Physical Properties of Spectroscopically Confirmed Galaxies at Redshift ≥ 6

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Reionization in the Red Centre

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Outline

- Introduction
- A sample of 67 spectroscopically-confirmed galaxies at $z \geq 6$
- Rest-frame UV continuum slope
- Rest-frame UV continuum morphology
- Merging/interacting systems
- Lyα morphology of LAEs
- Positional differences between UV continuum and Lyα emission
- Lyα luminosity functions from z = 5.7 to 7.7
- Rest-frame Lyα luminosity and EWs
- UV luminosity function of LAEs
- SED modeling and stellar populations
- LAE vs. LBGs
- Nonparametric measurements of morphology (CAS+GM_{20})
- ……

Cosmic reionization and high-z galaxies

Cosmic reionization

- Neutral IGM ionized by the first astrophysical objects at $6 < z < 15$
- Evidence: CMB polarization + GP troughs in quasars + …
- Responsible sources for Reionization

High-z galaxies ($z \geq 6$)

- HST + the largest ground-based telescopes
- A few hundred galaxies or candidates at $z \geq 6$; many at $z \geq 8$ (e.g.; Bouwens 2011; Oesch 2012; Ellis 2013; and many more papers)

Current studies

- Mostly done with photometrically-selected LBGs with decent IR data (e.g., several HST ultra/deep fields)
- Lack of a large spectroscopically-confirmed sample with deep IR data (HST + Spitzer)

A study of spectroscopically-confirmed galaxies at z ≥ 6

➢ A simple idea

- HST and Spitzer imaging of spectroscopically-confirmed galaxies in the Subara Deep Field (SDF) and SXDS.
- Three HST programs and two Spitzer programs

➢ Our imaging data

- Optical data from Subaru Suprime-Cam (PSF ≈ 0.6−0.7”)
- Broad-band data (AB mag at 3σ): BVRi ≈ 28.5, z ≈ 27.5, y ≈ 26.5
- Narrow-band data (26 mag): NB816 and NB921, NB973 (25 mag)
- HST near-IR data (~2 orbits per band): WFC3 F125W (or F110W) and F160W
- Spitzer mid-IR data (3 ~ 7 hrs): IRAC 1 and 2

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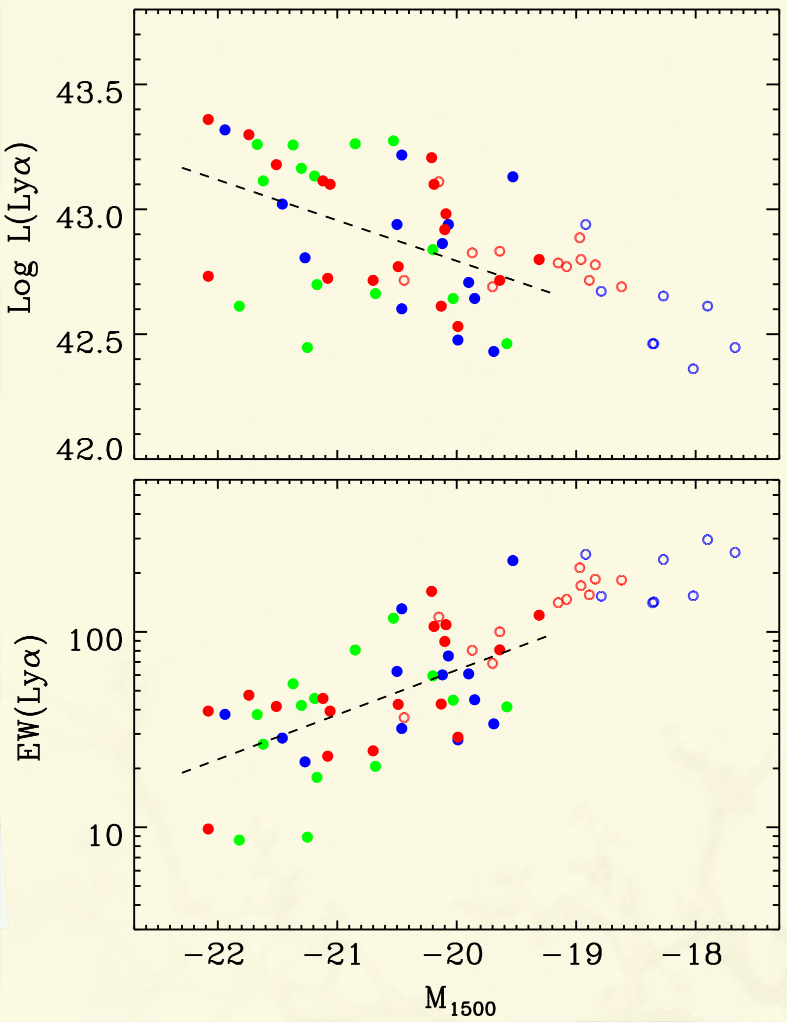
➢ Our galaxy sample

- A total of 67 galaxies:
  22 LAEs at z ≈ 5.7;
  16 LBGs at z ≈ 6;
  28 LAEs at z ≈ 6.5;
  1 LAE at z ≈ 7
- A complementary sample to LBGs discovered by HST

