A Candidate Brightest Proto-Cluster Galaxy at z = 3.03

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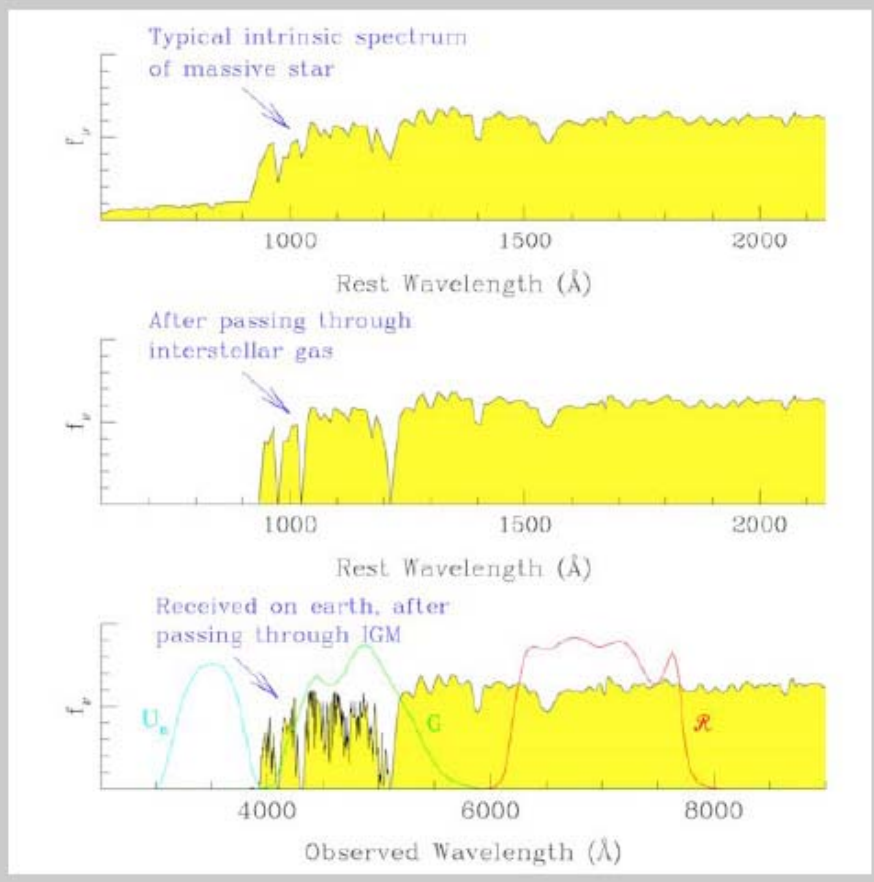
astro-ph > arXiv:0803.3808, submitted to ApJL

Seminar by **Paramita Barai**

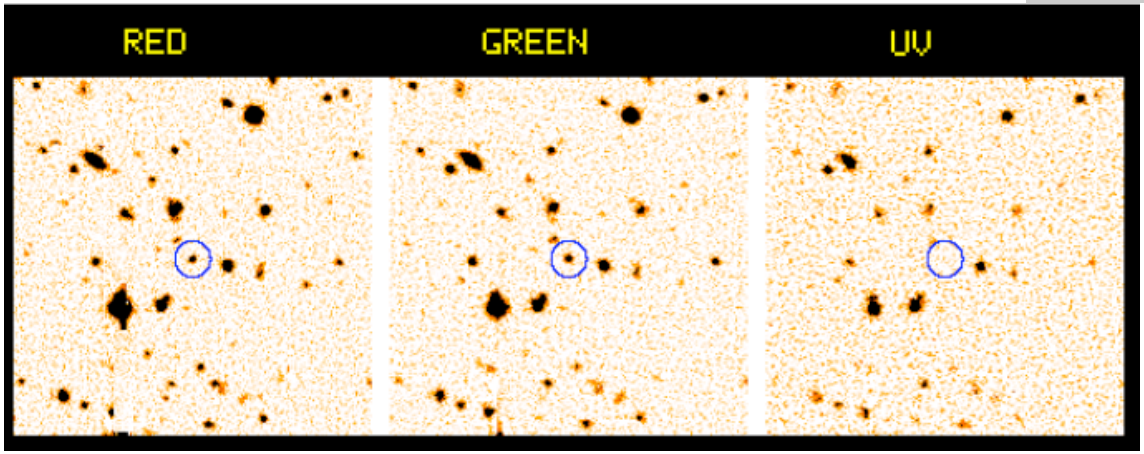
9th May, 2008

Lyman Break Galaxy (LBG)

