# MIRACLES

**M**apping of **I**onizing **RA**diation on the **C**osmic web with **L**yα **E**mission and **S**hadow

**Yuichi Matsuda(NAOJ)**

**&**

**MIRACLES Team**

# Thanks to your feedback at the last WS, we have started this program from S21A.



Subaru Telescope
National Astronomical Observatory of Japan

| | |
|---|---|
| Semester | S21A |
| Proposal ID | S21A0114QI |
| Received | 09/08/2020 |

## Application Form for Telescope Time (Queue Normal+Intensive Programs)

1. Title of Proposal

Mapping of ionizing radiation on the cosmic web with Lya emission and shadow

2. Principal Investigator


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3. Scientific Category

- ☐ Solar System
- ☐ Extrasolar Planets
- ☐ Star Formation and Young Disk
- ☐ ISM
- ☐ Normal Stars
- ☐ Metal-Poor Stars
- ☐ Compact Objects and SNe
- ☐ Milky Way
- ☐ Local Group
- ☐ Nearby Galaxies
- ☒ IGM and Abs.Line Systems
- ☐ Cosmology
- ☐ Gravitational Lenses
- ☐ Clusters and Proto-Clusters
- ☐ Galaxy Properties and Environment
- ☐ High-$z$ Galaxies(LAEs, LBGs)
- ☐ High-$z$ Galaxies(others)
- ☐ AGN and QSO Activity
- ☐ Miscellaneous

4. Abstract *(approximately 200 words)*


We propose direct Ly$\alpha$ imaging of the cosmic web toward the $z = 3.09$ SSA22 protocluster with HSC. This program will map out the spatial distribution of both ionized HII gas (via Ly$\alpha$ emission) and neutral HI gas (via Ly$\alpha$ absorption) simultaneously in and around the protocluster in a cosmological volume of $180 \times 180 \times 50$ comoving Mpc by using the same, deepest NB497 image. We will unveil (1) the physical properties of the gas filaments, (2) the connection between the cosmic web and galaxies/AGNs, and (3) the role of the cosmic web on cluster formation. To identify HII gas filaments down to Ly$\alpha$ surface brightness of $\mathrm{SB_{Ly\alpha}} = 3 \times 10^{-19}$ ergs s$^{-1}$ cm$^{-2}$ arcsec$^{-2}$ with a 3-$\sigma$ level at a 3-arcsec resolution, we request 63 hours integration for NB497, in addition to 6 hours for $g$-band, and 9 hours for $r$-band images for precise continuum correction. To trace HI gas overdesity with a 5 cMpc resolution, we request 3 hours integration for NB527 to select $\sim$400 LBGs at $z = 3.3$ with Ly$\alpha$ emission as background light sources. This special combination of emission and absorption line studies will enable us to constrain the total mass of main gas reservoir and radiative feedback process during the peak epoch of galaxy, super massive black hole, and cluster formation.


5. Co-Investigators

4 more Co-Is

| Name | Institute | Name | Institute |
|---|---|---|---|
| Hideki Umehata | RIKEN | Michele Fumagalli | Durham University |
| Ken Mawatari | Univ. of Tokyo | Ian Smail | Durham University |
| Hidenobu Yajima | Univ. of Tsukuba | David Alexander | Durham University |
| Masayuki Umemura | Univ. of Tsukuba | Yoichi Tamura | Nagoya Univ. |
| Masao Mori | Univ. of Tsukuba | Keiichi Matsuda | Nagoya Univ. |
| Takuya Hashimoto | Univ. of Tsukuba | Satoshi Kikuta | NAOJ |
| Scott Chapman | Dalhousie University | Kentaro Nagamine | Osaka Univ. |
| Tomoki Hayashino | Tohoku Univ. | Masami Ouchi | Univ. of Tokyo |
| Toru Yamada | JAXA | Yoshiaki Ono | Univ. of Tokyo |
| Charles Steidel | Caltech | Kotaro Kohno | Univ. of Tokyo |

6. Thesis Work

☐ This proposal is linked to the thesis preparation of _____

7. Subaru Open Use Intensive Programs

☒ This is a proposal for Intensive Programs.



Proposal ID S21A0114QI

Title of Proposal

Mapping of ionizing radiation on the cosmic web with Lya emission and shadow

12. Observing Run

| Instrument | Hours | Moon phase | Moon distance | Seeing | Transparency | OnSrc Hours |
|---|---|---|---|---|---|---|
| HSC | 98 | dark/gray | 120 | 3 | 0.7 | 81 |

*comments:*

Total Requested Number of Hours 98 Minimum Acceptable Number of Hours 9

13. Instrument Requirements *Specify the set of filters to use (HSC).*

We are going to use $g$, $r$, $NB497$ and $NB527$ filters.

14. List of Targets

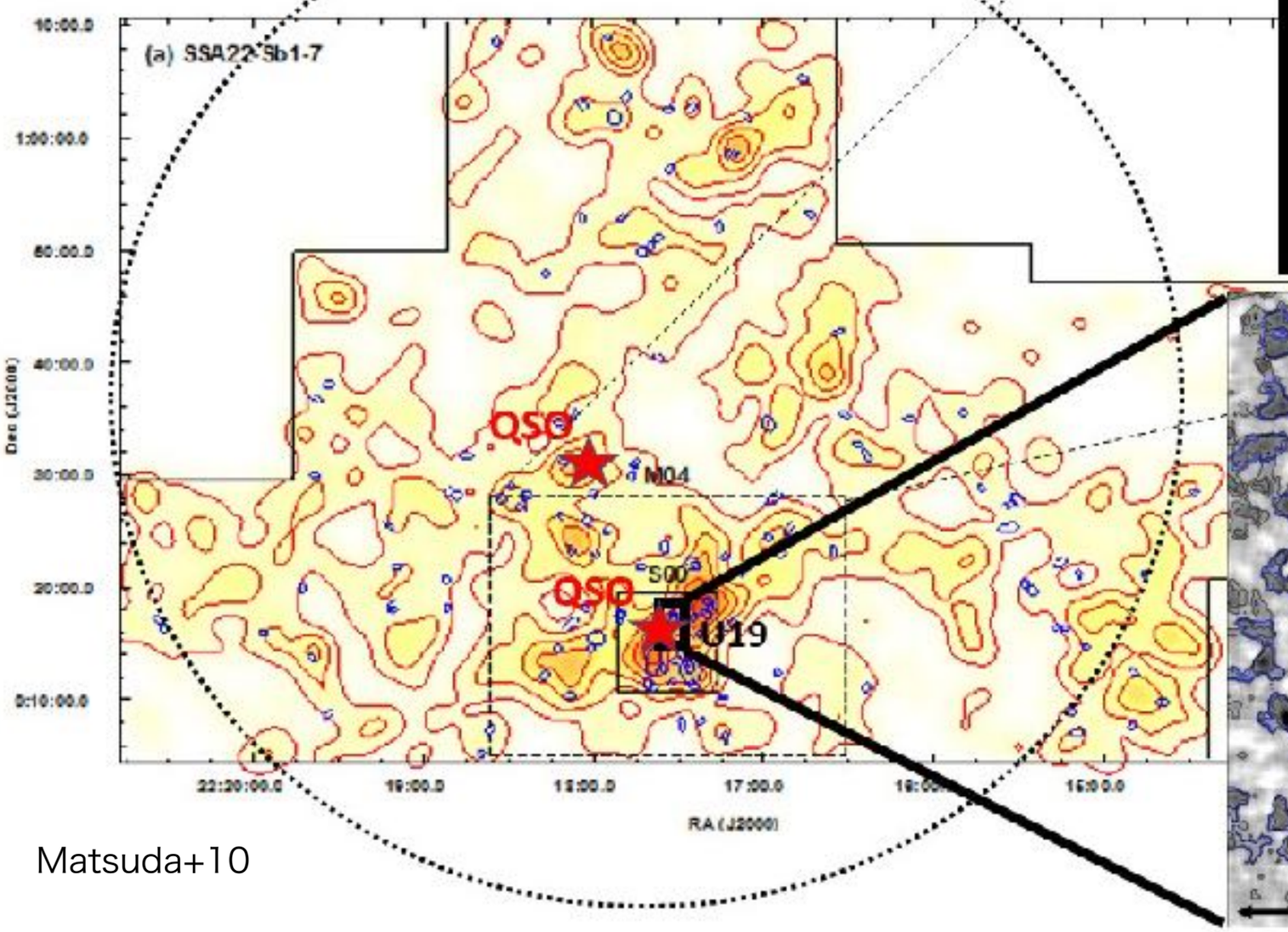
| Target Name | RA | Dec | Magnitude (Band) |
|---|---|---|---|
| SSA22 | 221734.00 | +001700.0 | 30.4 ABmag arcsec$^{-2}$ ($NB497$) |

