Discovery of Ultra Diffuse Galaxies

van Dokkum et al. 2015a, ApJL, 798, L45
van Dokkum et al. 2015b, ApJL, 804, L26
Koda et al. 2015, ApJL in press

Ryu Makiya (IoA/UT)
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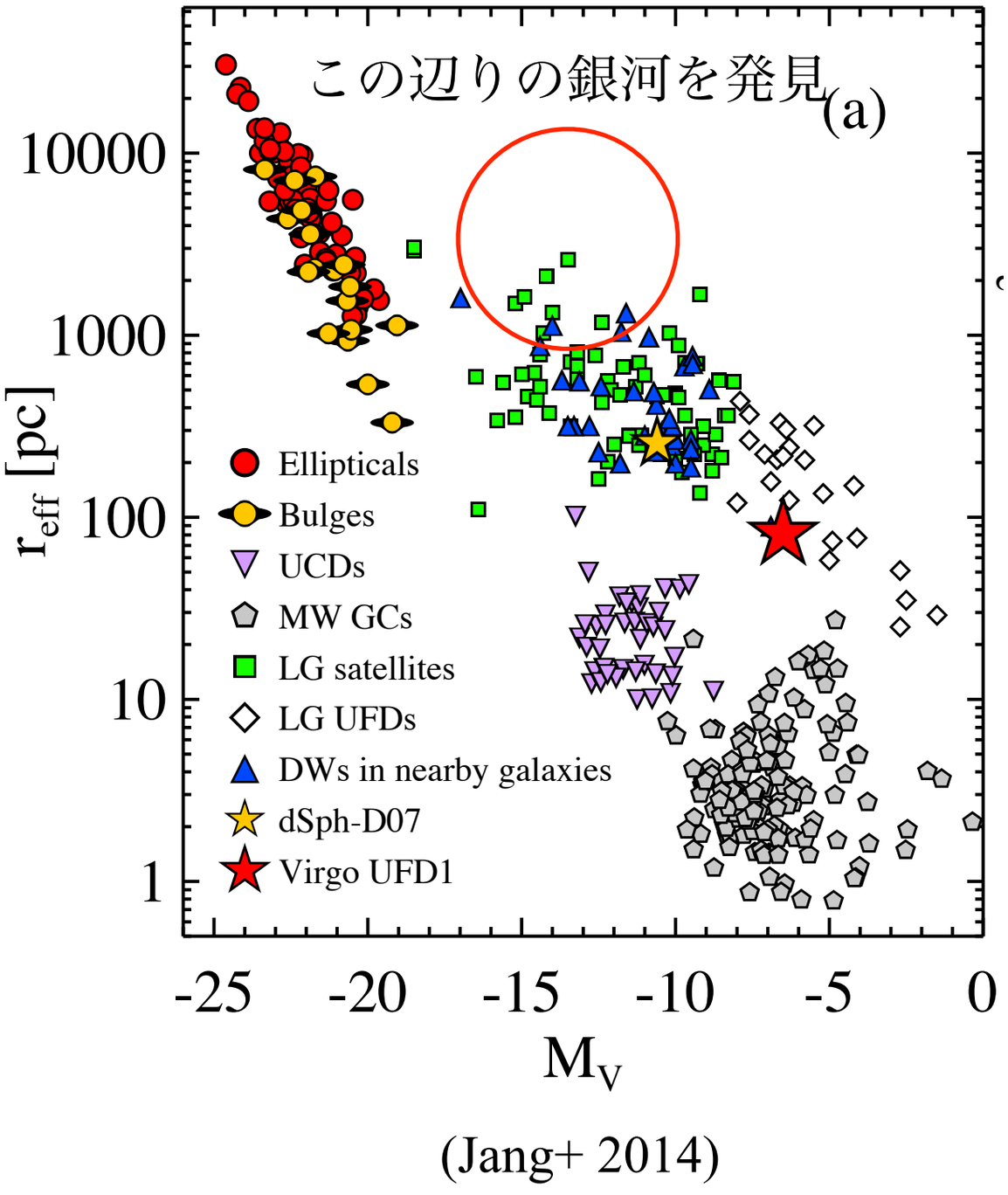
Introduction

- Ultra Diffuse Galaxies (UDGs) :
  - 暗くて (Mv ~ -13) 大きい (~ kpc) 銀河
  - Dragonfly によって偶然発見
- dwarf elliptical や dwarf spheroidal, ultra compact dwarf とも違う種族？
- 関連するトピック
  - missing satellite problem
  - star formation quenching
  - 再電離
  - Pop III



(Jang+ 2014)

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]
[1] Department of Astronomy, Yale University, New Haven, CT 06511, USA
[2] Department of Astronomy, University of Toronto, Toronto, ON M5S 3H4, Canada
[3] Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138, USA
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ABSTRACT

We report the discovery of 47 low surface brightness objects in deep images of a $3^\circ \times 3^\circ$ 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 $r_{\rm eff} = 1.5$–4.6 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 covered by a deep *Hubble Space Telescope* Advanced Camera for Surveys (ACS) observation. The ACS imaging shows a large spheroidal object with a central surface brightness $\mu_{475} = 25.8$ mag arcsec^{-2}, a Sérsic index $n = 0.6$, and an effective radius of $7''$, corresponding to 3.4 kpc at the distance of Coma. The galaxy is not resolved into stars, consistent with expectations for a Coma cluster object. We speculate that these "ultra-diffuse galaxies" may have lost their gas supply at early times, possibly resulting in very high dark matter fractions.

