Roman Early-Definition Astrophysics Survey Opportunity:

(1) Submission Title or Survey Name: Roman Cosmic Dawn Survey

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(4) Do you support the selection of a Roman Early-Definition Astrophysics Survey:

Yes. We support an early definition survey, in which we propose to conduct a deep (27-28 mag) and wide (~20 deg2) optical to NIR imaging survey, atop the fields of the forthcoming Roman supernova (SN) wide survey. The obtained dataset is useful to select star-forming galaxies at z~13-15 (a.k.a cosmic dawn), which are bright enough to be followed up by spectroscopy with other telescopes (e.g., JWST, ALMA, TMT, GMT, ELT) to understand the physics of the first galaxy formation. Combination with the SN survey provides a deep legacy dataset from R- to K-bands after the completion of the two surveys. Early selection of this survey will provide the community with a testbed for photometric analyses in the survey-scale data, calibration datasets for the photometric redshift (photo-z) analysis, and a sizeable sample of z~13-15 galaxies within the limited lifetime of JWST (~5-15 years) and before the first lights of 30 m-class telescopes.

(5) Describe the science investigations enabled by the survey:

A key science driver is a search for star-forming galaxies at z~13-15, a.k.a cosmic dawn. Recent studies have reported mature stellar populations in z~6-9 galaxies (Figure 1 left, e.g., Hashimoto et al. 2018, Mawatari et al. 2020) and identifications of bright galaxies at z~4-10 (Figure 1 right, e.g., Morishita et al. 2018, Bowler et al. 2020, Harikane et al. 2021), including a spectroscopic confirmation of GN-z11 at z=10.96 (e.g., Oesch et al. 2016, Jiang et al. 2021). These studies suggest the existence of a number of early star-forming galaxies at z>11.

In this early definition survey with ~20 deg2 RZYJHFK imagings, **we expect to detect up to ~300 z~13-15 galaxies (Figure 2) including >100 bright sources (m<~27 ABmag) that can be followed up by spectroscopy** with other large telescopes (e.g., JWST, ALMA, TMT, GMT, ELT). This will be the first statistical sample of z~13-15 normal galaxies that are not extremely luminous like starbursts and AGNs, but representative of the galaxy population at these redshifts.

The spectroscopy for them will allow us to understand the physical properties (e.g, redshift, metallicity, dynamical mass, ionization state) and the physics of the first galaxy formation. Note that the Roman high latitude survey (HLS) can only search sources up to z~13 due to the lack of the K-band image, and the detected sources are very bright (Muv < -22 mag) due to its shallow survey depth, which may not be representative of the galaxy population at these redshifts.

As shown in Figure 2, the predicted number density of z~13-15 galaxies varies widely among theoretical models. Interestingly, some models suggest a rapid decline of the number density at z>11 in contrast to the extrapolation of the observations at z<~10 (e.g., Bowler et al. 2020). This may imply the emergence of the first galaxies at z~11-15. In this survey, we can constrain the number density of z~13-15 galaxies, even if non-detections. Comparisons with theoretical models will allow us to investigate when these first galaxies form in the early universe.

Thanks to its wide-field imaging capability and sensitivity in the NIR, **Roman is the best observing facility to conduct a search for normal star-forming galaxies at z~13-15.** Although JWST can search for z>11 galaxies, its small field of view will limit the survey area and only identify faint galaxies (m~29-30 mag) that would be difficult to be followed up by spectroscopy. Euclid covers only up to the H-band, and cannot select z>11 galaxies. Ground-based telescopes have limited imaging sensitivities in the NIR, not useful to discover normal z~13-15 galaxies.

