遠方銀河観測の進展

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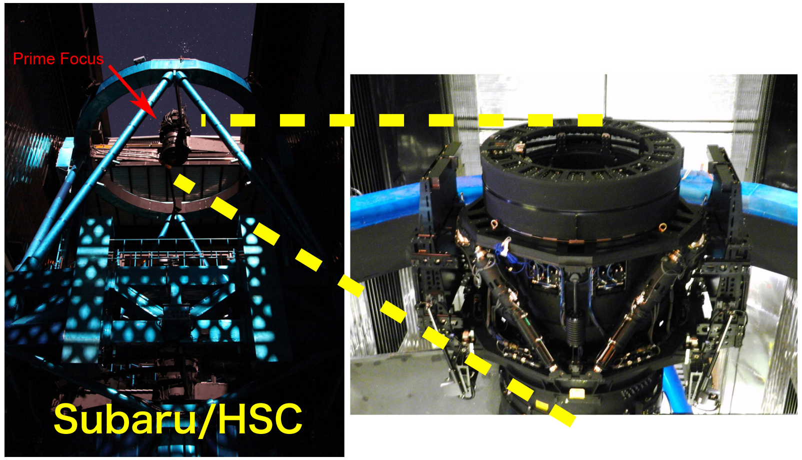
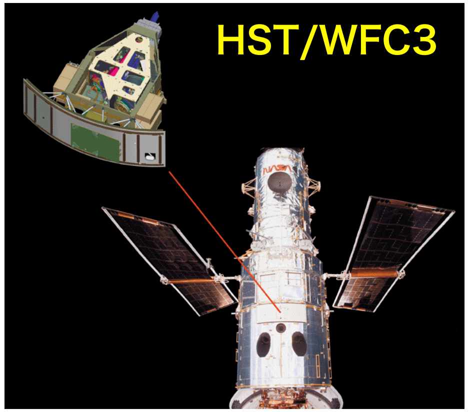
第30回理論懇シンポジウム「星の物理の新地平」， 2017 December

Recent Updates

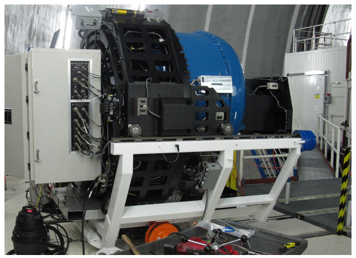


- Large-area optical imaging survey:
  e.g., Subaru HSC SSP
  (>1000 deg^2 down to i=26mag)
  → identify bright rare galaxies, investigate the large-scale structure

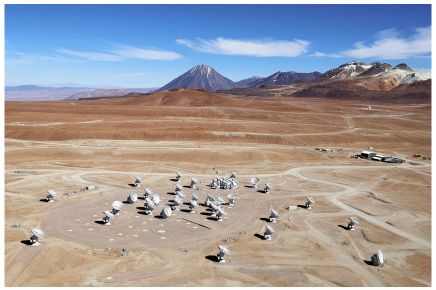


- Deep optical and near-infrared imaging survey:
  e.g., HUDF, CANDELS, HFF
  (~0.3 deg^2 down to H-band = 27-29.5 mag)
  → identify faint galaxies

Keck/MOSFIRE



ALMA

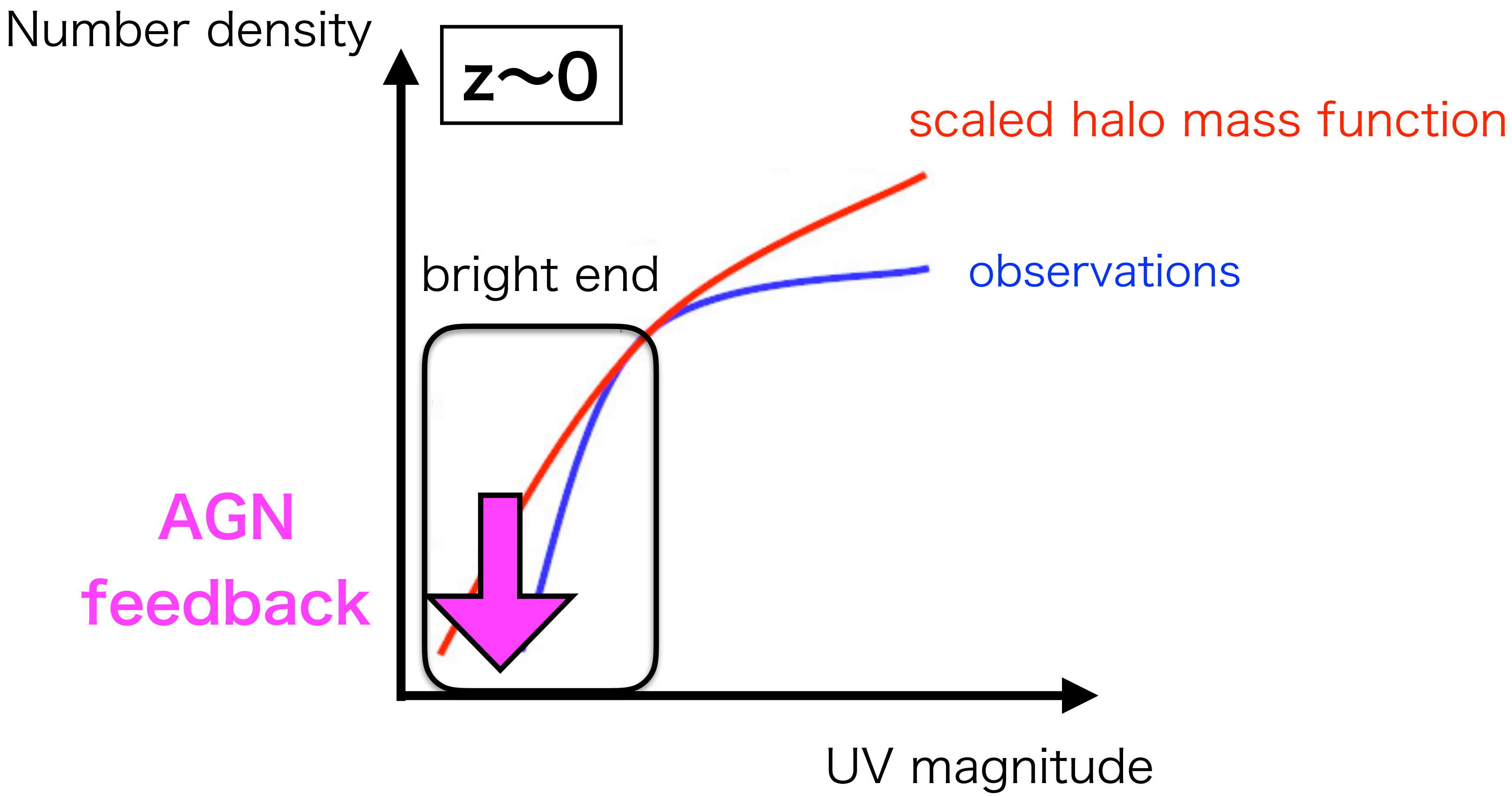


- Deep spectroscopy with new instruments:
  e.g., Keck MOSFIRE, VLT X-shooter, ALMA
  → detect faint emission lines

Contents

- **Galaxy Evolution**
- Cosmic Reionization
- First Galaxies

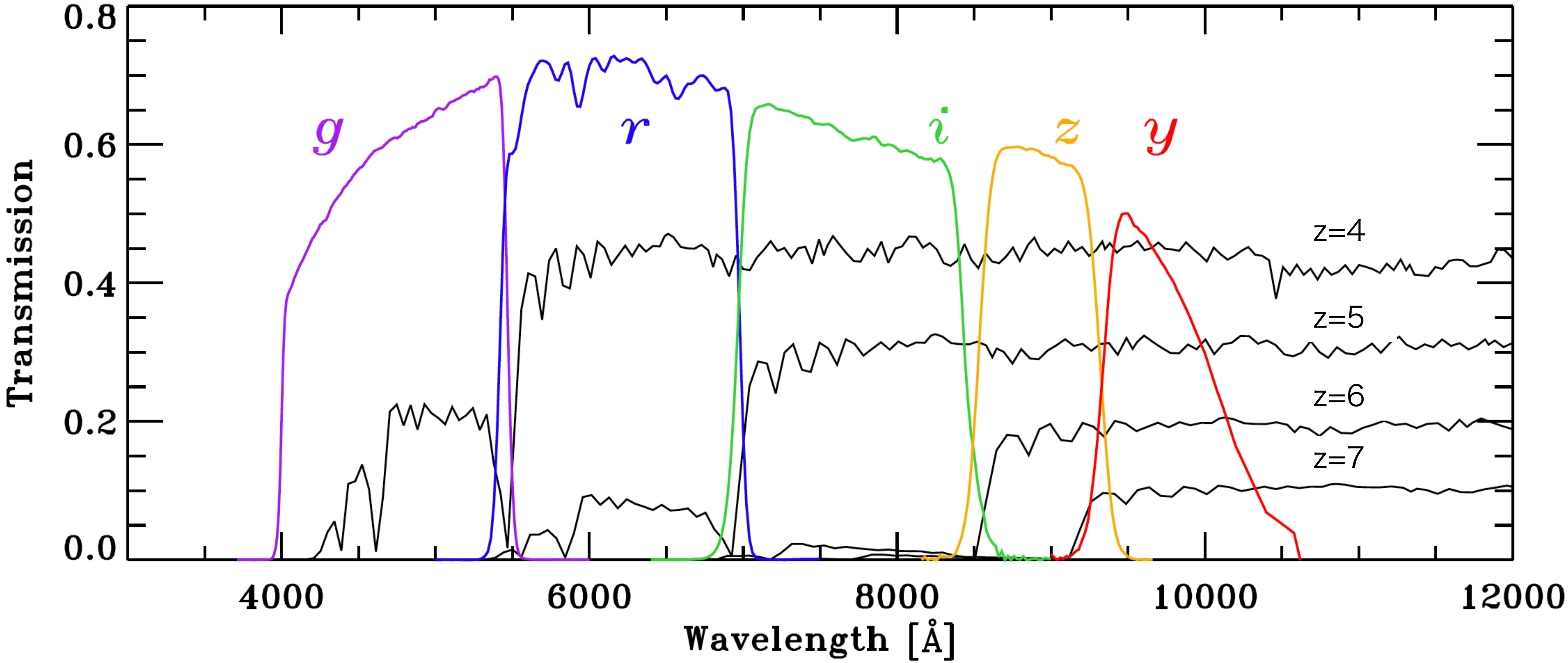
Luminosity Function at Low-z



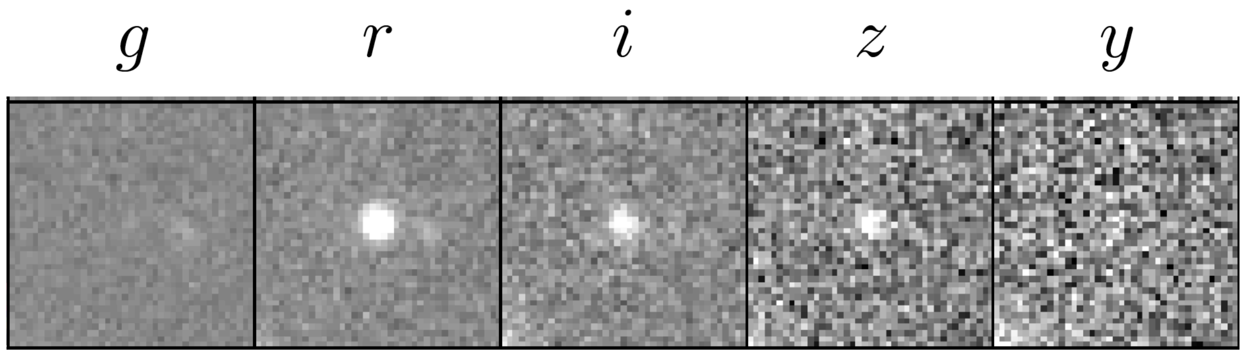
(http://ned.ipac.caltech.edu/level5/March12/Silk/Silk2.html)

・Bright end of the UV luminosity function at **low-z**
 - **exponential cutoff** due to **AGN feedback** (e.g., Croton+06, Loveday+12)

Lyman Break Galaxies (LBGs)



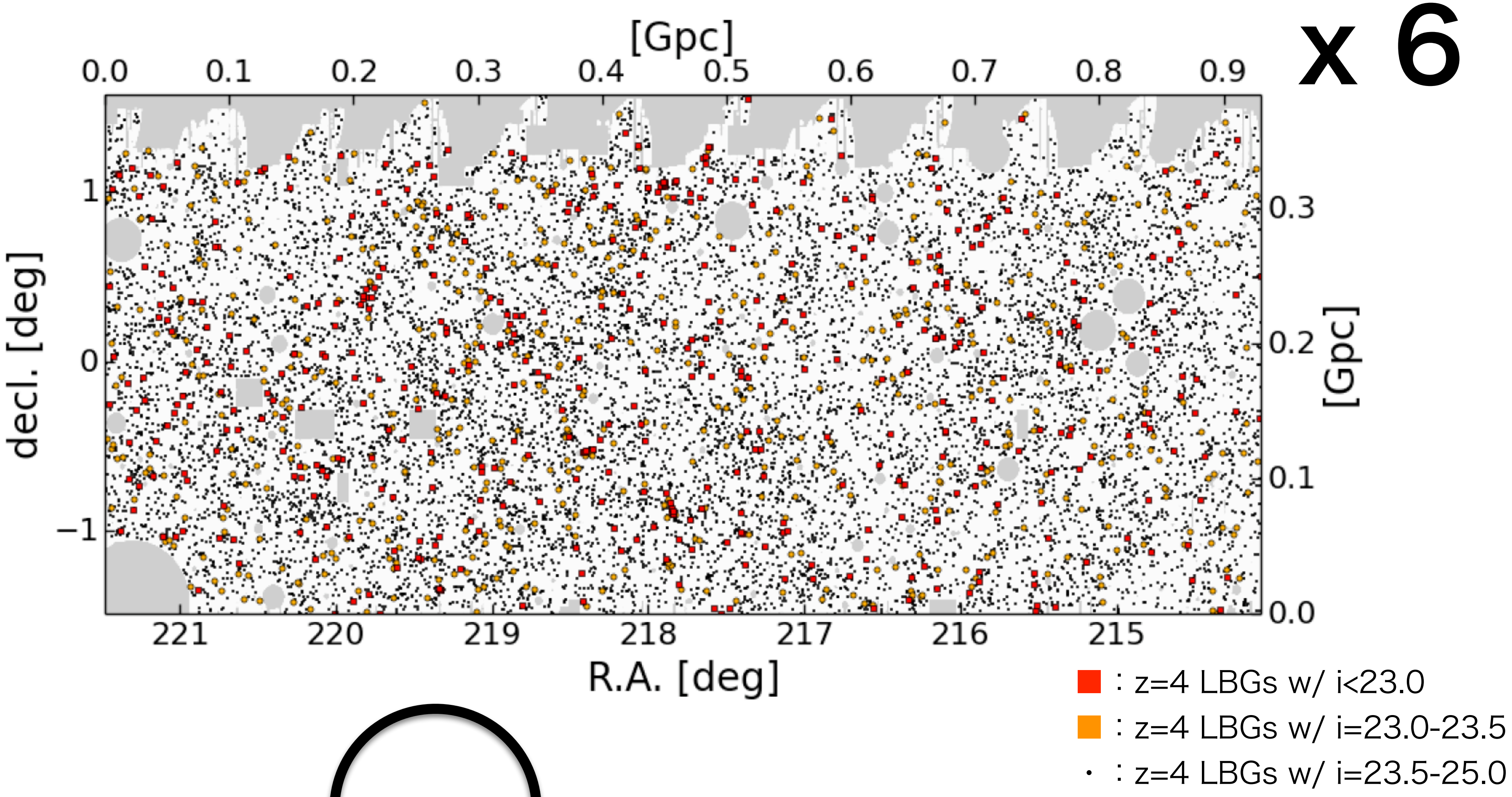
z=4

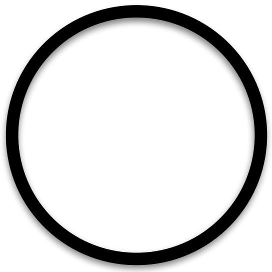


Ono et al. (2017), PASJ in press, arXiv:1704.06004

HSC LBG Sample

x 6

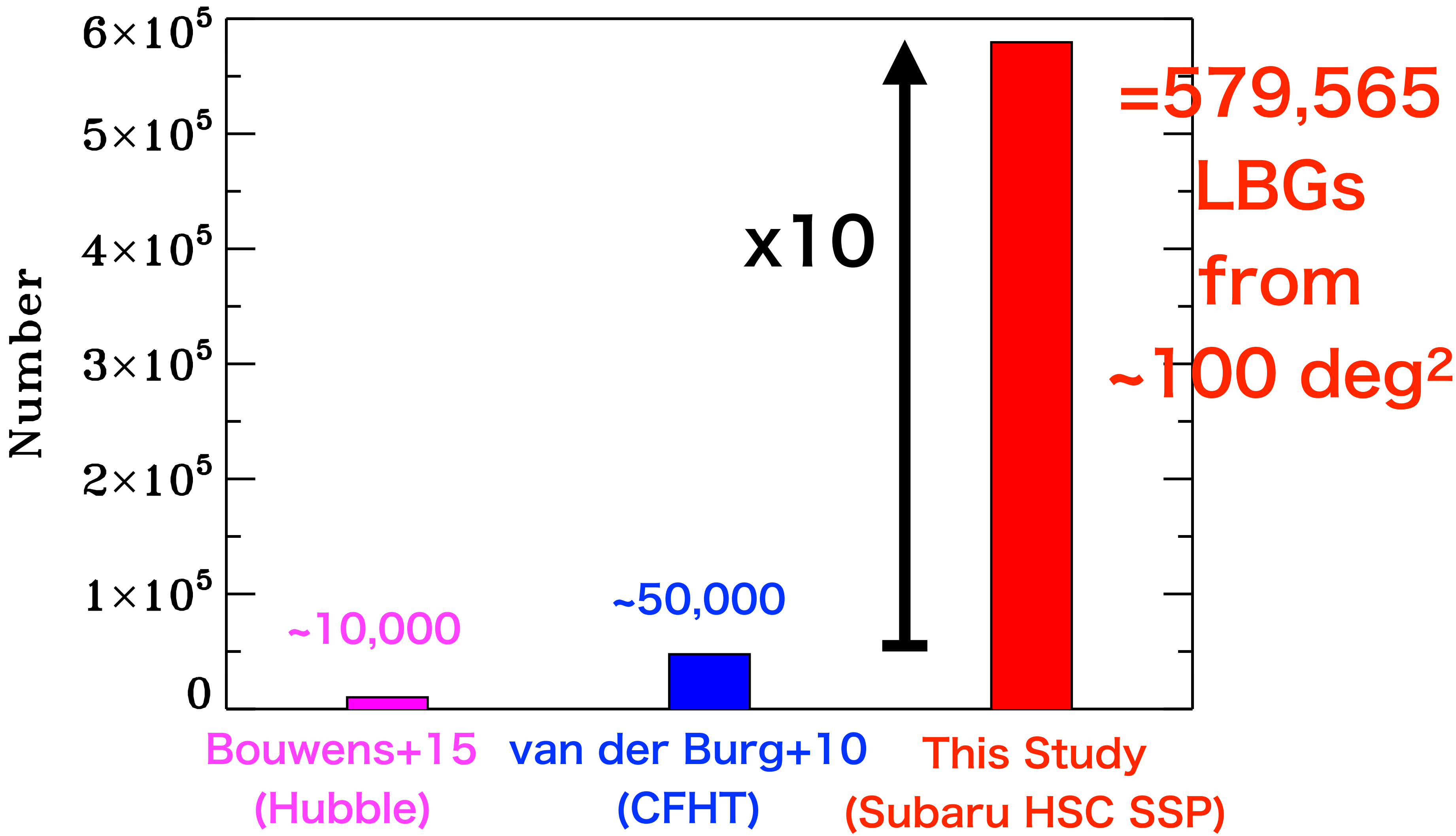




c.f., COSMOS

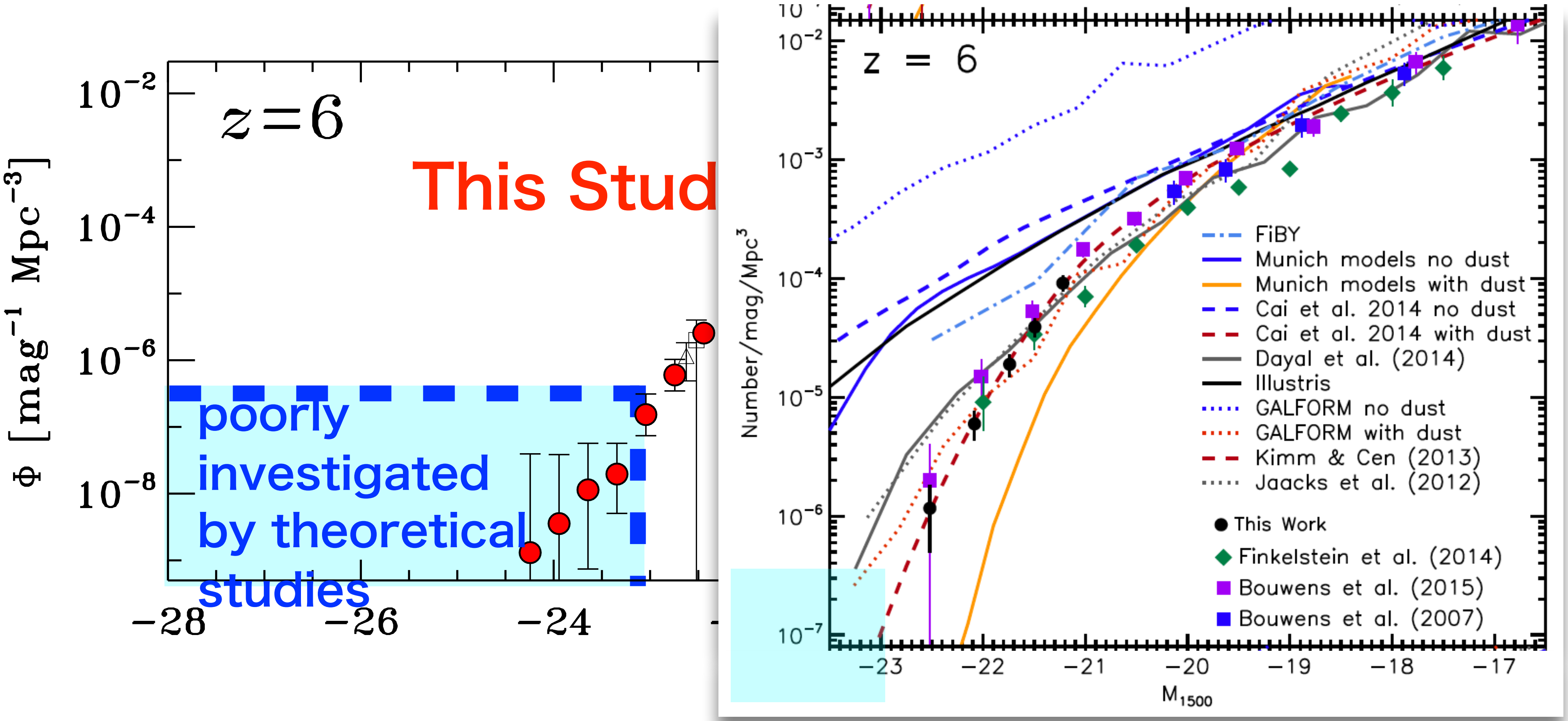
Harikane et al. (2017), PASJ in press, arXiv:1704.06535

