New method for probing Lyman continuum galaxies with high LyC escape fraction

Satoshi Yamanaka (Waseda University)

Akio Inoue (Waseda University)
Toru Yamada (JAXA/ISAS)
Ikuru Iwata (NAOJ),
Erik Zackrisson (Uppsala University)
Genoveva Micheva (AIP)
Mariko Kubo (NAOJ)
Ken Mawatari (ICRR)
Takuya Hashimoto (Waseda University)
Takuya Otsuka (Tohoku University)
Yuki Kimura (Tohoku University)

June 7, 2019
6th Galaxy Evolution Workshop 2019 @ ICRR

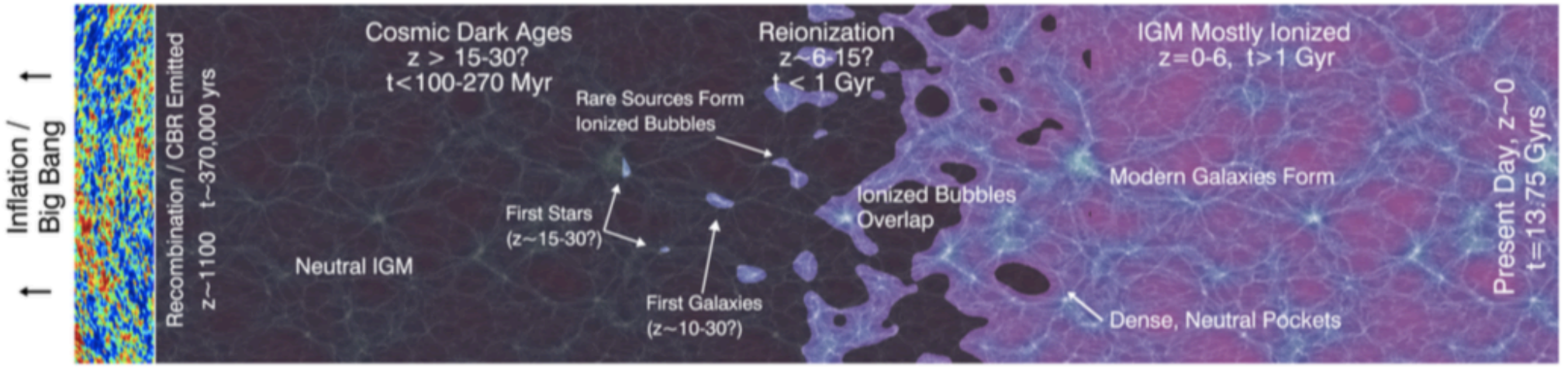
Contents

Introduction

Cosmic reionization

- Neutral hydrogen in the intergalactic medium (IGM) is ionized
- Reionization seems to be finished until z~6
- The sources of cosmic reionization is not well understood
- One of the key parameter is the escape fraction of ionizing photons

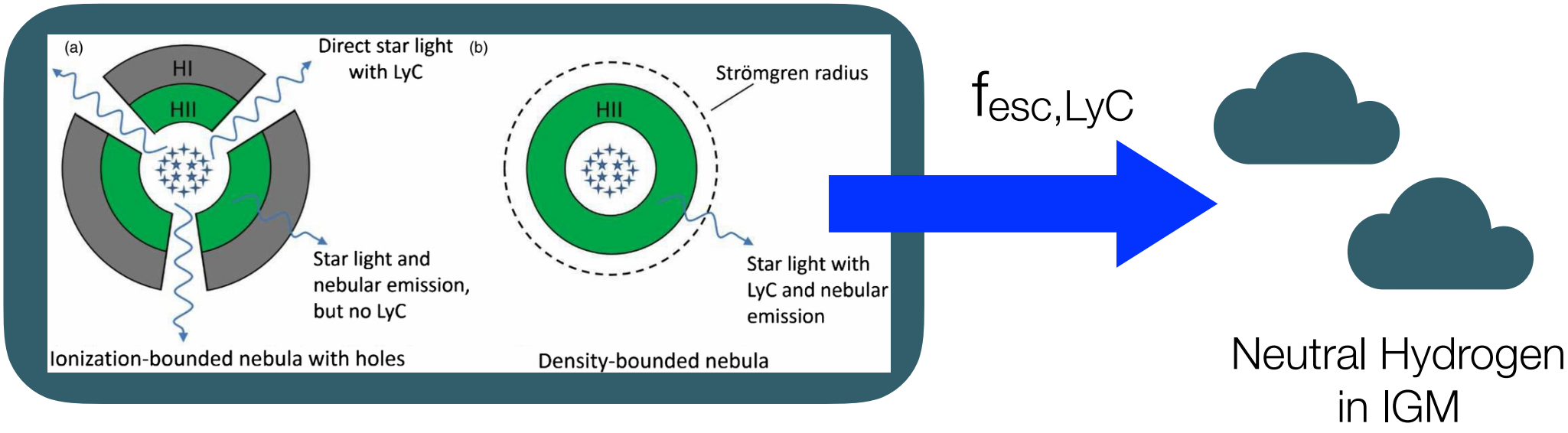
Robertson+10



Introduction

Escape fraction of ionizing photons

- The fraction of ionizing photons (Lyman continuum; LyC, λ_{rest}<912A) which escape from galaxies into the surrounding IGM.
- One of the key parameter for understanding the sources of cosmic reionization.