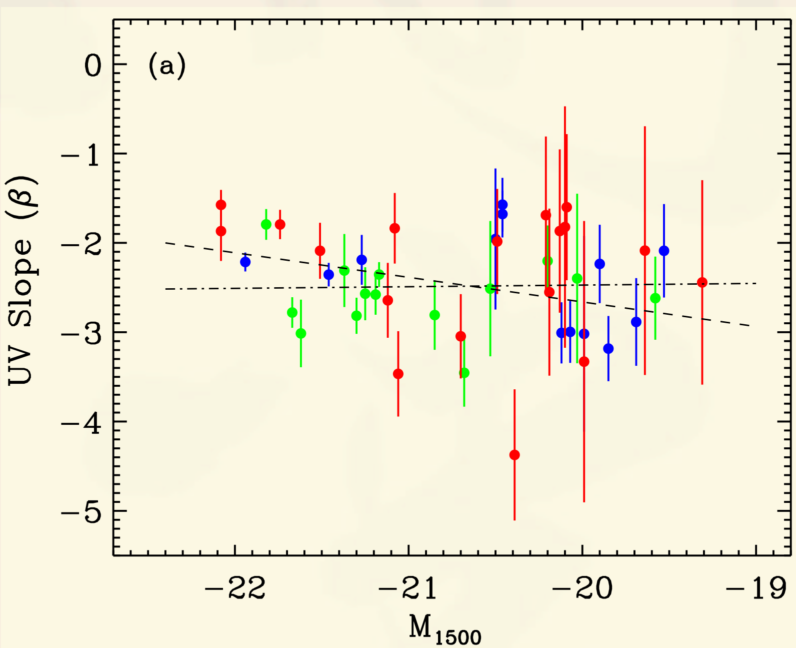


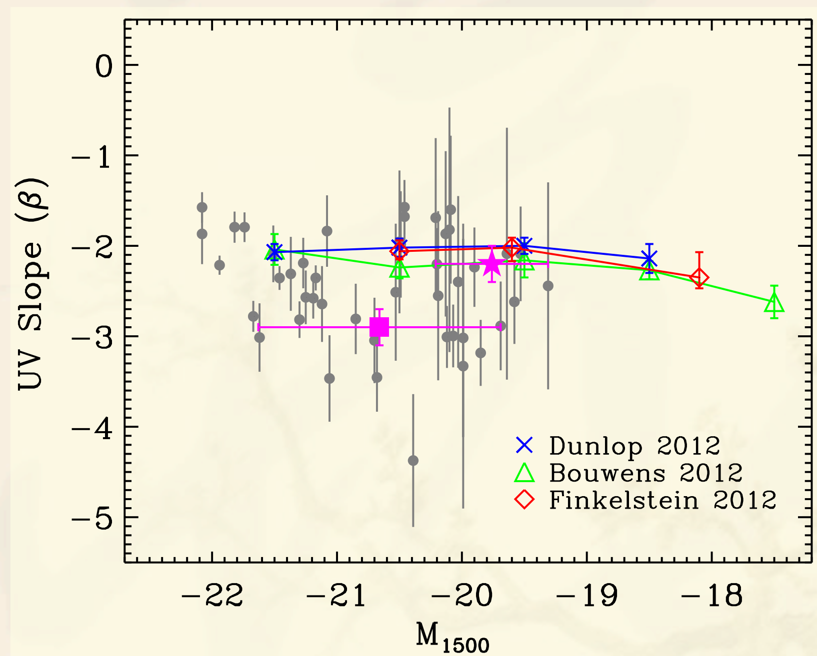
Note:
- LAEs: found by the narrow-band (NB) technique
- LBGs: found by the dropout technique

Rest-frame UV continuum slope

➢ UV continuum slope β ($f_\lambda \sim \lambda^\beta$)

- –1.5 ≤ β ≤ –3.5; median β ≈ –2.3
- Slightly steeper than LBGs in previous studies (β ≈ –2 ~ –2.1)
- The β – M_{1500} relation is weak at the bright end
- LAEs do not have steeper β than LBGs