HSC LBG Sample



Ono et al. (2017), PASJ in press, arXiv:1704.06004

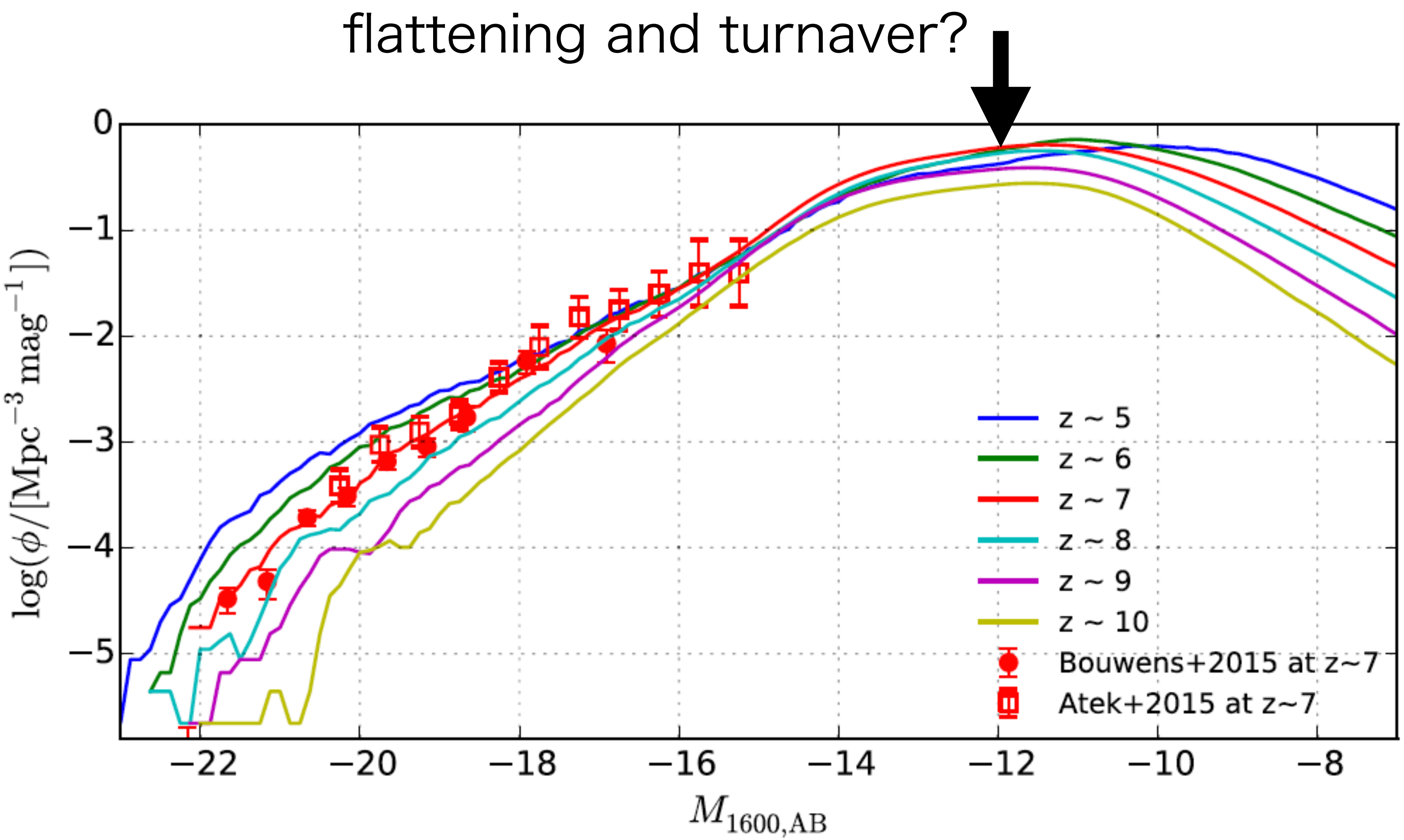
Bright End of the UV LF



- Red circles: our results of the galaxy UV LFs
- The bright end shape cannot be explained by the Schechter function.
- DPL and lensed Schechter provide better fits.

Ono et al. (2017), PASJ in press, arXiv:1704.06004, Bowler et al. (2015), MNRAS, 452, 1817

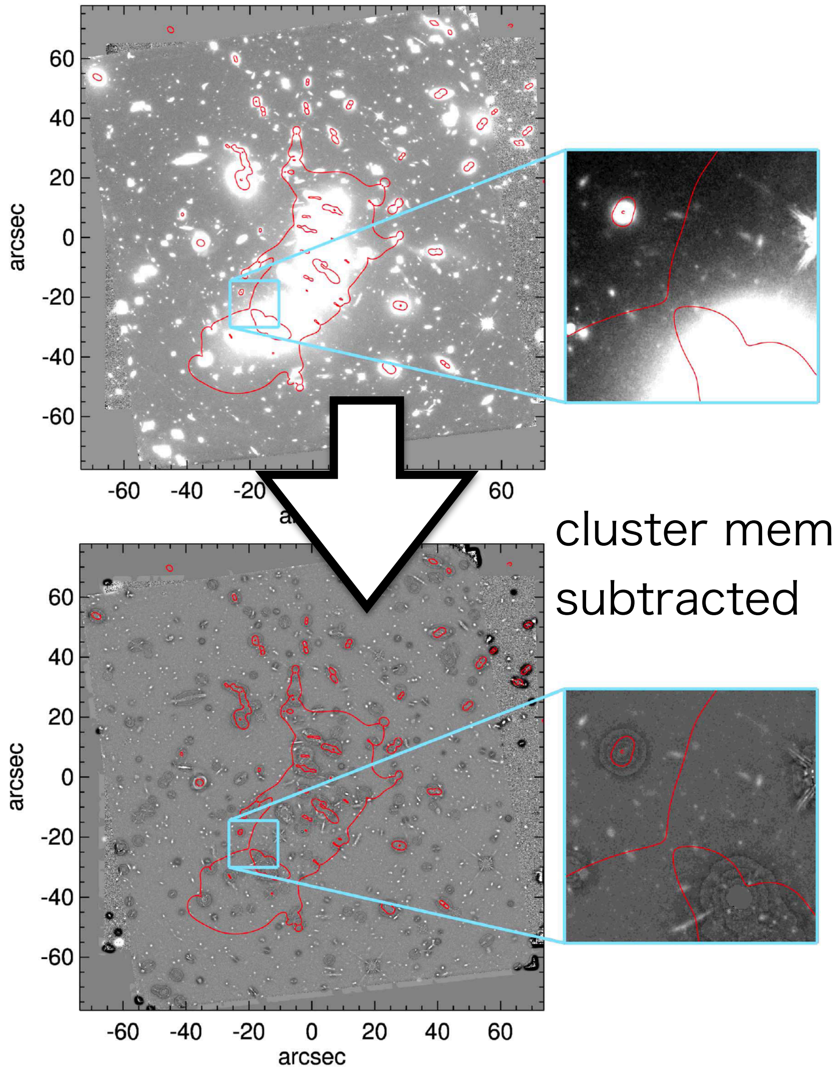
Faint End of the UV LF



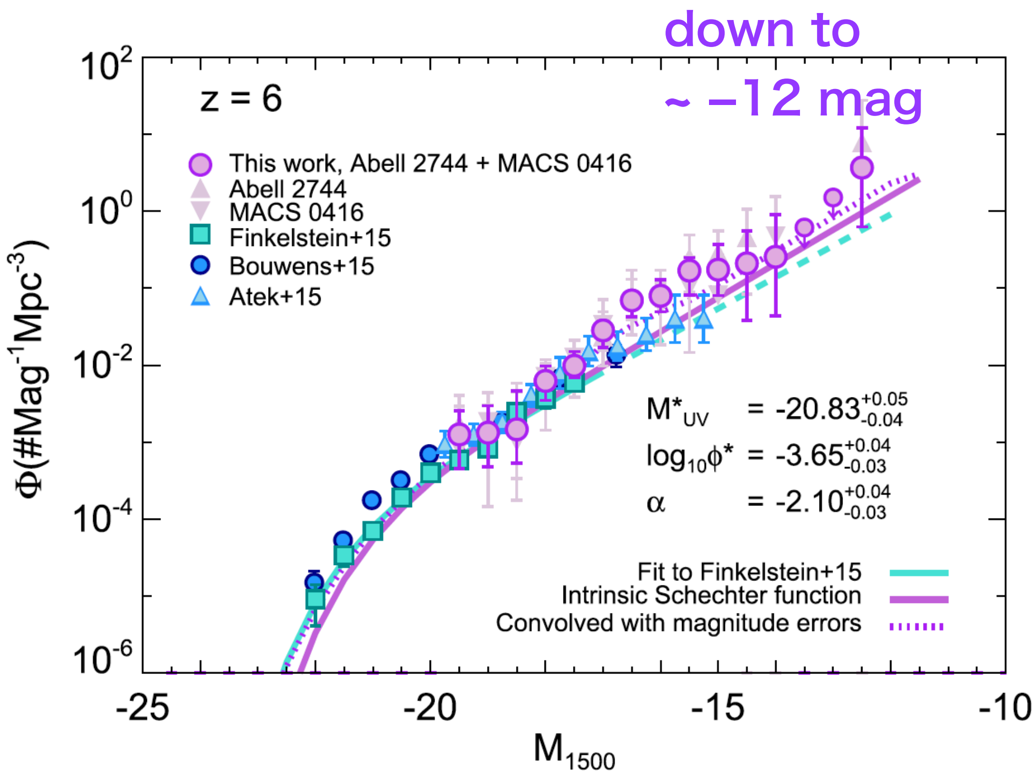
・Theoretical studies of galaxy formation predict a flattening at M_{UV} ~ −14 mag.

Liu et al. (2016), MNRAS, 462, 235

Faint End of the UV LF



cluster members subtracted

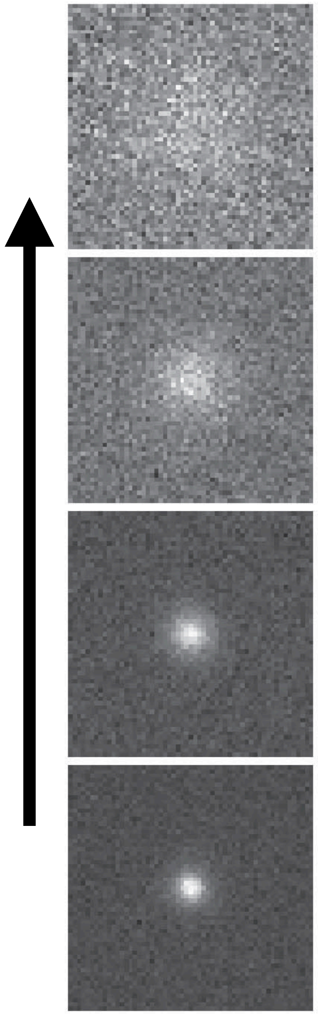


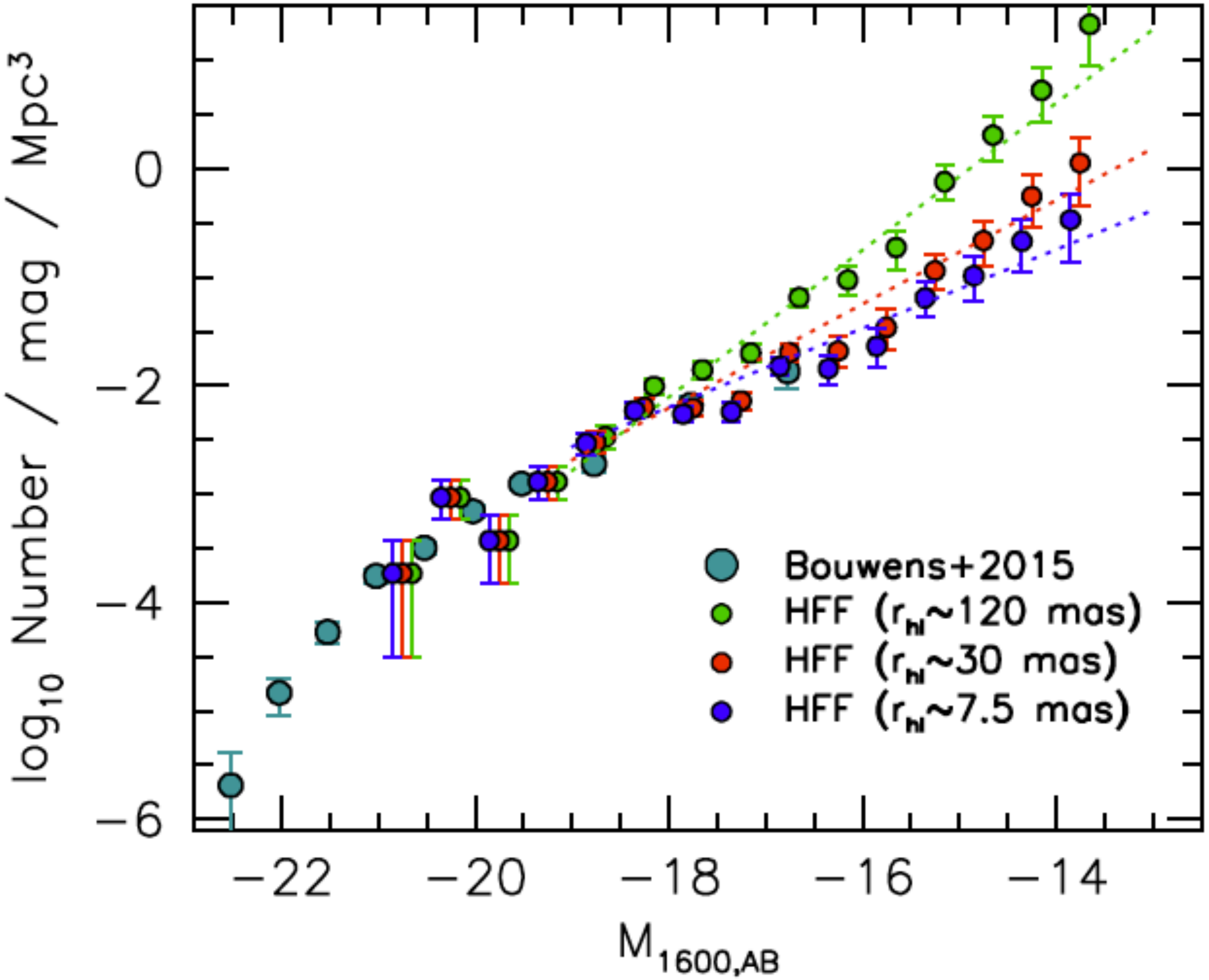
- Theoretical studies of galaxy formation predict a flattening at M_{UV} ~ −14 mag.
- Some obsevational studies use Hubble Frontier Fields (HFFs) data and present LF measurements down to very faint magnitudes of ~ −12 mag.

Livermore et al. (2017), ApJ, 835, 113

Uncertainty: High-z Galaxy Size

hard to detect
large galaxies
at a fixed mag



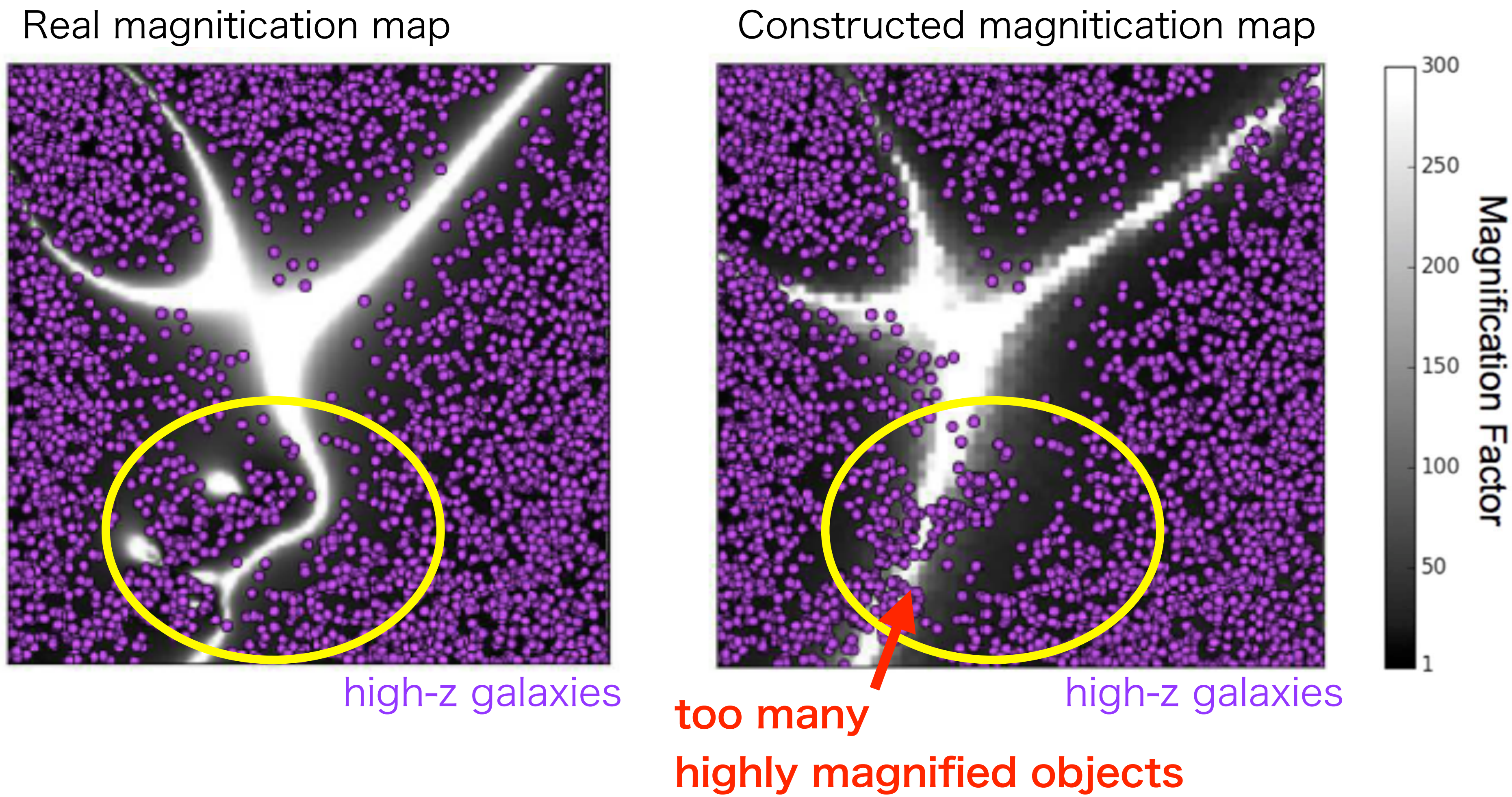


- In the calculation of effective survey volumes, the galaxy size distribution is needed.
- However, the size distribution is not investigated well, particularly for faint galaxies.

  → faint-end shape has a large systematic uncertainty.

Bouwens et al. (2017), ApJ, 843, 41

Uncertainty: Cluster Mass Modeling

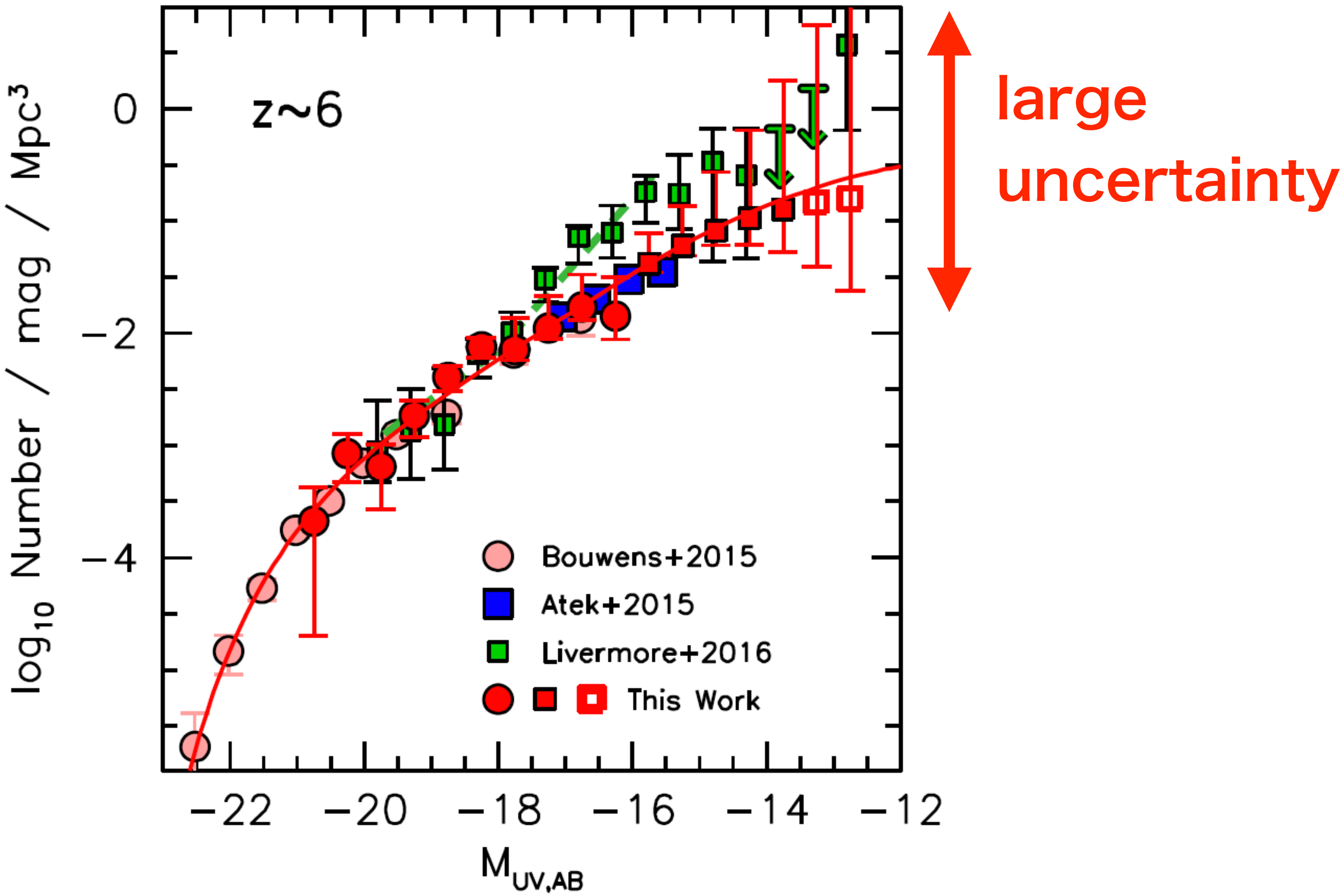


- Left: A small number of galaxies have large μ because of the small volume.
- Right: Many sources appear to have large μ compared to the left panel.

