

**[1] Title: *Subaru PFS/NINJA Roman Investigation of Neutral-hydrogen and Galaxies (SPRING)***

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**[3] Required Observation Plans of Subaru Telescope**

Wide and deep observations of the high-redshift universe are critical to study reionization, where inhomogeneities exist on spatial scales larger than currently probed. Roman and Subaru synergistically create a great opportunity to study reionization and the galaxies responsible over wide fields of view, unlocking new insights to highly prioritized science.

**Table 1:** Summary of our required Subaru observations.

Instrument	Requested Nights	Fields	Notes
PFS	Nominal: 35 dark/grey nights (effectively ~25 nights after fiber sharing)	Deep and Ultra Deep layers of the HLWAS (COSMOS & XMM-LSS; ~19.2 deg <sup>2</sup> )	After the Roman HLWAS deep layers are done, but no need to wait for Rubin/LSST.
	Minimum: 20 nights. (observing ~15 deg <sup>2</sup> comparable to PFS-SSP)	Northern field of the HLTDS (ELAIS-N1; ~10.7 deg <sup>2</sup> )	Some observations can be conducted in the HLTDS Core Component duration.
NINJA	Nominal: 10 bright nights Minimum: 5 nights	Medium layer of the HLWAS accessible from Subaru (~1000 deg <sup>2</sup> )	Targeting bright galaxies at z>9 complementary to the PFS observations

As summarized in Table 1, we propose a Subaru/PFS and NINJA spectroscopic survey targeting fields that have been observed with Roman, aiming to advance our understanding of cosmic reionization and early galaxy formation. Our target selection, summarized in Table 2 (below), focuses on high-redshift galaxies at the epoch of reionization ( $z \sim 7$ ) identified through deep Roman imaging datasets. Additionally, we will prioritize Lyman alpha emitters (LAEs) where available, leveraging Roman Grism/Prism spectroscopy (see section [4] below).

**1. PFS observations** will cover a total of ~30 deg<sup>2</sup> field that is observed with (1) the Deep and Ultra Deep layers of the Roman High Latitude Wide Area Survey (HLWAS) and (2) the northern field of the High Latitude Time Domain Survey (HLTDS). We plan to observe these fields in ~24 PFS pointings, with ~9 hours of exposure per pointing. This will reach a 5 sigma Lyman-alpha (LyA) line flux limit of  $\sim 5 \times 10^{-18}$  erg/s/cm<sup>2</sup> at  $z=7.7$  (according to the PFS Spectral Simulator). Accounting for a weather factor of 0.7 and overheads (1.2 hours per night), we request a total of 35 dark/grey nights ( $9/0.7 \times 24 / (10-1.2) = 35$  nights). We estimate a target density of ~1300 per PFS field of view (FoV) of  $z > 7$  galaxies for the PFS spectroscopy (Priority 1-3 in Table 2). In addition, we have a variety of filler targets, as written in Table 2 with density estimates. We also aim to coordinate with other groups targeting these fields to maximize the scientific output. Because of the fiber sharing, our effective request is ~25 nights ( $= 35 \times 1300 / (2400 - 600 \text{ (for calibration)})$ ).

2. We also request **NINJA spectroscopy** targeting bright ( $M_{UV} < -23.5$  mag) galaxies at  $z > 9$ , which PFS cannot detect due to its limited wavelength coverage. The targets will be identified in the Medium layer of the HLWAS, whose deep datasets ( $\sim 3$  mag deeper than Euclid) allow us to select secure galaxy candidates at  $z > 9$ . We will request a total of 10 bright nights to observe all (Nexp $\sim 5$ ) of these galaxies, with the exact number of nights to be determined after the sensitivity estimate of NINJA is established.

**Timing of Spectroscopy:** We want to conduct the PFS and NINJA spectroscopy after the relevant Roman observations are taken to select the targets. However, we can conduct some of the PFS observations during the Roman survey duration. For example, in the HLTDS field, we can conduct part of PFS spectroscopy targeting galaxies selected with the Pilot Visits datasets in the Core Component duration. We do not need to wait until the LSST data are taken in the HLWAS field because the Roman Z-band images are deep enough to select high redshift galaxies.