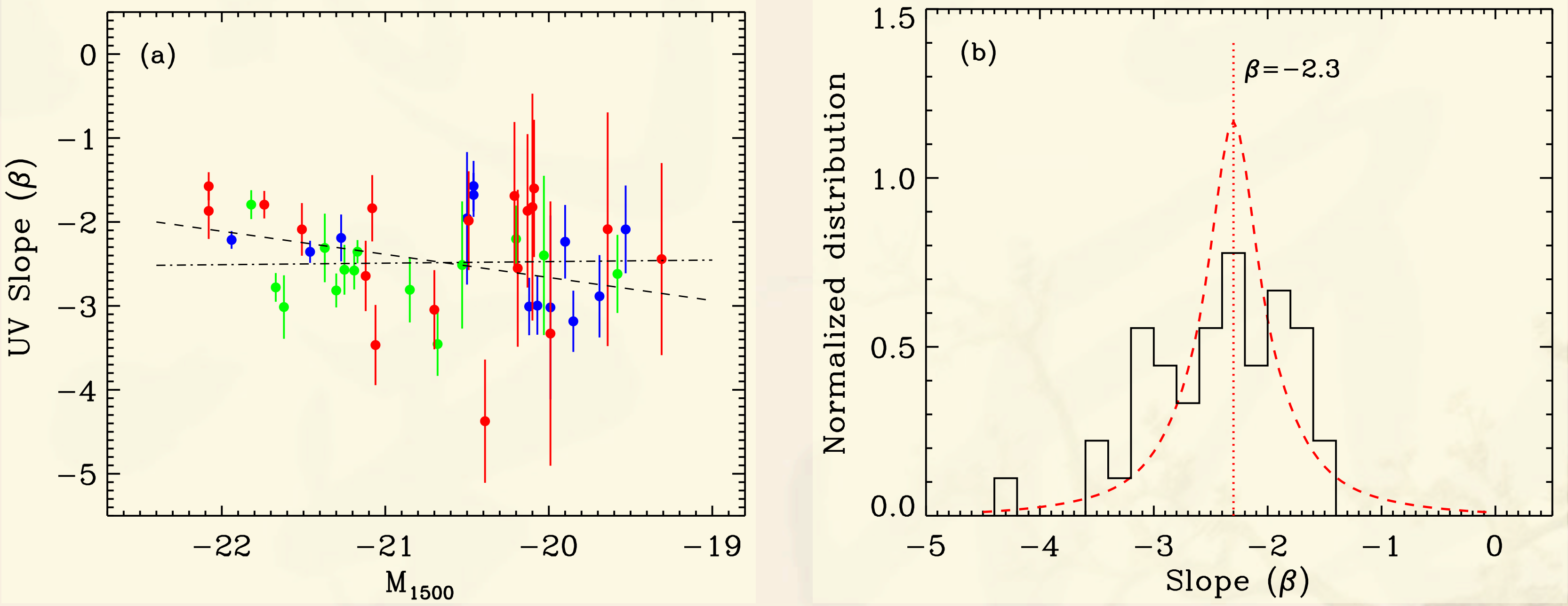




(Jiang et al. 2013a, ApJ)

➢ Extremely blue galaxies

- Statistically significant excess of galaxies with β ~ –3
- Nearly zero dust and metallicity + extremely young + …
- Current simulations cannot produce β ≤ –3 (Finlator 2011)
- How to: top-heavy IMF, high escape fraction, etc. (e.g. Bouwens 2010)

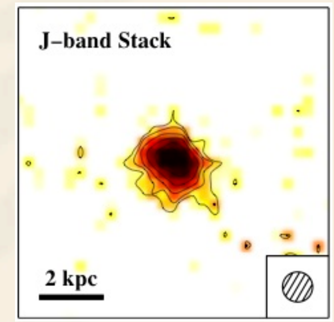


(Jiang et al. 2013a, ApJ)

Morphology

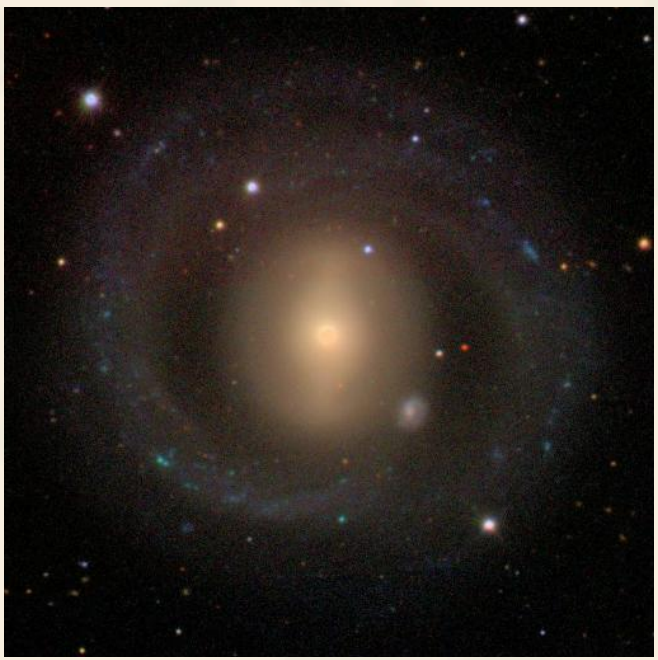
➢ Galaxies at $z \geq 6$ are faint and small

- At higher redshift: size evolution, $(1+z)^4$ surface brightness dimming
- At higher redshift: less well developed, more peculiar
- Galaxies at $z \geq 6$: occupy several pixels even in HST images