Dragonfly の観測により coma cluster で47個もの
diffuse galaxies を新たに発見した

Dragonfly telephoto array

- University of Toronto の装置
- 主目的 : 近傍銀河の diffuse 成分を見る
- spatial resolution ~ 6 arcsec, μ_{limit} ~ 29.3 mag sec^{-2}, FoV ~ 3×3 deg^2
- 市販の Canon 400mm lenses を10本
  - unprecedented nano-fabricated coatings with sub-wavelength structure on optical glasses.
  - 10本のカメラで同じ場所を観測することで余計な光を取り除ける
  - 安い

http://www.dunlap.utoronto.ca/instrumentation/dragonfly/

Discovery of Ultra Diffuse Galaxies

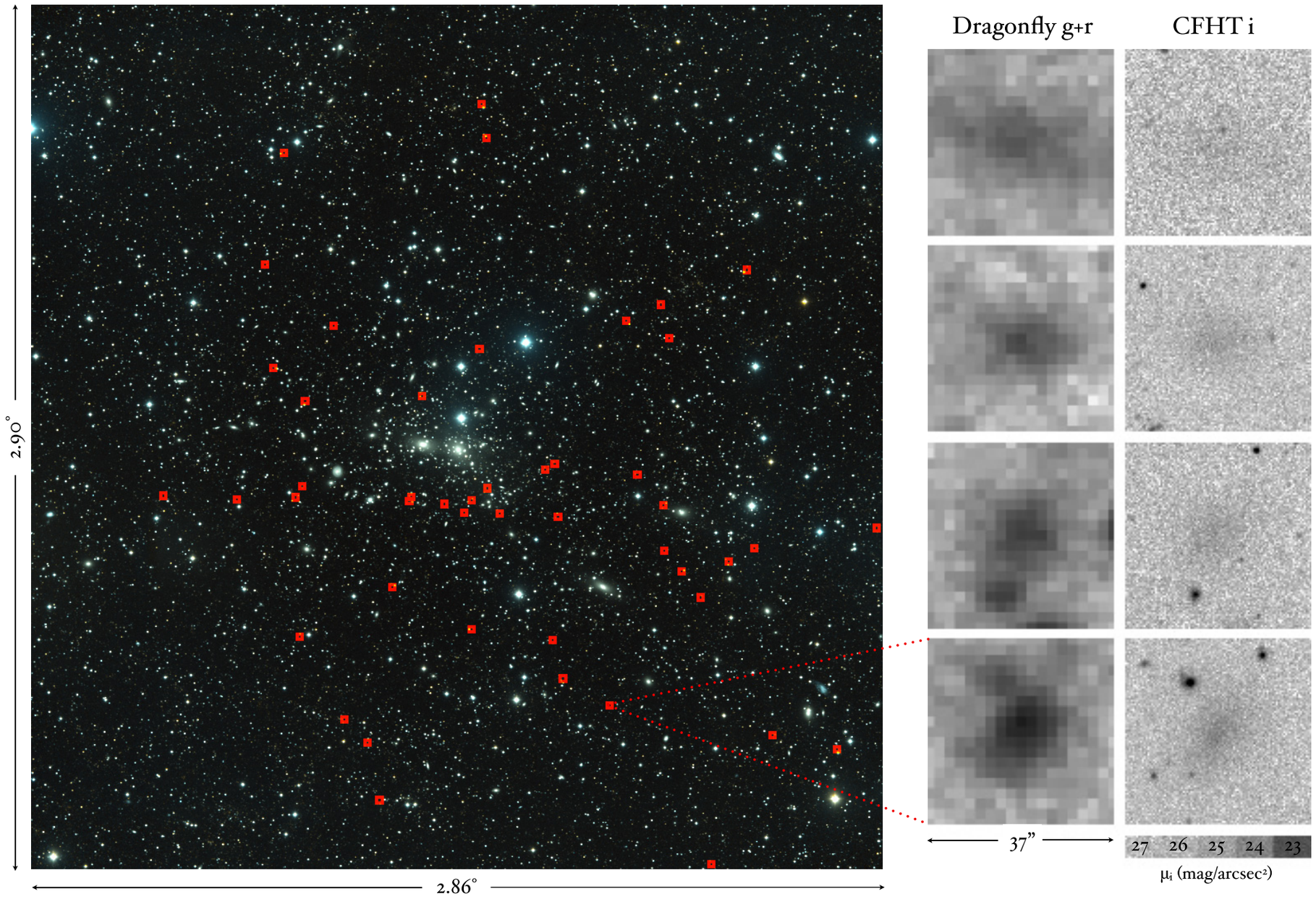

Figure 1. Main panel: spatial distribution of the newly discovered galaxies, projected on a color image of the Coma cluster created from the Dragonfly *g* and *r* images. Only the 2.°86 × 2.°90 area that is covered by CFHT imaging is shown. Panels at right: typical examples of the galaxies, spanning a range in brightness.

