Subaru Prime Focus Spectrograph

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1. Introduction

“How did the Universe start?” “Will the Universe end at some point?” “How did we come to exist?” These have been fundamental questions about the Universe since the dawn of humankind. Surprisingly, the Universe is found to be largely made of “dark matter,” which has never been detected directly, and “dark energy,” which is a much more mysterious negative pressure accelerating the expansion of the Universe. However, we do not understand either constituent physically. Likewise, the standard picture of galaxy evolution based on the hierarchical assembly of dark matter is insufficient to explain what we see from observation, such as the mass growth of galaxies, the diversity of present-day morphologies, and the distribution of dwarf galaxies around our home, the Milky Way.

The Subaru Prime Focus Spectrograph (PFS, http://pfs.ipmu.jp/; http://pfs.ipmu.jp/blog/) project squarely aims at addressing these long-standing questions. This innovative instrument under development enables us to take spectroscopic observations of 2394 astronomical objects simultaneously on a large patch of sky several times larger than the size of the full moon. The lights from each star and/or galaxy observed are dispersed and recorded as spectra simultaneously covering a wide range of wavelengths from the near-ultraviolet, through the visible, and up to the near infrared regime (380 – 1260 nm). Table 1 compare the major parameters of the PFS instrument with those of the other competing instruments that

Table 1: Comparison of PFS specifications with other competing spectroscopy projects that are on a similar timeline to PFS

	PFS	DESI	WEAVE	MOONS
Telescope	Subaru (8.2m)	Kitt Peak Mayall (4m)	WHT (4.2m)	VLT (8.2m)
Field-of-View	1.2 sq. deg.	7 sq. deg.	~3 sq. deg.	0.14 sq. deg.
Multiplex	2394	5000	800	1024
Resolving power	~2000-4000	3000-5000	5000, 20000	~5000, 9000, 20000
Science operation	2021	2019	2019	2020