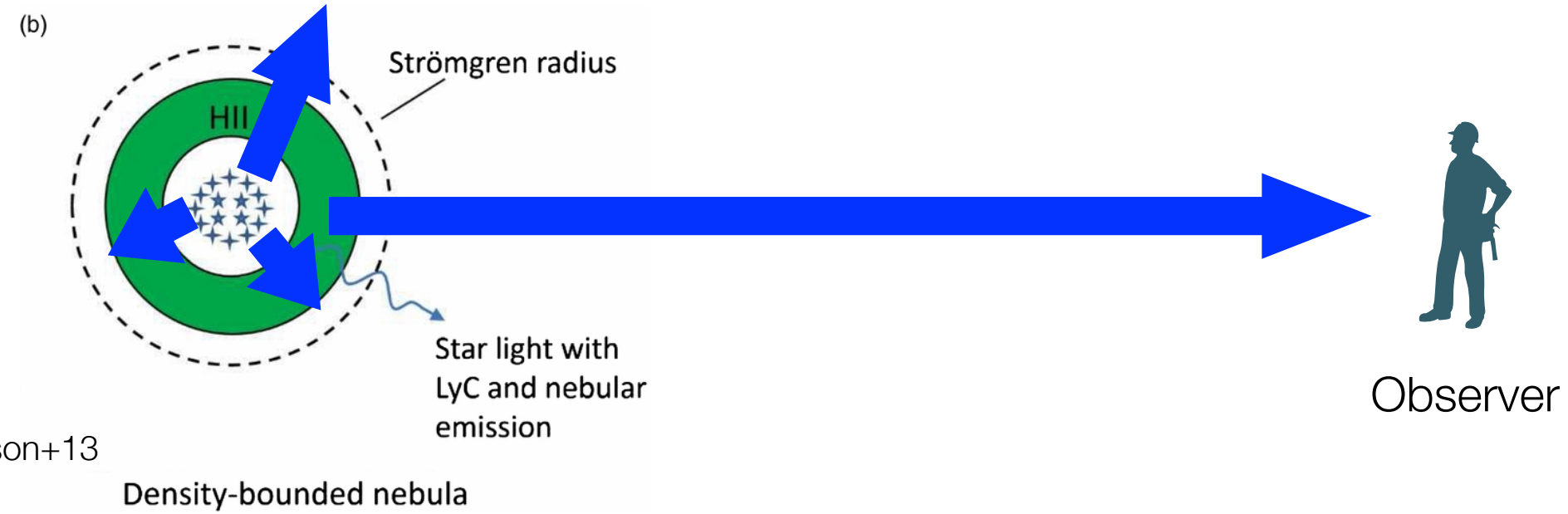


Zackrisson+13

Introduction

Escape fraction of ionizing photons

- The escape fraction of LyC, $f_{esc,LyC}$, is measured as the ratio of **observed** to **intrinsic** number of LyC photons
- Due to the foreground IGM absorption by HI clouds, it is almost impossible to directly measure the escaped LyC photons for galaxies at $z > 5$.

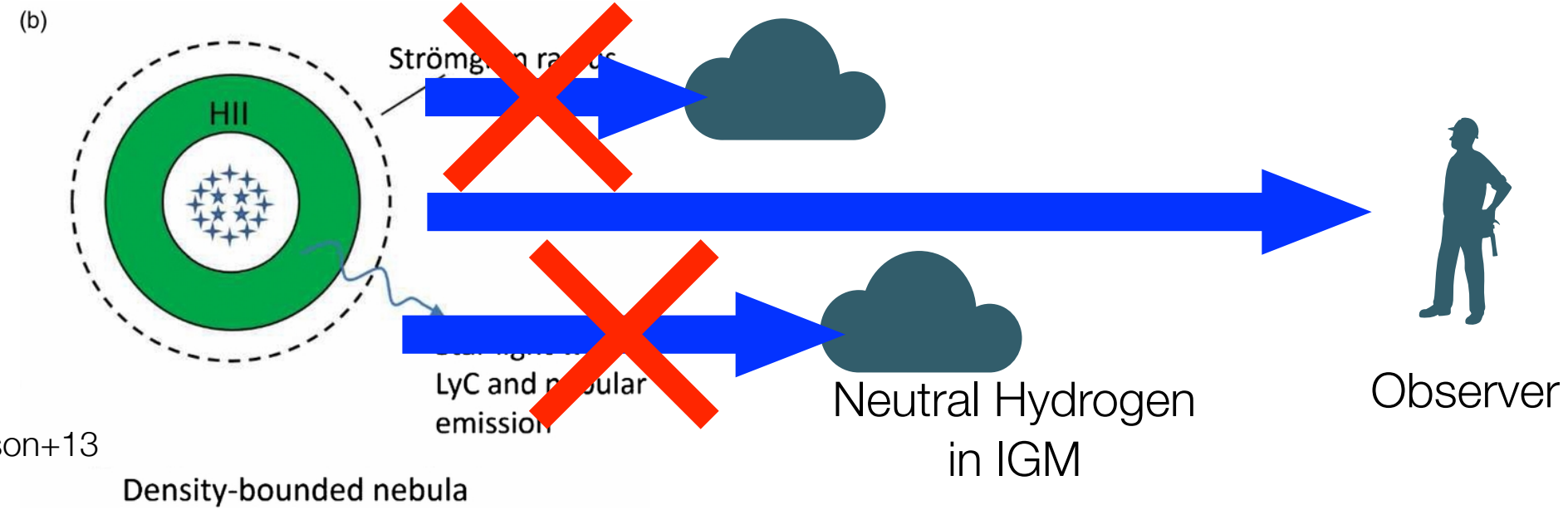


Zackrisson+13

Introduction

Escape fraction of ionizing photons

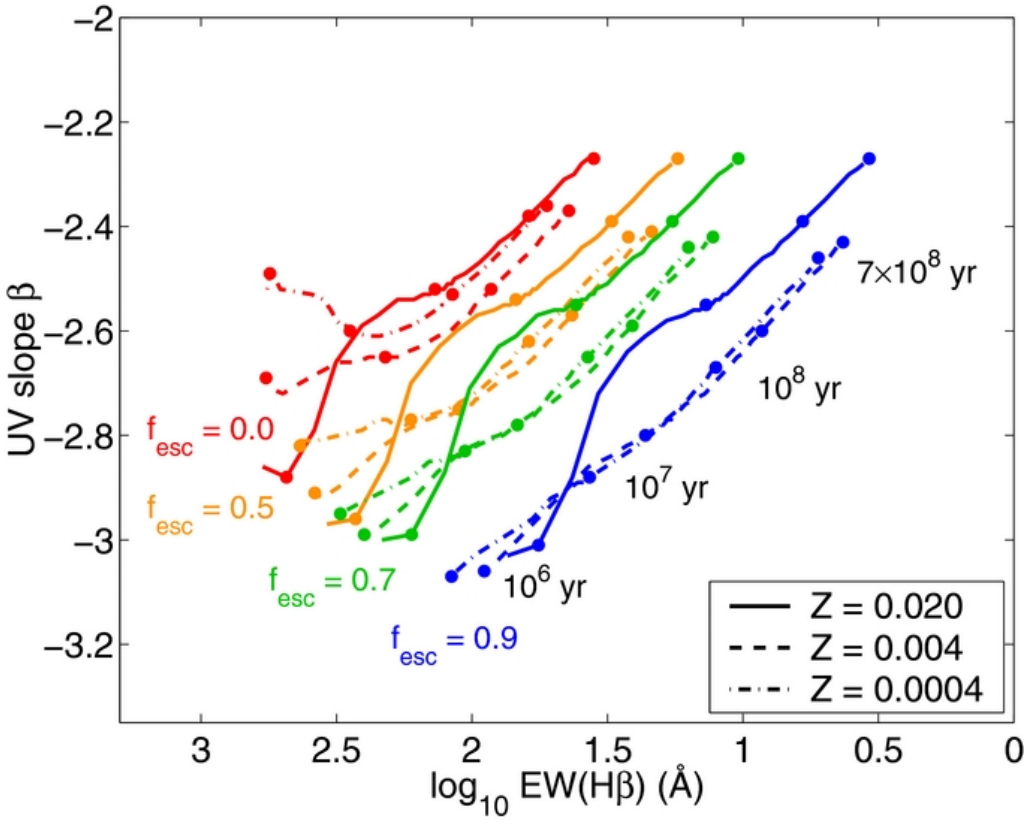
- The escape fraction of LyC, $f_{esc,LyC}$, is measured as the ratio of **observed** to **intrinsic** number of LyC photons
- Due to the foreground IGM absorption by HI clouds, it is almost impossible to directly measure the escaped LyC photons for galaxies at $z > 5$.