- SDSS と CFHT のデータを使って diffuse じゃないものや星のコンタミを取り除く
- CFHT でも実は見えていた

サイズと形状の評価

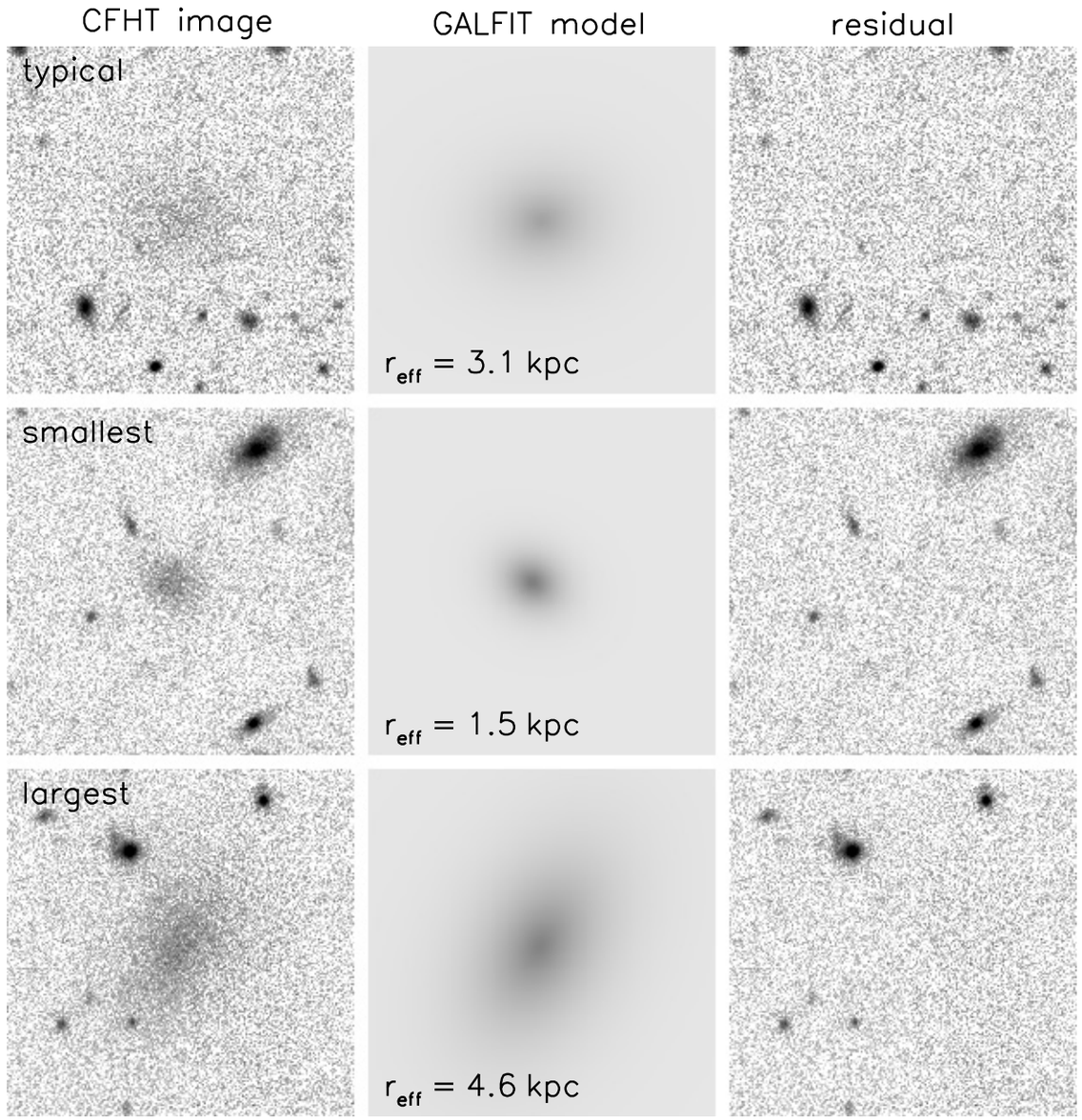

Figure 2. Examples of structural parameter fits to the CFHT data. Each panel spans $37'' \times 37''$. The left column shows the summed $g+i$ images, the middle column shows the best-fitting GALFIT models (with $n = 1$), and the right column shows the residuals from the fits. The size and surface brightness of the galaxy in the top (DF1) row are close to the median of the sample. The middle row shows the smallest galaxy in the sample (DF43), and the bottom row shows the largest (DF44).