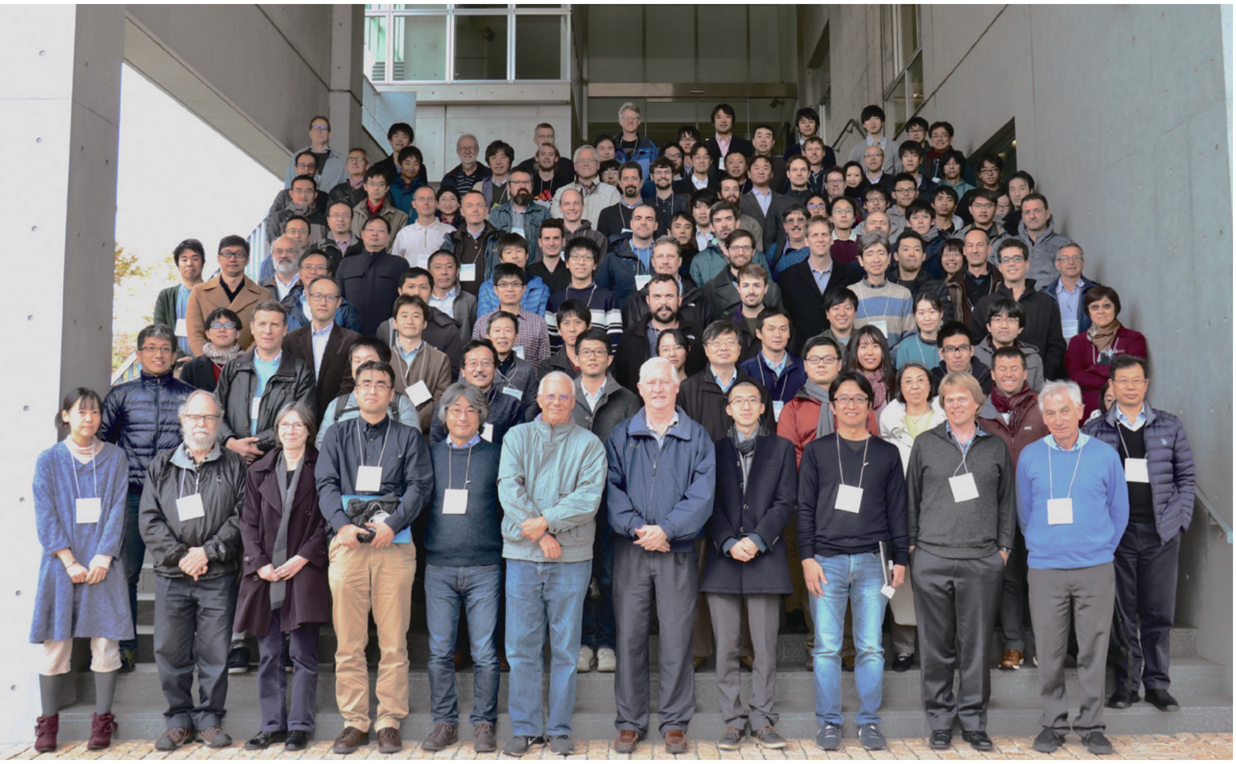

Figure 1: A group photo at the PFS collaboration meeting held at Kavli IPMU in November 2017.

are under development and will come online in a similar timeline to PFS. The table clearly shows that PFS is quite unique and powerful. This exciting PFS project is being promoted under the initiative of the Kavli IPMU, involving international partners across the world—the National Astronomical Observatory of Japan, the Academia Sinica, Institute of Astronomy and Astrophysics in Taiwan (ASIAA), California Institute of Technology (Caltech), NASA Jet Propulsion Laboratory (JPL), Johns Hopkins University, and Princeton University in the US, Laboratoire d'Astrophysique de Marseille (LAM) in France, the Brazilian Consortium, Max Planck Institut für Astrophysik (MPA) and Max Planck Institut für Extraterrestrische Physik (MPE) in Germany, and the Chinese Consortium. Figure 1 is a group photo taken at the PFS collaboration meeting held at Kavli IPMU in November 2017. We had more than 130 participants, and the photo clearly shows that the PFS collaboration is a truly international project. The Principal Investigator (PI) is Kavli IPMU Director, Hitoshi Murayama, the Project Manager (PM) is Naoyuki Tamura, and the Project Scientist (PS) is Masahiro Takada. Kiyoto Yabe and Yuki Moritani are among the most active members on this project. These members at Kavli IPMU have been working to hold the collaboration of the different institutes together and drive the project to progress efficiently.

2. The Instrument

The PFS project takes the full advantage of the unique capabilities of the 8.2 m Subaru telescope, its light-collecting power, wide field of view at the prime focus, and superb image quality. The PFS instrument is composed of four subsystems, whose distribution on the telescope is illustrated in Figure 2. The lights from astronomical objects and the sky are fed to the fibers configured at the Subaru