Akio Inoue, Ikki Mitsuhashi, Mariko Kubo
Rieko Momose, Satoshi Yamanaka

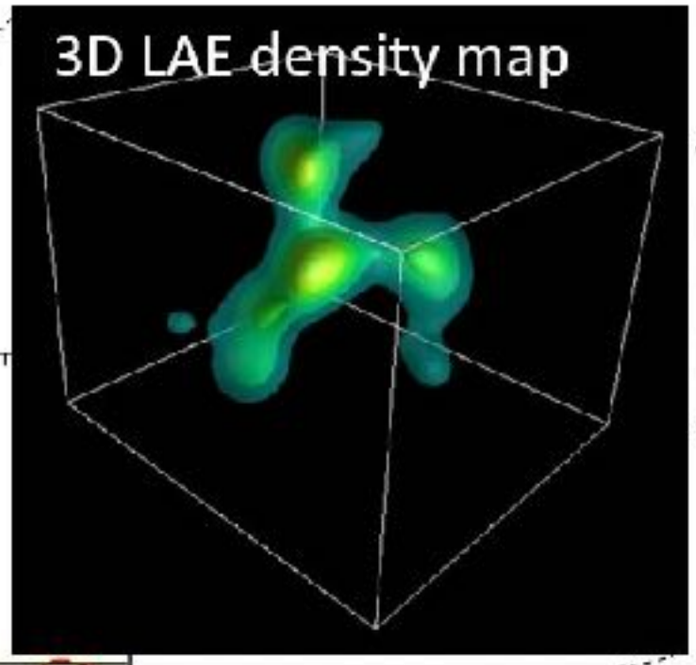
# HSC Observations of Cosmic Web

**(1) The physical properties of the cosmic web (width, length, mass, & ionizing radiation field)**
**(2) The connection between the cosmic web and galaxy / black hole growths**
**(3) The role of the cosmic web on cluster formation**