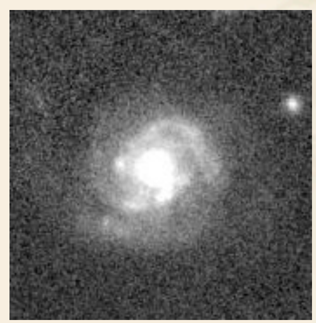
$z \geq 7$ (Oesch 2010)

z<0.1



4’

z=1



4”

z=3

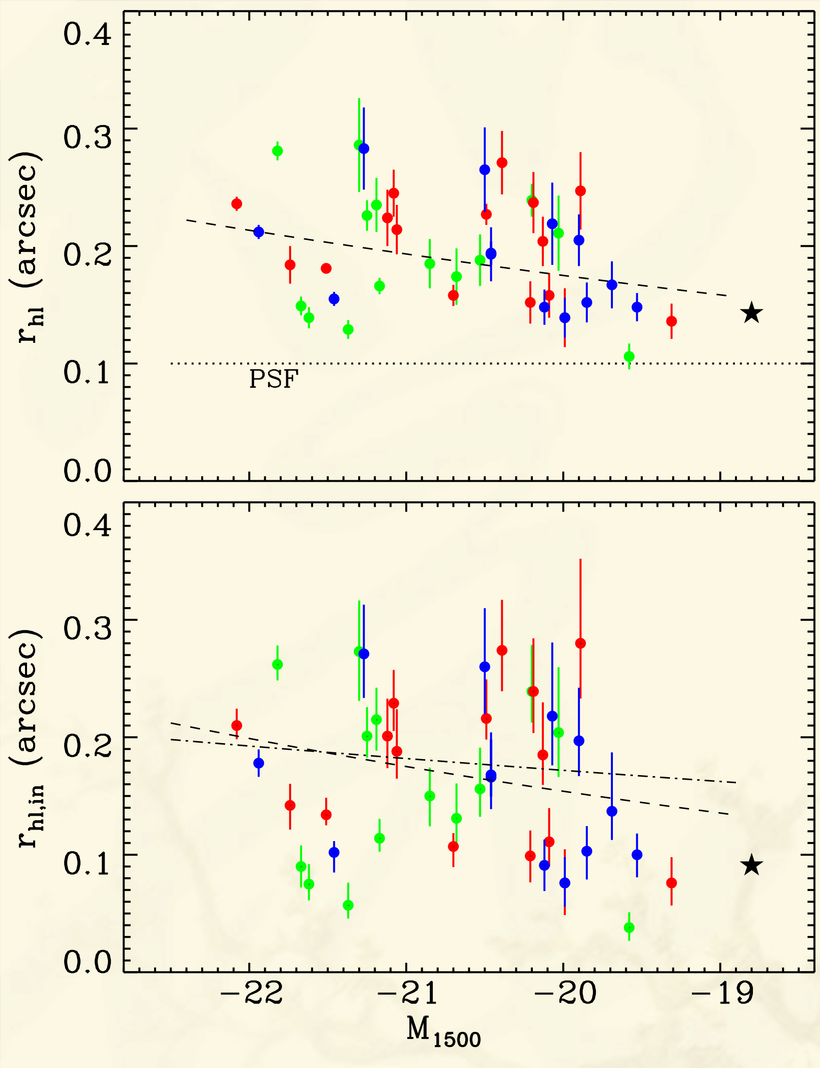
2”

z=6

1”

Galaxy size

- Half-light radius r_{hl}
  - For galaxies at $M_{1500} < -19.5$ mag
  - Measured $r_{hl} \approx$ 0.1”–0.3”
  - Intrinsic $r_{hl,in} \approx$ 0.05”–0.3” (0.3–1.7 kpc)
  - Small and compact
- Size-luminosity relation
  - Brighter galaxies tend to be larger
  - $r_{hl,in} \sim L^{0.14}$; very weak at the bright end
- Comparison with previous work
  - Similar to photometrically-selected LBGs
  - In particular, LAEs are not smaller