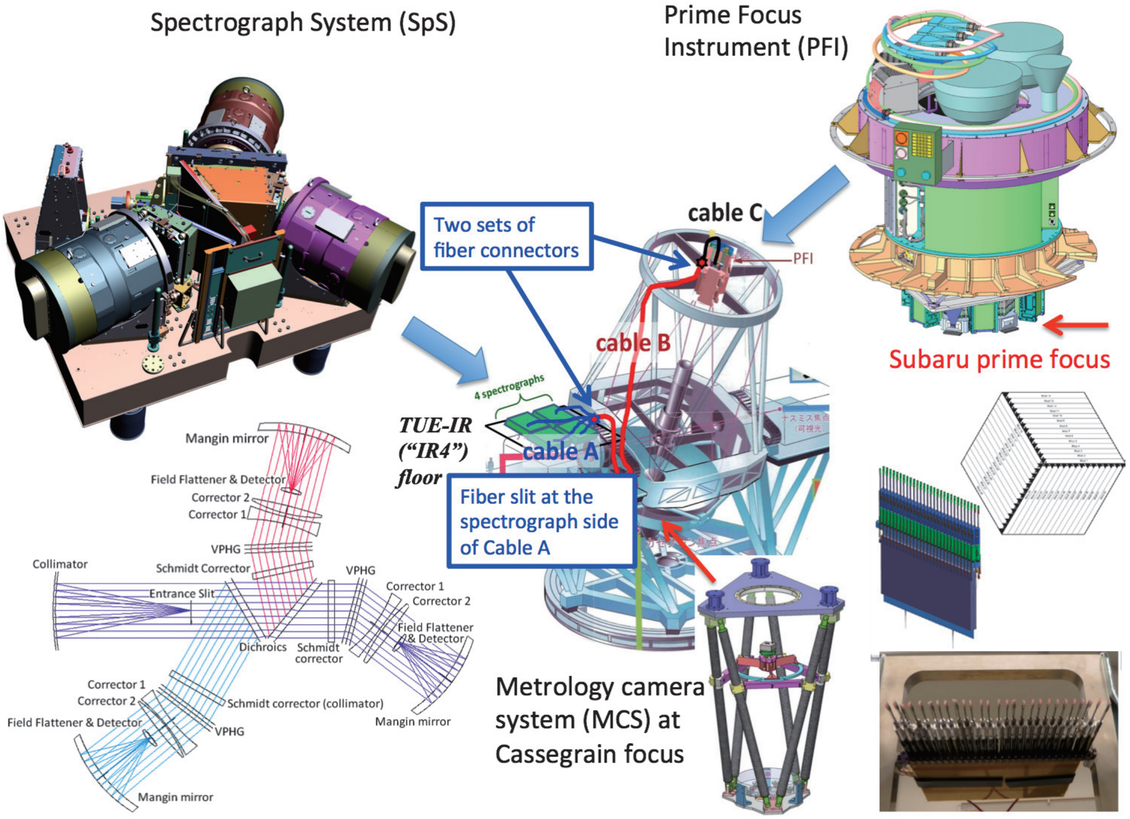

Figure 2: A schematic view of the configuration of PFS instruments. An overall sketch of the Subaru Telescope is presented in the middle with the PFS fiber cable routed from the prime focus to the spectrograph system. On the right, a solid model of PFI (top), a schematic view of the focal plane (middle), and a photo of the Cobra engineering model fiber positioners module are presented. On the left, a solid model of one spectrograph module (top) and a ray-trace view of it (bottom) are shown.

prime focus and transmitted via the fiber cables to the spectrograph system in the telescope enclosure building, and then the spectral images of them are delivered on the spectrograph detectors. PFS shares the Wide Field Corrector and the mechanical housing of a prime focus instrument called POpt2 equipped with an Instrument Rotator and Hexapod, all of which have already been constructed for the Subaru Hyper Suprime-Cam (HSC), the prime-focus ultra wide-field imager for which Kavli IPMU also played a major role in the construction and project promotion/management. The focal plane will be equipped with 2394 reconfigurable fibers distributed in the 1.3-degree wide hexagonal field of view. “Cobra,” the actuator, is comprised of two motors and is used for moving each fiber to the position of an astronomical object of interest on the focal plane. The “patrol area,” where each fiber attached to Cobra can move around, is a 9.5-mm diameter circle. Forty-two “Cobra modules,” each of which consists of 57 Cobras mounted at 8-mm intervals, will be used for the observation. The spectrograph has been designed to cover a wide range of wavelengths simultaneously from 380 nm to 1260 nm in one exposure. The Metrology Camera System takes images of backlit fibers on the primary focal plane and measures their current positions, so it will work as the encoder in the fiber positioning process. The HSC and PFS enable deep imaging and spectroscopic surveys of the same region of sky using the same 8.2 m telescope, allowing a good understanding of various systematics in the data.

