Galaxy Evolution Workshop 2018:

A Hard Ionising Spectrum in z=3-4 Lyman Alpha Emitters

Kimihiko Nakajima (NAOJ)

In collaboration with

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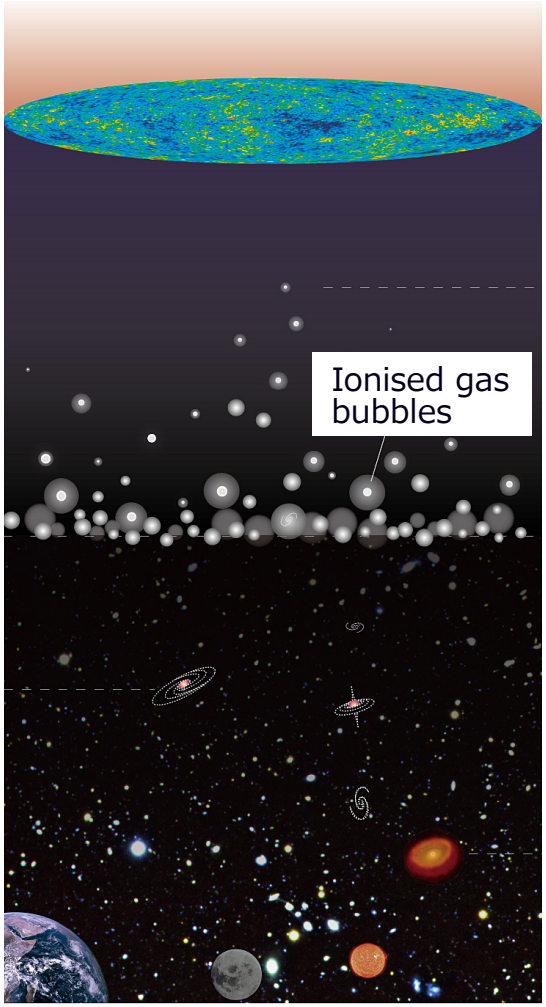
D. P. Stark (U. Arizona),

I. Iwata (Subaru), A. K. Inoue (Osaka Sangyo U.)

When and How Cosmic Reionisation occurred?



credit: Subaru telescope, NAOJ

z~1100 : Neutral Universe

Recombination

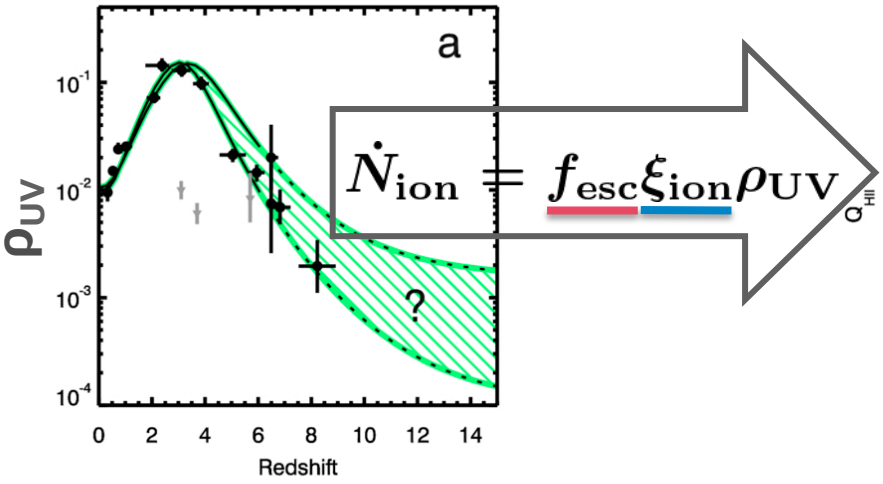
Reionisation

z~6 : Ionised Universe

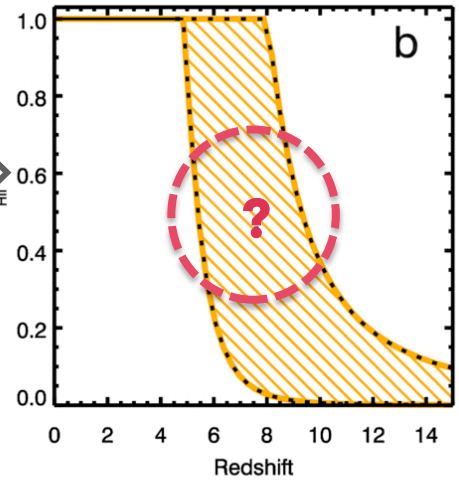
z=0 :

Galaxies governed Reionisation process?

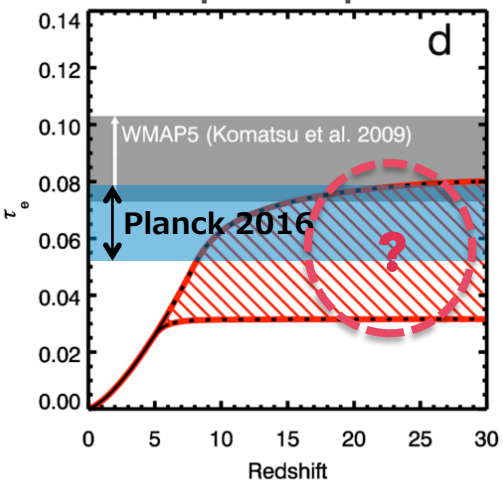
History of cosmic star-formation



Fraction of ionised hydrogen



Electron scattering Optical depth



$$\dot{Q}_{\rm HII} = \frac{\dot{N}_{\rm ion}}{\langle n_{\rm H} \rangle} - \frac{Q_{\rm HII}}{t_{\rm rec}}$$

$$\tau_{el}(z) = \int_0^z c\, dt\, n_e(z)\, \sigma_T$$

Robertson et al. 2010, Nature 468, 55

See also Robertson et al. 2015, Faisst 2016

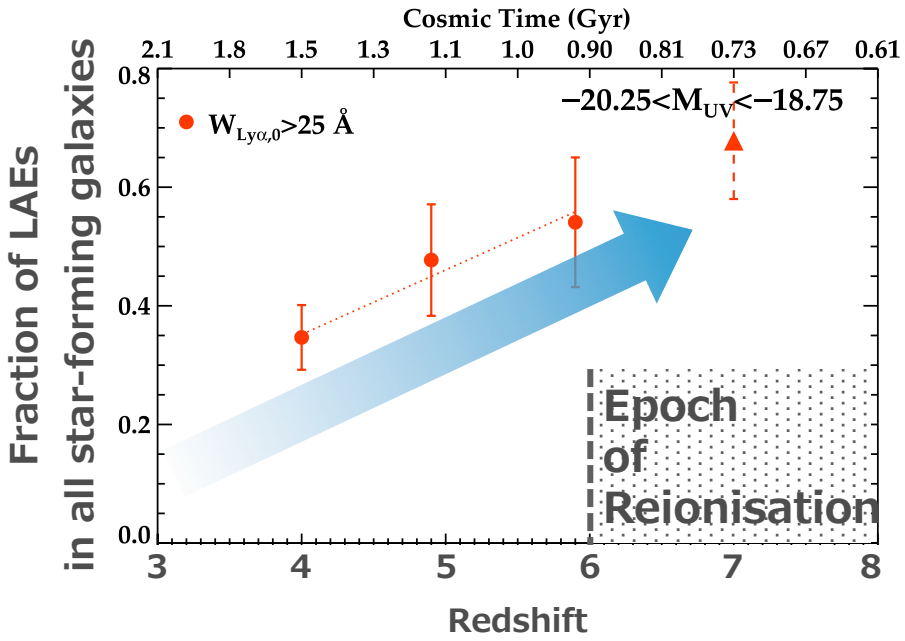
$$f_{\rm esc} = \dot{n}_{\rm ion,esc} / \dot{n}_{\rm ion}$$

Fraction of ionising photons that escape into IGM

$$\xi_{\rm ion} = \dot{n}_{\rm ion} / L_{\rm UV}$$

Efficiency of ionising photon production

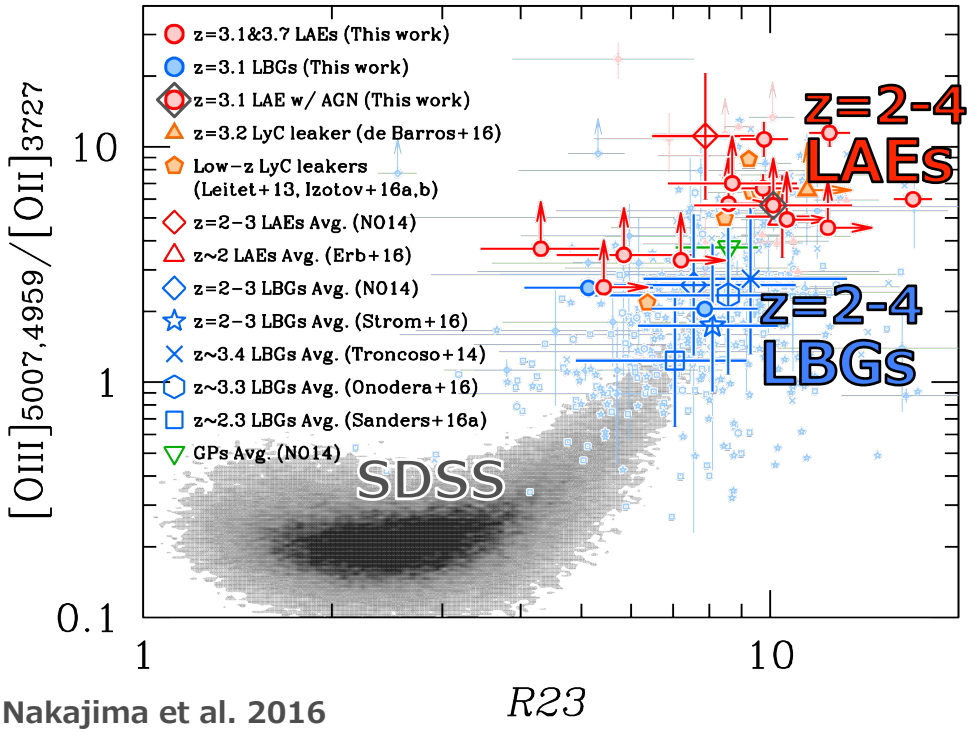
Lyα emitters (LAEs) as Probes of Early galaxies