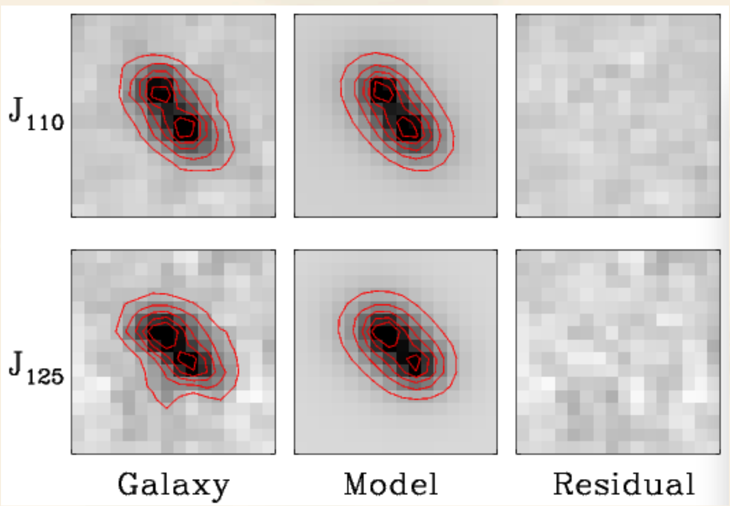


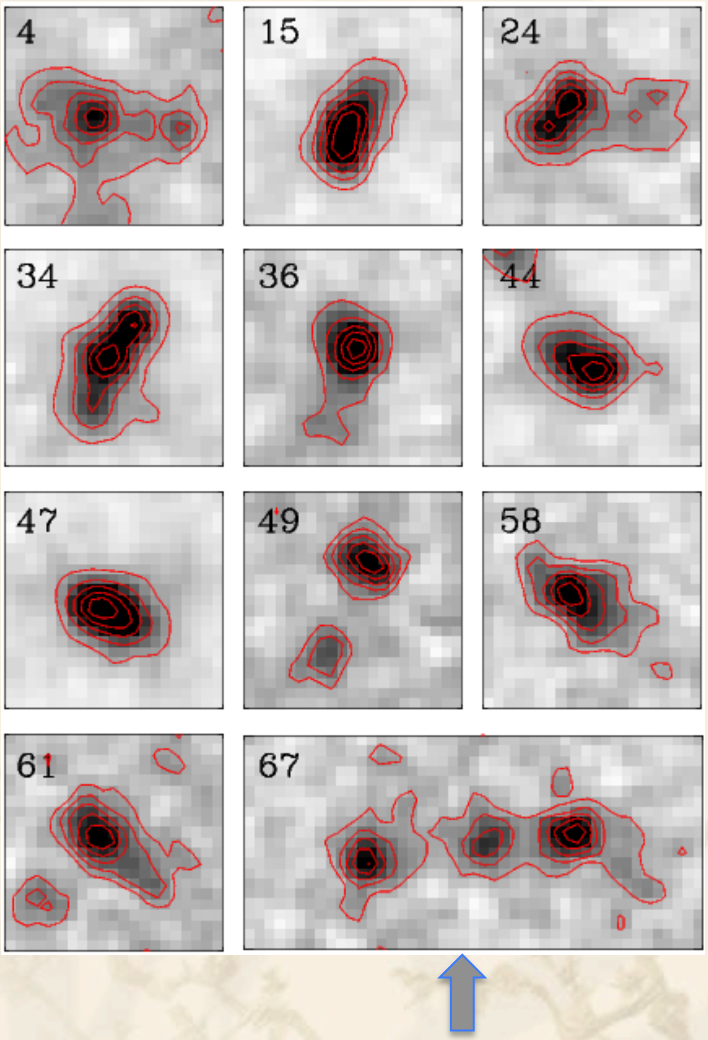
(Jiang et al. 2013b, ApJ)

Interacting/merging systems

- Merging galaxies
  - Visual identification at $M_{1500} < -20.5$ mag
  - ≥ 2 distinct cores, extended, or long tails
- Fraction of mergers
  - 38% – 50% at $M_{1500} < -20.5$ mag
  - 39% – 56% at $M_{1500} < -21$ mag

z=6.96 LAE
(Iye 2006)



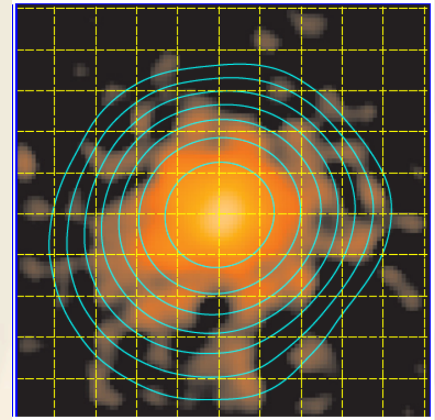


Giant LAE at z=6.6
(Ouchi 2008)

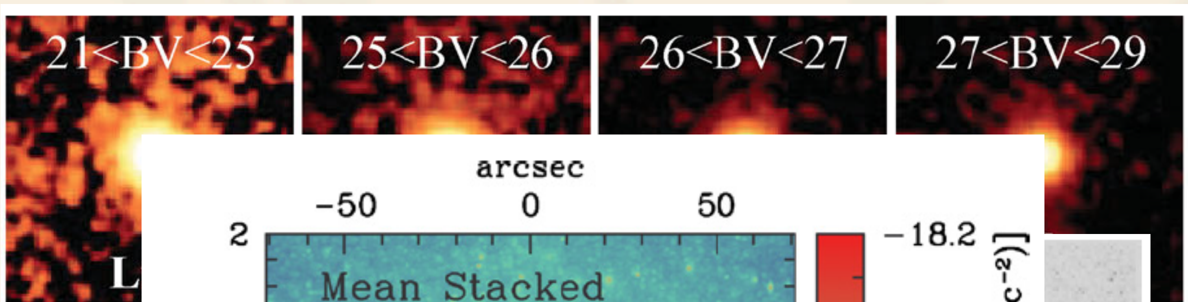
Lyα morphology in LAEs

➢ Diffuse Lyα halos

- Based on ground-based NB (Lyα) images
- At low redshift: controversial
- At high redshift: predicted by simulations