Survey Volume ~180 x 180 x 50 cMpc$^3$

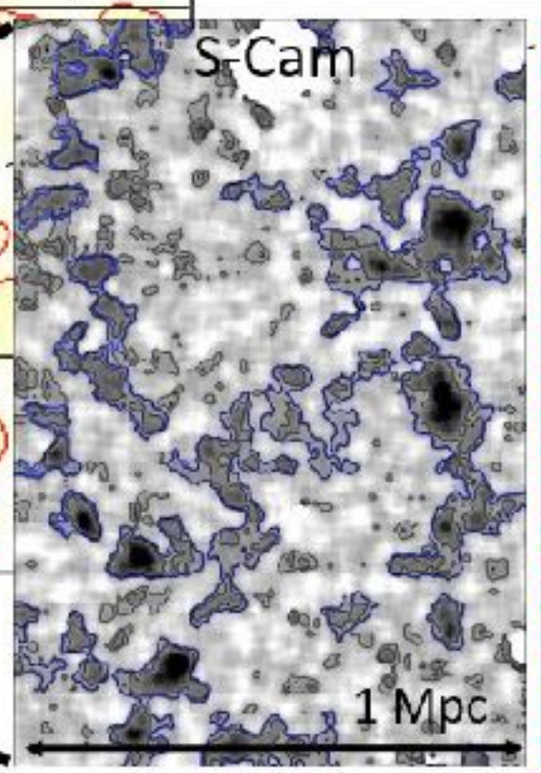


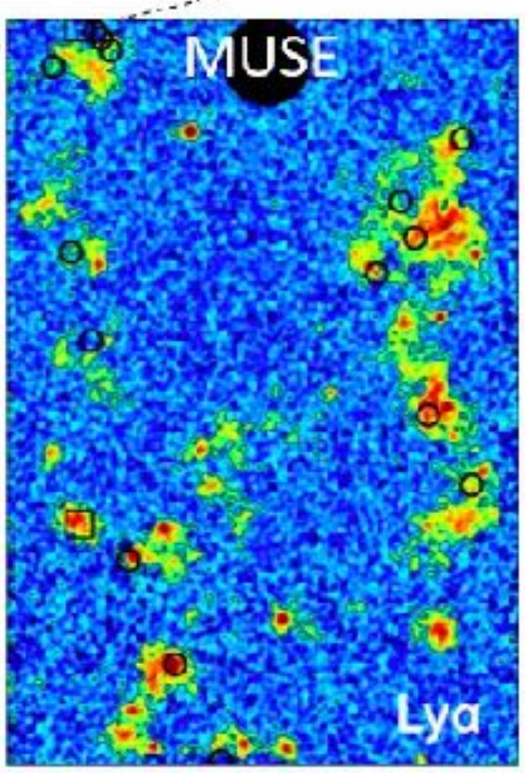

Matsuda+10




Matsuda+05

Umehata+19



