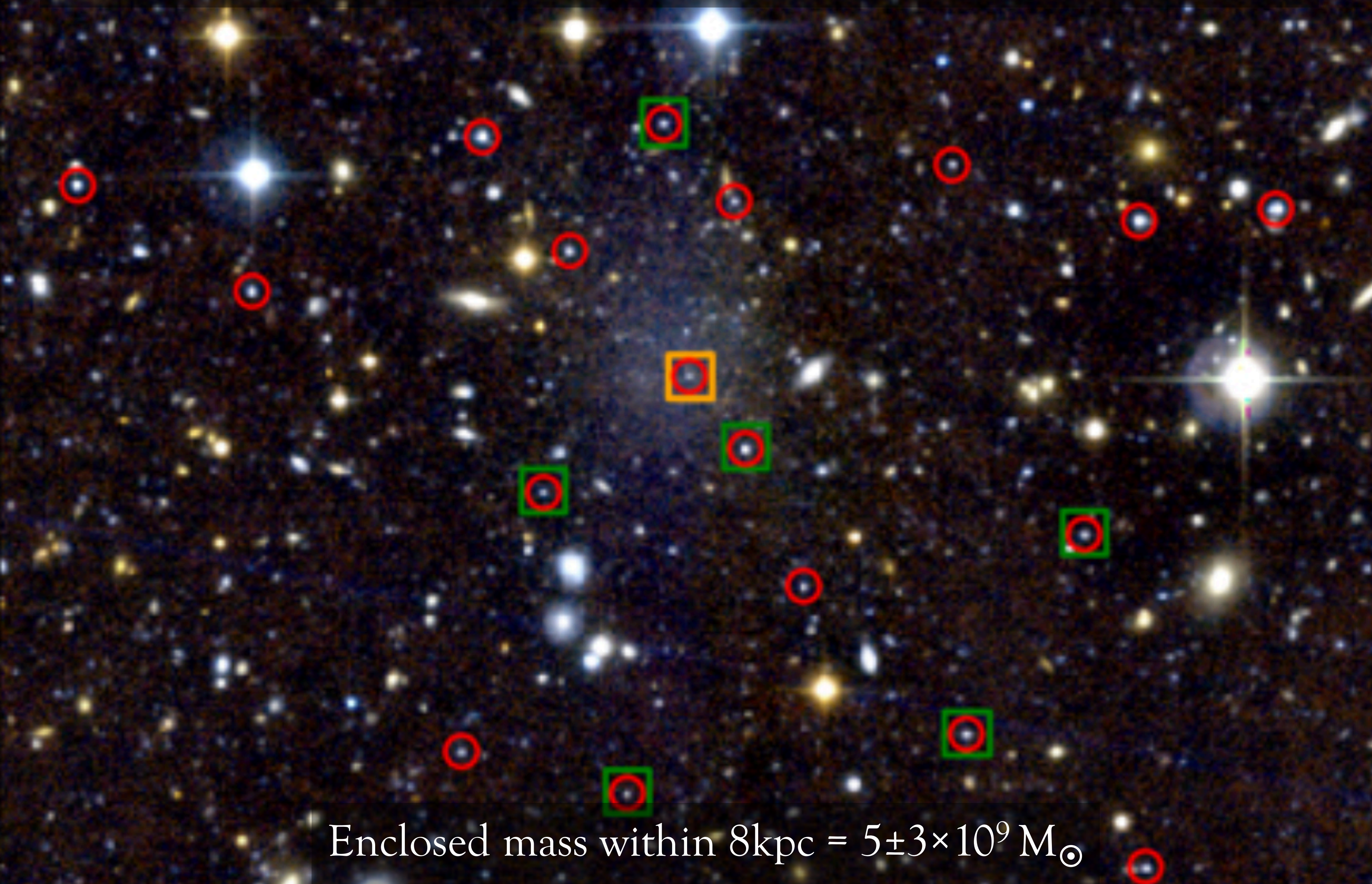
- Two enclosed masses for 2 different populations
  - $\rho = c \times r^{-\gamma}$, with $\gamma \approx 1.5$
- Consistent with them having similar dark matter haloes

