

# Subaru and WFIRST: A Partnership for the 2020s

## An Activity White Paper for submission to the 2020 Decadal Survey

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### 1. Executive Summary

Joint WFIRST/Subaru observations have the potential to enable transformative science that cannot be done by either telescope alone. WFIRST will image the near-infrared sky to unprecedented depth and area. Subaru, with its wide field and unique instruments for both imaging and spectroscopy, is a superb complement. WFIRST and Subaru will also both be deploying cutting edge coronagraphic instruments.

Representatives from the WFIRST Formulation Science Working Group (FSWG), the WFIRST Project, the Japanese Subaru community, and the Japanese WFIRST working group organized the second Subaru-WFIRST Workshop in December 2018 to discuss the most compelling science enabled by joint observations. Eight groups, namely Exoplanet microlensing, Coronagraph Instrument (CGI) support, SuperNovae and Time Domain, Deep Surveys, Cosmology, Nearby Galaxies, Milky Way, and Solar System, have considered the feasible programs that either significantly enhance the WFIRST Core Survey science cases or enable new science programs based on the unique combination of Subaru and WFIRST. Another group looked at enabling new discoveries via competitively selected general observer programs. This white paper highlights these science programs and potential observing strategies.

As part of the Japanese contribution to NASA's WFIRST mission, NAOJ has pledged 100 nights of Subaru time to be executed concurrently with WFIRST operations starting ~2025. This white paper is the first step towards guiding the discussion of this observing program. Since the programs outlined by the eight working groups exceed the allotted nights and describe compelling science, astronomers should explore other opportunities for these joint observations through the Japanese Subaru observing proposal process, exchanges with Keck/Gemini, and through other opportunities.

### 2. Mission Capabilities

**2.1 Subaru Telescope:** The Subaru Telescope is a large optical-infrared telescope with an effective aperture of 8.2m located at the summit of Mauna Kea, Hawaii, U.S.A., operated by National Astronomical Observatory of Japan (NAOJ). As of February 2019, the Subaru Telescope has 7 facility instruments (HSC, FOCAS, HDS, MOIRCS, IRCS, COMICS, AO188) and 3 visiting (PI-type) instruments (IRD, SCExAO, CHARIS) for science operations. The instruments expected to be active during the mid -2020s are detailed here. **HSC** (Hyper Suprime-Cam) is an optical imager with a large FoV (1.5-deg in diameter) with a mosaic of CCDs, mounted at the prime focus of Subaru Telescope. In addition to *grizy* broad-band filters, HSC has a suite of narrow band (NB) filters supplied by users. The availability of many NB filters can be recognized as an important advantage even in the era of LSST. **PFS** (Prime Focus Spectrograph; expected 2022) is a fiber-fed multi-object spectrograph with a very wide FoV (1.25-deg<sup>2</sup>) attached to the prime focus. The instrument is under development with a large international collaboration. The PFS provides spectra of 2,400 objects simultaneously over 0.38-1.26 $\mu$ m, with a resolving power of ~2,300-5,000 depending on the wavelength range. **ULTIMATE** (Ultra-wide Laser Tomographic Imager and Mos with AO for Transcendent Exploration) is a wide-field NIR instrument with ~20' diameter FoV assisted by GLAO, providing 0.2-arcsec spatial resolution in the K-band. The project is partly funded by NAOJ and is now under conceptual

design phase, aiming to have its first light in ~2026. The capabilities of deep narrow-/medium-band imaging in all NIR ranges as well as deep K-band imaging will be complementary to the capabilities of WFIRST.

To support the wide-field survey programs using these primary instruments as efficiently as possible under the recent budget situation of Subaru Telescope, all other existing instruments are expected to be decommissioned by ~2025. However, the observatory is willing to consider continuous operation of some of the existing instruments as well as the visiting instruments with unique capabilities on a best effort basis if there is a sufficient demand and they are externally funded.

**2.2 WFIRST** The Wide Field Infrared Survey Telescope (WFIRST) is a 2.4m telescope equipped with a large area, 300-megapixel, near-infrared camera for imaging and slitless spectroscopy (The WFI, Wide Field Instrument) and an on-axis, visible-light Coronagraph Instrument (CGI) for imaging, polarimetry, and low-resolution spectroscopy of circumstellar disks and nearby giant exoplanets. The 0.281 deg<sup>2</sup> WFI field of view (FoV) is 200× that of HST's Wide Field Camera 3 near-IR channel and 90× that of HST's (optical) Advanced Camera for Surveys. The CGI is expected to provide several orders of magnitude greater starlight suppression than existing instruments or any planned for the 2020s. WFIRST was the highest ranked large space mission in the 2010 decadal survey of astronomy and astrophysics (Astro2010; NWNH). WFIRST will have 2.4m and 18 H4RG (4k×4k) detectors in WFI. CHGI will use electron-multiplying CCD (EMCCD) in the focal plane. WFIRST at L2 after its planned launch in late 2025.