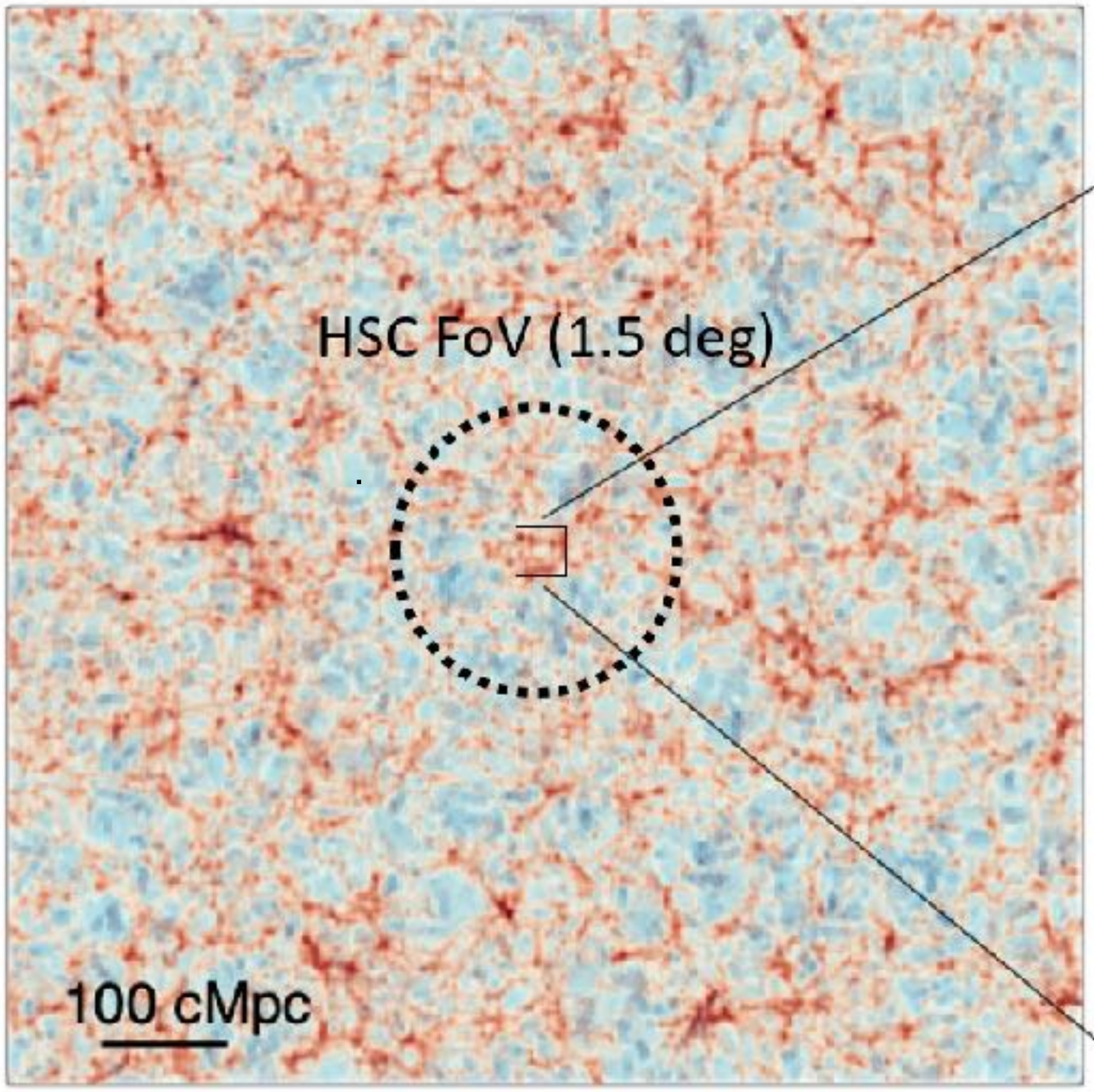



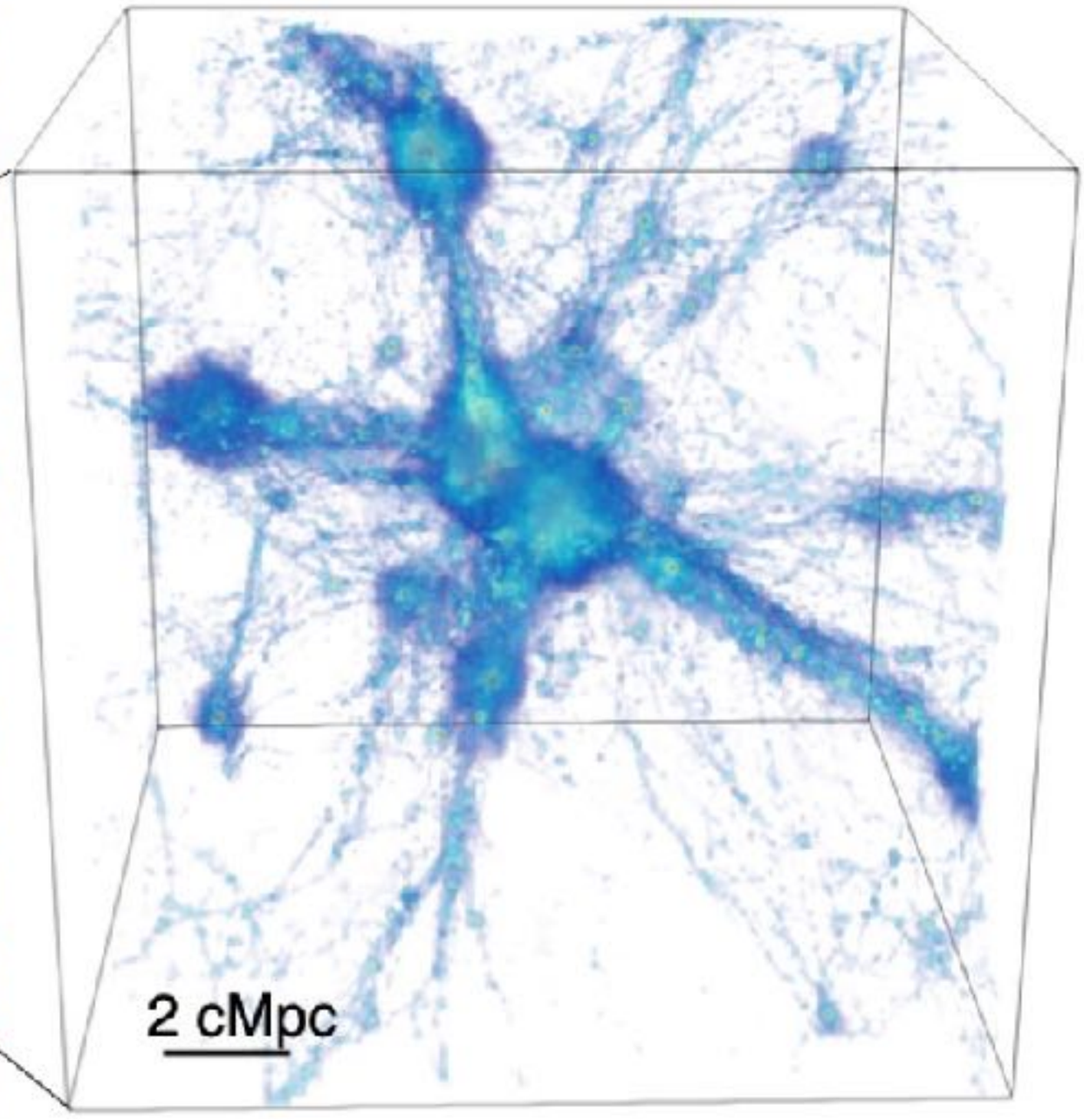
# Cosmic Web & Galaxy/Cluster formation

Yajima+21

(a) 2D dark matter map at z=3

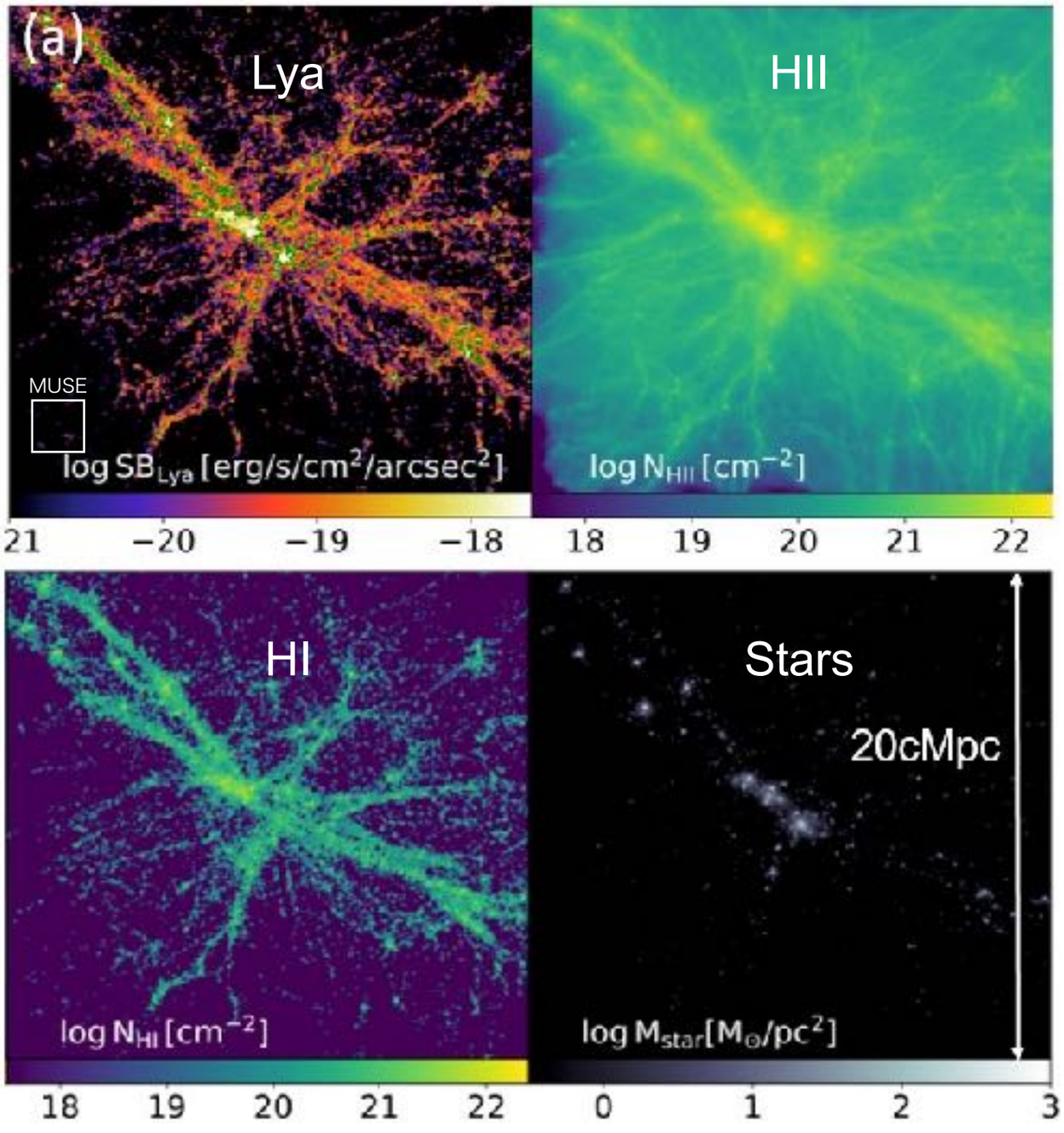