Dynamical mass measurement based on globular clusters

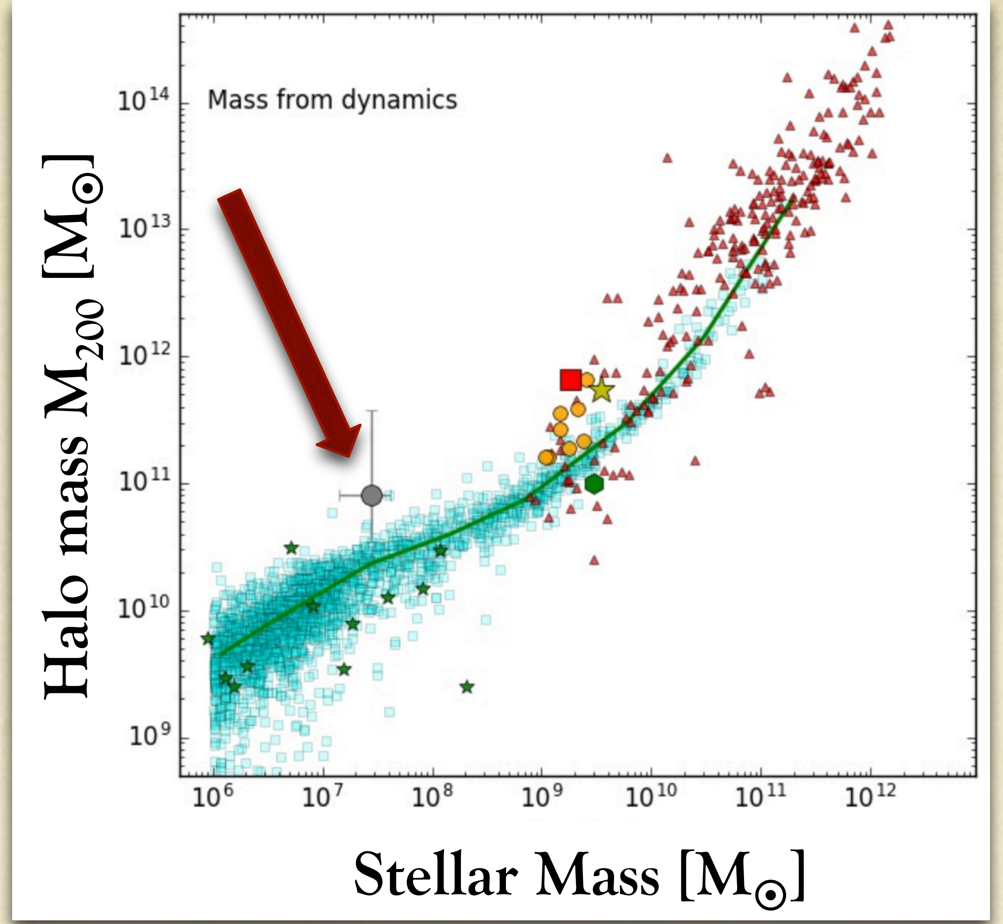
Beasley+16



Enclosed mass within 8kpc = $5\pm3\times10^9\ M_\odot$

From central mass to virial mass

Beasley+2016



Different interpretations of the same measurement:

- *"An overmassive dark halo around an ultra-diffuse galaxy in the Virgo cluster."* Beasley+2016
- *"This shows that [this UDG] is a genuine dwarf galaxy despite its effective radius of 2.4 kpc, disfavouring the possibility of a 'failed' L* galaxy."* Amorisco & Loeb 2016

How to explain the UDG population?

- Tidal debris
  - Very unlikely given their smooth morphologies
- Tidally disturbed/heated “normal” dwarf galaxies
  - Unlikely given their extended radial distribution vdBurg+16
- Failed Milky-Way type galaxies
  - Still unclear why some haloes would have “failed”
- High-spin tail of the dwarf galaxy population Amorisco & Loeb 2016
  - May be explained by standard model of disk formation