- GALFIT で size を評価

μ vs effective radius

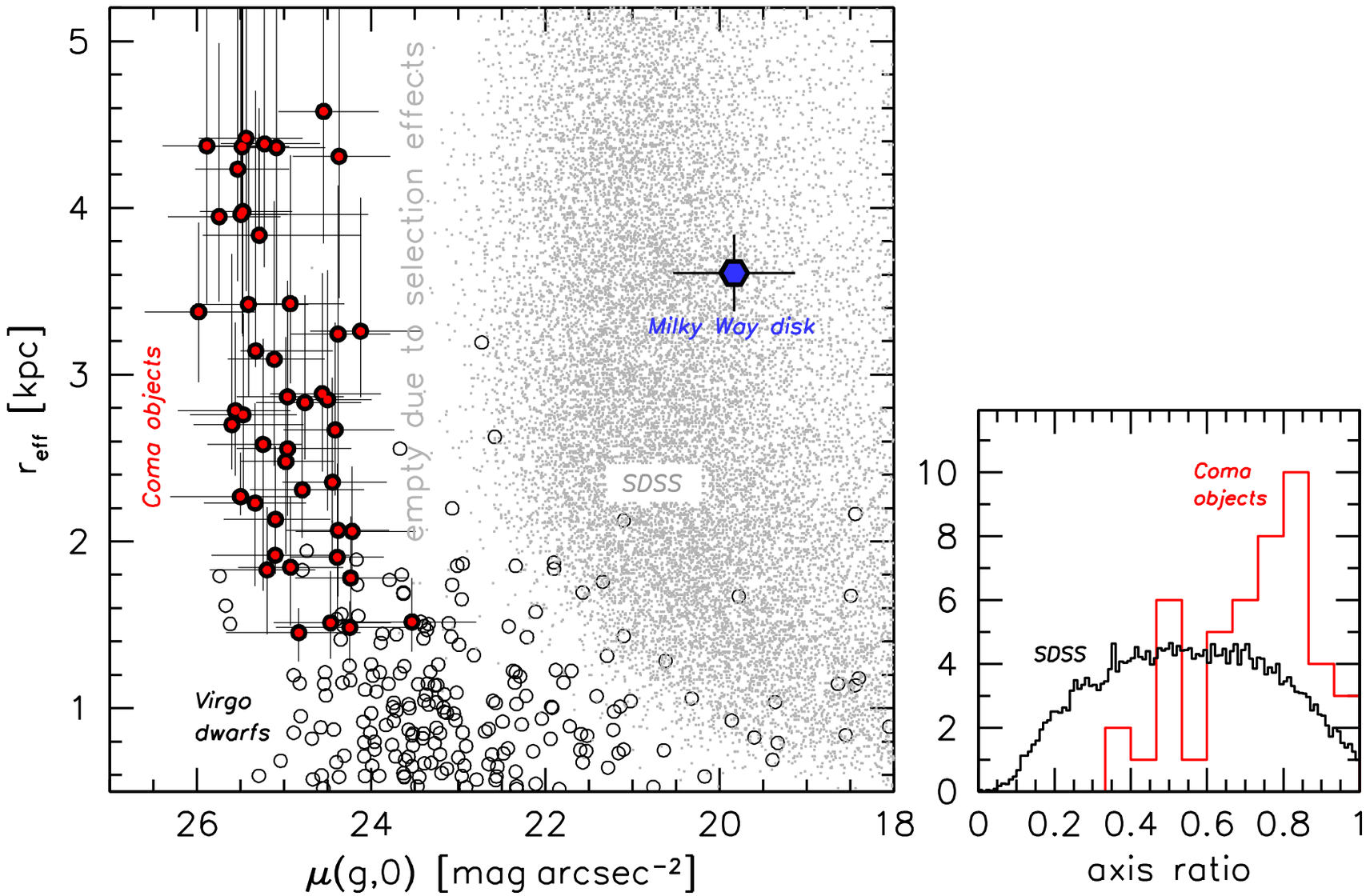

Figure 3. Main panel: location of the newly found galaxies in the effective radius—central surface brightness plane, compared to galaxies at $0.02 < z < 0.03$ in the SDSS (Simard et al. 2011), early-type galaxies in the Virgo cluster (Gavazzi et al. 2005), and the disk of the Milky Way (Bovy & Rix 2013). Right panel: axis ratio distribution compared to that of similar-sized SDSS galaxies.

- SDSS では見ていなかった領域を開拓
- SDSS 銀河に比べて統計的に丸い形をしている

本当に大きいのか？

- 距離はまだわからない
  - もし前景天体であればサイズ評価が全く変わる
- 銀河の分布を見ると中心領域に集中しており, また東西に伸びる構造も他の銀河の分布と一致 => coma のメンバーである可能性が高い
- van Dokkum+ 2015b
  - 47個のうち一番視直径の大きい天体について Keck でスペクトルを取得 => coma と同じ redshift であると確定
- 今後もっとスペクトルを取っていく予定

Implication for the total mass of UDGs

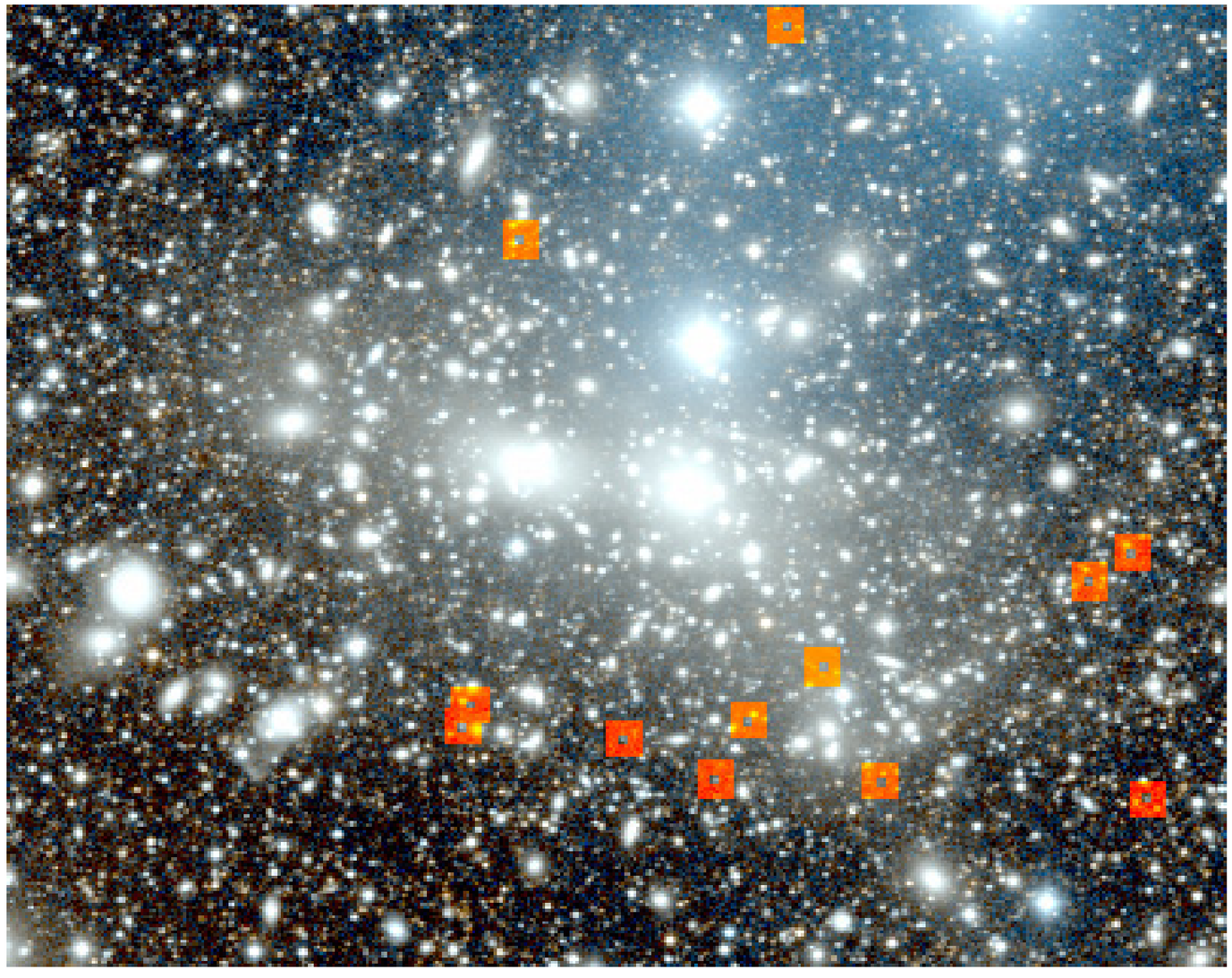

Figure 5. Central 0.°89 × 0.°70 (1.6 Mpc × 1.2 Mpc) of the Dragonfly image shown in Figure 1. The newly found galaxies appear to avoid the region where ICL is detected.