Current plans call for dedicated dark energy surveys including a High Latitude Survey (HLS, imaging and grism spectroscopy) over several thousand square degrees and a dedicated supernova survey (imaging and grism/prism spectroscopy). Additionally, a dedicated microlensing survey will find thousands of exoplanets in a survey that will complete the overall census of solar systems started by Kepler. 25% of the primary mission of 5 years will be dedicated to General Observer (GO) observations that are competitively selected via a dedicated TAC; the amount of GO observations is expected to be closer to 100% in a possible extended mission. The CGI technology demo will make use of ~3 months of observing time during the first 18 months of the mission. Should the performance of the instrument warrant it, additional science observations using CGI may be part of the GO program.

### 3. Exoplanet Microlensing

The prioritized Subaru synergistic surveys to complement and enhance the WFIRST microlensing are described below.

**1. Subaru/HSC Concurrent Microlensing Observations for Mass Measurements of Planetary systems and Isolated Planetary Mass Objects.** The only way to understand the mass of free-floating planets (FFPs) is to detect the parallax effect by conducting concurrent observations from two separated observatories both which are equipped with a wide-FOV and large mirror. This can be achieved by using Subaru/HSC and WFIRST. Subaru/HSC is the best instrument for concurrent observations of FFP events for the following three reasons. First, the large HSC FOV can cover the 2.0 deg<sup>2</sup> WFIRST microlensing field with just 2 frames, enabling us to conduct high-cadence imaging for every target in the field. Second, the large primary mirror with a good natural seeing can achieve high S/N and detect faint objects which are too faint for other small telescopes. Third, Subaru's longitude is perfect to collaborate with LSST, which is also expected to conduct concurrent observations but less intensive imaging at a different time zone. In addition, such concurrent HSC observations with WFIRST can measure the parallax for bound planetary events as well, which is complementary to the orbital parallax measurement by WFIRST itself. Thus, the concurrent WFIRST – Subaru/HSC observations along with other complementary telescopes will enable us to measure the mass of FFPs and bound planets. We propose 20 min Subaru/HSC observations for 54 nights per 72-day WFIRST microlensing campaign, which sums to only 13.5 nights for the six 72-day WFIRST microlensing seasons.

**2. NIR Spectroscopic Follow-ups of High-magnification Microlensing events using IRD.** The measurement of the physical parameters of microlensing planets relies on the empirical relations to estimate the angular radius of the source stars. The empirical relations we use for the optical microlensing field could not be applied for the WFIRST events due to the difference in the stellar properties (e.g., age and metallicity) and environment (e.g., distance and extinction). We propose to conduct near-infrared (NIR) high-resolution ( $R > 3000$ ) spectroscopic observations of high-magnification microlensing events that will be observed by WFIRST using IRD or PFS. High-magnification events with the magnification of  $> 50$  allow us to obtain spectra of the intrinsically faint source stars in the galactic bulge, which will provide precise estimation of stellar intrinsic color, magnitude, and radius from the measurements of stellar effective temperature, surface gravity, and metallicity. This precise estimation can then be used to re-calibrate the empirical relations for the WFIRST passbands. These observations will be also useful to study the statistical properties of the bulge dwarfs and subgiants (See Section 9). Note that NIR is necessary for the high extinction in the WFIRST field. Because this observation is time critical, observations will have to be conducted as a target-of-opportunity (ToO) program. We expect  $\sim 15$  ToO triggers per year, each of which requires 1.5-hours telescope time in average. Therefore, we would require a total of 11.2 telescope nights during the 4 years of the WFIRST-microlensing survey period.

**3. ULTIMATE-Subaru Concurrent Observations.** We propose concurrent observations with ULTIMATE-Subaru to obtain the K-band light curves for most events observed by WFIRST. This allows us 1) to measure the satellite parallax of bound planetary events; 2) to estimate the angular source size with better precision; and 3) to study the metallicity of the lens (i.e., planet host) stars. The HSC program can also measure the satellite parallax with higher cadence, but ULTIMATE-Subaru will achieve better photometric precision toward the fields with high extinction. The IRD program can obtain more precise information of the source stars, but for a limited sample. As the Z087-K and/or W149-K color measurements can be measurable for most events with ULTIMATE-Subaru, this program is complementary to the IRD program and both are needed for the better understanding of source star radii and filter calibration. Finally, by using the color of Z087-K and/or W149-K, we could estimate the metallicity of the planet hosts with better precision than we could do with WFIRST filters alone. This will allow us to study the possible relation between bound planet frequency and host metallicity for the first time for microlensing planets. ULTIMATE-Subaru can cover the WFIRST microlensing field in 32 visits with each of 0.5 min exposure and 0.5 min readout time. In total, 3.4 nights per season are required.

