Unravelling the morphologies of Luminous Compact Galaxies using the HST/ACS GOODS survey

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Plan of the talk:

- Motivation for this work
- Datasets used
- Choosing a sample of LCGs
- Bulge-Disk decomposition
- Classification scheme
- Important results
- Conclusions

Motivation for this work

What are *Luminous Compact Galaxies?*

- It all began in 1986 with the publishing of a catalog of faint candidate QSOs by Koo, Kron and Cudworth (1986) PASP 98, 285

The QSO candidates were selected from objects having star like images and broadband colors unlike those of common stars.

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The QSO candidates were selected from objects having star like images and broadband colors unlike those of common stars.

- However, spectroscopic followups revealed a class of strong, narrow emission line objects. Koo and Kron (1988) ApJ 325, 92

  They were designated as compact blue galaxies and considered to be contaminants!

Motivation for this work

- Pre-refurbished HST WFC imaging published by Koo et al (1994) ApJ 427, L9

No luck with morphological classification!

The name Compact Narrow Emission Line Galaxies(CNELG) was coined and analogy was drawn with local HII galxies.

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- High resolution spectra obtained with Keck by Koo et al (1995) ApJ 440,L49

  Velocity widths between 28-157kms^{-1} and $M_B \sim -21$. Consistent with extreme star forming galaxies.
  Suggested to be progenitors of local spheroidal galaxies by fading of 4-5 magnitudes.

Motivation for this work

- Hammer et al (2001) AJ 550,570 used VLT spectra to accurately calculate the SFRs for these Luminous Compact Galaxies and proposed them to be progenitors of bulges of massive spirals.

The gas needed to feed the observed star formation is likely to be falling in from the outskirts of the galaxy, being tidally pulled out from interacting companion galaxies.

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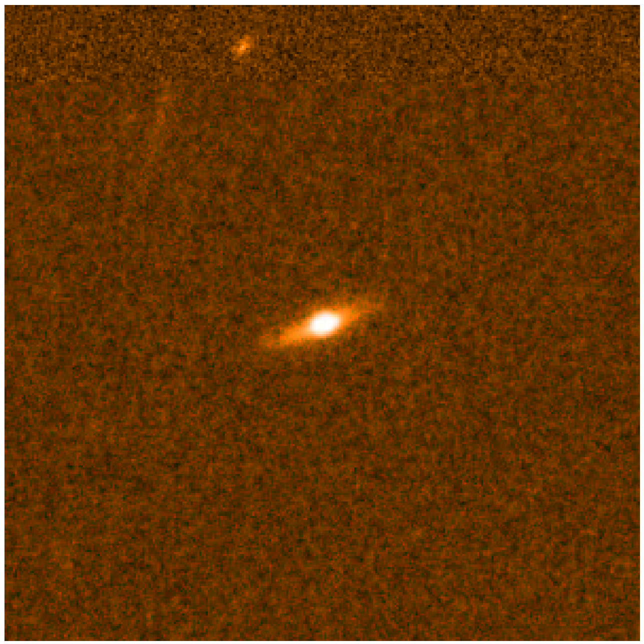
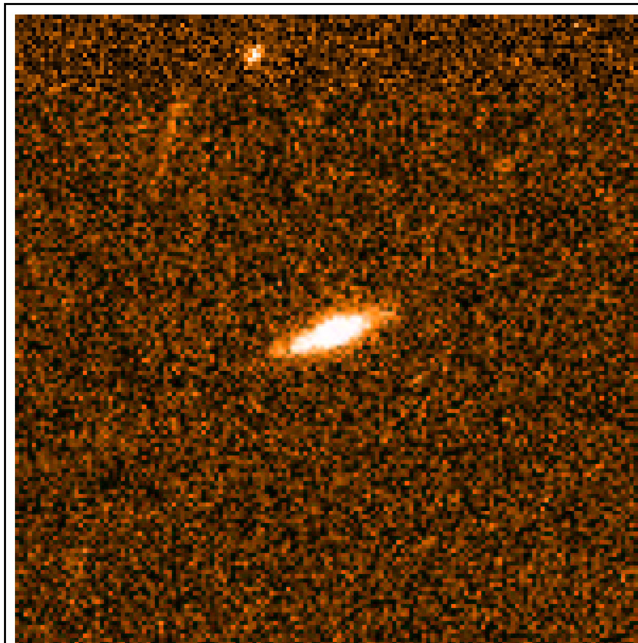
So what has changed since 2001?

What is new?

The difference between ACS and WFPC2...



904604 ACS z=0.99



Simulated WFPC2

Datasets used

- The publicly available version v1.0 of the reduced, calibrated, stacked and mosaiced images of the *Chandra Deep Field South* (CDFS) acquired with HST and ACS as part of the *Great Observatories Origins Deep Survey*, GOODS
- Spectroscopic redshifts taken from the publicly available redshift catalog of the *Vimos VLT Deep Survey* VVDS
- The near-IR J & Ks band imaging data from the ESO GOODS/EIS Release Version 1.0 which was obtained as part of the GOODS using ISAAC instrument mounted at ESO-VLT. This data release includes 21 fully reduced VLT/ISAAC fields in J and Ks bands, covering $131\,\mathrm{arcmin}^2$ of the GOODS/CDFS region.
- Public data made available as part of the GOODS, Spitzer Legacy Data Products, Third Data Release (DR3), consisting of the "Best-effort" reductions of 24 micron data for CDFS taken with the Multiband Imaging Photometer for Spitzer (MIPS), and a 24 micron v0.91 source list for the CDFS of all sources brighter than 80μJy.

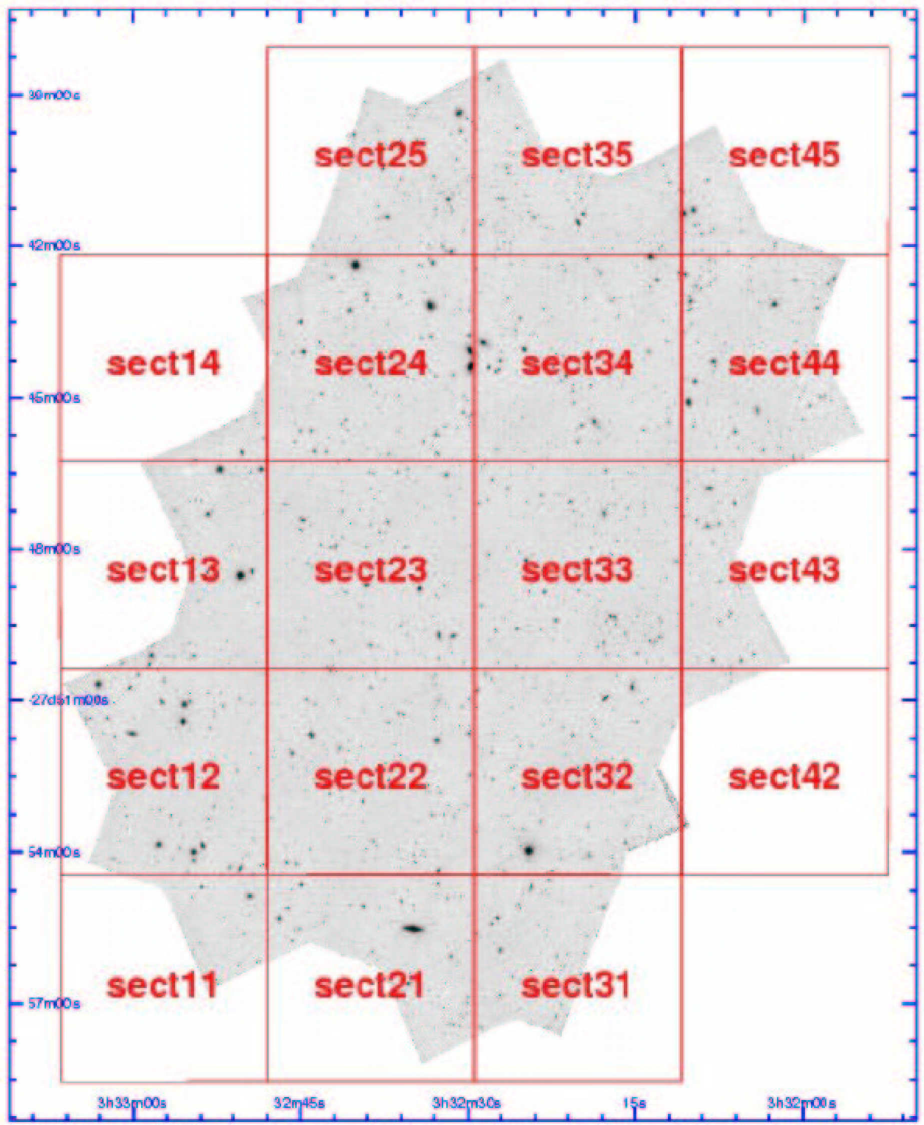
The HST/ACS GOODS survey

The GOODS aims to unite extremely deep observations from NASA's Great Observatories, the Spitzer Space Telescope, Hubble, and Chandra, ESA's XMM-Newton, and from the most powerful ground-based facilities, to survey the distant universe to the faintest flux limits across the broadest range of wavelengths.

The HST/ACS GOODS survey

- $\sim$ 320 $arcmin^2$ around HDF-N and CDFS
- 4 filters viz.. B V i z
- 0.03 arcsec/pixel. FWHM $\sim$ 0.12 arcsec.
- Total Exptime 5250 to 10500 sec taken over 5 epochs.
- 18, 8192 X 8192 sections in CDFS and 17 in HDF-N.