- 銀河団の中心付近には UDGs がいない => tidal force で壊されるから？
- DM halo が生き残るためには DM mass fraction > 98% が必要

APPROXIMATELY A THOUSAND ULTRA DIFFUSE GALAXIES IN THE COMA CLUSTER

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

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ABSTRACT

We report the discovery of 854 ultra diffuse galaxies (UDGs) in the Coma cluster using deep R band images, with partial B, i, and Hα band coverage, obtained with the Subaru telescope. Many of them (332) are Milky Way-sized with very large effective radii of $r_{\rm e} > 1.5\,$kpc. This study was motivated by the recent discovery of 47 UDGs by van Dokkum et al. (2015a); our discovery suggests $> 1,000$ UDGs after accounting for the smaller Subaru field (4.1 degree^2; about 1/2 of Dragonfly). The new Subaru UDGs show a distribution concentrated around the cluster center, strongly suggesting that the great majority are (likely longtime) cluster members. They are a passively evolving population, lying along the red sequence in the color-magnitude diagram with no signature of Hα emission. Star formation was, therefore, quenched in the past. They have exponential light profiles, effective radii $r_{\rm e} \sim 800\,$pc-5 kpc, effective surface brightnesses $\mu_{\rm e}(R)$ =25-28 mag arcsec^{-2}, and stellar masses $\sim 1\times10^7{\rm M}_\odot$ - $5\times10^8{\rm M}_\odot$. There is also a population of nucleated UDGs. Some MW-sized UDGs appear closer to the cluster center than previously reported; their survival in the strong tidal field, despite their large sizes, possibly indicates a large dark matter fraction protecting the diffuse stellar component. The indicated baryon fraction $\lesssim 1\%$ is less than the cosmic average, and thus the gas must have been removed (from the possibly massive dark halo). The UDG population is elevated in the Coma cluster compared to the field, indicating that the gas removal mechanism is related primarily to the cluster environment.

Subject headings: galaxies: clusters: individual (Coma) – galaxies: evolution – galaxies: structure

