# Roman CCS White Paper

# Title: A set of multi-tiered "Wedding Cake" deep fields for galaxy evolution leveraging the HLWAS infrastructure

**Roman Core Community Survey:** *High Latitude Wide Area Survey*

**Scientific Categories:** *galaxies; large scale structure of the universe; supermassive black holes and active galaxies*

**Additional scientific keywords:** *Galaxy evolution; high-redshift galaxies*


**Submitting Author:**
Name: L. Y. Aaron Yung
Affiliation: NASA Goddard Space Flight Center
Email: aaron.yung@nasa.gov

**List of contributing authors** (including affiliation and email):

| | |
|---|---|
| Micaela Bagley | (University of Texas in Austin, mbagley@utexas.edu) |
| Henry Ferguson | (Space Telescope Science Institute, ferguson@stsci.edu) |
| Steven Finkelstein | (University of Texas in Austin, stevenf@astro.as.utexas.edu) |
| Jonathan Gardner | (NASA Goddard Space Flight Center, jonathan.p.gardner@nasa.gov) |
| Jenny Greene | (Princeton University, jgreene@astro.princeton.edu) |
| Yuichi Harikane | (University of Tokyo, hari@icrr.u-tokyo.ac.jp) |
| Timothy Heckman | (Johns Hopkins University, theckma1@jhu.edu) |
| Casey Papovich | (Texas A&M University, papovich@tamu.edu) |
| Rachel Somerville | (Flatiron Institute, rsomerville@flatironinstitute.org) |
| Allison Strom | (Northwestern University, allison.strom@northwestern.edu) |



**Abstract:**
"Galaxies by the Millions" is one of the promises that the Roman Space Telescope will realize, but the current uniform-depth HLWAS design is not reaching depths needed to uncover galaxy evolution across cosmic time. Deep extragalactic IR imaging with Hubble and JWST has provided significant insights on galaxy evolution over the recent 95% of cosmic history but within survey areas that are severely restricted by the observatories' limited field of view. With a field of view two orders of magnitude larger than Hubble's and an angular resolution of matching quality, Roman is set to redefine deep-field galaxy surveys *at-large*. These *deep-wide* galaxy surveys will yield a wealth of data that will benefit the large extragalactic community and will set the course for follow-up studies with Roman and other observatories. Therefore, these surveys need to be done early in the Roman mission. In this white paper, we advocate for a set of multi-tiered "wedding cake" deep fields within the premises of the future HLWAS "sheet cake", leveraging the HLWAS design and infrastructure to step through various depths while carefully

balancing survey areas and anticipated object counts. This additional deep component to the HLWAS is guaranteed to yield significant scientific output and will empower the cosmic origins community to pursue follow-up studies with Roman General Astrophysics programs and will open the avenue for synergistic investigations with many other observatories.

# A set of multi-tiered "Wedding Cake" deep fields for galaxy evolution leveraging the HLWAS infrastructure

Deep IR imaging has a long history of piercing into the unknown epochs in cosmic history and has enabled numerous groundbreaking discoveries in galaxy evolution across cosmic time. From the original Hubble Deep field taken in 1995 [1] to the CANDELS legacy fields [2,3], to the Hubble Ultra-Deep Field (HUDF) [4] and the eXtreme Deep Field (XDF) [5], to a new era of ultra-deep surveys enabled by JWST [6,7], every step forward reveals galaxies and quasars beyond the expectation at the time of designing these surveys and have delivered a wide range of key constraints on galaxy evolution, including luminosity, color, morphology, physical properties, and the list go on.

Due to their limited field of view, legacy Hubble and recent JWST deep extragalactic surveys are prone to cosmic variance and other systematic uncertainties [8,9,10]. The Roman Space Telescope's unprecedented wide-field survey capabilities bear great potential to lead the way to *a new era of "deep-wide" galaxy surveys, where surveys spanning multiple sq-degs can reach depths comparable or surpassing that of the Hubble Ultra-Deep Field.* The projected uniform-depth ***"sheet cake"*** design of the Roman HLWAS lacks the deep component necessary for uncovering some of the most interesting aspects of galaxy evolution, especially the galaxy populations forming within the first billion years after the big bang (or $z > 6$). We propose to introduce a set of multi-tiered ***"wedding cake"*** deep fields within the premises of the future HLWAS, which will provide the necessary deep IR imaging and grism spectroscopy for unraveling galaxy evolution at-large.