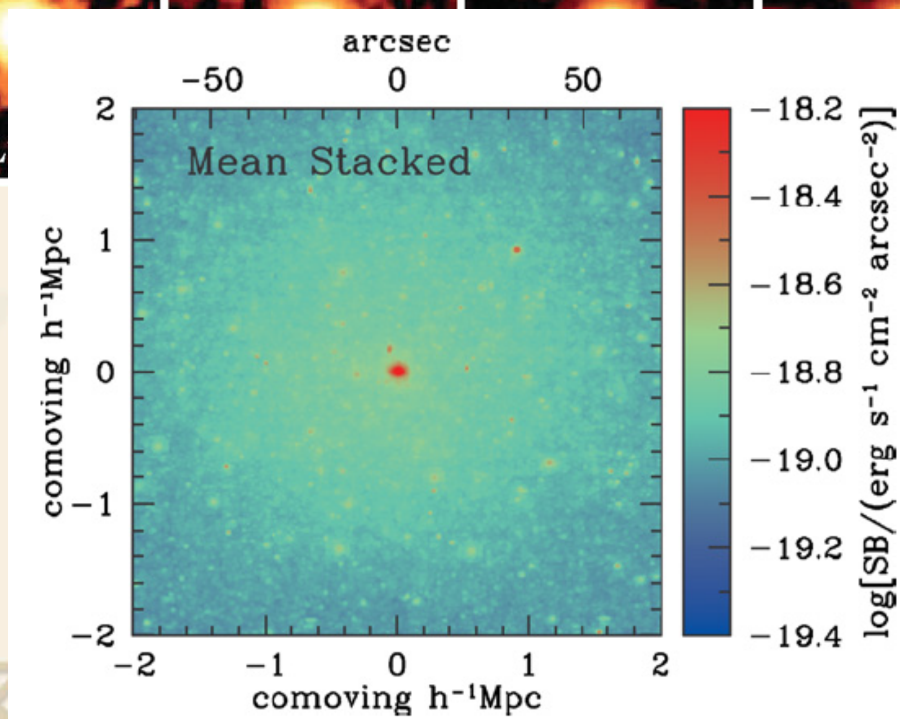


2 < z < 3
(Steidel 2011)



z = 3.1 LAEs
(Matsuda 2012)

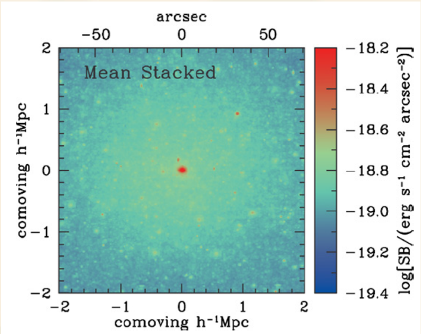
z = 3.1 LAEs
(Feldmeier 2013)

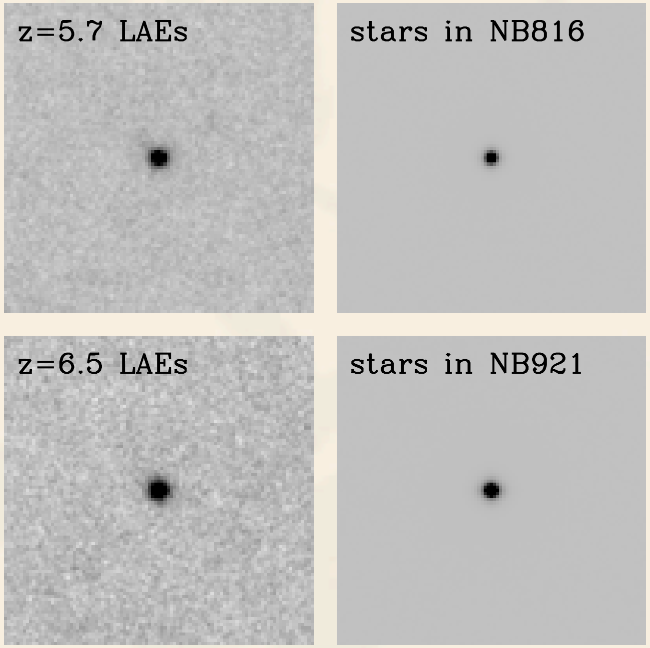


z = 5.7 LAEs
(Zheng 2011)

➢ No Lyα halos found at z=5.7 and 6.5

- Stack 43 LAEs at z=5.7 and 40 LAEs at z=6.5
- Stacked images: resolved but not very extended
- Possible reasons: dust, halo distribution, or no halos, etc.