すばる Suprime-Cam のアーカイブデータを見てみたらUDGsを~1000個見つけた

すばる観測

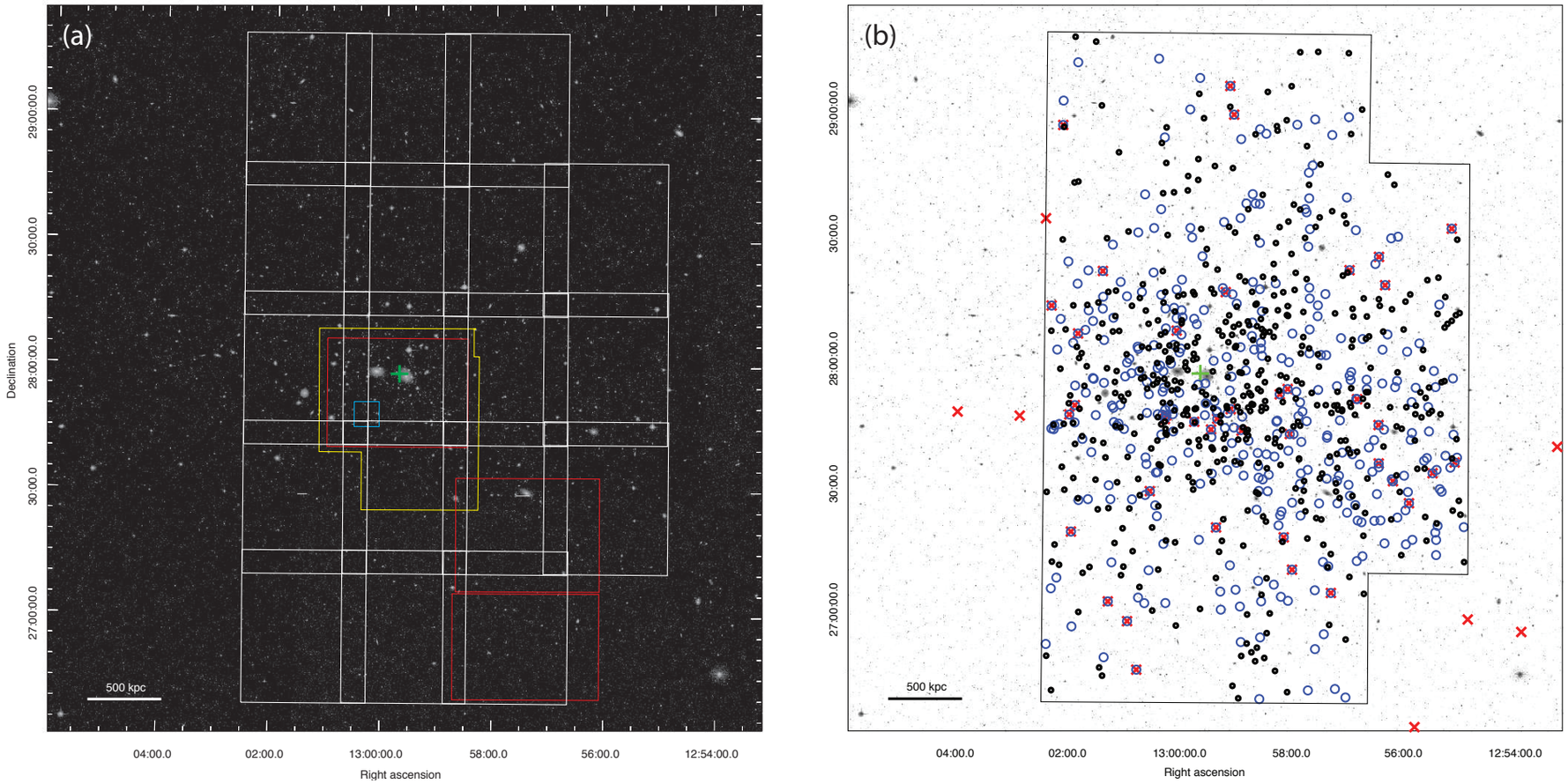


FIG. 1.— The 2.86 deg ×2.90 deg ($\sim 4.87 \times 4.94\,\mathrm{Mpc}^2$) area centered on the Coma cluster, the same area as in Figure 1 of van Dokkum et al. (2015a). (a) Image from the Digitized Sky Survey. The white borders show the 18 fields covered in the Subaru R band (Okabe et al. 2014), which have the total area of 4.1 degree^2, about 1/2 of the Dragonfly coverage. Red indicates the area analyzed by Yamanoi et al. (2012). Yellow outlines the area analyzed by Yagi et al. (2010) using the Subaru B, R, Hα, i bands. Cyan indicates the area in Figure 2. The center of the cluster (α_{J2000},δ_{J2000})=(12:59:42.8,+27:58:14) is marked with a green cross (White et al. 1993). (b) The same area as in (a), showing the distribution of the 854 Subaru UDGs (circles). The MW-sized UDGs, with large effective radii (> 1.5 kpc), are shown in blue. The Subaru field coverage in R is enclosed with the solid line. The 47 Dragonfly UDGs are indicated with red crosses.

- 視野内の全ての Dragonfly (DF) 天体 (40個) をすばるでも検出
- definition of UDGs
  - $18 < M_R < 26$, FWHM > 4 arcsec, μ_e - $<\mu(r_e)>$ 0.8
- 全部で 854 個の ultra diffuse galaxy を発見
- control field では13個のみ

すばる観測

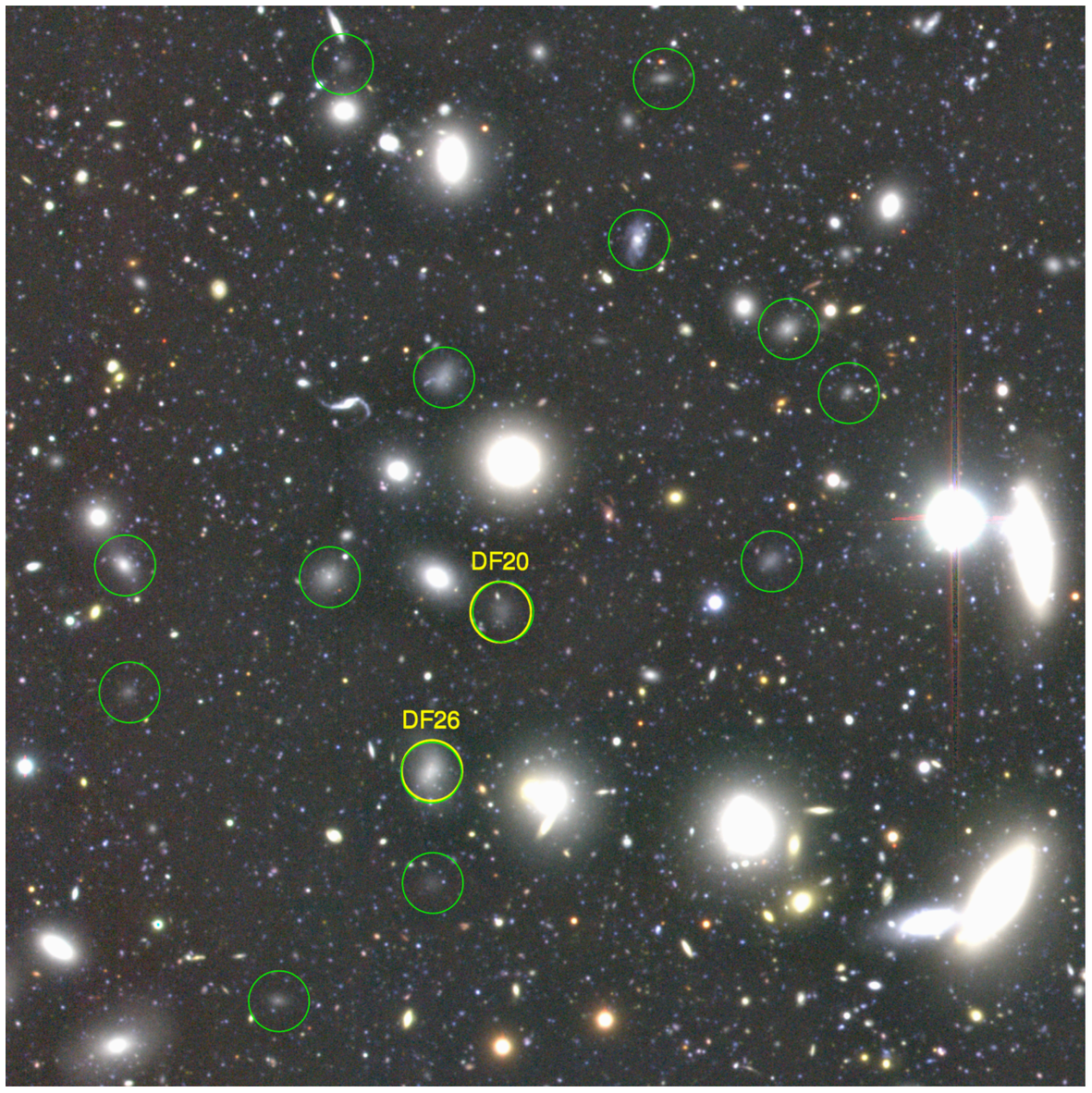
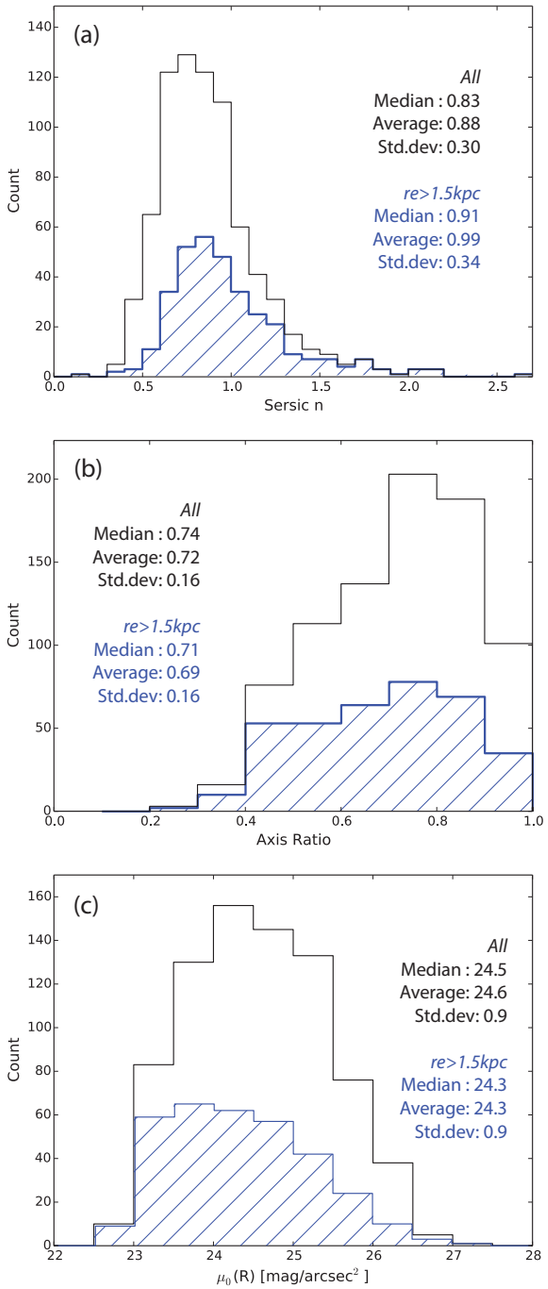