- High-redshift : $z > 2.5$
- Star-forming galaxies
- Detection : UV dropout
  - Seen in G & R filters
  - Not in U



Lym an break galaxy spectrum



LBG-2377

- Lyman break galaxy discovered at $z = 3.03$
  - Light from 11.5 Gyr before
- Very bright, $m_R = 22.2$

- Multiple peaks in brightness profile images
  - Angular separation ~ 0.8″
  - Comoving separation ~ 25 h^{-1} kpc
- High SNR UV spectroscopy : ~5 components with a velocity dispersion of σ ~ 460 km s^{-1} for the 3 strongest components

- Analysis $\Rightarrow$ Massive system in a late stage of merging

Imaging

- 2001 April 18 : Low-Resolution Imaging Spectrometer (LRIS) on Keck I telescope
- LBG-2377
  - R = 22.2, z ~ 3 LBG candidate
  - R.A. 16:44:48.3, Dec. +46:27:08.2 (J2000.0)
- Isophotal magnitudes

$$u' = 26.5 \pm 0.46,\ \mathrm{B} = 24.3 \pm 0.10,\ \mathrm{V} = 22.6 \pm 0.03,\ \mathrm{R} = 22.2 \pm 0.06,\ \text{and}\ \mathrm{I} = 22.3 \pm 0.07.$$

- Contour plot ⇒ Single extended system with multiple vigorous star forming regions
- Peak ratio of 3 strongest components = 10:5:1
  - Separations of ~ 0.6″ – 1″ (~ 20 – 30 h^{-1} kpc, comoving)
- No significant grav. lensing source candidates within ~ 10″