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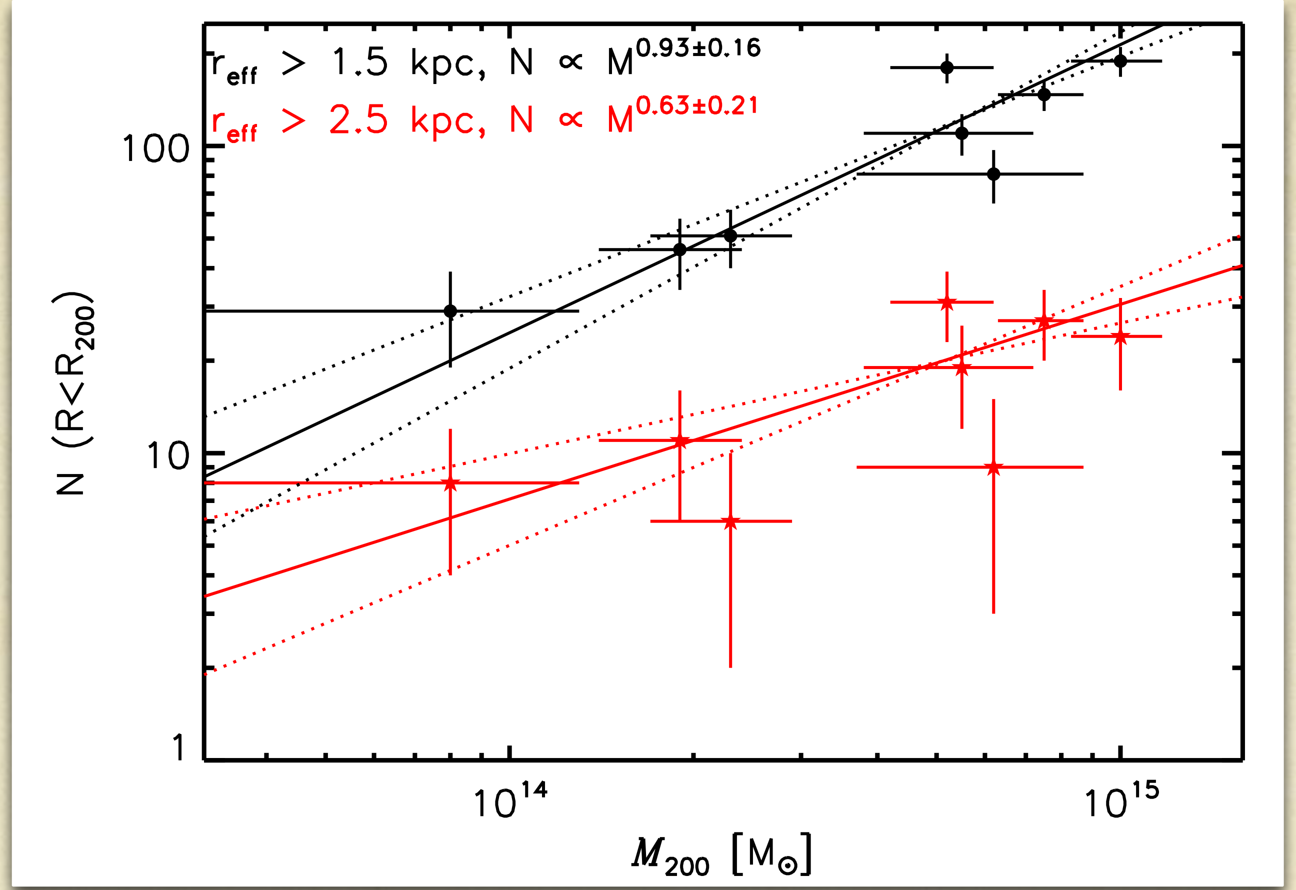
Field studies and halo mass measurements essential to make progress

Field studies



- Does this relation extend down to much lower mass haloes?
- What would their properties be?
- Without a cluster in the FoV, only ~ 10^{14} total mass at z<0.07 per sqr degree -> Need large area surveys for a statistical study

Measuring halo masses of UDGs

- Difficult to use methods that rely on stellar tracers of the potential
  - Even getting a redshift takes a long time
  - Perhaps using Globular Clusters is an (expensive) option for UDGs in low-*z* clusters
- An alternative is to measure the gravitational distortion of source galaxies behind the UDGs
  - CFHT data were taken with weak gravitational lensing in mind
  - Signal from failed Milky-Way type haloes should clearly stand out

Summary

vdBurg+16b
A&A, 590, A20
ArXiv:1602.00002

- Abundance of UDGs in clusters surprising and not yet understood
- First constraints from a systematic study in 8 nearby clusters
  - UDGs abundant in each cluster, with abundance scaling with M_{200}
  - Steep size distribution (largest UDGs rare)
  - Colour-magnitude distributions (old stellar populations)
  - They follow dynamically old galaxies spatially, with central deficit
- Measurements already used to constrain theoretical models

See Amorisco & Loeb 2016

- Several scenario's being considered
  - Essential to estimate field abundance and measure halo masses