(b) 3D gas map in protocluster



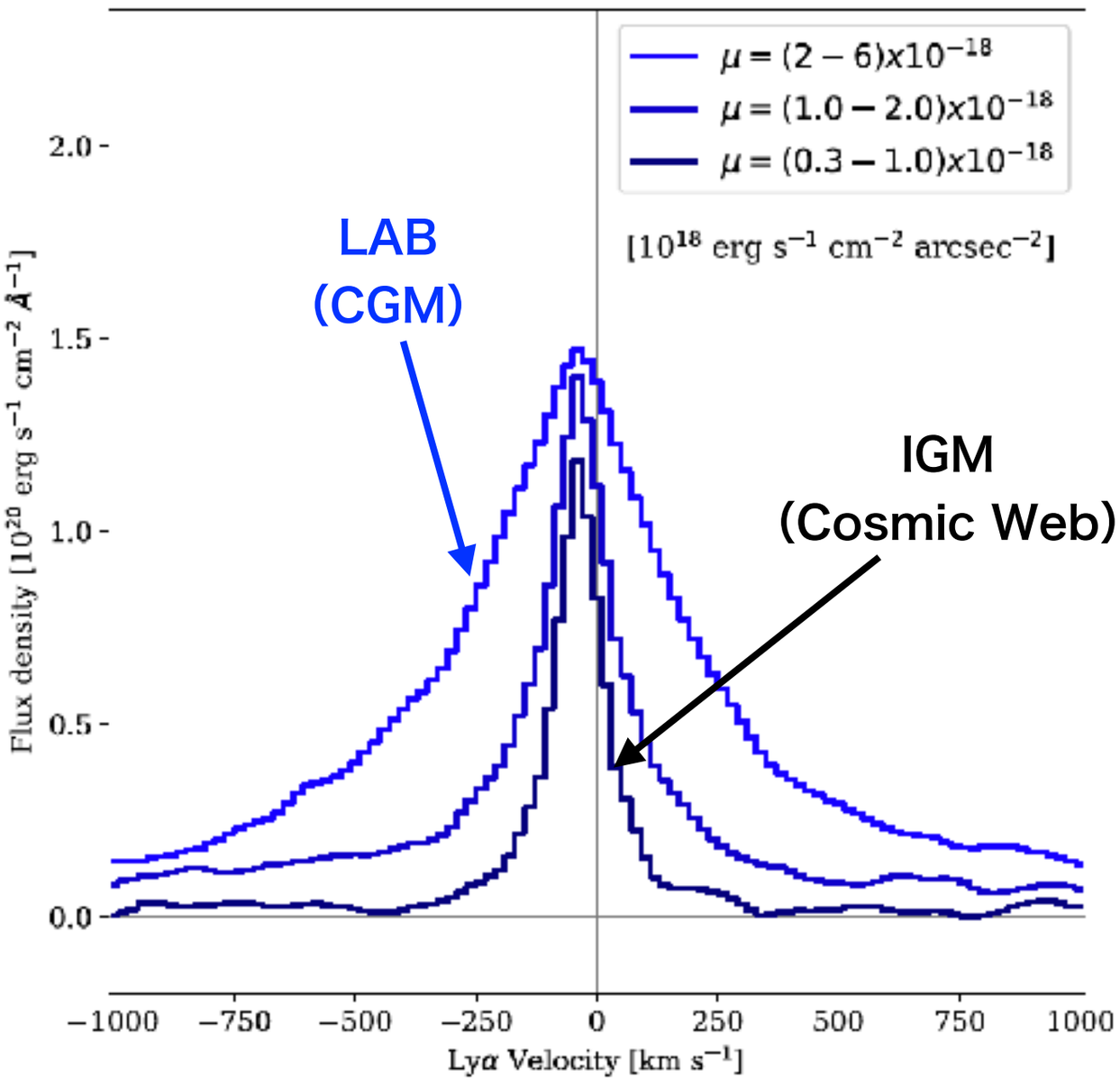



# Lya emission

Yajima+21

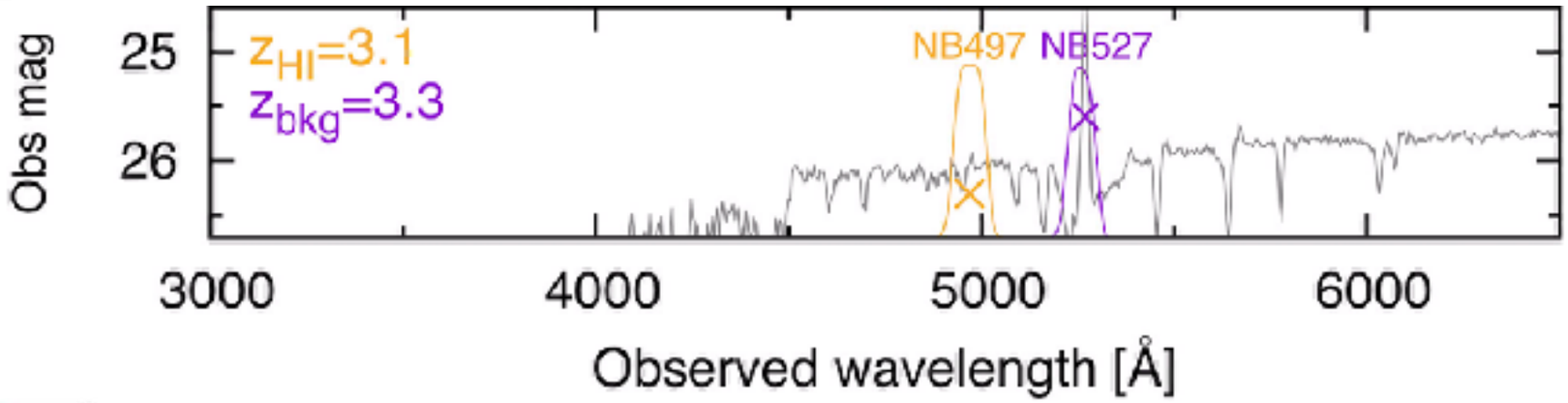