Contour plot ⇒ Spans ~ 2″× 3″

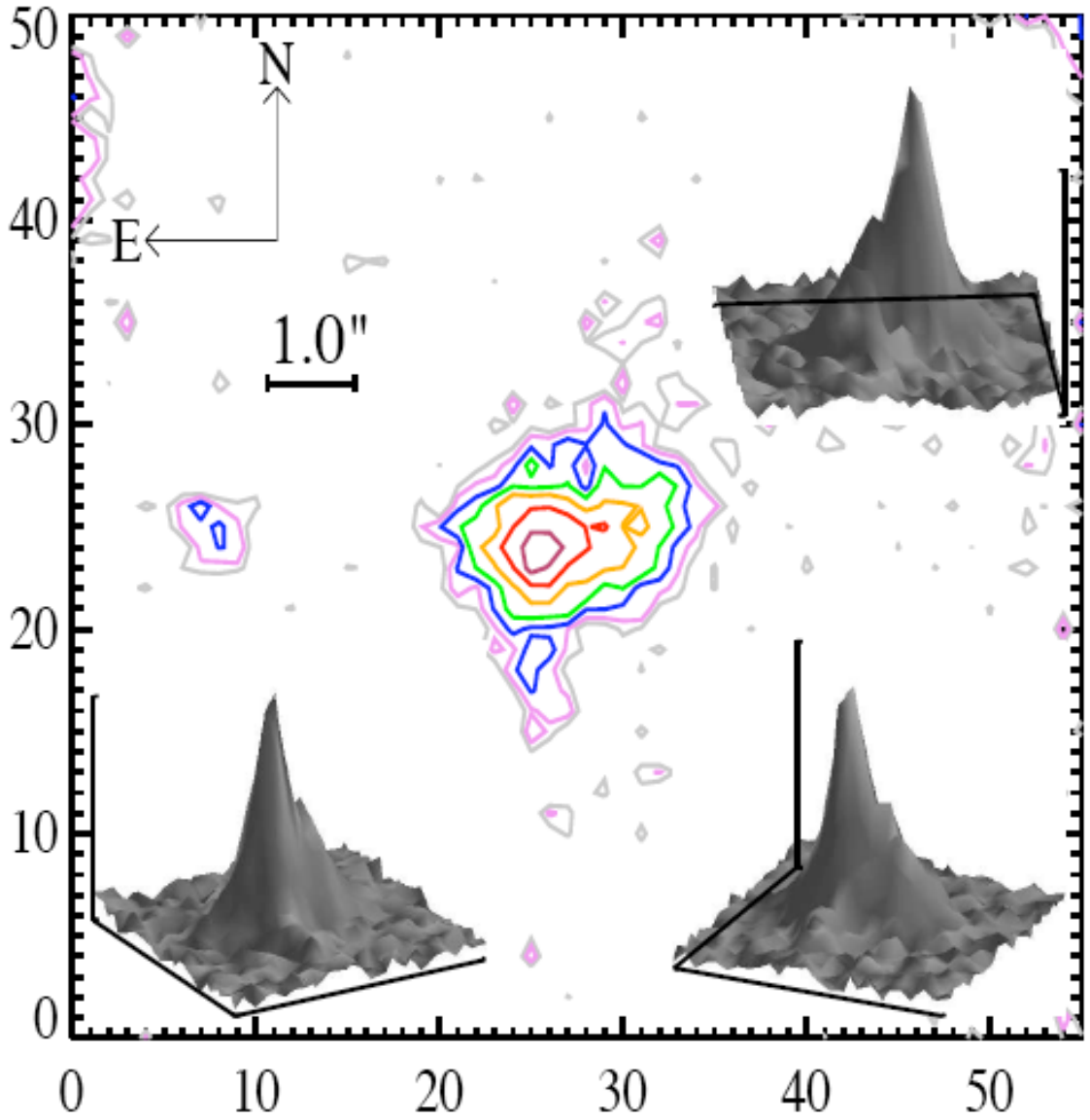


Fig. 1.— Contour plots of LBG-2377. The 2-D plot indicates a primary peak located slightly to the E of the object centroid. Secondary and tertiary peaks are detected W and SE of the centroid, respectively. Three 3-D contour plots are inset with rotations (clockwise from upper-right), 185°, 335°, and 30° (S= 0°).

Spectroscopy

- Confirmed $z = 3.03$
- Low-resolution multi-object spectroscopy on 2004 Feb 18
  - Using 300 line mm^{-1} grism on LRIS with spectral resolution of ~ 10Å FWHM
- Authors followed up with high-resolution, high SNR longslit observations on 2007 May 21
  - Used 600 line mm^{-1} grism on LRIS
  - SNR ~ 10 – 15
  - Resolution ~ 2 – 3 Å