#### [4] Relevance to the Roman CCS or other Roman programs

This program has direct relevance to two of the Roman Core Community Surveys and to a broad class of anticipated General Astrophysics Surveys. The primary survey regions identified for this work are the deepest region of the High Latitude Wide Area Survey and the full Northern portion of the High Latitude Time Domain Survey. The proposed PFS and NINJA observations are essential to complete the reionization study by unleashing the full capacity of the Roman survey data. Spectroscopy of strong line emitters will be useful to calibrate the photo- $z$ , which show up as unusual colors in the broadbands.

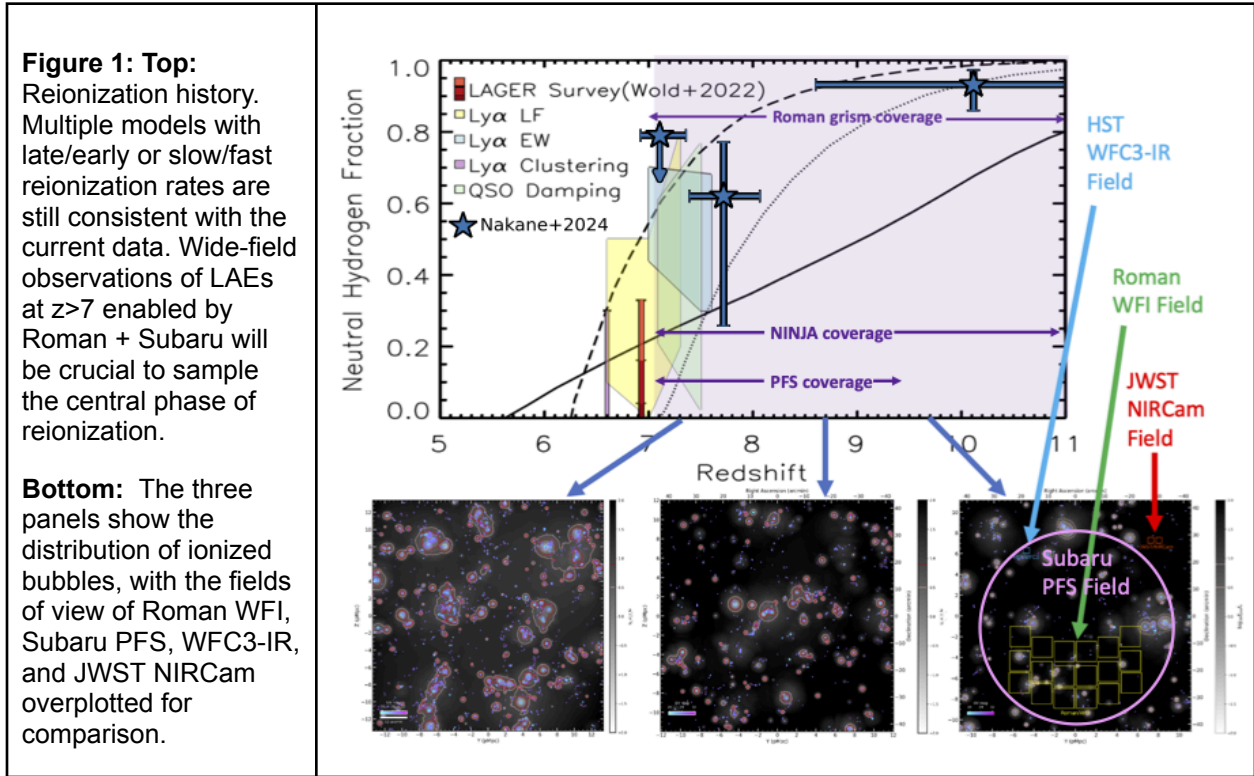
Members of this white paper are also planning General Astrophysics Surveys for several square degrees of deep *Roman* slitless spectroscopy achieving line flux limits of  $10^{-17}$  erg/cm<sup>2</sup>/s, which will increase the number of target line-emitting galaxies for the proposed Subaru observations (see Table 2), further enhancing the synergy between Roman and Subaru communities. The aim of this Roman+Subaru survey is to map the evolution of reionization at  $z > 7$  using LAEs as tracers of ionized regions. Roman will give an unbiased survey to find the distribution of LAEs over unprecedented volumes, and PFS will give detailed information about LyA line profiles to probe the ionization state of the surrounding gas, thanks to its medium resolution ( $R \sim 3000$ ).

