ILLUMINATING GALAXY EVOLUTION AT COSMIC NOON WITH ISCEA: THE INFRARED SATELLITE FOR COSMIC EVOLUTION ASTROPHYSICS

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ABSTRACT

ISCEA (Infrared Satellite for Cosmic Evolution Astrophysics) is a small astrophysics mission whose Science Goal is to discover how galaxies evolved in the cosmic web of dark matter at cosmic noon. The ISCEA Science Objective is to determine the history of star formation and its quenching in galaxies as the function of local density and stellar mass when the Universe was 3 – 5 Gyrs old (1.2 < z < 2.1). ISCEA is designed to test the following Science Hypothesis: During the period of cosmic noon, at 1.7 < z < 2.1, environmental quenching is the dominant quenching mechanism for typical galaxies not only in clusters and groups, but also in the extended cosmic web surrounding these structures. ISCEA meets its Science Objective by making a 10% shot noise measurement of star formation rate down to 6M⊙ yr⁻¹ using Hα out to a radius > 10 Mpc in each of 50 protocluster (cluster and cosmic web) fields at 1.2 < z < 2.1. ISCEA measures the star formation quenching factor in those fields, and galaxy kinematics with a precision < 50 km s⁻¹ to deduce the 3D spatial distribution in each field. ISCEA will transform our understanding of galaxy evolution at cosmic noon.

ISCEA is a small satellite observatory with a 700 cm² (30 cm equivalent diameter) aperture telescope with a field of view (FoV) of 0.32 deg², and a multi-object spectrograph with a digital micro-mirror device (DMD) as its programmable reflective slit mask. Using the approach pioneered by the DMD-based Infrared Multi-Object Spectrograph (IRMOS) on Kitt Peak, ISCEA will obtain spectra of ~ 1000 galaxies simultaneously at an effective resolving power of R = 1000, with 2.8” × 2.8” slits, over

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the near-infrared wavelength range of 1.1 to 2.0µm, a regime not accessible from the ground without large gaps in coverage and strong contamination from airglow emission. ISCEA will achieve a pointing accuracy of $\leq 2''$ FWHM over 200s. ISCEA will be launched as a small complete mission into a Low Earth Orbit, with a prime mission of 2.5 years. ISCEA’s space-qualification of DMDs opens a new window for spectroscopy from space, enabling revolutionary advances in astrophysics.
1. INTRODUCTION

Galaxies form and assemble within the cosmic web, with evolutionary histories that are determined by a combination of internal and environmental processes. Galaxy clusters emerge from the cosmic web at the intersections of filaments, and it has long been known that the properties of galaxies in these densest environments are influenced by a host of processes. These environmental processes include abrupt mechanisms like ram pressure stripping, mergers, and tidal interactions (e.g., Toomre & Toomre 1972; Gunn & Gott 1972; Mihos & Hernquist 1994, 1996; Moore et al. 1996; Hopkins et al. 2009; Haas et al. 2013; Schawinski et al. 2014; Faisst et al. 2017) as well as the slower process of strangulation and starvation (e.g., Larson, Tinsley, & Caldwell 1980; Balogh, Navarro, & Morris 2000; Feldmann, Carollo, & Mayer 2011; McGee, Bower, & Balogh 2014), with the different processes varying in importance as a function of environmental density and galaxy mass. Together these different mechanisms yield the long-observed star formation-density relation at low redshift (Dressler 1980; Balogh et al. 1998) in which star formation is quenched in dense environments. Subsequent work in the intervening decades has demonstrated that the star formation–density relation extends over a wide range of densities (e.g., Balogh et al. 2004; Tanaka et al. 2004) and is already in place by $z \sim 1$ (e.g., Cooper et al. 2010). Studies of cluster environments at low redshift have also shown that environmental factors influence galaxy properties even out well beyond the virial radius where the local densities are only moderately enhanced relative to field levels (e.g., Chung et al. 2011). Environment however is not the only factor that influences the star formation history of a galaxy. Mass-quenching, which is related to the dark matter mass of galaxies, occurs when gas falling onto galaxies is shock heated, hence prevented from cooling and forming stars. It is understood to be an important quenching mechanism for massive galaxies (e.g., Croton et al. 2006; Cattaneo et al. 2008; Peng et al. 2010; Woo et al. 2013; Carollo et al. 2013; Woo et al. 2014; Schawinski et al. 2014).

From a theoretical perspective, the onset of this star-formation vs. density relation is expected to occur at $z \sim 2$, with the precise timing being a function of mass. For example, the IllustrisTNG simulations predict that there already exists a substantial (factor of 2.5) decline in the specific star formation rates (sSFRs) for galaxies with mass $> 10^{10.5} \, M_\odot$ in clusters relative to the field, with this transition being delayed for lower mass galaxies (Harshan et al. 2021). The details of this transition, including both the timing and how it depends on local density, are however dependent on the relative importance of the various environmental mechanisms. Understanding this physics is critical to our general picture of galaxy evolution, and yet remains relatively poorly constrained – especially during this critical epoch during which star formation in the Universe peaks and massive galaxies and nascent (proto-)clusters are rapidly assembling.

Existing observations present a complex and incomplete picture. Many studies have found evidence for a reversal of the star formation-density relation at $z > 1$, with enhanced sSFRs relative to field levels in overdense environments (Cooper et al. 2008; Tran et al. 2010; Brodwin et al. 2013; Alberts et al. 2016; Hatch et al. 2017). Meanwhile, there is also evidence for molecular gas deficits in star-forming galaxies within $z \sim 1.5$ galaxy clusters, indicating that environmental factors are actively depleting their gas supply, and tentative evidence for environmental quenching at $z \sim 2$ based upon clustering of quiescent galaxies (Ji et al. 2018). Together, these results paint a picture of accelerated evolution in the densest environments, with both star formation and its quenching starting earlier than in lower densities. The detailed dependence of star formation and its quenching upon environment is however unclear during the $z \sim 2$ epoch when the most massive galaxies are expected to feel the onset of quenching. Recently, Harshan et al. (2021) conducted a pioneering investigation of the star formation histories of galaxies in a low-mass ($M \sim 5 \times 10^{13} \, M_\odot$) protocluster using spectral energy distribution (SED) fitting. They found that the most massive galaxies ($\log(M_*/M_\odot) > 10.5$) showed a slight $1\sigma$ decrement in sSFRs relative to the field, which is suggestive of the onset of quenching but at odds with the star formation reversal seen by other groups.

At a fundamental level, one of the key outstanding questions in our picture of galaxy formation is the relative importance of environmental and mass-quenching as a function of local density and redshift, and the need for data to resolve this question is most acute at $z \sim 2$. Many of the trends identified at lower redshift should first manifest at this epoch. This is where the cosmic star formation rate (SFR) density peaks (Madau and Dickinson 2014), and we expect galaxy groups and clusters to be assembling rapidly (based on simulations). By $z \sim 1-1.5$, many of the most massive clusters have already formed their cores and quenched their massive galaxies. To understand these mechanisms we must study and characterize the star-forming properties of the galaxies in overdensities at $z \sim 2$. Such an investigation has not been possible previously either from the ground, because of limitations for ground-based observatories, or from space because current space-based facilities do not have a sufficiently large field-of-view (FoV) to cover galaxies from the cores of protoclusters, to the filaments, to the field. Next generation facilities like JWST will provide high-fidelity information on the field population and can also target the very cores of clusters; however the FoV of JWST is very limited and covering the full cluster environment requires tiling together $> 100$ JWST fields. On the other hand, wide area slitless spectroscopic surveys, such as those planned for Euclid and Roman, do not have the necessary spectroscopic resolution to measure accurately the velocity structure of the protoclusters. The ideal means of addressing this
question is to look at a statistical sample of protocluster environments at this epoch, with sufficient spatial coverage to study lower density environments as well as dense cluster cores.

In the recent years infrared galaxy cluster searches have begun to extend to z > 1.5, driven by improved data and selection methods (e.g. Papovich 2008; Eisenhardt et al. 2009; Muzzin et al. 2013b; Noirot et al. 2018; Gonzalez et al. 2019; Wen & Han 2021). At the same time, the Atacama Cosmology Telescope (ACT, see Hilton et al. 2021) and South Pole Telescope (SPT, see Bocquet et al. 2019) surveys have identified a handful of clusters at z > 1.5, providing a sample of very high mass clusters that can be used to probe the most extreme central densities. In all cases, high-redshift clusters are expected to be rapidly growing within the larger protocluster environment. These protoclusters span the full range of local densities from field levels to dense cluster cores, providing an opportunity to assess the impact of environmental factors on galaxy evolution at all density levels – including in the filamentary structures surrounding the forming cluster cores in which “pre-processing” of future cluster galaxies may occur. It has also recently been argued that simulations indicate that gas accretion is less efficient within filaments at z ~ 2 due to high angular momentum, and that this may contribute to the large fraction of passive galaxies in filaments (Song et al. 2021). The new samples of high-redshift cluster candidates are now sufficiently large that with deep studies over the entire protocluster regions statistically robust analysis of environmental quenching as a function of local density and stellar mass becomes possible. Protoclusters are also the unambiguous formation sites of the first massive galaxies, and hence the best locations in which to constrain the elusive processes leading to the formation of passive, early-type galaxies. Within the protocluster regions, which have angular extents of tens of arcmin at z = 2 (Overzier 2016), addressing this science requires high-fidelity SFR estimates (e.g. via Hα), stellar masses, and robust local density determinations.

To find definitive answers to the outstanding questions on galaxy evolution at cosmic noon, we propose the Infrared Satellite for Cosmic Evolution Astrophysics (ISCEA). ISCEA is a space mission with a 700 cm² (27cm × 27cm square or 30cm diameter equivalent) aperture telescope in Low Earth Orbit (LEO), to obtain 1.1-2μm near-infrared (NIR) slit spectra at R = 1000 of galaxies with SFR as low as 6M⊙yr⁻¹ over a FoV 218 times that of HST and 128 times that of JWST. It has superior spectroscopic coverage and resolution compared to HST, SPHEREx, Euclid and Roman (Table 1).

ISCEA is optimally matched to the sizes of the high redshift protocluster regions (Fig. 1), enabling study of the distribution of star-formation and Active Galactic Nuclei (AGN, another indicator of galaxy evolution) not only in cluster cores, but also the infalling galaxy population in filaments and associated substructures that will accrete onto the cluster at later times. We will quantify the distribution of star formation and AGN activity over entire protocluster regions surrounding collapsed cluster cores, including regions that span three orders of magnitude in local density, log(1 + δ) = -1 to 2, where δ = (ρ - 〈ρ〉)/〈ρ〉.

In this paper, we present an overview of the science investigation with ISCEA. The ISCEA instrument and mission design will be presented elsewhere. §2 discusses the ISCEA Science Goal & Objective. §3 contains the detailed derivations of the ISCEA science, instrument, and high-level mission requirements. §4 describes the ISCEA Baseline Mission. §5 presents the simulations of ISCEA data. §6, §7, §8 discuss ISCEA data acquisition, data analysis, and data products respectively. §9 discusses the modeling and mitigation of systematic effects that affect the ISCEA science investigation. We discuss how ISCEA tests its Science Hypothesis and meet its Science Objective in §10, and the ISCEA secondary science program in §11. §12 contains the summary and conclusion.

Table 1. ISCEA will provide an unprecedented combination of spectral resolution R=1000, ultra depth, and wide FoV for precluster studies, unmatched by current or planned space-based IR projects. ISCEA depth assumes the typical 668ks (including 80% additional time for pointing jitter compensation) of observing time per protocluster field. HST depth is the 3-D HST Treasury Program 5σ line flux limits for "typical objects" (Brammer et al. 2012; VanDokkum et al. 2013; Mocanu et al. 2016). Euclid and Roman depths correspond to their wide-area surveys. SPHEREx will be limited by its large pixel size (6′′ pixel scale, vs. 1.4′′ for ISCEA) in crowded fields such as clusters at z ~ 2. Fields shaded in green satisfy the observational requirements for the science case here. Only ISCEA meets all of these requirements.

| Mission          | ISCEA | HST  | JWST | Euclid | SPHEREx | Roman |
|------------------|-------|------|------|--------|---------|-------|
| Slit spectroscopy| Yes   | No   | Yes  | No     | No      | No    |
| Spectral resolution| 1000  | 130  | 100-2700 | 380 | 35-130  | 460   |
| FoV (deg²)       | 0.32  | 0.00147 | 0.0025 | 0.53  | 39.6    | 0.281 |
| Depth (erg s⁻¹ cm⁻²) | 3 × 10⁻¹⁷ (5σ) | 5 × 10⁻¹⁷ (5σ) | 3.5 × 10⁻¹⁹ (10σ) | 2 × 10⁻¹⁶ (3.5σ) | N/A  | 10⁻¹⁶ (6.5σ) |
| Integration time per target | 668ks | 5ks  | 100ks | 4.32ks | 2.4ks  |
| Launch date      | ~ 2027 | 1990 | 2021 | ~ 2022 | ~ 2024  | 2027  |
2. ISCEA SCIENCE GOAL & OBJECTIVE

The Science Goal of ISCEA is to discover how galaxies formed and evolved within the cosmic web of dark matter at cosmic noon, in particular, the extent to which local density is destiny for these galaxies. The redshift regime $z \sim 2$ is not only the peak era of star formation in the Universe (see Fig. 2), but also an epoch at which galaxies and galaxy groups are undergoing rapid assembly and the influence of environment is beginning to be keenly felt in the most overdense regions. In cluster and group mass halos various processes such as strangulation, starvation, ram pressure stripping, and galaxy interactions are expected to truncate accretion and quench satellite galaxies, with some of these processes also acting within the filaments of the cosmic web.

To meet its Science Goal, the ISCEA Science Objective is to determine the history of star formation and its quenching in galaxies as a function of local density and stellar mass when the Universe was $3 - 5$ Gyr old ($1.2 < z < 2.1$), in order to understand the importance of environmental influences versus mass quenching in establishing the galaxy populations we see today.

The ISCEA mission is designed through the flow-down of the science objective to the science requirements to the technical requirements, and implemented on a small complete mission that meets all its requirements. ISCEA advances NASA astrophysics science objectives, and addresses the Astro2020 key science question "How do the histories of galaxies and their dark matter halos shape their observable properties?", in the decadal survey priority area "Unveiling the Drivers of Galaxy Growth" (NAS Astro2020 Decadal Survey Report 2021). During the 2 months of each year when the ISCEA protocluster fields are not accessible due to orbital constraints, we will carry out a secondary science program to discover and study low mass stars and brown dwarfs in young stellar clusters (see §11).

To meet its Science Goal and Objective, ISCEA is designed to test the following Science Hypothesis: During the period of cosmic noon, at $1.7 < z < 2.1$, environmental quenching is the dominant quenching mechanism for typical galaxies not only in clusters and groups, but also in the extended cosmic web surrounding these structures. We discuss the ISCEA requirement flow-down in detail in the following section.
The volume density of cosmic star formation rate (SFR), the key indicator for galaxy evolution, as a function of redshift $z$ and lookback time (Madau and Dickinson 2014). Colors denote data sets from different observational data sets. ISCEA will explore the peak epoch in galaxy evolution, which occurred during the peak in the cosmic SFR density ($1.2 < z < 2.1$).