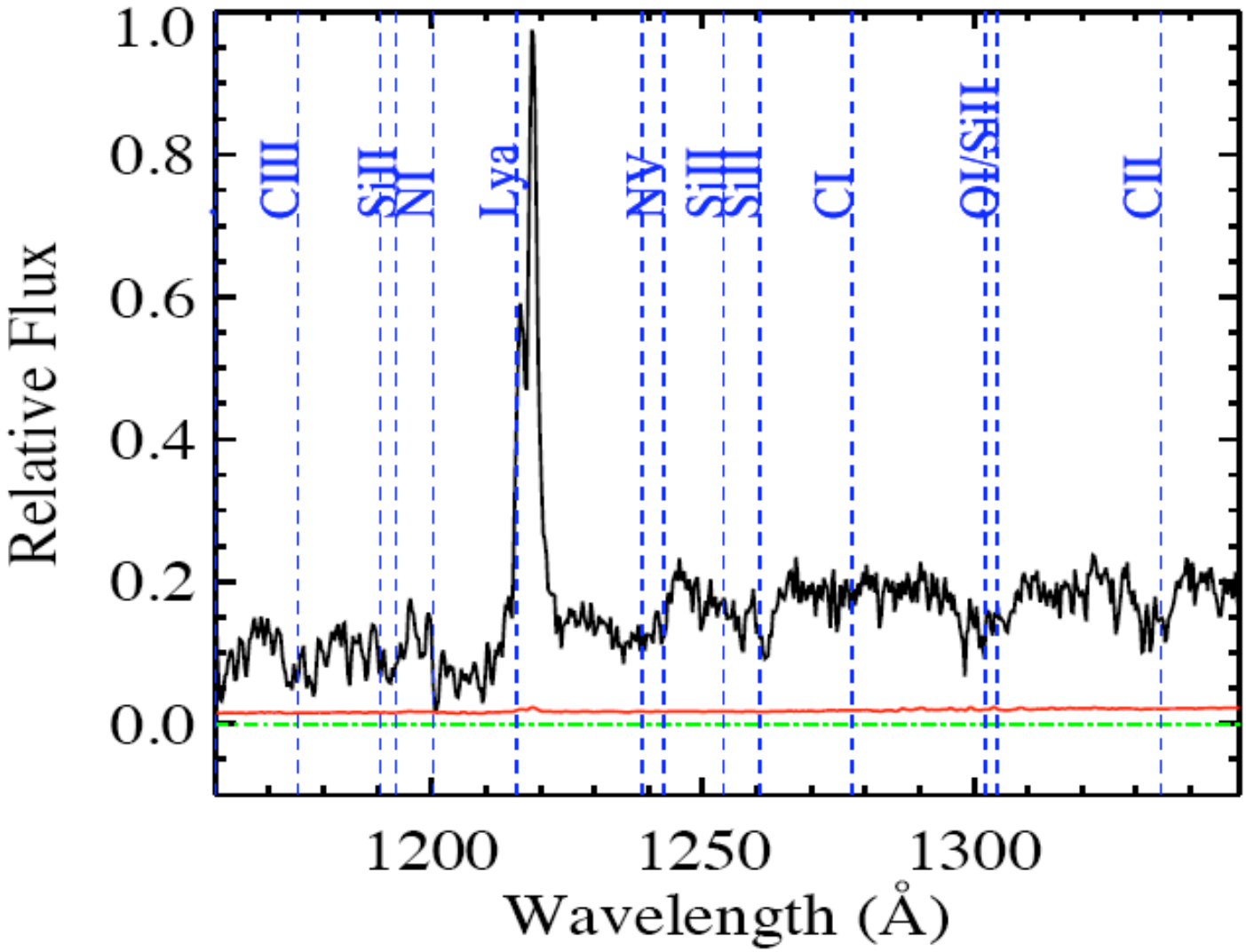


Fig. 2.— Spectrum of LBG-2377. This section is shown to illustrate both the double-peak Ly-α emission feature and broad, complex interstellar absorption features [vertical *(blue)* dashed lines]. In all sepctra in this paper, the green line indicates zero flux and the red line is the error array.

Spectroscopy

- Spectrum of LBG-2377
  - Dominated by O and B star continua
  - Strong Ly-α emission
  - Little reddening
- $\Rightarrow$ Consistent with general properties of $z \sim 3$ LBGs showing Ly-α emission
- High-resolution high-SNR spectra shows 2 strong peaks with 2 possible weak peaks
- Rest-frame FUV shows complex series of interstellar atomic lines :
  - Gas absorption over velocities $\geq$ 2000 km s^{-1}
  - ~ 5 components
- Over 20 FUV ISM absorption lines studied

Components Detected

- Identified redshifts of components from ≥5 photospheric lines of each
  - SiIII, CIII, CII, NIII, OIV, SV

Table 1. LBG-2377 Components

Comp.	z_{Phot}	z_{ISM} [a]	$z_{Ly\alpha}$	Δv_{ISM} [a b]	$\Delta v_{Ly\alpha}$ [b]
A	3.0385	3.0354	(3.0488)[c]	-230	(765)[c]
B	3.0343	3.0308	...	-260	...
C	3.0289	3.0258	3.0416	-230	945
D	3.0244	3.0209	3.0341	-260	725
E	(3.0161)[c]	(3.0143)[c]	(3.0263)[c]	(-135)[c]	(760)[c]

[a]Averaged fit to multiple features.

[b]Approximate velocity offset with respect to the stellar photospheric velocities in km sec^{-1}.

[c]Features are weak and respective values have a lower confidence level.