#### 4. Coronagraph Instrument (CGI) Support

WFIRST CGI will demonstrate in space critical coronagraph technology and state of the art wavefront control, which will be crucial for future missions such as HabEx and LUVOIR. After this technical demonstration, CGI will be able to measure point source brightness with a source-to-star flux ratio as faint as  $1e-7$  at  $\sim 0.2''$  and  $5e-8$  at  $\sim 0.3''$  ( $SNR > 10$ ) within 10 hours of integration time. CGI will also be able to measure point source spectra with  $R \sim 50$  or greater spectral resolution with a source-to-star flux ratio as a similar contrast above ( $SNR > 10$ ) within 100 hours of integration time. These capabilities will enable exploration of new parameter space for exoplanet discovery to obtain R50 spectra of young massive Jovian planets, to break  $v \sin(i)$  degeneracy in the mass of RV planets, to obtain R50 spectra of Jupiter analogues, and to image circumstellar disks, especially their inner regions.

Subaru telescope will help CGI (1) to discriminate detected sources from background stars and measure disk levels before the launch of WFIRST, (2) to find additional CGI targets at infrared (optically noisy young targets), (3) to characterize gas giants, (4) to characterize debris disks both at optical (CGI) and infrared (Subaru), (5) to measure accretion of young planets embedded in disks (e.g., H alpha vs. Pa beta), in particular ALMA or NIR disks with substructures, (6) to follow-up single transits of TESS with CGI and

IRD, (7) to characterize CGI target stars including their spin-axis. One important note is that the programs (1) and (2) need a time allocation even before the launch of WFIRST.

Some more details on these items are as follows. The main purpose of (1) is to identify bright contaminating sources (off-target before WFIRST observations) with Subaru high-contrast imaging and the goal is to maximize likelihood of CGI success in the regime of limited observing time. On-target polarimetry is also important to constrain the debris disks, if any. The main purpose of (2) is to add new CGI target planets around noisy young stars to be discovered by IRD. The main purpose of (5) is to detect possible accreting planets in emission rather than continuum. The targets are protoplanetary disks with substructures such as gaps and spirals that can be a signpost of planets. Such targets are revealed first by NIR polarimetry and more recently by ALMA submillimeter high-resolution imaging.

## 5. Supernovae and Time Domain

**Overview of WFIRST SN survey.** One of the major goals of WFIRST is to perform the most precise measurement of dark energy in the redshift range of  $0.4 < z < 1.7$  with Type Ia Supernova (SNe Ia). WFIRST is the only facility which can achieve high photometric precision in NIR, which enables us to probe the expansion history of the universe from acceleration to deceleration at high redshifts.

WFIRST will observe photometrically up to 20000 SNe Ia over the observable redshift range. In addition, hundreds of live SNe Ia will be spectrophotometrically observed with the low-dispersion prism (a few percent of those with imaging light curves, also depending on survey strategy). The main roles of the Subaru Telescope for the WFIRST supernova program would be spectroscopic follow-up of a larger fraction of the  $z < 1.0$  SNe, and a dedicated redshift-identification program of the majority of the galaxy hosts of the SNe.

### Part 1: Live Supernova Spectrum

The most secure usage of SNIa are when a live supernova spectrum is acquired to secure its identification and redshift. Although spectra of SNe Ia at  $z > 1$  can be taken with the low-dispersion prism onboard WFIRST, spectroscopy for SNe Ia at  $z < 1$  can be more effectively taken with ground telescopes. For ground telescopes with 8-10m aperture, the magnitude limit of spectroscopy with reasonable single-night exposure time (3-4 hrs) is 24th mag in i-band which corresponds to  $z=1$  SN Ia. The number of active supernovae would be in an order of 50 SNe per PFS 1.55 deg FoV. These observations must be coordinated with HLS to make full use of the 2400 PFS fibers. Thanks to its excellent astrometry, PFS can also obtain host-galaxy observations after the SN has faded to enable better host-galaxy subtraction.

### Part 2: Supernova Host Galaxy Spectrum

As the WFIRST Supernova Survey progresses, Subaru/PFS will play a crucial role to observe SN Ia host galaxies and obtain their spectroscopic redshift as well as properties of host galaxies. Identification of redshifts of host galaxies from Subaru/PFS will allow for a photometric analysis like that done with Pan-STARRS1 (Jones et al. 2018b) and expected for DES and LSST. To maximize the size of the sample and measure enough low and high-mass galaxies across the redshift range to properly characterize the evolution of supernova luminosities with galaxy properties, our target is 70% completeness up to  $z=1.4$ . To determine the number of nights, we studied combining Keck DEIMOS DEEP survey data and the COSMOS survey and applied this to PFS predictions. We find our target can be achieved in 25 nights. This program is also recommended to be coordinated with HLS field to make the best use of PFS fibers.