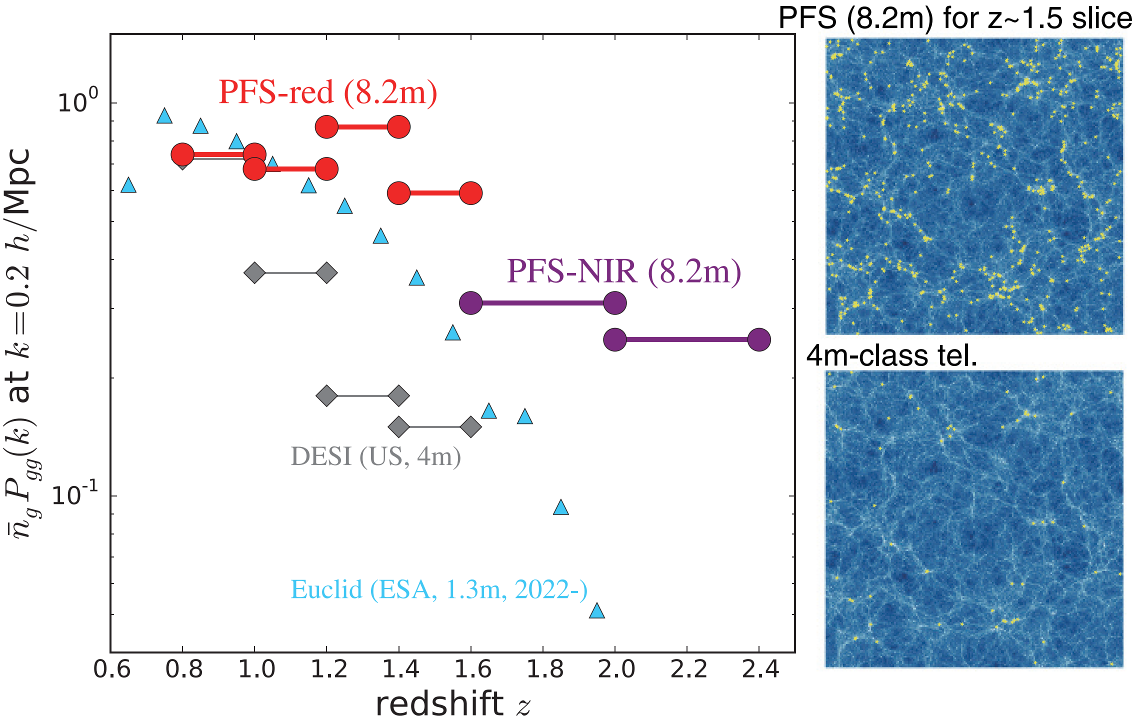

Figure 3: An illustration of the PFS cosmology survey. PFS maps out the three-dimensional (3D) distribution of galaxies by measuring distances to the galaxies from their spectroscopic observation. The upper-right panel shows a simulated distribution of galaxies in the Universe at redshift z~1.5; the yellow dots are galaxies and the blue-color map shows the underlying dark matter distribution. Lower-right panel shows the similar simulation, but if a 4m-class telescope instead of the 8.2m Subaru telescope is used. The left panel shows the number density of PFS galaxies at each redshift slice. The higher value in the y-axis value means a higher number density of galaxies in the 3D map. These can be compared to other competing surveys: 4m US-led DESI project and the ESA satellite mission, Euclid.

3. Scientific Objectives

The combination of the large aperture, wide field-of-view, and massively-multiplexed spectroscopic capability of PFS/Subaru promises to enable a broad range of scientific topics in cosmology and astrophysics. The PFS team is planning to carry out a coherent, large-scale spectroscopic program with PFS, spending about 300 Subaru nights over 5 years. The scientific objectives consist of three pillars, namely, the Cosmology, Galaxy Evolution and Galactic Archaeology programs.