Zackrisson+13

Introduction

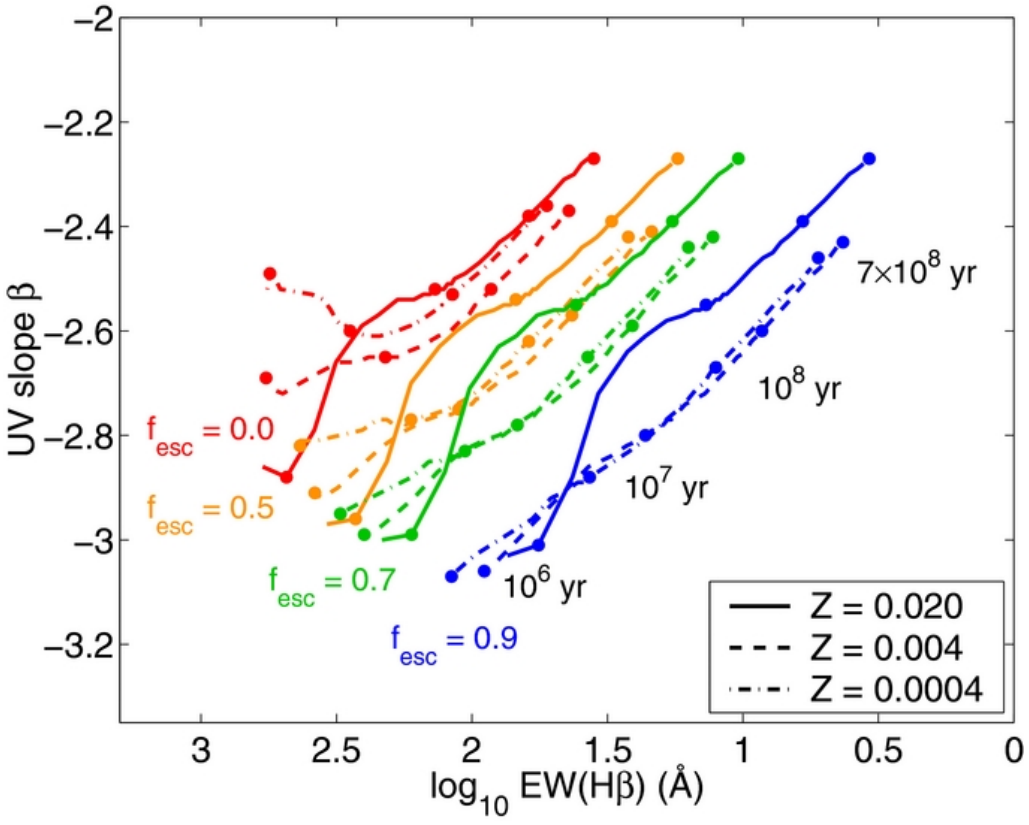
EW(Hβ)–β method



- EW(Hβ)–β method is proposed by Zackrisson+13
- Zackrisson+13 predicts that galaxies are separately distributed on the space of Hβ equivalent width (EW) and the UV spectral slope β according to fesc.
- EW(Hβ) represents the amount of LyC photons used in the galaxy.
- The UV spectral slope β represents the stellar population of the galaxy, and it roughly indicates the intrinsic production rate of LyC photons

Introduction

EW(Hβ)–β method



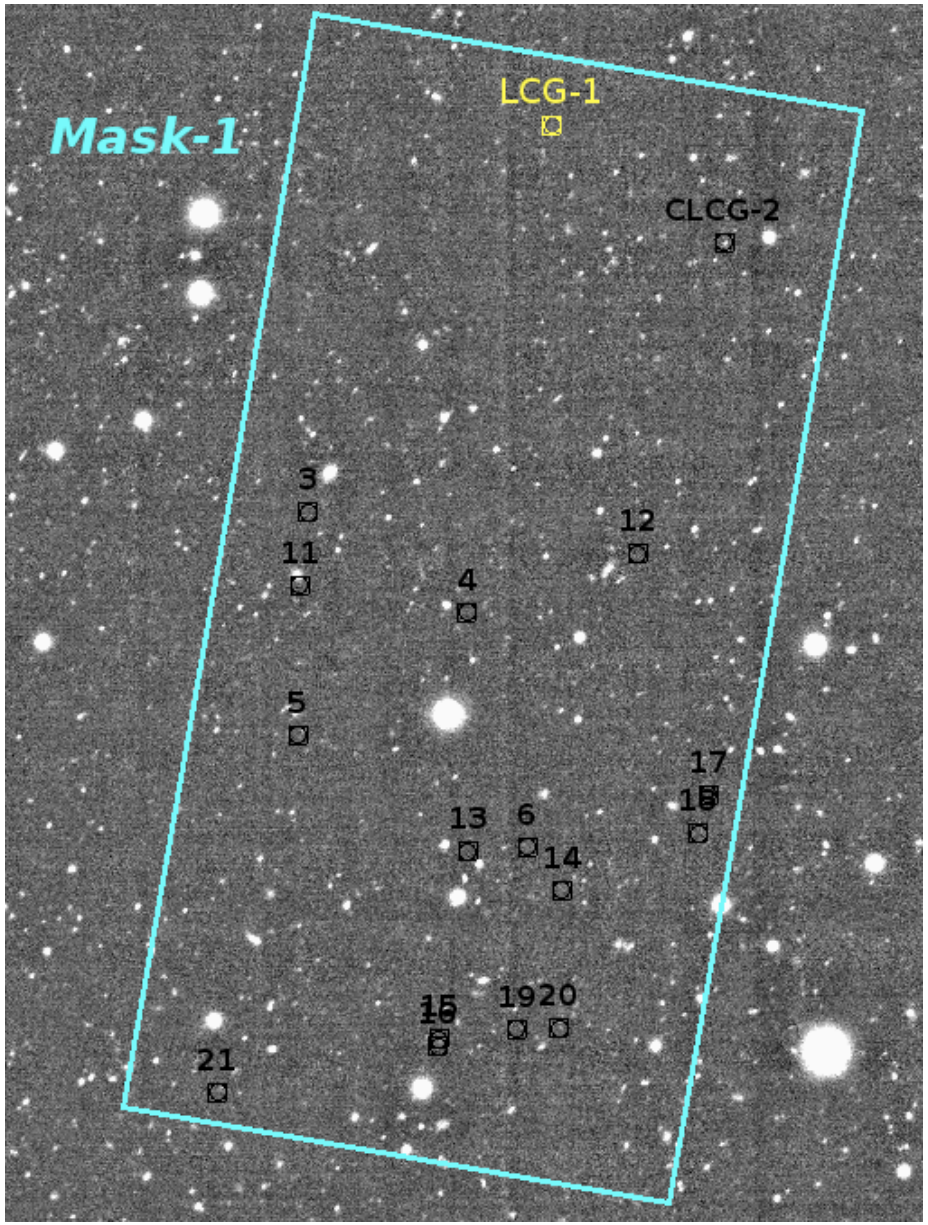
- From the *JWST* observation,
  we can indirectly investigate
  the $f_{esc,LyC}$ value of star-forming
  galaxies at $z > 6$
  by using the EW(Hβ)–β method.

- Before applying this new method
  to galaxies at $z > 6$,
  the method needs to be verified
  for galaxies for which $f_{esc,LyC}$ values
  have already been obtained
  through more direct method.