  → too many intrinsically faint sources.

Bouwens et al. (2017), ApJ, 843, 129

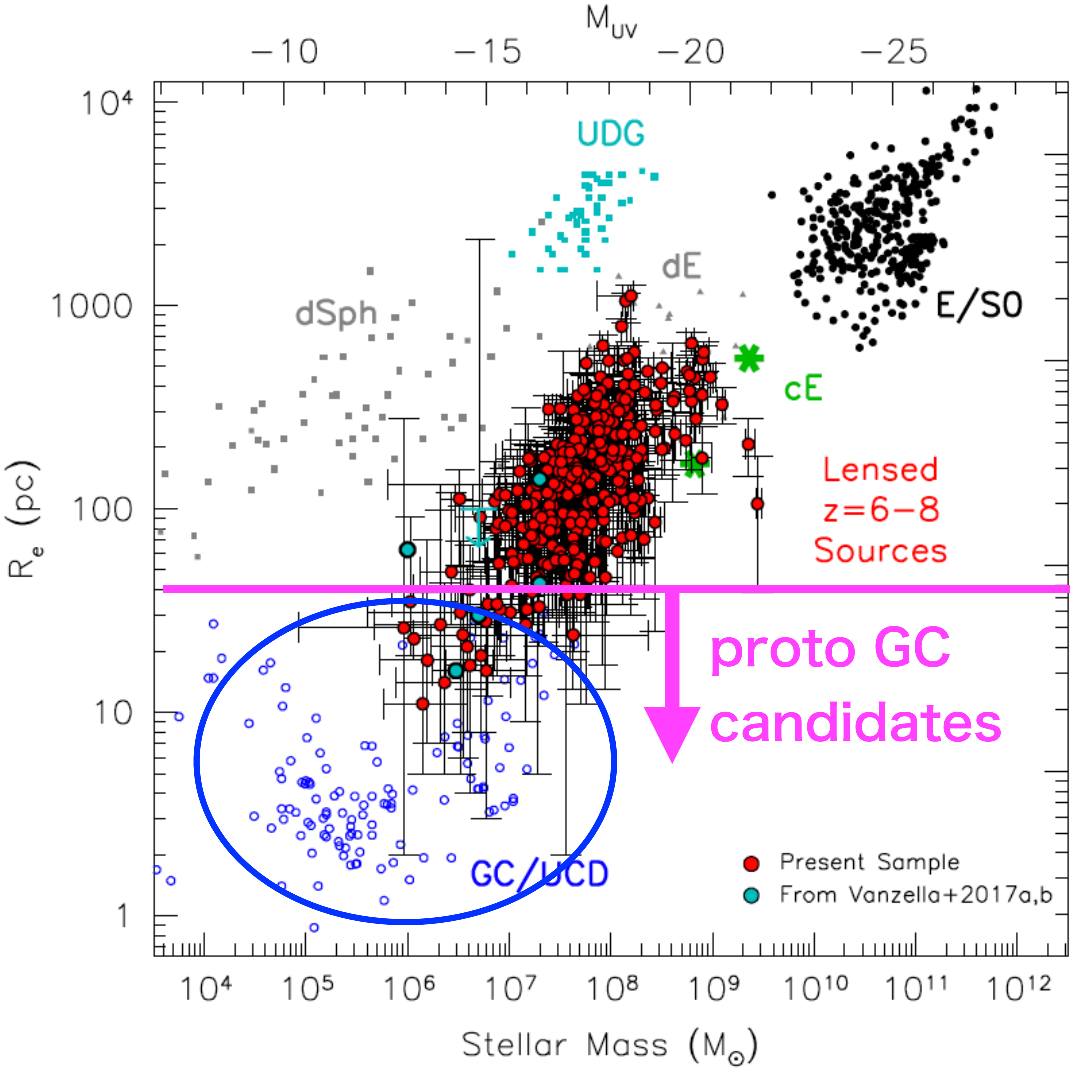
Faint End of the UV LF

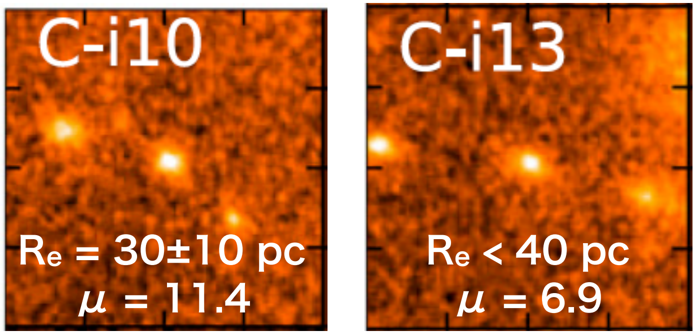


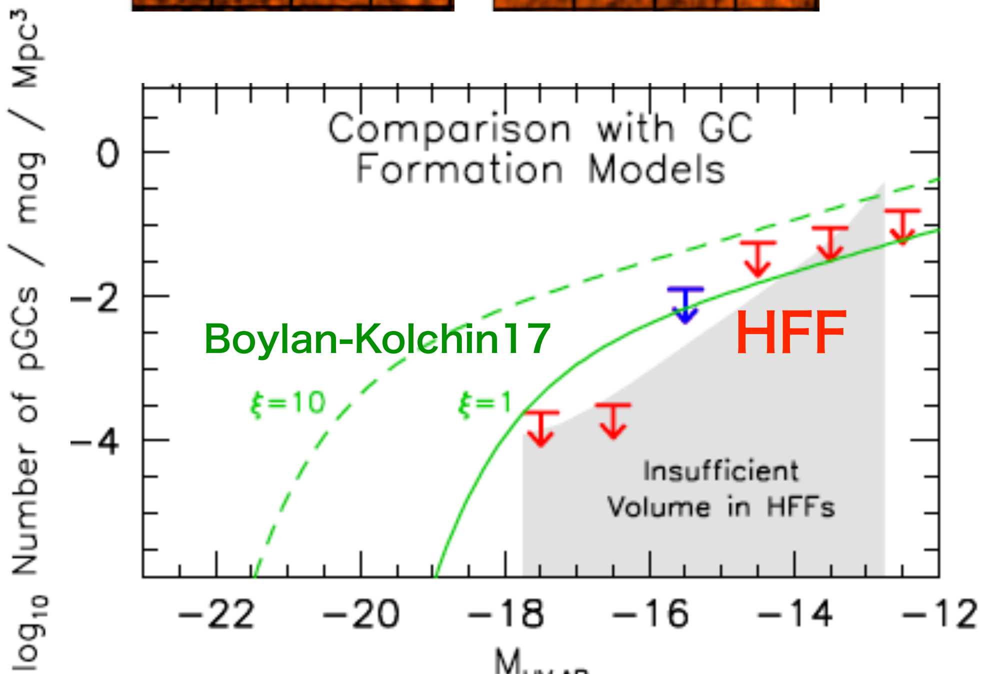
- Faint galaxies are treated as unresolved, very small sources.
- Uncertainties of cluster mass models are considered.
- Unclear whether LF gets increased or flattened at faint M_{UV}.

Bouwens et al. (2017), ApJ, 843, 129; See also, Kawamata et al. (2017), arXiv:1710.07301

Luminosity Function of Proto-GCs



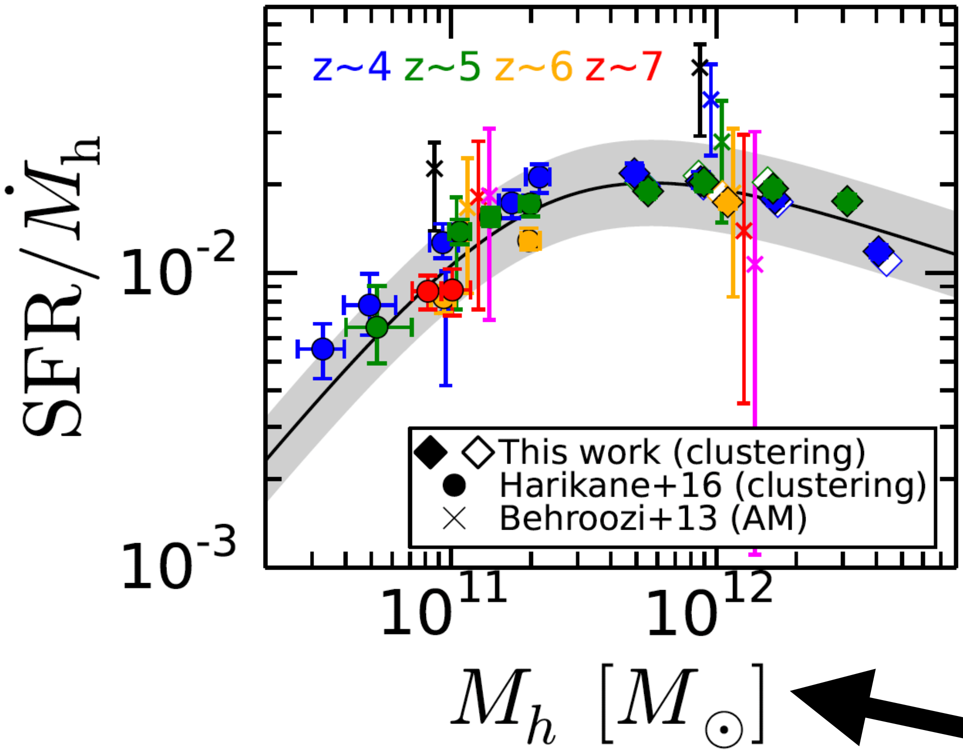


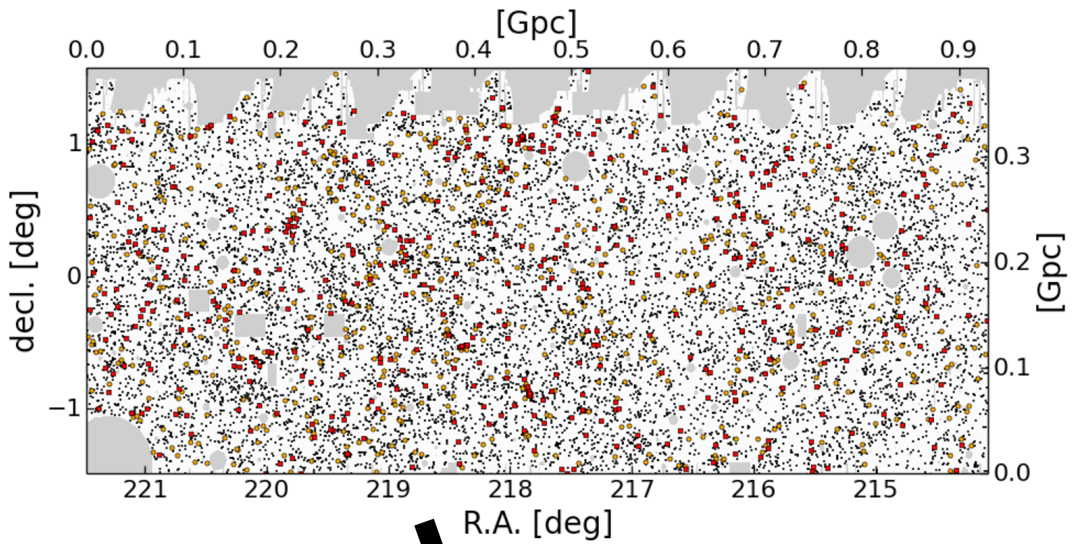


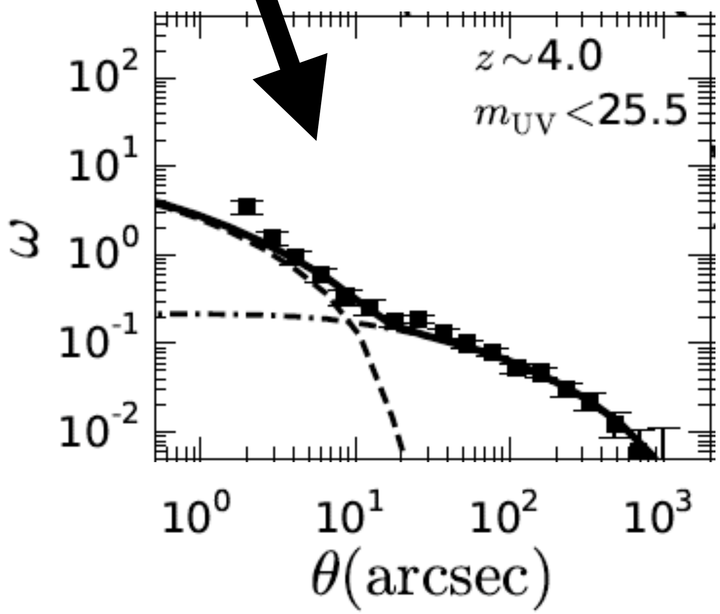
- Some lensed high-z galaxies are as small as local globular clusters (~10 pc).
- Assuming that sources w/ <40 pc are possible progenitors of globular clusters (GCs), the number densities of proto-GCs are derived and compared with model predictions.

Bouwens et al. (2017), arXiv:1711.02090; Kawamata et al. (2015), ApJ, 804, 103

Cosmic SFR Density



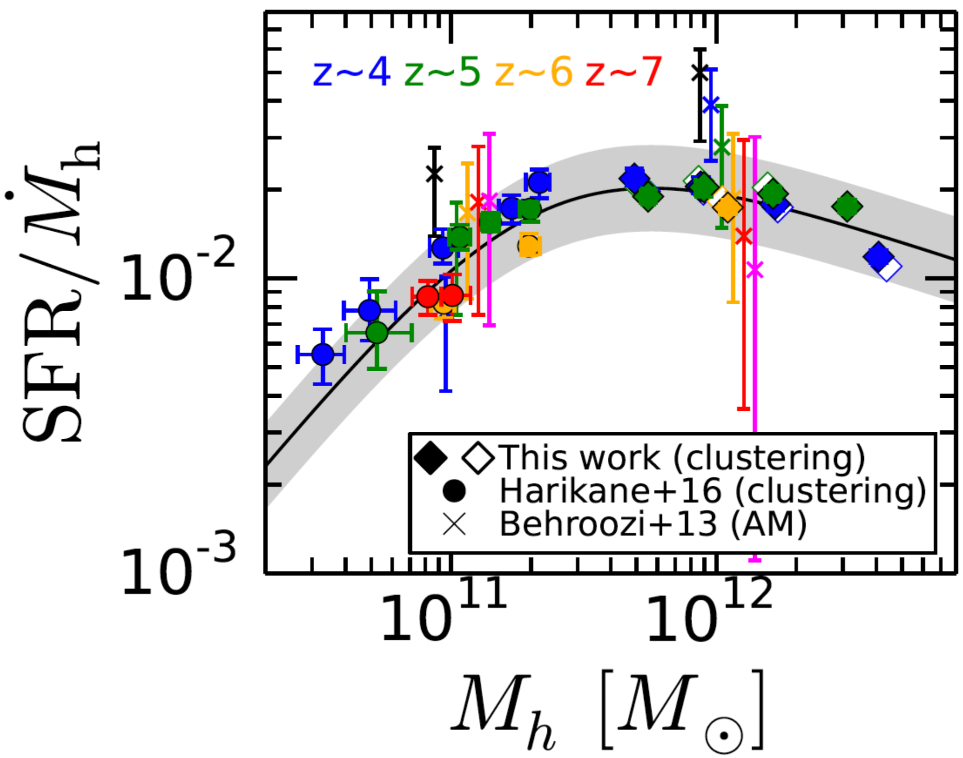




- Clustering analyses of z=4-7 galaxies found in the HSC SSP
- No evolution of SFR/(dM_h/dt) vs. M_h.

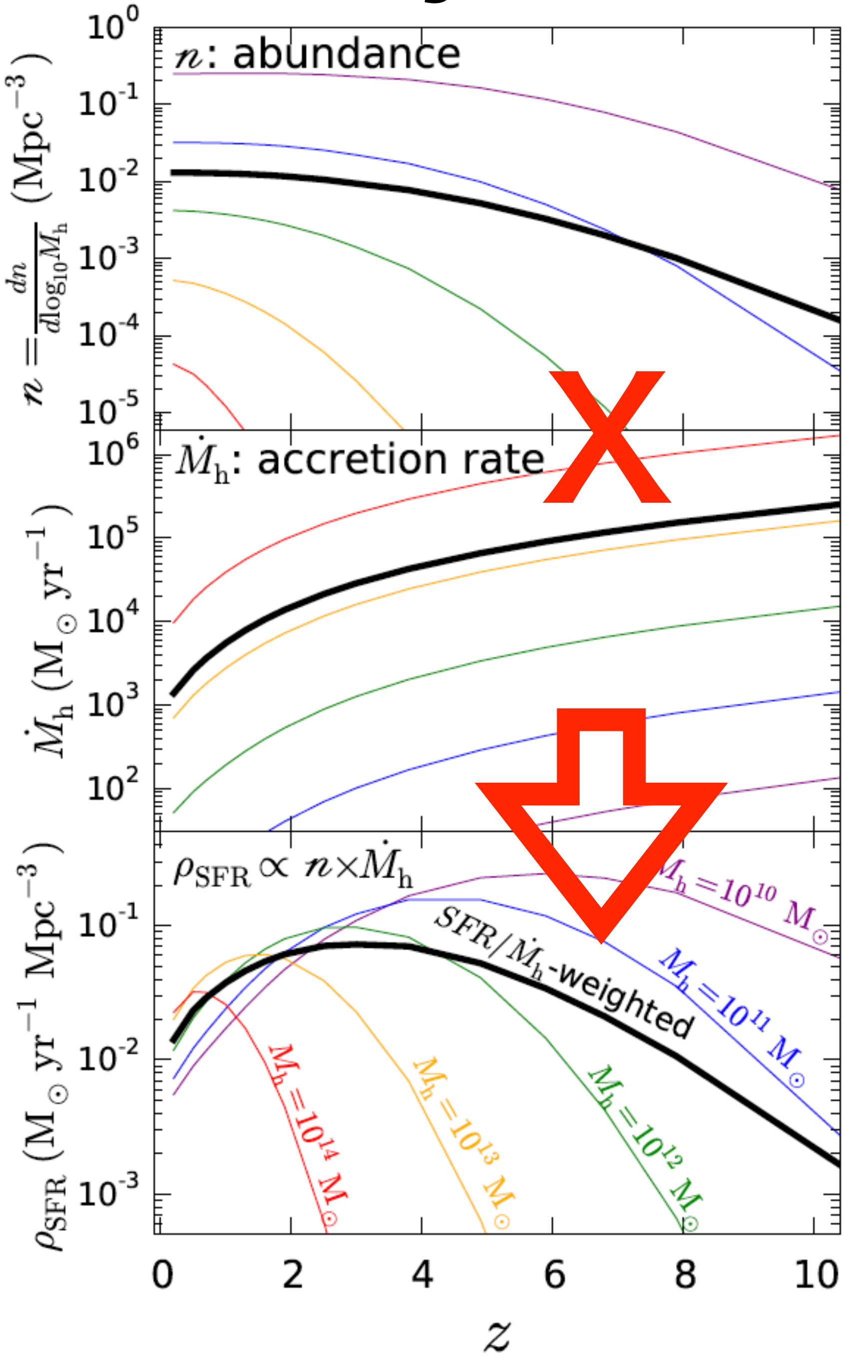
Harikane et al. (2017), PASJ in press, arXiv:1704.06535

Cosmic SFR Density



$$n \times \dot{M}_\mathrm{h} \times \frac{\mathbf{SFR}}{\dot{M}_\mathrm{h}} \to \rho_\mathrm{SFR}$$

- The shape of the expected SFR density from the constant SFR/(dM_h/dt) is similar to the observed one.
  increase: halo number density
  decrease: accretion rate



Harikane et al. (2017), PASJ in press, arXiv:1704.06535

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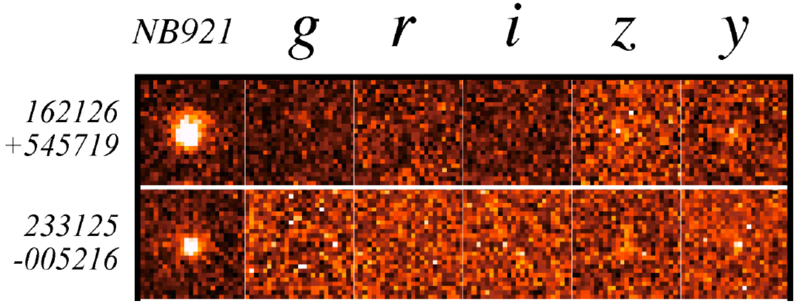
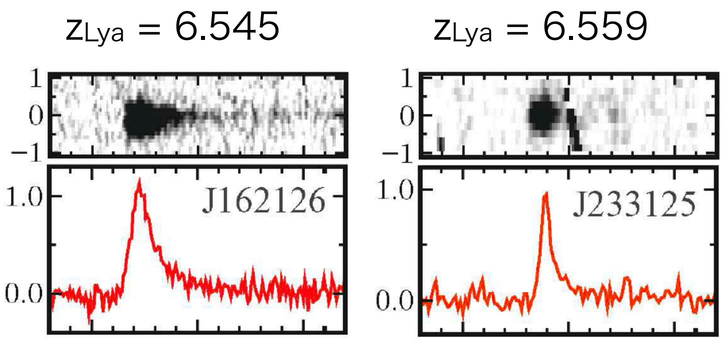
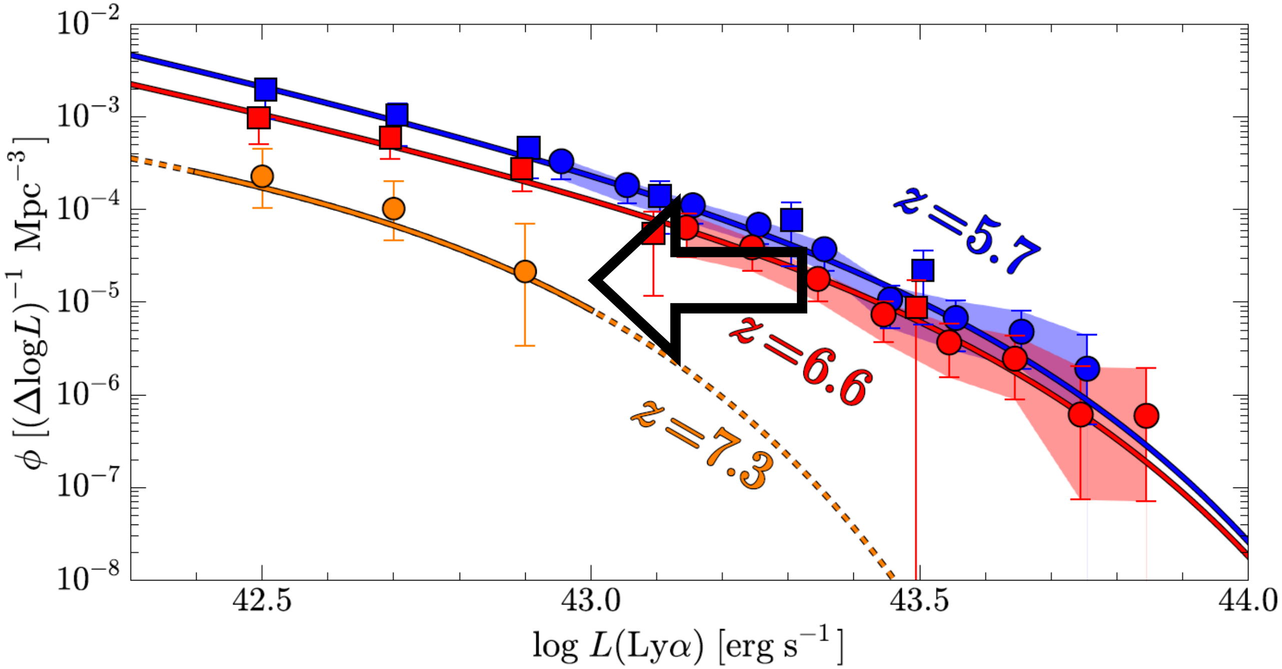
Lya LF Evolution