**Figure 3.** ISCEA increases the scale and resolution of 3D galaxy maps of clusters by $> 10 \times$ current observations. **Left:** A Great Observatories image of the $1.9' \times 1.9'$ core of $z = 1.75$ cluster IDCS J1426.5+3508, with the few galaxies with spectroscopic redshifts indicated with green squares (from HST/WFC3 grism) and red circles (from Keck LRIS & MOSFIRE). **Middle:** Image zoom-out illustrating the limited spectroscopic sampling currently possible (with the same green squares and red circles as in the left panel). **Right:** Spitzer IRAC 3.6 $\mu$m image, showing 78% of the large ISCEA FoV. (Stanford et al. 2012; Brodwin et al. 2012, 2016; Gonzalez et al. 2012; Mo et al. 2016)

3. **ISCEA REQUIREMENTS**

3.1. **ISCEA Science Requirements**

ISCEA’s Science Objective, “Determine the history of star formation and its quenching in galaxies as a function of local density and stellar mass when the Universe was 3-5 Gyrs old ($1.2 < z < 2.1$),” flows down to four **ISCEA Science Requirements**:

1. Measure Star Formation Rate (SFR) using H$\alpha$ emission lines at $S/N \geq 5$ for $\geq 100$ galaxies out to a radius of 10 Mpc in each of 50 protocluster fields at $1.2 < z < 2.1$;

2. Measure Star Formation Quenching Factor (SFQF) out to a radius of 10 Mpc in each of 50 protocluster fields at $1.2 < z < 2.1$;

3. Measure 3D galaxy distribution out to a radius of 10 Mpc in each of 50 protocluster fields at $1.2 < z < 2.1$;

4. Measure radial velocity with $\Delta v < 50$ km s$^{-1}$ for each target galaxy.
Galaxy evolution peaks at $1.7 < z < 2.1$ (Fig. 2). To meet the ISCEA science objective, we require 45 bins (5 bins in stellar mass $M_*$, times 9 bins in local mass density $\delta$), similar to the low redshift zCOSMOS 20k study at $0.4 < z < 0.7$ (Kovac et al. 2014), with the same binsize in $M_*$ of 0.25 dex, and $\sim$3 bins in $\delta$ per order of magnitude. ISCEA probes the key range of $M_* = 10^{10} - 10^{12} M_\odot$, resulting in 5 bins of 0.25 dex. ISCEA covers three orders of magnitude in $\log(1+\delta)$, −1 to 2, resulting in 9 bins with three bins per order of magnitude. In each bin, we require 100 galaxies to measure SFR with 10% shot noise (sufficient statistical precision) since the shot noise is $1/\sqrt{N}$, where $N$ is the number of objects used in the measurement. ISCEA measures the H$\alpha$ line flux and its intrinsic scatter to derive the SFR using a detailed physical model. At ISCEA’s H$\alpha$ line flux limit of $3 \times 10^{-17}$ erg s$^{-1}$ cm$^{-2}$ (chosen to optimize the study of environmental effects on galaxy evolution, see §3.2), the average number of galaxies is $\sim 210$ inside a protocluster region observed by ISCEA, based on the ISCEA mock (see §5.3). Assuming an overall observing efficiency of 48% (80% per field, see §5.6, and a factor of $\sim 1.7$ margin to allow for instrument and spacecraft constraints), 45 protoclusters at $1.7 < z < 2.1$ are required to yield 4500 galaxies. ISCEA will also observe five protoclusters at $1.2 < z < 1.7$, to calibrate and tie into the existing extensive data on clusters at $z < 1.7$.

The ISCEA target list includes the five highest redshift Sunyaev-Zel’dovich (SZ) clusters at $z > 1.5$ observed by SPT (Bocquet et al. 2019) and ACT (Hilton et al. 2021). The SZ signal (Sunyaev & Zeldovich 1972) results from the scattering of the Cosmic Microwave Background photons off the free electrons in the hot ionized gas that permeates each cluster. SZ clusters are generally more massive than the clusters selected using photometry (Wen & Han 2021), and provide unique insight into the physical mechanism for star formation quenching in massive clusters at cosmic noon (see §1).

Galaxy velocity measurements with $\Delta v \sim 50$ km s$^{-1}$ will enable us to definitively associate any given galaxy with a cluster, group or filament, and assess whether any observed groups and filamentary structures are truly associated with the protocluster, or lie outside the turnaround region for the protocluster. This requires a redshift precision only available from $R \sim 1000$ slit spectroscopy (Fig. 4).

The cosmic web out to a radius 10 Mpc around a cluster contains all relevant information regarding galaxy evolution as a function of local density. This requires a FoV $> 24' \times 40'$ centered on each cluster, to reach the radius of 10 Mpc, while providing sufficient statistics ($\geq 100$ galaxies per protocluster) to meet the science requirements (see Fig. 1). To meet all Science Requirements, ISCEA will observe 50 protocluster fields at $1.2 < z < 2.1$ (including 90% at $z > 1.7$) to measure galaxy spectra with $S/N \geq 5$ (on the strongest emission line or absorption feature) at $R = 1000$ (effective) using slit spectroscopy for $\geq 100$ galaxies on average inside each protocluster.

### 3.2. ISCEA Instrument Requirements

**ISCEA** Science Requirements flow down to **ISCEA Instrument Requirements**:

**Wavelength Range**: 1.1−2.0 $\mu$m, to enable the detection of the two strongest emission lines per galaxy, including H$\alpha$ as tracer of star formation activity over $1.2 < z < 2.1$. H$\alpha$ emission line flux is considered the ideal tracer of SFR (Kennicutt 1998). The minimum wavelength is set by requiring the observation of [O III] emission line at $z \geq 1.2$. 

Spectral Resolving Power: \( R = \lambda / \Delta \lambda \geq 1000 \) with slit spectroscopy, to measure galaxy velocities. This is required to map the cosmic web in sufficient details to study environmental effects on galaxy evolution (see Fig. 4).

Spectroscopic Multiplex Factor (number of spectra obtained simultaneously): \( \geq 300 \), to observe all cluster galaxy and cosmic web galaxy candidates in a single observation. Fig. 5 shows that by using a DMD as the spectroscopic target selector, ISCEA can obtain \( \sim 1000 \) non-overlapping spectra simultaneously.

Flux Limit: \( 3 \times 10^{-17} \text{erg s}^{-1} \text{cm}^{-2} \). ISCEA’s flux limit is set by the SFR measurement requirement. The SFR vs. galaxy position (with respect to other nearby galaxies and to the protocluster as a whole) can tell us how SFR tracks with density and radius, which allows us to predict how a galaxy might evolve, i.e., if it will end up as a spiral or elliptical. ISCEA requires SFR measurements to the limit of \( 6 \text{M}_{\odot} \text{yr}^{-1} \), corresponding to a stellar mass of \( \lesssim 10^{10} \text{M}_{\odot} \) on the star-forming main sequence at \( 1.2 < z < 2.1 \) (see, e.g., Daddi et al. 2007; Koyama et al. 2013; Shivaei et al. 2015; Valentino et al. 2017), optimal for studying environmental effects on galaxy evolution (see Fig. 30). A SFR of \( 6 \text{M}_{\odot} \text{yr}^{-1} \) roughly translates to the H\( \alpha \) emission line flux limit of \( 3 \times 10^{-17} \text{erg s}^{-1} \text{cm}^{-2} \) (Kennicutt 1998). ISCEA’s 3\( \sigma \) line flux limit. The ISCEA 3\( \sigma \) line flux limit of \( 1.8 \times 10^{-17} \text{erg s}^{-1} \text{cm}^{-2} \) enables definition of quiescent galaxies as galaxies with no detectable emission lines at this limit.

Spectroscopic “Slit” Size (DMD pixel scale): \( 2.8'' \times 2.8'' \), to ensure that each “slit” (i.e., DMD micro-mirror) is small enough to select \( \sim 1 \) galaxy and minimize its sky background, but large enough to capture most of the light from the galaxy in the presence of pointing jitter.

FoV: \( \geq 24' \times 40' \sim 0.27 \text{deg}^2 \), centered on a cluster, to reach the radius of 10Mpc, while providing sufficient statistics (\( \geq 100 \) galaxies per protocluster field) to meet the science requirements, see Fig. 1 (right panel).

3.3. ISCEA Mission Functional Requirements

ISCEA Instrument Requirements flow down to the high-level ISCEA Mission Functional Requirements as follows.

Telescope Aperture: \( \geq 700 \text{ cm}^2 \) (27cm \( \times \) 27cm square), in order to meet the flux limit and the signal-to-noise ratio (S/N) requirements for ISCEA in 2.5 years, based on our exposure time estimates. The ISCEA exposure time calculator (ETC) assumes
### Table 2. ISCEA meets science requirements with significant resiliency to pointing performance and thermal control. The available observing time per target field is assumed to be 1Ms (maximum time per target is 1.2Ms).

| Scenario  | Parameters                        | Observing Time |
|-----------|-----------------------------------|-----------------|
| Reference | $T_{\text{optics}} = 181K$, $T_{\text{detector}} = 100K$, no pointing jitter | 371ks           |
| Requirement | $T_{\text{optics}} = 181K$, $T_{\text{detector}} = 100K$, 2′ pointing FWHM over 200s | 371ks×1.8=668ks |
| Variation 1 | $T_{\text{optics}} = 181K$, $T_{\text{detector}} = 90K$, 2′ pointing FWHM over 200s | 310ks×1.8=558ks |
| Variation 2 | $T_{\text{optics}} = 181K$, $T_{\text{detector}} = 90K$, 2.2′ pointing FWHM over 200s | 310ks×2.1=651ks |
| Variation 3 | $T_{\text{optics}} = 185K$, $T_{\text{detector}} = 90K$, 2′ pointing FWHM over 200s | 430ks×1.8=774ks |
| Variation 4 | $T_{\text{optics}} = 185K$, $T_{\text{detector}} = 90K$, 2.2′ pointing FWHM over 200s | 430ks×2.1=903ks |

The observatory will have a pointing jitter ≤ 0.5′′, and the minimum requirement is that the pointing FWHM over 200s must be greater than 2.2′′.

**Observing Strategy:** Each protocluster will be observed multiple times. This enables us to access the faintest galaxies repeatedly, the number of galaxies targeted, and resolve any blended spectra of galaxies occasionally selected by the same spectrograph. Since emission line galaxies (ELGs) have sufficient pointing precision to differentiate individual galaxies in order to measure their spectra. The pointing jitter of 2′′ FWHM is well matched to the slit size (i.e., DMD micro-mirror scale) of 2.8′′ × 2.8′′, without being overly stringent and without gaps in atmospheric transmission.

**Mission Life:** 2.5 years, to meet science requirements, based on exposure time calculations (Table 2).

**Launch Window:** No constraints.

**Extended Mission Life:** 1-2 years, to enable the Guest Observer (GO) program.

**Observatory Orbit:** Sun Synchronous LEO. A space platform is required to explore the peak epoch of galaxy evolution robustly and without gaps. The pervasive presence of strong and highly variable hydroxyl (OH) lines in the Earth’s atmosphere, and the substantial opacity gaps (especially at ~ 1.4μm and ~ 1.9μm) limit the possibility of obtaining homogeneous high $S/N$ spectra of faint sources in the NIR from the ground. Fig. 6 shows the atmospheric transmission at Mauna Kea, representative of the best observing conditions from the ground. The gaps in atmospheric transmission correspond to redshift ranges for Hα, Hβ, [O III] and [O II] (key spectroscopic features for galaxies) inaccessible from the ground, see Table 3. These introduce large gaps in the galaxy evolution history during the critical epoch of mass assembly in protoclusters. Ground-based facilities, even those with NIR coverage, e.g. MOSFIRE at Keck on Mauna Kea, and ESO’s MOONS in Chile, are inadequate for meeting the ISCEA Science Objective. ISCEA requires the continuous coverage of 1.1–2.2μm for any target in the sky throughout the year over a wide FoV to track SFR with Hα. It will detect Hα at z = 0.7–2.1, Hβ at z = 1.3–3.1, [O III]λ5007 at z = 1.2–3.0, and [O II]λ3727 at z = 2.0–4.4. ISCEA will detect Hα and [O III] for any galaxy with $1.2 < z < 2.1$ to robustly determine redshift and SFR. ISCEA will also detect both [O III] and [O II] emission lines at 2 < z < 3, with discovery potential for protoclusters up to z = 3.

**Observatory will accommodate a spectrograph and an imaging channel:** needed for ISCEA science data acquisition via spectroscopy, and calibration, target selection and verification via imaging.

**Observatory will have a pointing jitter ≤ 2′′ full-width-at-half-maximum (FWHM) over 200 sec:** The observatory must have sufficient pointing precision to differentiate individual galaxies in order to measure their spectra. The pointing jitter of 2′′ FWHM is well matched to the slit size (i.e., DMD micro-mirror scale) of 2.8′′ × 2.8′′, without being overly stringent and without gaps in atmospheric transmission.

1. https://www2.keck.hawaii.edu/inst/mosfire/home.html
2. https://www.eso.org/sci/facilities/develop/instruments/MOONS.html
Figure 6. The atmospheric transmission at Mauna Kea for a typical water vapor column of 1.6mm and an airmass of 1 (see http://www.gemini.edu/observing/telescopes-and-sites/sites). The ISCEA wavelength range cannot be accessed from the ground without large gaps in redshift and thus galaxy evolution (see Table 3).

| Redshift Gap | 1.3–1.5\,\mu m | 1.8–2\,\mu m |
|--------------|-----------------|--------------|
| z(H\alpha)   | 1.0–1.3         | 1.7–2.1      |
| z(H\beta)    | 1.7–2.1         | 2.7–3.1      |
| z([O III])   | 1.6–2.0         | 2.6–3.0      |
| z([O II])    | 2.5–3.0         | 3.8–4.4      |

Table 3. Redshift gaps corresponding to atmospheric gaps in Fig. 6. ISCEA observes star-forming galaxies at cosmic noon (1.7 < z < 2.1) not accessible from the ground.

becoming a mission cost driver. The pointing jitter has two effects on the observed spectrum of a galaxy: (1) a reduction in the effective spectral resolution $R$ ("spectral blurring"), due to the galaxy's position being jittered in the dispersion direction, and (2) a reduction of $S/N$ ("aperture effect"), due to the decreased coverage of the galaxy when the DMD micro-mirror misses the galaxy (see illustration from our simulation in Fig. 7). Our simulations (see also §5.4) show that a pointing jitter of 2" FWHM leads to < 10% degradation in $R$ from $R = 1000$, which requires that the ISCEA spectrograph is designed with $R = 1100$ to compensate this, and a loss in $S/N$ of < 15%, which needs to be compensated by increasing the observing time on the faintest galaxies. §5.4 contains a detailed discussion of the DMD micro-mirror "slit" loss and pointing jitter modeling.

4. ISCEA BASELINE INVESTIGATION

The ISCEA Baseline Mission is 2.5 years in duration, and observes 50 protoclusters in sequence. These are selected from 100 protocluster candidates with imaging and quick spectroscopic observations. In each protocluster field, we target > 1000 galaxies with photometric redshifts (photo-z’s) closest to the confirmed BCG (Bright Cluster Galaxy) spectroscopic redshift. Each protocluster field will be observed for a total of 668ks (including the average additional time of 80% to compensate for $S/N$ loss due to pointing jitter, see §5.4), to reach the ISCEA flux limit of $3 \times 10^{-17}$\,erg\,s$^{-1}$\,cm$^{-2}$ at 5$\sigma$ (see Table 2). Each observation is divided into multiple visits, each with a slightly different roll angle to optimize access to targets and resolve the occasional blended spectra of galaxies selected by the same slit (i.e., DMD micro-mirror). ELGs with $S/N \geq 5$ will be replaced with new
galaxies for the next protocluster visit (> 2 weeks later). The faintest galaxies will remain on the target list for all visits to the field, reaching a line flux limit of $3 \times 10^{-17}$ erg s$^{-1}$ cm$^{-2}$ at 5$\sigma$. At least $\sim$1000 galaxy spectra will be obtained per cluster field. Our Monte Carlo simulations indicate that ISCEA science requirements (see §3) are met with $> 30\%$ margin (see §5.6).