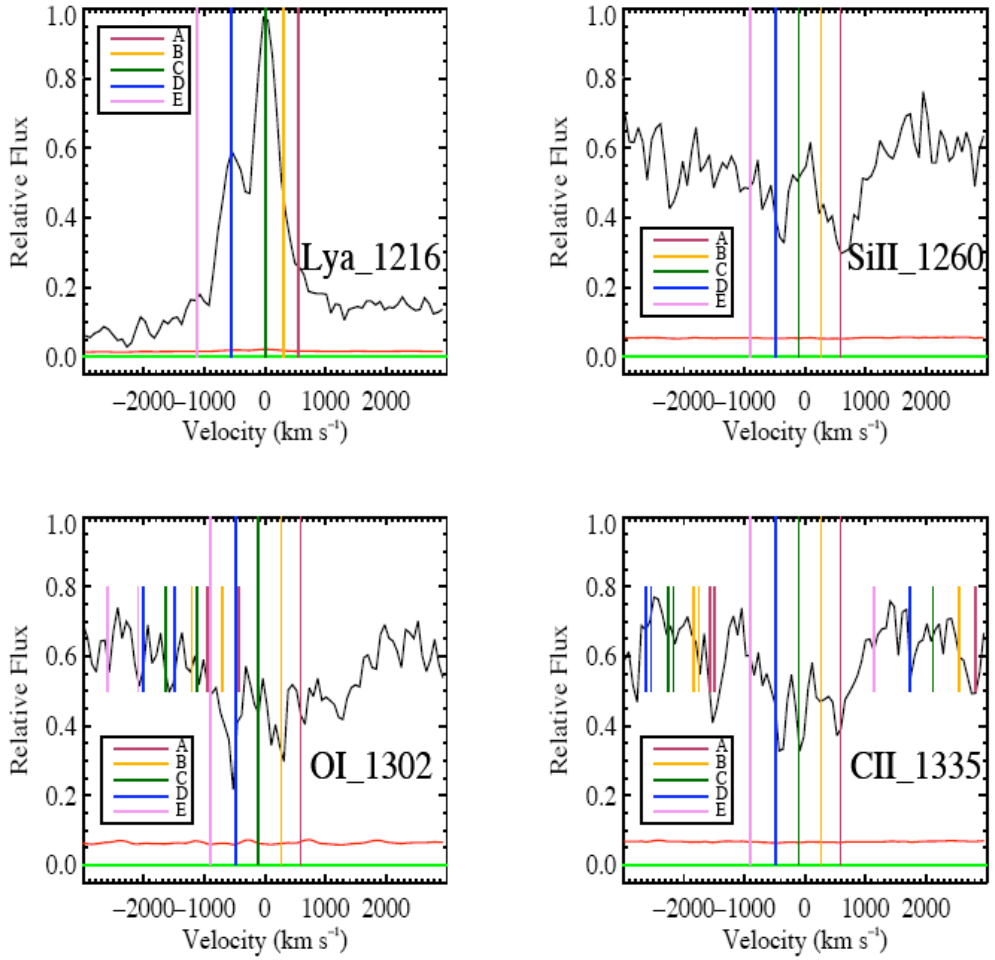


Fig. 3.— Spectrum of LBG-2377 showing five tentative components (A - E in Table 1) identified using 21 ISM features. Velocities. are with respect to the average of components A, C, & D. *Upper left:* The two strong Ly-α emission lines (components C & D) and three potential weak Ly-α lines [A, B, & E]. *Clockwise from the upper right:* Fits for the ISM transitions SiII, CII, and OI. Also shown are the stellar photospheric features SiIII 1294.5, 1296.7, CIII 1296.3, CII 1323.9, NIII 1324.3, and OIV 1343.4 (not labeled for clarity) indicated by short vertical lines. The signal-to-noise ratio is ~ 15 in these regions, therefore the more prominant features are real. Each absorption feature is in agreement with their respective systemic redshift to within the spectral resolution (~ 150 km sec^{-1}).