At the time of this white paper call, the conceptualized HLWAS is made up of *"tiles"* and *"sectors"* [11, also see Fig. 1]. A *tile* consists of multiple exposures with four WFI broad-band filters and grism; and a *sector* consists of 32 tiles arranged in a 8 x 4 configurations, spanning ~11 sq-deg each. The HLWAS is projected to cover a total of 1,700 sq-deg with 155 sectors. The baseline depth anticipated to be reached by the HLWAS is 25.8-26.7 AB, assuming an exposure duration of ~146 sec. In order to reach depths required to detect galaxies at extreme distances, we propose to add a deep component to the HLWAS leveraging its survey infrastructure. We are aware that the HLWAS design will be updated following this white paper call. Therefore, we hope that expressing these recommendations in relative terms to the HLWAS can help keep up with the updates to be applied to the HLWAS survey strategies.

## Modifications for deep tiles

Within the HLWAS concept, a tile consists of multiple exposures in selected WFI broad-band filters F106, F158, F184, F129, and two grism exposures. For the modified *deep tile*, we propose to include additional filters F062, F087, F146, and F213, and two additional grism exposures. These modifications are summarized in Fig. 1. With these modifications, each deep tile will double the observing time of a regular HLWAS tile. These additional filters will enable efficient redshift estimates for a larger number of sources at $z \geq 4$ with the Lyman-break technique [12] and will enable a wide range of color-based source selection and diagnostics [e.g. 13, 14]. The total of four grism exposures per deep tile will be essential to obtaining precise spectroscopic redshift for sources detected at $z < 4$. Grism spectra are also great for detecting strong emission line features and can be used for BPT-like diagrams for SF galaxy / AGN selections [15,16,17].

## Projected survey sizes and depths

We propose to modify a couple of HLWAS sectors into *deep sectors*, with the constituent tiles modified into *deep tiles*. By repeating or extending the exposure time of HLWAS sectors, the set of multi-tiered deep fields will reach:

- a moderate depth of m ~ 24.5 - 27.3 for two sectors (~22 sq-deg) with exposure duration of 1 hour (or ~24x of the baseline exposure time).

- a deep field reaching m ~ 26.5 - 28.3 for 16 tiles in a 4x4 configuration (half a sector, ~ 5.5 sq-deg) with exposure duration of 5 hours (or ~120x of the baseline exposure time)

- an ultra-deep field reaching m ~ 28.8 - 29.2 for 6 tiles in a 3x2 configuration for a close-to-square aspect ratio (one-eighth of a sector, ~2 sq-deg) with exposure duration of 20 hours (or ~480x of the baseline exposure time)

The modifications needed for adding a *deep component* to the HLWAS are summarized in Fig. 1.