First, the PFS Cosmology program aims at mapping out the Universe over the wide range of redshifts, 0.6 < z < 2.4, and over the wide solid angle on the sky, 1,400 square degrees, by measuring redshifts of more than 4 million emission-line galaxies. This redshift range includes eras of the Universe changing from decelerating expansion to accelerating expansion. By measuring the scale of baryon acoustic oscillations imprinted onto the galaxy distribution in the PFS galaxy map, we can measure the cosmological distance and the expansion rate at each redshift, and then use the information to explore the nature of dark energy causing the accelerated expansion. Furthermore, by measuring the clustering statistics of galaxies, which quantifies the inhomogeneous distribution of galaxies on the galaxy map as a function of length scale and redshift, we can measure the time evolution of cosmic structure formation and then

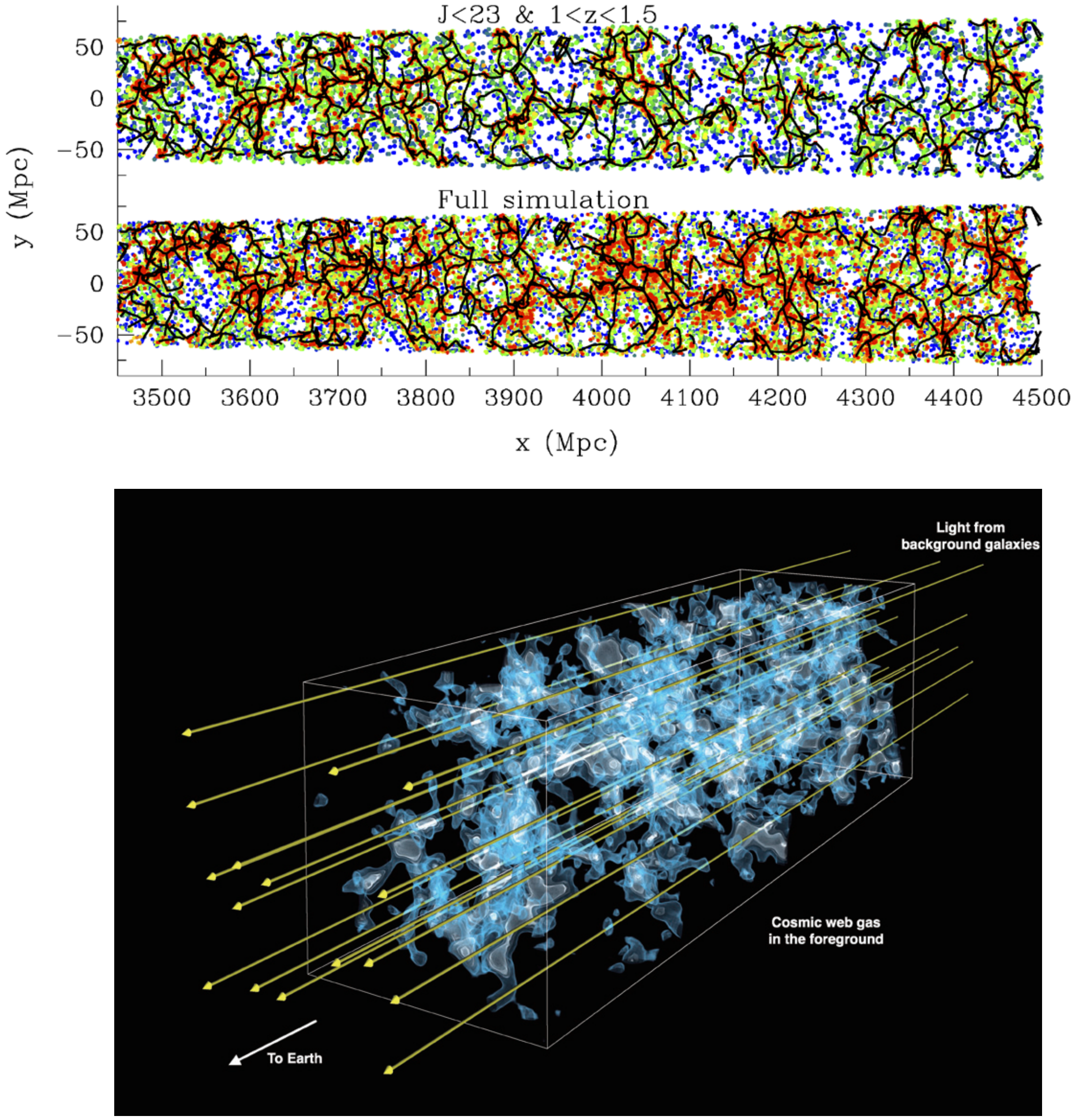

Figure 4: (Top panel): The three-dimensional map of galaxies at 1 < z < 1.5 that are observed by the PFS Galaxy Evolution program. The blue, green, and red galaxies correspond to galaxies residing in low-, intermediate-, and high-density environments. The black lines denote filaments in the cosmic web structure. The lower figure represents all the galaxies in the same redshift slice, and the comparison shows that the PFS survey samples about 70% of all the galaxies in these structure. (Bottom panel): An illustration of "intergalactic medium (IGM) tomography" that the PFS survey will carry out. By using star-forming bright galaxies as a backlight, we can reconstruct the three-dimensional distribution of neutral hydrogen in the Universe by measuring absorption features in the PFS spectra of each galaxy.

use the information to explore the nature of dark matter, which plays a major role in the structure formation. Figure 3 shows how PFS can map out the three-dimensional distribution of galaxies as a function of redshift. The right panel shows that PFS provides us with a high-density map of galaxies, thanks to the power of the large-aperture Subaru telescope, compared to a map done with a 4m-class telescope, and the galaxy map can be used to accurately infer the three-dimensional dark matter distribution in the Universe.

The second program is the PFS Galaxy Evolution survey, which carries out detailed deep spectroscopic observations for hundreds of thousands of galaxies over several target fields of about 15 square degrees in total, which represents a cosmological volume. The program aims at charting the evolution of galaxies over cosmic epochs during which most of stellar masses in galaxies are assembled in the context of hierarchical structure formation scenario. Here the detailed spectroscopic data of individual galaxies