The CDFS field



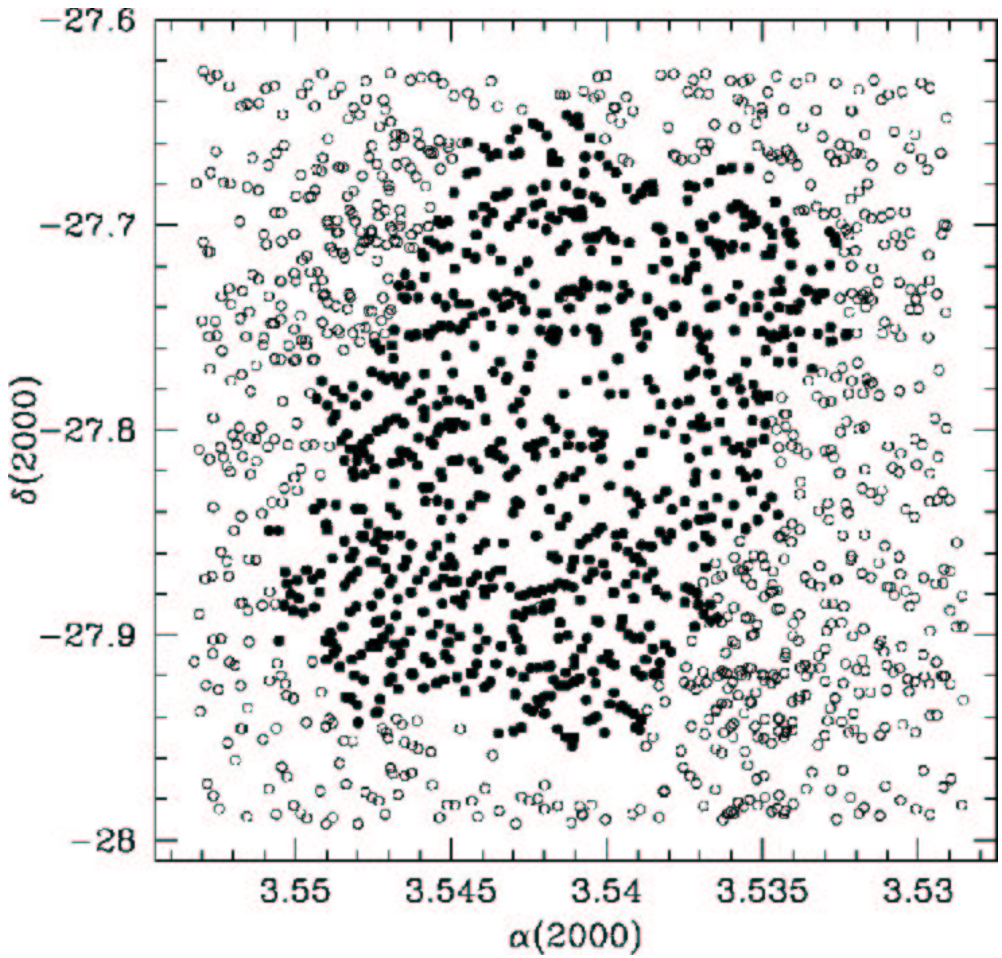
Compiling the photometry

Using the SExtractor based source catalog published by the GOODS team.

- 29599 sources detected in CDFS.
- z band used as the detection filter.
- $\sim$ 3200 sources brighter than 24 magnitude in the z band.

Getting the redshifts

- VVDS: ViMOS VLT Deep Survey. Le Fevre et al, Submitted A&A(2004). 1599 redshifts in area $\sim$ 450 $arcmin^2$ overlapping with CDFS.



Getting the redshifts

Results of crosscorrelation between the HST/ACS catalog and VVDS redshift catalog

- *VVDS: 784 objects*

So finally we have a catalog with 784 galaxies, which have photometry in 4 filters plus redshift.

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Need to calculate the absolute magnitudes!

Calculate the absolute magnitudes

The transformation equation is...

$$m_B = M_B + DM(z) + K_B(z) + A_B$$

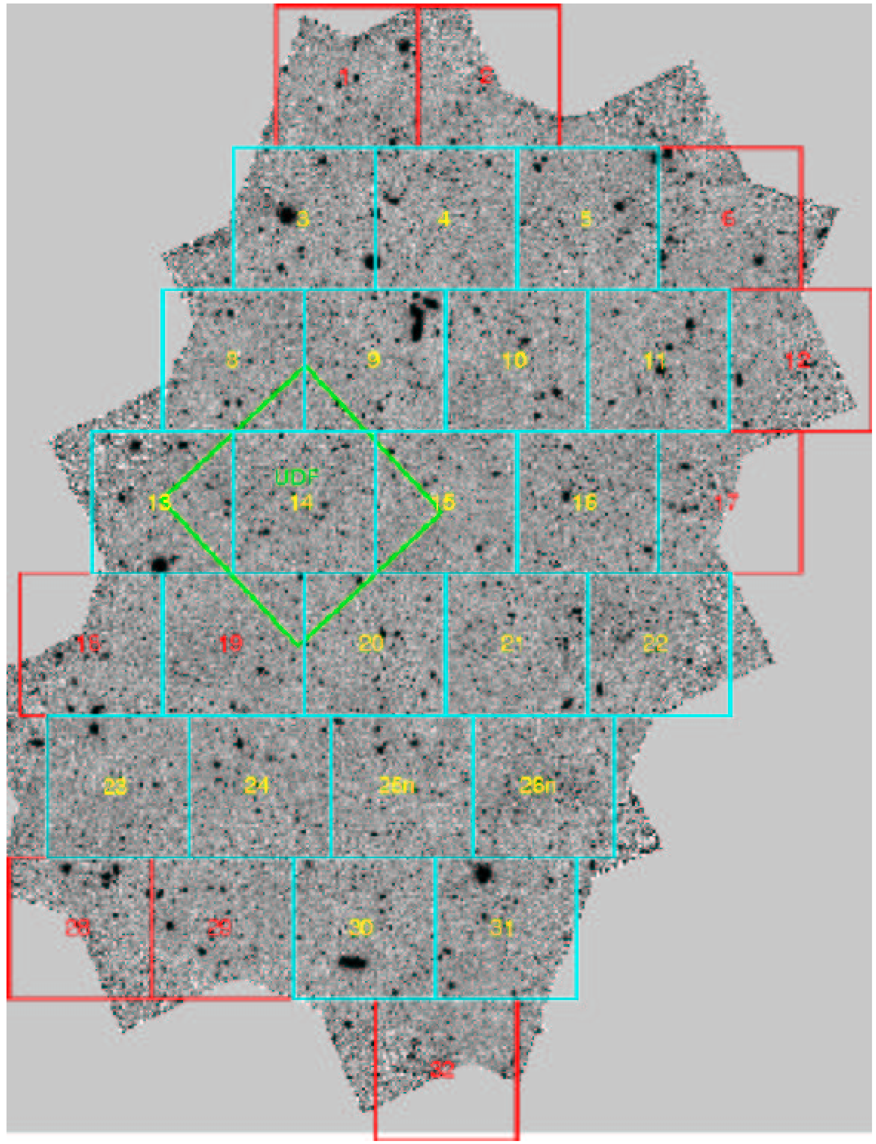
How to get the kcorrections when spectra is not available/ not usable?

- Fit template galaxy spectra to broadband galaxy magnitudes and use the resulting SEDs to estimate the kcorrections.

Using published(not public!) code by Hammer et al 2001 AJ 550:570
To each set of multi-band galaxy magnitudes we fit a SED which is a linear combination of some galaxy spectral templates. The templates have been optimized to minimize the residuals between the actual galaxy magnitudes and the galaxy magnitudes reconstructed from the galaxy SED fit.

- Input: multi band magnitudes, magnitude errors, redshifts
- Output: Absolute magnitudes...

VLT/EIS J & Ks band photometry



Get the J & Ks band photometry

As part of the Great Observatories Origins Deep Survey (GOODS), near-infrared imaging observations of the Chandra Deep Field South (CDF-S) are being carried out in J, H, Ks bands, using the ISAAC instrument mounted at the Antu Unit Telescope of the VLT at ESO's Cerro Paranal Observatory, Chile.

- 21 fully reduced VLT/ISAAC fields in J and Ks bands, covering 131 $arcmin^2$ of the GOODS/CDFS region
- SExtractor based photometry kindly provided by Hector Flores.
- Catalog has $\sim$ 8000 sources.

Calculate the absolute magnitudes

- 513/784 objects have J and Ks band photometry.
- Used Hammer's code for calculating Absolute magnitudes using the technique of spectral template fitting.
- 435/513 objects have reliable Absolute magnitudes(upto redshift 1.2).

Choose a sample of LCGs

Sample Selection criterion for *Luminous Compact Galaxies*, LCGs (In accordance with Hammer et al. 2001 AJ 550:570)

- Luminous $M_B \leq$ -20

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156/435 galaxies satisfy this criterion...