FIG. 2.— Subaru BRi color image of the $\sim 6' \times 6'$ region ($\sim 170 \times 170\,\mathrm{kpc}^2$ region at $d = 97.7\,\mathrm{Mpc}$), shown in cyan in Figure 1a. The Dragonfly and Subaru UDGs are marked respectively with yellow and green circles with a diameter of $20''$ ($\sim 9.5\,\mathrm{kpc}$).

- すばるで数が増えたのは seeing と S/N が向上したから
- 多くは過去のカタログにも載っていたが diffuse に分類されていなかった (理由不明)
- 中心領域にもそれなりの数がいる

Structural properties of UDGs

- UDGs は丸い (axis ratio ~ 1)
- exponential profile
- size-magnitude plane において distinct population ではなさそう



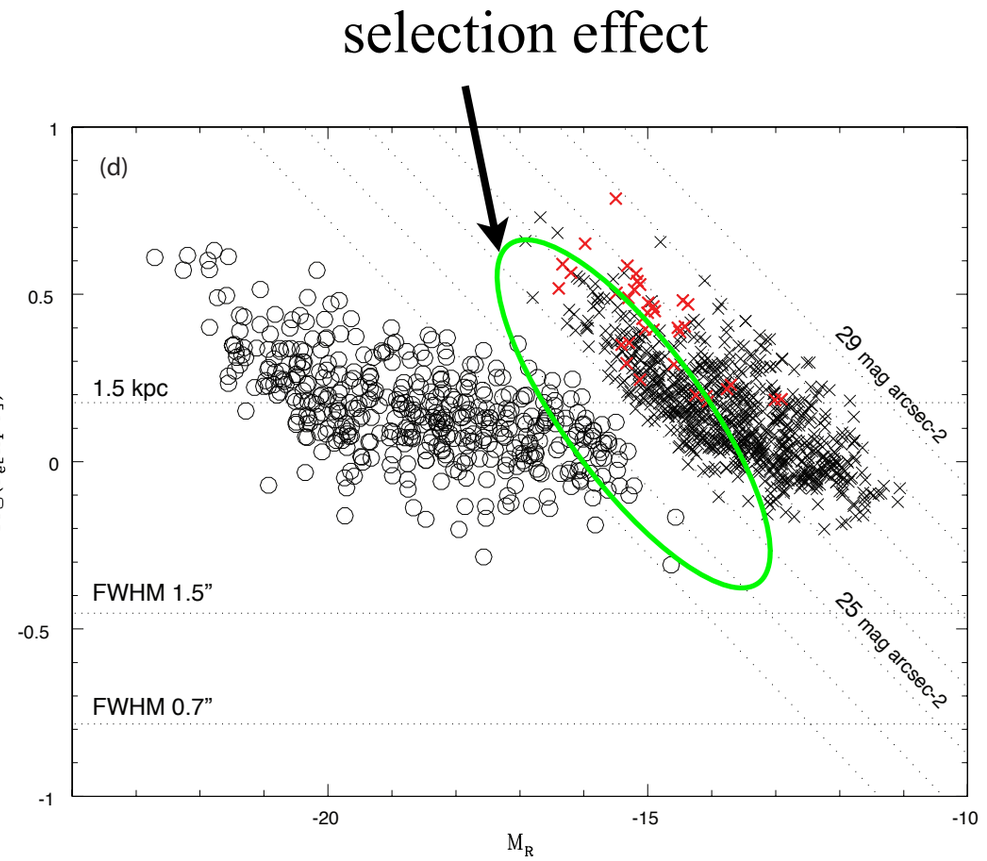


FIG. 4.— Structural properties of UDGs. (a) Histograms of Sersic index n, (b) axis ratio b/a, and (c) central SB μ_0(R) with their medians, averages, and standard deviations. Black lines are for all 854 UDGs, while blue are for 332 MW-sized UDGs alone. (d) Effective radius vs. R magnitude. The parameters of the UDGs (crosses; red for the Dragonfly UDGs) are derived with GALFIT. Normal galaxies (circles) –spestroscopically-confirmed Coma members (Mobasher et al. 2001) – are also plotted for comparison (from Komiyama et al. 2002, with the conversion R(AB)-R(Vega)=0.21). Dotted, diagonal lines show constant SBs (μ_es) from 23 to 29 mag arcsec^{-2} with a 1 mag arcsec^{-2} interval for the case of an exponential profile (note $\mu_0 = \mu_e - 1.82$ for $n = 1$). The gap between the normal galaxies and UDGs is due to selection effects. Horizontal lines show r_e of PSF with a FWHM of 1.5 arcsec (Komiyama et al. 2002) and a FWHM of 0.7 arcsec (this study).