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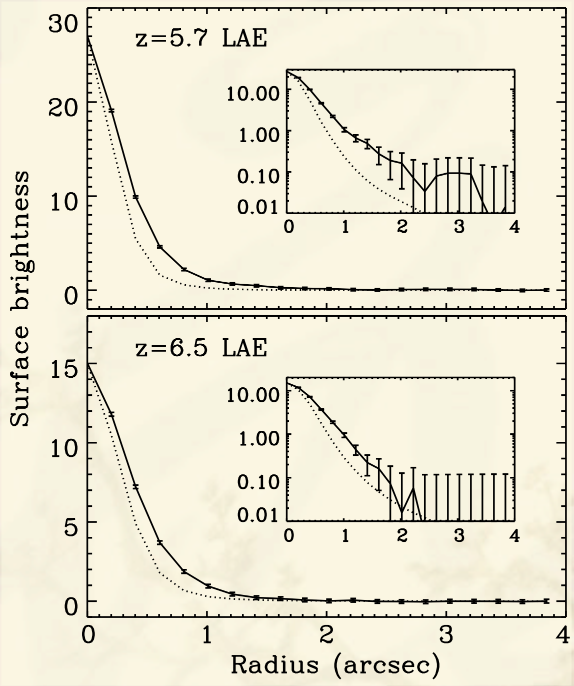
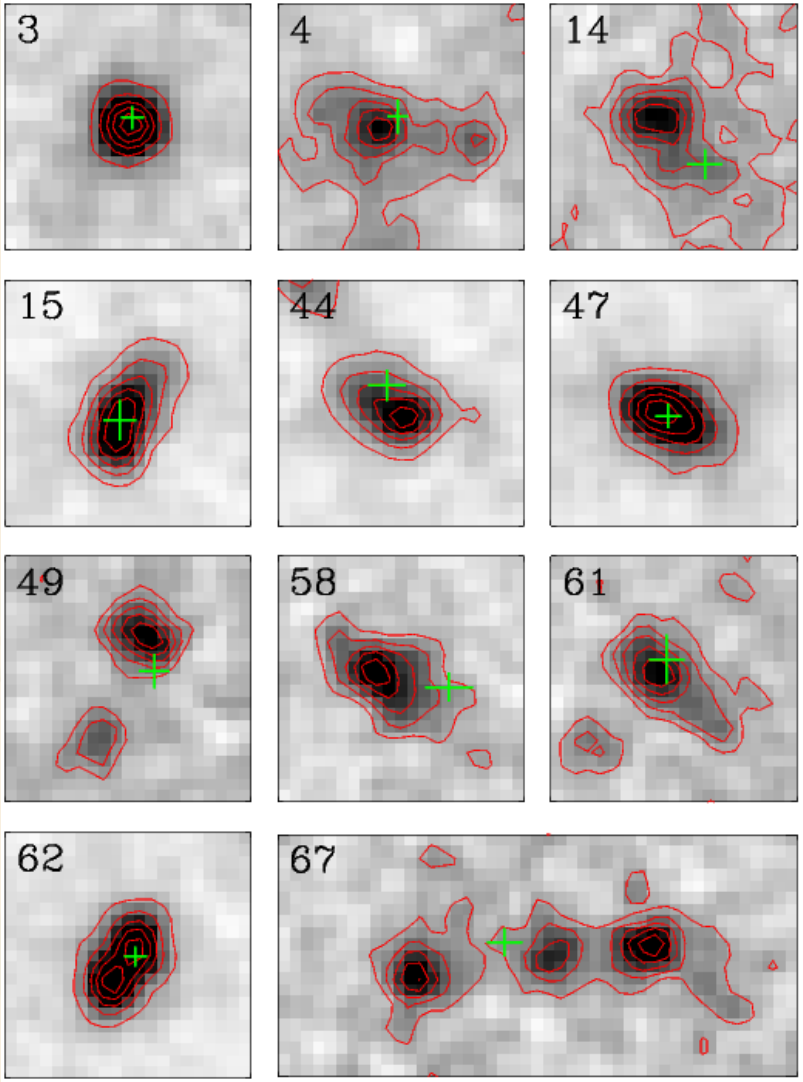


(Jiang et al. 2013b, ApJ)

Lyα–continuum misalignment in LAEs

- Lyα and continuum emission
  - Originated from the same SF regions
  - Lyα affected by resonant scattering
- Data
  - UV continuum: HST near-IR images
  - Lyα: Subaru narrow-band images
- Results
  - Compact LAEs: no offsets
  - Interacting systems: a variety of positional differences
  - Disturbed ISM distribution
  - Consequence for spectroscopy