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- Compactness
  δm_z = m_z(4.5kpc) - m_z(13.5kpc) $\leq$ 0.75

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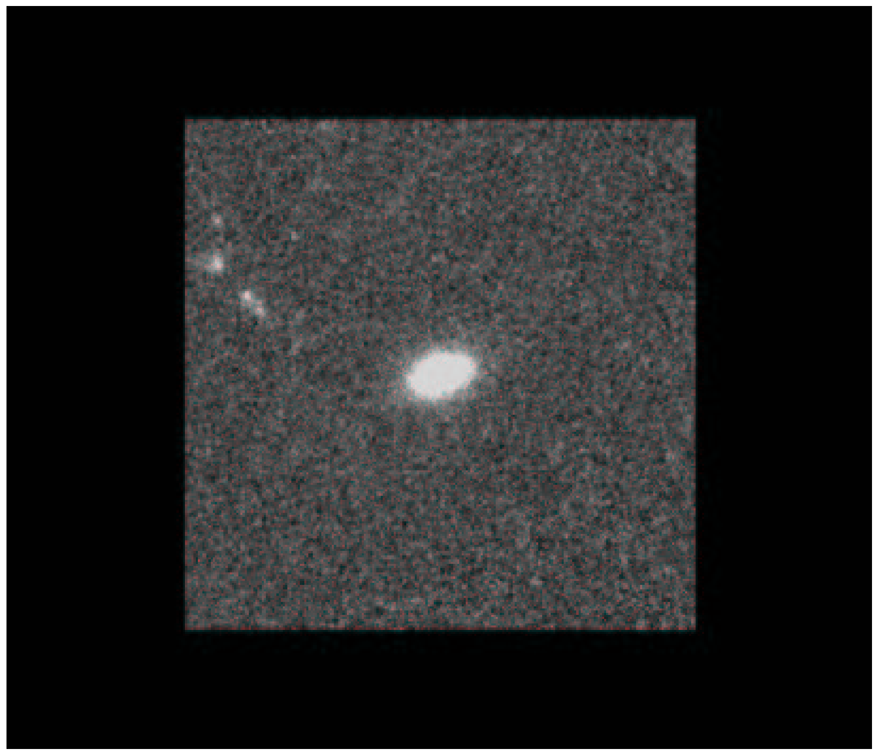

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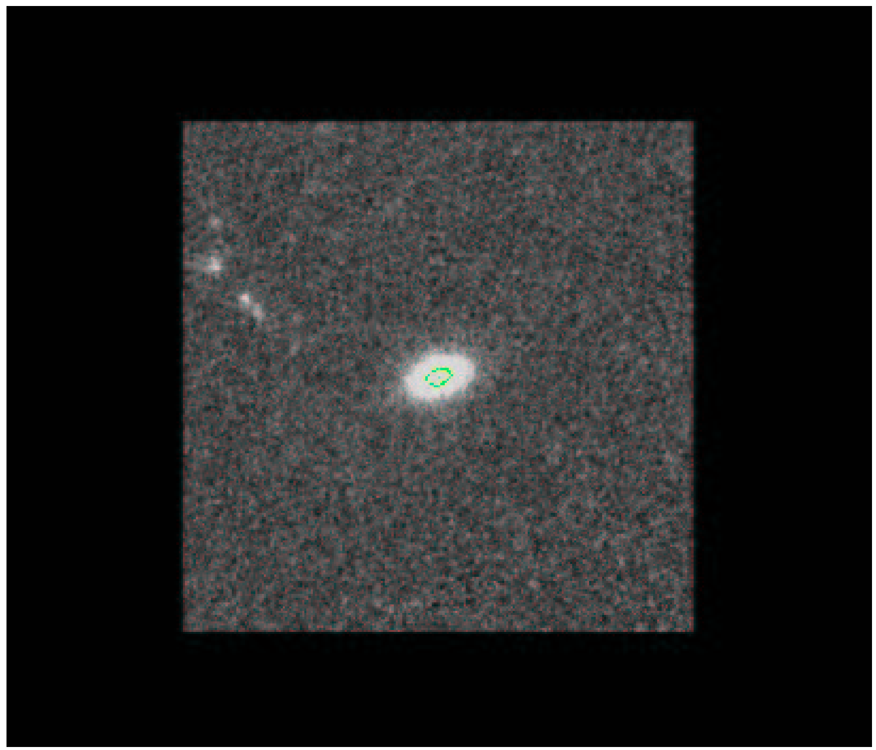

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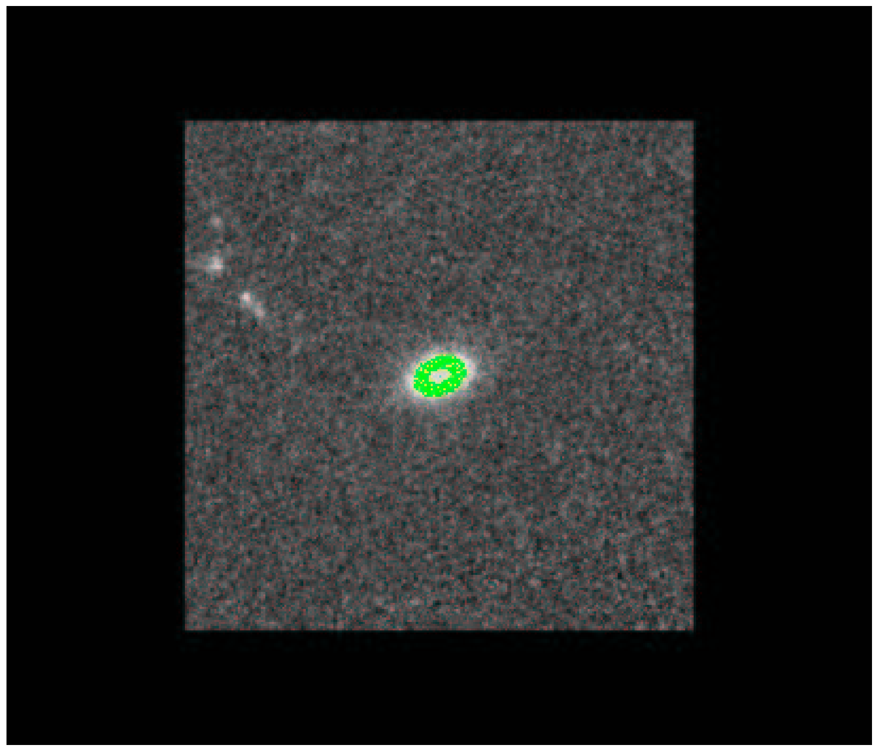

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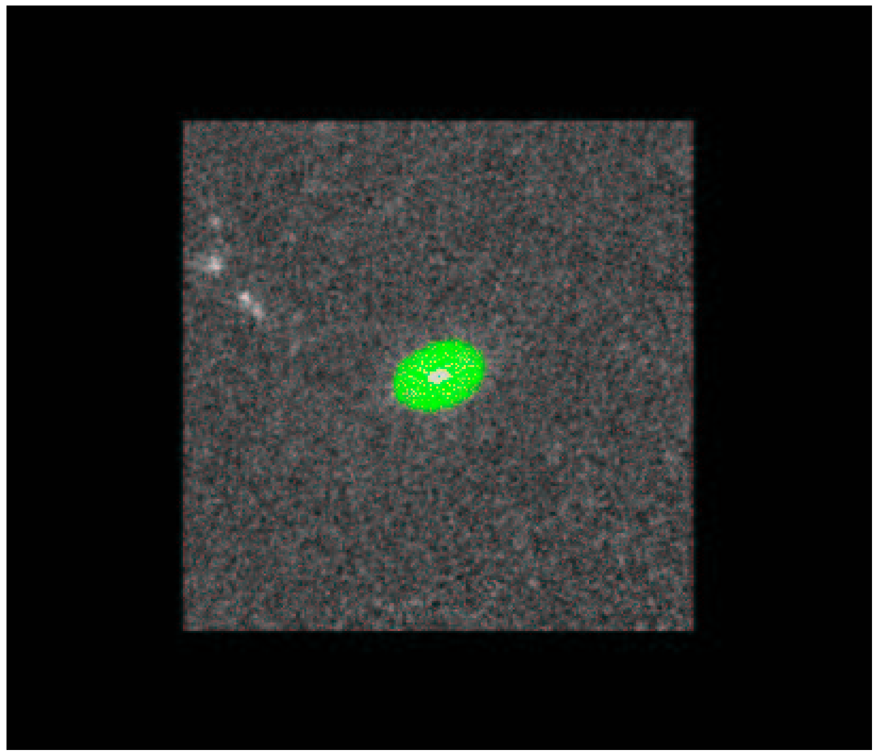

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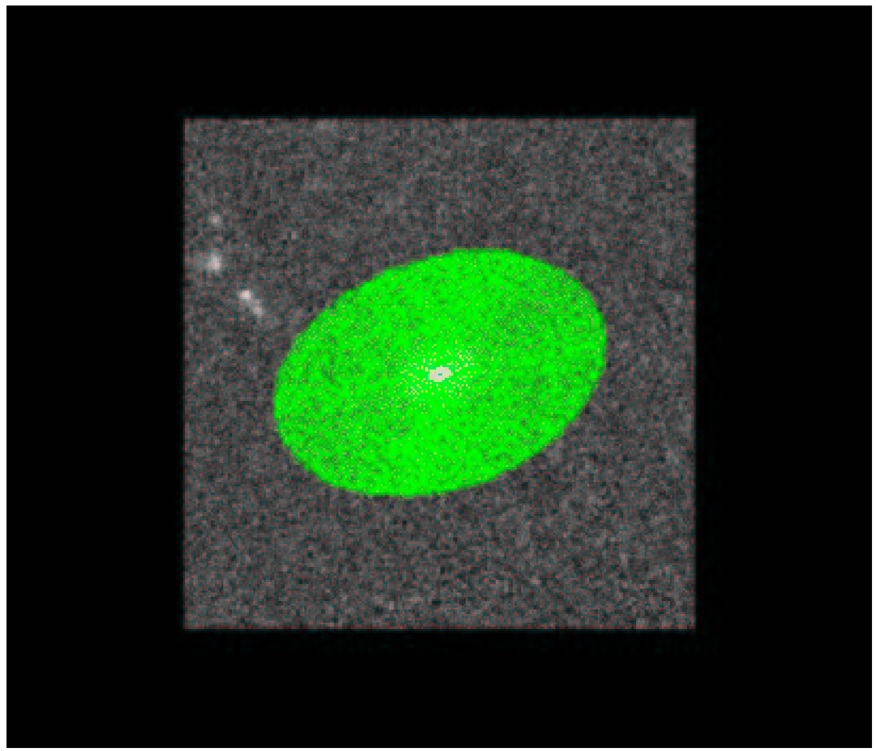