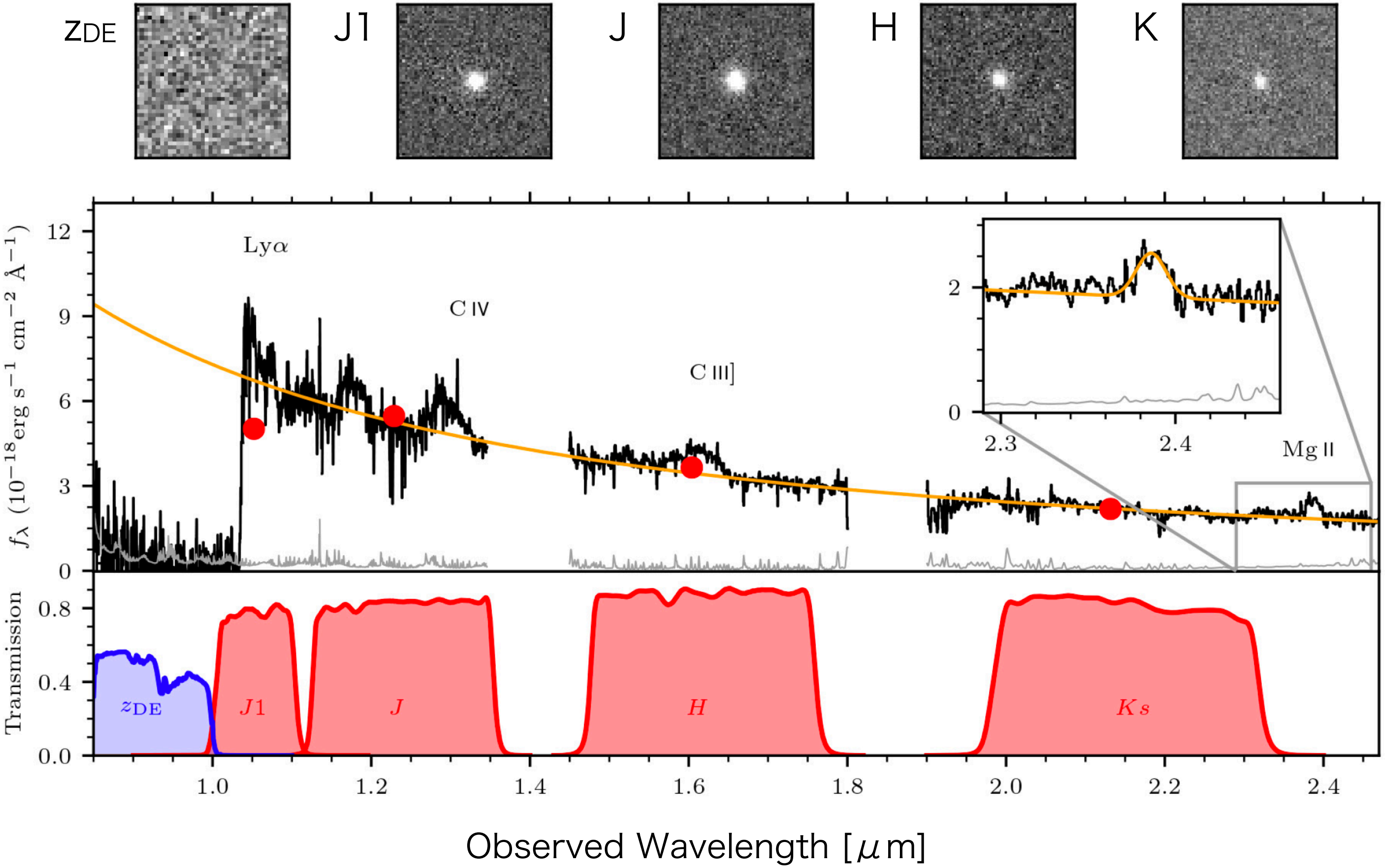




- Lya LF estimates based on the Subaru HSC >1000 Lya emitters (LAEs).
- ~100 are spectroscopically confirmed.
- Comparison with theoretical results
  → x_{HI} = 0.3 ± 0.2 at z=6.6, x_{HI} = 0.55 ± 0.25 at z=7.3

Shibuya et al. (2017), PASJ in press, arXiv:1705.00733; Konno et al. (2017), PASJ in press, arXiv:1705.01222

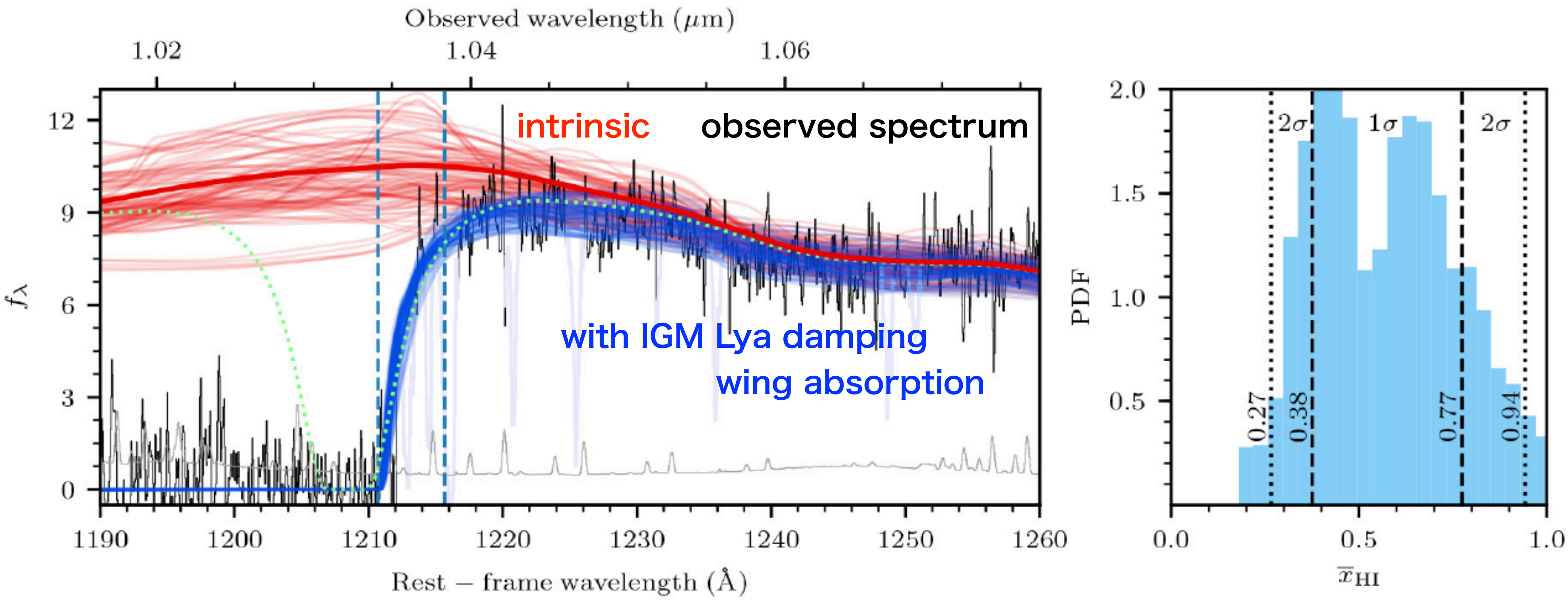
QSO Lya Damping Wing Absorption



- z=7.54 quasar was identified very recently (ALLWISE+UKIDSS LAS+DECaLS).
- Follow-up spectroscopy with Magellan/FIRE and Gemini/GNIRS.

Banados et al. (2017), Nature in press, arXiv:1712.01860

QSO Lya Damping Wing Absorption



- z=7.54 quasar was identified very recently (ALLWISE+UKIDSS LAS+DECaLS).
- Follow-up spectroscopy with Magellan/FIRE and Gemini/GNIRS.
- Lya damping wing analysis gives $x_{HI} = 0.56^{+0.21}_{-0.18}$.

Banados et al. (2017), Nature in press, arXiv:1712.01860

Ionized Hydrogen Fraction $Q_{\rm HII}$

$$(Q_{\rm H_{II}} \equiv 1 - x_{\rm H_I})$$

$$\dot{Q}_{\rm H_{II}} = \frac{\dot{n}_{\rm ion}}{\langle n_{\rm H} \rangle} - \frac{Q_{\rm H_{II}}}{t_{\rm rec}}$$

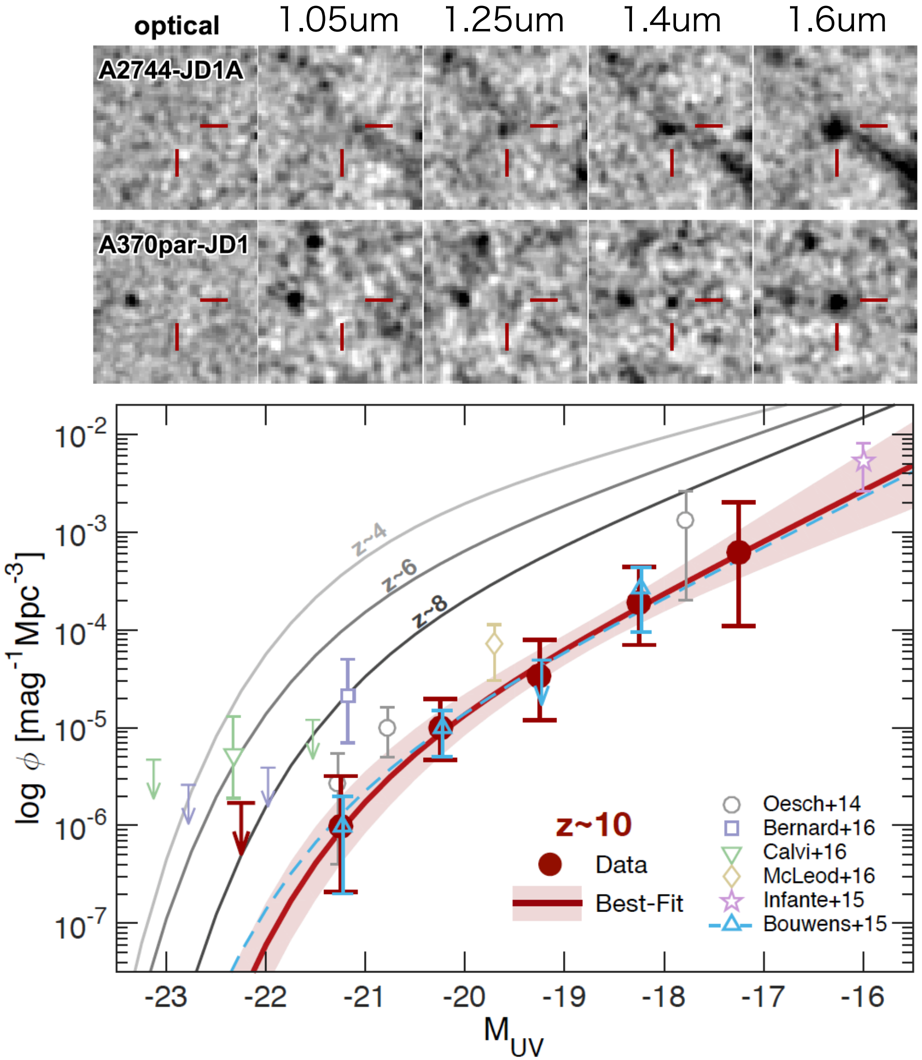
Ionization   Recombination

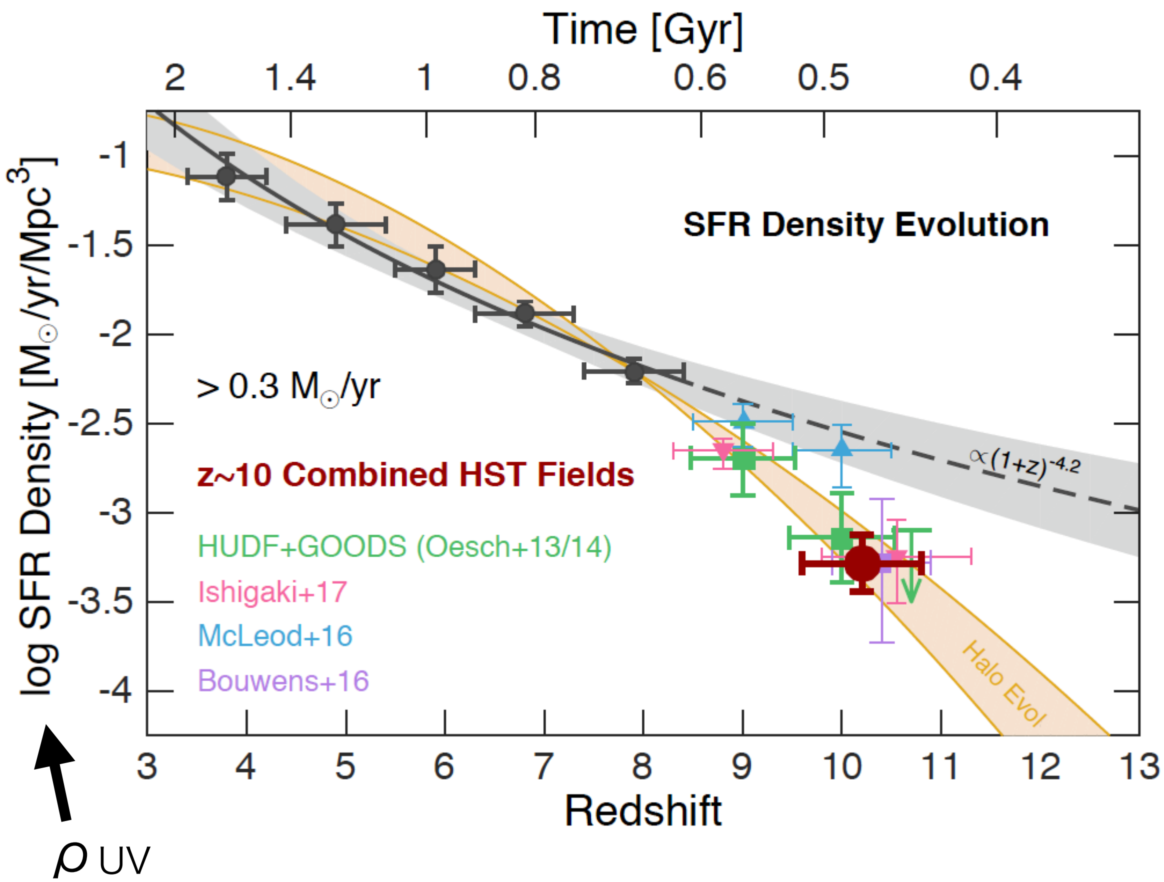
Ionizing photon production rate: $\dot{n}_{\rm ion} = \langle f_{\rm esc} \xi_{\rm ion} \rangle \, \rho_{\rm UV}$

- Key quantities:
  - + $\rho_{\rm UV}$: UV luminosity density (Integration of UV luminosity functions)
  - + $\xi_{\rm ion}$: ionizing photon production efficiency (conversion factor between UV luminosity density and ionizing photon number density)
  - + $f_{\rm esc}$: fraction of ionizing photons that escape from galaxies

e.g., Madau et al. (1999), ApJ, 514, 648

UV Luminosity Density ρ_{UV}

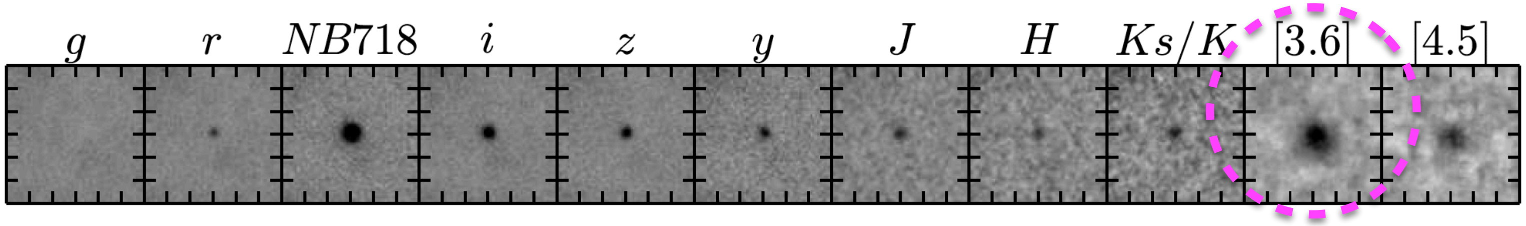


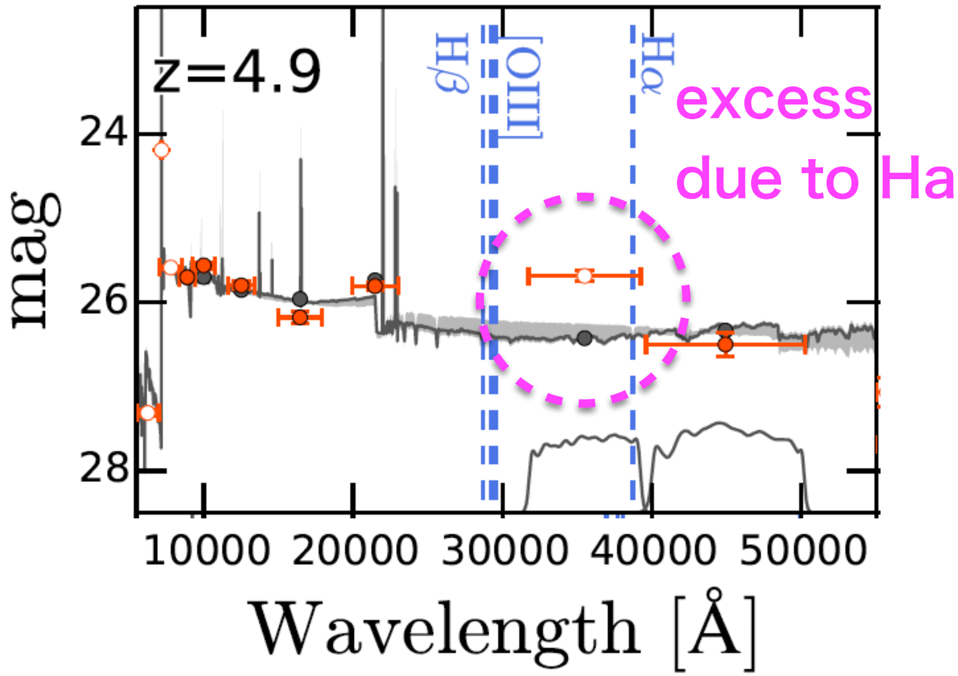


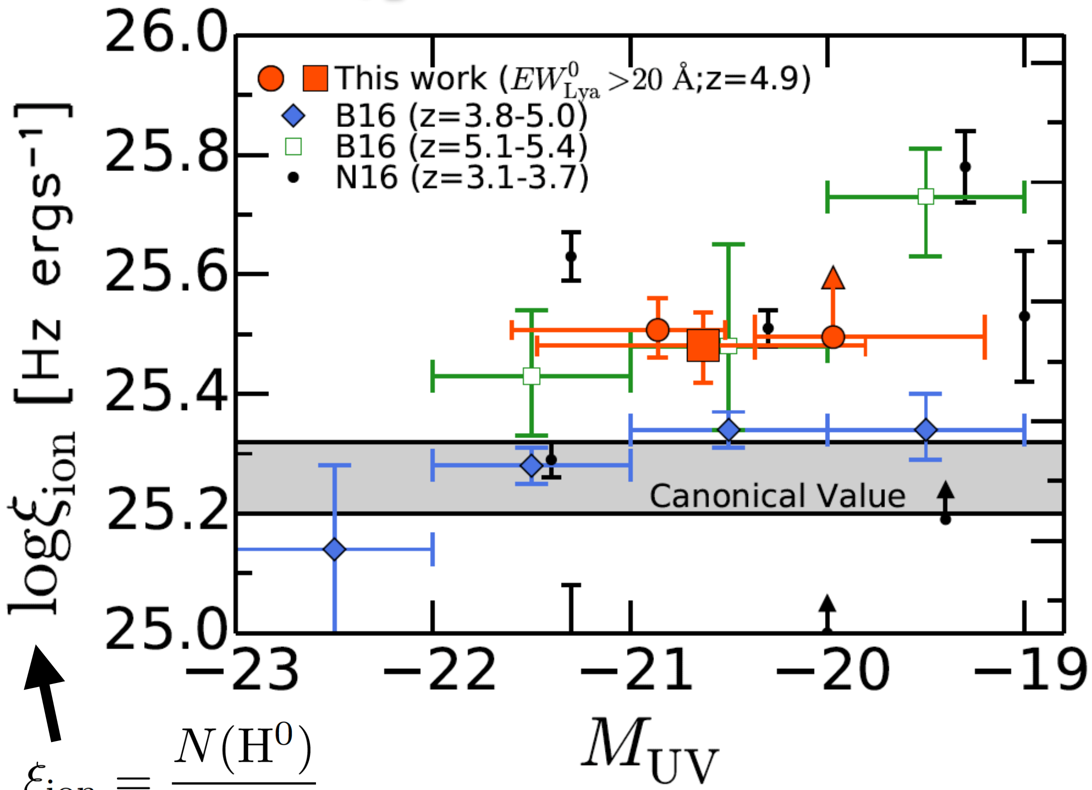
- UV luminosity density = the integration of UV LFs times UV luminosities
- Measured up to around z~10, although the faint ends of UV LFs are still uncertain whose contribution to the UV luminosity density is relatively large.