**ISCEA** meets science requirements with significant resiliency to pointing performance and thermal control (see Table 2), since the available observing time per protocluster is at least 1Ms (with a maximum of 1.2Ms). If the ISCEA instrument and mission requirements are fully met, i.e., $T_{\text{optics}} \leq 181K$ and pointing jitter $\leq 2''$ FWHM over 200s, these margins will be used to enhance ISCEA science, as 668ks of observing time per target is sufficient to reach the H$\alpha$ line flux limit of $3 \times 10^{-17}$ erg s$^{-1}$ cm$^{-2}$ at 5$\sigma$. Since $(1000ks - 668ks) \times 50 = 16.6Ms = 24\times668ks + 568ks$, **ISCEA can use these margins to observe 24 additional confirmed protoclusters at $1.7 < z < 2.1$ to the H$\alpha$ line flux limit of $3 \times 10^{-17}$ erg s$^{-1}$ cm$^{-2}$ at 5$\sigma$ (for a total of 69 at $z > 1.7$), using 568ks for additional target selection if needed.** Alternatively, ISCEA can observe the same 50 protoclusters to the fainter H$\alpha$ line flux limit of $\sim 2.4 \times 10^{-17}$ erg s$^{-1}$ cm$^{-2}$ (corresponding to the SFR of $\sim 4.8 M_{\odot}$ yr$^{-1}$). We will do a detailed trade study during Phase A comparing the scientific gains from these two options.

The Baseline Mission design is supported by the following sections as follows:

- §4.1 describes the ISCEA protocluster target selection, and §4.2 the ISCEA galaxy target selection in each protocluster, respectively.
- §5.1 present the ISCEA mock.
- §5.2 discusses the validation of the galaxy photo-z’s.
- §5.3 predicts the number of ISCEA galaxies per protocluster field using the ISCEA mock.
- §5.4 models the effects due to pointing jitter.
- §5.5 discusses ISCEA velocity measurements.
- §5.6 presents details of the derivation of the ISCEA observing efficiency.
- §6 describes ISCEA data acquisition.
- §7 describes how the ISCEA Baseline Mission is supported by the ISCEA Science Operations Center (SOC).
- §8 describes the expected data products.
- §9 discusses systematic effects relevant to the ISCEA science investigation and their mitigation.
- §10 shows how the ISCEA Baseline Mission tests the ISCEA Science Hypothesis to meet the ISCEA Science Goal and Objective.
Figure 8. Sky distribution of high-redshift ($z > 1.2$) clusters accessible to ISCEA, from ACT, SPT, and the equatorial survey fields from the Wen & Han (2021) cluster catalog, with a density map from AllWISE shown as the background. All clusters at $z > 1.7$ are plotted in green regardless of the source catalog. The inset panel shows the density of high-redshift clusters within one of the Wen & Han (2021) cluster fields. The ISCEA preliminary target list consists of 100 cluster candidates selected from this distribution, including 90 clusters at $1.7 < z < 2.1$, and 10 clusters at $1.2 < z < 1.7$. The ISCEA confirmed target list will consist of 50 clusters (including 90% at $1.7 < z < 2.1$).

• §11 describe the ISCEA secondary science program to make full use of the two winter months each year when the protocluster targets have limited visibility due to spacecraft orbital constraints.

4.1. Protocluster Target Selection

The ISCEA preliminary target list consists of 100 protocluster candidates, including 90 protocluster fields at $1.7 < z < 2.1$, and 10 at $1.2 < z < 1.7$, each centered on a cluster candidate. We have selected 90 fields at $1.7 < z < 2.1$ to prioritize highest redshift clusters from the Wen & Han (2021) cluster catalog. These are supplemented by five massive SZ clusters at $z > 1.5$ from ACT and SPT, in order to improve statistics at the highest local densities to gain insight into the physical mechanism of star formation quenching in clusters at this epoch (see §1). The Wen & Han (2021) catalog currently provides the largest sample of $z > 1.8$ cluster candidates with photometric redshifts, and hence is the best available sample for this program. Fig. 8 shows the spatial distribution of ISCEA preliminary cluster targets in the sky, with the zoomed inset illustrating the cluster target density within one of the fields of Wen & Han (2021). The ISCEA confirmed target list will consist of 50 protoclusters (each a cluster with its adjacent cosmic web environment), with 90% of the protoclusters at $1.7 < z < 2.1$.

The Wen & Han (2021) cluster galaxy photo-$z$’s are computed using a nearest-neighbor algorithm based on the 7-band photometry from HSC SSP ($grizy$) and WISE (W1, W2) over $\sim 800$ deg$^2$. The training sample for the algorithm contains 554,996 galaxies with spectroscopic redshifts, of which 240,409 are matched with the HSC-SSP × unWISE galaxies and have magnitudes in the $grizyW_1$ bands. This extensive set of spectroscopic data includes the data from SDSS DR14 (Abolfathi et al. 2018), DEEP3 (Cooper et al. 2011), PRIMUS DR1 Cool et al. (2013), VIPERS PDR1 (Garilli et al. 2014), VVDS (Le Fèvre et al. 2013), GAMA DR2 Liske et al. (2015), WiggleZ DR1 (Drinkwater et al. 2010), zCOSMOS DR3 (Lilly et al. 2009), UDSz (Bradshaw et al. 2013; McLure et al. 2013), FMOS-COSMOS (Silverman et al. 2015; Kashino et al. 2019) and 3DHST (Skelton et al. 2014; Momcheva et al. 2016). To have enough data for training at $z > 1$, their spectroscopic training set is supplemented by accurate photo-$z$’s from the COSMOS2015 catalogue, which are based on 30-band photometry with an accuracy of 0.021 (Laigle et al. 2016). This results in photo-$z$’s with impressive precision and accuracy. Wen & Han (2021) define the photo-$z$ uncertainty as

$$
\sigma_{\Delta z} = 1.48 \times \text{median} \left( \frac{|z_p - z_s|}{1 + z_s} \right) \approx 0.055z_s - 0.0145, \tag{1}
$$

where $z_p$ is photo-$z$, and $z_s$ is spectroscopic redshift. They estimated an outlier fraction of $\sim 6\%$, with outliers defined as photo-$z$’s with a deviation larger than $3\sigma_{\Delta z}$ or 0.15, compared to spectroscopic redshifts. They found that $\sigma_{\Delta z} \sim 0.11$ at $z \sim 2$ (see the lower panel of their Figure 1). The addition of ISCEA’s 1.1–2 $\mu$m broadband imaging will break common degeneracies of the photo-$z$
estimation method, hence result in a further improvement of the photo-z estimates (see §5.2). Fig. 9 shows the distribution of the 90 ISCEA protocluster candidates at $1.7 < z < 2.1$ in redshift and cluster mass $M_{500}$ (mass contained within radius $r_{500}$, where $\rho_{\text{local}} = 500\rho_c$, with $\rho_c$ denoting the critical density).

We estimate that $> 50\%$ of the ISCEA cluster candidates to be bona fide clusters at $1.7 < z < 2.1$. There are many hundreds of cluster candidates to choose from at $1.2 < z < 1.7$, with most of those expected to be bona fide clusters in that redshift range, due to the increasing photo-z accuracy and precision with decreasing redshift (see Eq. 1). We will prioritize the 90 highest redshift cluster candidates at $1.7 < z < 2.1$, and choose 10 cluster candidates at $1.2 < z < 1.7$ to tie in with existing observational data. Our ISCEA mock catalog (§5.1) indicates that the Wen & Han 2021 catalog is complete at $z \sim 1.7$, but highly incomplete at $z > 1.76$ (Fig. 9, left panel), increasing the likelihood of the highest $z$ cluster candidates being at $z > 1.8$, since we expect 69 clusters at $z > 1.8$ over the ISCEA survey area of $\sim 800 \text{ deg}^2$. Since ISCEA focuses on protoclusters to probe environmental effects on galaxy evolution over three orders of magnitude in local mass density, the cluster mass in each protocluster is of secondary importance. Note that ISCEA provides follow-up opportunities for future studies to derive cluster masses and enable additional science through studies of lensing (e.g., from Roman observations) or targeted SZ studies from CMB telescopes.

ISCEA will carry out quick spectroscopy (4 hours) of each of the 100 candidate protocluster fields (see §6.3), to obtain spectroscopic redshifts for > 10 galaxies (expected to be met with a large margin since the ISCEA $5\sigma$ H$_\alpha$ line flux limit for spectroscopy in 4 hours is $2.2 \times 10^{-16}$erg/s/cm$^2$, see Fig. 10 left panel), including the Brightest Cluster Galaxy (BCG) in each field. This will result in the ISCEA confirmed target list of 50 protoclusters to meet the ISCEA Science Requirements (see §3.1). We also have the flexibility to adjust the ISCEA target list as additional high-redshift clusters from ACT, SPT, and newer, on-going surveys are confirmed. Doing so can further increase the galaxy yield by enabling inclusion of the protoclusters associated with the most massive clusters at that epoch.

4.2. Galaxy Target Selection

In each BCG-confirmed protocluster field, ISCEA will obtain $\sim 1000$ spectra simultaneously (see Fig. 5). Since each protocluster field will be visited multiple times, separated by more than 2 weeks, we will update the galaxy target list by removing bright galaxies with high S/N spectra, and replace them with new galaxy targets. Thus ISCEA will obtain spectra of > 1000 galaxies per field (see §6). ISCEA will target 1000 galaxies with photo-z’s closest to that of the BCG in the first visit, and expand the target list in subsequent visits as needed, by selecting the next galaxies with photo-z’s closest to the BCG not yet targeted.

Fig. 10 shows the distribution in the estimated H$_\alpha$ line flux (left panel), and the observed brightness in the ISCEA $H$-band, WISE 3.5$\mu$m and HSC $\gamma$-band (right panel), for the 1000 galaxies with photo-z’s closest to that of the cluster BCG, for the 100 ISCEA preliminary protocluster target fields (see §4.1), each the size of the ISCEA FoV. On average, ~77% of the 1000 galaxies in each field are estimated to be above the ISCEA flux limit of $3 \times 10^{-17}$erg s$^{-1}$ cm$^{-2}$ (see Fig. 11). Note that ISCEA images all galaxies to AB=25 in the ISCEA broad $H$-band (see §6.3), which encompasses all of the 1000 target galaxies in each of the ISCEA candidate protoclusters from the Wen & Han (2021) catalog (see Fig. 10, right panel). The SZ clusters are more massive and expected to contain a larger number of bright galaxies.

Fig. 12 shows a representative ISCEA candidate protocluster target field, centered on candidate cluster J123345.3-002945 at $z \sim 2$ from the Wen & Han (2021) catalog. There are $\sim 300$ galaxies within $\Delta_z^{\text{photo}} < 0.2$ of the cluster BCG photo-z in this ISCEA candidate protocluster field, which indicates the rough number of galaxies in an ISCEA protocluster field belonging to the protocluster, since the photo-z error is $\sim 0.11$ Wen & Han (2021). Using the ISCEA mock (see §5.1), we can estimate the number of protocluster galaxies expected in each ISCEA FoV by counting the number of galaxies with H$_\alpha$ line flux brighter than $3 \times 10^{-17}$erg s$^{-1}$ cm$^{-2}$ within a volume of $12\text{Mpc} \times 24\text{Mpc} \times 24\text{Mpc}$ at $z \sim 2$ centered on each BCG. Note that at $z \sim 2$, 1 proper
Figure 10. The distributions in the estimated Hα line fluxes (left) and observed/predicted brightness (right) of the 1000 galaxies closest to the BCG’s photo-z in the ISCEA FoV for the 100 preliminary protocluster target fields. Shown are the observed brightnesses in WISE 3.5 µm (dark gray) and HSC/y–band (light gray) as well as the predicted brightness of the galaxies in the ISCEA 1.1-2 µm broad H–band (red).

Figure 11. The fraction of ISCEA Hα detections among the 1000 galaxies closest to the BCG’s photo-z in the ISCEA FoV for the 100 preliminary protocluster target fields. The median fraction is 77 ± 4%.

Mpc ∼ 2′. We find that there are ∼210 protocluster galaxies on average with Hα line flux brighter than 3 × 10⁻¹⁷ erg s⁻¹ cm⁻² within an ISCEA protocluster field, for clusters with the same M₅₀₀ and at the same redshifts as those on the ISCEA preliminary target list at z > 1.7 (see §5.3). Thus ∼210 galaxies out of > 1000 observed galaxies in each ISCEA field are in the cluster or its cosmic web environment, and 70% of the number of galaxies within Δz_photo < 0.2 of the cluster BCG photo-z in a typical ISCEA candidate protocluster field. This is not surprising, since the photo-z scatter (see Eq. 1) is ∼ 0.11 at z = 2 (Wen & Han 2021), and the ISCEA flux limit is faint enough to include the majority of Hα ELGs in a protocluster.

This photo-z based “blind” selection enables us to target ELGs as well as passive galaxies. Most of the photo-z selected galaxies are expected to be ELGs. The faint Hα line flux limit of ISCEA, 3 × 10⁻¹⁷ erg s⁻¹ cm⁻², enables us to achieve high completeness for star-forming galaxies on the main sequence with S/N ≥ 5 spectra, and derive the fraction of passive galaxies based on the absence of emission lines at the 3σ Hα line flux limit of 1.8 × 10⁻¹⁷ erg s⁻¹ cm⁻². The fraction of quiescent galaxies is an important indicator of galaxy evolution (see §10).

5. SIMULATING ISCEA DATA
5.1. ISCEA mock catalog

In order to flow down the ISCEA Science Objective to requirements, we have created a state-of-the-art galaxy mock catalog by applying a semi-analytical model of galaxy evolution, Galacticus (Benson 2012), to the cosmological N-body simulation UNIT (Chuang et al. 2019), which has a particle mass of $1.2 \times 10^9 h^{-1} M_\odot$ in a 1 (Gpc/$h$)$^3$ simulation cube, and assumes the Planck Collaboration (2016) cosmology. Merger trees from the UNIT simulations (generated using the Rockstar halo finder; Behroozi, Wechsler & Wu 2013) are input to the Galacticus semi-analytic model which solves for the properties of galaxies forming inside the halos of each tree, and outputs these galaxies at every snapshot of the UNIT simulation.

We use the same galaxy formation physics in Galacticus as used by Zhai et al. (2019) to study expected numbers of emission line galaxies for future surveys. The parameters of the Galacticus model physics were calibrated to approximately match available observational data on galaxy evolution, including stellar mass functions and star formation rates. Additionally, Zhai et al. (2019) calibrated the emission line luminosity functions (and associated dust extinction model) predicted by Galacticus to match the HiZELS (Sobral et al. 2013) observations.

The resulting ISCEA mock catalog provides physical properties (comoving position, redshift, line-of-sight velocity, halo mass, stellar mass, SFR), as well as observed quantities ($H_\alpha$ and [O III] line luminosities, and broad-band magnitudes in ISCEA, WISE, and HSC bands) for each model galaxy. Additionally, meta-data describing cluster membership and central/satellite status is provided for each galaxy.