Observation

Details of spectroscopic observation

- The target field is the SSA22 field.
  (Steidel+98, Hayashino+04,
  Matsuda+04, Yamada+12)
- One full-night observation of the K-band multi-object spectroscopy with Keck/MOSFIRE
- The integration time of Mask1 is 2.45h.



Observation

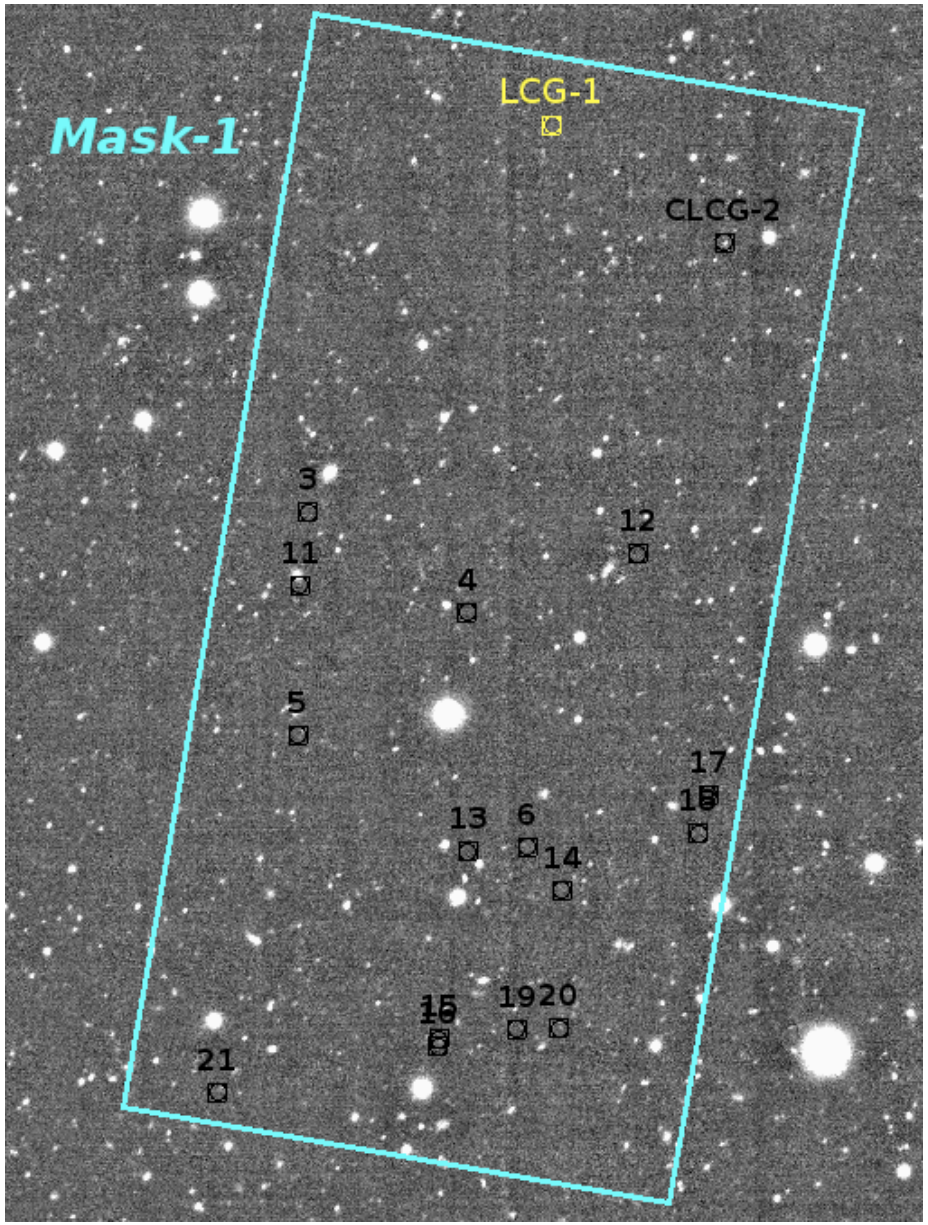
Details of spectroscopic observation

- Main target is **LCG-1** which is the Lyman Continuum Galaxy (LCG) at z_{spec}=3.287 reported by Micheva+17.

- We simultaneously observe 19 Lyman Break Galaxies (LBGs) at z_{phot} ~ 3 in Mask1.

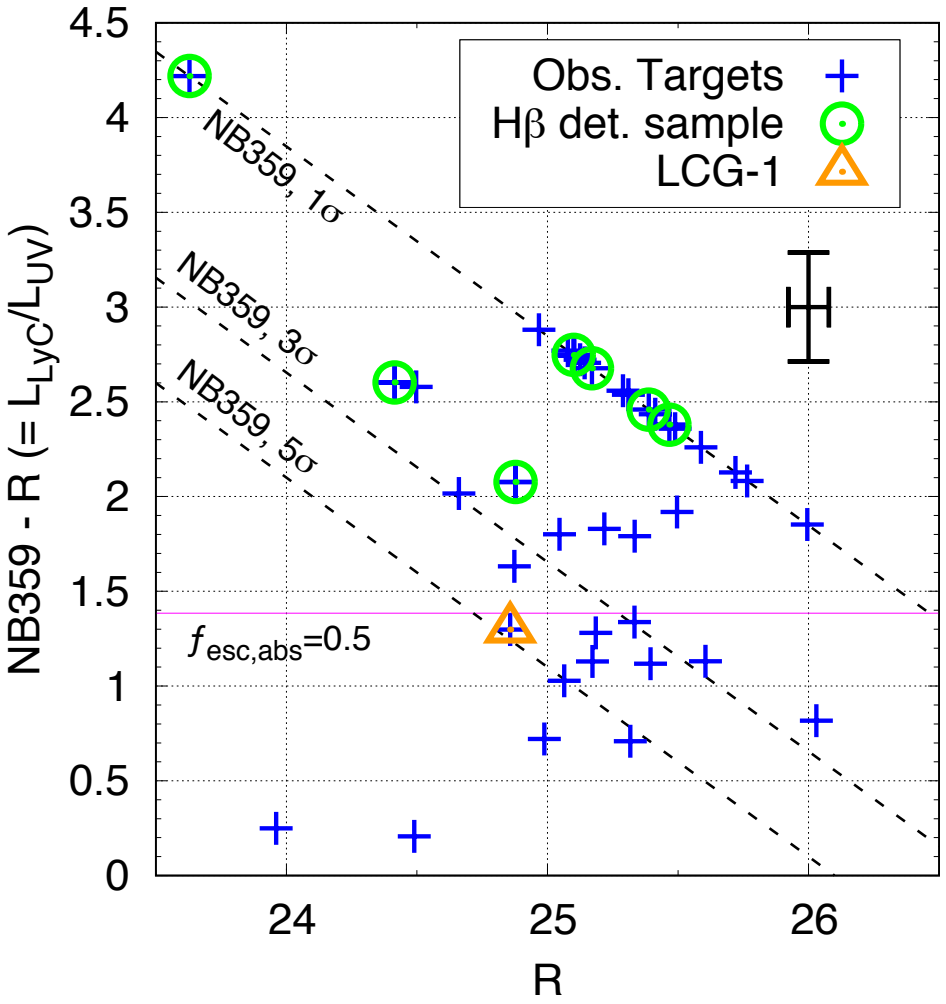
- Their spectroscopic redshift is determined by [OIII] λλ5007/4959.