Color-magnitude diagram

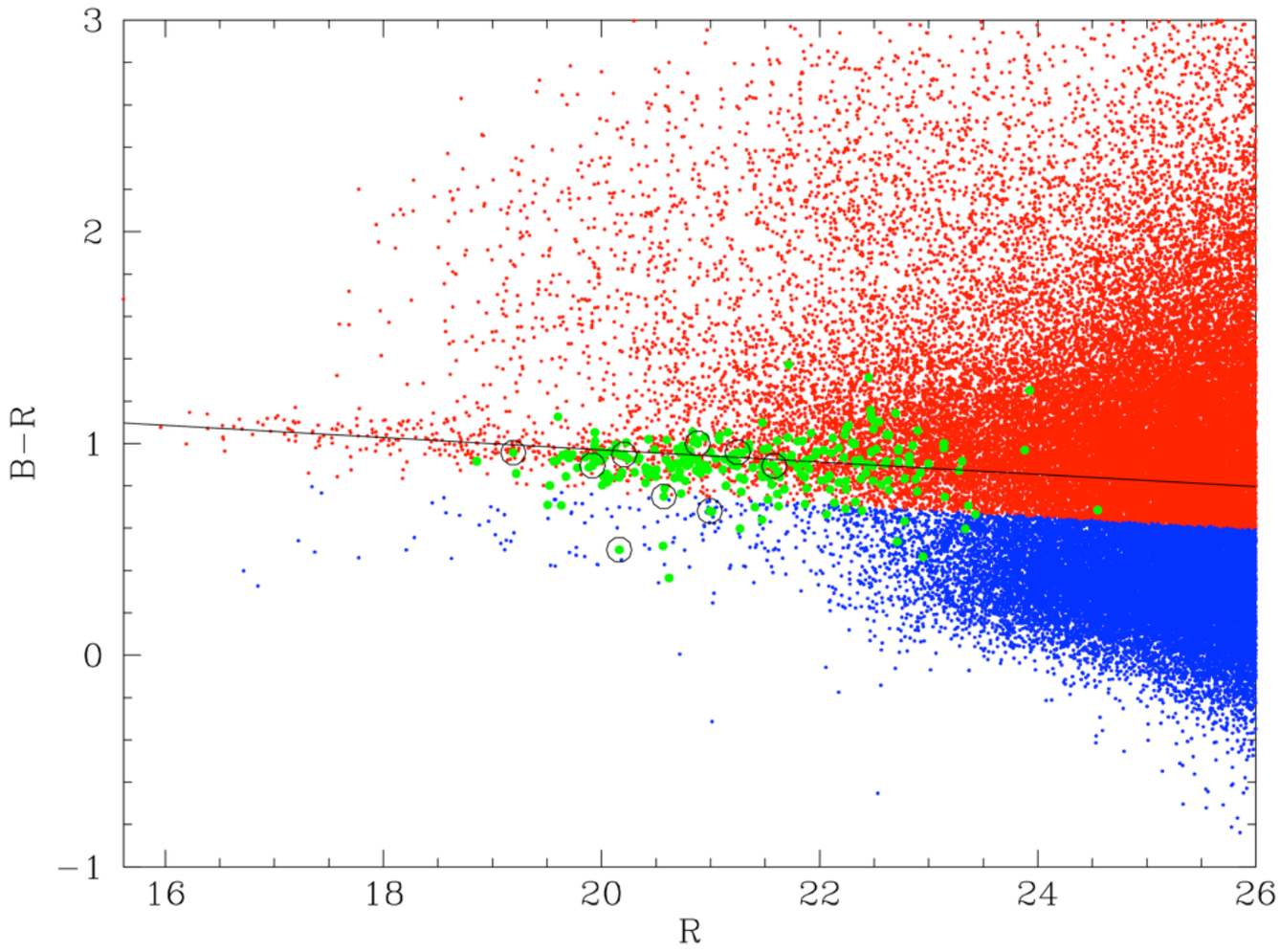


FIG. 5.— Color-magnitude diagram using B and R band photometry. The green points are 232 UDGs observed both in B and R with Subaru (the Dragonfly UDGs are circled), and the red and blue are red and blue galaxies taken from the Coma1 field of Yamanoi et al. (2012) which includes cluster members as well as background galaxies. Due to saturation, most giant galaxies are not included, but the red-sequence is evident. The UDGs clearly follow the red-sequence population of the Coma cluster.

- ほぼすべての UDGs が passive galaxy
- Hαは検出されず

Origin of UDGs

- ガスを剥ぎ取るには？

  1. SN feedback や AGN activity によるガスの剥ぎ取り (Dekel & Silk 1986; Arimoto & Yoshii 1987),
  2. ram-pressure stripping (Gunn & Gott 1972),
  3. tidal-interaction and harassment (Moore et al. 1996)

- cluster 領域で UDGs が多いことを考えると 2., 3. が有望？

- 以下真喜屋の感想

  - サイズをどう説明するのかは結局よくわからない
    - バリオンガスが抜ける時に DM が引きずられる？
    - ultra compact dwarf との関連は？
    - 2. や 3. はむしろ銀河を小さくするはずだし, tidal tail みたいな構造は見えていないので 2. や 3. のシナリオは厳しそう