Stark et al. 2011, ApJL, 728, L2

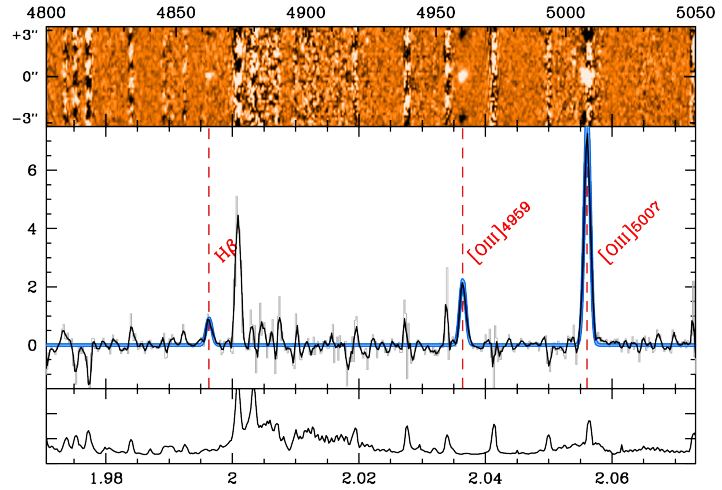
- Low-mass, metal-poor, young star-forming galaxies
- Typical in early universe

Lyα emitters (LAEs) as Probes of Early galaxies



Nakajima et al. 2016

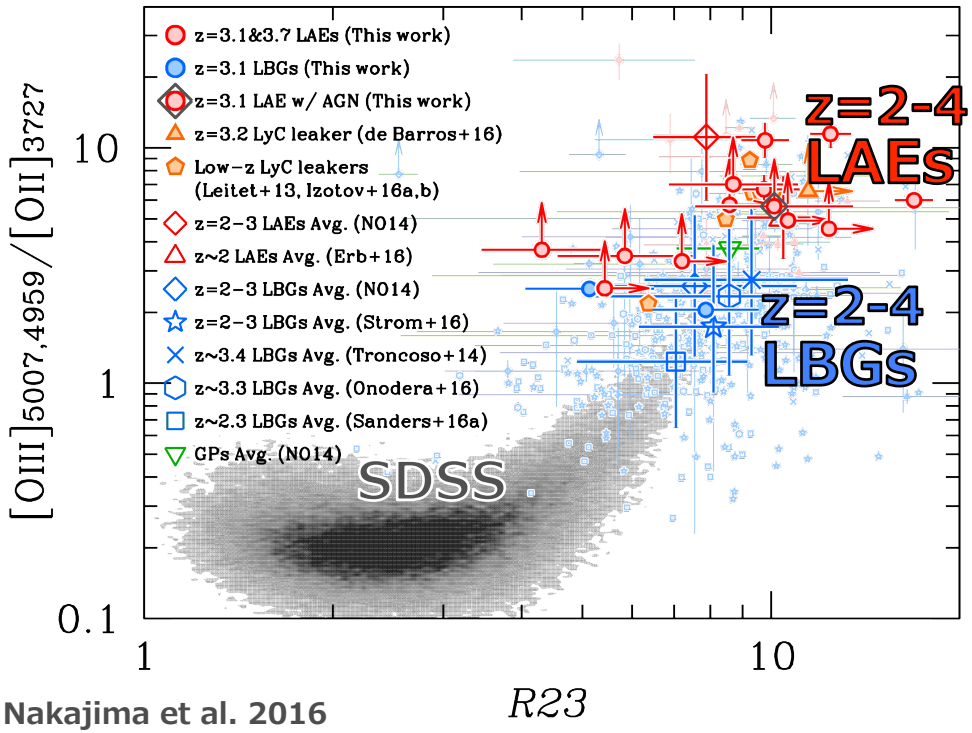
z=3.1 LAE's MOSFIRE K spectrum



See also Nakajima&Ouchi 2014, Erb+2016, Kojima+2017

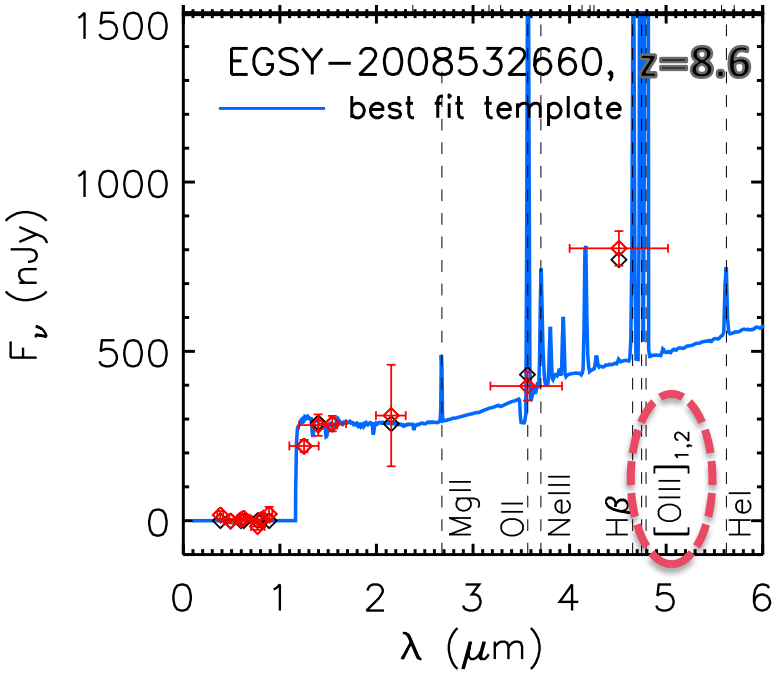
- Low-mass, metal-poor, young star-forming galaxies
- Typical in early universe
- Intense nebular lines, e.g. [OIII]5007,4959

Lyα emitters (LAEs) as Probes of Early galaxies



Nakajima et al. 2016

Roberts-Borsani et al. 2016



See also Smit+2014,2015

See also Nakajima&Ouchi 2014, Erb+2016, Kojima+2017

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LAEs present Hard Ionising Spectrum ..?

$$\xi_{\rm ion} = \dot{n}_{\rm ion} / L_{\rm UV}$$

Efficiency of ionising photon production

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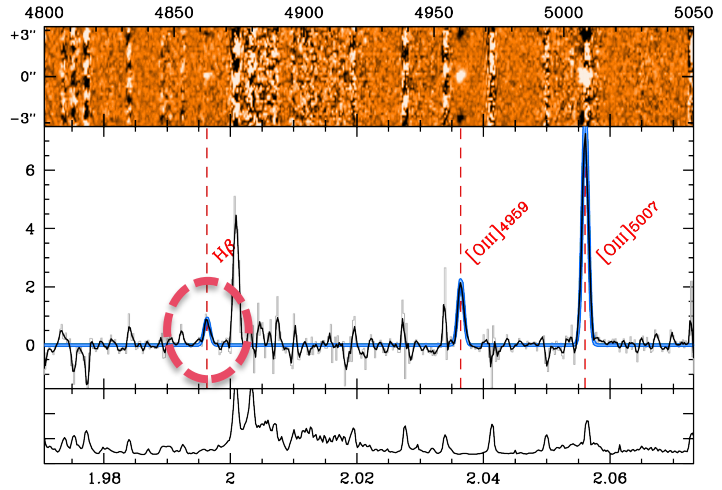

Nakajima et al. 2016

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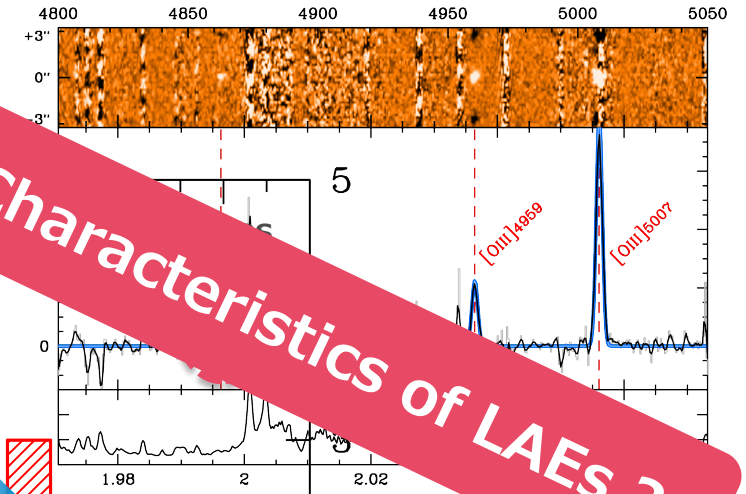
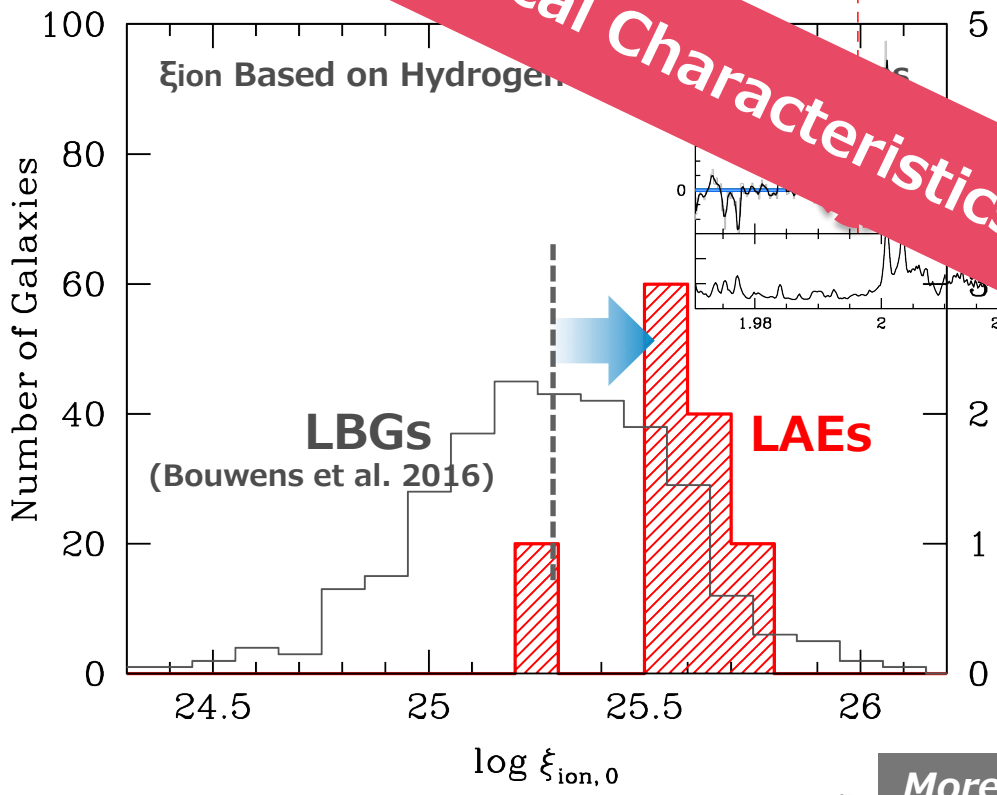


Typical Characteristics of LAEs ?