Comparison with Other LBGs

- Generally in LBGs : Ly-α emission and ISM absorption lines show observed velocity offsets of ~ +650 and ~ –200 km s^{-1} from their systemic velocities
  - Caused by an expanding galactic-shell of gas and dust driven by SNe and stellar winds
  - Ly-α photons are absorbed in the approaching shell, but are resonantly scattered off the receding portion and remain

- 2 Ly-α peaks in LBG-2377 $\Rightarrow$ 2 expanding galactic-scale shells with a systemic velocity difference of ~ 500 km s^{-1}

What does theory say ?

- LBG-2377 $\rightarrow$ a forming brightest cluster galaxy

  ΛCDM model:

- Dark matter halo mass, $M \sim 10^{13}\ M_{\odot}$
  - Both from kinematics & luminosity

- Assuming NFW halo : Maximum circular velocity, $v_{\rm max} \sim 1.5\sigma = 700$ km s^{-1}

  $\Rightarrow M_{\rm vir} \sim 10^{13}\ M_{\odot}$ at $z \sim 3$
- Using LBG luminosity function, number density of such ($m_R = 22.2$) objects $\sim 10^{-7}$ Mpc^{-3} h^3
  - Predicts halos with $v_{\rm max} \sim 700$ km s^{-1} at $z = 3$

- Consistent $\Rightarrow$ LBG-2377 is inside a massive ($v_{\rm max} \sim 700$ km s^{-1}) halo

More Theory …

- Massive halos at $z \sim 3$ contain substructures
- N-body ΛCDM simulation (Stewart et al. 2007, arXiv:0711.5027) of 80 h^{-3} Mpc^{-3} box
  - 3 halos with $v_{max} > 600$ km s^{-1} at $z = 3$ ($V_{max} = 620, 645, 740$ km s^{-1})
  - Each have 5-8 sub-halos with mass $10^{11}\, h^{-1}\, M_\odot < M < 10^{12.5}\, h^{-1}\, M_\odot$, within (physical) virial radii $R_{vir} \sim 90\, h^{-1}$ kpc $(M/10^{13}\, h^{-1}\, M_\odot)^{1/3}$

- Typical substructure mass for obs. LBG hosts at $z \sim 3$

$\therefore$ Such objects (LBG-2377) are very likely to exhibit multiple components

Merger Tree Analysis

- Follow merger trees of 3 halos with $v_{max} > 600$ km s^{-1} :
- Evolve from, $M = 10^{13–13.5}\, h^{-1}\, M_{\odot}$ at $z = 3$

  $\Rightarrow$
- To, $M = 10^{13.9–14.3}\, h^{-1}\, M_{\odot}$ at $z = 0$ (cluster-mass systems)
- These are among the 12 most massive halos in sim. box at $z = 0$

- LBG-2377 $\Rightarrow$ will evolve into the dominant galaxy within a large group / cluster by the present

Ly-α Emission

- Double peak Ly-α
- Low-resolution spectroscopic survey: ~3% show double peaks
- Predict: with high-resolution and high-SNR, ~30% have multiple massive components
  - Separate interacting / merging systems
- Consistent with theory:
  - Fraction of expected major mergers at ~3 from num. sims.
  - Galaxy formation theories implying mergers are important for star formation in LBGs

Discussion: Nature of LBG-2377

1. Single extended LBG ($M \sim 10^{13}\ M_{\odot}$) having multiple regions of vigorous star formation
2. Single extended LBG ($M \sim 10^{12}\ M_{\odot}$), over-luminous due to high bursts of star formation
3. Multiple unbound $M \sim 10^{12}\ M_{\odot}$ LBGs nearby

4. Multiple LBGs in a $M \sim 10^{13}\ M_{\odot}$ halo in a late state of merging

- (4.) $\rightarrow$ most favorable by data

Summary

- LBG-2377
  - Bright Lyman break galaxy, z = 3.03
  - Multiple components
- Very massive system with a halo mass $M \sim 10^{13}\ M_{\odot}$
- In a late state of merging
- Simulation $\Rightarrow$ Halos at z = 3 contain sub-halos consistent with the observed components
- By z = 0, will probably evolve into a halo of mass $M \sim 10^{14}\ M_{\odot}$ found in group/cluster
- Such $z \sim 3$ systems are likely progenitors of brightest cluster galaxies

Backup

LBG