The parameters of the Galacticus model have been tuned using optimization algorithms to find the best match to current observational data. As new observational data become available, including data from ISCEA, we will repeat this optimization process (which is fully automated) to refine the model, allowing for the production of new and improved mock catalogs. New data may also highlight limitations of the current model (i.e. mismatches which cannot be resolved by retuning of parameters). These will drive investigations of how to improve the model physics to better understand any such new data.

Of particular interest will be results from ISCEA which characterize the properties of galaxies in and around protoclusters, across a broad redshift range. The effects of environment within the cosmic web is still poorly constrained observationally and poorly understood theoretically. We expect that ISCEA data will be invaluable in improving the model of environmental processes in the Galacticus model. These too will be incorporated into future generations of highly realistic galaxy mock catalogs, which will provide a powerful tool for detailed understanding of galaxy evolution in the cosmic web.
5.2. Photometric Redshift Verification & ISCEA Broadband Magnitudes

It is important to validate the protocluster targets for ISCEA using the existing multiwavelength, WISE-selected cluster catalogs from Wen & Han (2021). We identified clusters of interest from the Wen & Han (2021) catalog, selecting them based upon their predicted redshift. We visually inspected the clusters using the WISE imaging database to remove cluster targets located near bright stars, and candidates that are detected due to artifacts in the WISE data.

We then independently evaluated the photo-$z$‘s of the clusters using the photometric data from the Wen & Han (2021) catalog, which includes photometry from Subaru/HSC (griz$Y$) and WISE W1 (3.4$\mu$m) and W2 (4.6$\mu$m) imaging. We independently measured photo-$z$‘s for the galaxies in clusters at $z_{\text{phot}} > 1.7$ from the Wen & Han (2021) catalog using EAZY-py3. EAZY-py fits the photometry using a non-negative linear combination of a set of galaxy spectral templates. We used the recommended set of templates from $\text{tweak}_\text{fsps}_\text{QSF}_1\text{2}_\text{v3}_\text{param}$ (G. Brammer 2021, private communication), which include a range of galaxy types (star-forming and quiescent) with varying amounts of dust attenuation assuming a modified dust attenuation law (Kriek & Conroy 2013). Compared to the Wen & Han (2021) photo-$z$‘s, the values we derive have very small bias, $\text{med}(z)/(1+z) = 0.011$ for all galaxies. The scatter is larger, $\sigma_0 = 0.13$, excluding outliers (where $\sigma_0$ is the normalized absolute deviation, see Brammer, van Dokkum, and Coppi 2008), but this is reasonable considering we are comparing photo-$z$‘s derived from two independent methods, and consistent with the scatter in photo-$z$ estimates from independent codes reported elsewhere (Dahlen et al. 2013; Wen & Han 2021 do not provide uncertainties on individual estimates).

Fig. 13 shows the best-fit photo-$z$ template (constructed from the non-negative linear combination of the EAZY-py templates) for four galaxies in our sample. These are “brightest cluster galaxies” (BCGs) in that they have the brightest WISE W1 magnitude of all galaxies associated with their respective clusters from the Wen & Han 2021 catalog.

From the best-fit spectral template fit to each galaxy from our photo-$z$ fits, we synthesized (predicted) magnitudes in the ISCEA passband, $\text{ISCEA } m_{\text{AB}}$, assuming filter with uniform throughput (i.e., a tophat filter) in the wavelength range $1.1 < \lambda / \mu \text{m} < 2$. We integrated the best-fit template for each galaxy with this filter (following standard practices, see e.g., Fukugita et al. 1998 and Papovich et al. 2001). Fig. 13 shows the ISCEA magnitudes for the four example BCGs. Fig. 14 shows the distribution of ISCEA

3 https://eazy-py.readthedocs.io/
magnitudes for the galaxies in the Wen & Han (2021) cluster sample. The BCGs for the 100 highest redshift clusters are indicated (where the BCG is defined as the brightest galaxy in the ISCEA $H$-band in each Wen & Han 2021 cluster). The distribution of ISCEA magnitudes peaks around 21.5 AB mag, with a significant tail below 22nd magnitude (this results from the fact that the Wen & Han 2021 catalog is selected with HSC $i < 26$ and detection in W1 ($\lesssim 21.3$ AB mag).

5.3. Number of ISCEA Galaxies Per Protocluster Field

We use the ISCEA mock (see §5.1) to investigate the expected number of galaxies in protoclusters that can be detected by ISCEA based on their H$\alpha$ line flux. To do this, we search for clusters with $M_{500} > 0.7 \times 10^{14} M_\odot$ (the same threshold as Wen & Han 2021) in the full volume of the simulation. For each cluster, we count the its member galaxies (i.e., satellites in the cluster dark matter halo) that have an H$\alpha$ flux of greater than $3 \times 10^{-17}$ erg s$^{-1}$ cm$^{-2}$ (the ISCEA 5$\sigma$ line flux limit). We then count the number of galaxies above the ISCEA flux limit in a volume of $\sim 12$ Mpc$\times$24 Mpc$\times$24 Mpc centered on the cluster, which gives the number of ISCEA galaxies in a protocluster field.

Here we quantify halo mass in terms of $M_{500}$. We find that in the ISCEA mock a halo mass of $M_{500} = 0.7 \times 10^{14} M_\odot$ corresponds roughly to $M_{200} = 10^{14} M_\odot$. Fig. 15 (left panel) shows the resulting mean number of cluster member galaxies (i.e., mean number of satellites in the cluster halo) in bins of cluster mass, $M_{500}$. Also shown is the distribution of estimated cluster masses of ISCEA protocluster candidates from the Wen & Han (2021) catalog (in red). Specifically, the solid red histogram shows the clusters at $z > 1.7$ and the dashed red histogram shows the clusters at $z > 1.8$. The weighted mean is 33 galaxies per cluster for the clusters in the Wen & Han (2021) catalog at $z > 1.7$.

We also use the ISCEA mock to count the number of galaxies (all, including satellites) in a volume of $12 \times 24 \times 24$ Mpc$^3$ around the cluster central. The $12 \times 24$ Mpc$^3$ corresponds to ISCEA FoV (24' $\times$ 48'). The 24 Mpc in the radial direction, chosen to be the same as the protocluster dimension in the transverse direction, corresponds to roughly $\Delta z = 0.02$ over the ISCEA redshift range of $1.2 < z < 2.1$. Fig. 15 (right panel) shows the mean number of galaxies above the ISCEA H$\alpha$ line flux limit in that volume as a function of $M_{500}$ of the cluster. Also shown in red is the distribution of estimated cluster masses from the Wen & Han (2021) catalog, with the same line types as in the left panel. The weighted mean is 210 galaxies with H$\alpha$ line flux $> 3 \times 10^{-17}$ erg s$^{-1}$ cm$^{-2}$ in the volume of $12 \times 24 \times 24$ Mpc$^3$ around the cluster central, for the clusters in the Wen & Han (2021) catalog at $z > 1.7$. This enables us to estimate the fraction of $\sim 1000$ galaxies observed by ISCEA in each protocluster field that are in the cluster or its cosmic web environment to be $\sim 21\%$.

5.4. DMD Aperture Loss and Pointing Jitter Modeling and Mitigation

We have simulated the decrease in S/N of the observations due to DMD micro-mirror aperture loss (i.e., slit loss) and the pointing uncertainty (a.k.a. “jitter”) of ISCEA. The aperture loss is due to the finite size of a micro-mirror (i.e., slit, 2.8'' $\times$ 2.8''), and the jitter is caused by pointing instabilities after slews and during exposures, resulting in a shift of the source towards the edges.
of the micro-mirror. In order to simulate both of these contributions to the S/N decrease, we have implemented the following model:

(1) The source is defined by a Gaussian spatial profile, and an input model spectrum.

(2) A spectral cube is created.

   (i) For each wavelength, the input source profile is convolved with the corresponding wavelength-dependent optical point spread function (PSF) to get an image at that wavelength. Fig. 16 shows the convolved source at two different wavelengths (corresponding to [O II] and Hα wavelengths at z = 2). The source is bigger at longer wavelengths because of the larger PSF.

   (ii) The image is then scaled by the flux at the corresponding wavelength.

   (iii) Noise is added to each of the layers of the cube according to the S/N-wavelength dependence from the ETC (§3.3)

(3) The simulated spectrum including jitter is computed following the steps below and iterated over all jitters:

   (i) A DMD micro-mirror (i.e., slit) of 2.8′′ × 2.8′′ is placed on the source. The center of the slit is varied in each iteration according to the pointing uncertainty (see illustration in left panel of Fig. 7). The source flux is integrated in each of these "jitter boxes" at all wavelengths to obtain a full spectrum.

   (ii) A wavelength shift is applied to the spectrum as light falls on different detector pixels in the dispersion direction for each jitter position. This simulates the decrease in spectral resolution due to jitter.

   (iii) At the end of the iterations, the spectra obtained from the individual jitter positions in (i) and (ii) are summed up and combined to form the final spectrum (representing the total integration).

(4) The resulting wavelength-dependent S/N of the simulated spectrum including jitter is computed and compared to the S/N obtained without jitter (Fig. 17).

We have assumed a jitter characterized by a FWHM of 2′′ and a Gaussian distribution that is sampled every 200 seconds (a 2000 second integration time would therefore have 10 jitters in this simulation). Note that the actual jitter might be closer to a random walk than a Gaussian distribution. More detailed modeling of the satellite’s motions will be necessary to estimate the true pattern. Furthermore, we assumed an “ideal” source defined by a Gaussian spatial profile with a FWHM of 0.3′′ and an SED with \( F(H\alpha) = 3 \times 10^{-17} \text{erg s}^{-1} \text{cm}^{-2} \), normalized to an H-band magnitude of 25 AB at \( z = 2 \). This represents a typical faint

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4 We assume the diffraction limited case in which FWHM(PSF) \( \propto \lambda/D \), where \( D \) is the diameter of the telescope, see also §3.3.
emission-line galaxy (galaxy #6 from Table 5). We assume the established ETC parameters (see §3.3) and an exposure time of 371 ks, the required integration time to reach S/N=5 for the Hα line flux limit of $3 \times 10^{-17}$ erg s$^{-1}$ cm$^{-2}$ in the absence of pointing jitter (see Table 2).

Fig. 17 shows an example of the final output S/N (black solid line) and the S/N difference compare to a simulation without jitter (blue dashed line). Note the difference in S/N as a function of wavelength due to the DMD micro-mirror aperture loss and pointing jitter. In this case, the S/N is decreased to about 95% at bluest and 85% at reddest wavelengths. The differential decrease in S/N as a function of wavelength is due to the wavelength-dependent size of the PSF, which leads to an increase in aperture loss at the red end of the spectrum.

We find that the decrease in spectral resolution due to pointing jitter is similar at all wavelengths and does not change significantly with the properties of the jitter. Specifically we find a $\sim 6\%$ decrease in spectral resolution measured on the Hα and [O III] lines. In the ISCEA instrument design, we have included a conservative 10% increase in spectral resolution in order to have margins.

Fig. 18 and Fig. 19 summarize the main results of our study on S/N decrease due to DMD micro-mirror aperture loss and pointing jitter. The left panel of Fig. 18 shows the decrease in S/N (in percentage) as a function of pointing uncertainty for [O III] (orange) and Hα (blue)$^5$. The right panel of Fig. 18 shows the factor of increase in exposure time to balance out the effects of pointing uncertainty (i.e., to reach the original S/N without aperture loss and pointing uncertainty) for both lines. The left panel of Fig. 19 shows S/N decreases due to pointing jitter as a function of target redshift for the Hα line. The right panel of Fig. 19 shows again the factor of increase in exposure time to balance out the effects of pointing uncertainty for the faintest

Note that the effect is larger for Hα as it is at redder wavelengths thus is affected more by DMD micro-mirror aperture loss.

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**Figure 16.** The PSF-convolved model galaxy at two different wavelengths used to create a simulated observed data cube through a micro-mirror. Note that the source is larger at longer wavelengths because of the increased PSF size. The location of the micro-mirror (i.e., slit) is shown as blue square and the pointing uncertainty (FWHM of 2") is indicated as orange cross.

**Figure 17.** The final output S/N as a function of wavelength including pointing uncertainties (black; left $y$–axis) and the difference in S/N to an observations with no jitter (blue dashed; right $y$–axis). In this example, the S/N drops from $\sim 95\%$ (w.r.t. perfect pointing) at the bluest to $\sim 85\%$ at the reddest wavelength due to increased DMD micro-mirror aperture loss (i.e., slit loss) at longer wavelengths.
Figure 18. Left: Decrease in S/N (in per-cent) as a function of FWHM pointing uncertainty (i.e., jitter) for [O III] (orange) and Hα (blue). Right: the factor of increase in exposure time to balance out the effects of pointing uncertainty (i.e., to reach the original S/N without slit loss and pointing uncertainty) as a function of FWHM pointing uncertainty.

Figure 19. Left: S/N decreases due to pointing jitter as a function of target redshift for the Hα emission line. Right: Factor of increase in exposure time to reach the original S/N. Three different pointing jitter performances (in units of FWHM over 200s) are shown: 1.4″ (dashed lines), 2″ (solid lines), and 2.2″ (dotted lines). For the 100 ISCEA candidate protoclusters, the mean of the required factor of increase in exposure time is 1.8 for a 2″ FWHM pointing jitter over 200s, and <2.1 for 2.2″ FWHM pointing jitter over 200s.

Note that the necessary exposure time needed to reach the original S/N is set by the reddest emission line we want to observe. For z = 2, the S/N loss in Hα is the conservative maximum (at lower redshifts, Hα would be bluer, hence less affected by DMD micro-mirror aperture loss due to smaller PSF). Note that two contributions to S/N decrease are simulated: 1) DMD micro-mirror aperture loss (i.e., slit loss), and 2) S/N loss due to pointing jitter. The former results in a constant S/N decrease depending on the size of the source and the PSF. This value for DMD micro-mirror aperture loss can be read off at a jitter FWHM of 0″; it is a ∼ 3% S/N loss for Hα for our galaxy model (see assumptions above). On the other hand, due to the smaller PSF at bluer
wavelength, the [O III] emission line is less affected by DMD micro-mirror aperture loss. The second contribution decreases the S/N for increasing pointing jitter.

5.5. ISCEA Galaxy Radial Velocity Measurements

Naively, \( R = 1000 \) spectroscopy gives \( (1 + z)\Delta v/c = \Delta \lambda/\lambda = 0.001 \), so \( \Delta v = 300/(1 + z) \text{km s}^{-1} \). However, each spectroscopic resolution element is sampled by two pixels, and the actual redshift precision of an ELG is determined by how well the emission lines can be centroided on each pixel. If the line is unresolved (but well sampled) and relatively high SNR, 1/5 pixel is a good estimate for line centroiding accuracy. This gives a factor of ten improvement in \( \Delta \lambda \) per spectroscopic resolution element for a high SNR line. Allowing for lower SNR, we can expect to measure individual bright lines to \( \sim 30-50(1 + z)^{-1} \text{km s}^{-1} \). There will be errors on this because of the brightness of the galaxies themselves, effects due to things other than galaxy motion (e.g. AGN, winds, etc).