Oesch et al. (2017), arXiv:1710.11131

Ionizing Photon Production Efficiency $\xi_{\rm ion}$





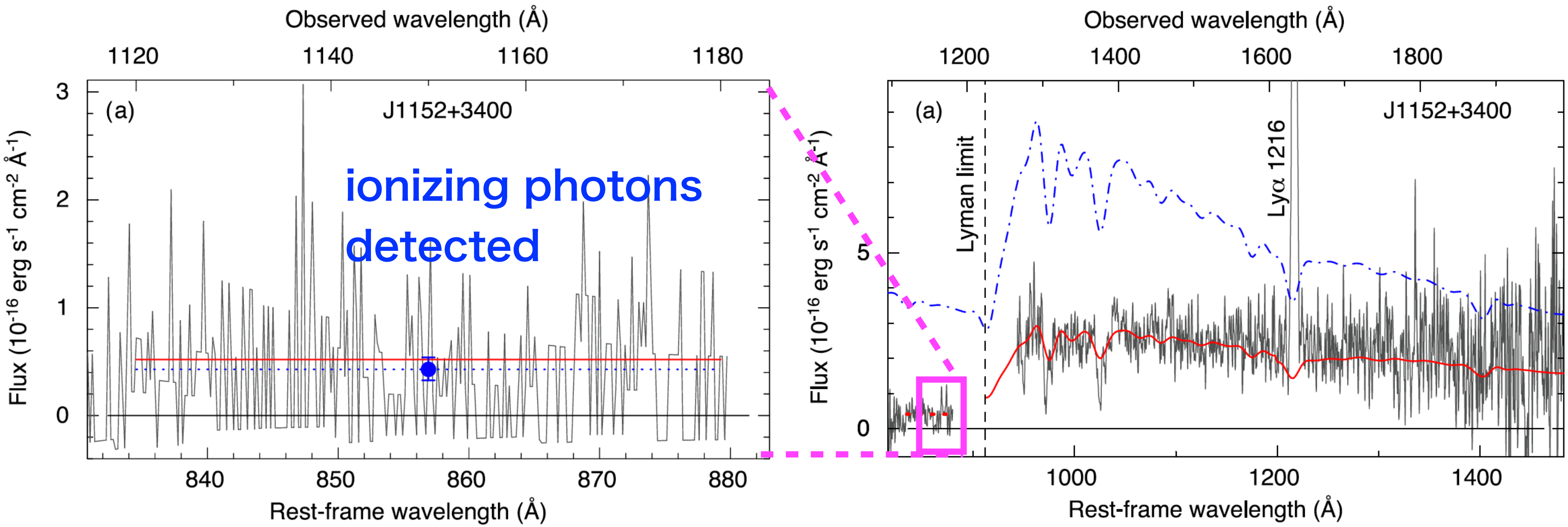


$$\xi_{\rm ion} = \frac{N(\mathrm{H}^0)}{L_{\rm UV}}$$

- H-alpha fluxes are estimated from the excess of broadband SED and converted to $\xi_{\rm ion}$.
- Obtained down to $M_{\rm UV}$ = −19 mag. Unexplored for fainter galaxies.

Harikane et al. (2017), arXiv:1711.03735

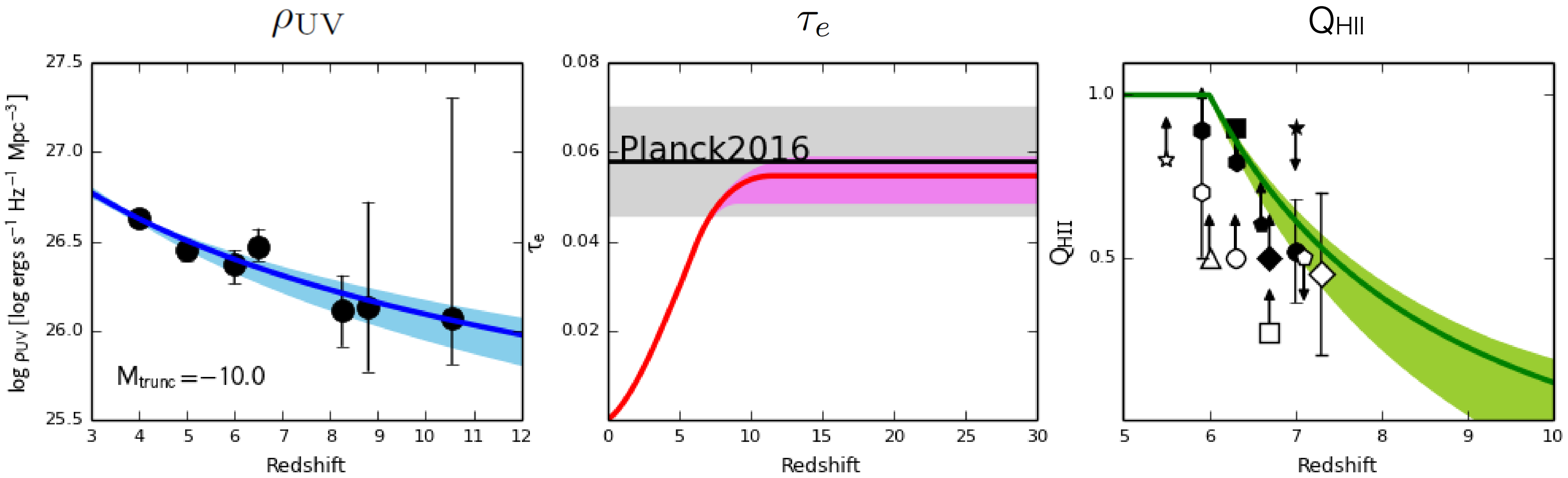
Ionizing Photon Escape Fraction f_{esc}



- Direct observations of ionizing photons from local galaxies whose properties are similar to high-z galaxies.
- Escape fractions of ionizing photons f_{esc} are estimated to be 6-13%.
- Direct measurements of f_{esc} for high-z galaxies is difficult due to IGM abs. Should be studied with indirect methods.

Izotov et al. (2016), MNRAS, 461, 3683

Reionization History



$$\dot{Q}_{\rm HII} = \frac{\dot{n}_{\rm ion}}{\langle n_{\rm H} \rangle} - \frac{Q_{\rm HII}}{t_{\rm rec}}, \qquad \dot{n}_{\rm ion} = \langle f_{\rm esc} \xi_{\rm ion} \rangle \rho_{\rm UV}$$

Ionization Recombination

- Simultaneous fitting to the observational data of $\rho_{\rm UV}$, τ_e, and $Q_{\rm HII}$.
  Parameters: $\langle f_{\rm esc} \xi_{\rm ion} \rangle$, $M_{\rm trunc}$, functional form of $\rho_{\rm UV}$.
- There exist reionization scenarios that are consistent with the observational results with $\langle \log f_{\rm esc} \xi_{\rm ion} \rangle = 24.52^{+0.14}_{-0.07}$ and $M_{\rm trunc} > -12.5$ mag.

Ishigaki et al. (2017), arXiv:1702.04867

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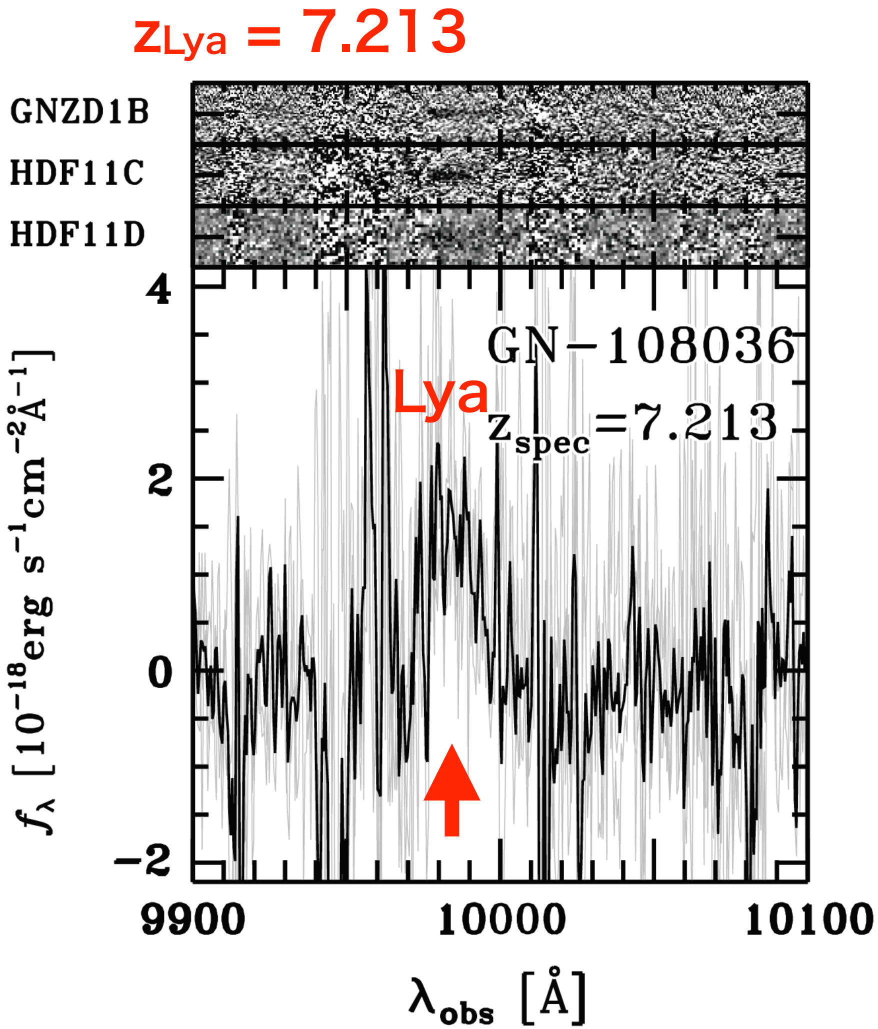
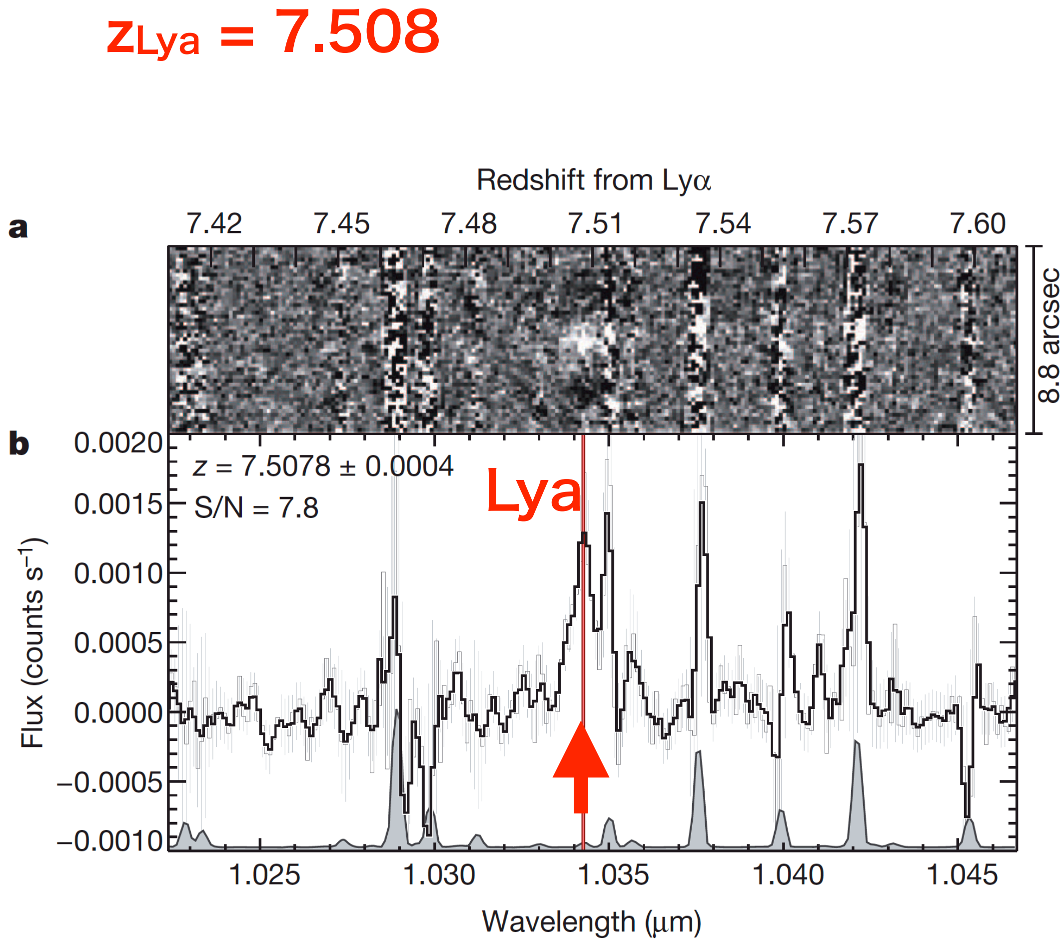
Previously Identified z>7 Galaxies w/ Lya





Ono et al. (2012), ApJ, 744, 83; Finkelstein et al. (2013), Nature, 502, 524
See also, Iye et al. (2006), Vanzella et al. (2011), Pentericci et al. (2011), Schenker et al. (2012), Shibuya et al. (2012),

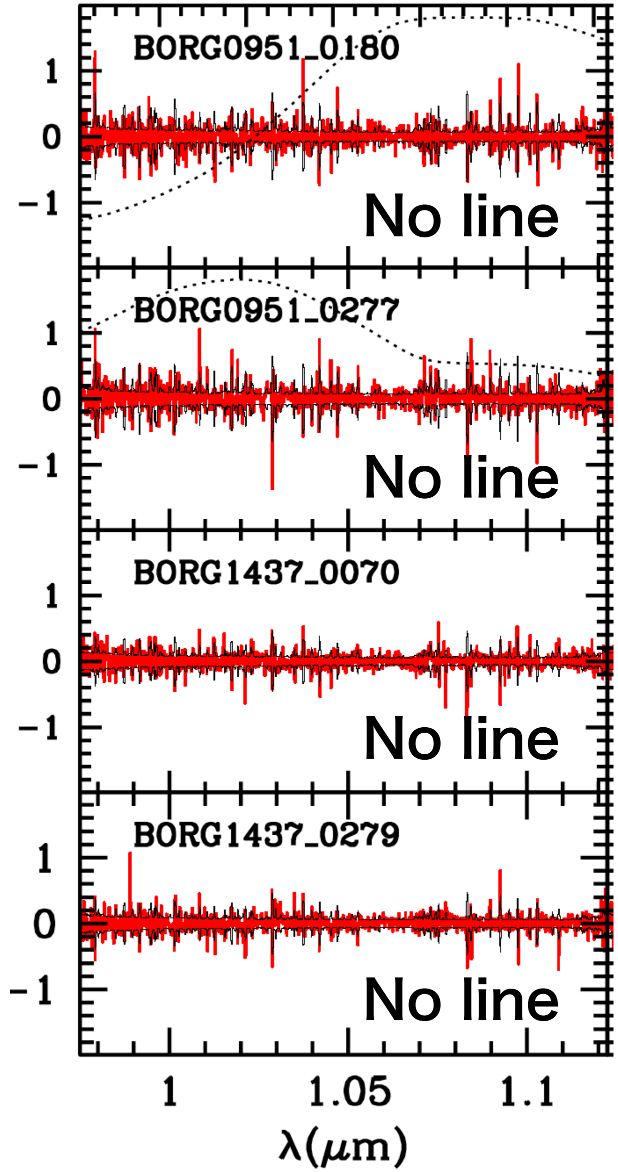
Unsuccessful Spec. Surveys at the EoR

- Treu et al. (2013)
  Keck MOSFIRE spectroscopy for **13** candidates at z~8
  no significant detection of Lya

- Caruana et al. (2014)
  VLT FORS2 spectroscopy for **22** candidates at z~7
  no evidence of Lya

- Pentericci et al. (2014)
  VLT FORS2 spectroscopy for **23** candidates at z~7
  only two confirmed at z<6.7

- Schenker et al. (2014)
  Keck MOSFIRE spectroscopy for **16** candidates at z>7
  only one tentative detection at z=7.62

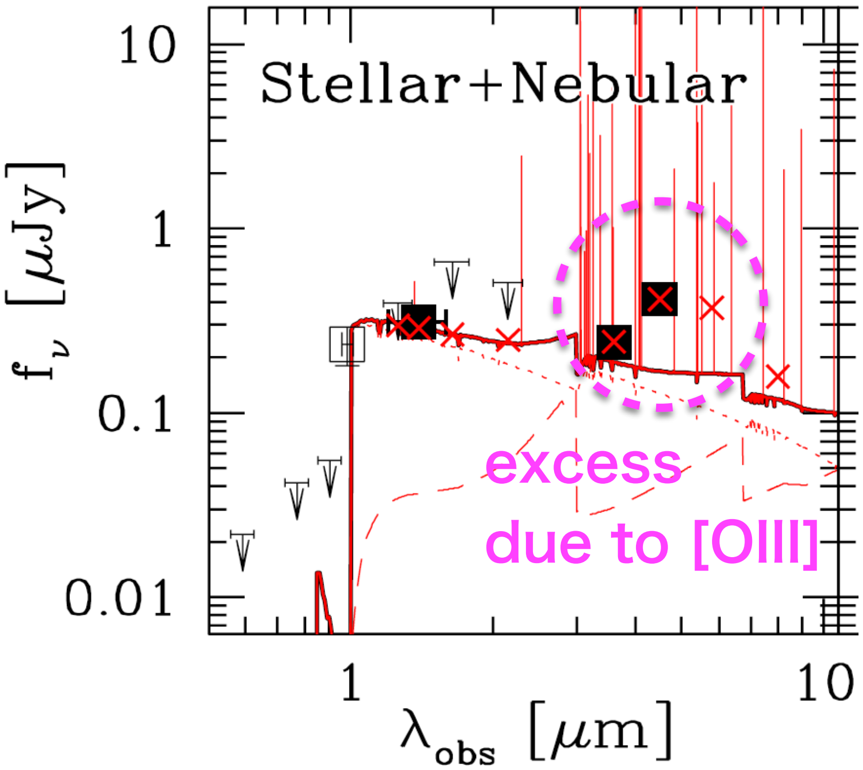


probably due to **high x_{HI}** on average at the epoch of reionization.

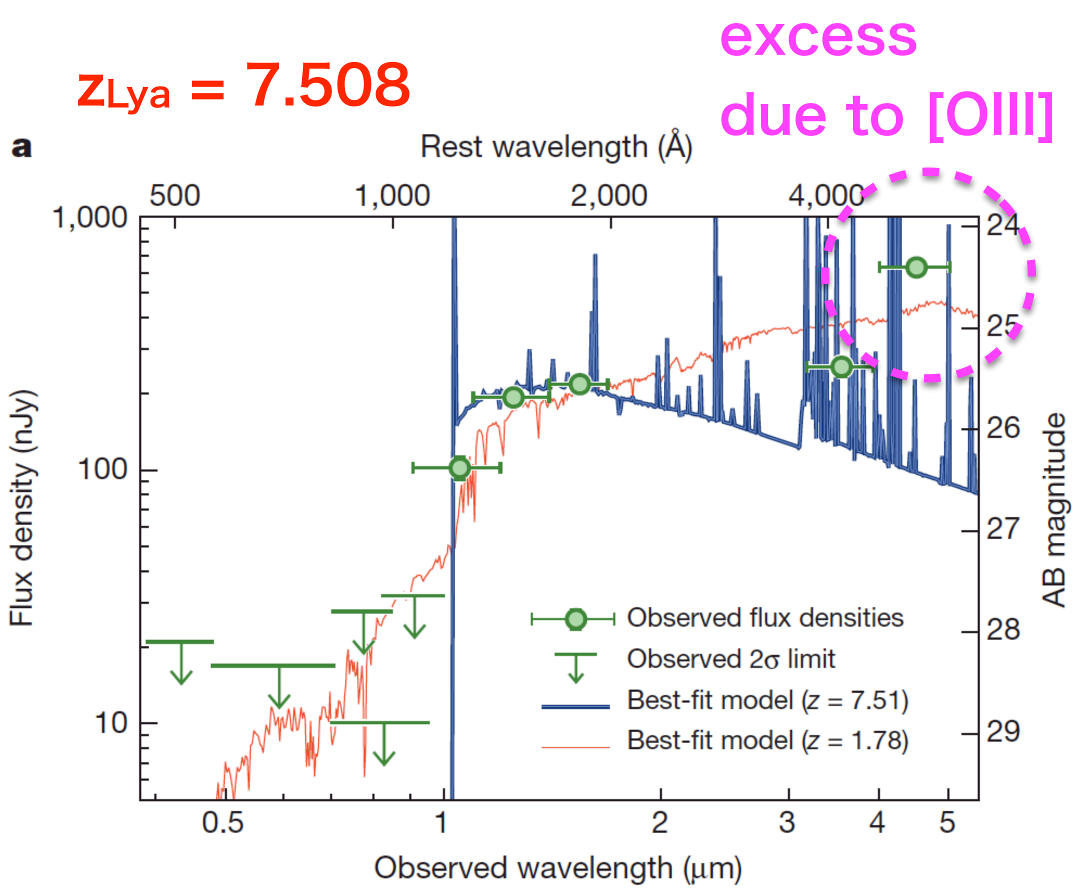
see also Tilvi et al. (2014), Faisst et al. (2014), Vanzella et al. (2014)

Excess due to Strong [OIII] Emission?