**Choice of WFIRST SN Survey Field(s):** The above discussion was made based on the assumption that at least one WFIRST Supernova field is visible from the Subaru telescope and the Subaru team would like to express their interest to have at least one field in northern hemisphere (e.g. the EGS or ELAIS fields). If WFIRST can extend its current field of regard 7 degrees, CDF-S can be also be in the CVZ and it would be an ideal field since it is accessible from LSST and Subaru and overlaps with a Euclid Deep Field See Section 6 for more discussion of deep field placement. In Figure 6.1, we show potential WFIRST CVZ field choices in green and indicate low extinction regions in pink.



## 6. Deep Fields

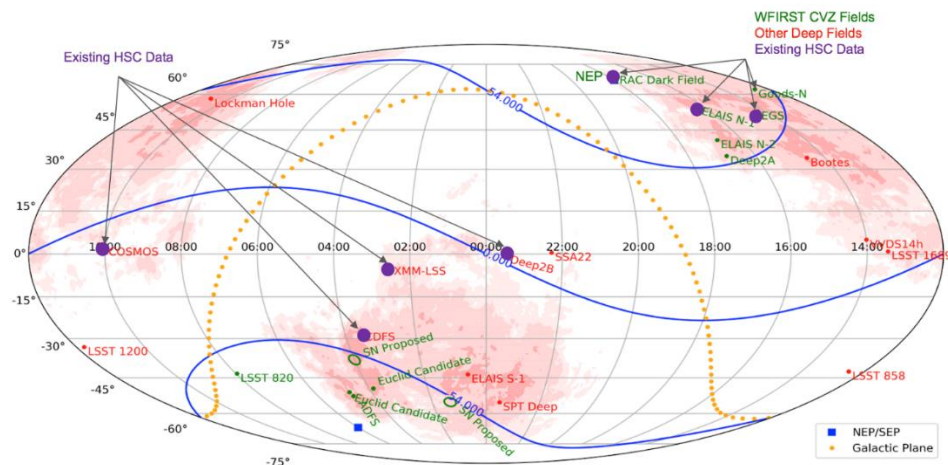
Subaru is the premier Northern hemisphere telescope to complement WFIRST for deep field observations and in many ways is superior to LSST for areas of the sky both telescopes can access. For single pointing (1.8 deg diameter circle) imaging depth, Subaru HSC is 1.5 times faster than LSST, due to the larger mirror area, with only 1, 1.5, and 3h require to match the annual deep drilling field depths per pointing. Furthermore, Subaru provides significantly more flexibility in filter choice and cadence in the optical bands and could easily exceed the LSST deep drilling field depths. Importantly, Subaru can also take the data much more quickly than LSST, which is cadence constrained and will not reach the required depths until ~7 years after WFIRST's expected 2025 launch date. In addition to the imaging flexibility, the PFS provides an un-paralleled wide-field sensitive spectroscopic capability that is an ideal complement to WFIRST grism and prism observations. The combination of these two capabilities provides a path to ground breaking cosmology and galaxy evolution science.

The existing Subaru data the SSP deep/ultra-deep fields represent a significant resource of over 100 nights of observing time that could be leveraged by WFIRST GO or directed medium deep survey fields. Figure 6.1 shows several of these fields such as EGS, COSMOS, SXDS and the Chandra deep field south. Carrying out surveys of the existing HSC/PFS Deep/Ultra-deep fields to magAB~27 5 sigma will yield a wide range of joint science. Reaching a commensurate depth with WFIRST will be relatively fast (~1-2h per pointing).

**Ultra-deep survey:** Ultra-deep surveys are needed to study the most distant (high-redshift) objects and make detailed high signal-to-noise morphological and spectroscopic studies of moderate redshift objects. As such carrying out a large area (~1 deg) survey with WFIRST to Hubble Ultra-Deep Field (~30th magnitude) depths at 0.6-2um should be a key part of WFIRST survey planning. While JWST could provide comparable 2-5um imaging over this area, but Subaru HSC will be the ONLY instrument capable of providing comparably deep 0.4-0.6um (g and r band) data to suitable depths. Reaching a comparable depth of  $g_r=30$  (significantly deeper than the LSST deep drilling depths) would require ~10 and 23 nights respectively. These data can only be acquired with Subaru, since even HST cannot reach these depths over that area.

**WFIRST/Subaru Super-Nova Survey:** It is anticipated WFIRST will undertake a deep SNe (see Section 5) covering 5-15 square degrees to 25-26th ABmag in single epoch observations at 0.8-2um with complementary low-resolution prism observations of the field. The final depth of these data would be 28-29th AB mag with 50h prism exposures. Ideally, matched cadence 0.4-0.8um imaging (g,r,i) data and optical spectroscopy would be obtained at similar depths. Subaru could provide both and match the cadence better than LSST. The imaging data could be obtained with HSC with 2-4 nights per year and a comparable amount of spectroscopy for a total of 4-8 nights per year of Subaru.

Fig 6.1: The locations of various existing deep fields with the limits of the WFIRST CVZ and the ecliptic equator marked in blue. WFIRST CVZ fields suitable for the supernova survey are labeled in green and others in red. Fields with existing Subaru data are marked in purple. Adapted from Foley et al. 2018.