Therefore the ISCEA redshift precision will be \( \sim 1-2 \times 10^{-4} \). The measured redshift

\[
z_{\text{obs}} = z_{\text{cos}} + z_{\text{pec}},
\]

where \( z_{\text{cos}} \) is the cosmological redshift, and \( z_{\text{pec}} \) corresponds to the peculiar radial velocity of an individual galaxy \( v_{\text{pec}} \). For clusters embedded within the protocluster environment, the peak of the distribution in \( v_{\text{pec}} \) corresponds to the mean velocity of the cluster. The \( v_{\text{pec}} \) of galaxies in a protocluster field relative to this mean velocity can be used to identify the members of the cluster, as well as filaments and groups associated with the protocluster.

5.6. ISCEA Observing Efficiency

ISCEA’s observing time per field of 668ks includes an overhead of 80% (see Table 2) to compensate the loss in light from the galaxy targets due to pointing jitter of 2″ FWHM over 200s (see §5.4), so that each measured spectrum has a signal-to-noise ratio \( \geq 5 \) at the ISCEA Hα line flux limit (see §3.3). Therefore the pointing jitter effect is already mitigated, and does not lead to a decrease in ISCEA observing efficiency. The detailed modeling of subtle effects due to the DMD will be carried out during the Phase A study (see §7.2).

We conducted simulations of galaxy target selection by the DMD over multiple visits of a typical ISCEA target protocluster field, to estimate the fraction of target galaxies that will be observed. For each visit, we prioritize the faintest galaxies (which need to be observed the longest) to be placed on an “open” micro-mirror. Galaxies that reach the required S/N \( \geq 5 \) in their spectra (identified via quick data processing and analysis by the SOC, see §7.1) are then replaced by the next brightest galaxies. This simple observing strategy ensures the most uniform observations. In the following, we show the results of our pointing (i.e., targeting) simulations for a protocluster field at \( z \sim 2 \), centered on cluster candidate J123345.3-002945 from the Wen & Han (2021) catalog. The results are very similar for other protocluster fields in our target sample as the density of galaxies is similar in them.

By dividing the total observing time per field into 10 visits (each with a combined exposure time of 66.8ks), ISCEA can observe \( \sim 90\% \) of the targeted \( \sim 300 \) galaxies within \( \Delta z_{\text{phot}} = 0.2 \) of the BCG (Fig.20, left panel)\(^6\). This result is relatively insensitive to the actual number of visits, as long as the number of visits is greater than 3. The main reason for this is because the spatial density of available micro-mirrors (i.e., “slits”) is significantly higher than the expected number of selected galaxies. The remaining \( \sim 10\% \) of galaxies are mainly bright galaxies for which less than \( \sim 600\text{ks} \) of observations are needed to achieve the desired S/N. These galaxies are not observed in favor of completing the observations of fainter galaxies. However, their brightness, hence relatively short observation times, would make them possible targets to follow-up in future observations.

Since ISCEA can obtain \( \sim 1000 \) spectra simultaneously, we can utilize the unused micro-mirror columns by targeting additional galaxies. Specifically, we will be able to add \( \sim 700 \) galaxies to the target list per field with photo-z’s closest to the BCG spectroscopic redshift, but with \( \Delta z_{\text{phot}} > 0.2 \), to supplement the list of \( \sim 300 \) galaxies with \( \Delta z_{\text{phot}} \leq 0.2 \). Note that this leads to a completeness in targeting protocluster galaxies of \( \sim 100\% \). This is because ISCEA observes \( \geq 1000 \) galaxies closest in photo-z to the cluster BCG, including \( \sim 500 \) within \( \Delta z_{\text{phot}} = 0.33 \) of the confirmed cluster BCG, which is \( 3\sigma \) given the 1σ photo-z scatter is \( \Delta z_{\text{phot}} \sim 0.11 \) at \( z \sim 2 \).

Since we do not know the Hα flux of the targeted galaxies \textit{a priori}, we compute expected fluxes based on their estimated stellar masses and star formation rates (e.g., Daddi et al. 2007). The resulting Hα flux estimates are uncertain by a factor of \( \sim 2 \) that potentially could cause us to miss faint galaxies, which decreases the true sample completeness. We simulated this effect by a Monte Carlo sampling, thereby changing the obtained fluxes according to this expected uncertainty and re-selecting the sample

\(^6\) This number is very similar in the other protoclusters.
Figure 20. Left: Monte Carlo simulation results of 10 *ISCEA* spectroscopic visits to the protocluster field at $z \sim 2$, centered on cluster candidate J123345.3-002945 from the Wen & Han (2021) catalog, the same target field as shown in Fig. 12. Each visit is represented by a bar, with new, continued, and completed observations denoted by blue, gray, and orange, respectively (note that roughly all observations in the 10th visit are completed – hence the similar size of the orange and gray bars). The black curve shows the cumulative number of targets observed as a function of the number of visits. After 10 visits, about 90% of the galaxies are observed. Right: Decrease factor in the observing efficiency of galaxies above the *ISCEA* flux limit due to a factor of 2 uncertainty in the estimated H$\alpha$ line flux, which is used for estimating the *ISCEA* observing efficiency.

500 times. The right panel of Fig. 20 shows the resulting distribution of the factor by which the completeness is decreased. We find a median of $89 \pm 1\%$.

In summary, the *ISCEA* observing efficiency includes three factors:

1. The fraction of target galaxies observed by dividing the total observing time per field into multiple visits: $\sim 90\%$ (Fig. 20, left panel).

2. The decrease factor in the observing efficiency due to the factor of 2 uncertainty in the estimated H$\alpha$ line flux: $\sim 89\%$ (Fig. 20, right panel).

3. The completeness in targeting protocluster galaxies: $\sim 100\%$.

Thus the overall *ISCEA* efficiency of observing a protocluster field is therefore $\sim 80\%$ ($\sim 0.9 \times 0.89$).

6. DATA ACQUISITION

6.1. Pointing Correction

To meet the *ISCEA* pointing requirement of $\leq 2''$ FWHM over 200s, the *ISCEA* instrument includes an imaging channel which images bright stars nearly continuously to enable pointing corrections. Fig. 21 shows the differential star counts from the 2 Micron All Sky Survey (2MASS) at $b > +75^\circ$ (Skrutskie et al. 2006), which provides a lower bound since the star counts increase at lower Galactic latitudes. We expect to find $\geq 10$ stars brighter than Vega H mag 13 in each *ISCEA* FoV for the *ISCEA* target fields (see Fig. 8), which can be used for guiding and pointing corrections.

6.2. Calibration

The *ISCEA* spectral calibration involves several basic steps. These include transforming the relative astrometry between direct and dispersed images (to allow for accurate slit placement of targets from direct images), determination of the spectral shapes (the size and curvature or spectral trace) as a function of position, the wavelength zero-point, the dispersion solution, the line spread function, and the relative and absolute flux calibration of the spectra over the full field of view. With this information, the pipeline software will extract and measure the effective spectrum of each targeted source. Calibration parameters will be applied to the 2D and 1D extracted spectra through the use of a number of calibration reference files in the *ISCEA* pipeline. A full set of initial versions of these files will be created before launch, based on laboratory measurements. Once in orbit, the files will be updated during initial checkout, and then periodically throughout the mission as needed, based on routine data quality assessment and/or changes to the in-flight system.

The *ISCEA* mission calibration plan follows a well-established methodology. The team calibrates individual detector pixels by targeting open clusters with sufficient stars to fill the *ISCEA* FOV, following a strategy similar to that used for the IR channel of
Figure 21. The 2MASS Point Source Catalog source counts (per 0.2 mag bin) for several hundred square degrees near the north Galactic pole (Skrutskie et al. 2006). Blue, green, and red histograms represent \( J \), \( H \), and \( K_s \), Vega mag counts, respectively. There are plenty of bright stars available for ISCEA pointing correction in each FoV.

WFC3 on HST (Sabbi et al. 2010). Baseline flat-field calibrations will be first obtained on the ground; the extensive set of data will allow the removal of high-frequency spatial variations due to the detector response (P-flats). Low frequency modulations related to the optical system response (L-flats) will be corrected through pointed on-sky observations, targeting rich stellar clusters like Omega Centauri (NGC 5139) or NGC 2516, to compare the same flux of the same stars at different field positions. To achieve high signal-to-noise in relatively short, but typical, individual ISCEA spectroscopic observations of about 200 sec, requires bright standard stars of 10 - 14 AB mag. Multiple, dithered, 100-200 sec exposures of the clusters with sufficient (tens to hundreds) stars per ISCEA FoV, will allow for precise relative photometric calibration across the FoV. Absolute flux calibration will target spectrophotometric standard stars used by WFC3/IR, including both white dwarfs and G-type stars (Bohlin, Hubeny, and Rauch 2020). Dispersion solutions will be calibrated on the ground and verified on-orbit, using well characterized NIR spectra of compact planetary nebulae (Lumsden, Puxley, & Hoare 2001) and K and M stars via Hydrogen Paschen, Brackett and other emission and absorption features throughout the ISCEA wavelength range. Unresolved emission lines will also be used to update the ISCEA line spread function as a function of wavelength. The spectral trace (curvature and shape vs. wavelength) can be measured by any bright point source, so the star cluster observations will also provide a full mapping of the trace across the FoV, important for accurately extracting the 1D spectra from the 2D spectral images. Fainter stars within each ISCEA target field will be used to align the slits (i.e., the DMD micro-mirrors), providing the relative astrometry between image and spectra. There are \( \sim 1000 \) stars at AB < 17 per square degree that can be used for slit positioning (see Fig. 21).

Preflight: The SOC will prepare a list of \( \sim 100 \) isolated spectrophotometric standards spread across the sky, along with a list of bright PNe and open clusters for use in wavelength and relative photometric and trace calibrations for commissioning and during the science phase of the mission. In addition, they will select the expected stars in each target field suitable for slit alignment.

The most critical calibration is the mapping between DMD micro-mirrors and the pixels of the imaging and spectroscopic detectors. This is routinely done creating a regular pattern of bright spots on the DMD and imaging their position on the detectors. The team validates the baseline maps obtained on the ground with on-sky pointing on bright extended regions, e.g., the Orion Nebula, with the same regular DMD patterns. Since there are no moving parts in the optical systems, we expect the solutions to remain stable and with only sporadic checks required. We can easily automate the procedure with minimal impact on the mission efficiency.

Both the spectrometer and imager assemblies are calibrated before integration with the telescope using SwRI facilities in San Antonio to characterize plate scale and vignetting, optical image quality, focus and opto-mechanical alignment, relative spectral response, and pointing dynamic performance. Once integrated with the telescope, end-to-end Instrument Performance Tests (IPT) are performed to verify end-to-end opto-mechanical alignment, and radiometric performance.

Inflight: Wavelength and relative and absolute photometric standards will be taken as described above. In addition, a 100 sec imaging only exposure will be taken for each primary protocluster target, to verify the positions of all galaxies with respect to the
stars within the field. This enables the accurate selection of galaxies for spectroscopy. The parallel images of the spectroscopic science data will be downlinked periodically for calibration and verification. On orbit commissioning activities include: 1) dark count measurement before opening the aperture cover, 2) DMD imager to spectrograph mapping, 3) NIR wavelength calibrations using stellar sources, and 4) sensitivity and pointing calibrations by observations of NIR calibration stars. Suitable NIR photometric and spectroscopic calibration targets are available throughout the sky; calibration observations are made monthly for the first 6 months and bi-monthly thereafter to monitor instrument performance.

6.3. Science Observations

Upon the completion of initial calibrations in orbit, ISCEA interleaves target verification and science observations in Year 1. It carries out 1 hour imaging per field over 1.1-2.0μm to AB=25 at S/N=5, and 4 hour spectroscopy per field to continuum AB=19.5 at S/N=3 (emission line flux limit of $2.2 \times 10^{-16}$ erg s$^{-1}$ cm$^{-2}$ at S/N=5) for 100 candidate protocluster fields, to obtain the redshifts of the already identified Bright Cluster Galaxy (BCG) and $\sim$1000 galaxies closest to it in photo-z in each. Each protocluster is confirmed using spectroscopic redshifts of > 10 brightest galaxies including the BCG. ISCEA’s final target list of 50 confirmed protocluster fields at $1.2 < z < 2.1$ is based on the imaging and fast spectroscopy of the 100 candidate protoclusters, including 45 confirmed at $1.7 < z < 2.1$, and 5 at $1.2 < z < 1.7$.

All galaxies from Wen & Han 2021 catalog are brighter than AB mag 24 in the ISCEA 1.1–2.0μm broadband (see Fig.10, right panel). ISCEA broad-band imaging fills in an important gap in imaging coverage from HSC (optical) to WISE (3.4μm), and helps improve photo-z accuracy (see §5.2).

In each BCG-confirmed protocluster field, we select $\sim$1000 galaxies with photo-z’s closest to the spectroscopically confirmed BCG redshift as spectroscopic targets. We estimate that in each protocluster target field, there are $\sim$210 galaxies with H$\alpha$ line flux above $3 \times 10^{-17}$ erg s$^{-1}$ cm$^{-2}$ in the cluster or its cosmic web environment, based on the ISCEA mock (see §5.3). The photo-z based “blind” selection enables us to target ELGs as well as passive galaxies. Most of these are expected to be ELGs. The quiescent galaxies can be identified using the non-detection of emission lines at the ISCEA 3σ H$\alpha$ line flux limit of $1.8 \times 10^{-17}$ erg s$^{-1}$ cm$^{-2}$. The fraction of quiescent galaxy is an important indicator of galaxy evolution.

The galaxy target list for each ISCEA protocluster field will be prepared and tested before its scheduled observation by ISCEA. The galaxy target lists for the first batch of protocluster targets will be ready before the prime mission begins. The SOC will develop and test the data processing pipelines during the year before launch.

Fig.5 illustrates how ISCEA will select galaxy targets for multi-slit spectroscopy. The 1020x510 micro-mirrors on the DMD maps to 2040x1020 pixels on the 2048x2048 detector, providing a FoV of $48'' \times 24''$, with 2.8''x2.8'' per DMD micro-mirror. Only 2040x2040 of the 2048x2048 pixels are active; the 4 rows of pixels on each edge are reference pixels. By switching on 1 micro-mirror in each of 1020 micro-mirror columns on the DMD, ISCEA will measure $\sim$1000 non-overlapping spectra simultaneously. Since each spectrum is $\sim$1161 pixels long on the H2RG detector, the top 70 micro-mirrors correspond to incomplete spectral coverage, with 5.5% of the spectral coverage missing for the topmost micro-mirror (worst case). The bottom 440 micro-mirrors correspond to complete spectral coverage on the detector. Since both [O III] and [O II] are captured on all galaxy spectra at $1.2 < z < 2.1$, this should have no impact on redshift measurements. We expect this to have no impact on the cluster observations, and a very small impact on the observation of the cosmic web filaments. We will mitigate this by tiling the protocluster field for representative protoclusters to achieve uniform spectral coverage, and model the systematic effects from the incomplete spectral coverage for the other protocluster fields. During Phase A, we can carry out a trade study of adding a second H2RG detector in the spectroscopic channel, so that all 1040x768 available micro-mirrors on the DMD correspond to complete spectral coverage, expanding the FoV to $48'' \times 36''$.

7. DATA ANALYSIS

7.1. Data Processing

Data will be retrieved from the spacecraft once every 24 hours to enable the updating of the target list. New target lists will be uplinked at least once per week. The raw data volume is 56G bits per 24 hours of observing time without compression, with an overhead of < 10% for calibration data (both complete and parallel images).