z_{Lya} = 7.213



z_{Lya} = 7.508

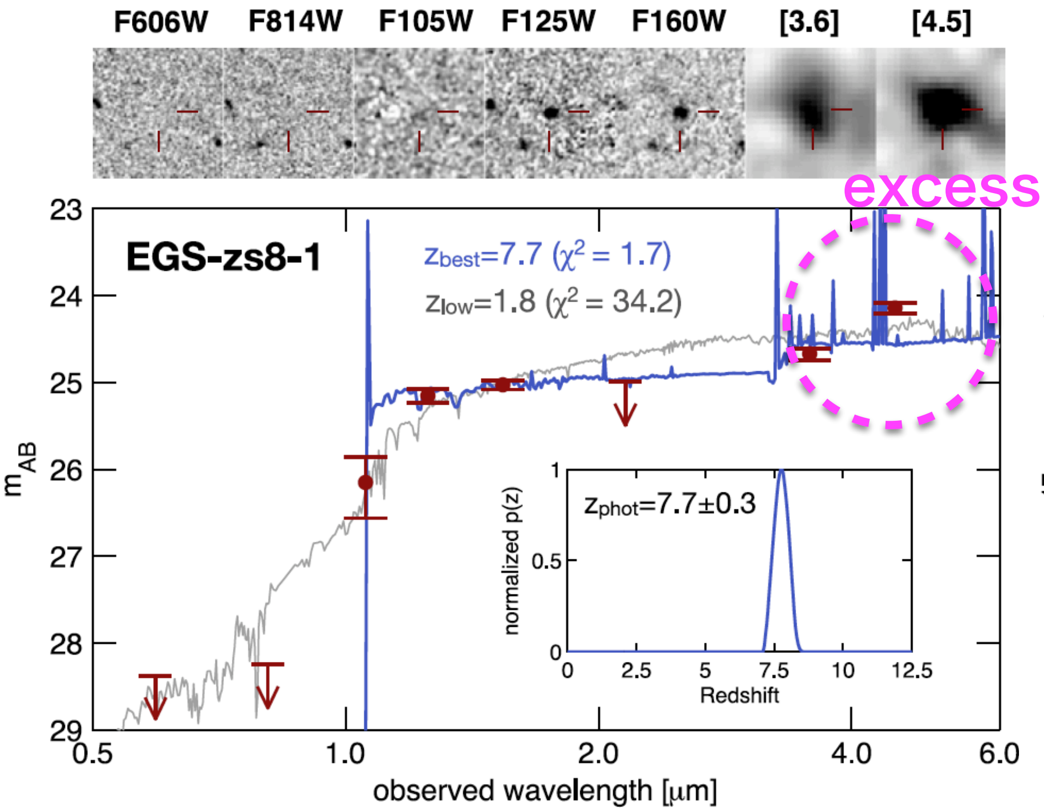


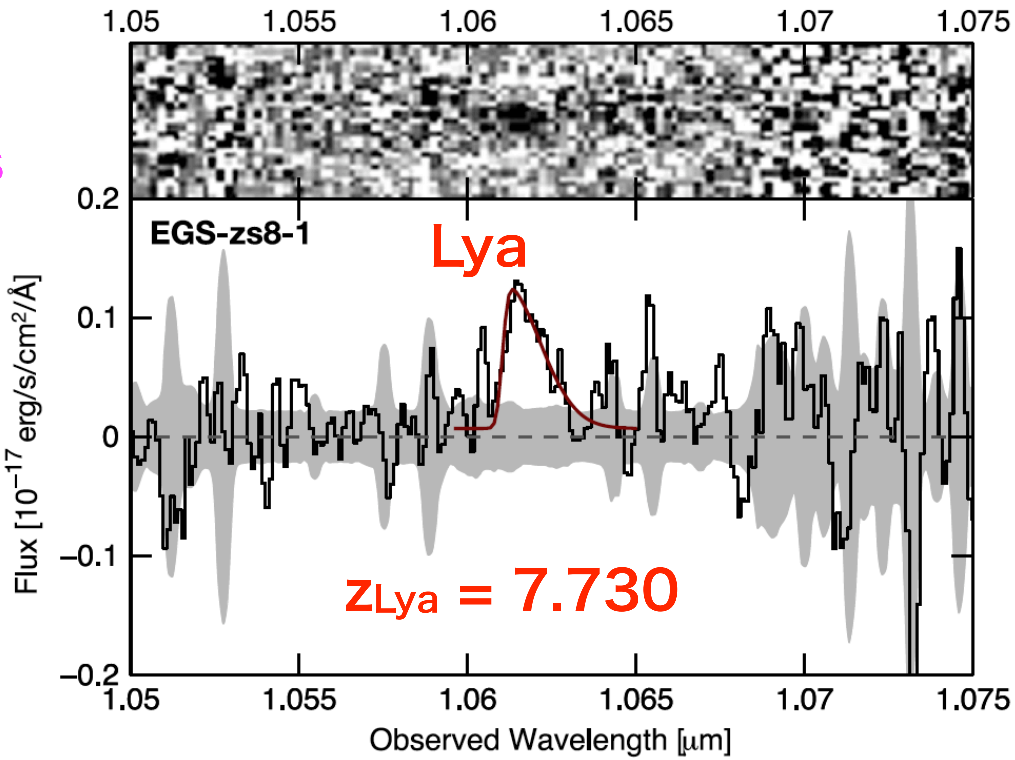
・Previously identied z>7 galaxies w/ Lya show flux excess in 4.5 μm broadband photo. consistent with strong [OIII].

・Strong [OIII] → high ionization state → low N_{HI} or in an ionized bubble → easier for Lya to escape

Ono et al. (2012), ApJ, 744, 83; Finkelstein et al. (2013), Nature, 502, 524

Lya Identification with [OIII] Excess

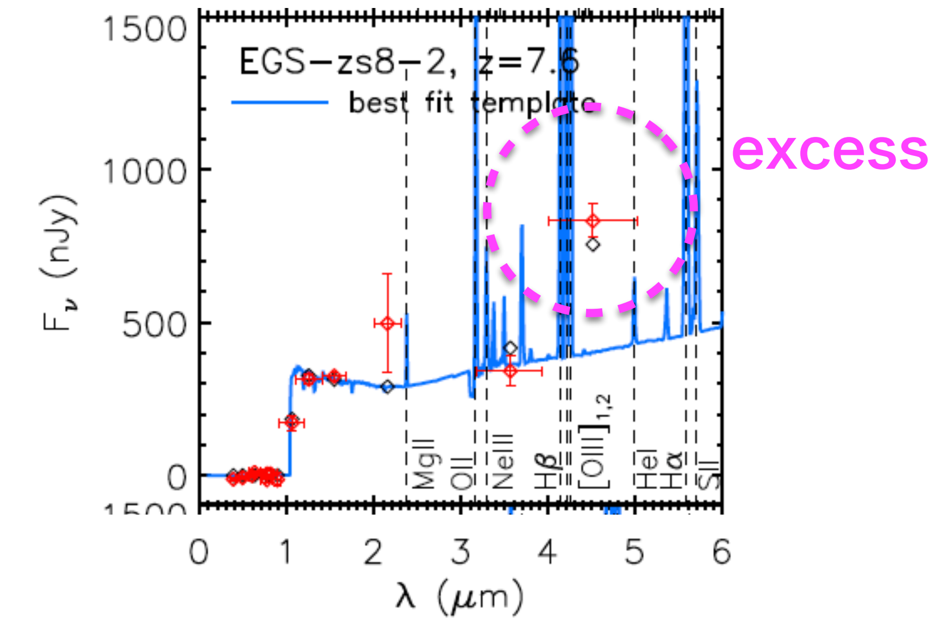


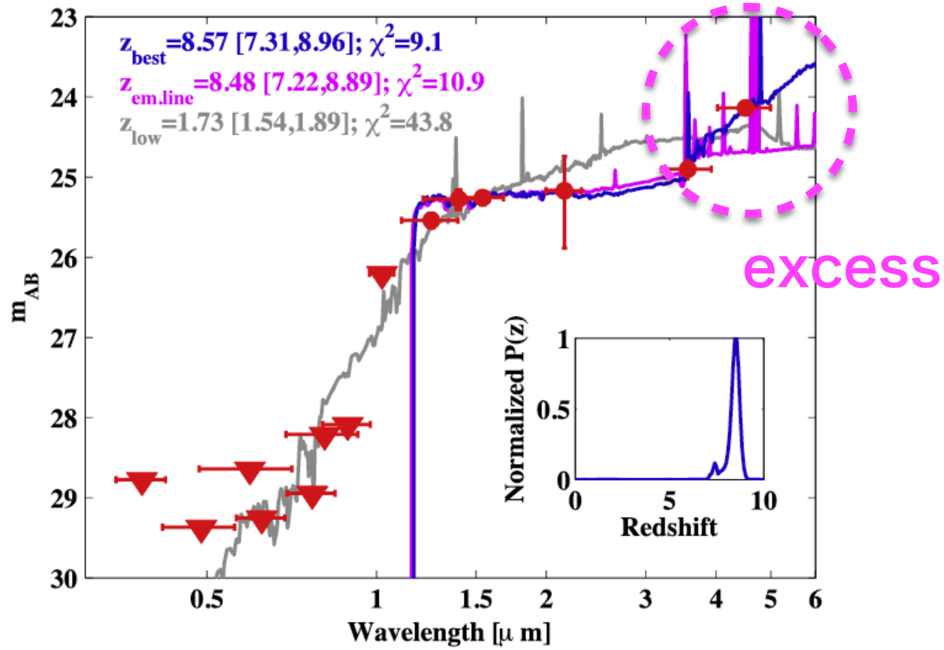


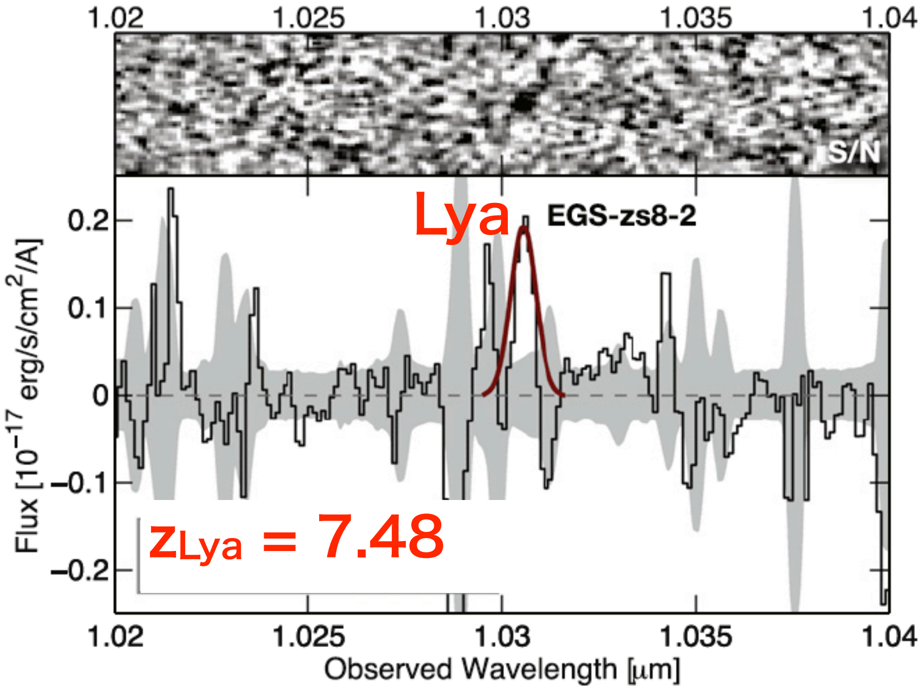
- A z~8 candidate shows a similar excess in 4.5μm.
- Follow-up Keck MOSFIRE spectroscopy reveals Lya emission at z_{Lya} = 7.730.

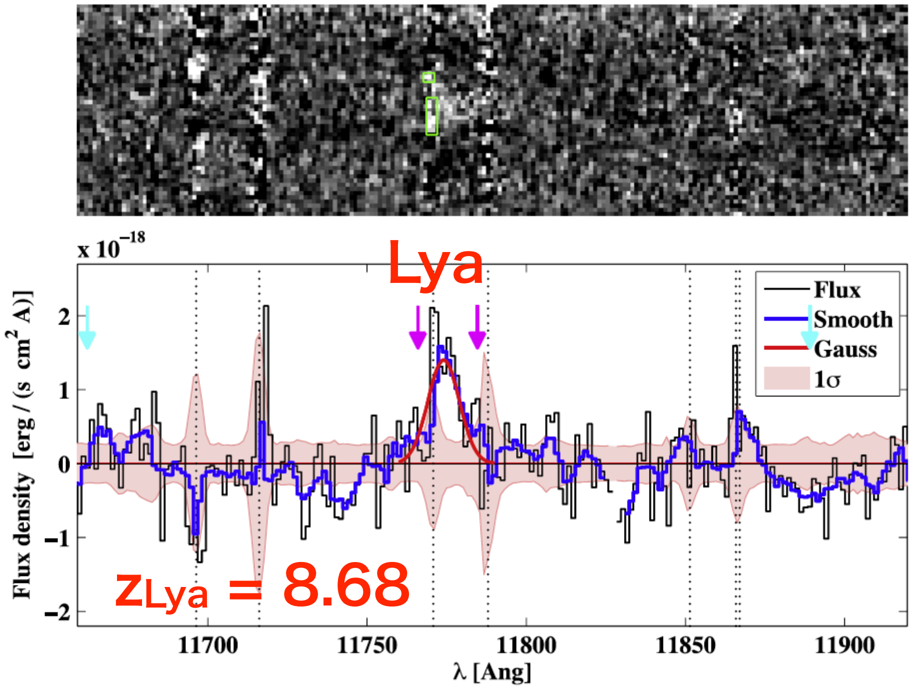
Oesch et al. (2015), ApJ, 804, L30

Lya Identification with [OIII] Excess





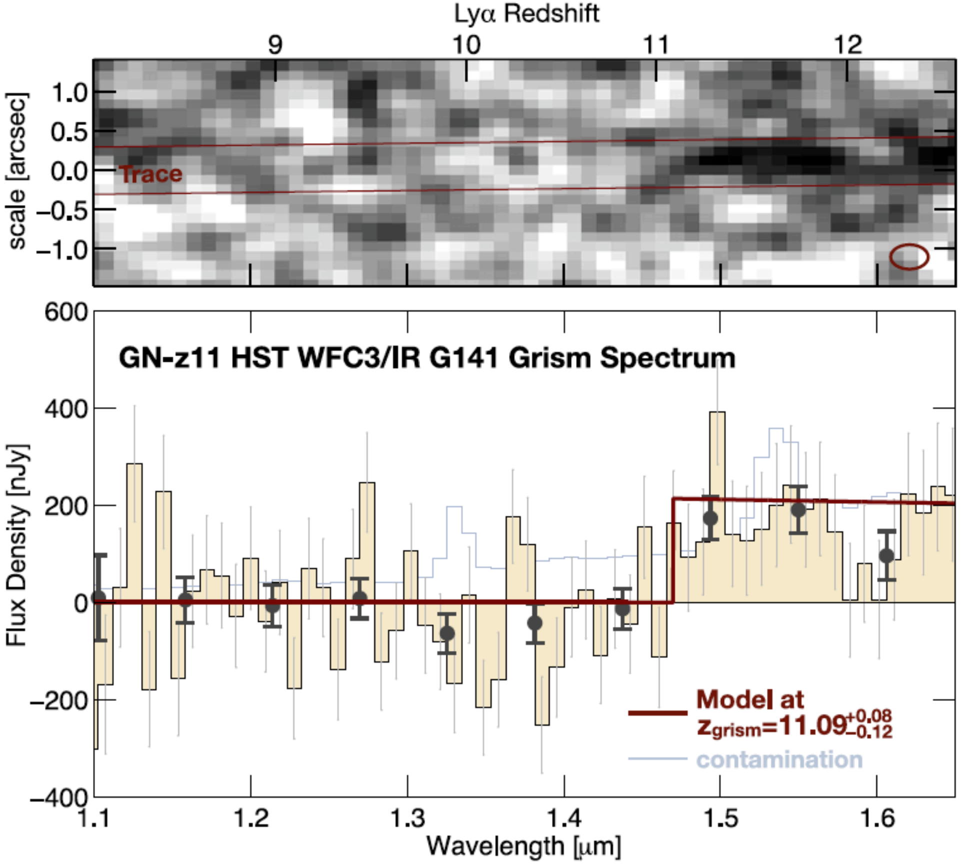


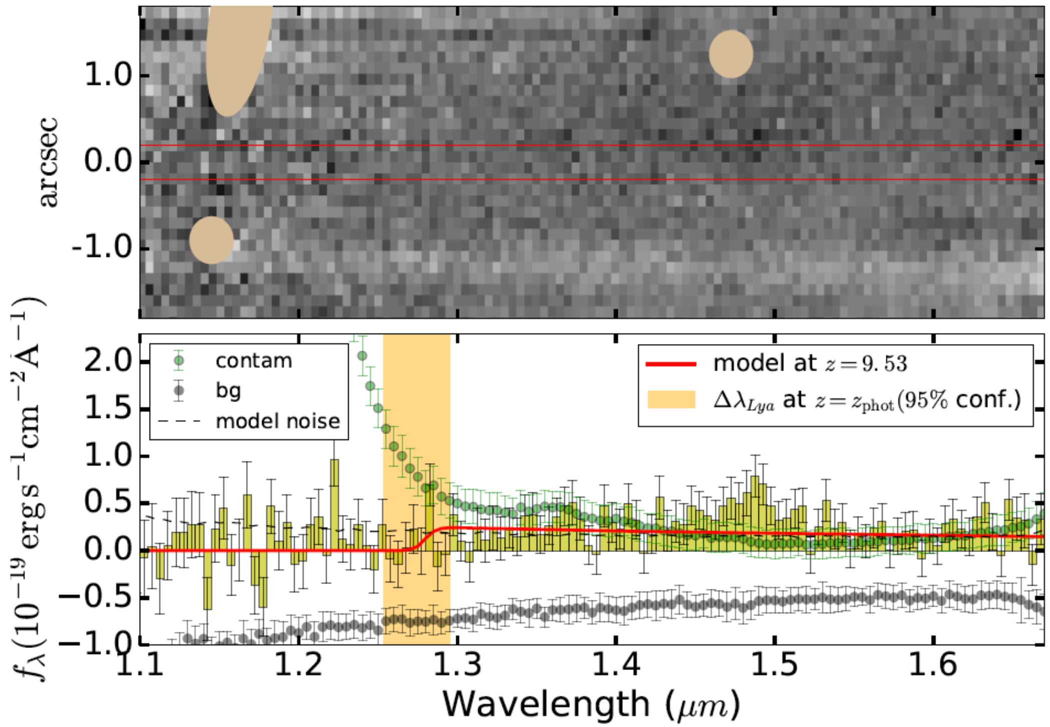


Roberts-Borsani et al. (2016), ApJ, 823, 143; Zitrin et al. (2015), ApJ, 810, L12

Identified with Low-resolution Spec.

z_{grism} = 11.1 z_{grism} = 9.53

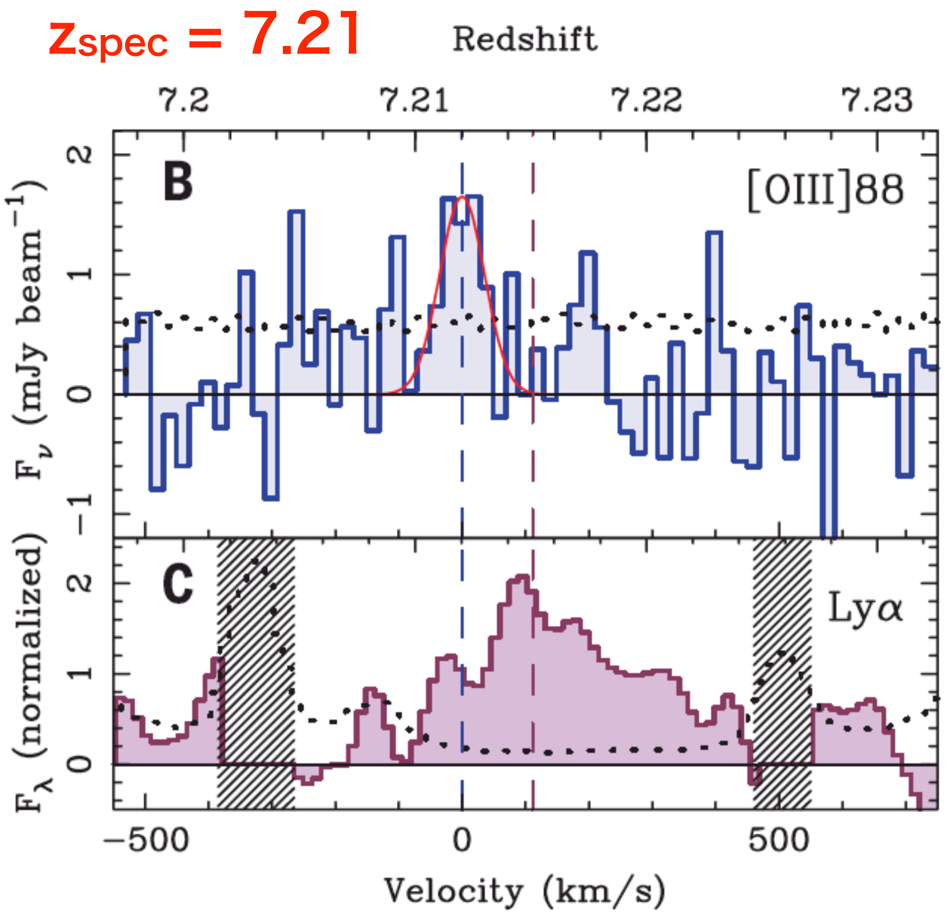


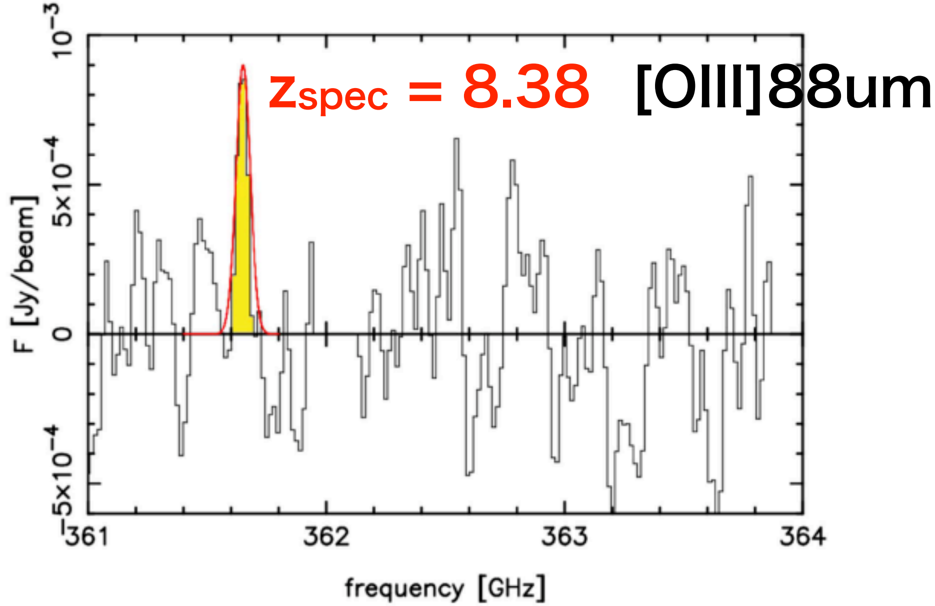


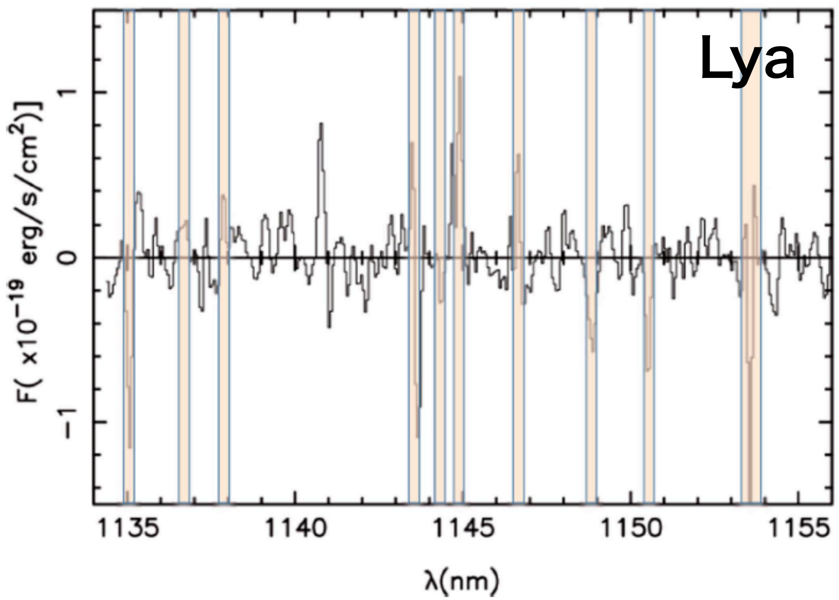
- identified at very high-z with Lyman brean in low-resolution spectra