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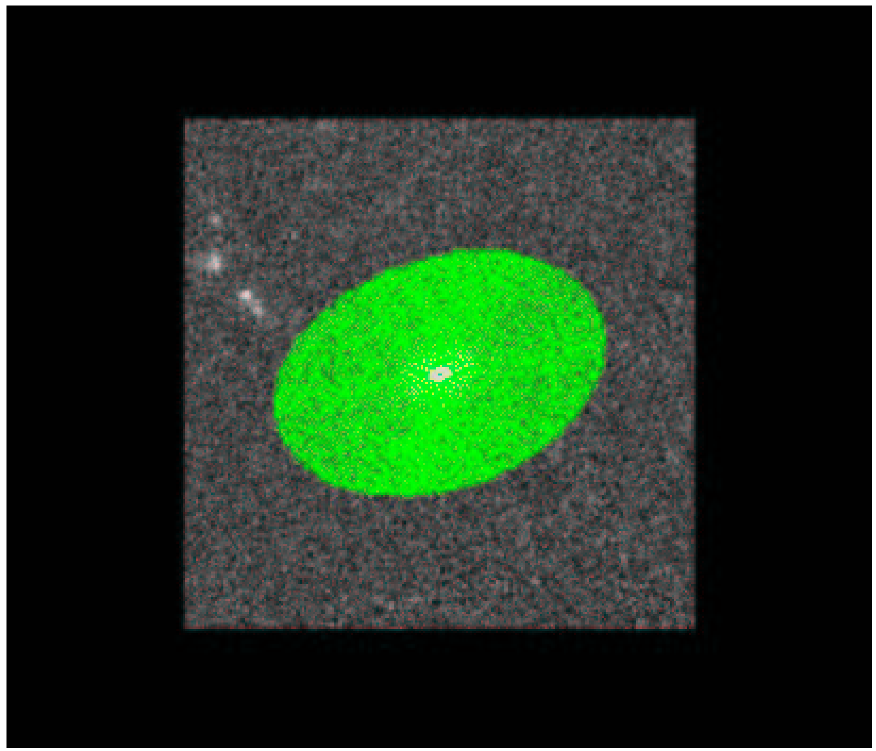

80/156 galaxies satisfy this criterion...

Choose a sample of LCGs

- Presence of Emission Line
  EW_0[O II] $\geq$ 15 Å

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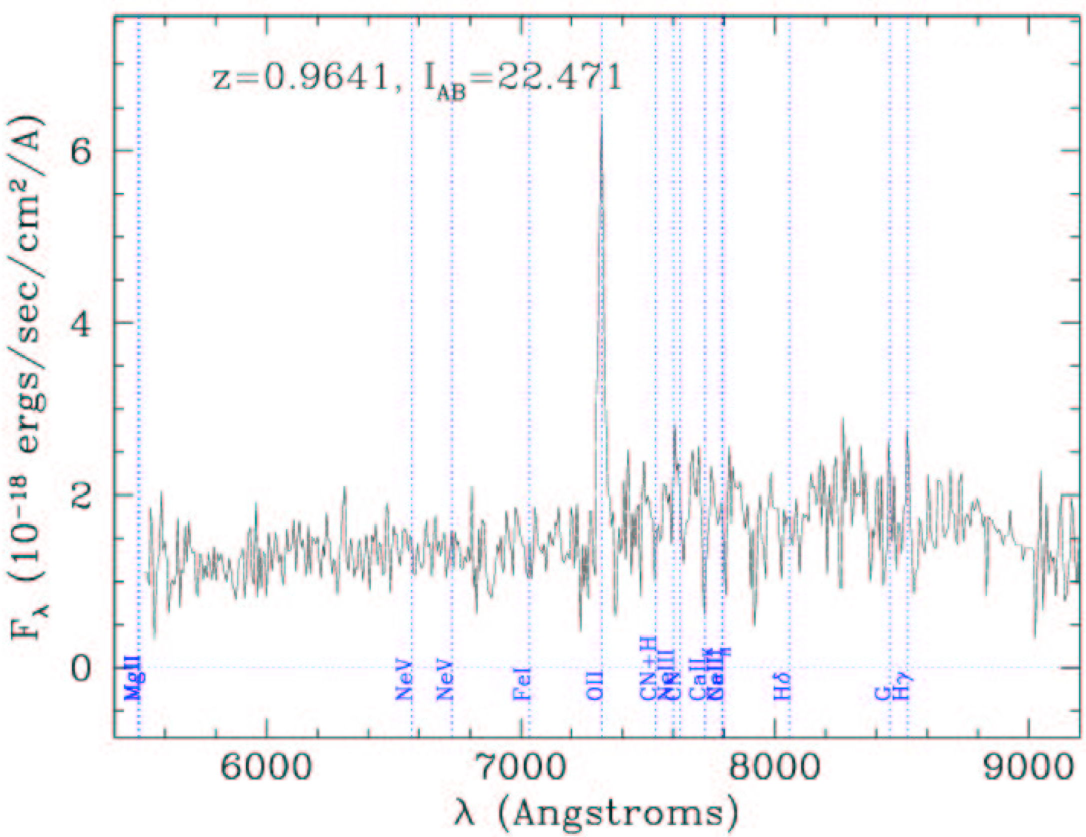
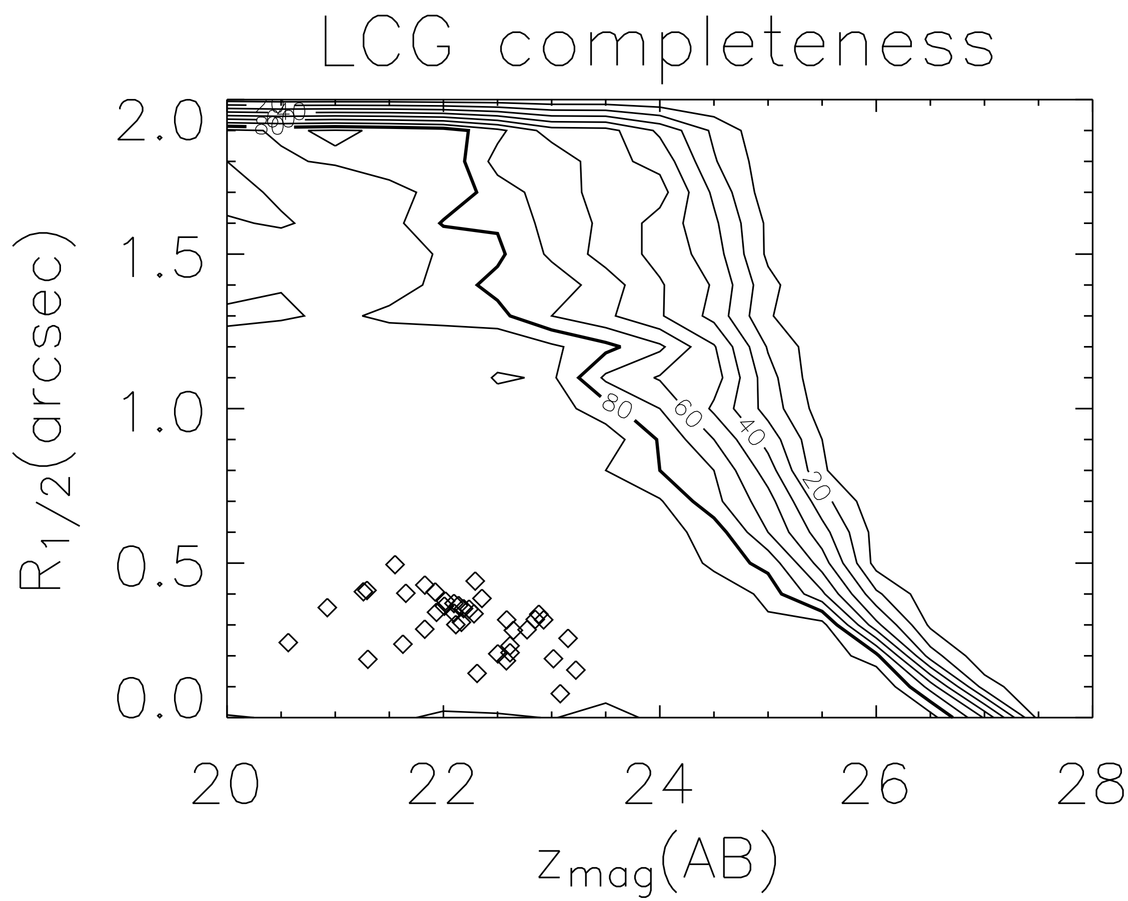
  EW_0[O II] $\geq$ 15 Å