#### [5] Scientific Rationale/Justification

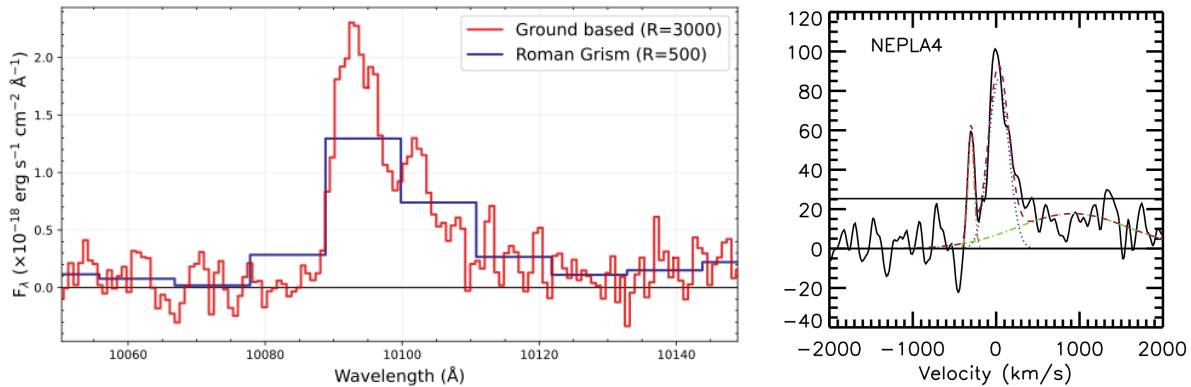
**Cosmic Reionization:** Reionization of Hydrogen in the intergalactic medium (IGM) was the landmark event of Cosmic Dawn. It was the first time that stars had a global impact on the universe and the last time that most of the ordinary matter in the universe participated in a phase transition. Multiple lines of observational evidence (including microwave background observations, quasar spectra, and LyA lines from galaxies) have led to a broad-brush understanding of reionization history, showing that the universe was largely neutral at redshifts  $z > 10$  and largely ionized at  $z < 6$ . Theoretical simulations show that reionization proceeded inhomogeneously through the formation of ionized bubbles that began in the densest regions, where stars and black holes formed first, and proceeded through the growth and overlap of these bubbles, which ultimately filled the universe apart from residual dense, neutral gas within galaxies. We can now study the properties of galaxies at the relevant redshifts in unprecedented detail, thanks to rest-optical images and spectra from JWST.

**However, crucial details of the reionization process remain unclear. At the heart of the reionization epoch, the characteristic diameter of ionized bubbles is  $\sim 20$  comoving Mpc, or  $\sim 6$  arcminutes on the sky, larger than the size of a JWST field of view.** Mapping statistical samples of these bubbles requires the much wider field capabilities of *Roman* and Subaru. Moreover, extreme and rare objects— including quasars, the most luminous galaxies, and galaxy

protoclusters— play crucial roles in some reionization models and can only be found in surveys covering many square degrees.



The Subaru + *Roman* synergistic program outlined in this white paper will drive progress on reionization by examining multiple aspects of this period. PFS spectroscopy is a uniquely powerful tool for studying LyA in large galaxy samples at redshifts  $z > 7$ , which can be unleashed on the deepest 30 deg<sup>2</sup> of the Roman high latitude core community surveys. NINJA will enable the complementary study of the very brightest reionization-epoch galaxies found in ~1000 deg<sup>2</sup> or ~  $5 \times 10^{10}$  cMpc<sup>3</sup> at  $z > 9$ .