Oesch et al. (2016), ApJ, 819, 129; Hoag et al. (2017), arXiv:1709.03992

ALMA Detection of [OIII]88um



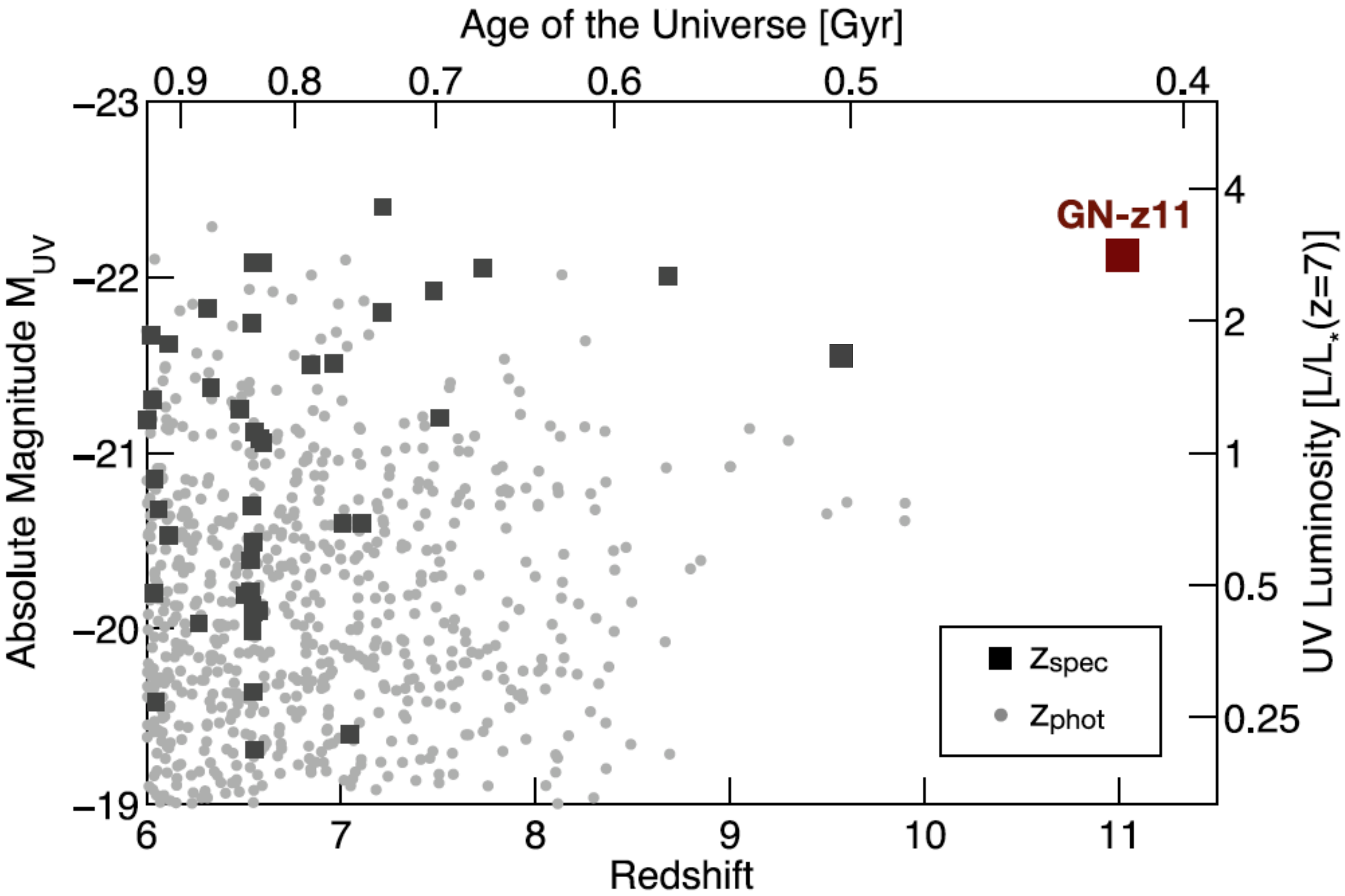




・Unaffected by the increased IGM neutral fraction.

Inoue et al. (2016), Science, 352, 1559; Laporte et al. (2017), ApJ, 837, L21

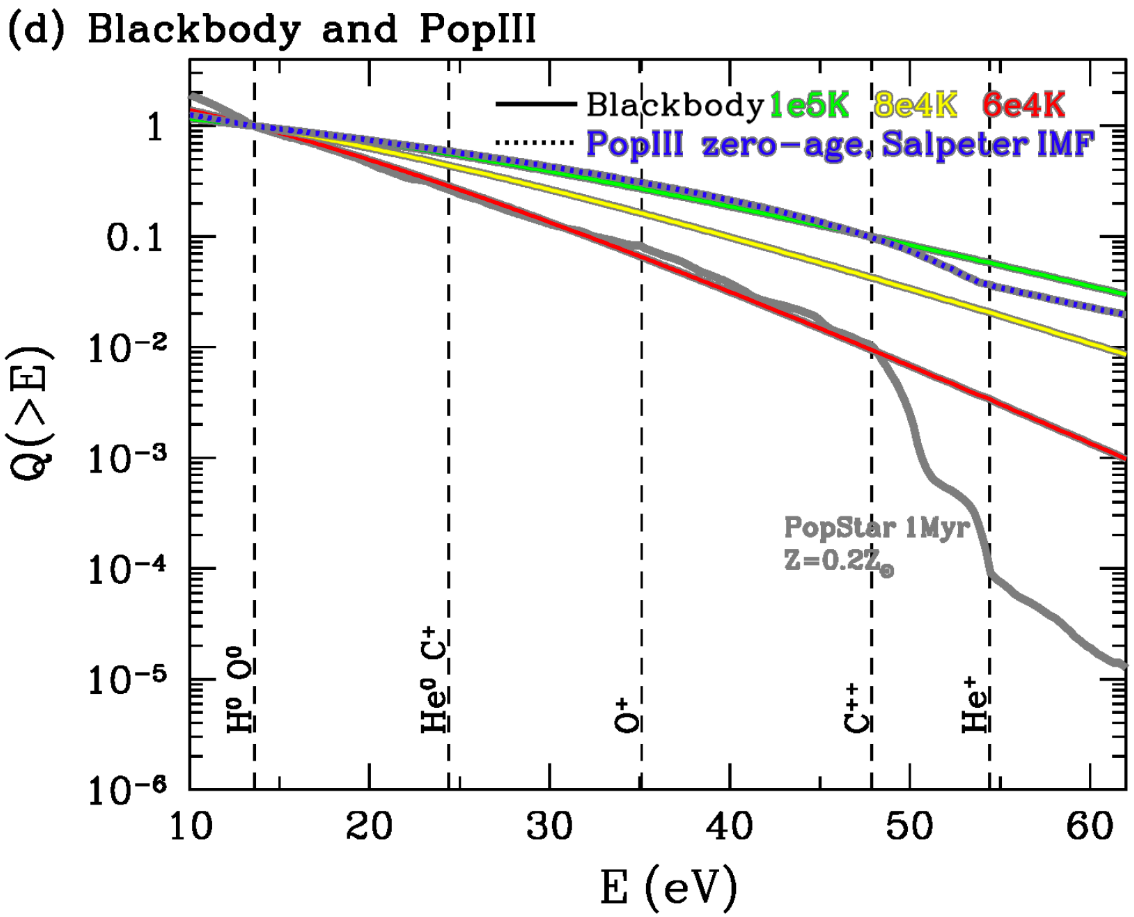
High-z Galaxies with Spec Confirmation

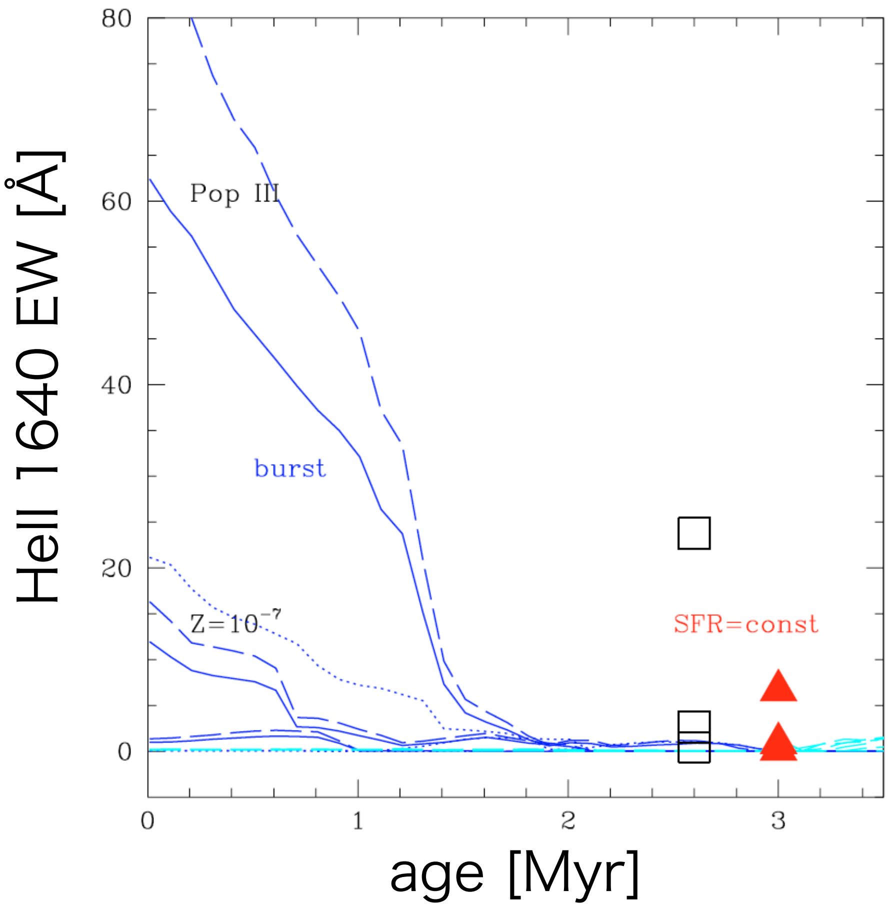


- A number of galaxies have been spectroscopically identified at z>6.
- Do they include Pop III star dominated galaxies?

Oesch et al. (2016), ApJ, 819, 129

Pop III

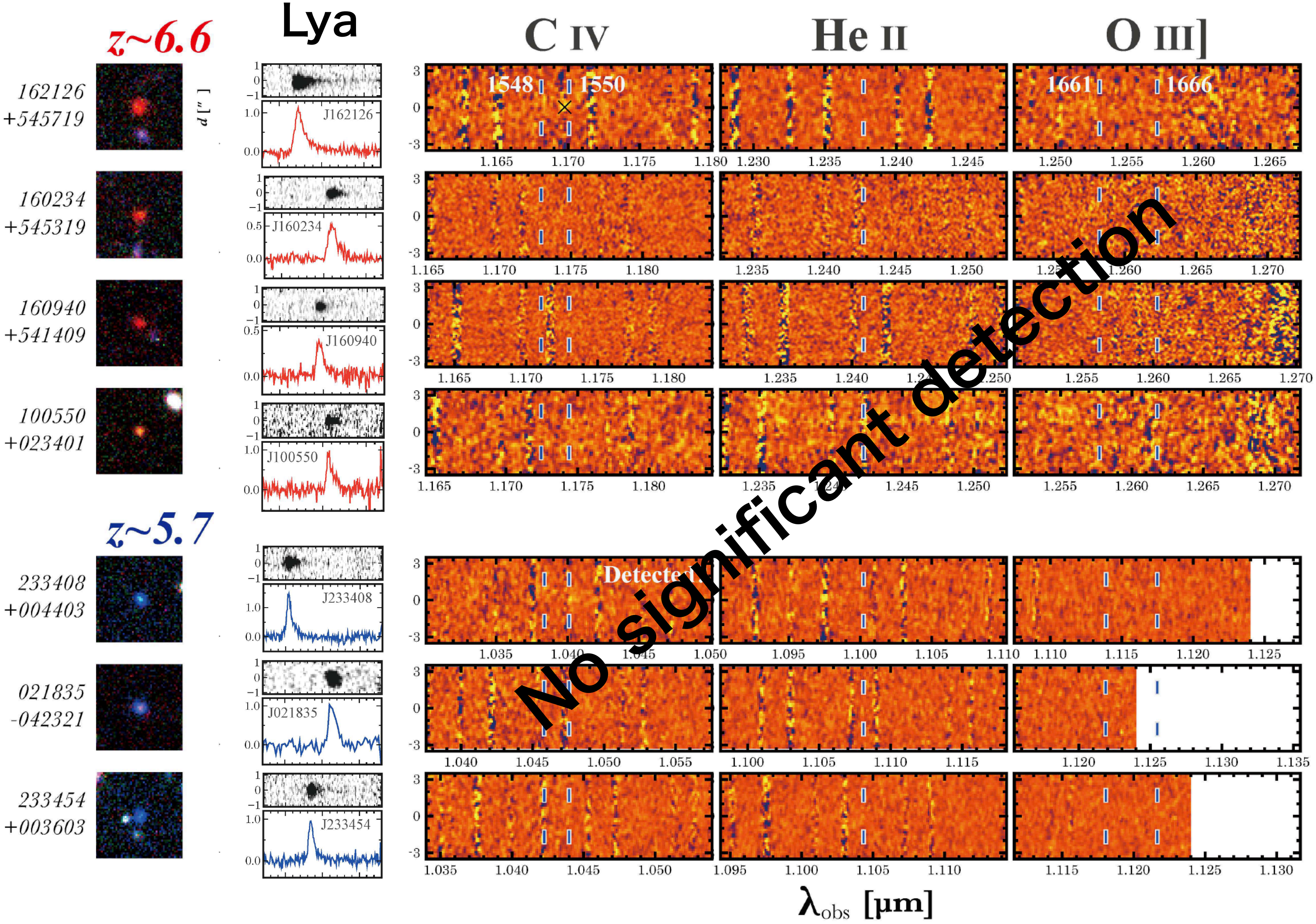




- Pop III star dominated sources would have harder SED.
- One of the good Pop III probes would be HeII 1640.

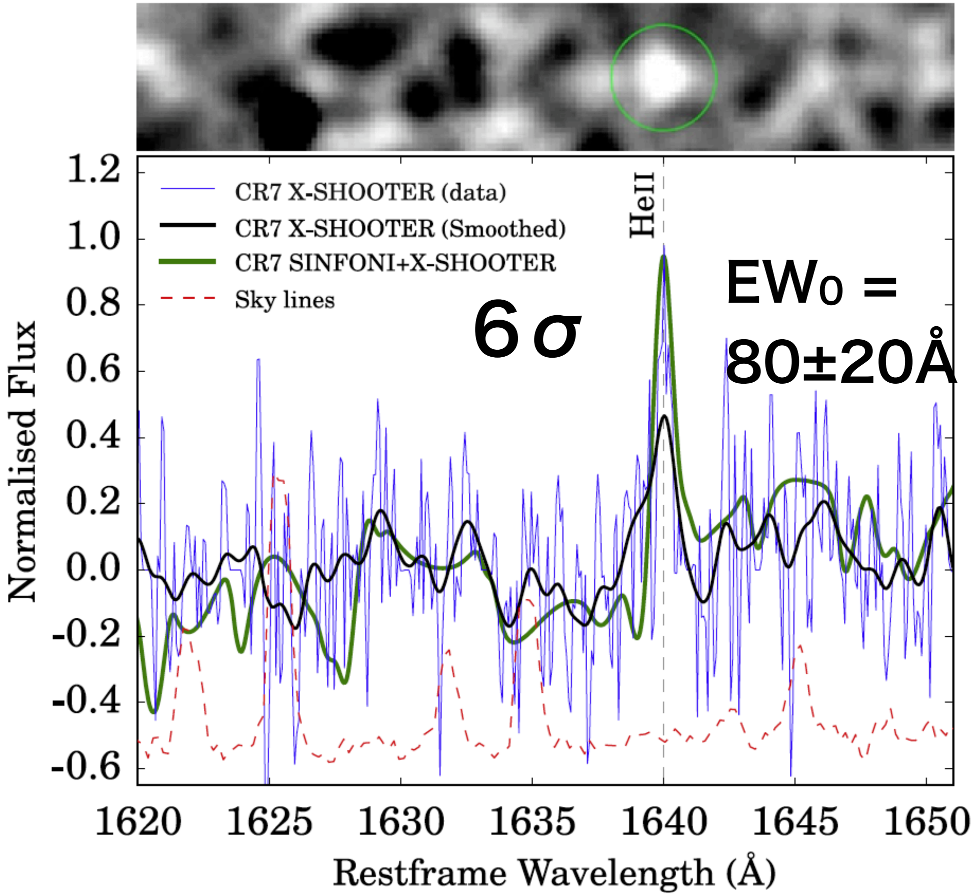
Nakajima et al. (2017), arXiv:1709.03990; Schaerer (2003), A&A, 397, 527

Bright LAEs



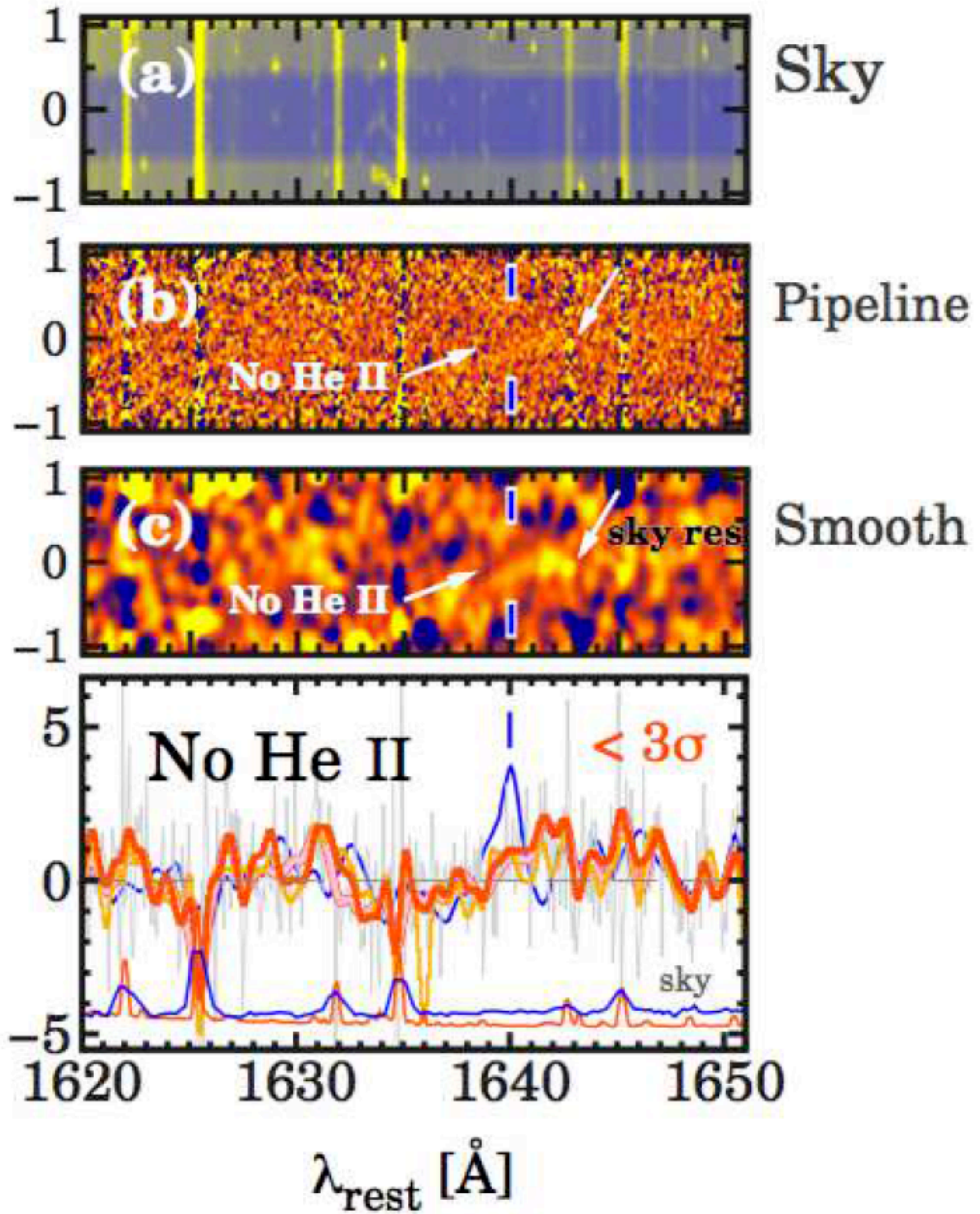
Shibuya et al. (2017), PASJ in press, arXiv:1705.00733