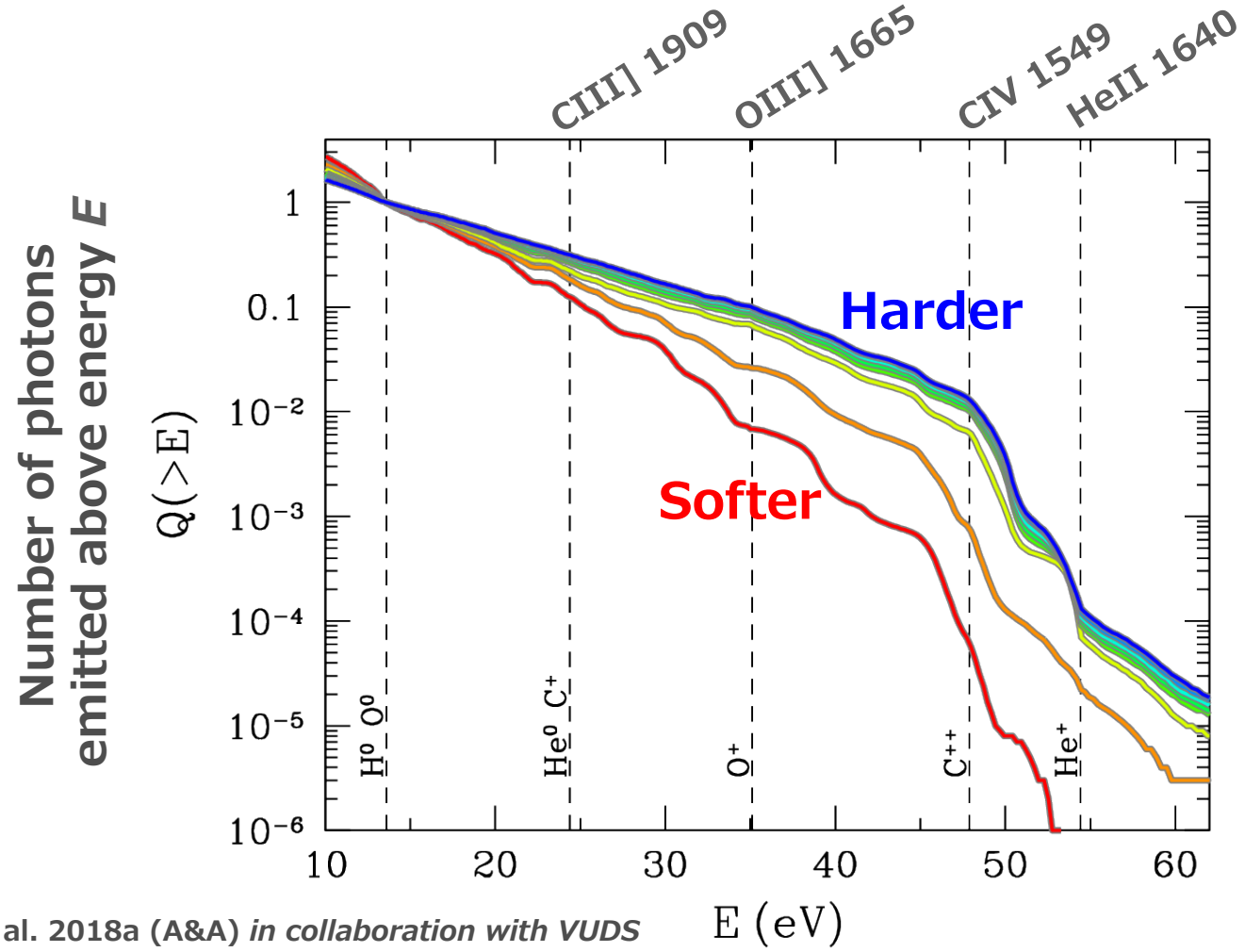


More efficient production of ionising photons

Nakajima et al. 2016

Refer also to Poster by M. Hilmi

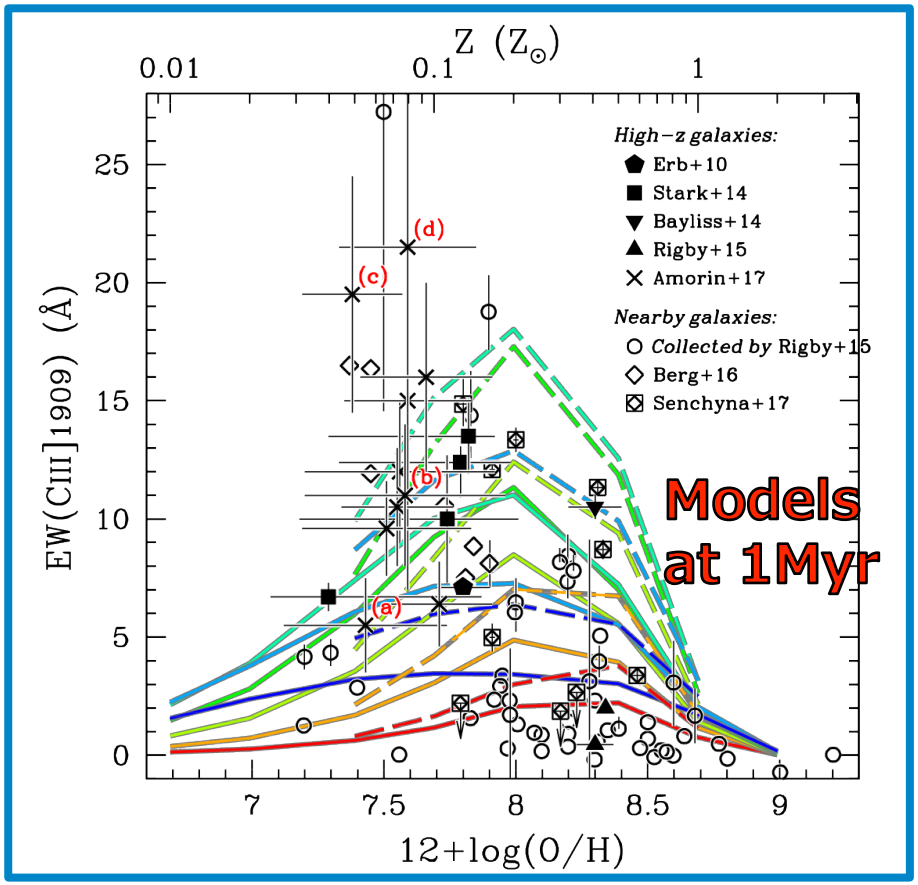
Nature of Ionising Spectrum Examined by UV Emission lines

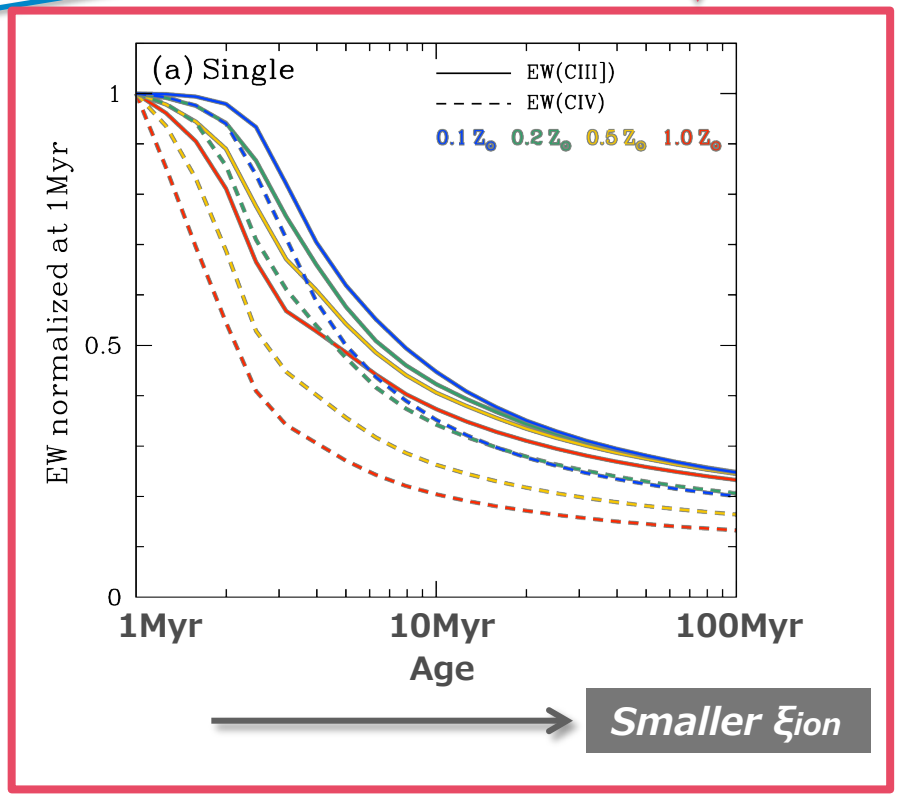


Nakajima et al. 2018a (A&A) *in collaboration with VUDS*

UV line diagnostics of ξion

$$EW(CIII]) = \frac{Flux(CIII])}{f_{\lambda,1909}} \propto \frac{N_{ion}(>24.4eV)}{L_{UV}} = f(Z,U,\xi_{ion}(age))$$