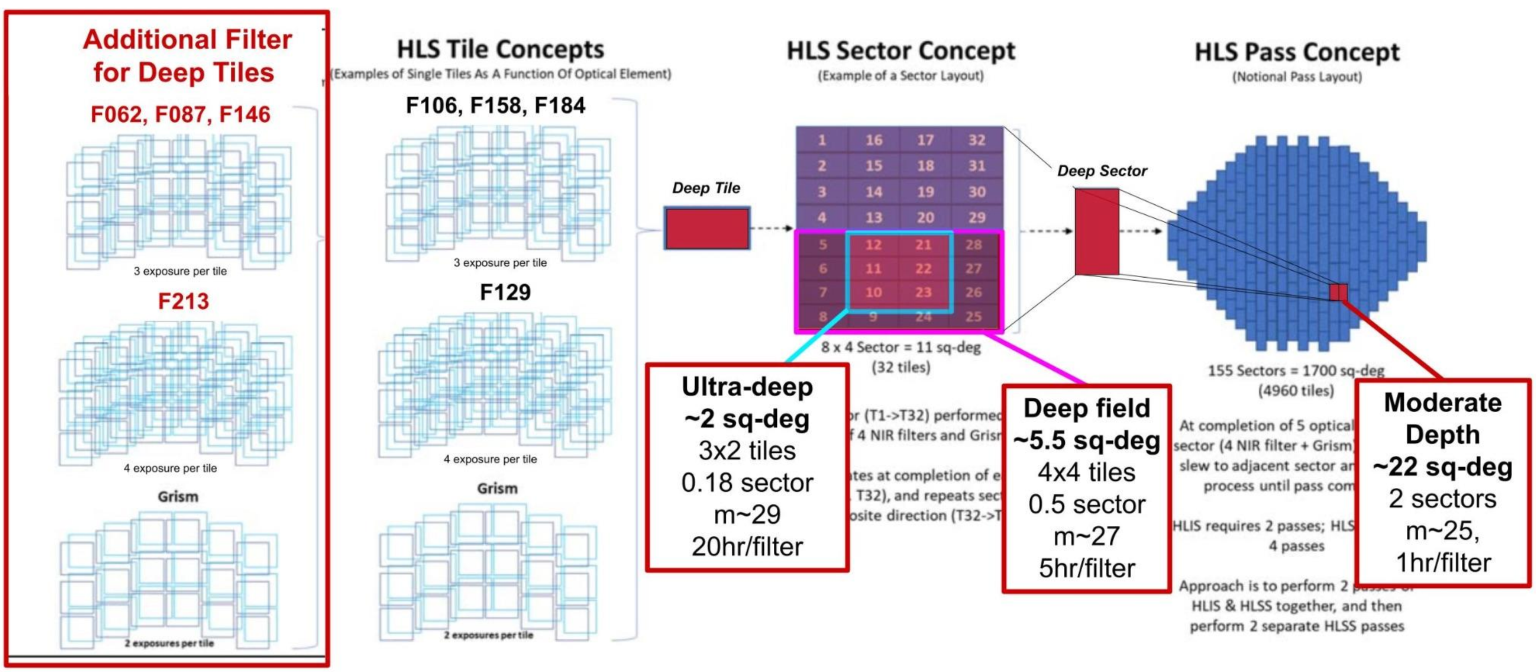


**Figure 1.** Summary of the proposed deep component to the HLWAS leveraging its current infrastructure. The modified "*deep tiles"* and "*deep sectors"* are highlighted in red. This diagram is adapted and modified from [11].

## Projected scientific return

Yung et al. (2023) presented a set of simulated lightcones based on the well-established Santa Cruz semi-analytic model (SAM) for galaxy formation. The Santa Cruz SAM is a physically-backed, computationally-efficient model that has been shown to well-reproduce existing observational constraints of galaxy populations across a wide range of redshifts and have been used to create *forecasts* to guide the observing strategies for future *JWST* surveys [9,18,19,20]. The set of five lightcones, each has a 2-sq-deg footprint and together contains >25 million galaxies spanning $0 < z < 10$, forming in dark matter halos with a minimum mass of $\log(M_h/M_{sun}) \sim 10$. Fig. 2 shows selected slices from $z \sim 4$ to $z \sim 9$ from one of the lightcones to illustrate the anticipated outcome of a 2-sq-deg *Roman Ultra-Deep Field*.