The ISCEA data will be processed through two, automated pipelines - one for science data and one for calibration observations. In-orbit calibration data, as described in §6, will be processed through the calibration pipeline to produce calibration reference files which are used by the science data pipeline. Production and testing of the calibration reference files, along with the design and implementation of the science and calibration pipelines, will be the responsibility of the SOC. An initial set of calibration reference files will be produced by the SOC from the ground test data, updated during in-orbit commissioning and initial calibration. Subsequent updates will occur when changes to the flats, wavelength zero points or dispersion solutions, etc. are determined via
regular and periodic calibration observations, as outlined in §6, and when reprocessing of the ISCEA science data is necessary or planned as part of regular reprocessing during the mission. The pipeline executives, responsible for executing and managing data flow, as well as the individual pipeline software modules used to generate L1-L4 data, will be under version control at the SOC during the mission.

Basic processing steps such as dark current subtraction, relative and absolute flux calibration, source identification and extractions will be common to all science and calibration data, although details of how these steps are applied are specific to the type (images or spectra) of data moving through the pipelines. For example, as described in §6, the ISCEA spectral calibration involves several steps, such as transforming the relative astrometry between direct and dispersed images, determination of the spectral trace as a function of position on the array, measurement of the wavelength zero-point and dispersion solution, and the line spread function, and relative and absolute flux calibration of the spectra over the full field of view to produce the L2-L4 data. The necessary calibration parameters will be applied to the 2D and 1D extracted spectra through the use of the calibration reference files (themselves a combination of 2D image files and lists of coefficients) in the ISCEA science pipeline, necessary for the production of L2 through L4 science data. In addition to the science and calibration data, the calibration reference files used by the pipeline will be delivered to the archive. The pipelines will generate regular, automated Data Quality Assessment (DQA) reports for the science data (L1-L4) which will be analyzed by the SOC and ISCEA science team, and delivered to the IRSA archive. Fig. 22 shows the ISCEA data flow. Table 4 shows the data levels and associated processing.

7.2. Modeling Instrument Effects

The size of the individual DMD micro-mirrors, about 13.0 µm × 13.0 µm (13.7 µm × 13.7 µm center-to-center) is only a few times larger than the wavelengths of interest for ISCEA. Therefore, besides reflection, some diffraction and scattering effects will be present. Spreading the reflected light into a larger solid angle than the nominal one (given by the f/# of the input beam onto the DMD) causes a loss of light, as the collecting optics act as an aperture stop. This may be regarded as equivalent to the slit losses typical of conventional slit spectrographs, with two exceptions: a) some light diffracted from other mirrors may enter the beam, creating an extra background that reduces the "contrast" of the system; b) the diffraction pattern is characterized by lobes and their spacing depends on the wavelength. They modulate the fraction of light captured by the collecting optics, introducing a color term that may be significant affecting both throughput and point spread function.
| Level | Data Level Definitions and Processing |
|-------|-------------------------------------|
| L0    | Packetized data                     |
| L1    | Uncalibrated FITS files. Includes meta and engineering data |
| L1 to L2 | Removal of basic detector signatures and artifacts. Application of flux calibration to 2D data. |
| L2    | Basic calibrated 2D images and spectral data (detector signatures removed and flux calibrated images) |
| L2 to L3 | Extraction of 1D spectra. |
| L3    | Extracted 1D spectral data          |
| L3 to L4 | 1D spectral fits to emission and absorption features. |
| L4    | Basic spectral fit parameters (redshift, flux, line width) and associated catalogs |
| L4 to L5 | Derivation of SFR, ages, SF histories and AGN strengths as a function of mass, local environment and redshift |
| L5    | High level data products and catalogs |

Table 4. ISCEA data levels and associated processing.

These effects can be modeled treating the DMD as a blazed diffraction grating and calculating the far-field diffraction pattern. However, an accurate estimate of the DMD efficiency and contrast must take into account the geometry of the system, the degree of coherence of the illuminating source, its position vs. the center of a mirror, polarization effects, etc. Analyzing these effects requires a more advanced treatment based on the exact solution of the Maxwell equations for the specific DMD and ISCEA configuration. The ISCEA science team is developing a full theoretical model to quantitatively assess the relevance of these effects, together with an optical system to validate the predictions at visible wavelengths. The model will be used to optimize the opto-mechanical design of ISCEA during Phase A, enabling the mission to achieve its required sensitivity and contrast with margins.

7.3. Science Data Analysis

7.3.1. Photometric Redshifts and Stellar Population Properties

We will derive stellar population parameters (stellar masses, continuum dust attenuation, rest-frame colors) for all galaxies observed by ISCEA using the measured SEDs from optical/NIR/mid-IR photometry combined with the spectroscopic and/or photometric redshifts. The photometry for our samples spans HSC grizY, WISE W1 (3.4 µm) and W2 (4.6 µm), with additional coverage from 1.1-2 µm imagine from ISCEA H-band (see Fig. 13). In addition, the majority of ISCEA targets fall within the coverage of LSST, where we can expect ugrizY coverage extending nearly 1 mag deeper than HSC over the 10 year baseline of LSST (the 2 year LSST coverage will be comparable to HSC, providing important calibration and the u-band coverage).

We will first update the photometric redshifts for the galaxies in our sample. Prior to ISCEA launch we will use photometric redshifts based upon the photometry existing at that time (HSC + WISE + possibly Rubin data) to validate the redshift estimates for the candidate protocluster fields. Following launch we will use updated photometric redshifts that incorporate ISCEA H-band photometry to select protocluster fields for spectroscopy and for slit assignment for galaxies within these fields. Finally, we will use the spectroscopically targeted galaxies to quantify any biases and systematics in the photometric redshifts.

With the photometric and spectroscopic redshift catalogs, we will then model the photometry using standard SED-fitting practices that include a Bayesian modeling formalism with flexible star-formation histories (e.g., Leja et al. 2017, 2019; Carnall et al. 2019). Based on previous performance with these methods, with the expected photometry we will achieve typical accuracy of stellar mass of $0.2 - 0.3$ dex (modulo systematic uncertainties in IMF). In addition, we will derive continuum dust attenuation values to apply to the ISCEA line-flux measurements, and we will test these against measurements from the Balmer decrement for those galaxies in ISCEA with multiple H-recombination lines detected.

7.3.2. Spectroscopic Redshifts and Emission line Analyses

ISCEA will measure redshifts and Hα line fluxes for >50,000 galaxies, including an estimated $\approx 210 \times 50 = 10,500$ protocluster member galaxies (including $\approx 33 \times 50 = 1650$ cluster member galaxies), over the redshift range $1.2 < z < 2.1$. Hα is a fundamental tracer of the SFR as it measures the direct number of ionizing photons from OB associations. We will convert the Hα luminosities to SFRs following Kennicutt (1998); Kennicutt & Evans (2012). We will correct these estimates for dust attenuation using several measures. First, the ISCEA spectra will cover Hβ for galaxies with redshifts $z \gtrsim 1.3$ (see Fig 23). This
includes nearly all the protoclusters in our sample. We will measure Balmer decrements, $\text{H}\alpha/\text{H}\beta$, for individual galaxies where $\text{H}\beta$ is well detected, comparing the Balmer decrement to the theoretical value expected for Case-B recombination (Osterbrock 1989). For fainter galaxies, and as a cross check of these corrections for all galaxies, we will stack the spectra of galaxies in bins of stellar mass and redshift to measure the average dust attenuation from the Balmer decrement in the stacks. As the dust attenuation is expected to decrease with decreasing stellar mass and SFR (Pannella et al. 2009; Reddy et al. 2015), the uncertainties (and scatter) in the dust attenuation at the lower end of the mass/SFR function will have less impact on our study. We will also make the first measurement of how dust attenuation varies as a function of environment (over three orders of magnitude in density) at fixed mass and SFR at these redshifts. Finally, we will also check the dust reddening from the Balmer decrement to independent estimates from the optical photometry (see above), which will cover the UV rest frame wavelengths (and we can also check if the emission lines suffer more attenuation than the stellar continua, see Kashino, Capak, & Scoville 2013; Reddy et al. 2015; Valentino et al. 2017).

The emission line measurements will also provide estimates of the gas-phase metallicity in the ISCEA galaxies. We can derive metallicity estimates using $\text{H}\alpha/\text{N} \text{II}$ for galaxies with direct detections (ISCEA's spectral resolution is sufficiently high for differentiating $\text{H}\alpha$ and $\text{N} \text{II}$), and we can derive these values for galaxies in stacks of bins of stellar mass, SFR, and environment. The $\text{H}\alpha/\text{N} \text{II}$ is a reliable tracer of metallicity (e.g., Kewley et al. 2019), but prone to uncertainties. However, by using this ratio for all galaxies in our sample, we remove much of the systematic uncertainties, and this has been attempted previously using smaller samples. Furthermore, we can compare these values to estimates from $[\text{O} \text{III}]/\text{H}\beta$. This will allow us to study the dependence of metallicity on environment, which is a tracer of galaxy gas flows, feedback and metal enrichment. We can also test how dust attenuation and metallicity relate in these galaxies by studying the relation between the Balmer decrements and $\text{H}\alpha/\text{N} \text{II}$ ratios for galaxies (both direct detections and from the stacked spectra).

7.3.3. Quantifying the Environment Using the Local Galaxy Density

We will define environmental densities using multiple methods and metrics. First, we will use friends-of-friends (FoF) algorithms (e.g., pyfof\(^7\)) to statistically identify associated galaxies. Combined with measurements of the distance to the Nth nearest neighbor (including Bayesian methods using the distance to all Nth neighbors, Ivezic et al. 2005; Kawinwanichakij et al. 2017) or density measurements, we can derive statistical relations between density and structure mass (e.g., Peng et al. 2010; Muldrew et al. 2012; Kovac et al. 2014; Kawinwanichakij et al. 2017). For objects detected from the ACT and SPT surveys, we can compare the density measurements here with the measurements derived from the SZ signal. Simultaneously, we can use these measurements to assign to each galaxy a local density estimate which we will use as a proxy for environment using $\delta = (\rho - \langle \rho \rangle)/\rho$, where $\rho$ is the local environment and $\langle \rho \rangle$ is the average density of all galaxies. These metrics can achieve relative accuracy in $\log(1 + \delta)$ of 0.1–0.15 dex (Kovač et al. 2010).

Applying these density metrics to protoclusters in the ISCEA mock catalog (see §5.1), we find that with ISCEA we will probe densities over a large range, from cluster cores ($\log(1 + \delta) \sim 2$) to the field ($\log(1 + \delta) \sim -1$), within each ISCEA field of view. With the full sample of ISCEA observations this will enable us to then use the derived properties to study properties of galaxies as a function of SFR, stellar-mass and environment. The measurements will be used to test the ISCEA Science Hypotheses, which we describe below in §10.

8. DATA AND INVESTIGATION PRODUCTS

Quantity and Quality of Data: The ISCEA investigation will return $> 50 \times 1000=50,000$ galaxy spectra, including $> 50 \times 1000 \times 0.77=38,500$ ELG spectra with $S/N \geq 5$, covering the wavelength range of 1.1-2 um at a resolution of $R = 1000$. Note that 0.77 is the fraction of 1000 ISCEA galaxy targets per protocluster field expected to have $\text{H}\alpha$ line flux above the ISCEA line flux limit (see Fig. 11 in §4.2). Of these galaxies, $\sim 210 \times 50 = 10,500$ are in the clusters and their cosmic web environments (see §5.3). The other galaxies observed by ISCEA in each protocluster field, $\sim 28,000$, are foreground or background galaxies providing valuable information on the evolution of cosmic large scale structure. Since we select galaxy targets closest to the cluster BCGs in photo-z to utilize all 1000 DMD "slits" for non-overlapping spectra, most of these are at $z > 1.7$, as 90% of ISCEA protocluster fields are selected to be at $1.7 < z < 2.1$, and the photo-z uncertainty is $\sim 0.11$ at $z = 2$ (Wen & Han 2021).

Fig.23 shows examples of simulated ISCEA spectra for $z = 2$ galaxies as tabulated in Table 5. Along with the ELG spectra, ISCEA will also obtain high $S/N$ spectra of bright elliptical galaxies; both in the cluster and in the cosmic web. These data will provide an invaluable resource for the astronomical community to answer research questions not directly addressed by the ISCEA science team.

\(^7\) https://github.com/simongibbons/pyfof
| ID | Age  | F(Hα) | H-mag | E(B-V) | Metallicity | Description                      |
|----|------|-------|-------|--------|-------------|----------------------------------|
| 1  | 3 Gyr| 3     | 20.6 AB | 0 mag | solar       | Bright central galaxy            |
| 2  | 3 Gyr| 3     | 21.5 AB | 0 mag | solar       | Average galaxy                   |
| 3  | 3 Gyr| 3     | 22 AB   | 0 mag | solar       | Faint galaxy                     |
| 4  | 0.8 Gyr | 5    | 21 AB   | 0 mag | 0.5 solar   | Young, star-forming galaxy       |
| 5  | 0.8 Gyr | 5    | 21 AB   | 0.5 mag | solar       | Young, dusty, star-forming galaxy |
| 6  | 3 Gyr| 3     | 25 AB   | 0 mag | solar       | Faint emission-line galaxy       |

Table 5. List of example galaxies with simulated ISCEA spectra in Fig. 23 at redshift z = 2. The Hα fluxes in the second column are in units of $10^{-17}$erg s$^{-1}$ cm$^{-2}$. ISCEA will detect the continuum with SNR > 3 for galaxies as faint as $H < 21.5$ in the nominal survey exposure time (668 ks), enabling measurements of galaxy redshifts (from continuum breaks and absorption features) and permit stellar population studies.

**Investigation Products:** ISCEA Science Team will fulfill the investigation objectives and requirements by disseminating the results of the investigation by publishing the resultant science papers in refereed scientific journals, and making community presentations. Given the high scientific interest that the astronomical community will have in the data, the high-level products (L5) generated by the science team will be released to the public through IRSA, along with the L1-L4 products (see §7.1).

The L5 data products will include the data for all spectroscopic targets with a redshift measurement. For each galaxy we will release the fully calibrated (i.e., wavelength and flux) one dimensional combined spectrum and the corresponding error spectrum. In addition, we will release a catalog including both basic measurements performed on the spectra, and physical parameters computed from these measurements.

Specifically, the spectral measurements will include:

- **Redshift:** for each galaxy we will provide measured spectroscopic redshift, together with the quality flag describing the reliability of the measurement.
- **Emission line measurements:** we will release the total flux in the emission lines detected above 5σ, and 3σ upper limits for the undetected lines covered by the observed spectral range. Estimate of line equivalent width (or lower limits) will also be provided.
- **Continuum measurements:** for the brightest galaxies with detected continuum, we will provide measurement of the 4000Å/Balmer break, and the strength of the detected absorption lines.

Galaxy physical properties released with the catalog will include:

- **Activity classification:** using emission-line-based diagnostic diagrams (e.g., [O III]/Hβ vs stellar mass M*, see Juneau, Dickinson, & Alexander 2011); BPT (Baldwin et al. 1981) diagrams (from [O III]/Hβ, [N II]/Hα, and [S II]); and other diagnostics from emission line fluxes, we will classify galaxies activity into star forming and AGN.
- **Stellar population properties:** We will provide the stellar mass, age, star-formation history and continuum extinction derived from stellar population synthesis modeling of the broadband data.
- **Instantaneous SFR (from Hα) and nebular extinction from Balmer line ratios, when available.**
- **Local density:** estimates of the local environmental density described in §7.3.3 and §10.