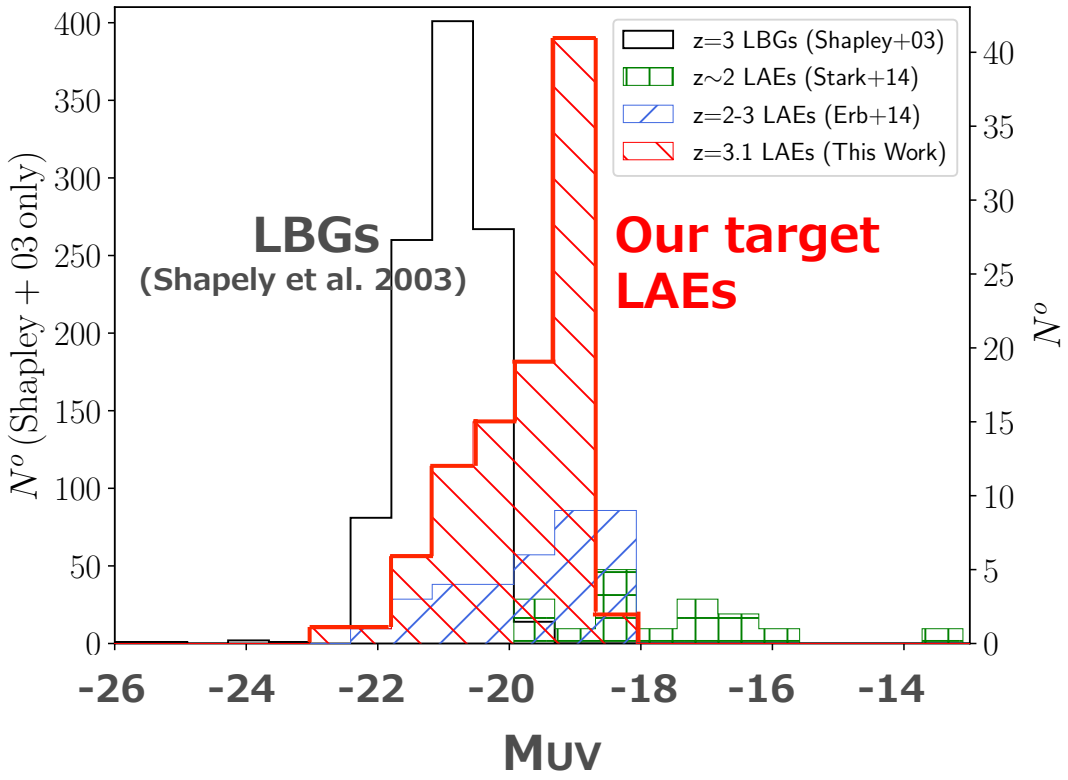




Nakajima et al. 2018a (A&A) *in collaboration with VUDS*

See also Stark+2014, Gutkin+2016

VLT/VIMOS (11hrs) Observation Identifying Lyα from ~70 Faint z=3 LAEs



Nakajima et al. 2018b (MNRAS)

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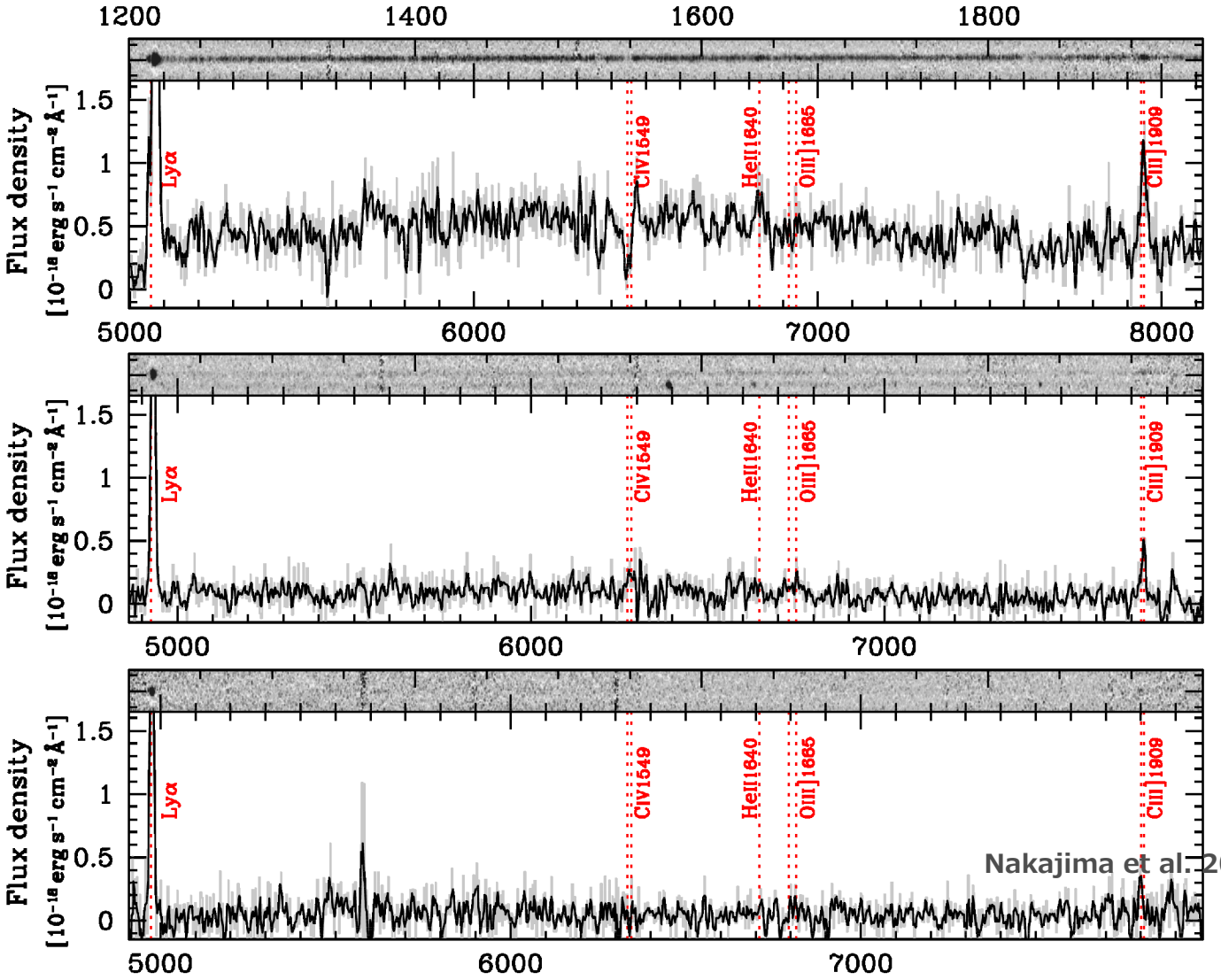