for the sample enable us to investigate star formation activities, stellar and gas kinematics, and the role of feedback driven by star formation or central black hole accretion as a function of galaxy mass (size) and its surrounding environment. In addition, the new Kavli IPMU member, Khee-Gan Lee, has led the team to propose a new, exciting science case that can be done within the PFS Galaxy Evolution program. By taking spectra of star-forming, bright galaxies at high redshifts, z ~ 3 as a "backlight" and then measuring absorption systems due to neutral hydrogen in their spectra, we can also map out the three-dimensional distribution of neutral hydrogen that exists in intergalactic space. This is called "intergalactic medium (IGM) tomography." With this method, we can unveil the distribution of IGM hydrogen, which cannot otherwise be observed as it does not emit light, and then study the interplay between IGM and galaxies. Figure 4 illustrates that the PFS Galaxy Evolution program will make a detailed map of galaxies and intergalactic medium in the same cosmic web of the Universe at high redshifts z > 1. These data will be complementary to the PFS Cosmology program, because the Galaxy Evolution survey will give a much more detailed understanding of the nature of emission-line galaxies that are targeted by the PFS Cosmology program.

The third program is the PFS Galactic Archaeology program. We plan to use PFS to measure the radial velocities and chemical abundances of numerous stars in the Milky Way, Andromeda Galaxy, and dwarf galaxies to infer the past assembly histories of these galaxies as well as their dark matter distribution. In particular, dwarf galaxies are a dark matter-dominated system in their kinematic properties, but an accurate knowledge of the dark matter distribution is still lacking. By measuring the radial velocities of member stars over an entire region of some dwarf galaxies with PFS, we can unveil the distribution of dark matter. When combined with gamma-ray observations from the Fermi satellite, we can further explore a possible gamma-ray signal from the dwarf galaxies via annihilation or decay of dark matter particles in more detail. Even if we cannot find such a signal, we can improve the constraints on properties of dark matter such as the cross section or decaying time scale. This research goal lies in interdisciplinary fields between particle physics, astrophysics and cosmology. Figure 5 illustrates the power of the PFS Galactic Archaeology program. Thanks to the large-aperture Subaru telescope, PFS enables to measure the radial velocities and chemical abundances of stars out to a much larger distance up to ~30 kpc, which covers the entire region of the Milky Way Galaxy. This program would not be practical with a 4m-class telescope.