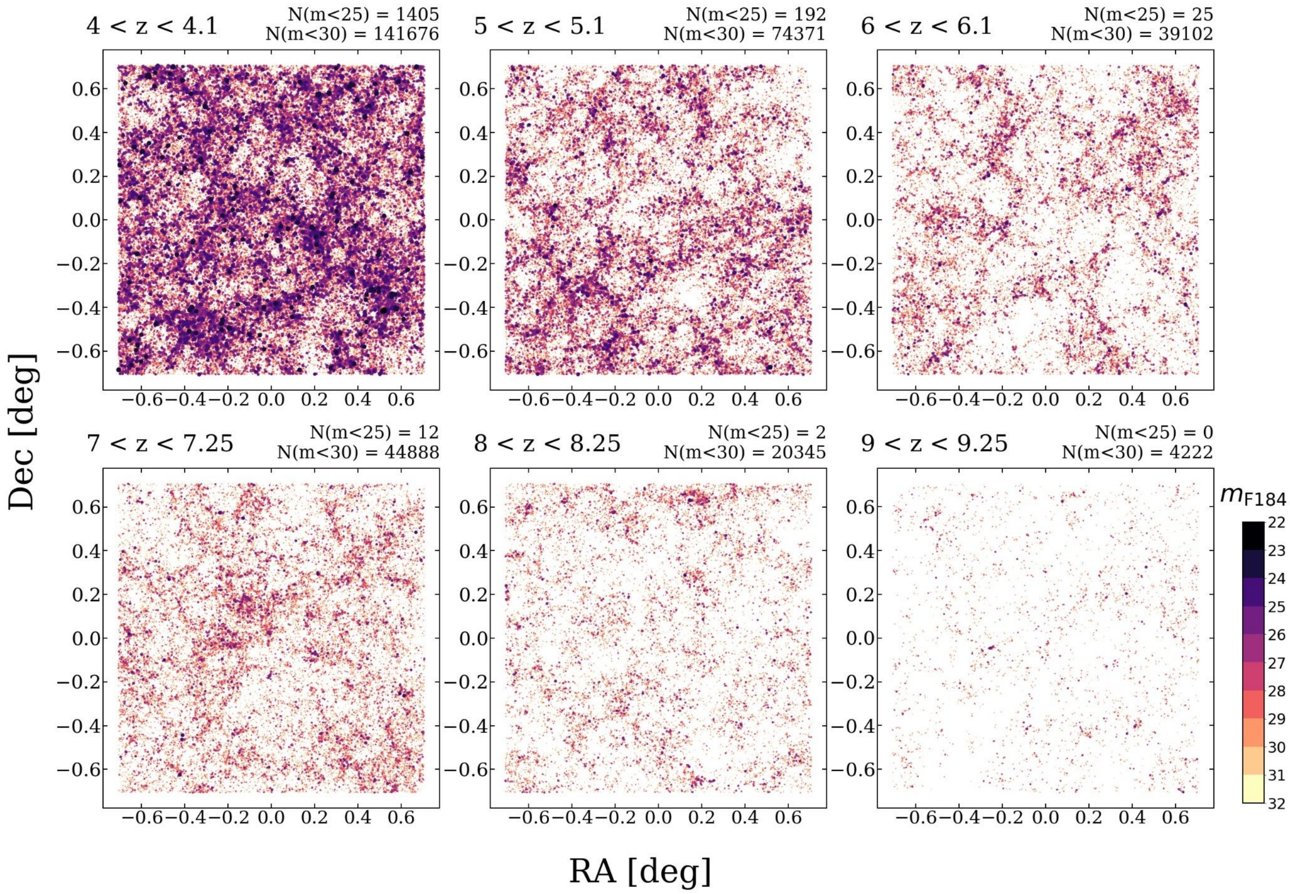


**Figure 2.** A summary of the footprint and galaxy populations in a simulated 2-dq-deg lightcone at various redshift slices between $z \sim 4$ and 10. The data points are color-coded by the observed-frame IR magnitude in the Roman WFI F184 band. The sizes of the data points are also scaled to emphasize brighter objects and do not reflect their predicted angular sizes. In addition, the number of bright and faint objects ($m_{F184} < 25$ and $m_{F184} < 30$, respectively) within each slice is indicated at the top-right corner of each panel. This figure is adapted from [10].

Here we estimate the projected scientific return of the Roman deep-field surveys based on these predictions. The number of galaxies anticipated in the moderate, deep, and ultra-deep fields as a function of redshift are shown in Fig. 3, which is estimated based on a total of 10 sq-deg of simulated sky. Based on these results, we estimate the redshift range of which the wedding cake surveys are capable of covering. This estimation requires approximately 10,000 objects to be detected in the highest redshift bin for the proposed survey area and depth combination (e.g. moderate depth is effective up to $z \sim 6$; deep $z \sim 8.5$; ultra-deep $z \sim 9.5$, respectively).