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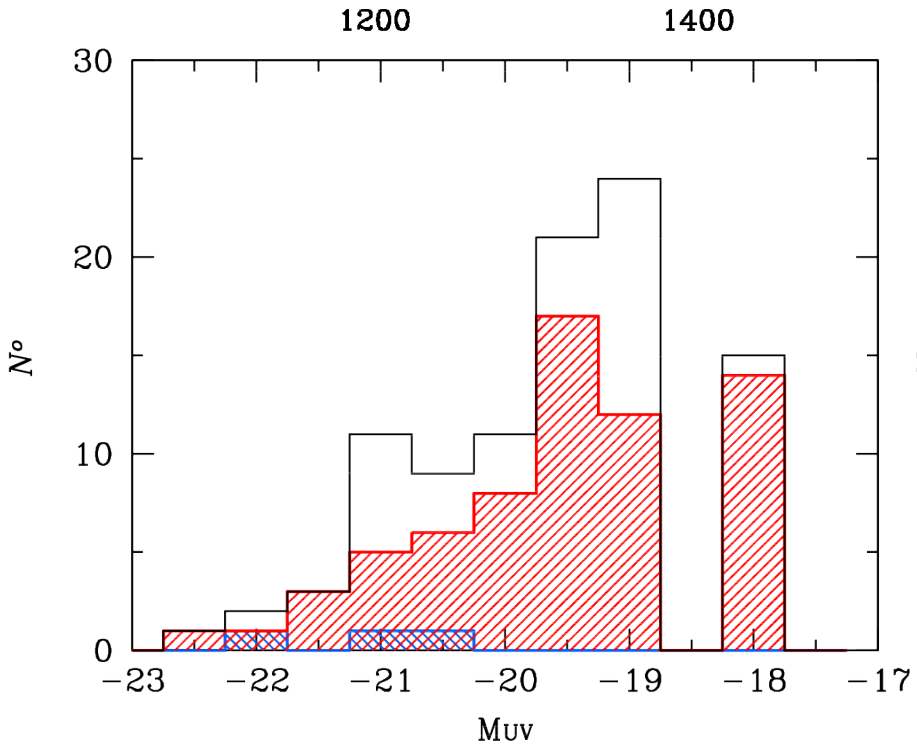
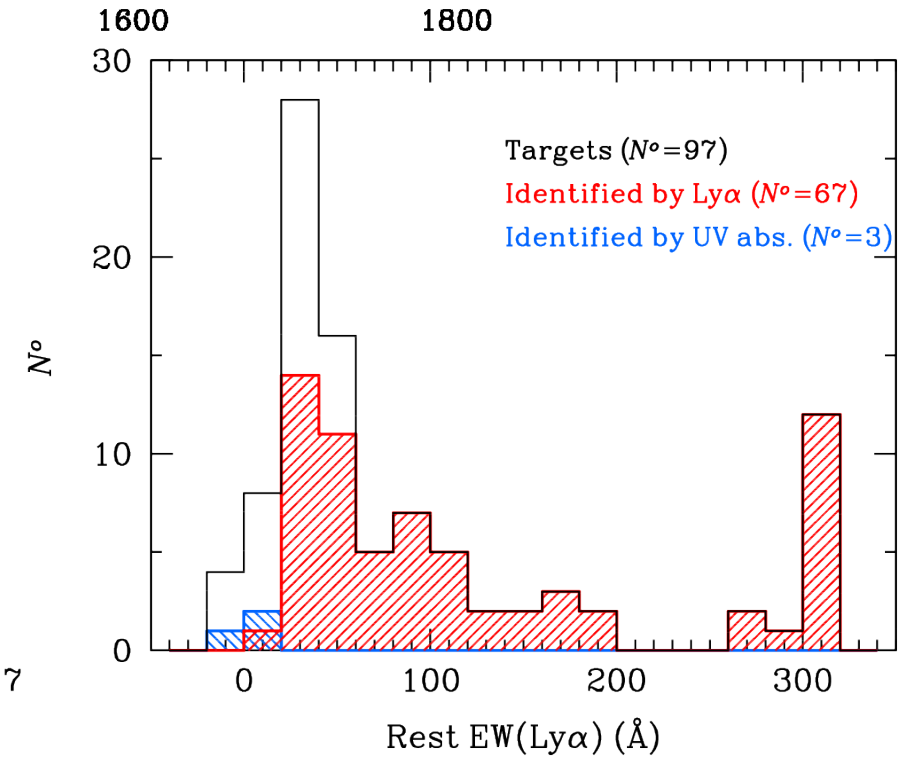
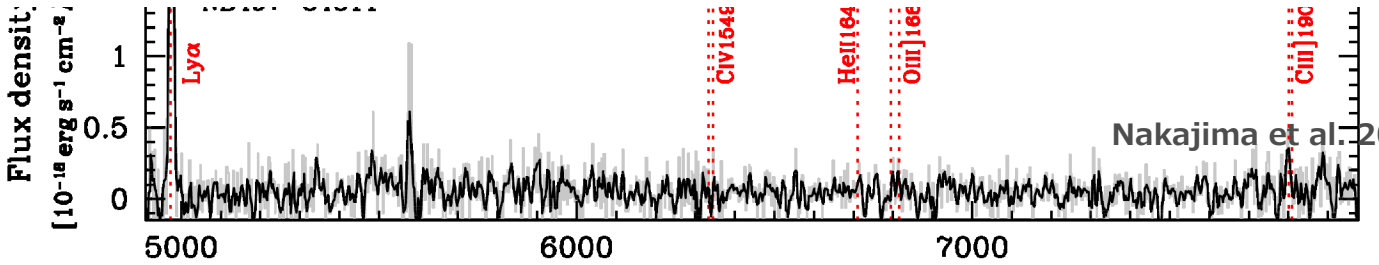
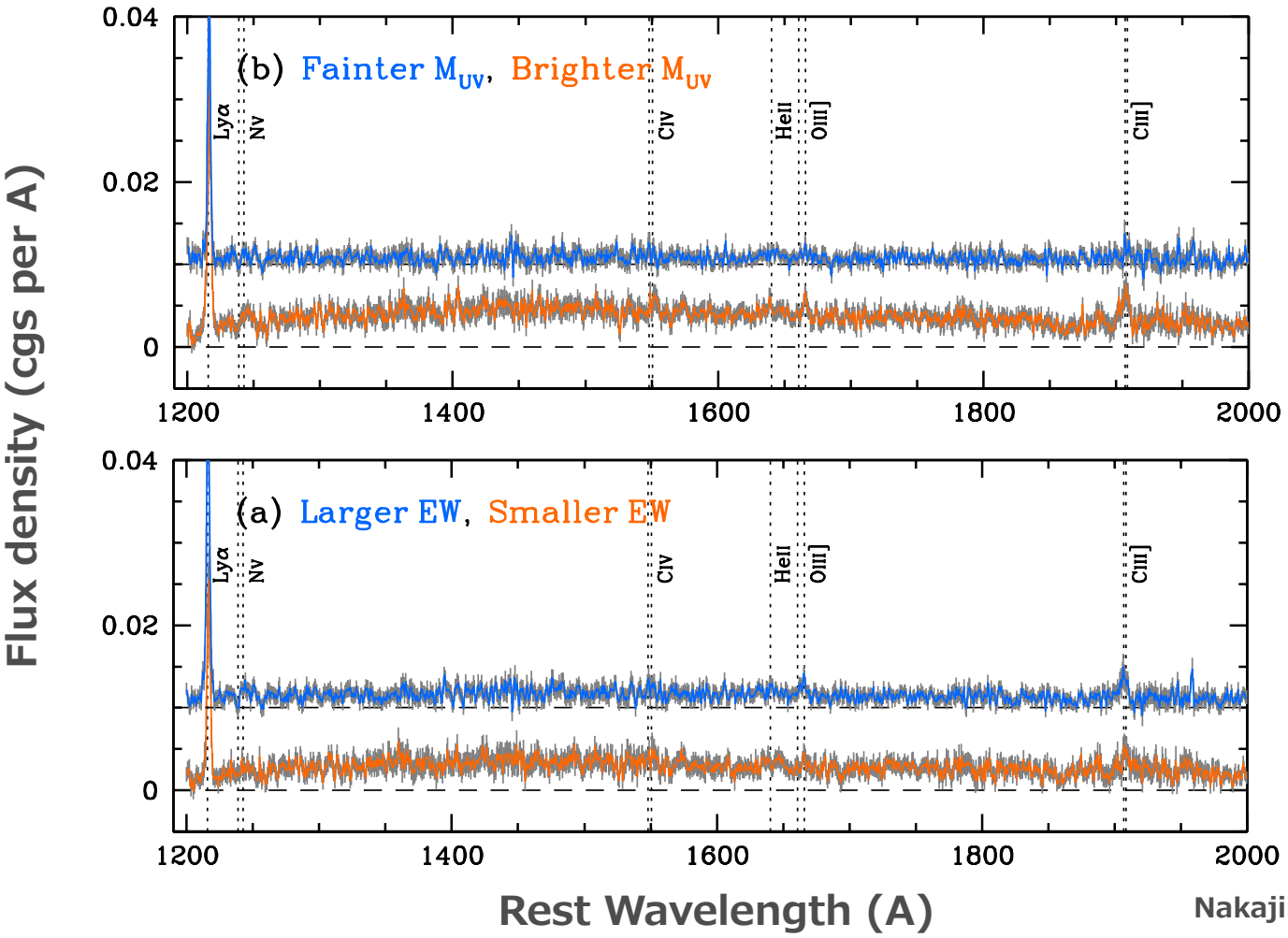






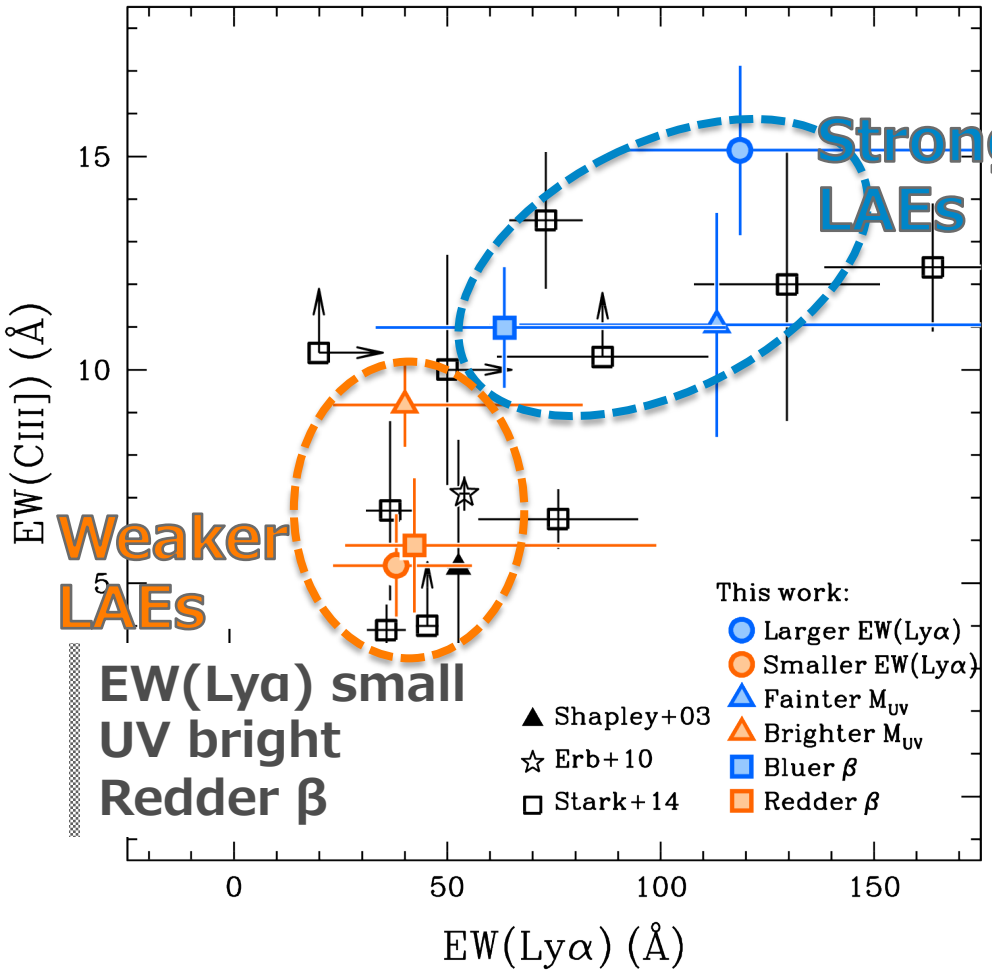
Nakajima et al. 2018b (MNRAS)