9. MODELING AND MITIGATION OF SYSTEMATIC EFFECTS

9.1. Completeness of Star-Forming Galaxies

In each of its 50 protocluster fields, ISCEA selects > 1000 galaxy targets with photo-z’s closest to the spectroscopically confirmed cluster BCG redshift (see §4.2). There are ~ 300 galaxies within $\Delta z_{\text{phot}} = 0.2$ of the cluster BCG (see §4.2) in a typical ISCEA field, and ~ 210 galaxies above the ISCEA Hα line flux limit in a cluster and its cosmic web environment based on the ISCEA mock (see §5.3). Thus ISCEA is highly complete in observing ELGs above the ISCEA flux limit in each protocluster.

In the galaxy target list for an average ISCEA protocluster target field, consisting of > 1000 galaxies (including all galaxies in the cluster or its adjacent cosmic web), we estimate the missing fraction of ELGs with $f_{\text{line}} > 3 \times 10^{-17}$erg s$^{-1}$ cm$^{-2}$ to be ~
10%, due to the fraction of target galaxies missed by ISCEA in its multiple visits to each field (see §5.6). Significant amount of additional observing time is required to increase the completeness above 90% (see §5.6). It would be optimal to carry out additional observations only in a few fields to increase completeness, as a baseline of comparison to mitigate the systematic effect due to Hα sample incompleteness.

In addition, we can validate this fraction by carrying out a blind survey of ELGs using the DMD in the IFU mode. IFU mode can be easily implemented by scanning a slit across a spatially extended object. DMDs, however, allow for a more efficient strategy where the spectra are produced opening simultaneously multiple slits with a pre-defined pattern (Fixsen et al. 2009). A sequence of such images can pass through an inversion procedure allowing the reconstruction of the datacube with improved signal-to-noise in low signal regime (Hadamard Transform Spectroscopy). The use of the DMD in the IFU mode is beyond the scope of the ISCEA Baseline Mission, but will be investigated for possible implementation during the extended mission.

9.2. Definition of Quiescent Galaxies

ISCEA obtains spectra of > 1000 galaxies in a protocluster field with photo-z’s closest to the confirmed BCG spectroscopic redshift (including ~ 300 within ∆zpho = 0.2), which means that we will have spectra for all of the quiescent galaxies in each of the protoclusters down to the same stellar mass threshold. As such, we will have upper limits on the SFR for these galaxies even if Hα is undetected. Since the ISCEA Hα line flux limit of 3 × 10^{-17} erg s^{-1} cm^{-2} at 5σ (1.8 × 10^{-17} erg s^{-1} cm^{-2} at 3σ) corresponds to a high completeness of galaxies on the star-forming main sequence at our stellar mass limit, we can define the ISCEA sample of quiescent galaxies as galaxies which have no detectable line emission (see Fig.25 for the 5σ limit). We will investigate the
implications of this sample definition of quiescent galaxies using the ISCEA mock and available observational data, to establish a validated metric for comparing ISCEA data with galaxy evolution models.

The lack of emission lines does post a challenge for redshifts because ISCEA will only have sufficient sensitivity to obtain continuum redshifts for high mass galaxies. However, the 7 band imaging from HSC (grizy) and WISE (W1, W2), and the broadband NIR imaging from ISCEA (1.1-2μm) can be combined with the spectra to refine the redshift estimates for quiescent galaxies via spectral breaks. The ISCEA spectroscopy will also provide important information on the galaxy stellar populations as it probes rest-frame optical features sensitive to ages, star-formation histories, and chemical enrichment. We plan to model jointly the photometry (HSC, WISE, ISCEA, and future LSST data, see below) with the ISCEA spectroscopy. This follows on recent work that combined such datasets in joint analysis (e.g., D’Eugenio et al. 2020; Estrada-Carpenter et al. 2020; Carnall et al. 2021; Khullar et al. 2021). This will allow us to test for evolution in continuum-detected galaxies that depend on environment.

10. TESTING THE ISCEA SCIENCE HYPOTHESIS

To meet its Science Objective, ISCEA is designed to test this Science Hypothesis: During the period of cosmic noon, environmental quenching is the dominant quenching mechanism for typical galaxies not only in clusters and groups, but also in the extended cosmic web surrounding these structures. The ISCEA baseline mission will obtain spectroscopic data for a sample of 50 protocluster fields at $1.2 < z < 2.1$ (90% at $z > 1.7$, and 5 are SZ-detected clusters at $z > 1.5$). The sample contains galaxies spanning three orders of magnitude in local density (environment), enabling quantitative measurements of quenching and star formation as a function of galaxy stellar mass, local density, and proximity of galaxies to filaments during this critical epoch. The advantage of ISCEA is that with its large FoV and observing strategy, we can measure spectroscopic redshifts and Hα-derived SFRs for galaxies in all these structures within a single dataset. Thus, ISCEA will provide the largest sample of clusters/overdensities along with cosmic web galaxies ever targeted with spectroscopy and is sufficient to place studies of environment at $z \sim 1.7 - 2.1$ on a comparable footing as studies at $z \sim 1$ (GOGREEN) and $z \sim 0$ (SDSS). However, ISCEA works this problem at higher redshift (when the impact of environment first manifests) and it contains substantially higher area coverage (compared to studies using ground-based telescopes, such as Gemini/GMOS) and does not suffer from potential under-sampling of galaxies in high-density environments (e.g., because of fiber-collisions, for SDSS, for example). ISCEA is designed to achieve its Science Goal and Objective (see §3.1), and transform our understanding of cosmic evolution at cosmic noon.

With ISCEA’s large FoV of 0.32 deg$^2$, a single pointing covers the full protocluster environment. It has been shown in recent years that at least at lower redshift the relative importance of environmental and mass quenching is a function of stellar mass (e.g. Thomas et al. 2005; Peng et al. 2010; Davies et al. 2016), and also that even at $z \sim 1-1.5$ cluster galaxies show evidence of depleted gas and quenching at least out to the virial radius (e.g. Alberts et al. 2016). The latter supports the expectation that the bulk of the quenching occurs at higher redshifts and larger radii than probed by existing studies. Based on these observations, we can make a hypothesis to test when (at what redshift(s)) and where (in what environments) quenching occurs and how these processes depend on stellar mass. The ISCEA hypothesis is that by $z \sim 2$ quenching by “environment”-related processes is a critical and likely dominant factor driving the subsequent decrease in star formation seen in galaxies not only in clusters and groups but also in the surrounding cosmic web, acting in tandem with mass-related processes (where galaxies quench once their halos achieve a certain mass). The key to testing the above hypothesis is to measure SFRs and stellar masses for the statistical sample of galaxies spanning the full range of local densities at $z \sim 2$. Because our hypothesis is that the environmental and mass-quenching depends on galaxy stellar mass, structure (halo) mass, and local density, we must measure the differential effects for each within the same structures. This is achieved because of ISCEA’s large FoV which enables us to trace galaxy SFRs and stellar masses from high-density environments into the cosmic web and to the field in the same connected structures. Fig. 24 shows the region of the parameter space of “quenched fraction” of galaxies probed by ISCEA as a function of redshift, stellar mass, and environment, in comparison to other studies of galaxies. ISCEA is therefore the first of its kind, and will measure these metrics at $1.2 < z < 2.1$ with the lowest systematics of any current (or planned) other projects.

ISCEA will test its Science Hypothesis by quantifying several key metrics of the galaxy population. This includes the galaxy “red” fraction (the quenched population), the “green” fraction (galaxies in transition), and the “blue” fraction (star-forming galaxies). The galaxies will be selected based on their colors (e.g., rest-frame UVJ, see Williams et al. 2009; Whitaker et al. 2011; van der Burg et al. 2013; Foltz et al. 2018), their specific SFRs ($sSFR \equiv SFR / M_*$, see Barro et al. 2017), and/or based on spectroscopic line indices (see, e.g., Haines et al. 2017). We will confirm the vast majority of these galaxies using the ISCEA spectroscopy. Assuming a conservative total observing efficiency for ISCEA of 80% (see §5.6), the 45 protocluster fields at $1.7 < z < 2.1$ provide a sample of (45 structures) × (210 galaxies per structure) × (80% efficiency) ≈ 7560 galaxies (including 45 × 33 = 1485 galaxies in the densest areas, e.g., cores of clusters, see §5.3). All of the ISCEA galaxies will have stellar masses, log($M / M_\odot$) ≥ 10, with which to measure the dependence of sSFR upon local density. With this sample size we can divide the
Figure 24. Compilation of the fraction of quenched galaxies as a function of stellar mass, redshift, and environment taken from the literature, and illustrating the mass range probed by ISCEA. Each curve on the plot shows a measurement of the fraction of quenched galaxies taken from datasets in the literature (Peng et al. 2010; Muzzin et al. 2013; Omand, Balogh, and Poggianti 2014; Balogh et al. 2014; Kawinwanichakij et al. 2017). Here the “quenched fraction” is defined as the ratio of the number of “quenched” galaxies to the total number of galaxies (though the definition of “quenched” varies somewhat in the literature). This includes measurements from SDSS at \( z \sim 0 \) for galaxies in the highest densities (i.e., galaxy clusters, with \( \log(1 + \delta) \sim 2 \)), measurements at \( z \sim 0.9 \) ranging from rich clusters to the field, and values at \( z > 1.5 \) comparing the effects of group versus the field. All previous studies at \( z > 1.5 \) rely on small samples (sometimes including only a single cluster/overdensity) and are highly heterogeneous in their photometric and spectroscopic coverage. The ISCEA exploration region augments these studies by enabling the first study of the galaxy quenched fraction over \( 1.2 < z < 2.1 \), where galaxy structures are collapsing, and spanning the full range of density, from the cores of clusters, cluster outskirts into the cosmic web, groups, and the field with sufficient statistics to test the ISCEA Science Hypothesis.

Sample into five bins in stellar mass even within the highest density regions and within nine bins in local density (extending from the densest “cores” to the sparser “field”) while still maintaining sufficient statistics for 10% statistical uncertainty per bin. To extract maximal information we will also fit a parametric model for the quenching function as shown in Fig. 24, with only the slopes of the halo and environmental quenching lines and their amplitudes as free parameters, which provides a sufficient level of constraint to determine the redshift evolution of the quenching function over the full redshift range probed by ISCEA.

In what follows we describe the primary methods we will use to estimate important quantities to test the ISCEA Science Hypothesis.

- **Estimating SFRs**: The ISCEA spectroscopy will cover H\( \alpha \) luminosities for all objects in the redshift range of the samples. This will be the primary means by which we will estimate galaxy SFRs. We will use standard conversions between H\( \alpha \) luminosities and the SFR (Kennicutt 1998; Kennicutt & Evans 2012), adjusted to our assumed IMF. We will apply dust attenuation corrections using multiple methods as discussed above (§7.3.2). Fig. 25 shows the SFR detection limit for ISCEA estimated by mapping the H\( \alpha \) emission to the star formation main sequence (SFMS). The contours show the distribution of galaxy SFRs and stellar masses for galaxies at \( 1.9 < z < 2.0 \) from the ISCEA mock (see §5.1). The dashed line shows the empirical relation derived from galaxy H\( \alpha \) emission at \( z \sim 2 \) (from MOSDEF, Shivaei et al. 2015). The red-shaded area shows the region below the ISCEA detection limit at \( z = 2 \) assuming the 5\( \sigma \) detection limit for H\( \alpha \) and an average dust attenuation that increases with stellar mass following Pannella et al. (2009). ISCEA will be sensitive to the H\( \alpha \) emission from all galaxies above \( \log M_*/M_\odot \gtrsim 10 \) at \( z = 2 \) (and will be sensitive to H\( \alpha \) emission from fainter / lower-mass galaxies at lower redshifts).
Figure 25. The SFR detection limit for ISCEA derived from mapping the Hα emission to the star formation main sequence (SFMS). The contours show the distribution (25%, 50%, 75%, and 95%-tiles) of galaxy SFRs and stellar masses for galaxies at $1.9 < z < 2.0$ from the ISCEA mock. The dashed line shows the empirical relation derived from galaxy Hα emission at $z \sim 2$ (from MOSDEF, Shivaei et al. 2015). The red-shaded area shows the region below the ISCEA detection limit at $z = 2$ assuming the $5\sigma$ detection limit for Hα ($3 \times 10^{-17}$ erg s$^{-1}$ cm$^{-2}$) and an average dust attenuation that increases with stellar mass following Pannella et al. (2009). ISCEA will be sensitive to the Hα emission from all galaxies above log $M_*/M_\odot \gtrsim 10$ at $z = 2$ (and will be sensitive to Hα emission from fainter / lower-mass galaxies at lower redshifts).

Figure 26. A $10^\circ \times 10^\circ$ slice at $1.9 < z < 2.0$ from the ISCEA mock. The left is "truth" using a mass-limited galaxy sample from our mock catalog. The middle panel shows the results for galaxies detected in Hα-emission by ISCEA. The right panel shows results using only photo-z’s. In each panel, the gray squares show a density map of $5' \times 5'$ regions with $\geq 1$ galaxy in them (a surface density of $\Sigma > 0.04$ galaxy per arcmin$^2$). The circles show galaxies with $> 5, > 10, > 50$ “friends” (from the FoF algorithm) from each sample, as labeled. The large yellow circles show the top (most massive) 0.5% $M_{200}$ objects (from the $M_{200}$ distribution in the mock).

More importantly, the ISCEA spectroscopy provides accurate redshifts for galaxies, which is otherwise a major limiting factor for deriving the quiescent-galaxy fraction. ISCEA will be able to measure redshifts in the case of passive galaxies (with no detectable emission features) to a continuum magnitude of $\sim 21.5$ (AB) at $3\sigma$ in the nominal exposure time (668 ks) in the ISCEA-H band (see Fig. 23). This corresponds to stellar mass limit of log $M_*/M_\odot \gtrsim 11 - 11.3$ for passive galaxies from $z = 1.5 - 2.1$, modulo assumptions about the star-formation history. For galaxies below this mass with no detectable emission lines, we will assign probabilistic association with the protocluster volume based on photometric redshifts. We
will also model ISCEA data quantitatively using the ISCEA mock, which will be continuously modified and improved for application to ISCEA data.

**Figure 27.** Example of how ISCEA traces the true large scale structure. The panels show a zoom-in from the ISCEA mock catalog, centered on several fiducial structures identified from our friends-of-friends algorithm for galaxies in the redshift slice, 1.9 < z < 2.0 (each panel is 1.2° × 1.2°). Each panel shows the galaxy density distributions selected by different means, including the “True” distribution (left panel, showing results for all galaxies with stellar mass $\log M_*/M_\odot > 9.5$), the ISCEA-selected measurement (center panel, showing results for all galaxies with Hα flux above the ISCEA detection limit), and results based solely on photometric redshifts (right panel). Circles show objects with a high number of “friends” (as labeled). The gray scale shows the local galaxy density in $10'' \times 10''$ cells per galaxy per cell. Note that the ISCEA–measured galaxies trace the structures with high fidelity as evidenced by the “true” surface density from the mock out to tens of arcminutes from the centers of the structures. This allows us to use the ISCEA dataset to quantify galaxy properties over a wide range of environment. This is not achievable with the photometric-redshift measurements (right panel) where the measured galaxy density is noisy because of redshift errors.