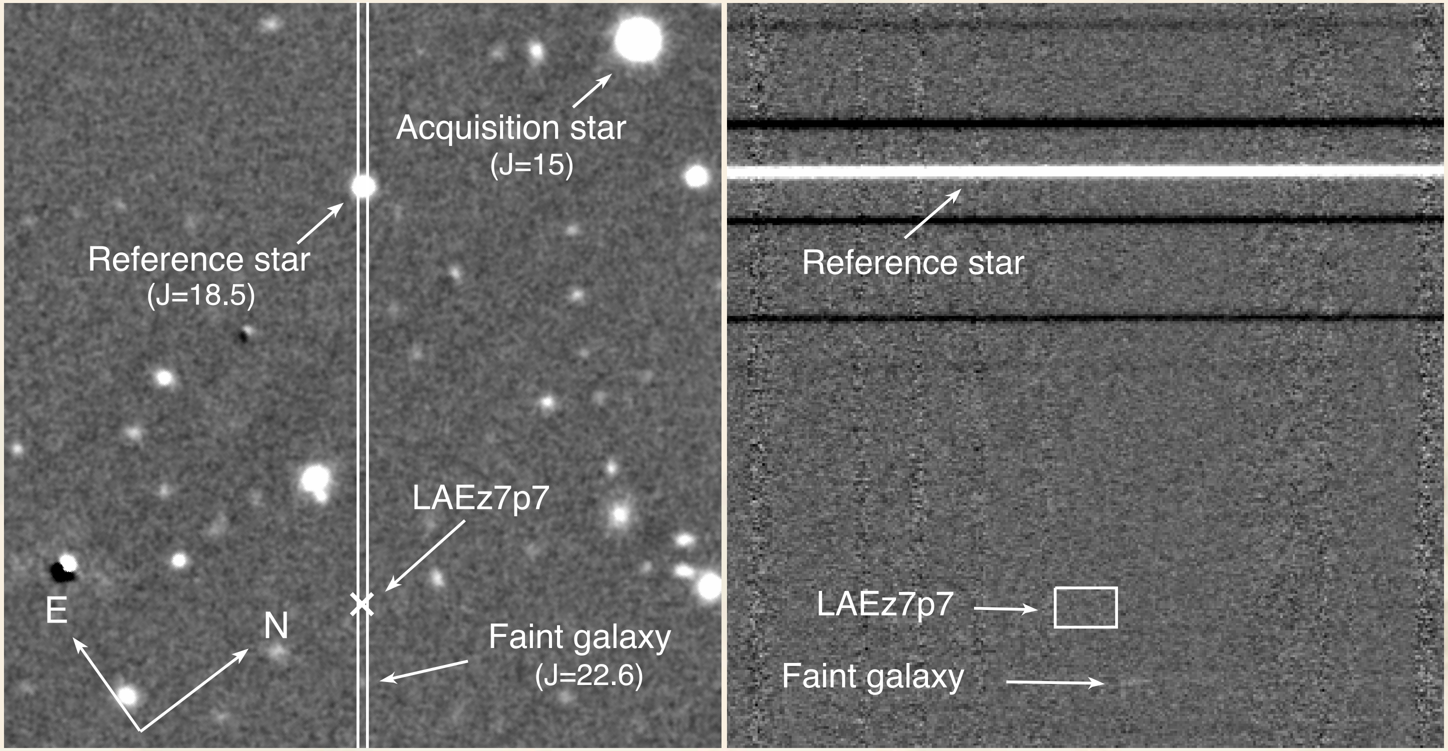


(Jiang et al. 2013b, ApJ)

Deep spectroscopy of a z=7.7 LAE candidate

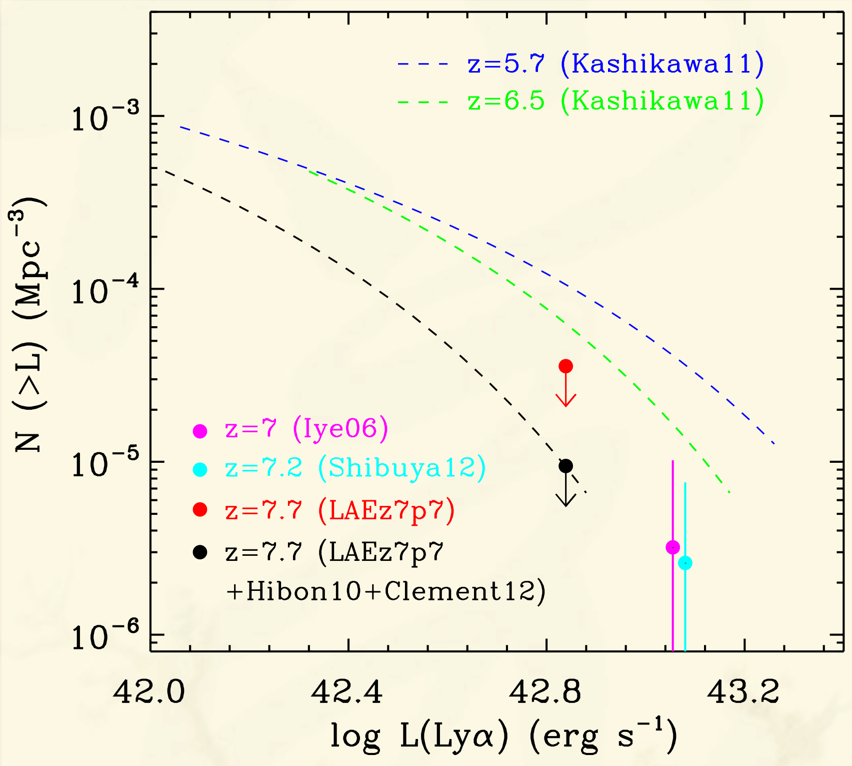
➢ Observations

- Target: brightest z=7.7 LAE candidate from Krug et al. (2012)
- Instrument: LUCI on the 2×8.4m LBT; t_{int} = 7.5 hrs, with good conditions
- Results: non-detection → not a LAE at z=7.7



➢ Observed Lyα LF at z ≥ 5.7

- Rapid evolution from z = 5.7 to 6.5 based on a large sample of LAEs
- A z=7 LAE and a z=7.2 LAE suggest such a trend towards higher redshift
- The upper limit at z=7.7 is >5 times lower than the z=6.5 LF
- Explanations:
  - Not likely by intrinsic evolution
  - Likely by neutral IGM
  - Lyα reduced by a factor of two



(Jiang, Bian, et al. 2013c, ApJ)

Note: details in Bian's talk after lunch

Summary

- A systematic study of spectroscopically-confirmed galaxies at $z \geq 6$
- Steep UV continuum slopes
- Galaxy size: mostly small and compact
- Large fraction of merging galaxies in the bright end
- No diffuse Lyα halos were found around LAEs
- Significant positional differences between Lyα and UV continuum
- Rapid evolution of Lyα LF from $z=5.7$ to 6.5 caused by the IGM