VLT/VIMOS (11hrs) Observation
Identifying rest UV lines in Stacks of 70 z=3 LAEs



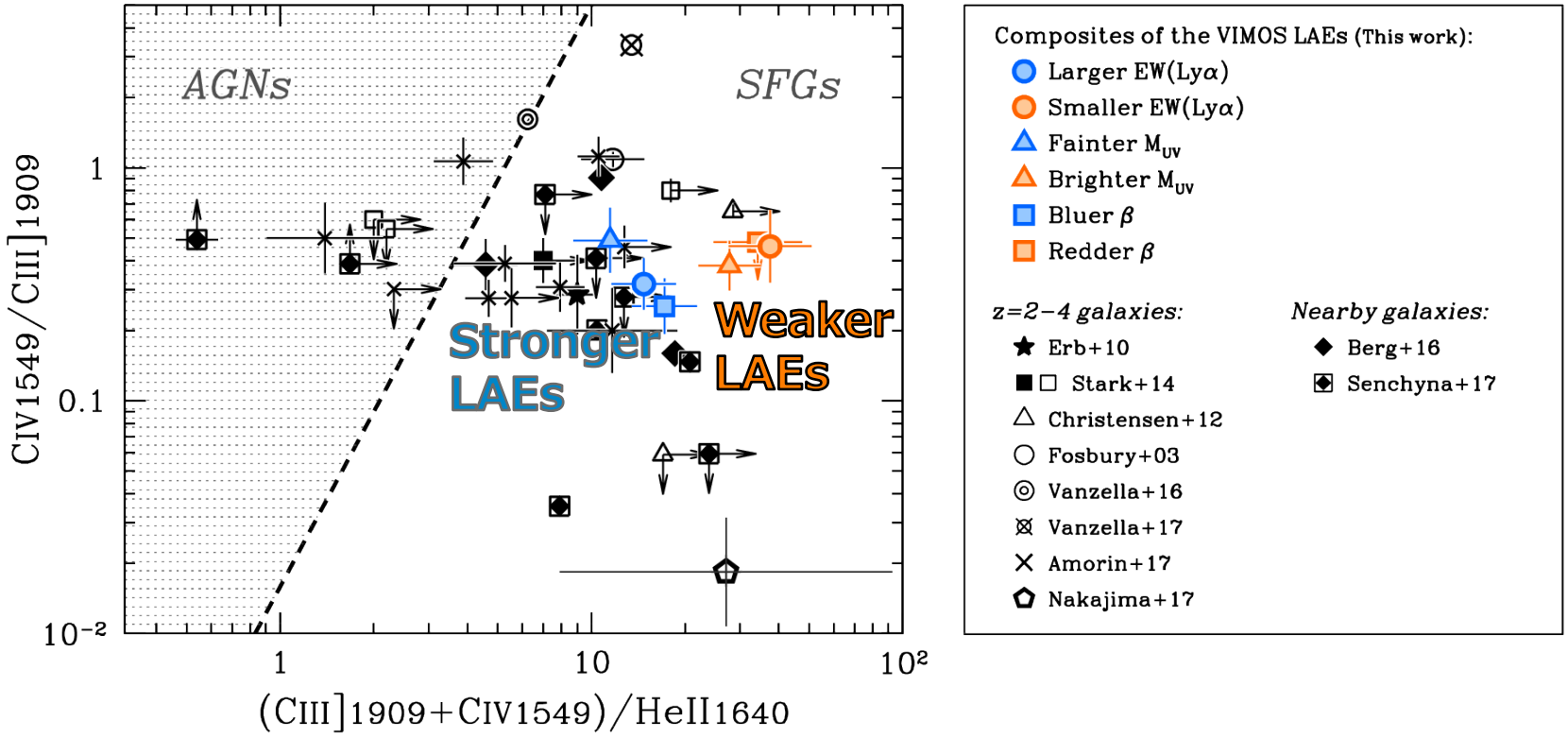
Nakajima et al. 2018b

Strong CIII] Associated with Strong Lyα



Nakajima et al. 2018b

Stronger LAEs Characterised by lower metallicity



Nakajima et al. 2018b

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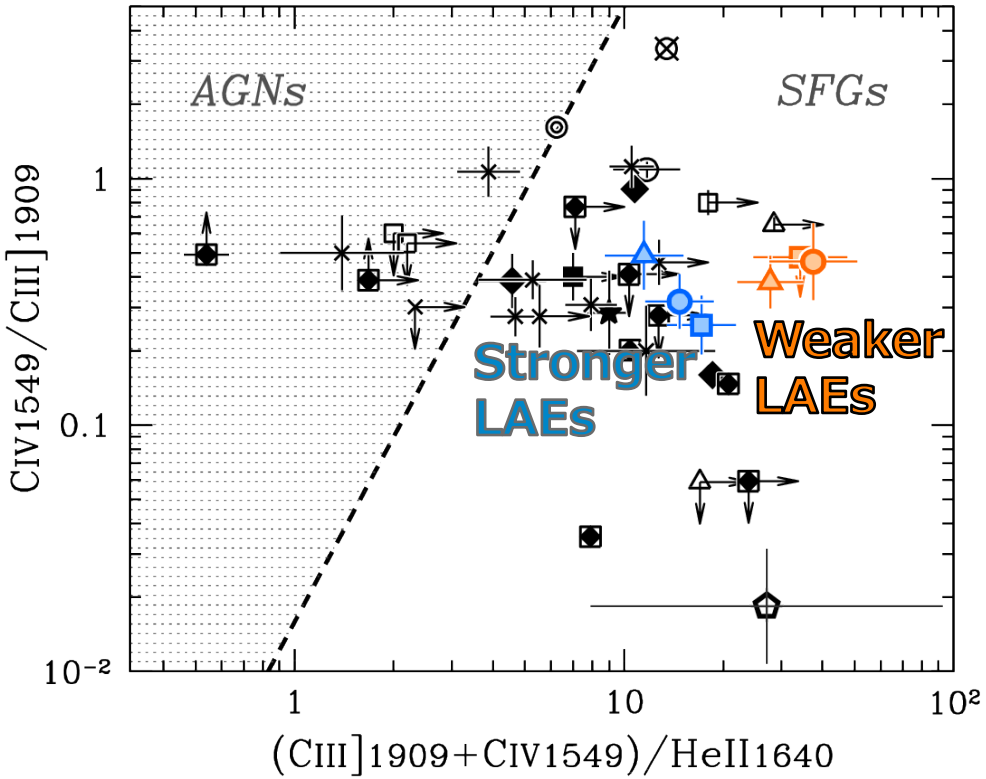
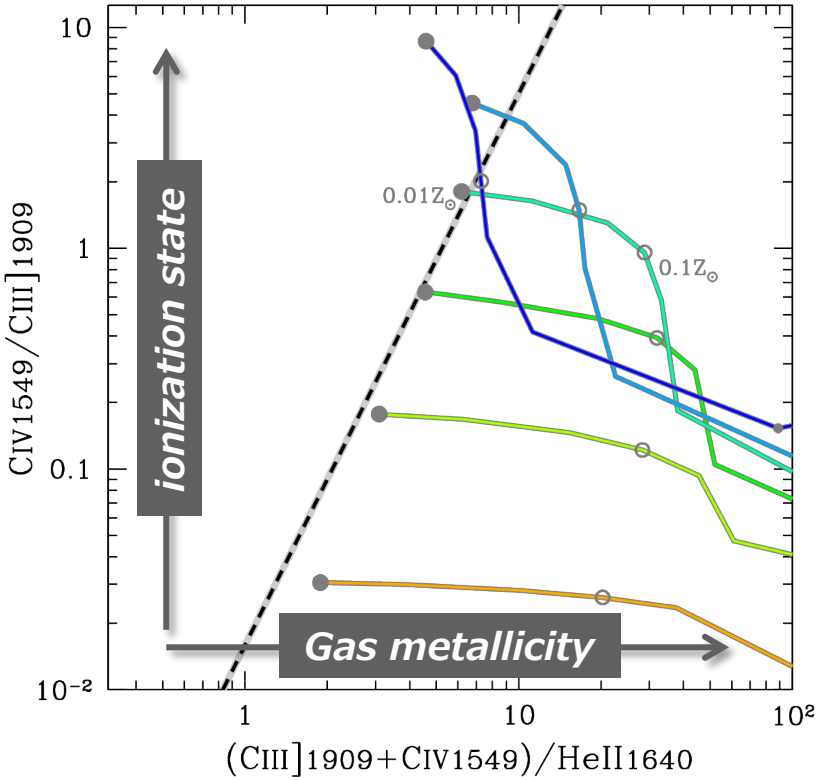