Ancillary sciences enabled by this survey:
Pair-instability supernovae (PISNe) and superluminous supernovae (SLSNe) at z>6: Massive stars that explode as SNe are believed to play a critical role in cosmic reionization. By observing SNe at z>6, we can directly characterize the properties of massive stars contributing to cosmic reionization. By adding a one-year cadence, we expect to discover ~20 PISNe and ~2 SLSNe at z>6 by using the H-K color information (Moriya et al. 2021).
Passive or post-starburst galaxies at z~4: These galaxies can be identified with their prominent Balmer break. We expect to find ~2000 of them, allowing for the first statistical study to address galaxy quenching in the early universe. They are the most massive galaxies in the universe, and their stellar mass and abundance may challenge the current galaxy evolution model.
Low-mass star-forming galaxies at z=1-2: These young galaxies present powerful emission lines such as the hydrogen Balmer and metal lines (e.g., Ha, [OIII]5007) that boost the broadband photometry. By using the machine learning classifier (e.g., Kojima et al. 2020), we expect to identify >5000 such low-mass (<~10^7 Msun) galaxies over z=1-2, allowing us to examine the earliest phase of galaxy evolution such as chemical enrichment and star formation.
Photo-z calibration: Roman's deep photometric data can benefit the photo-z calibration for the forthcoming weak lensing surveys beyond z>1. Combined with ground-based imaging data (e.g., Subaru/HSC Deep field), the photo-z accuracy is better than 3% (scatter) and 10% (outlier rate).

(6) Provide a possible observational outline of the survey:

Optical element choices: We will take WFI imaging data with the RZYJHFK bands. H, F, and K imagings are needed to select H-dropout (z~13) and F-dropout (z~15) galaxies. R, Z, Y, and J images will be used to remove foreground interlopers in the selection of z~13-15 galaxies.
Possible location: The best choice would be the fields of the Roman SN wide survey. By targeting the SN wide survey fields, we will obtain a deep (~27-29 mag) and wide (~20 deg2)

legacy dataset with the almost full-band Roman images after the completion of the two surveys (see Table 1). A possible alternative is the Euclid Deep field (EDF, ~40 deg2) with the relatively shallow (~26.3-26.5 mag, 5sigma) Euclid YJH imaging data, allowing us to integrate longer in Roman's K-band. The NEP and CDFS EDFs will be covered with deep (~27 mag) optical griz Subaru/HSC images[1], which are useful to remove foreground interlopers.
Survey area: We propose a ~20 deg2 survey as a nominal plan, which is the same as the Roman SN wide survey[2]. 10 deg2 area is at least needed to construct a sizeable sample of bright galaxies at z~13-15. This is complementary to the wide-field shallow HLS (~1700 deg2, ~26 mag).
Cadence constraint: Since we will search for SNe at z>6, a one-year cadence works. The timing may also be coordinated with the SN survey.
Depth and total time needed: Depths of 27-28 mag are needed in all bands to select z~13-15 dropout galaxies (Table 1). Deep H and F images are important to identify Lyman breaks at z~13 and 15 in the H- and F-dropout galaxies, respectively. A total of ~690 hours (~625 h exposures + 10% overheads) is needed to cover the ~20 deg2 area with ~60 pointings.

(7) Describe specific preparatory activities enabled by early definition:

If this early definition survey is selected, we can conduct deep observations using ground-based and space facilities in advance of the survey. Blue optical images (e.g., u- and g-bands) taken with ground-based telescopes (e.g., Subaru/HSC, Rubin, and CFHT) are complementary to the Roman dataset covering the wavelength from R-band. Subaru/PFS intermediate-resolution (R~3000) optical-to-NIR (0.38-1.26 um) spectroscopic data can be taken through the Roman-Subaru synergistic observations, which is complementary to the Roman grism spectroscopy in terms of its resolution (R~600) and wavelength (1.00-1.93 um). These datasets are useful to remove foreground interlopers and to calibrate the photo-z analysis. JWST deep IR imaging and spectroscopic data obtained in advance, such as GTO JADES and the JWST NEP Time Domain Survey (Jansen & Windhorst 2018), serve as a "truth" field to fainter magnitudes to control systematics at the faint end of the proposed survey with a higher angular resolution (e.g., useful to understand what would be the importance of clumps and blending in these z~13-15 galaxies).

There are several theoretical predictions for early galaxy statistics both using numerical simulations and semi-analytic models. However, due to the limited volumes, some theoretical models cannot predict the number densities of relatively bright galaxies found in this survey and HLS. As a preparatory activity, we plan to extend these efforts and prepare a set of theoretical predictions that can be directly compared with this survey at z~13-15 (and HLS).