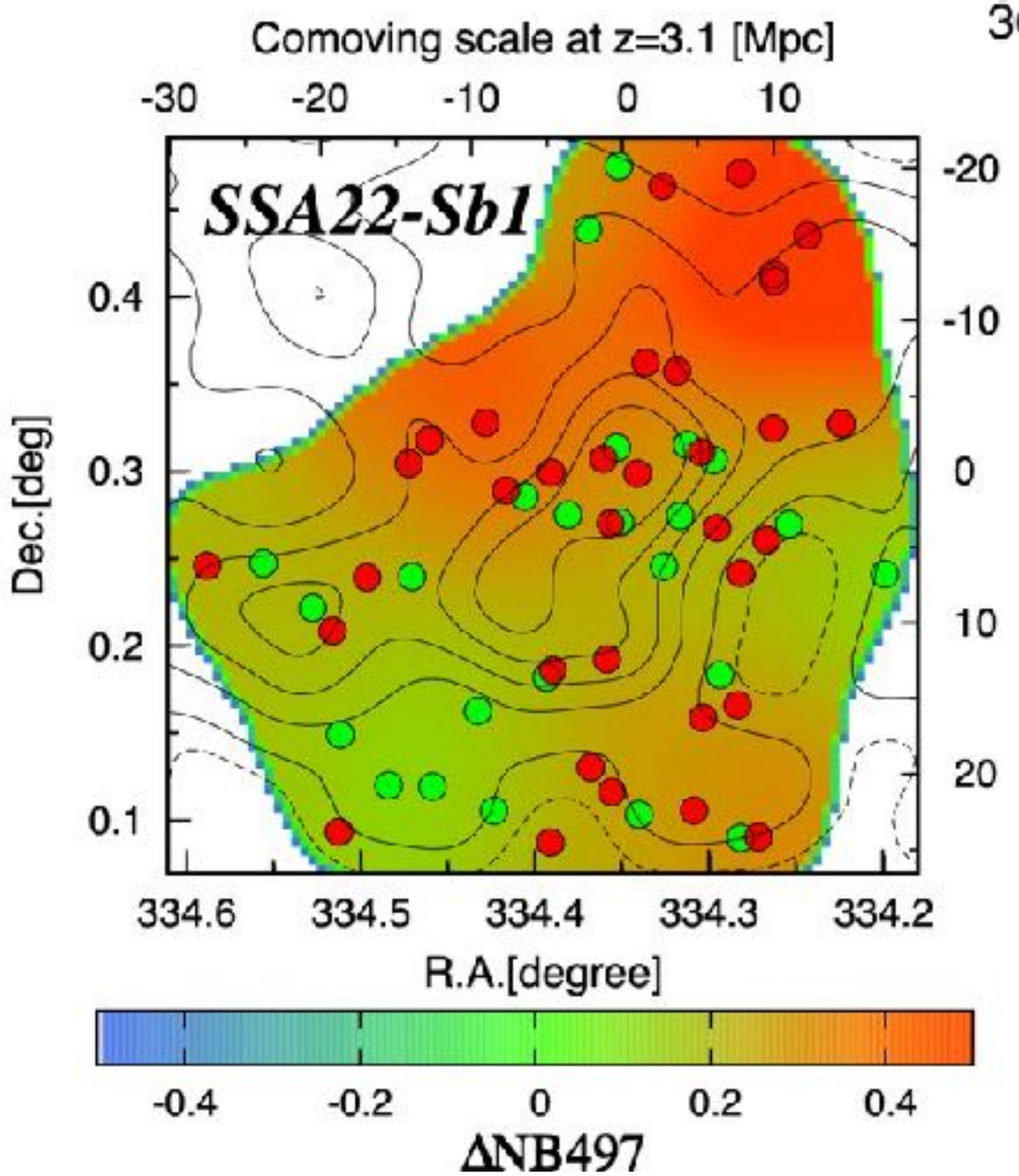

Umehata+19

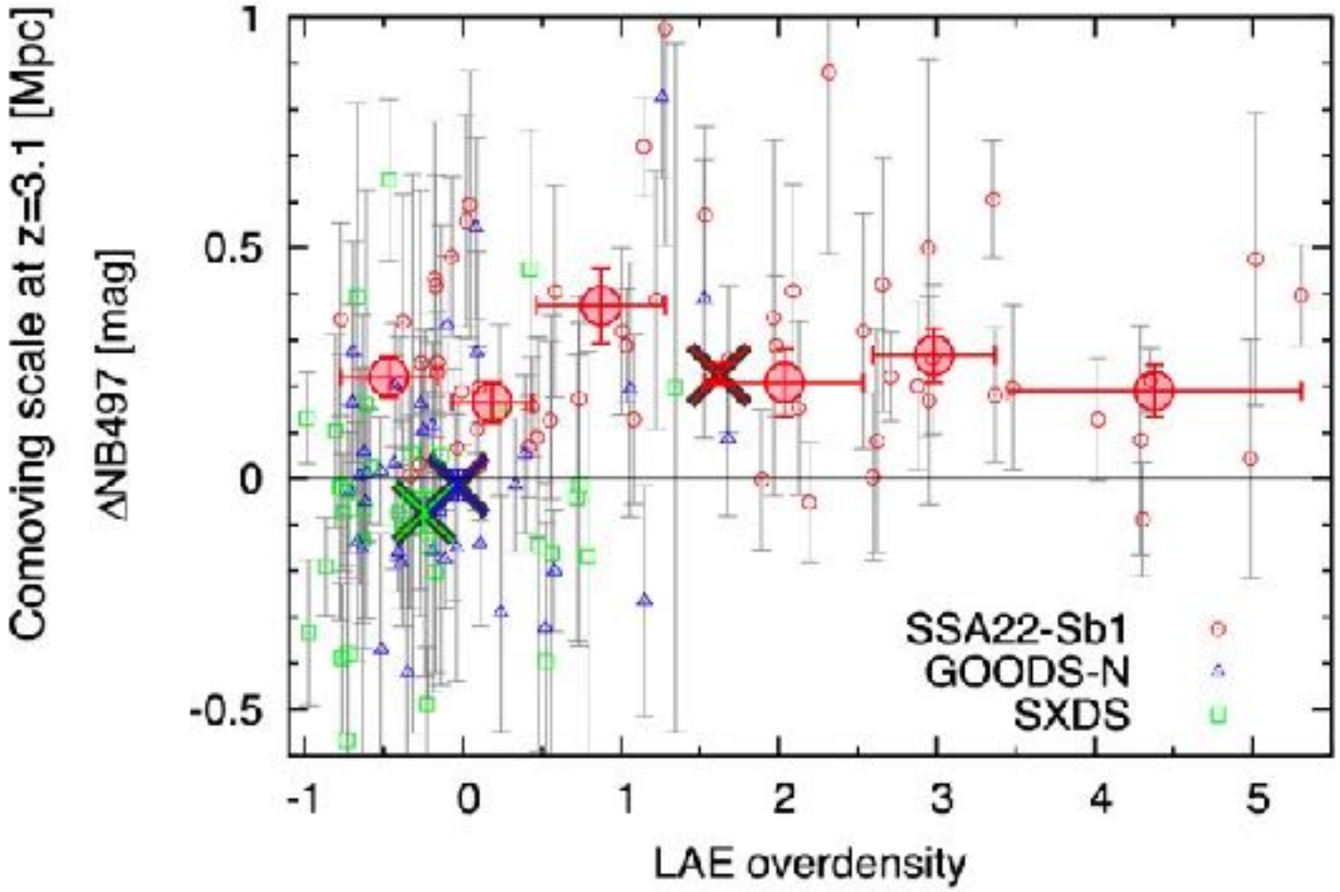


# Lya absorption

Mawatari+17




Coordinated CFHT/MegaCam U-band 13.1 hours program (Chapman+)