## 7. Cosmology

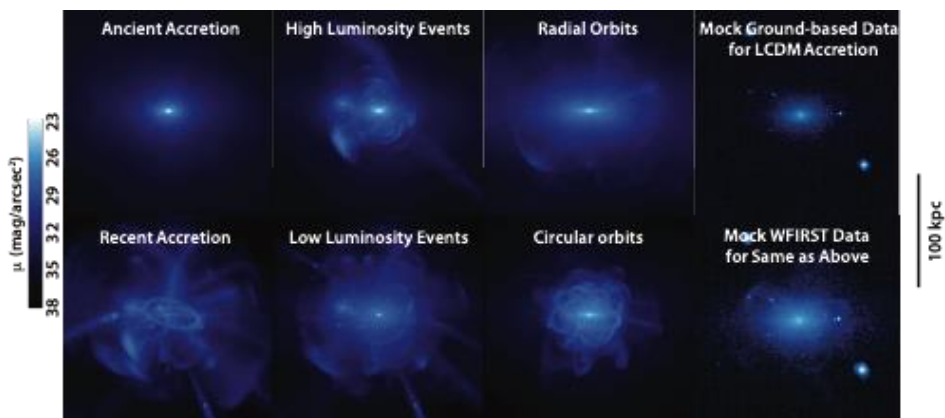
A major systematic uncertainty in weak lensing cosmology is photo-zs of lensing source galaxies. It will be a challenge to calibrate photo-zs of faint source galaxies down to about 25th magnitude in H-band ( $5\sigma$  point-source sensitivity), since deep calibration data set does not exist yet. Subaru will be a key component of this calibration using one of two possible strategies: spec-z with PFS or additional imaging with HSC.

**Spectroscopic redshifts (spec-z) follow-up survey by PFS:** A spec-z calibration sample needs to be a representative sample of the weak lensing source galaxy sample. One way to define such a sample is to use a self-organizing map (SOM; Masters et al., 2015, 2017) based on galaxy colors and fill out cells which do not have enough spec-zs. Given its wide and deep observational capability and high multiplexity, Subaru PFS will be the most efficient instrument to conduct such a survey. The WFIRST lensing sample will require up to 50h integrations with PFS to get reliable redshifts based on simulations validated against real observations with Keck (Masters et al. 2017). We will need these type of observations for  $\sim 2500$  galaxies in 3-5 PFS pointings, requiring a roughly estimated 25-50 nights of PFS. The advantage of spec-z calibrations is that it is a well-established method. Disadvantages include long exposure times and unproven sky subtraction of such a deep spectroscopic data with fibers.

**Intermediate band survey by HSC:** Images with intermediate bands with  $\Delta\lambda \sim 30\text{\AA}$  would be enough to capture (smeared) emission lines features to identify the full range of galaxy spectral energy distribution types. The main advantages of this method are that it captures all galaxies without the selection bias inherent in spec-z calibration samples, probes much larger numbers of objects, and allows one to reach below the spec-z sensitivity limit. The main disadvantage is this method has only recently been adopted for cosmology and so a more careful study required to define applicability to WFIRST. We estimate, we need about 60 nights to cover  $\sim 5$  HSC pointings with  $\sim 20$  intermediate band observations. In addition, since LSST will take only broadband images, this survey would be a unique legacy data set.

## 8. Nearby Galaxies

Simulations of galaxy formation show that the present day physical properties of stellar halos depend on their formation histories (Johnston et al. 2008; Cooper et al. 2010; Pillepich et al. 2014, D’Souza & Bell 2018). Because of this dependence, we can use stellar halo observations to constrain formation models, (see Figure 8. 1).



With a combination of the WFIRST IR photometry and Subaru optical photometry from pre-imaging, we can characterize the ages and metallicities of various halo structures to tightly constrain formation models. While

Figure 8.1: Left Panels: Examples of how halo morphology reflects the history of accretion (Johnston et al. 2008). Right Column: Simulated optimal ground-based map (1 hour with Subaru we need to go longer for useful pre-imaging) of a model halo is shown above a simulated WFIRST map of the same model requiring at least 12 WFIRST pointings. Deeper Subaru pre-imaging will allow far less WFIRST tiling. The maps have bins of  $1' \times 1'$ , corresponding to  $1 \text{ kpc} \times 1 \text{ kpc}$  at an assumed 3.5 Mpc distance.

WFIRST has a large field of view, most halos will require some amount of tiling. However, with Subaru pre-imaging, the brightest stellar halo structures can be mapped out ahead time ensuring that WFIRST covers the most interesting features of the stellar halos. The HSC has already provided stunning images of a few galaxy halos that reveal structure (e.g. M94 and NGC4631, Smercina et al. 2018; Tanaka et al. 2017, and Okamoto current program). While star/galaxy separation is not optimal in the ground-based imaging, such structures will be the highest priority for WFIRST imaging to obtain clean star samples to characterize their ages, metallicities, and stellar masses (e.g. Smercina et al. 2017, ApJL, 843, 6), maximizing efficiency.