Conducting this survey as early as possible is highly beneficial for the community, given the limited lifetime of JWST and the first lights of 30 m-class telescopes. This survey will provide the community with samples of z~13-15 star-forming galaxies, PISNe and SLSNe at z>6, and z~4 passive galaxies, and a dataset of the almost full-band Roman images over 20 deg2, which will be a testbed for photometric analyses. In the 2030s SKA can observe the fields to look for 21 cm signals at z~13-15 from the intergalactic medium, investigating the presence of X-ray heated regions or early ionized bubbles associated with the galaxies.

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[1] https://project.ifa.hawaii.edu/h20/observing_plan/

[2] The effective area of the Roman SN wide survey is ~20 deg2 for its 25% spectroscopy plan.

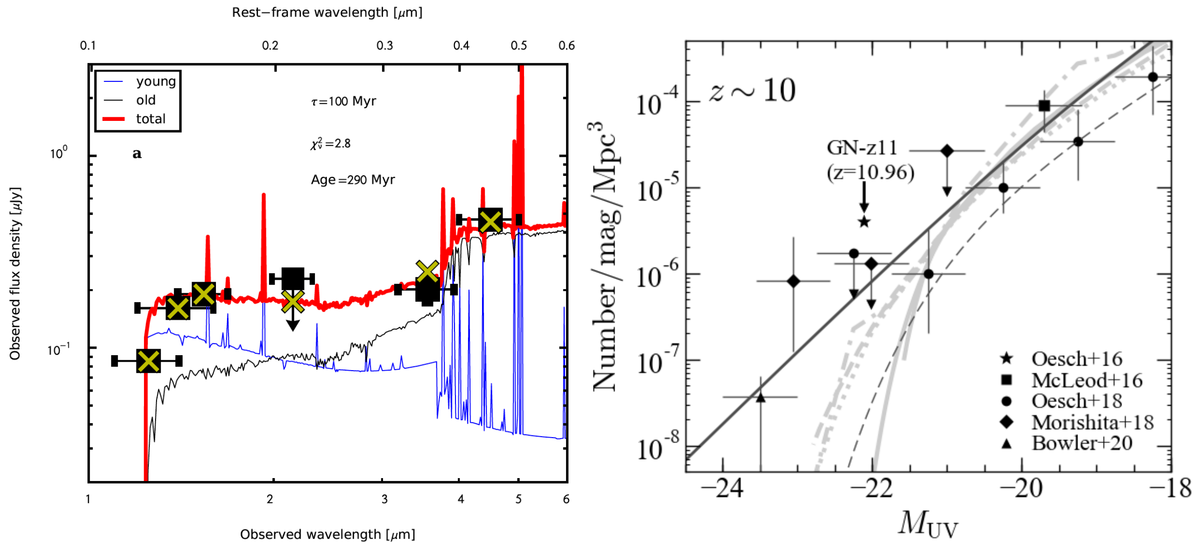

Figure 1: *(Left panel)* spectral energy distribution of a spectroscopically confirmed galaxy at z=9.11 (Hashimoto et al. 2018). The red Spitzer/IRAC color ([3.6]-[4.5]) indicates a prominent Balmer break in this galaxy, implying the onset of star formation at z~15. *(Right panel)* UV luminosity function at z~10. The black points show observed number densities of galaxies (McLeod et al. 2016, Oesch et al. 2018, Morishita et al. 2018, and Bowler et al. 2020), including a spectroscopically confirmed z=10.96 galaxy GN-z11 (star: Oesch et al. 2016, Jiang et al. 2021). The black solid line is the predicted UV luminosity function from Bowler et al. (2020), which is consistent with recent observations of these bright z~9-11 galaxies including GN-z11. The black dashed line is the Schechter function with phi* =10^(-0.6*(1+z)+1.65) Mpc^-3, Muv*=-20.5 mag, and alpha=-2.3 at z=10 (Harikane et al. in prep.). The gray lines show predictions from theoretical models (dot-dashed: Hutter et al. 2021 and Dayal et al. 2014, dotted: Yung et al. 2020, solid: Behroozi et al. 2019, dashed: Mason et al. 2015).