Nakajima et al. 2018b

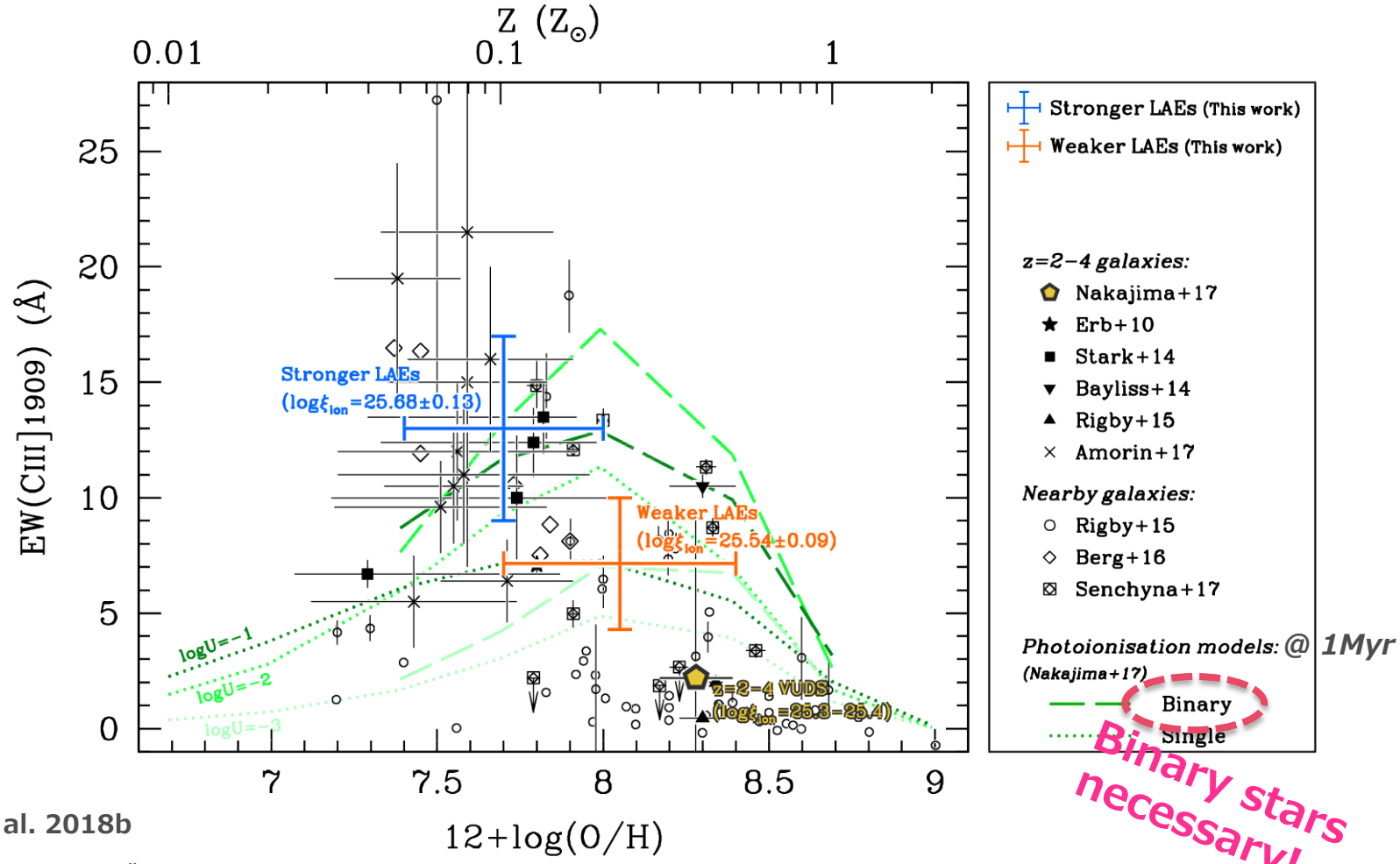


Nakajima et al. 2018a

Stronger LAEs: Z = 0.05 – 0.2 Z_{sun}

Weaker LAEs: Z = 0.1 – 0.5 Z_{sun}

LAEs' Hard ξion Confirmed with UV line analysis

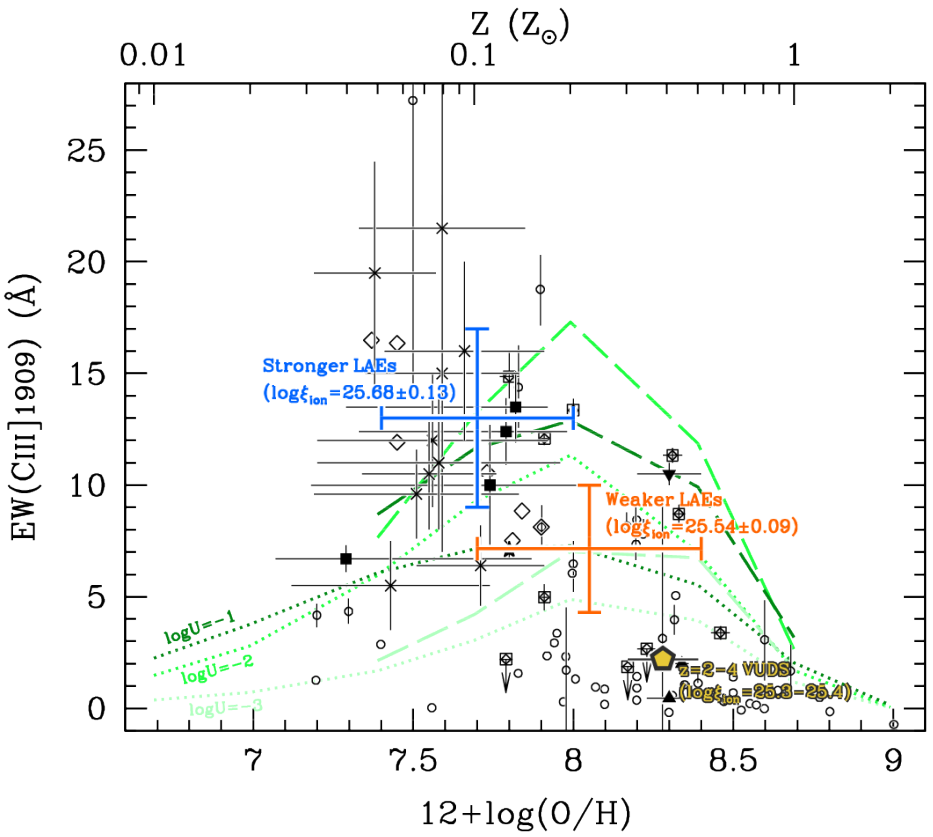


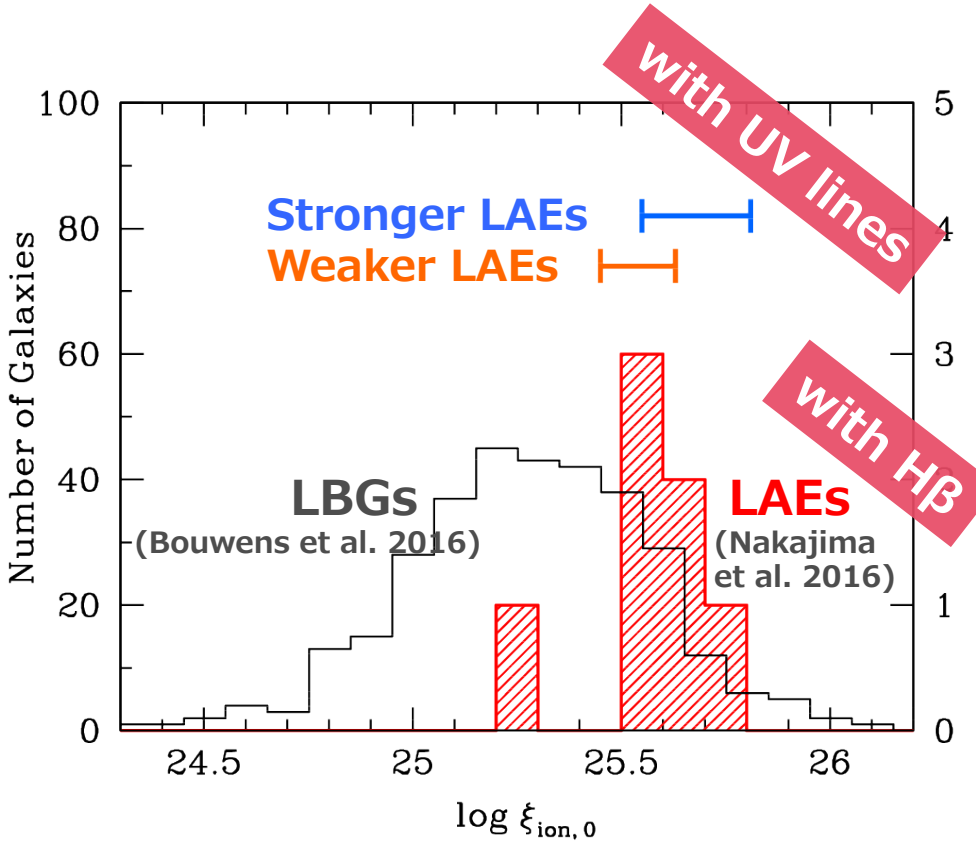
Nakajima et al. 2018b

Stronger LAEs: log ξion = 25.68±0.13

Weaker LAEs: log ξion = 25.54±0.09

LAEs' Hard ξion Confirmed with UV line analysis





Nakajima et al. 2018b

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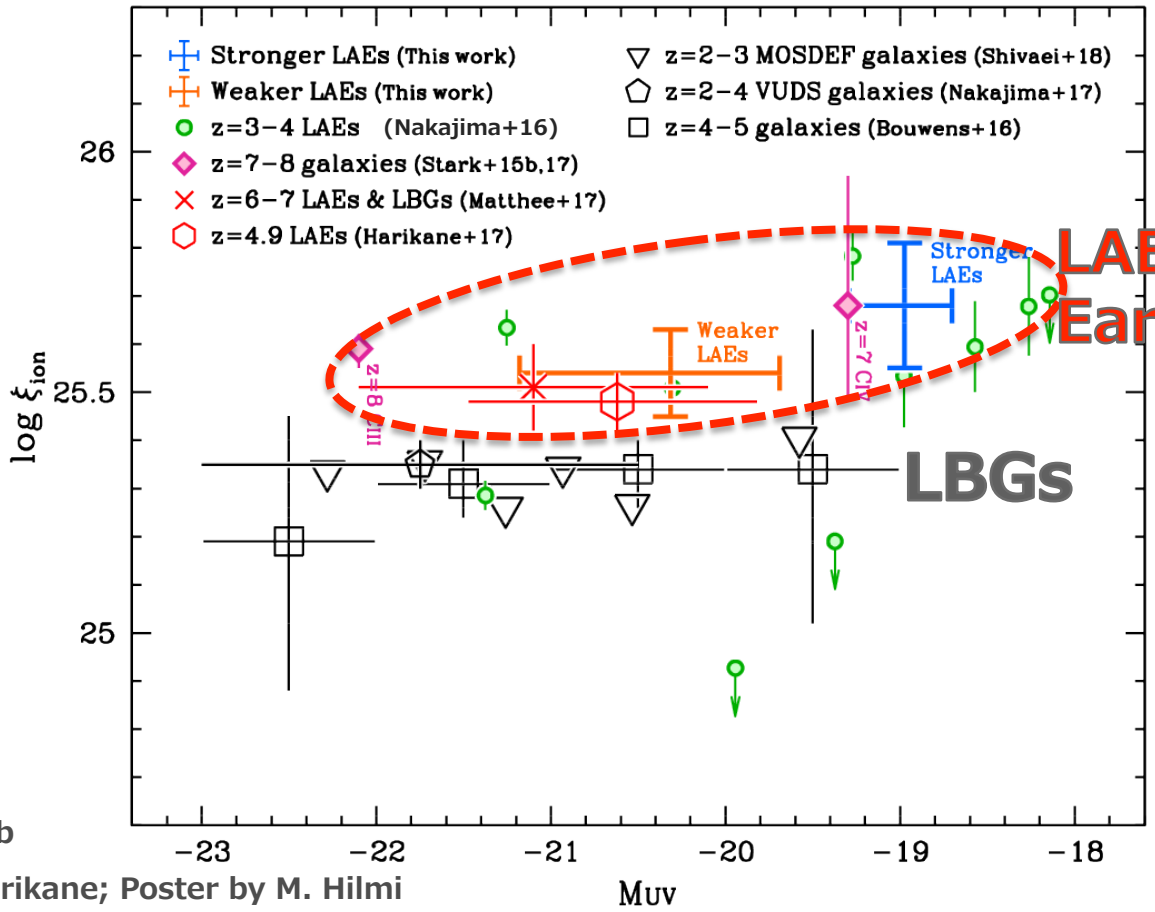
ξion as functions of UV luminosity, redshift and Lyα