4. Current Status

The construction of PFS instrument is well underway. The subsystems are being developed at the international partner institutes of the PFS collaboration. For example, the PFS consists of 4 spectrograph modules. The first one is being assembled and is under various tests such as image quality and thermal performance in the integration hall at LAM. The team at Caltech-JPL are integrating Cobra modules. The first Cobra module has already been integrated and tested, and shipped to ASIAA in Taiwan. Also the integration of next modules has been ongoing. We aim at completing the integration and test of all the 44 Cobra modules (including 2 spare modules) this year. The Prime Focus Instrument is being integrated at ASIAA in Taiwan and will be ready soon to have the Cobra modules

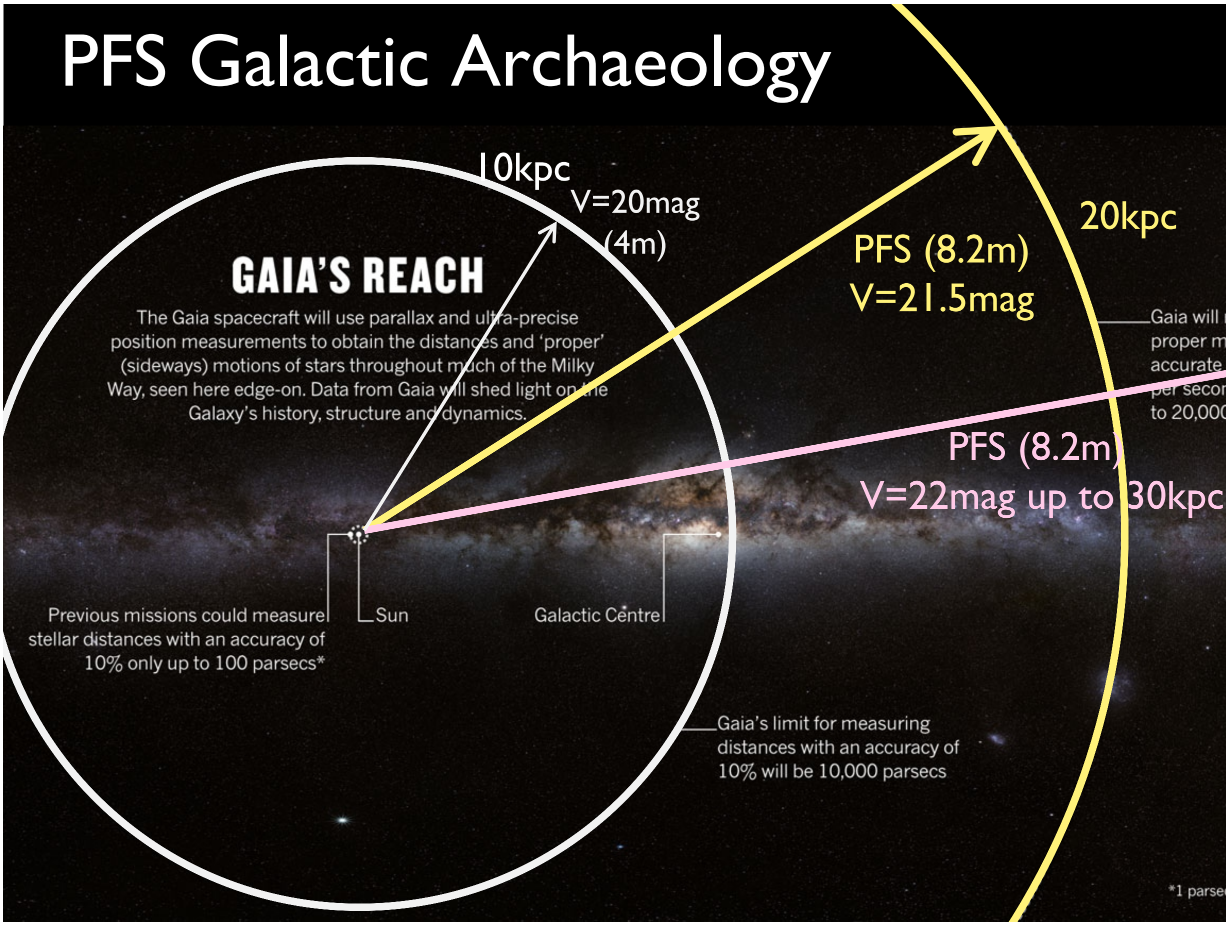

Figure 5: An illustration of the PFS Galactic Archaeology program, explaining how PFS is powerful for measuring the radial velocities and chemical abundances of numerous stars out to ~30 kpc from the Earth in the Milky Way Galaxy. The PFS survey is complementary to the ongoing survey by the ESA satellite GAIA that measures stars up to 10 kpc as well as to upcoming surveys that can be done with a 4m-class telescope that aims at carrying out more detailed (high spectral resolution) spectroscopic studies of stars up to ~10 kpc. (Background image credit: ESA.)

integrated and tested. The Metrology Camera System has been shipped in April from ASIAA to Hawaii. Then we plan to carry out various tests, first with the Metrology Camera System as stand-alone and then with it installed onto the Subaru telescope in the summer. All these integrations, developments, and scheduling of the subsystems are being led under the strong management of Project Manager Naoyuki Tamura and the PFS Project Office centered at Kavli IPMU.

Obviously the PFS is a complicated instrument, and it is of critical importance to succeed in various on-site tests of the performance and on-sky commissioning observations at the summit of Maunakea with PFS installed on the Subaru telescope. Yuki Moritani is leading the detailed planning of the commissioning observations, having discussions for optimization with other members in the PFS team and also the staff at the Subaru Observatory. The current plan is to start the commissioning observations in 2019, and to complete the major performance testing of the PFS instruments within about one year from the start. After this, in parallel with the efforts of stabilizing the instrument performance and operation, the PFS team envisions to start the large-scale observational program of the aforementioned PFS science by the end of 2021.