Furthermore, the Subaru data will become more valuable once the WFIRST observations are complete. The quality of the Subaru photometry will be improved by using the WFIRST data as a prior when deblending the stars (as for WFC3/IR in Williams et al. 2014). In addition, the filter combination of WFIRST is limited, and Subaru will provide several additional bands to constrain the spectral energy distributions (SED) of the stars to measure masses, metallicities, ages, and temperatures (Gordon et al. 2016). Such detailed characterizations constrain how galaxies occupy dark matter halos (Smercina et al. 2018, ApJ, 863, 152), and how stellar halos form (e.g., D'Souza & Bell 2018, MNRAS, 474, 5300; D'Souza & Bell 2018, NatAs, 2, 737).

Several galaxies are already planned to be observed with HSC; however, a dedicated program to 10 galaxies (10 nights) will likely double the sample for WFIRST planning. Moreover, the data would be available to the public, including the teams planning WFIRST observations.

## 9. Milky Way

Deep imaging with the high angular resolution of WFIRST will be very powerful for investigating stellar populations in the Milky Way. We here focus on two scientific cases which will become possible with the WFIRST microlensing survey and follow-up observations at Subaru: (i) detection of hypervelocity stars (HVSs), and (ii) characterization of microlensed sub-giants/dwarfs in the Galactic Bulge.

**Hypervelocity Stars (HVSs) in the Galactic Bulge.** HVSs are stars with highest velocities (Brown 2015), several thousands of  $\text{km s}^{-1}$ , and they are not likely to be bound to our Galaxy. Gaia will increase the number of HVSs (currently  $\sim 20$ ) significantly. One of the proposed scenarios for the formation of the HVSs is a close encounter between a tightly bound binary and a supermassive black hole (SMBH; Hills 1988), i.e. Sgr A\* in our Galaxy. One binary component is captured by a SMBH and the other is ejected at the very high velocity. HVSs with this origin in the Bulge, if confirmed, would be useful to understand their formation process in detail. Assuming the ejection rate of HVSs to be  $10^{-5} \text{ yr}^{-1}$  (Yu & Tremaine, 2003), roughly 130 HVSs are included within  $3^\circ$  from the Sgr A\*, and about 1/10 of them are expected to be in the WFIRST microlensing survey region covering  $\sim 2.8$  square degrees. The proper motions of almost all HVSs in the WFIRST Bulge field can be detected with a typical uncertainty of proper motion measurements of  $0.01 \text{ mas yr}^{-1}$ . The ground layer AO system (GLAO) and a new wide-field infrared camera, i.e. ULTIMATE-Subaru (wide-field imager), on the Subaru telescope will be useful for studying HVSs in the Bulge region; we can search for HVSs outside the WFIRST microlensing survey field such as the GC region including Sgr A\*. Follow-up observations of HVSs found by WFIRST can be conducted with Subaru. Spectra of stars with low extinction may be obtained with the PSF for determining the 3D velocities, while highly-reddened objects can be observed with the multi-slit spectrograph for ULTIMATE-Subaru.

**Characterization of microlensed sub-giants/dwarfs in the Galactic Bulge.** The presence of intermediate-age stars is one of the most important but intriguing discoveries among many findings regarding the Bulge stellar populations (Barbuy et al. 2018). The Bulge was considered to be composed of old stars,  $\sim 10 \text{ Gyr}$  (Zoccali et al. 2003), but Bensby et al. (2013, 2017) reported the presence of stars younger than 8 Gyr based on high-resolution spectra of microlensed sub-giants/dwarfs. However, the presence of the younger stars in the Bulge has been challenged by, e.g., Renzini et al. (2018) who used an intensive dataset collected with HST/WFC3 (but see also Bernard et al. 2018). Most of the previously detected microlensing events are limited by the sensitivity of optical microlensing surveys, and they are away from the Galactic plane by 1.5 degrees or more. In contrast, pioneering surveys using UKIRT and VISTA have detected infrared microlensing events at low Galactic latitudes. A great jump in infrared microlensing

surveys will be delivered by the WFIRST, while the ground-based microlensing surveys, e.g., by using the PRIME (being constructed in South Africa; PI. Sumi). Such surveys in the future will allow us to study sub-giants/dwarfs and subgiants in the low-latitude regions by using the same technique as Bensby et al. (2013) and other studies. In order to get reasonable estimates of surface gravity in addition to chemical abundances, it is crucial to collect high-resolution spectra with sufficiently high S/N,  $\sim 50$  or higher with the IRCS and the IRD for relatively bright microlensing events (with high amplification over 100).