Nakajima et al. 2018b

Refer to Talk by Y. Harikane; Poster by M. Hilmi

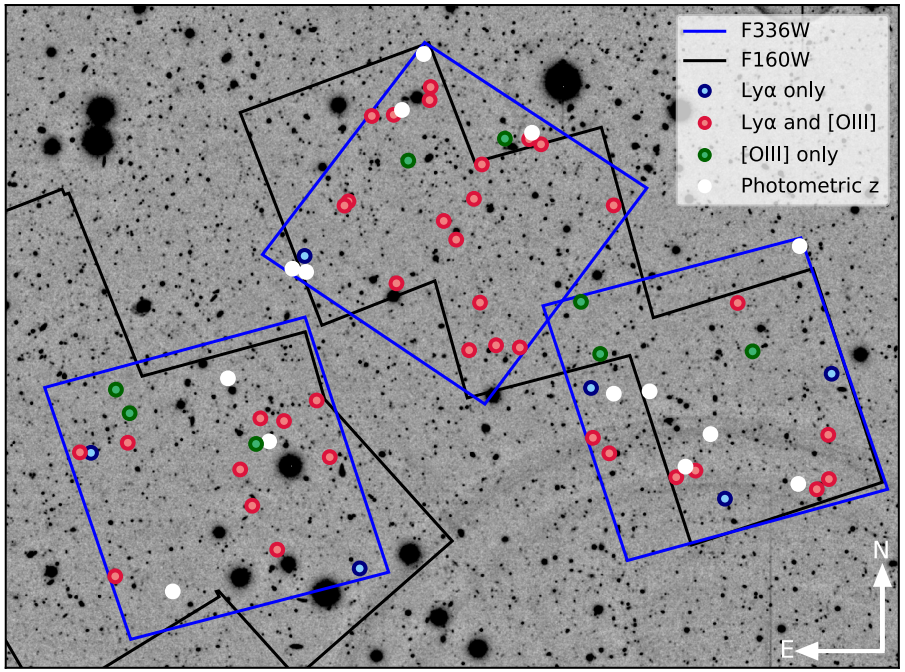
LBGs: Uniform ξion (~25.2--25.4), independent of MUV, *z*

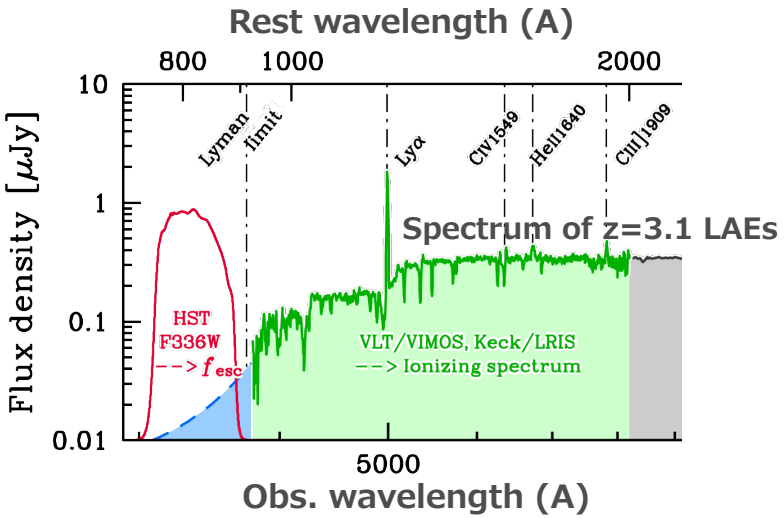
LAEs: Larger ξion (~25.5--25.7), particularly for faintest LAEs

→ Analogous to Galaxies in EoR

LymAn Continuum Escape Survey (LACES): UV Imaging of z=3 LAEs

- Deep (20orbits x3) HST/F336W imaging of 54 z=3 LAEs



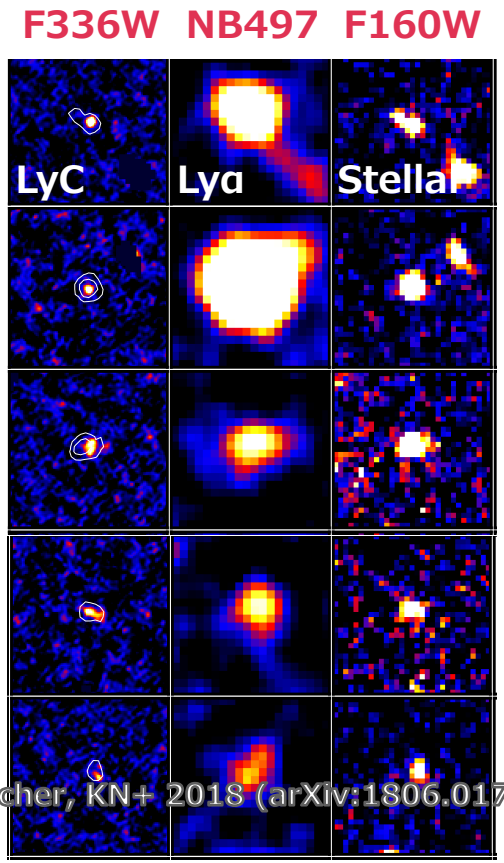


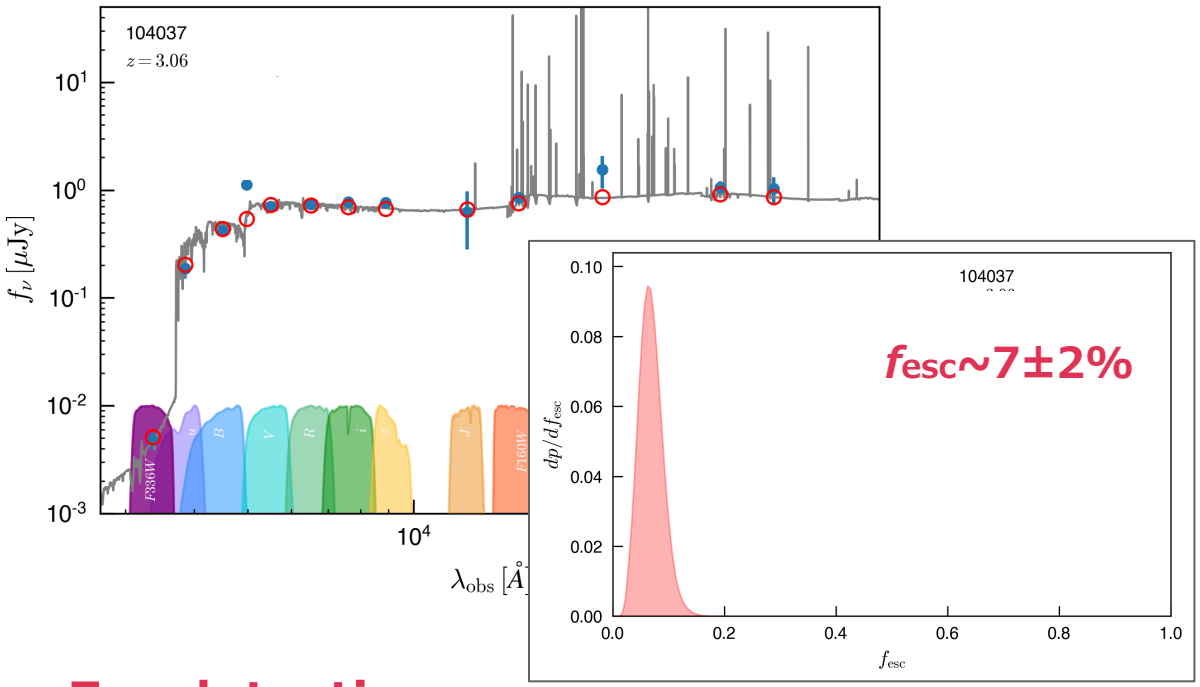
Fletcher, KN+ 2018 (arXiv:1806.01741)

See also Mostardi+15, Siana+15, Steidel+18, etc.

LymAn Continuum Escape Survey (LACES): UV Imaging of z=3 LAEs

- Deep (20orbits x3) HST/F336W imaging of 51 z=3 LAEs
- **High success rate** in securing significant F336W detections (~30%)
- Minimal foreground contamination





Fletcher, KN+ 2018 (arXiv:1806.01741)

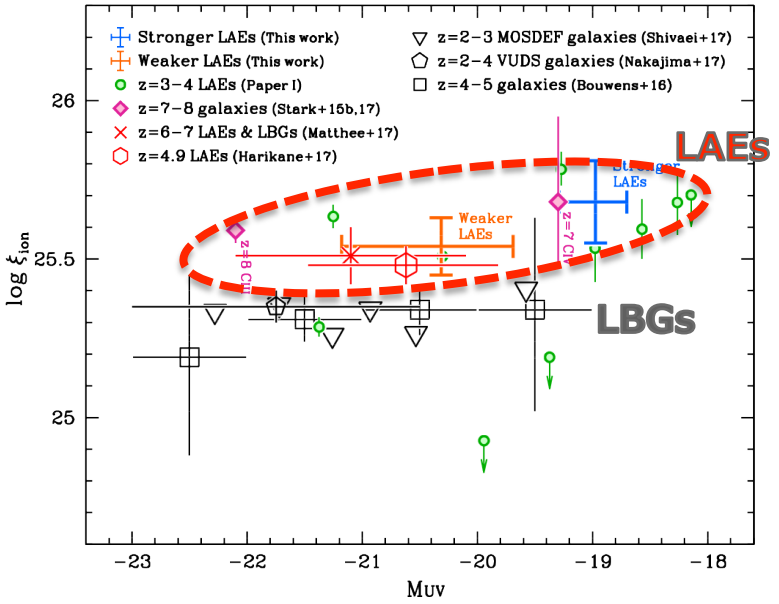
For detections:

Individual *f*esc ranges from ~2-80%

Summary

LAEs are ideal analogs of sources in Reionization era

- Low-mass, Low-metallicity, Young
- Intense [OIII]5007,4959
- **Hard Ionizing Spectrum**



Galaxies like LAEs could dominate Reionization process

- Hard Ionizing Spectrum
- **High Escape Fraction?**
- → *Being examined by LACES*