The three main science programs of PFS, Cosmology, Galaxy Evolution and Galactic Archaeology will make spectroscopic observations of different astronomical objects (stars and galaxies) in different fields in the sky, and the requirements on the quality of their taken spectra (exposure time and physical quantities we want to measure) are different in between the three programs. Hence, in order to make full use of observational nights at the Subaru telescope, it is very important to explore an optimal survey design of the PFS survey project by combining different observations of the three PFS science projects. In parallel to the instrumentation, the team being led by Kiyoto Yabe is developing an "Exposure Time Calculator (ETC)" that allows the simulation of an expected spectrum of an astronomical object for an assumed exposure time under the expected Maunakea observational conditions, where the expected performance of PFS instruments is taken into account. Using the ETC and the fiber assignment software, the team is exploring an optimal survey strategy by carrying out a simulation of the PFS survey program assuming target fields and target astronomical objects that the PFS Science teams are currently considering for 300 nights.

5. Future Prospects

As is obvious from what we have so far described, the Subaru PFS is a very powerful instrument. The 6.5m effective-aperture Large Synoptic Survey Telescope (LSST) is a US-led project starting around 2020 and is currently under construction, and will make possible the ultimate dedicated imaging survey of the Universe. However, a spectroscopic follow-up observation of LSST objects is not yet being planned. The extremely large-aperture telescope such as the Thirty-Meter Telescope in which astronomers in Japan are involved, is being planned to start its operation after 2025, but has a small field-of-view, and is more suitable to make a detailed spectroscopic observation of interesting, rare astronomical objects. The TMT is complementary to PFS in light of their roles. Thus PFS will make the Subaru telescope a world-leading astronomical facility in the decade of the 2020s. In fact, astronomers in Japan and US are starting discussions toward a collaboration combining both data from the NASA-led satellite mission WFIRST (its launch will be around 2025 at the earliest) and the PFS-led Subaru telescope. The PFS project is an extremely exciting project, and astronomers and physicists in Japan should not miss this great opportunity to advance our understanding of the physics of the Universe.

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