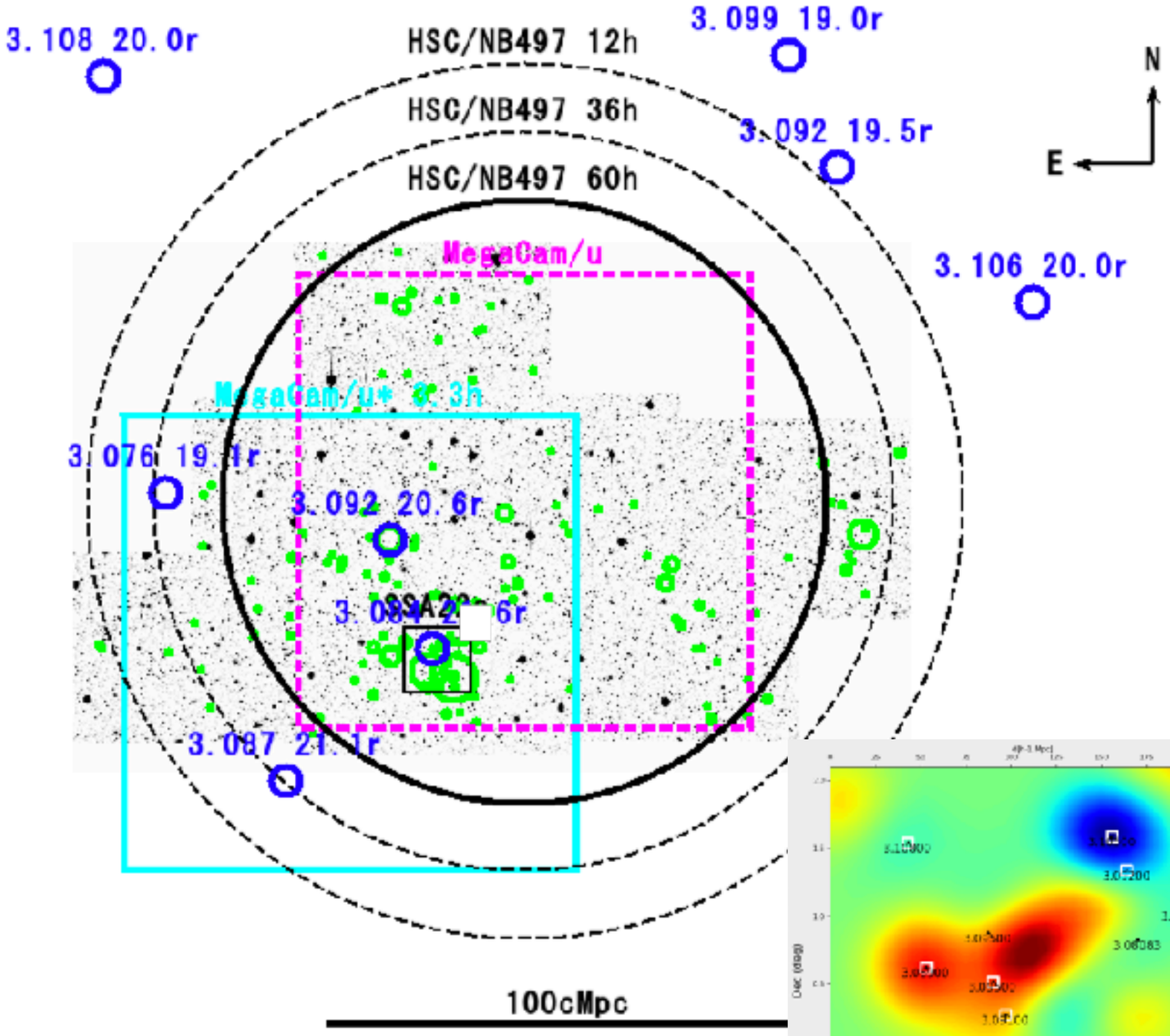
# Subaru TAC recommendations

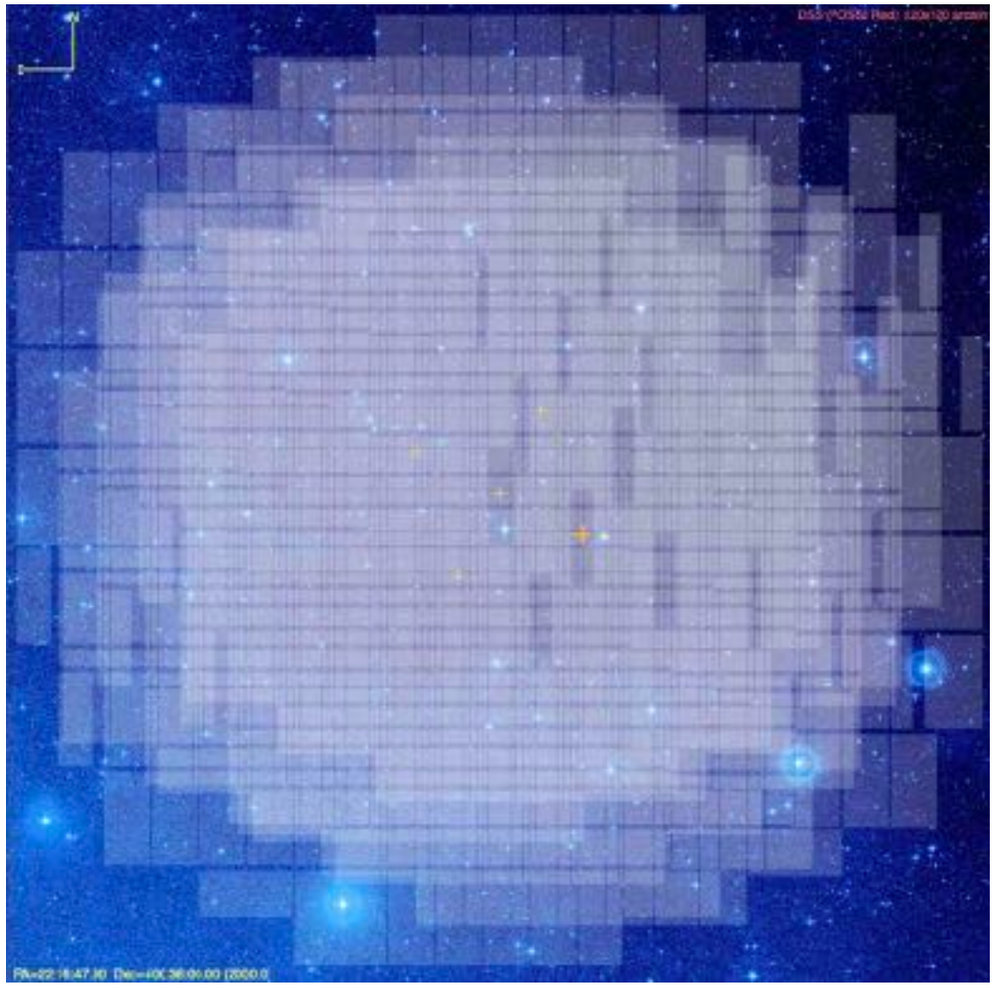
Since there are still some concerns raised by the referees and TAC as follows, we would encourage you to keep improving the observing and analyzing strategies.

(1) **Unknown systematic on the ultras-deep NB497 image:** The proposers will obtain 3 times deeper NB497 image than the currently existing data. Indeed, deeper images will open a new window to understand the relation between the cosmic web, galaxies, and clusters. This is also complementary with the deep MUSE fields, which have kinematic information but much smaller field of view. However, we are still skeptical if the proposers could achieve their desired depth by spending the integration time of 63 hrs by stacking data including those previously obtained. Moreover, a low-level sky residual of ~29 mag arcsec-2 on a small scale is pointed out in the HSC DR2 paper, including small scale fluctuation (e.g., Galactic cirrus). As the PI presented in the TAC interview, the team has already demonstrated several tests to confirm how the detection limit would be improved by stacking 3000 images and how well small scale fluctuation would be removed by subtracting BB image from NB image. However, we are still concerned about some systematic sources of fluctuations that we have not noticed yet.

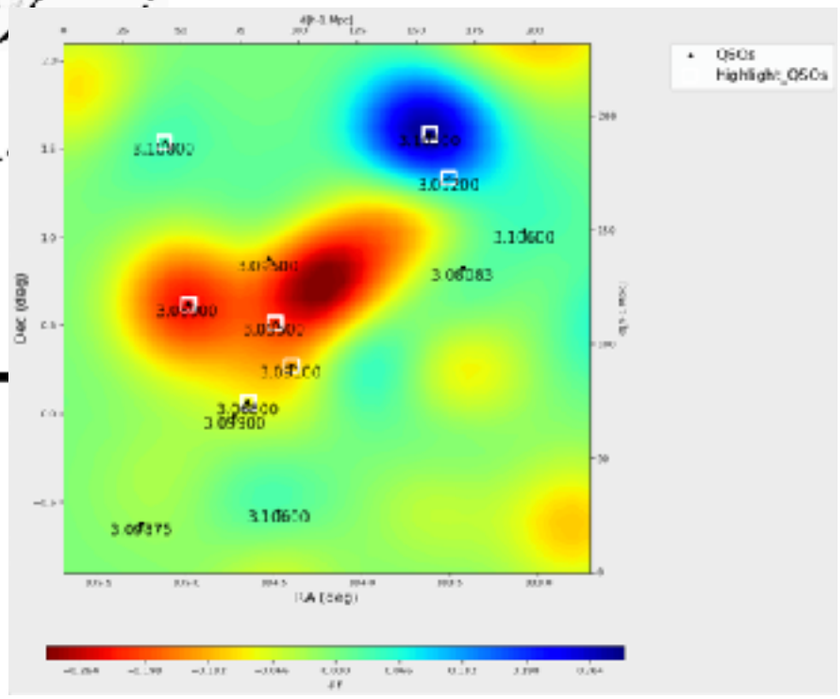
(2) **Coarse sampling of the background LBGs:** Although it is quite unique to get both the HI and HII content of the protocluster region, it is not clear how they connect the small scale structure that will be probed in emission (~50 ckpc scale) with the larger scale density fluctuations that will be probed in absorption (~5 cMpc scale). The depth of line of sight is much larger (~50 cMpc), about one order of magnitude larger than the spatial resolution in the tangential direction, although it is less likely that more than one cosmic web sheet locates on the same line of sight.