CR7



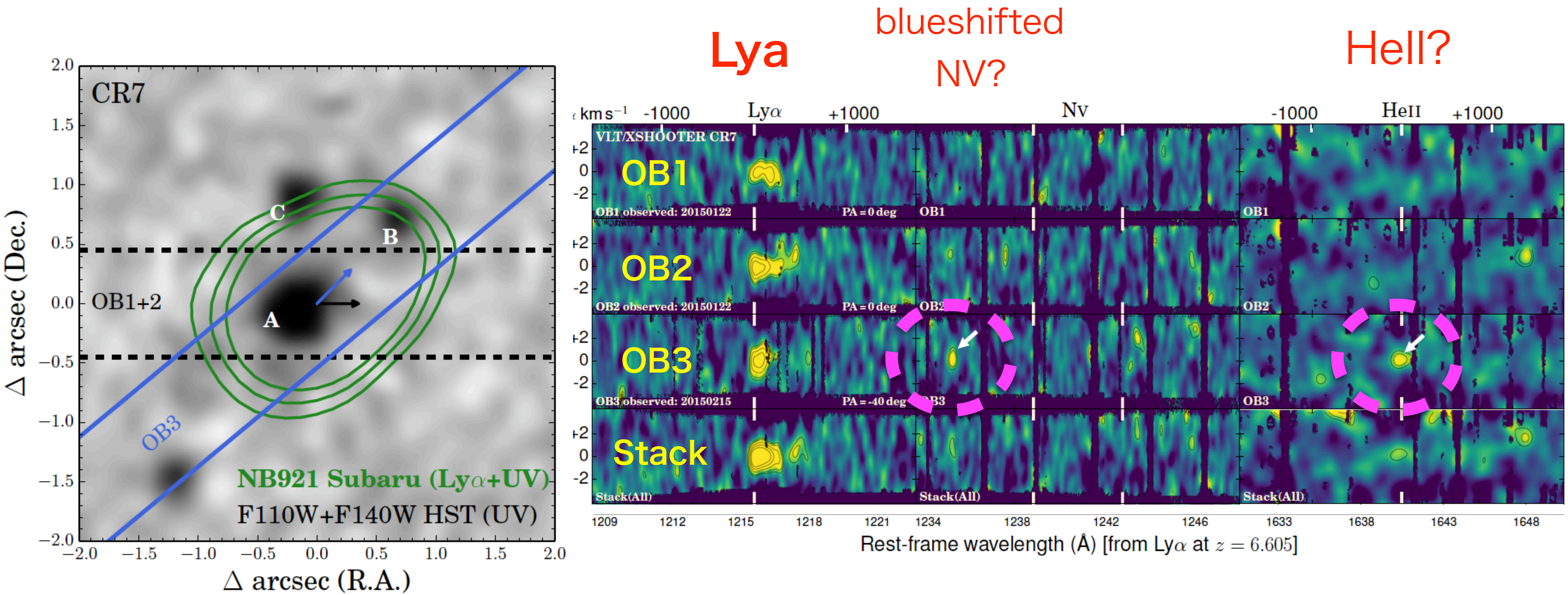
6σ

EW0 = 80±20Å



Sobral et al. (2015), ApJ, 808, 139; Shibuya et al. (2017), PASJ in press, arXiv:1705.00733

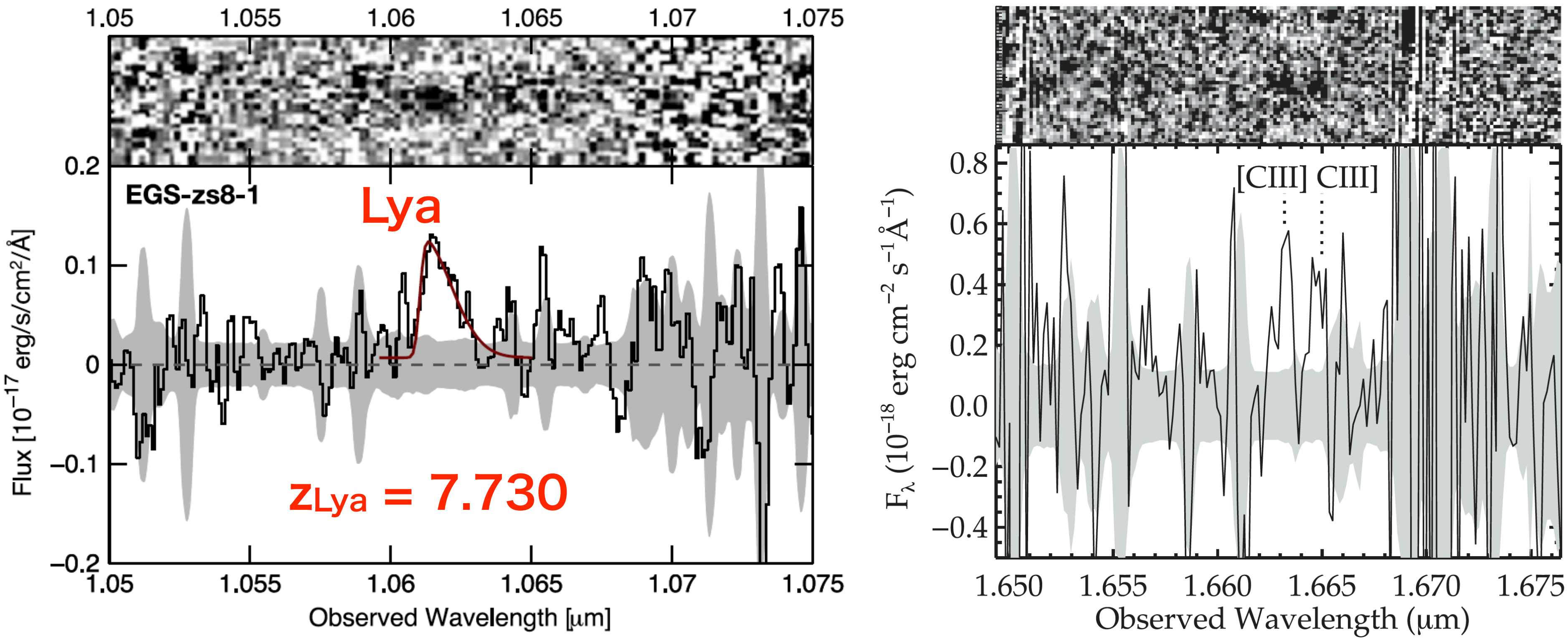
CR7



- Updated from the original authors: HeII is not detected in the stack but marginally detect in OB3 (2.6-sigma), suggesting that only component B shows HeII?
- In OB3, ~600km/s blueshifted NV is also detected?

Sobral et al. (2017), arXiv:1710.08422

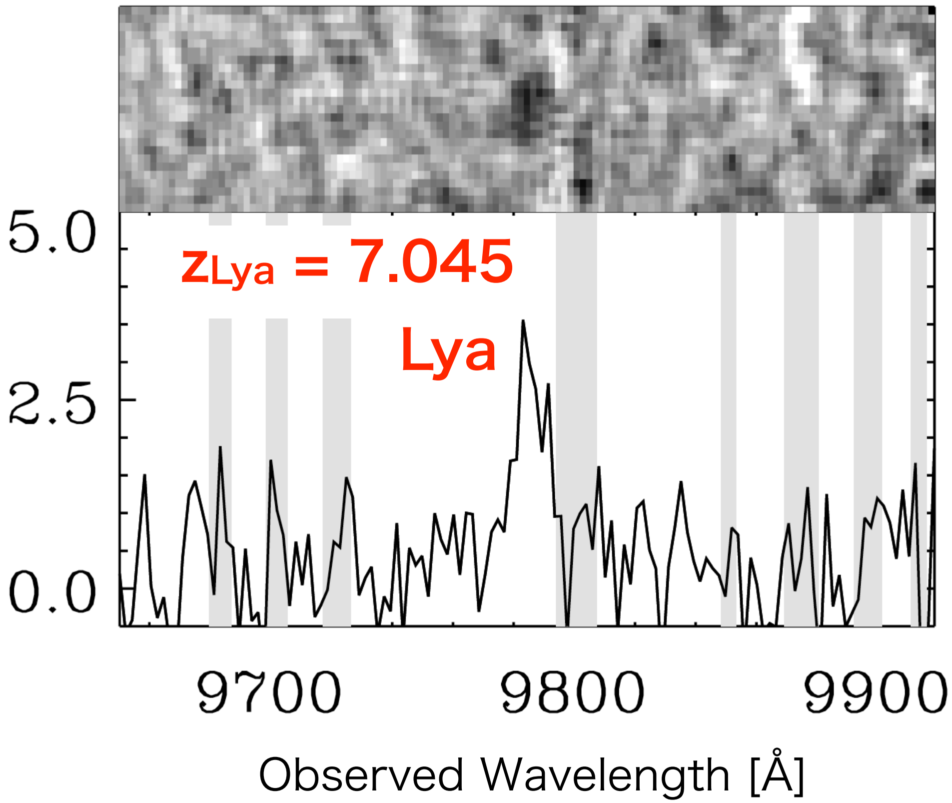
Bright LAEs

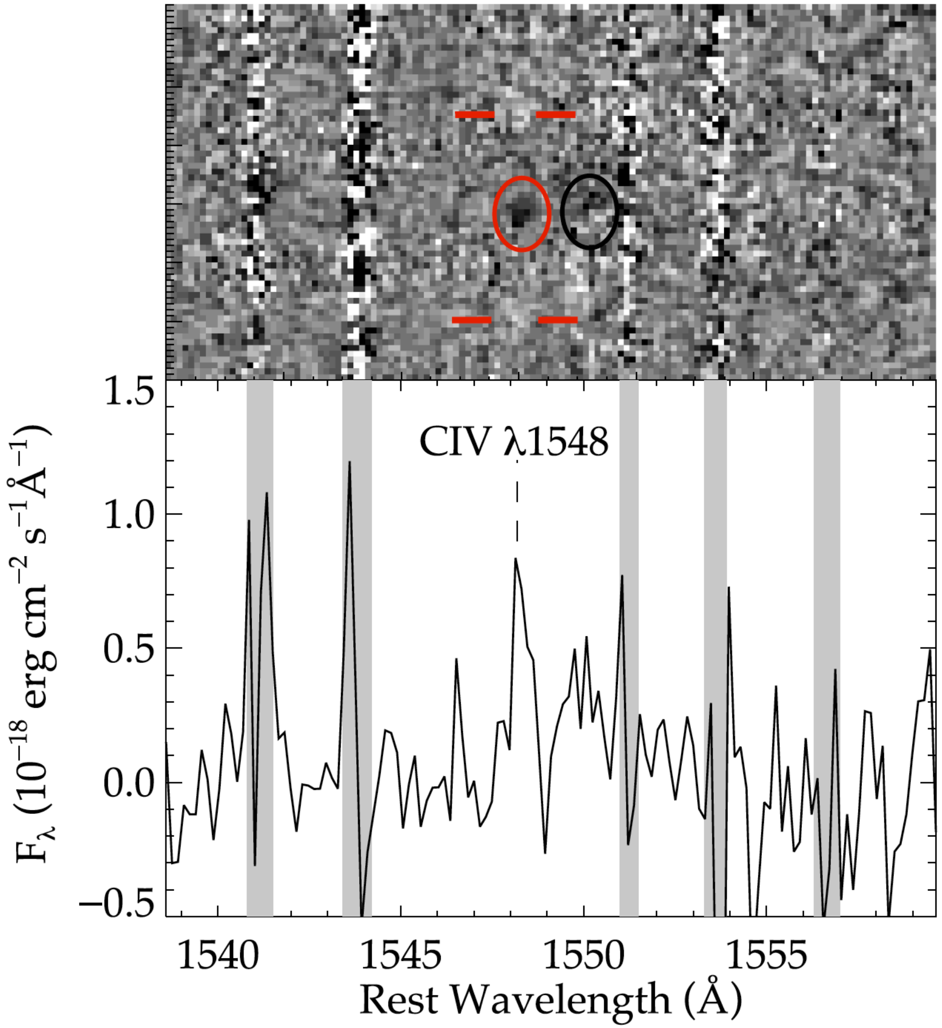


- z=7.730 spectroscopically confirmed galaxy with Lya EW_0 = 21Å.
- M_{UV} = −22 mag. (c.f., HSC LAEs M_{UV} ~ −21 mag)
- MOSFIRE follow-up shows strong CIII emission lines with EW_0 = 22Å, which is about x10 larger than those of the composite spectra of z=1-3 galaxies.

Oesch et al. (2015), ApJ, 804, L30; Stark et al. (2017), MNRAS, 464, 469

Faint LAEs

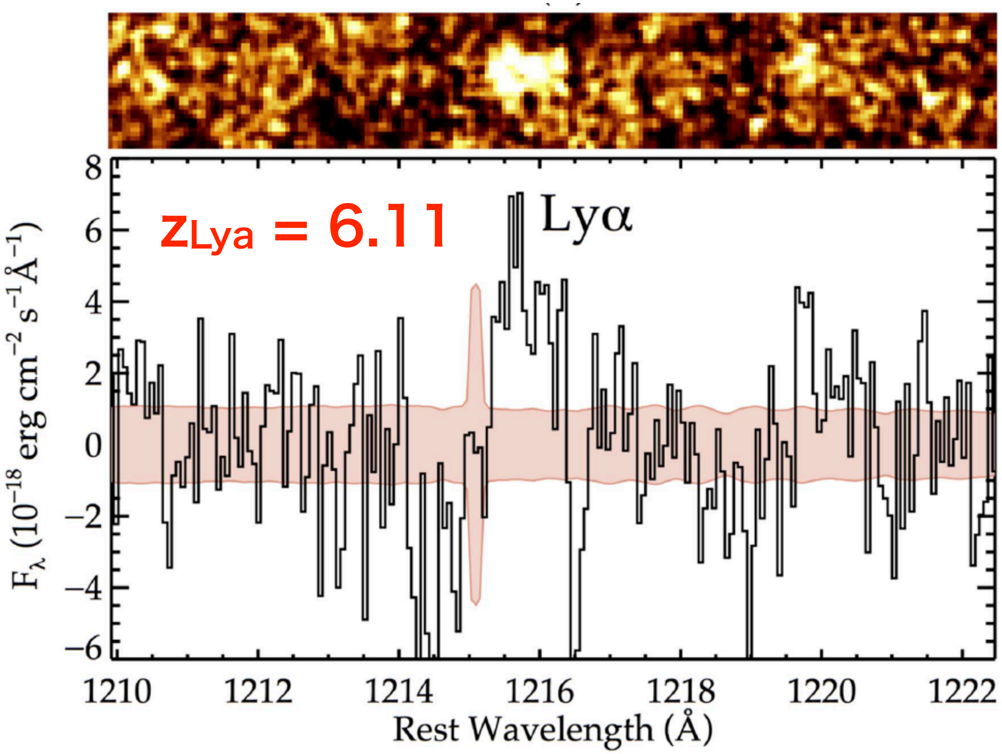


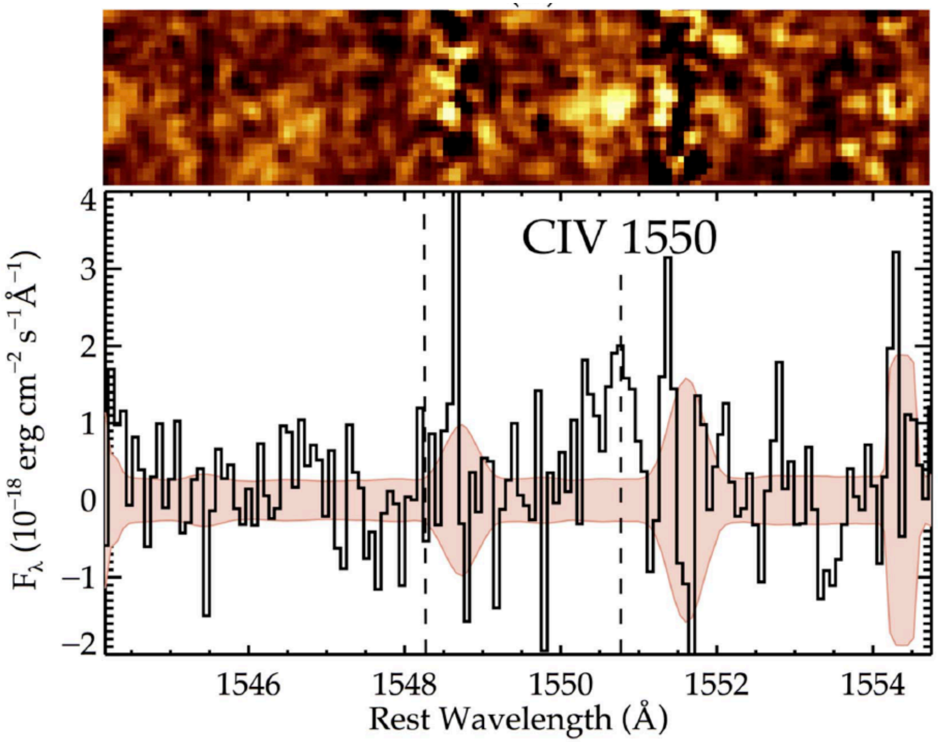


- z=7.045 spectroscopically confirmed galaxy with Lya EW_0 = 65Å and M_{UV} = −19 mag.
- CIV detected with EW_0 > 20Å. CIV is typically used as a signature of an AGN.
- No HeII or NV.

Schenker et al. (2012), ApJ, 744, 179; Stark et al. (2015), MNRAS, 454, 1393

Faint LAEs

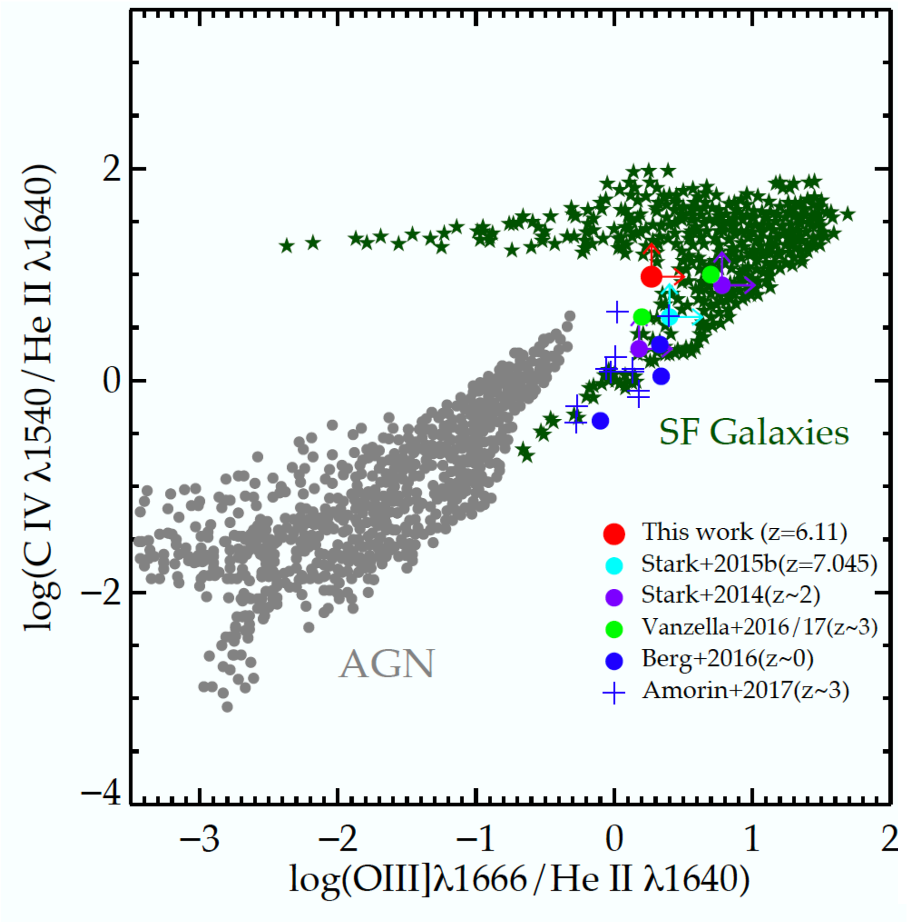


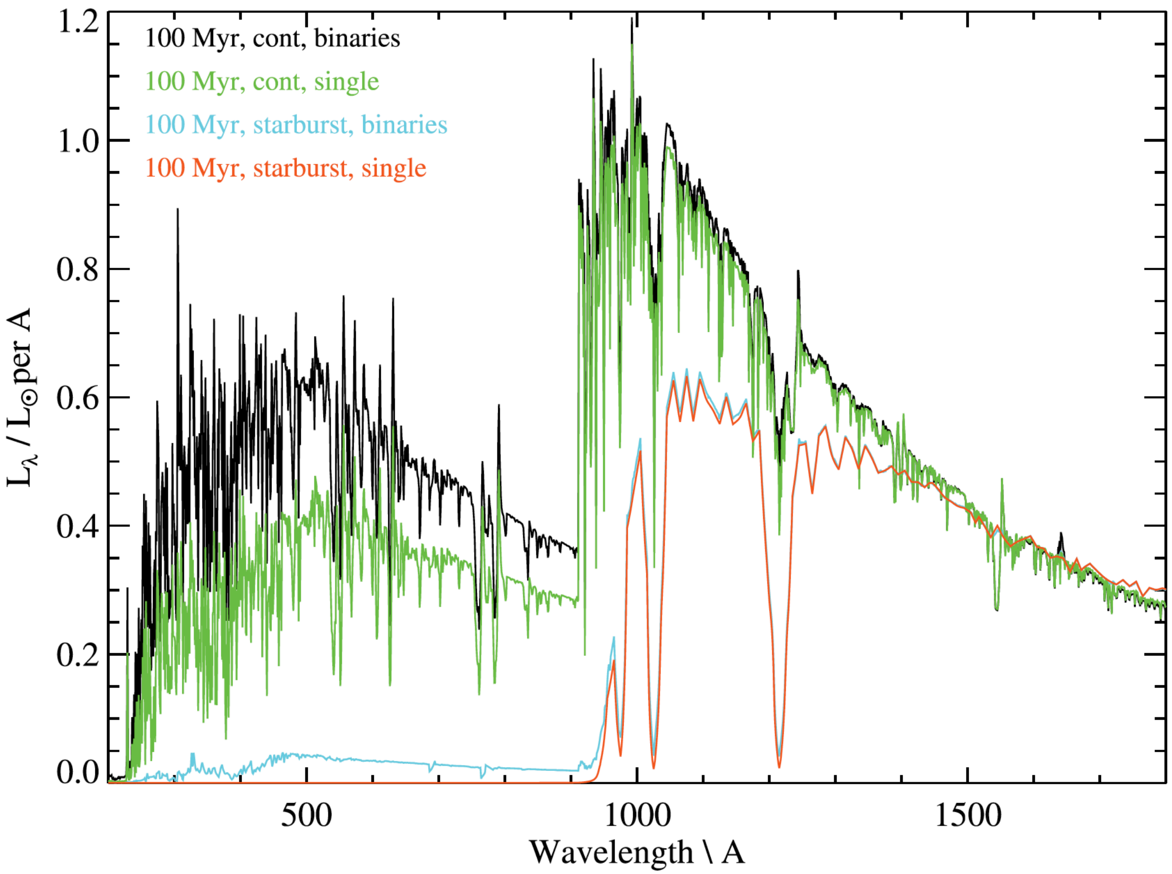


- z=6.11 spectroscopically confirmed galaxy with Lya EW_0 = 40Å and M_{UV} = −20 mag.
- CIV detected with EW_0 = 10Å. OIII] also detected. No HeII or NV.

Mainali et al. (2017), ApJ, 836, L14

Comparisons with Theoretical Results





- CIV-emitting faint LAEs have line ratios consistent with low metallicity hot stars.
- However, stellar population models still have large systematic uncertainties. (e.g., binary mass transfer, contribution from X-ray binaries)

Mainali et al. (2017), ApJ, 836, L14; Stanway et al. (2016), MNRAS, 456, 485

Summary

■ Galaxy Evolution

The galaxy UV LF based on large/deep surveys

bright end: excess from exponential decline

faint end: no significant evidence of flattening

■ Cosmic Reionization

Scenarios consistent with observational results exist, although ρ_{UV}, ξ_{ion}, and f_{esc} have large systematics.

■ First Galaxies

Spectroscopic identifications at z=7-11

No promising Pop III candidates