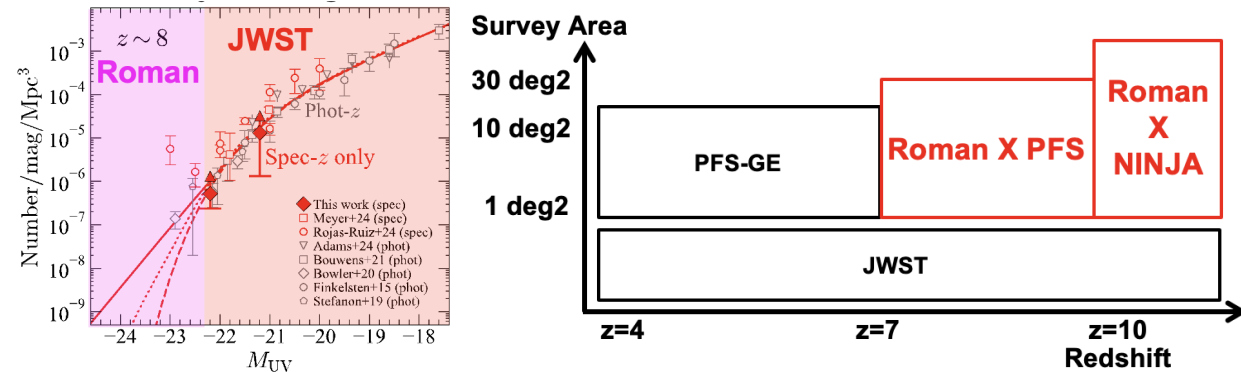


**Figure 2: Left:** Spectrum of a LyA galaxy observed by Keck/DEIMOS ( $R \sim 3000$ , comparable to PFS and NINJA) taken from Rhoads et al. 2013, artificially redshifted to  $z = 7.3$  (red curve) and resampled to the 11A pixel scale comparable to the Roman grism ( $R \sim 500$ , blue curve). The characteristic asymmetry of the LyA line is not seen in the low-resolution grism observations. **Right:** Spectrum of the  $z = 6.6$  LyA galaxy NEPLA4 (Songaila et al. 2018). This object shows a “bump” of transmitted LyA blueward of the systemic velocity, which demonstrates that the ambient medium is ionized. This feature would be lost at the resolution of the Roman grism or prism but could be detected with Subaru spectra..

With the proposed PFS and NINJA spectroscopy, we will obtain a large sample of  $\sim 10,000$  Ly $\alpha$  emitters. This extensive sample will enable us to accurately calculate the Ly $\alpha$  luminosity and correlation functions at the epoch of reionization and measure the neutral hydrogen fraction ( $x_{\text{HI}}$ ) within the 5% uncertainty, allowing us to investigate the evolution of  $x_{\text{HI}}$  and distinguish models of the reionization (Figure 2). We will also map ionized bubbles by observing the Ly $\alpha$  emitting fractions of galaxies across the wide  $\sim 30$  deg $^2$  field. Additionally, the medium resolution of PFS ( $R \sim 3000$ ), significantly higher than that of Roman's grism and prism ( $R \sim 100-600$ ), will allow us to measure the Ly $\alpha$  emission line profiles for each galaxy, which is valuable for investigating the ionized bubbles surrounding these galaxies, providing critical insights into the reionization process.

### Brightest Galaxies:

The proposed Roman-Subaru synergetic survey will provide an unprecedentedly large spectroscopic sample of galaxies at  $z > 7$  with  $M_{\text{UV}} < -22$  mag, which cannot be achieved with other telescopes or instruments. For example, Roman's images are  $\sim 50$  times wider than JWST surveys and  $\sim 3$  mag deeper than the Euclid survey, allowing us to construct a robust sample of bright galaxy candidates for Subaru spectroscopy. These galaxies will be useful not only for studies of cosmic reionization but also for broader investigations of galaxy formation. In particular, it will enable a precise determination of the bright end of the UV luminosity function at  $z > 7$  by accurately measuring the number density of bright galaxies without contamination from interlopers. This is crucial for understanding star formation in bright galaxies in the early universe, a topic of increasing tension with theoretical models, as highlighted by recent JWST discoveries. These observations will also offer key evidence into AGN participation in galaxy activities and their environment, highlighting the role of AGN on high-redshift SMBH-host galaxies co-evolution, intergalactic medium topology, and large-scale structure. The proposed Roman-Subaru program is a unique synergy that will directly bridge the missing parameter space between luminous quasars found by Euclid ( $M_{\text{UV}} < -26$  mag) and faint galaxies detected by JWST ( $M_{\text{UV}} > -22$  mag).



**Figure 3:** Left: UV luminosity function at  $z \sim 8$  (adopted from Harikane+25). The JWST studies are probing the magnitude range fainter than  $\sim -22.5$  mag. Roman will identify brighter galaxies, complementary to the JWST studies, and allow us to determine the shape of the bright end of the luminosity function. Right: Relation of our proposed Roman X Subaru synergetic observations compared to other surveys.