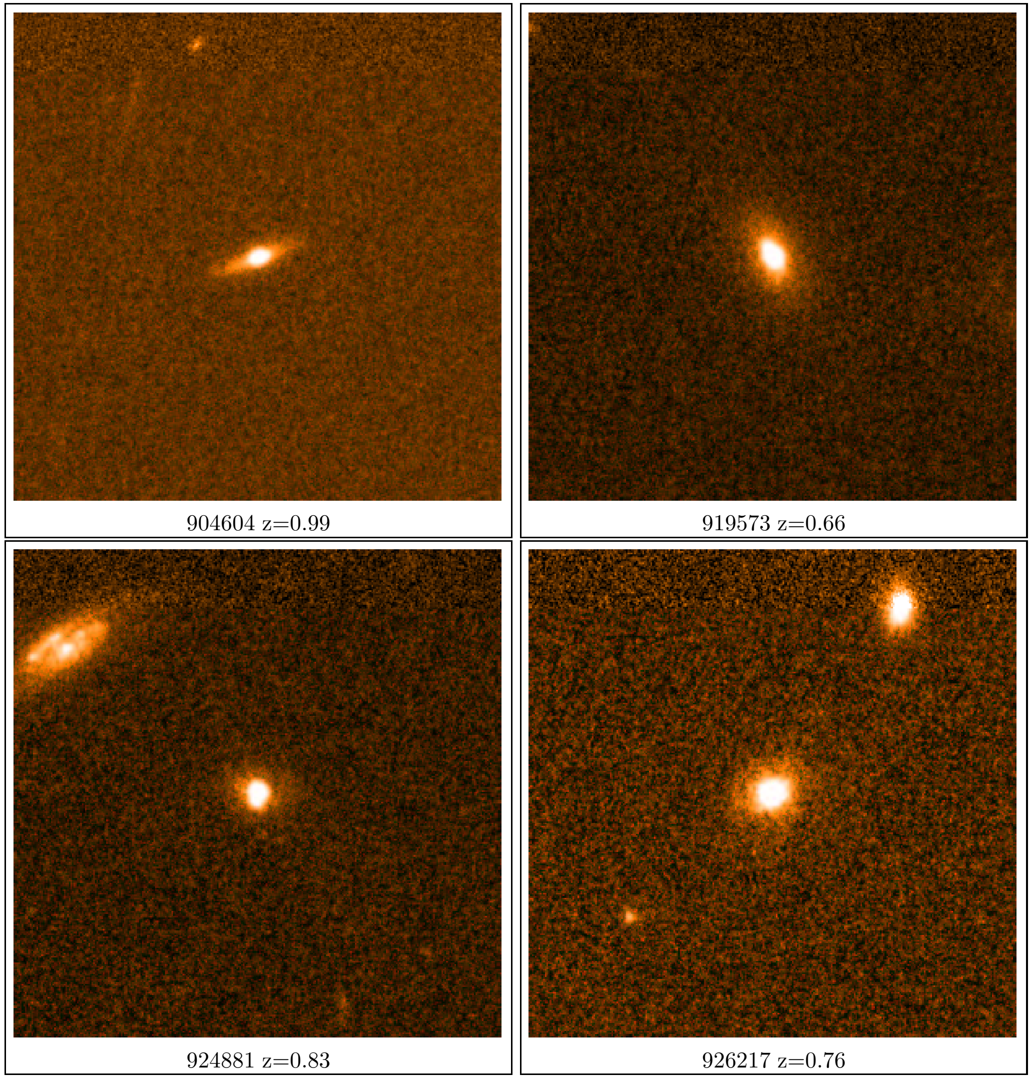
39/80 galaxies satisfy this criterion ($0.5 \leq z \leq 1.2$)



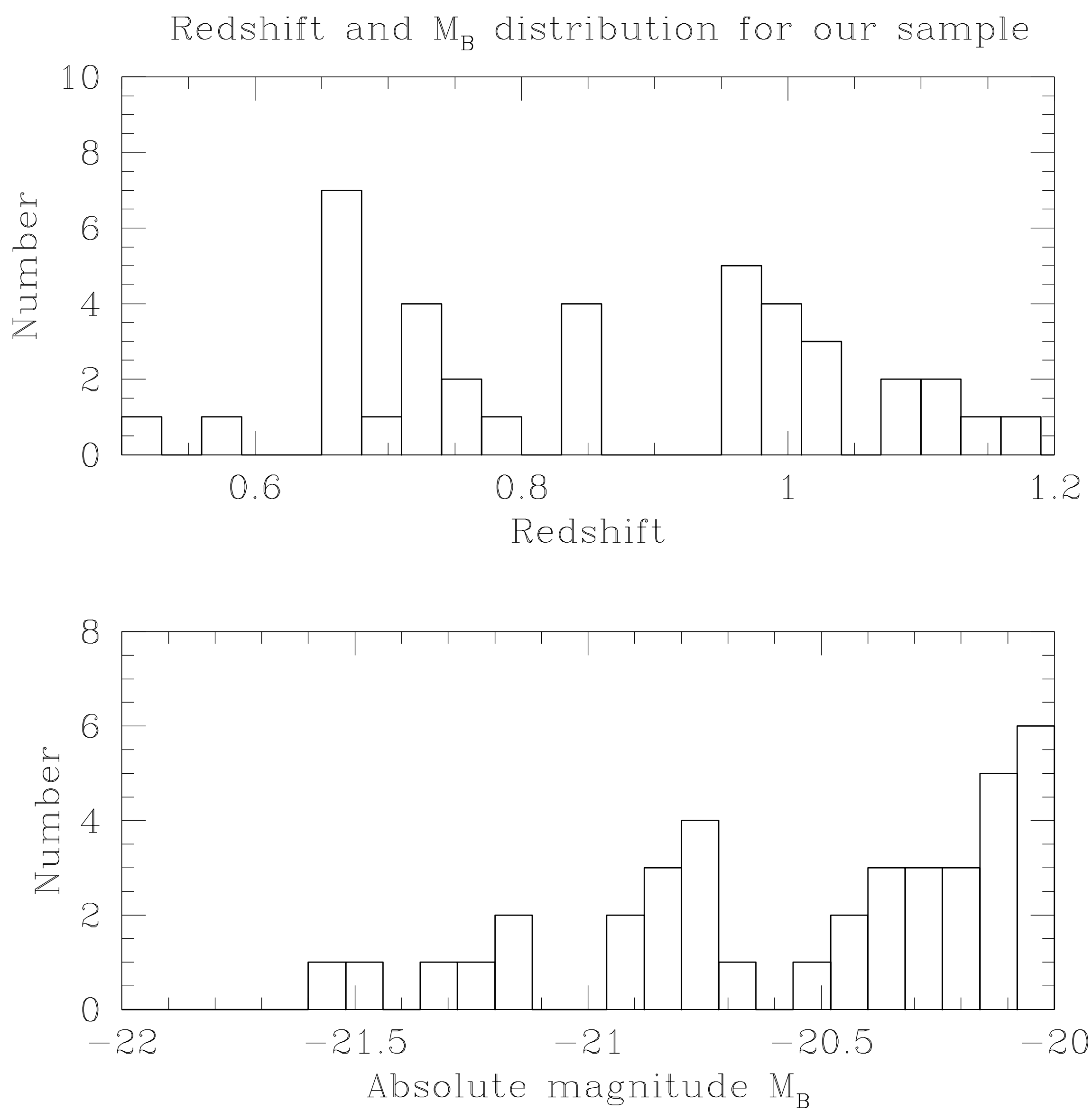
Completeness of the LCG sample



Some sample LCGs



Redshift and M_B distribution



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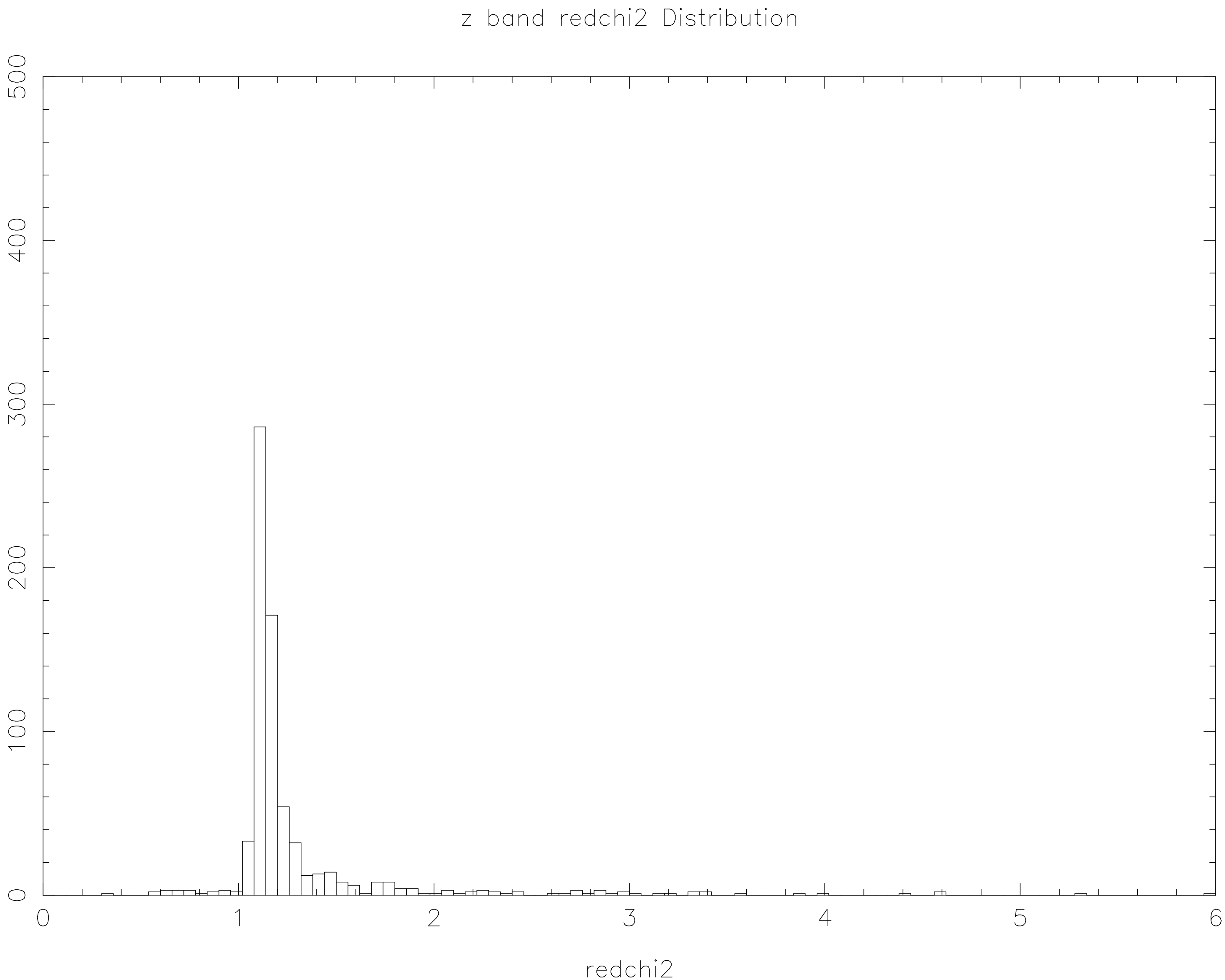
Bulge Disk decomposition