- Our final goal is to measure their emission line flux of Hβ λ4861.



Observation

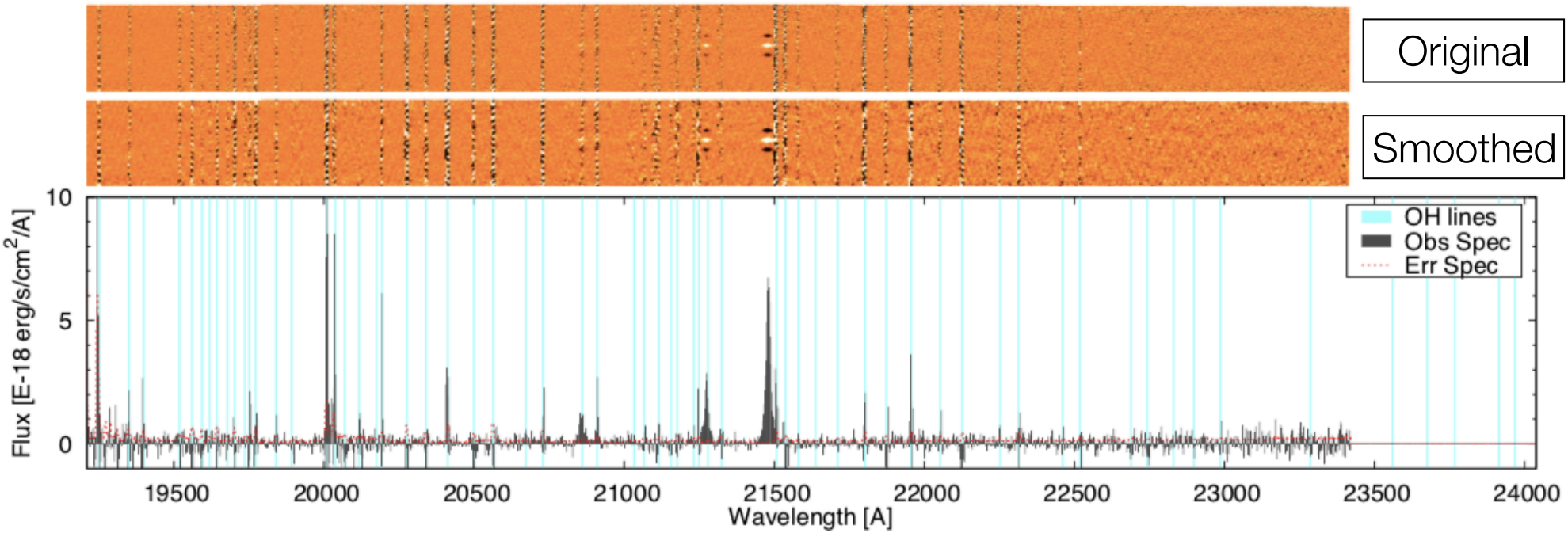
Target objects



- The color-magnitude diagram of NB359-R vs. R
- The mean uncertainties are shown at the top-right.
- In this work, we use and discuss the Hβ-detected objects (green circle).

Observation

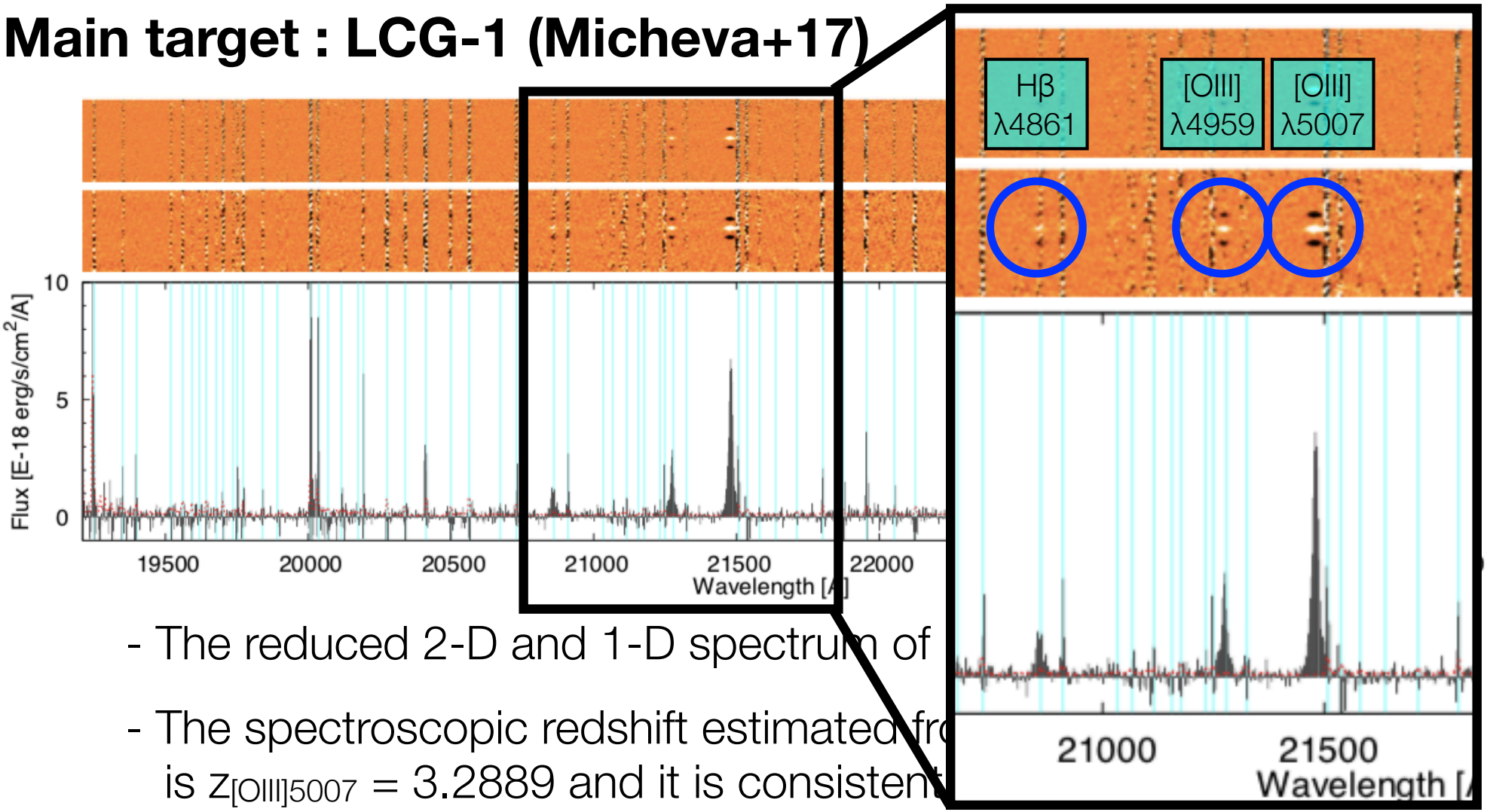
Main target : LCG-1 (Micheva+17)



- The reduced 2-D and 1-D spectrum of LCG-1 is shown
- The spectroscopic redshift estimated from [OIII] λ5007 is $z_{[OIII]5007} = 3.2889$ and it is consistent with Micheva+17
- The observation and the data reduction are OK.