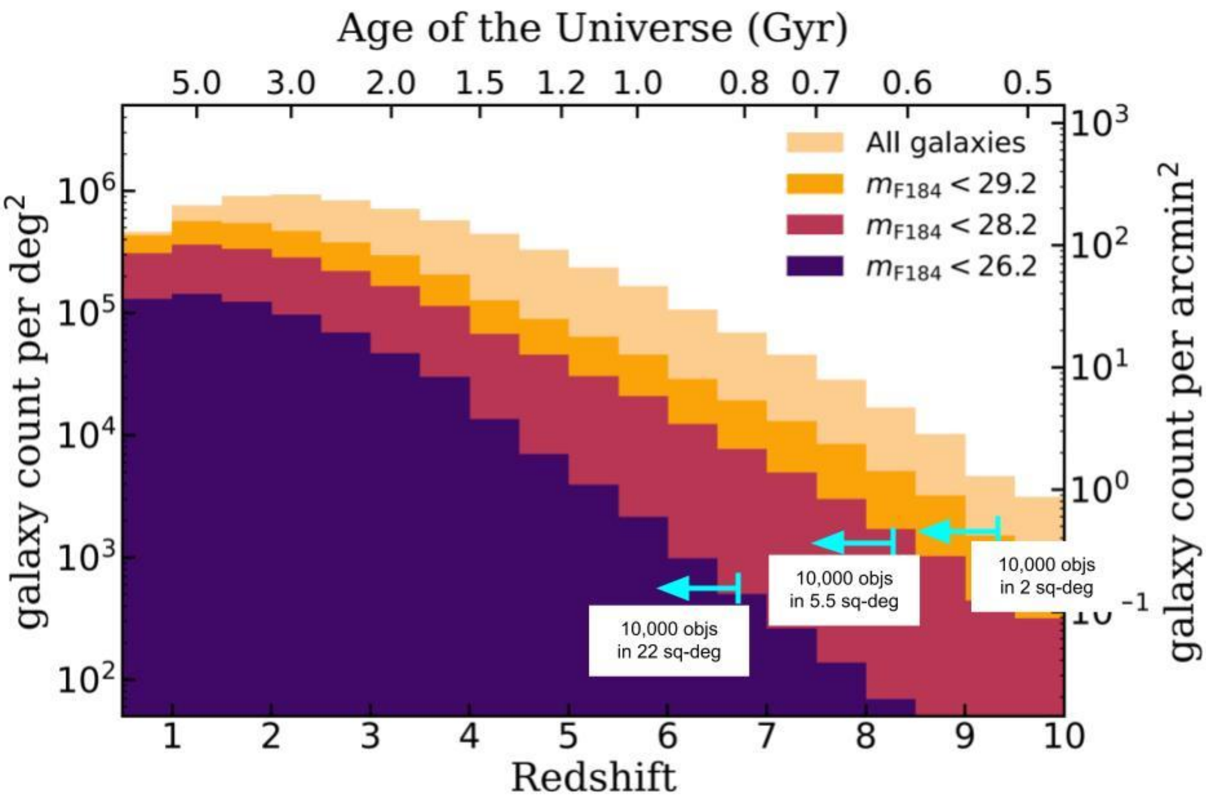


**Figure 3.** Based on galaxies found in five simulated 2-sq-deg lightcones (total of 10 sq-deg of simulated sky), this histogram shows the expected number of galaxies normalized to unit survey area (left: sq-deg; right: sq-arcmin) between $0.5 < z < 10$ in bins of $\Delta z = 0.5$ for galaxies. On the top axis, we show the age of the Universe corresponding to the redshift indicated on the bottom axis. We show the number of objects above several survey limits expected for the moderate depth, deep, and ultra-deep extragalactic surveys. This figure is adapted and modified from [10].

These *deep-wide surveys* will enable a wide variety of galaxy evolution studies. In particular, here we use results from these simulated Roman deep fields to demonstrate its power in constraining galaxy clustering at high redshift. In Fig. 4, we show the two-point angular autocorrelation functions (2PCFs) computed for many subregions at $4.0 < z < 4.5$ within the simulated lightcones. 2PCFs measure the excess of galaxy pair counts relative to a randomly distributed sample [21]. Through the four panels in the figure, we gradually step up from subregions with sizes comparable to the HUDF (~11 sq-arcmin) to the full 2-sq-deg fields to illustrate the benefit of a large deep field. The upper left panel shows that HUDF-like fields are severely affected by field-to-field variance, where the 2PCFs measured across multiple pointings can be highly inconsistent. Surveys with areas comparable to legacy Hubble and current JWST surveys (~100 sq-arcmin), as expected, can improve the statistical robustness of the 2PFC but are limited to small-scale separation (e.g. towards the left of each panel). With fields sizes comparable to a single Roman field-of-view (~0.28 sq-deg) and a proposed Roman ultra-deep field (~2 sq-deg), we will be able to constrain galaxy clustering on the very large scale, which cannot be done by any legacy, current, or other planned observatories.