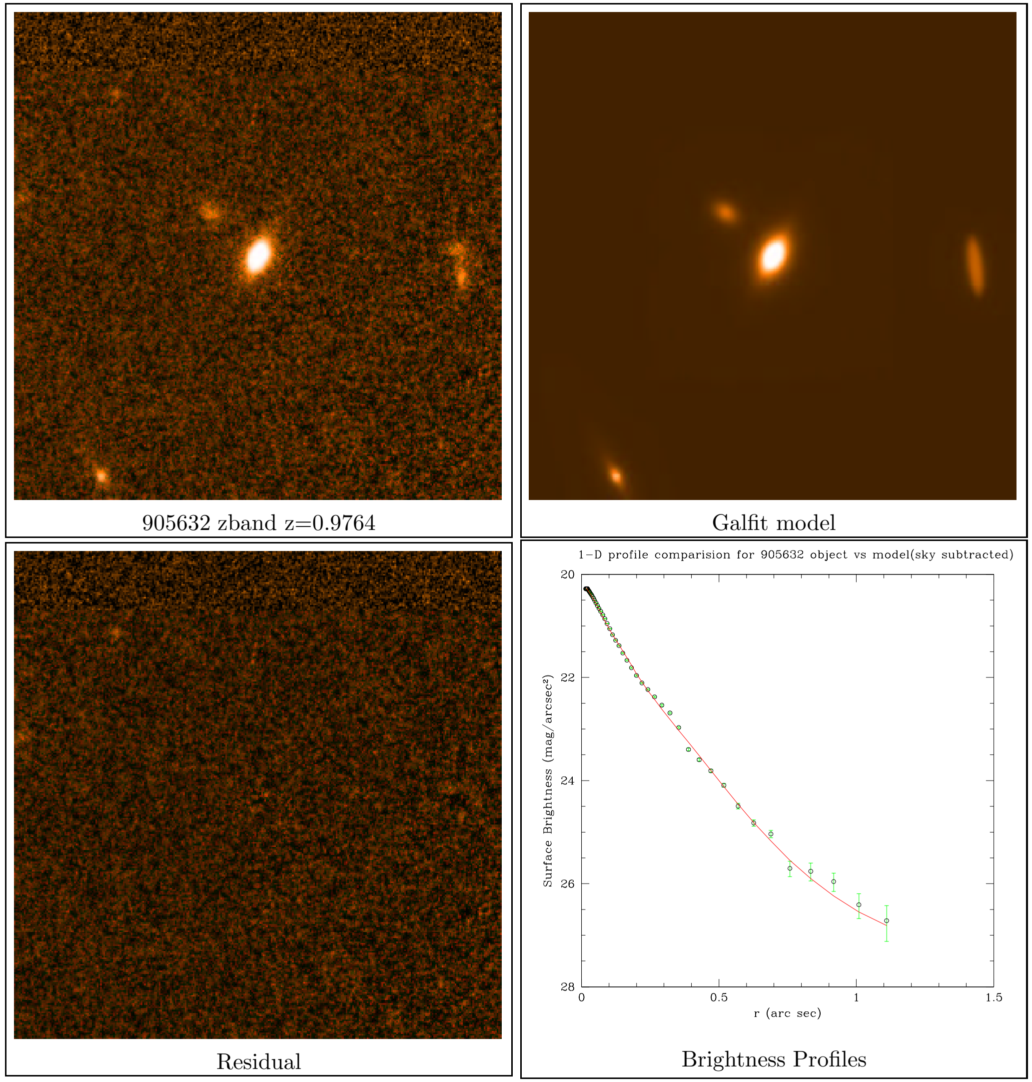
- Performed 2D Bulge-Disk decomposition in all 4 filters for the entire sample of 784 galaxies which have spectroscopic redshifts in the CDFS.
- Used *Galfit* Peng et al, AJ,124,266 2002.
- *Galfit* is a two-diamensional galaxy fitting algorithm designed to extract structural components from galaxy images.
- Sersic law: I(r) = $I_b(0)e^{-2.303b(r/r_e)^{1/n}}$ with P(2n,2.303b) = 0.5
- Exp. Disk: I(r) = $I_d(0)e^{-r/r_d}$
- Minimise

$$\chi^2_\nu = \frac{1}{\nu}\sum_{x,y}\frac{(flux_{x,y} - model_{x,y})^2}{\sigma^2_{x,y}}$$

Reduced Chi^2 distribution



Some results



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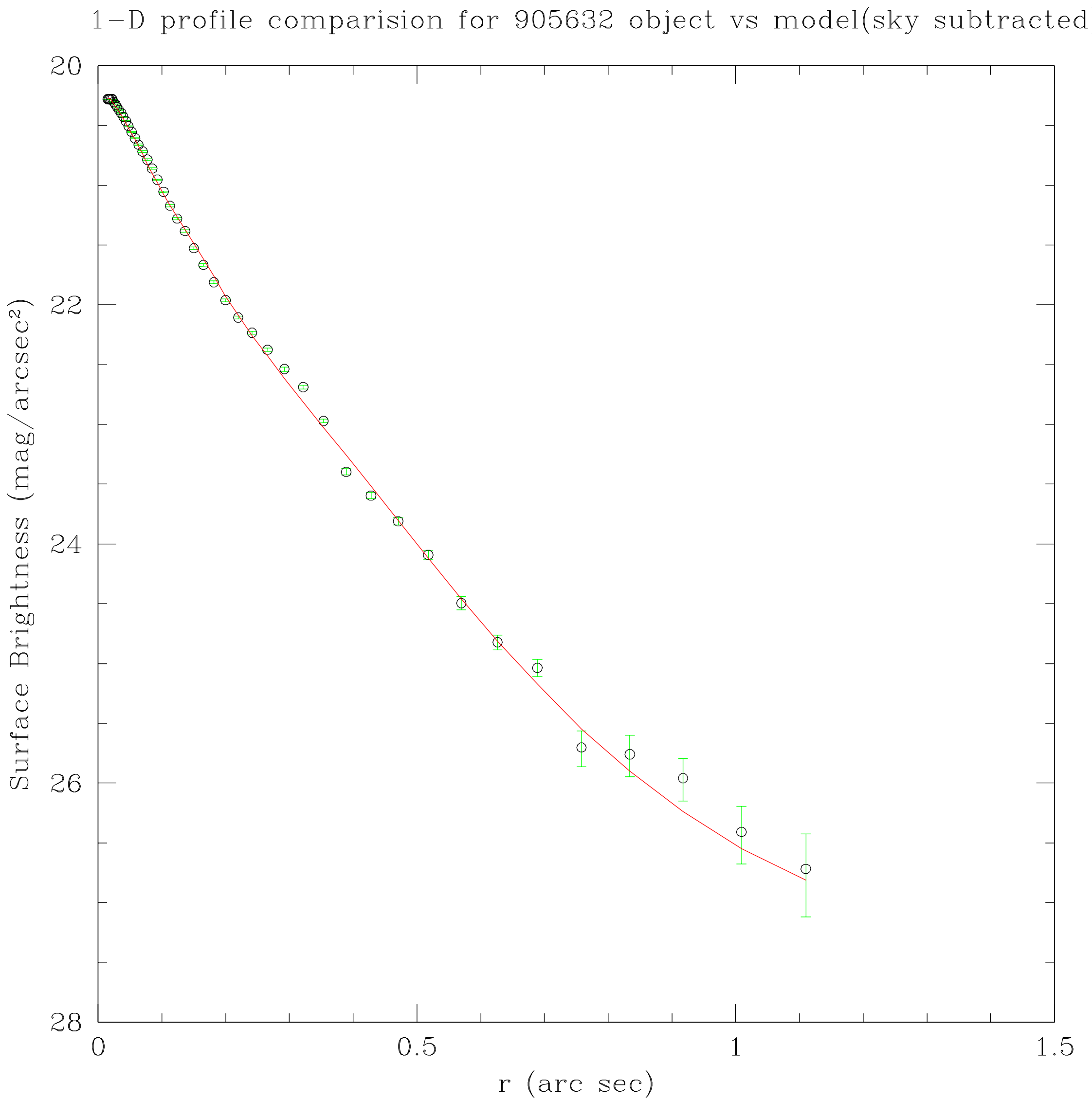