Observation

Main target : LCG-1 (Micheva+17)



- The reduced 2-D and 1-D spectrum of
- The spectroscopic redshift estimated fr
  is $z_{[OIII]5007} = 3.2889$ and it is consisten
- The observation and the data reduction are OK.

Analysis

Estimation of UV spectral slope β

- The UV spectral slope β is estimated from a least square fitting for the broad-band filters of Subaru S'cam/R, i', z', and HSC/y.

- The uncertainty in β is the fitting uncertainty.

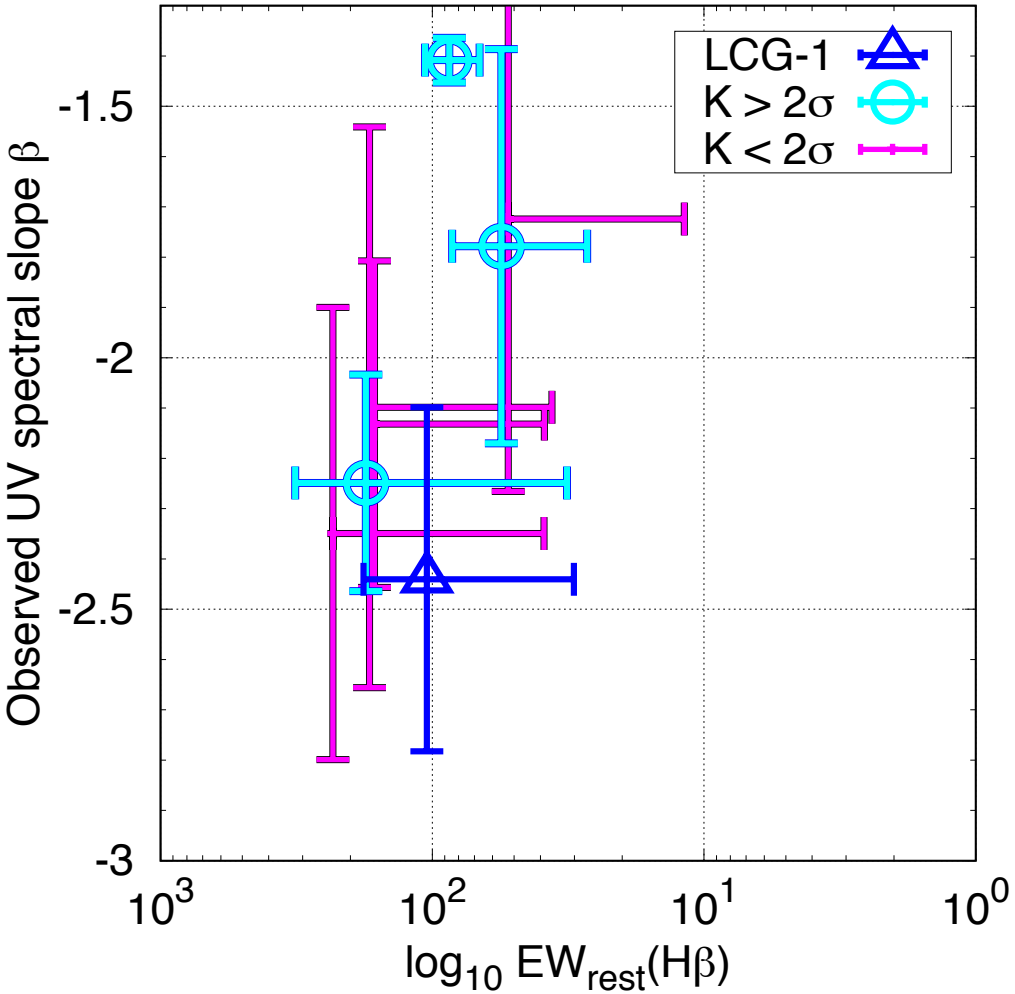
Estimation of EW(Hβ)

- The continuum flux is estimated from the broad-band photometry of UKRIT/K after subtracting the contribution of the [OIII] and Hβ lines.

- The objects detected with UKIRT/K-band at 2σ ($K > 2\sigma$)
  → Assuming a flat continuum spectrum, the EW(Hβ) is calculated from the continuum flux and the Hβ emission line flux.

- The objects not detected with UKIRT/K-band at 2σ ($K< 2\sigma$)
  → The confidence range of EW(Hβ) is estimated from the 3σ upper-limit of UKIRT/K and the extrapolation of UV spectral slope β.

Results



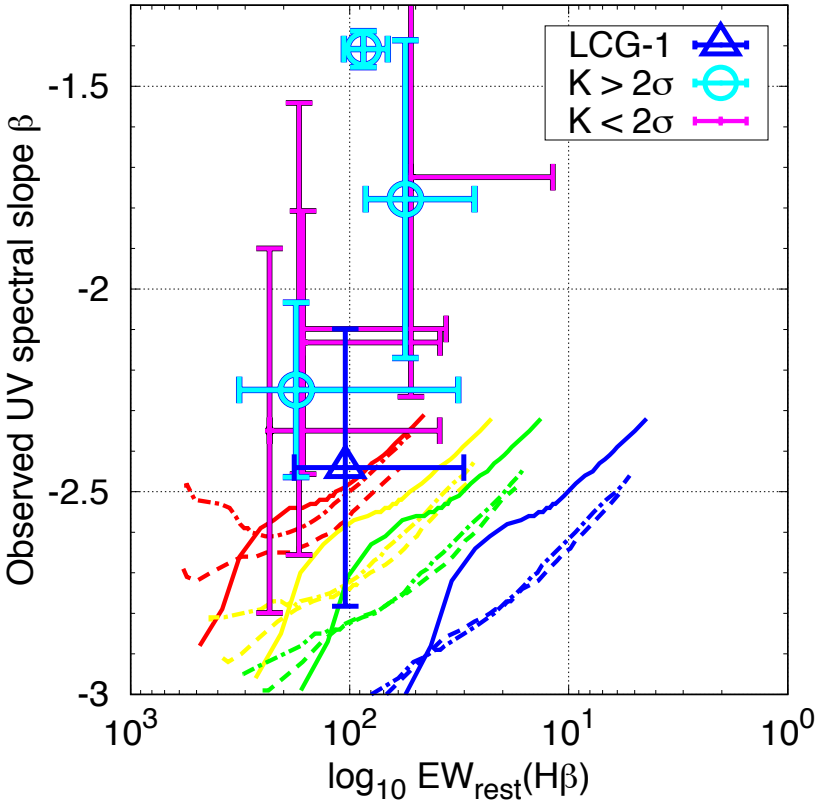
Cyan circles or Blue triangle (LCG-1) with error-bars