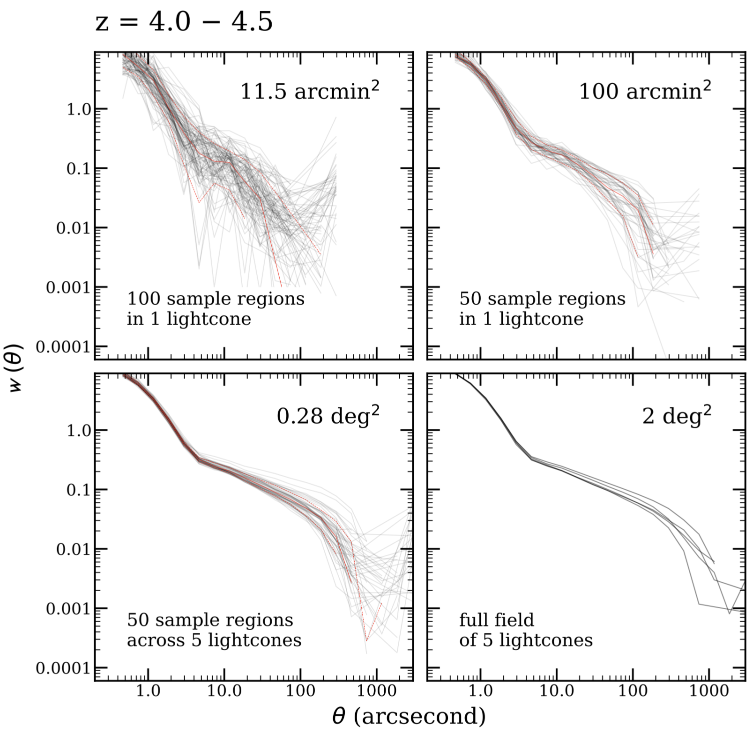


**Figure 4.** Predicted angular 2PCF, w(θ), calculated for galaxies with m F184 < 28, which is chosen to represent the depth expected to be reached by Roman moderate depth surveys. 2PCF computed for individual subregions are shown in gray. The red lines mark the median and 16th and 84th percentiles among all distributions. These panels step through various survey sizes and demonstrate the benefit of a *deep-wide* survey. **Top left:** HUDF-sized fields; **upper right:** CANDELS fields; **lower left:** a single Roman field-of-view; **lower right:** the proposed Roman Ultra-deep field. This figure is adapted from [10].

The significantly larger number of samples anticipated in these deep-wide surveys will also enable robust statistical inference for galaxy observable properties (e.g. luminosity, color, size, morphology) and inferred physical properties (e.g. stellar mass, star formation rate, metallicity), as well as their distributions (e.g. UV luminosity function), scaling relations (e.g. size-mass relation), and redshift evolution across multiple epochs of cosmic history.

Roman's capability to conduct multi-sq-deg deep surveys from space is set to discover large populations of distant quasars, in particular $z > 7$, and present a unique opportunity to study black hole growth in synergy with JWST. With its unprecedented IR sensitivity and spectroscopic capabilities, early JWST observations have revealed larger than expected supermassive black hole populations, both obscured and unobscured, embedded in high-redshift galaxies [e.g. 22,23,24]. JWST spectroscopic observations are also anticipated to deliver constraints on the first black holes forming in close proximity with the first galaxies [25]. Roman and JWST together will be able to jointly constrain the evolutionary course of these early forming quasars.

Adding a deep component to the Roman CCSs will enable a wide range of galaxy evolution studies and will help steer follow-up studies with Roman and other observatories. Therefore, it is extremely important to execute a Roman deep survey early on in the mission lifespan.

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