### Relation to the Subaru PFS SSP and JWST Surveys:

The targets of this Roman-Subaru program are complementary to those of the Subaru PFS SSP survey underway. The Subaru PFS SSP survey selects the targets at  $z < 7$  mainly from Subaru HSC optical imaging, while our Roman-Subaru program uses deep near-infrared observations that allow the selection of targets at  $z > 7$ . There are almost no overlaps between the targets of our program and the ongoing Subaru PFS SSP survey. Moreover, while JWST is actively observing  $z > 7$  galaxies selected from Hubble or their deep near-infrared images, the survey areas of the widest-area JWST data sets ( $< 1$  deg $^2$ ) are one to three orders of magnitudes smaller than our

Roman-Subaru program ( $\sim 30 \text{ deg}^2$  for PFS and  $\sim 1000 \text{ deg}^2$  for NINJA). JWST cannot accomplish our scientific goals due to these limited survey volumes.

### Cosmic Noon Science:

The proposed spectroscopic survey with PFS will also be useful for galaxies at the cosmic noon ( $1 < z < 3$ ). Roman grism survey at  $1\text{-}1.93\mu\text{m}$  can capture the H $\alpha$  emission line for  $0.5 < z < 1.9$  and [OIII] at  $1 < z < 2.8$ . Those are excellent fillers for our primary high- $z$  targets as they are numerous ( $> 3000$  in a single PFS FoV). We can investigate the kinematics of galaxies with higher-resolution spectra as well as precisely measure star formation and AGN activities, dust extinction, and gaseous metallicities and their environmental dependence based on emission line diagnostics by resolving individual emission lines and with higher sensitivities. Moreover, deep integration with PFS is well matched to the continuum/absorption line analysis of recently quenched galaxies. Color pre-selection based on photometry (rest-frame UVJ) can identify those galaxy candidates. We will put constraints on the timescale of quenching (based on Balmer absorption lines) and the timescale of star formation before quenching (based on Mg/Fe absorption line ratios), which are crucial to understanding the physical mechanisms of galaxy quenching.

**Table 2:** Summary of our main and filler targets. Our **main targets** are written in **bold**.

Target type	Selection method	Redshift	Surface density / PFS FoV	Priority	Comment
<b>Lyman alpha</b>	<b>Roman spectra</b>	<b>7-9</b>	<b>400-600</b> (Ref: Wold+24)	<b>1</b>	<b>Brighter than <math>1\text{e-}17 \text{ erg/cm}^2/\text{s}</math></b>
<b>Lyman break</b>	<b>Dropout</b>	<b>7-9</b>	<b><math>\sim 60</math></b> (Ref: Harikane+25)	<b>2</b>	<b>Brighter than <math>\sim 24.8 \text{ ABmag}</math></b> ( $\rightarrow$ LyA detected at $5\sigma$ if $\text{EW} > 5 \text{ \AA}$ )
		<b>7-9</b>	<b><math>\sim 700</math></b> (Ref: Harikane+25)	<b>3</b>	<b>Brighter than <math>\sim 25.6 \text{ ABmag}</math></b> ( $\rightarrow$ LyA detected at $5\sigma$ if $\text{EW} > 10 \text{ \AA}$ )
	Dropout and blue UV slope	3-7	$\sim 3000$	filler	UV slope selection complementary to PFS-SSP
	<b>Dropout</b>	<b>9-11</b>	<b>N/A</b>	<b>N/A</b>	<b>For NINJA spectroscopy.</b> <b>Brighter than <math>\sim 23.5 \text{ ABmag}</math></b>
Balmer break	Broad/medium-band images	0.7-2	$\sim 1000$	filler	Recently quenched galaxies. Brighter than $y=22.8 \text{ ABmag}$ or $\sim 10^{11} \text{ Msun}$ at $z=1.5$ .
Emission line	Roman spectra	0-3	$> \sim 3000$	filler	From grism spectroscopy ( $R=600$ ): H $\alpha$ at $0.5 < z < 1.9$ , [OIII] at $1 < z < 2.8$ , and [OII] at $1.7 < z < 4.1$

### [6] Possible coordination with other white papers

We welcome coordination and PFS fiber sharing with other white papers targeting the same fields. We expect that our PFS-targeted fields, the Deep and Ultra Deep layers of HLWAS and the northern field of HLTDS, will be targeted in other white papers (e.g., focusing on supernovae and cosmology) with PFS. Given the surface density of our main targets ( $\sim 1300/\text{FoV}$ ), we have a certain fraction of fibers that can be used for other white papers.