Table of results

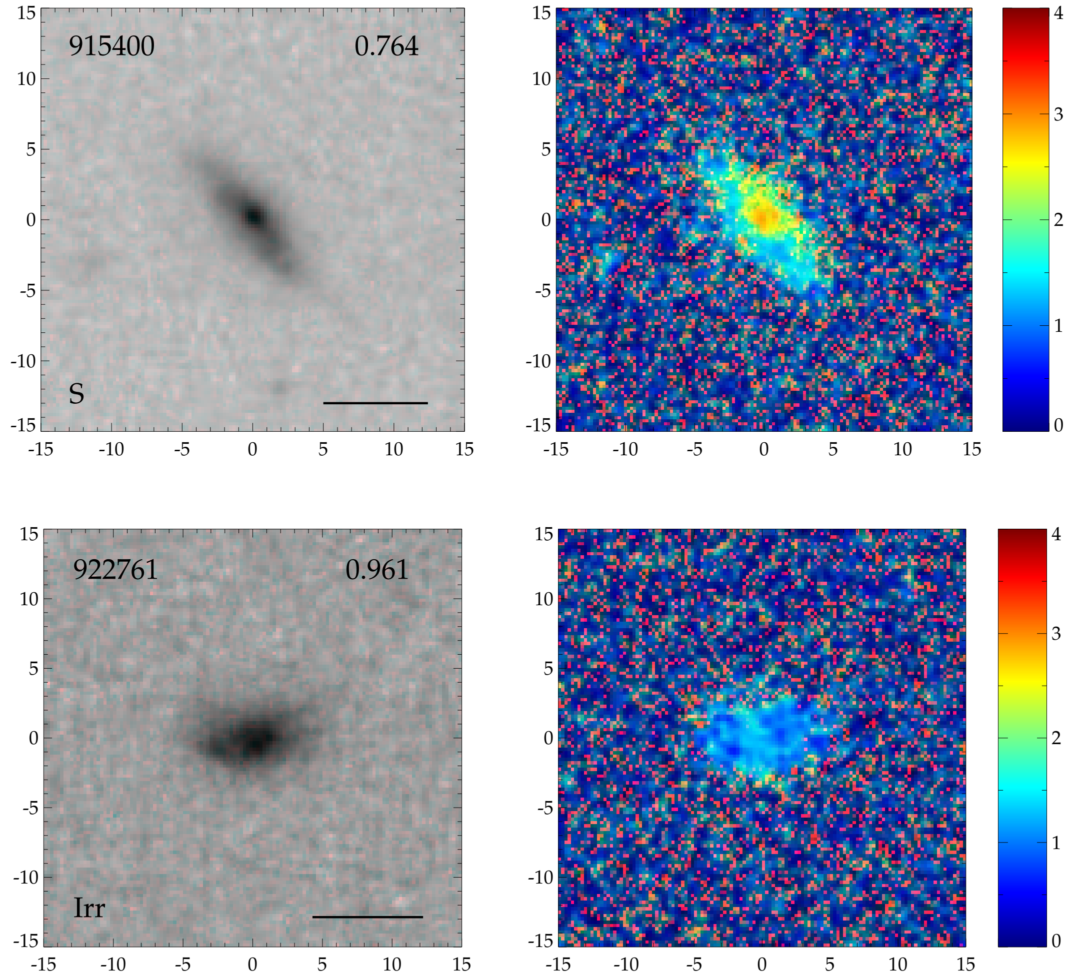
Basic data for galaxy 905632

- Redshift: 0.9764
- $EW_0(OII)$: 107.80 Å
- $M_B(AB)$: -20.0499

Galfit results

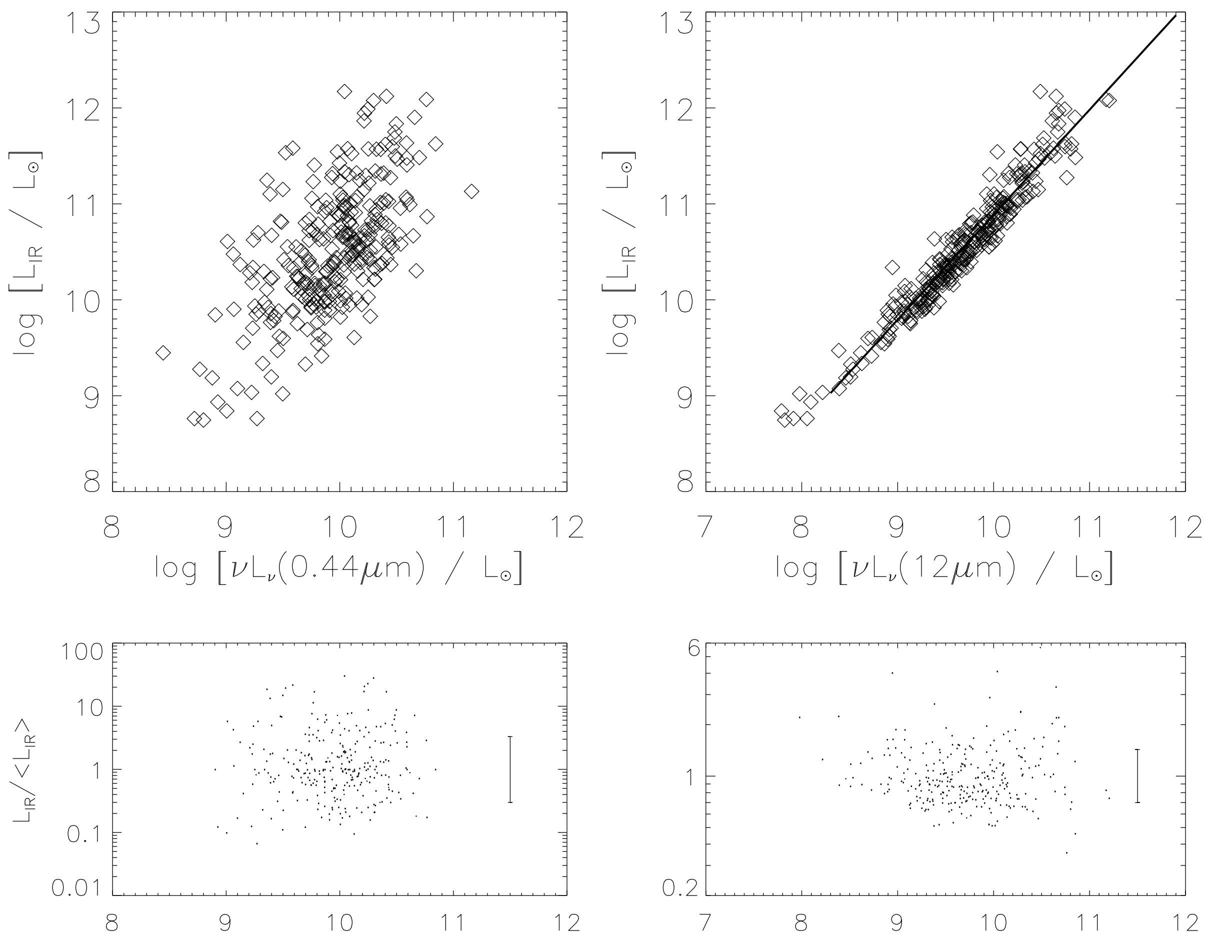
Band	Bulge Mag	Bulge re kpc	Bulge n	Disk mag	Disk rd kpc	χ^2_{Red}	B/T
F850LP	24.04 ± 0.08	0.612 ± 0.074	4.29 ± 0.43	23.29 ± 0.03	1.163 ± 0.017	1.093	0.33 ± 0.03

Color Maps



Star Formation Rate

Chary and Elbaz(2001).