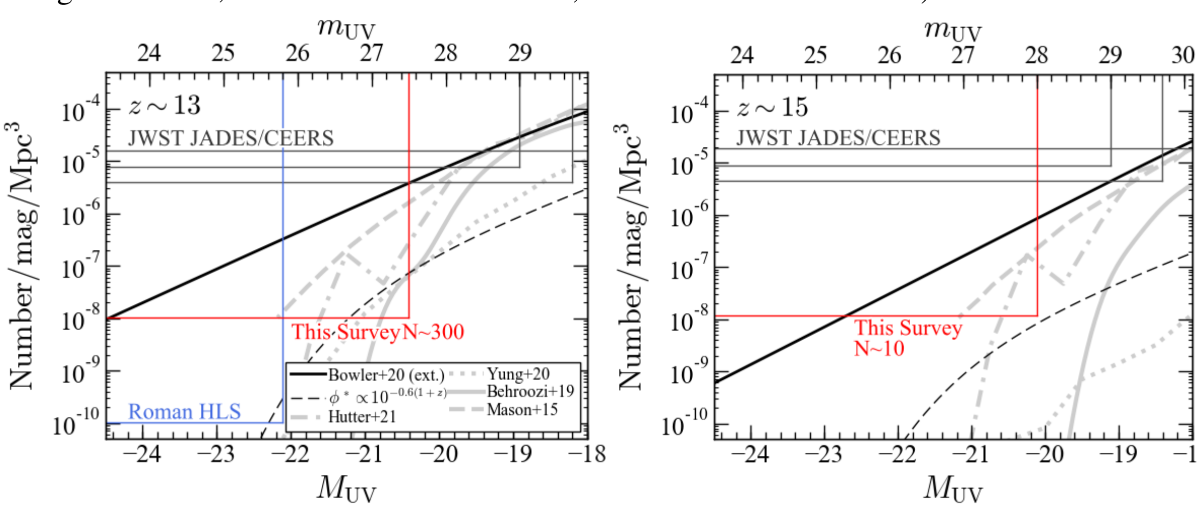

Figure 2: UV luminosity functions at z~13 (left) and 15 (right). The depth and volume of the proposed survey are indicated with the red lines. For comparison, Roman HLS (blue) and JWST JADES Deep and Medium and CEERS (gray) are plotted. The upper x-axes show apparent magnitudes in the detection bands (F184 and K213 for z~13 and z~15, respectively). The 6sigma sensitivity is used for z~15 to reduce the false positive rate, while 5sigma is enough for z~13 because two bands (F184 and K213) can be used. The black solid line is the predicted UV

luminosity function at each redshift calculated from an extrapolation of fitting functions in Bowler et al. (2020), which is consistent with recent observations of the bright z~9-11 galaxies and used to predict the number of detections (N~300 at z~13 and N~10 at z~15). The dashed line is the pessimistic case assuming the Schechter function with a rapid redshift evolution of the typical density of galaxies with phi* =10^(-0.6*(1+z)+1.65) Mpc^-3 (Harikane et al. in prep.). Even in this pessimistic case, we can detect several z~13 galaxies and constrain the number densities at z~13-15. The gray lines show predictions from theoretical models (dot-dashed: Hutter et al. 2021 and Dayal et al. 2014, dotted: Yung et al. 2020, solid: Behroozi et al. 2019, dashed: Mason et al. 2015). We plot predictions of Mason et al. (2015) at z~12 and 14 in the left and right panels, respectively.

Table 1: Exposure time and depth per each filter and pointing

Filter name	**R062**	**Z087**	**Y106**	**J129**	**H158**	**F184**	**K213**
Exp time /pointing	0.5h	0.5h	0.5h	0.5h	1.0h	1.0h	6.0h
Depth (5sigma, point source)	28.2 (29.0)*	27.8 (28.2)*	27.7 (28.1)*	27.6 (28.0)*	28.0	27.5	27.2
Depth (5sigma, 0.44”-radius aperture for an exponential profile with a 0.2” half-light radius)	26.9 (27.7)*	26.5 (26.9)*	26.5 (26.9)*	26.5 (26.9)*	26.9	26.5	26.3

* The values in parentheses are depths achieved in the two-year SN wide survey.

Note; Two depths for the point source and 0.2”-radius source are presented. Sizes of z~13-15 galaxies are expected to be ~0.1” (e.g., Malhotra et al. 2012, Shibuya et al. 2015). The zodiacal light is set at twice the minimum value.

A total of ~690 hours is needed to cover 20 deg2 assuming 10% overheads. The actual overheads will be determined by future discussions about details of exposure strategies.

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