## 10. Solar System Science

**Trans-Neptunian Objects (TNOs):** TNOs, a population of small bodies beyond Neptune's orbit (semi-major axes  $>30.1$  AU), represent the most pristine remnants of planetesimals formed in the early solar system. The surface temperatures of TNOs is very low, only a few 10s of K, which allows them to retain volatile compounds such as  $N_2$ , methane ( $CH_4$ ), and CO (Schaller and Brown 2007; Johnson et al. 2015). These ice species are crucial to understanding the initial conditions of the early solar system, as well as the formation and evolution of planetesimals. Detailed investigation of their surface characteristics is required to understand the composition and alteration processes, but is still limited due to their faintness.

Previous photometric observations revealed that TNOs exhibit a wide range of optical colors, from neutral to extremely red (e.g., Tegler and Romanishin 2000; Peixinho et al. 2004; Dalle Ore et al. 2015; Tegler et al. 2016). The red components are suggested to be irradiated organic materials. The colors are useful as a constraint not only on surface composition but also on their formation location. Previous near-infrared spectroscopic studies have detected a variety of ice species on the surfaces of TNOs. Three broad categories of TNO spectra are observed:  $CH_4$ -dominated for the largest dwarf-planets,  $H_2O$ -dominated for Haumea Family members and intermediate-sized TNOs, and featureless spectra for the smallest TNOs. Extensive spectroscopic surveys by VLT and Keck (Barucci et al. 2011; Brown et al. 2012) indicated that TNOs larger than  $\sim 800$  km in diameter have increasing amounts of  $H_2O$  ice on their surfaces, while the smaller objects show weaker or even non-existent  $H_2O$  absorption features in their spectra. One possible explanation for this trend is that larger objects are differentiated, which caused outflows of  $H_2O$  ice onto their surfaces early in their histories. Constraining the presence of  $H_2O$  ice on more TNOs across a variety of sizes and dynamical classes is required to adequately test this theory.

Coordinated observations with WFIRST and Subaru/HSC have the potential to make significant breakthroughs in the study of TNO surface characteristics. The HSC Subaru Strategic Program (SSP), an optical multi-band imaging survey covering  $1400 \text{ deg}^2$ , will be able to detect several hundred TNOs down to diameters of 100 km or smaller, and to determine their orbits and optical colors. WFIRST has a wide field-of-view ( $\sim 0.28 \text{ deg}^2$ ) and is sensitive enough to follow up on any TNOs detected as part of the HSC SSP in order to measure their near-infrared colors. Specifically,  $J - H$  color is important as a diagnostic of  $H_2O$  ice absorption between  $1.5$  and  $1.65 \text{ }\mu\text{m}$  (Figure 10.1).

**Other Minor Bodies and Irregular Satellites:** A further benefit of using these two facilities in conjunction is for following up observations of serendipitously detected small bodies in the WFIRST surveys, including new minor bodies (Near-Earth Asteroids, main-belt asteroids, hyperbolic asteroids, comets, active

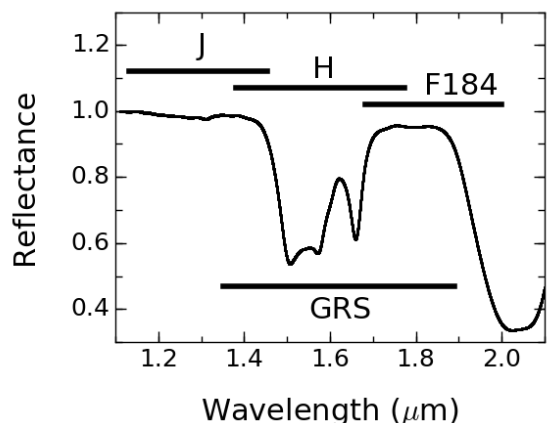


Figure 10.1: Near-infrared reflectance spectrum of crystalline  $H_2O$  ice. The  $1.65 \text{ }\mu\text{m}$  absorption feature is unique to crystalline  $H_2O$ ; the  $1.5$  and  $2.0 \text{ }\mu\text{m}$  features are present in the spectra of crystalline and amorphous  $H_2O$ . A majority of  $H_2O$  ice identified in the trans-Neptunian region is in the crystalline phase.

asteroids, Jupiter Trojans, Centaurs, etc.) and irregular satellites of the giant planets (Holler et al. 2018). Subaru follow-up can help further constrain the orbits and measure optical colors. The primary concerns will be ensuring Subaru observations are activated in a timely manner to follow-up on



newly identified moving targets and that the observations are made at an appropriate cadence so that the objects are not lost.

## 11. Guest Observer/Investigator Science: Keeping the Door Open to New Discoveries

Landmark results from flagship facilities are often from science not planned or anticipated 7 years before first light. WFIRST is an observatory with brand new capabilities; It will open the way for key discoveries in areas not immediately linked to its core survey plans. The possibility of such discoveries with WFIRST is enhanced by the General Observer (GO) program (nominally 25% during the prime mission, and potentially much more in an extended mission phase). It would be scientifically valuable to retain similar flexibility in Subaru time spent in support of WFIRST. This could be done in several ways. One option would be to set aside about 25 nights of the 100 planned nights, to be allocated for GO programs at the time when WFIRST GO programs are awarded. Part of that time could be made available before WFIRST launch for preparatory observations. Of course, for small allocations of Subaru time, existing time allocation processes may be sufficient.