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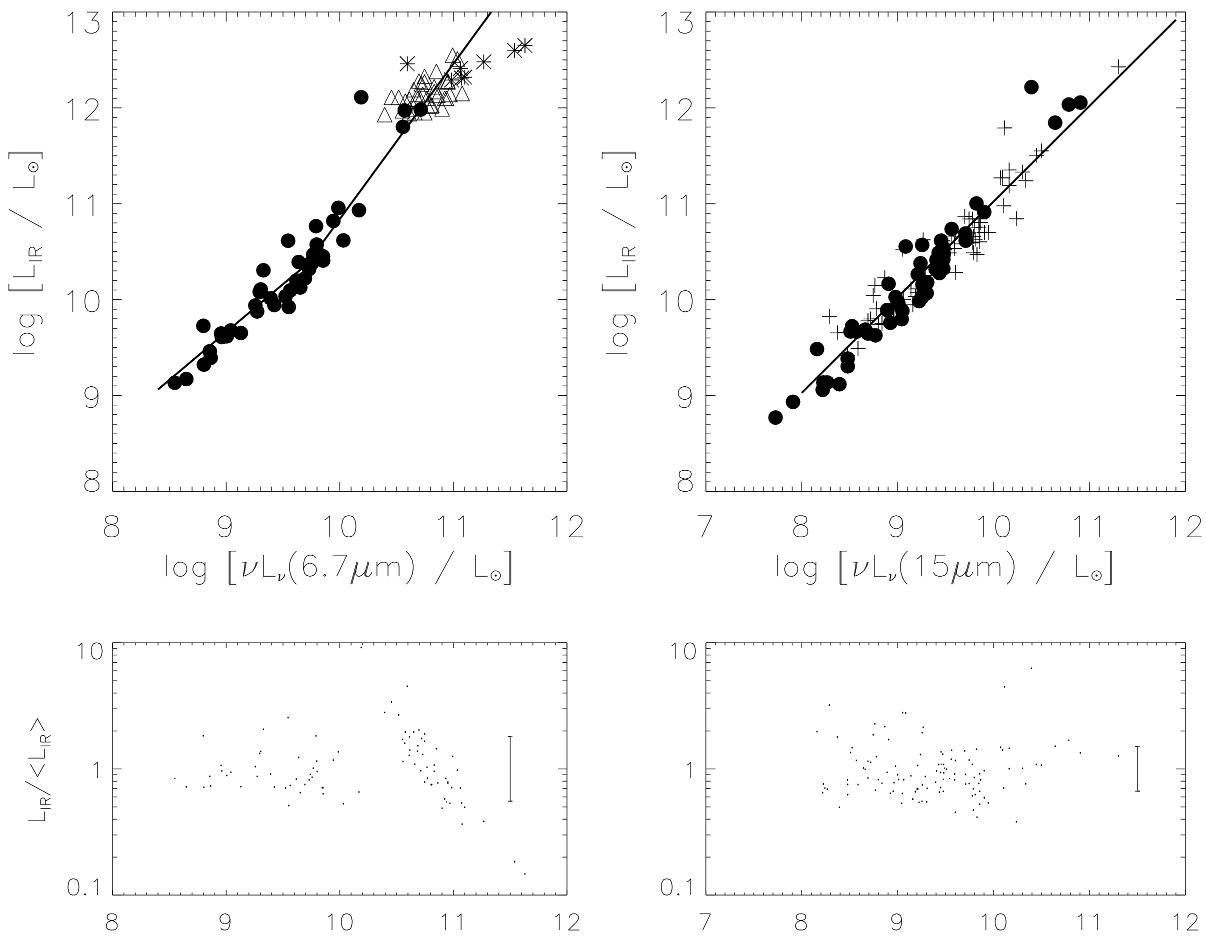

Star Formation Rate

Kennicutt(1998) has transformed the IR luminosity of starburst galaxies to a Star Formation Rate (SFR) giving an approximate estimate of the dust-enshrouded SFR (ρ) using the formula:

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$$\rho(M_{\odot} yr^{-1}) = 1.71 \times 10^{-10} L_{IR}(L_{\odot})$$

We obtain SFRs varying from $20 - 65 M_{\odot} yr^{-1}$ for our sample, which is the typical number expected for this class of objects.

Classification scheme

The galaxies that are well fit by bulge+disk two-dimensional structure, are classified into three ‘Hubble types’ mainly based on the *rest frame* B band B/T ratio.

- E ($0.8 < B/T \leq 1$)
- S0 ($0.4 < B/T \leq 0.8$)
- S ($0.0 < B/T \leq 0.4$)

In addition to performing automated classification, manual inspection was employed to check for obvious problems with the fits. In order to eliminate individual biases in performing morphological classification of galaxies, visual manual examination of multiband galaxy images, color maps and Galfit parameters was carried out by two people independently.

Table 6. Catalog of derived parameters for LCGs

Our ID	z	Stellar Mass $Log_{10}(M/M_{\odot})$	$L_{IR}(10^{10}L_{\odot})$	SFR $(M_{\odot}yr^{-1})$	HR[a]	Rest Frame B B/T	χ^2_{red}	Type[b]	Q[c]	$R_d(kpc)$[d]	M1/M2[e]
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
904260	0.983	10.32	< 10.37	–		–	–	S	3		M2
904604	0.990	10.94	< 10.59	–		0.33±0.01	1.063	S	1	2.53±0.04	
904680	0.964	10.28	< 9.83	–		–	–		4		M2
905632	0.976	10.23	< 10.18	–		0.33±0.03	1.093	S	1	1.16±0.02	
905983	0.860	10.36	< 7.22	–		0.08±0.02	1.129	S	2	1.85±0.01	
906961[f]	0.566	10.81	70.36	< 120.31	-0.55±0.03	–	–	E	–		
907047	1.112	10.65	< 14.49	–		–	–		4		M1
907361	0.731	10.96	< 6.69	–		0.80±0.04	1.322	E	2		
907794	1.144	10.92	20.82	35.60		0.67±0.09	1.099	S0	1		
908243	0.726	10.23	< 6.57	–		0.13±0.00	1.195	Tad	3		
909015	1.039	10.25	< 12.07	–		–	–		4		
909093	0.968	9.71	< 9.97	–		0.65±0.02	1.093	Tad	3		
909429	0.737	10.32	< 6.81	–		–	–		4		M2
910413	0.655	10.67	15.84	27.08		–	–	Tad	4		M2
911747	0.840	10.18	< 6.79	–		–	–		4		M2
911780	0.664	10.38	< 5.29	–		0.26±0.00	1.295	S	2	2.34±0.01	
911843	0.973	9.75	< 10.09	–		–	–		4		M2
912744	0.690	10.40	< 5.81	–		–	–	S	3		
913482	0.664	10.71	27.17	< 46.47	0.52±0.06	0.48±0.00	1.221	S0	3		
914038	0.667	10.50	12.00	20.53		–	–		4		M2
915400	0.764	10.42	< 7.44	–		0.08±0.01	1.333	S	2	2.45±0.02	
916137	0.980	10.33	< 10.29	–		0.60±0.02	1.094	Irr	3		
916446	0.839	10.10	< 6.77	–		–	–		4		M2
916866	0.987	10.22	< 10.48	–		0.38±0.02	1.136	S	2	1.40±0.03	
918147	1.099	10.77	39.48	67.51		–	–		4		M1
919573	0.665	10.61	5.89	< 10.08	-0.40±0.03	0.61±0.05	1.172	S0	3		
919595	0.785	10.24	< 7.95	–		0.12±0.00	1.182	S	3		
920435	1.034	9.44	< 11.91	–		0.49±0.01	1.116	S0	2		
921406	1.095	10.37	< 13.89	–		0.31±0.03	1.125	S	1	2.43±0.03	
922675	0.666	10.13	< 5.32	–		0.47±0.01	1.142	S0	1		
922733	0.650	10.05	< 5.01	–		–	–		4		M2
922761	0.961	9.71	< 9.77	–		0.24±0.01	1.095	Irr	3		
923085	1.122	10.68	15.74	26.92		0.87±0.01	1.212	Irr	3		
923926	1.012	10.74	< 11.23	–	0.12±0.07	0.64±0.02	1.113	S0	3		
924881	0.839	9.80	< 6.77	–		0.78±0.01	1.277	E	2		
926109	0.522	10.19	< 2.95	–		–	–		4		M1
926217	0.767	10.27	< 7.50	–		0.50±0.05	1.119	S0	1		
907305	1.185	10.11	< 17.21	–		–	–		4		M1
914895	0.736	10.09	< 6.78	–		–	–		4		M1

[a] X-ray hardness ratio, defined as (H-S)/(H+S) where H and S are the counts in the hard and soft bands respectively.
[b] Galaxy type — **E**: $0.8 < B/T \leq 1$; **S0**: $0.4 < B/T \leq 0.8$; **S**: $0.0 < B/T \leq 0.4$; **Irr**: irregular; **Tad**: Tadpole.
[c] Q quality factor — 1: secure; 2: possibly secure; 3: insecure; 4: undetermined.
[d] Exponential disk scale length(kpc) for disk dominated galaxies.
[e] Merging? — M1: obvious merging; M2: possible merging.
[f] This object could not be fitted properly due to the presence of a strong point source at the center.

Important results

The morphological mix of LCGs ($0.5 \leq z \leq 1.2$)

- Mergers: $\sim$36%
- Disk dominated: $\sim$25%
- S0: $\sim$17%
- Bulge dominated: $\sim$7%
- Irr/tadpole: $\sim$15%

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Given the strong redshift evolution exhibited by LCGs and the fact that a significant fraction of LCGs are in merging systems seems to indicate that LCGs might just be a phase in the hierarchical evolution of galaxies.

Important results

- We find that LCGs account for $\sim$26% of the $M_B \leq -20$ galaxy population in the redshift range $0.5 \leq z \leq 1.2$.
- We also derive SFR values ranging from $\sim$ 20 - 65 $M_{\odot}$/year as expected for this class of objects.

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What do they evolve into?

Important results

- The merger rate of galaxies was much higher at higher redshifts so that an average L^* galaxy is estimated to undergo 0.8 to 1.8 major merger events (leading to a complete disruption of the disk) from z$\sim$1 to z=0. (Le Fevre et al. 2000)

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- Now, unless we have a way of rebuilding the disk in such galaxies, we would expect that almost all L^* galaxies in the local universe are ellipticals.
- This prediction has been proved to be wrong in recent work (eg. Smith et al. 2005), where they find the fraction of early type galaxies f_{E+S0} to remain constant at all epochs at a value (much smaller than unity) of 0.4 ± 0.1.

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- If we combine all the evidence listed above, we envisage that it is likely that many of the LCGs that are undergoing mergers at intermediate redshifts might go on to form a disk from gas left over from the merger event, by the time they evolve to the current epoch.

Conclusions

- LCGs constitute one of the most rapidly evolving galaxy populations in the intermediate redshift range.
- The evolution is driven by mergers rather than passive evolution.
- LCGs are probably just a phase in the hierarchical evolution of galaxies.
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Unravelling the morphologies of Luminous Compact Galaxies using the HST/ACS GOODS survey (submitted to A&A)
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