- **Measuring Environment / Local Density:** We will measure the environment of galaxies using multiple methods that both identify the structures themselves and the local densities. First, we will identify the structures based on galaxies physically associated on the sky and redshift. For galaxies with measured spectroscopic redshifts, we will assign galaxies as “associated” if they fall within some range of velocity, typically $\Delta v \lesssim 2000$ km s$^{-1}$. This is sufficient to distinguish galaxies from the Hubble flow based on their peculiar velocities. For galaxies with photometric redshifts, we will use a probabilistic approach where some fraction of their probability density function ($P$) is contained within a specified $\Delta z$ (where typically we will require that $P = \int P(z) \, dz \gtrsim 70\%$ when integrated over a range of redshift of $\Delta z/(1+z) \approx 10\%$ about the mean redshift of the structure as defined by the ISCEA spectroscopy, but this may depend on galaxy type and color, see Papovich et al. 2010).

We will then assign galaxies to “structures” based on a friends-of-friends algorithm (see §7.3.2). The power of the friends-of-friends algorithm is that it associates galaxies into structures based on a linking length that we can adjust: based on the ISCEA mock, we find that a linking length of $\approx 2'$ (1 proper Mpc at $z = 2$) accurately identifies these galaxies into their “true” structures. We will update these simulations based on the final ISCEA performance specifications and using updated mocks, in order to calibrate these methods. Fig. 26 shows how the friends-of-friends algorithm applied to ISCEA–like data from the mock are able to recover structures (over fields of $10 \times 10$ deg$^2$). Fig. 27 shows examples of regions comparable to the size of the ISCEA FoV, where the algorithm recovers the galaxies associated with structures. Once we have identified galaxies in each structure, we will also measure the local density using either the number of galaxies per surface area ($\Sigma$ measured in # of galaxies per arcmin$^2$ or per Mpc$^2$) and/or the number per unit volume ($\rho$, measured in units of galaxies per Mpc$^3$). The local density, is then defined as the “overdensity”, $\delta$, relative to the mean density, $\Sigma$ or $\rho$, in the usual way (e.g., Peebles 1980),

$$\delta = \frac{\Sigma - \bar{\Sigma}}{\bar{\Sigma}},$$

such that $\delta > -1$ because $\Sigma > 0$ (and a similar relation exists for $\rho$). See also §7.3.3.
Fig. 28 shows that using this method we will be able to identify both the structures and recover the densities accurately with ISCEA data, which is not possible using photo-$z$’s. This provides confidence that we will recover the “richness” of structures accurately with ISCEA. For comparison, at this redshift structures with $>100$ “friends” have halo masses, $\log M_{200}/M_\odot > 13$. This correspond to progenitors of Fornax-sized clusters (or larger) at $z = 0$ (Moster 2012; Behroozi et al. 2019). Fig. 27 shows the surface density of galaxies measured with ISCEA compared to that from “truth” for several structures identified from our friends-of-friends algorithm applied to the ISCEA mock at $z = 1.9 – 2.0$. The surface density recovers the structure accurately, which means we will be able to trace the local density of galaxies in structures at $z \sim 2$ from the central regions (e.g., cluster and group “cores”) to the filaments and the field. This enables us to achieve the measurement to test the ISCEA Science Hypothesis. Note that Fig. 27 shows that this is not true for photometric-redshift surveys, where the accuracy is insufficient to measure the galaxy density accurately (nor is this sufficient to identify structures accurate from “friends-of-friends”, see Fig 26).

- **Stellar Masses and specific SFRs**: Stellar masses will be computed using the combination of deep $grizY$ photometry from the HSC Survey (Aihara et al. 2018) and ISCEA NIR photometry. In addition, we will include the WISE imaging (which will detect the massive, red galaxies in our sample), and LSST optical imaging ($ugrizY$) which will provide important coverage in the $u$-band (we expect to have $\sim 2$ year LSST imaging by the start of ISCEA.\(^8\) Lower et al. (2020) have recently shown that non-parametric models of the star-formation history yield much more robust and unbiased stellar mass determinations than standard parametric approaches (see their Figure 3). We plan to use their non-parametric approach with Prospector (Johnson et al. 2021) to determine stellar masses for the galaxies in our sample. Using these methods we expect to achieve stellar masses with an accuracy of $0.2 – 0.3$ dex (for fixed IMF, see Conroy 2013).

We will then estimate specific SFRs, using the measurements of the SFRs and stellar masses for all galaxies in the sample, following $sSFR = SFR/M_*$. We expect the errors on the sSFR to propagate from both the SFRs and stellar masses, and they may be as high as $\delta(\log sSFR) \sim 0.5$ dex for some objects. However, the measurements we need require only accuracy of $\sim 1$ dex, which is achieved by our measurements.

Using the measurements of stellar galaxy masses, SFRs (and specific SFRs), and local density measurements, we will then be in a position to test the ISCEA Science Hypothesis. For example, Fig. 29 shows the expected performance of ISCEA. The top panel shows the accuracy in measuring specific SFRs as a function of galaxy density, using customary units of $\log (1 + \delta)$. Using a sample of 45 clusters at $1.7 < z < 2.1$, ISCEA will achieve relative accuracy of $0.2 – 0.3$ dex in bins of density. This is a significant improvement over current studies at $z \sim 2$ that focus on measurements from individual clusters (e.g., Koyama et al. 2013 using observations of MAHALO fields). ISCEA enables us to measure the density in many more bins of density compared to the current “state of the field” (the top panel of Fig. 29 shows we expect to triple the number of bins in density while improving the uncertainties by more than a factor of two).

ISCEA data quality will also enable us to study the quenching timescales for galaxies in different environments. Using the ISCEA data, we will measure quenching timescales, which can be constrained by solving a continuity equation between star-forming galaxies (blue galaxies), which transition to quenched galaxies (these are so-called, “green” or “green-valley”), and then become fully quenched galaxies (red galaxies), all of which must occur with some transition timescale and quenching timescale ($t_Q$). The quenching timescale is then derived from the solution to these differential equation (e.g., see Foltz et al. 2018). The bottom panel of Fig. 29 shows the estimated accuracy of the quenching timescales for galaxies in ISCEA in three bins of redshift and two bins of density. This accuracy will enable us to rule out certain physical processes because such processes predict quenching timescales (e.g., if the example in Fig. 29 is correct, then we can rule out physical models such as “quiescence” or those that scale with gas-depletion timescales in favor of others, such as processes that scale with dynamical time [e.g., “overconsumption”, see McGee, Bower, & Balogh 2014]). It is crucial to make this measurement at $z \sim 2$ where the difference in quenching timescales is largest as such processes have less time to act. This enables us to differentiate between the importance of competing physical processes, which is most pronounced at high redshift when the timescales are shorter (compared to the Hubble time). Thus, we will test the ISCEA Science Hypothesis of the environmental quenching as the main quenching mechanism during cosmic noon.

ISCEA will provide data for measuring the star-forming fraction and quiescent fractions of galaxies as a function of local mass density (over three orders of magnitude) and stellar mass (over more than an order of magnitude). This will allow us to differentiate between mass quenching and environmental quenching as the dominating mechanism in typical (satellite versus

\(^8\) We assume that the 2 year depth of LSST will be approximately $\sim 0.9$ mag shallower than the full 10-year depth [https://www.lsst.org/scientists/keynumbers](https://www.lsst.org/scientists/keynumbers). This is comparable to the current HSC depth in $grizY$ which effectively doubles the existing exposure time (and LSST will ultimately be nearly 1 mag deeper than the HSC data).
Figure 28. The number of galaxies in a group (truth) against the number of galaxies in the group identified from our analysis of the ISCEA mock catalog for structures at $z = 1.9 - 2.0$. This provides confidence that we will recover the “richness” of structures accurately with ISCEA, particularly for the higher-mass structures. For comparison, at this redshift the structures with >100 “friends” have halo masses $\log(M_{200}/M_\odot) > 13$ in the ISCEA simulation. These all correspond to progenitors of Fornax-sized clusters or larger at $z = 0$ (Moster 2012; Behroozi et al. 2019).

central) galaxies. Fig. 30 shows the distribution of SFR for galaxies in the ISCEA mock catalog in two bins of stellar mass, $1 < M_* / 10^{10} M_\odot < 2$ and $2 < M_* / 10^{10} M_\odot < 3$, selected to have H$\alpha$ fluxes of $> 3 \times 10^{-17}$ erg s$^{-1}$ cm$^{-2}$, in redshift slices of $1.2 < z < 1.4$ (left panel) and $1.8 < z < 2.0$ (right panel). As expected, the SFR increases with redshift from $z \sim 1.3$ to $z \sim 1.9$. Furthermore, while the distribution of the SFR in the quiescent range is insensitive to stellar mass, it is very sensitive to local mass density (measured by $N_2$, the number of neighboring galaxies within a sphere of comoving radius of 2 Mpc). In the Galacticus model used to construct the ISCEA mock, this quenching is driven primarily by “starvation”, in which the circumgalactic medium of a galaxy is rapidly stripped away by ram pressure forces when it becomes a satellite in a larger system. This removes the supply of new, cooling gas for the galaxy, causing it to run out of fuel for new star formation and, eventually, to be quenched. This clearly shows that current galaxy formation theory predicts the dominance of environmental quenching over mass quenching for typical galaxies at cosmic noon ($1.2 < z < 2.1$), consistent with the ISCEA Science Hypothesis. This will be tested by the ISCEA measurement of the SFR distributions.

11. ISCEA SECONDARY SCIENCE PROGRAM

During two months each winter, the ISCEA protocluster targets have limited visibility due to spacecraft orbital constraints. This opens windows of opportunity to carry out a productive secondary science program on ISCEA during the Baseline Mission.

Complementary to our main extragalactic fields, the Milky Way provides a multitude of targets for compelling observations that uniquely exploit ISCEA capabilities. In particular, the spectral range of ISCEA is ideally tailored to the discovery and characterization of low mass stars and brown dwarfs, down to planetary masses, characterized by deep H$_2$O absorption bands (see Fig. 31). A spectroscopic survey of young stellar clusters representative of a variety of environments (source density, age, metallicity, etc...) can thus provide fundamental information on the bottom-end of the stellar Initial Mass Function, the environmental dependence of the minimum-mass for opacity limited fragmentation, and the origin and frequency of free-floating planetary objects, together with a multitude of spectra that can be used as proxies for exoplanet atmospheres.

12. SUMMARY

We have presented a comprehensive discussion of the science program on the Infrared Satellite for Cosmic Evolution Astrophysics (ISCEA), a small astrophysics mission with the Science Goal to discover how galaxies have formed and evolved in the cosmic web of dark matter at cosmic noon. ISCEA’s Science Objective is to determine the history of star formation and its quenching in galaxies as a function of local density and stellar mass when the Universe was 3-5 Gyrs old ($1.2 < z < 2.1$). ISCEA tests the Science Hypothesis that environment is the dominant cause of quenching in typical galaxies during cosmic noon by observing clusters, groups, and the extended cosmic web surrounding these structures at $1.2 < z < 2.1$.

ISCEA meets its Science Objective by making a 10% shot noise measurement of star formation rate (SFR) down to $6M_\odot$ yr$^{-1}$ using H$\alpha$ out to a radius of 10 Mpc in each of 50 protocluster (cluster + cosmic web) fields at $1.2 < z < 2.1$. ISCEA measures the
star formation quenching factor (the fraction of quiescent galaxies) in those fields, and galaxy velocity with a precision < 50 km/s to deduce the true, 3D distribution of galaxies in each protocluster field.

ISCEA meets its science requirements with significant resiliency to pointing performance and thermal control (see Table 2), with > 30% margin on observing time. If the ISCEA instrument and mission requirements are fully met, these margins will be used to enhance ISCEA science. ISCEA can observe 24 additional confirmed protoclusters at $1.7 < z < 2.1$ to the Hα line flux limit of $3 \times 10^{-17} \text{erg s}^{-1} \text{cm}^{-2}$ at 5σ (for a total of 69 at $z > 1.7$), using 568ks for additional target selection if needed. Alternatively, ISCEA can observe the same 50 protoclusters to the fainter Hα line flux limit of $\sim 2.4 \times 10^{-17} \text{erg s}^{-1} \text{cm}^{-2}$ (corresponding to the SFR of $\sim 4.8 \text{M}_\odot \text{yr}^{-1}$).

ISCEA provides ground-breaking data: galaxy spectra with both Hα and [O III] emission lines, or absorption features, to measure key galaxy properties over three orders of magnitude in local density over 50 fields, covering a wide range of environments, from crowded cluster cores to field galaxies, mapping the cosmic web surrounding each cluster directly tying the dense nodes to the surrounding filaments (see Fig. 1). ISCEA transforms our understanding of cosmic evolution by providing for the first time, robust measurements of how density quenches star formation in galaxies at $z \sim 2$ (see Figs. 24, 29 and 30).
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**Figure 30.** The distribution of SFR for galaxies in the ISCEA mock selected to have Hα fluxes of \( f_{\text{H} \alpha} > 3 \times 10^{-17} \text{ergs/cm}^2/\text{s} \), and stellar masses of \( 2 < M_*/10^{10} M_\odot < 3 \) (solid lines) and \( 1 < M_*/10^{10} M_\odot < 2 \) (dashed lines), in redshift slices of \( 1.2 < z < 1.4 \) (left) and \( 1.8 < z < 2.0 \) (right). Red and blue arrows illustrate the division between quiescent and star forming galaxies. Galaxies are split by a measure of their local environment, \( N_2 \), defined as the number of neighboring galaxies within a sphere of radius 2 Mpc (comoving). The distributions show that while the SFR in the quiescent range is insensitive to stellar mass, it is very sensitive to local mass density, consistent with the ISCEA Science Hypothesis, and fully testable with the data ISCEA will provide.

**ISCEA** is a small satellite observatory with a 27 cm × 27 cm square (equivalent to 30 cm diameter) aperture telescope, with a FoV of 0.32 deg\(^2\). Adopting the approach pioneered by the ground-based multi-object spectrographs IRMOS (MacKenty et al. 2006), RITMOS (Travinsky et al. 2018), and SAMOS (Robberto et al. 2016), ISCEA uses a DMD as its programmable slit mask to obtain spectra of ~1,000 galaxies simultaneously. It has an effective resolving power of \( R = \lambda/\Delta \lambda = 1000 \) with 2.8” × 2.8” slits over the near-infrared (NIR) wavelength range of 1.1 to 2 \( \mu \)m, a regime not accessible from the ground without large gaps in coverage and strong contamination from airglow emission (see Fig.6). ISCEA has a pointing accuracy of \( \leq 2” \) FWHM over 200 sec. This enables deep spectroscopy of hundreds of galaxies per protocluster field over a wide FoV. ISCEA has a Sun synchronous Low Earth Orbit (LEO) and a prime mission of 2.5 years. Given its unique capability for multi-slit spectroscopy in crowded fields, ISCEA can have a vigorous astrophysics Guest Observer program in its extended mission, thereby offering the community valuable opportunities to advance a broad range of science topics: from galaxy evolution to the Milky Way structure, from the spectroscopic follow-up of NIR counter-parts of gravity wave events, to the characterization of Outer Solar System objects. ISCEA’s space-qualification of DMDs opens a new window for spectroscopy from space, enabling revolutionary advances in astrophysics (see, e.g., Wang et al. 2019).

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Figure 31. The near-infrared spectral sequence from early-M dwarfs to early-Y brown dwarfs. All spectra are normalized to 1 at their peak and then a flux offset is applied (Helling & Casewell 2014).

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