Another option would be to have representatives of the GO community involved in the Subaru time allocation process. For example, GO related proposals can be identified by a checkbox on a proposal cover-page indicating the relevance to the WFIRST. The WFIRST GO representatives can attend a part of the Subaru TAC when those relevant proposals are discussed. This could be done without setting aside a specific number of nights for GO science, provided that the relevant Subaru proposal calls are kept open to observations related to both GO and core survey WFIRST projects. The ongoing Subaru/WFIRST Community Workshop series will provide a good venue for continuing this discussion; ultimately recommendations for how to proceed will come from the steering committee detailed (Section 12).

**Joint Time Allocation:** Finally, it may be valuable to consider establishing a joint time allocation process, capable of awarding WFIRST and Subaru time simultaneously. Synergy between the two observatories is well-served if astronomers don't need to win in two separate and highly competitive time allocation processes to do joint science. There is a long tradition of Joint Proposal opportunities from NASA Great Observatories. HST offers joint proposals with XMM-Newton, Chandra, Spitzer, and NOAO (including Gemini). Chandra offers joint proposals with HST, XMM-Newton, NOAO (including Gemini), NRAO, Swift, and NuSTAR.

**Shared PFS Fiber Allocation:** It also may be desirable to implement Guest Observer Fiber allocation during PFS follow-up of WFIRST observations, and especially WFIRST core surveys. A process for proposing to use N fibers per square degree, in a multi-use PFS observing program, would be a very good way to support more GO science with PFS.

Decadal survey endorsement of any of the above processes for science enhancement of WFIRST would be welcome

## 12. Future Process and Directions

Program	Instrument	Total nights
(S3) microlensing concurrent	HSC and ULTIMATE	17
(S3) microlensing NIR Spectroscopic ToO	Subaru IRD	11.2
(S3) microlensing concurrent	ULTIMATE	3.4
(S4) CGI follow-up and support	SCExAO/CHARIS/IRD	25
(S5) SN follow up	PFS	25
(S5) Live SN monitoring	PFS	20
(S6) Optical Imaging follow-up of SNe fields	HSC	8
(S6) Spectroscopic follow-up of SNe fields	PFS	8
(S6) Narrow band survey of SNe fields	HSC/PFS	6-10
(S6) Ultra Deep Fields	HSC	33
(S7) Spec-z follow-up for photo-z calibration*	PFS	25-50
(S7) Intermediate-band follow-up for photo-z*	HSC	60

(S7) Lensing and structure growth	PFS/HSC	~Tens (TBD)
(S8) Galaxy Halo Pre-imaging	HSC	10
(S9) Bulge HVs (characterization)	PFS	0.5
(S9) Bulge HVs (characterization)	ULTIMATE (MOS)	0.5
(S9) Bulge HVs (survey)	ULTIMATE- (Imaging)	2.5
(S9) Microlensed Bulge Objects	IRCS/IRD	15
(S10) TNOs	HSC	6
(S10) Other Minor Bodies	HSC	10
(S10) Irregular Satellites	HSC	6

Table 1: Proposed Subaru time for synergistic programs with WFIRST.

\*only one of these programs will proceed

This white paper has identified significantly more than 100 nights of compelling Subaru observations that would produce excellent synergistic science with WFIRST. Thus, there needs to be a process that defines how the Subaru nights pledged by JAXA will be used in conjunction with WFIRST. This process must accommodate pre-defined WFIRST surveys as well as a robust program of competitively selected GO WFIRST surveys. This process must ensure the engagement of the Japanese community as well as the worldwide WFIRST community. We have started to outline some suggestions in this document (particularly in Section 10 with regard to GO programs), but a more well-defined process and timeline needs to be worked out as we approach the 2025 launch of WFIRST. Toward that end, a steering group has been set up to define the path forward in how to best use the 100 allocated Subaru nights for WFIRST/Subaru synergistic science. This group consists of:

- Takahiro Sumi (Chair of WFIRST JAXA Working Group)
- Toru Yamada (JAXA WFIRST Representative)
- Yusei Koyama (Subaru Representative)
- Tadayuki Kodama (Chair of the Subaru Science Advisory Committee)
- David Spergel (WFIRST WFI Adjutant Scientist)
- Julie McEnery (WFIRST Deputy Project Scientist)
- Jason Rhodes (WFIRST Deputy Project Scientist)

This group will not define the Subaru observations, but will define the *process* by which those observations will be decided. This group plans to continue to solicit community input from both the WFIRST and Subaru communities and to have approximately yearly meetings to update the relevant communities about the evolving synergistic Subaru/WFIRST science cases.

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