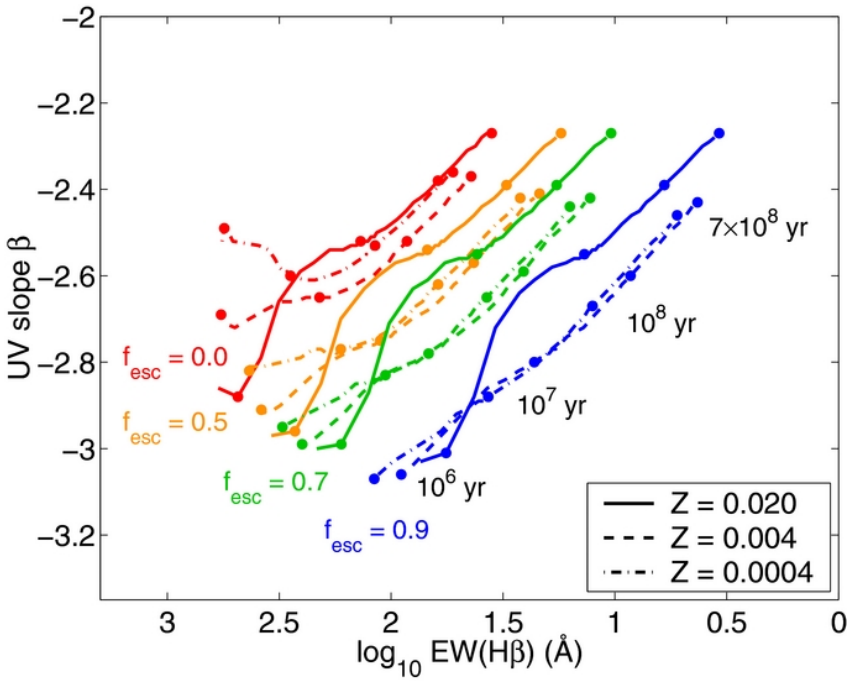
- The objects are detected with UKIRT/K-band at 2σ (K > 2σ).
- The EW(Hβ) is estimated from the continuum flux and Hβ line flux.

Magenta error-bars

- The objects are not detected with UKIRT/K-band at 2σ (K < 2σ).
- The confidence range of EW(Hβ) is shown.
- For the sake of clarity, the error-bar of β is shown at the left edge of the error-bar of EW(Hβ).

Discussions

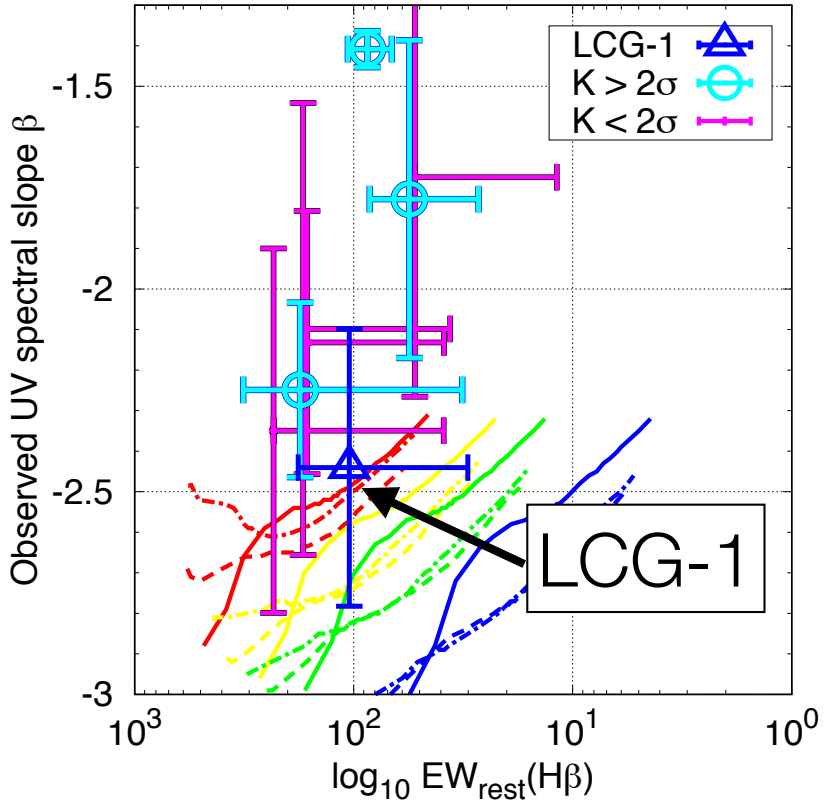


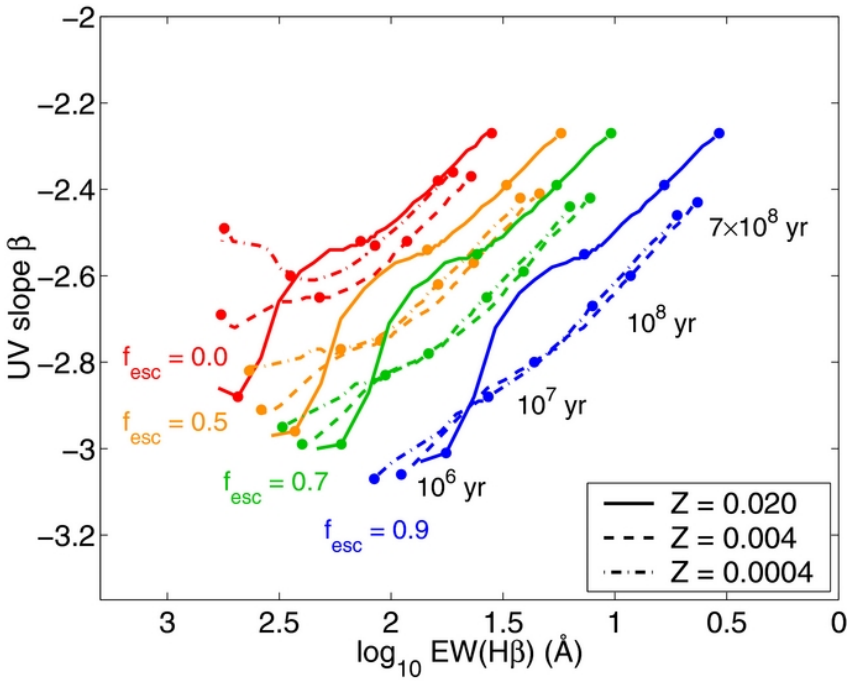


Assuming the following parameters, the observed NB359-R indicates $f_{esc,LyC} \lesssim 50\%$ for all of our targets.