# How to decrease systematics



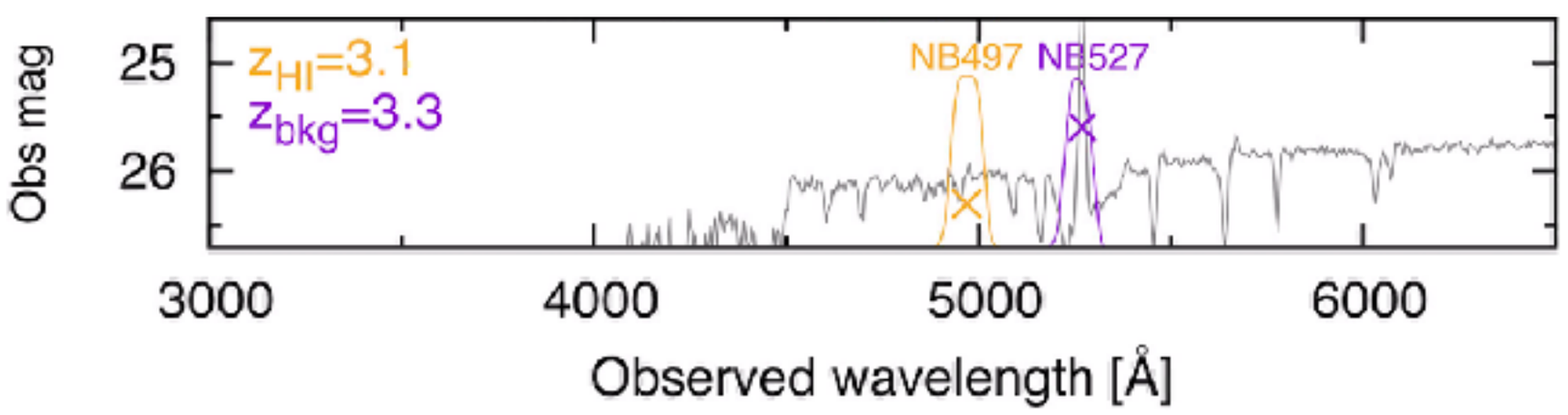
Dongsheng Sun's analysis

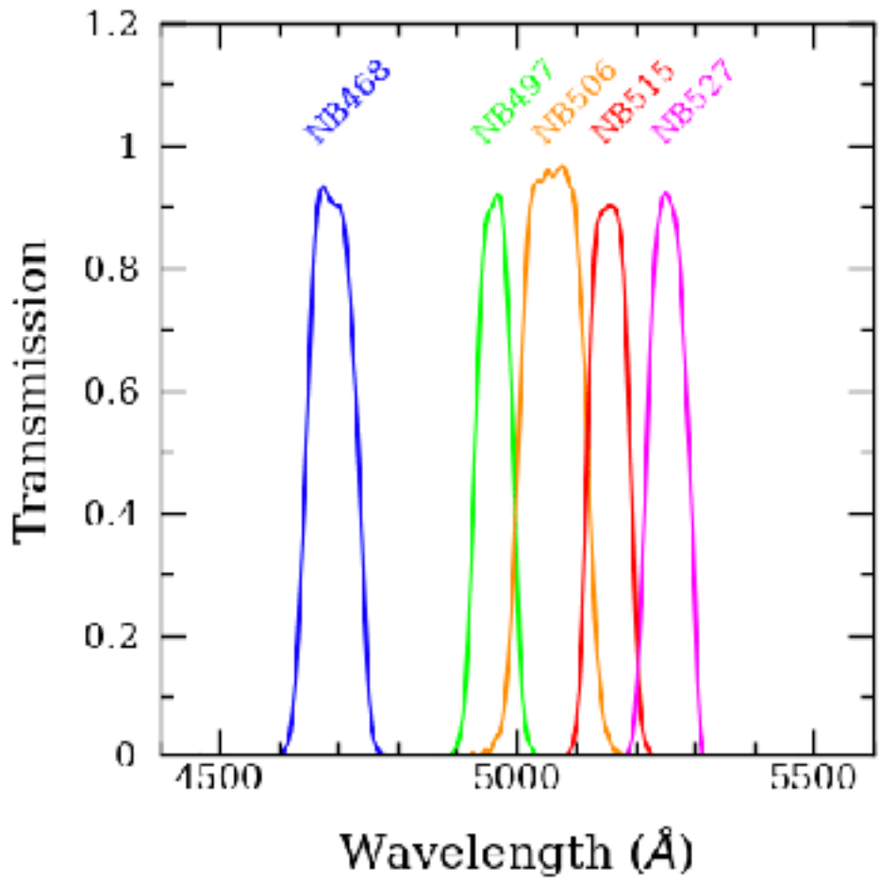


# How to increase background LBGs[9]

| マッピング空間分解能 | 背景天体の数密度(2D) | 背景天体の数密度(3D) | 必要な背景天体の絶対UV等級(ラフ) | 背景(bkg)と吸収体(gas)の赤方偏移 | bkg天体の連続光(Lyα直近) | bkg天体のLyα | ガス吸収バンド |
|---|---|---|---|---|---|---|---|
| 10 Mpc | $10^{-2}$ Mpc$^{-2}$ | $1.4\times10^{-4}$ Mpc$^{-3}$ | −20 mag | $z_{bkg}$=2.5, $z_{gas}$=2.2 | g/r=25.2 | NB430=24.2 | NB387=25.7 |
| | | | | $z_{bkg}$=2.8, $z_{gas}$=2.5 | g/r=25.4 | NB468=24.4 | NB430=25.9 |
| | | | | $z_{bkg}$=3.1, $z_{gas}$=2.8 | g/r=25.6 | NB497=24.6 | NB468=26.1 |
| | | | | $z_{bkg}$=3.3, $z_{gas}$=3.1 | g/r=25.7 | NB527=24.7 | NB497=26.2 |
| 5 Mpc | $4\times10^{-2}$ Mpc$^{-2}$ | $5.7\times10^{-4}$ Mpc$^{-3}$ | −19 mag | $z_{bkg}$=2.5, $z_{gas}$=2.2 | g/r=26.2 | NB430=25.2 | NB387=26.7 |
| | | | | $z_{bkg}$=2.8, $z_{gas}$=2.5 | g/r=26.4 | NB468=25.4 | NB430=26.9 |
| | | | | $z_{bkg}$=3.1, $z_{gas}$=2.8 | g/r=26.6 | NB497=25.6 | NB468=27.1 |
| | | | | $z_{bkg}$=3.3, $z_{gas}$=3.1 | g/r=26.7 | NB527=25.7 | NB497=27.2 |
| 3 Mpc | $11\times10^{-2}$ Mpc$^{-2}$ | $1.6\times10^{-3}$ Mpc$^{-3}$ | −17.5 mag (LFの外挿) | $z_{bkg}$=2.5, $z_{gas}$=2.2 | g/r=27.7 | NB430=26.7 | NB387=28.2 |
| | | | | $z_{bkg}$=2.8, $z_{gas}$=2.5 | g/r=27.9 | NB468=26.9 | NB430=28.4 |
| | | | | $z_{bkg}$=3.1, $z_{gas}$=2.8 | g/r=28.1 | NB497=27.1 | NB468=28.6 |
| | | | | $z_{bkg}$=3.3, $z_{gas}$=3.1 | g/r=28.2 | NB527=27.2 | NB497=28.7 |
| 100 kpc | 100 Mpc$^{-2}$ | 1.4 Mpc$^{-3}$ | inf ... | $z_{bkg}$=2.5, $z_{gas}$=2.2 | | | |
| | | | | $z_{bkg}$=2.8, $z_{gas}$=2.5 | | | |
| | | | | $z_{bkg}$=3.1, $z_{gas}$=2.8 | | | |
| | | | | $z_{bkg}$=3.3, $z_{gas}$=3.1 | | | |

Mawatari-san's estimate



# Current Status

- Semester: S21A-S23A (possible extension to S24A?)
  - u-band data (5h, 38%) - 13h
  - g-band data (1h, 12%) - 8h
  - r-band data (3.3h, 30%) - 10h
  - NB497 data (0h, 0%) - 63h
  - NB527 data (0h, 0%) - 3h
- Add NB506/515 to increase number of background LBGs?