Assumption :	intrinsic L_{LyC}/L_{UV} = 0.3, (Steidel+18), A_{UV}=1.67 (Micheva+17), IGM_trans=0.4 (Inoue+14)

Discussions



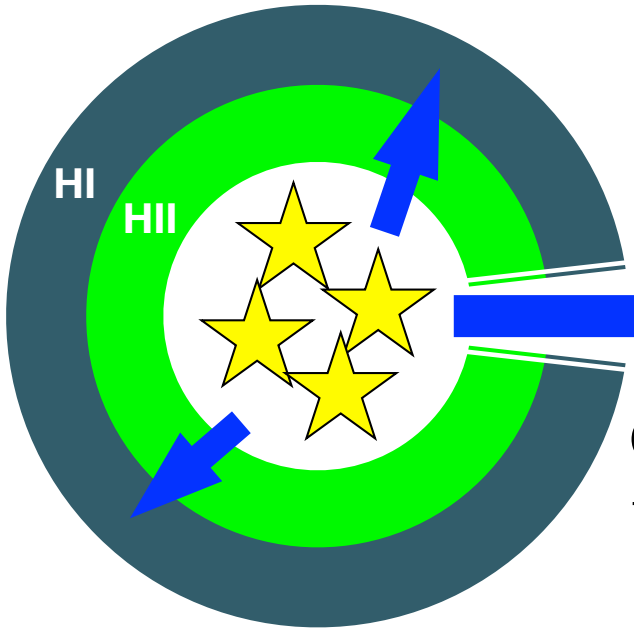


- LCG-1 is the highest $f_{esc,LyC}$ LCG in our sample, and the $f_{esc,LyC}$ value is 54% assuming the previous parameters.

- Although there is a large uncertainty in the assumptions, the observed β and EW(Hβ) of LCG-1 is not inconsistent with the prediction.

Discussions

Case of LCG-1



Most of LyC photons
cannot escape from galaxy
(global $f_{esc,LyC}$~ a few %)

Optically
thin hole

Part of LyC
escape from
galaxy

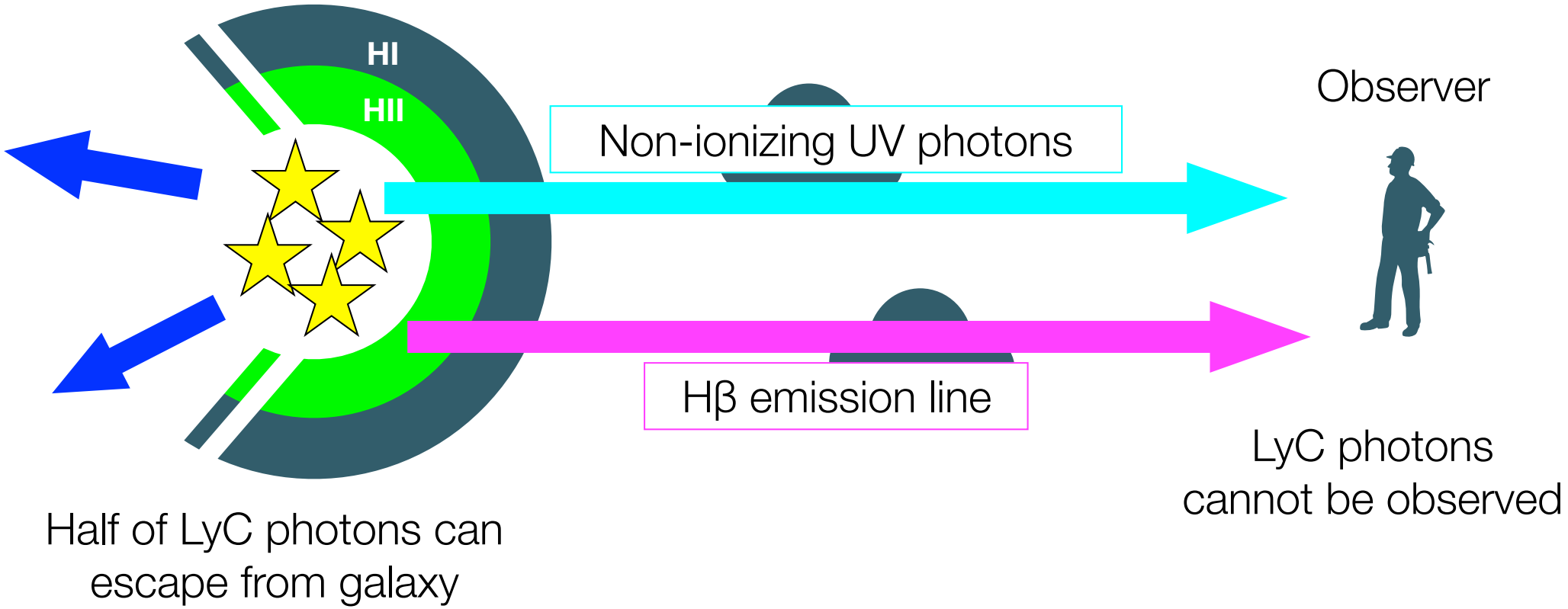
Observer

We directly observe
LyC photons
and identify it
as high $f_{esc,LyC}$ object

If the optically thin hole is aligned with the line-of-sight,
"apparent" escape fraction of Lyman continuum is large.
However, **"global"** escape fraction of Lyman continuum is small.

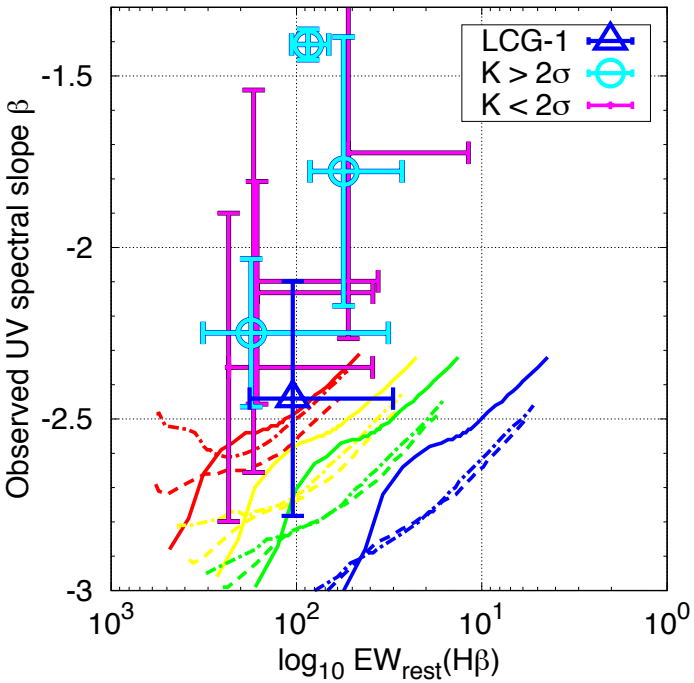
Discussions

Example case



If there is an above situation, the direct LyC measurement identifies this object as a $f_{esc,LyC}$~0% galaxy.
On the other hand, the EW(Hβ)–β method identify this object as a $f_{esc,LyC}$~50% galaxy.

Summary



- We conduct the K-band multi-object spectroscopy with Keck/MOSFIRE.
- We detect and measure the emission line flux of [OIII] λλ5007, 4959 and Hβ λ4861 from 8 objects.
- We estimate EW(Hβ) and verify the EW(Hβ)–β method
- The $f_{esc,LyC}$ expected from the EW(Hβ)–β method is consistent with the $f_{esc,LyC}$ expected from the NB359-R color.
- We need the further investigation for much higher $f_{esc,LyC}$ LCGs, and it is interesting to apply this method to star-forming galaxies at $z > 6$ by using future instruments such as JWST.