The FOBOS Spectroscopic Facility for Keck: Project Description

MSIP proposal category: "Development Investments"

1. Scientific Justification

1.1. **Introduction.** Led by NSF's LSST[1] and NASA-supported missions like Euclid[2] and WFIRST[3], astronomy is entering a new era of unprecedented deep-imaging campaigns that will survey huge volumes of the Universe. From the emergence of the earliest galaxies from a "primordial soup" of gas and dust, to the peak of cosmic star formation and the current era of accelerated expansion, these surveys will provide unprecedented statistics at key epochs of cosmic history.

Even so, gaining physical insight from panoramic imaging surveys will require intensive spectroscopic follow-up. The power of combining photometry and dedicated spectroscopy is widely appreciated and perhaps best illustrated by the success of the Sloan Digital Sky Survey (SDSS) which used this combination to record the properties of over 1 million galaxies, mapping the present-day universe and making SDSS one of the most highly cited surveys in the history of astronomy.

LSST's all-sky images, for example, will be 1,000 times deeper and detect far more distant galaxies than SDSS, but **no current U.S. facility is capable of obtaining spectroscopic follow-up of LSST galaxies** at a level required to capitalize on the $1B the U.S. has invested in that project. In fact, an SDSS-like spectroscopic study of 1 million galaxies at LSST depth would require 300 years of observing on the largest telescopes with current instrumentation!

This proposal addresses this challenge through the design of an ambitious spectroscopy facility on one of the world's largest telescopes. Timed to deploy on WMKO's[4] Keck II Telescope in 2028, just as various panoramic deep imaging surveys hit their stride, FOBOS's[5] 1800-fiber multiplex, deep sensitivity, high sampling density, and wide wavelength coverage is optimized for the *deep-drilling* spectroscopic training sets required to extract maximum information from wide-field photometry. Its flexible target allocation system and multiplexed IFU mode provide unique capabilities for realizing major progress on fundamental goals in Cosmology, Galaxy Formation, and Local Group Archaeology, and Time Domain Astronomy in the coming decade.

1.2. **Community Benefits.** Based on science requirements derived from reference-mission key programs, we present a comprehensive plan for optimizing and completing the design of the FOBOS instrumentation, calibration and support systems, operational and planning software, and data management systems. We propose community engagement activities to coordinate involvement of U.S. astronomers including those outside the Keck Community in developing and leading FOBOS public survey programs whose data products will benefit wide swaths of the astronomical community. In partnership with NOAO (this name might change), we will develop additional "open-access" models to offer ∼100,000 fiber-hours per year in support of individual, PI-led programs to be integrated into the FOBOS observing suite. Finally, we have emphasized the design of software platforms necessary for a seamless user experience from target submission to data product retrieval and analysis. FOBOS will be the first general-purpose spectroscopic instrument to automatically provide high-level data products such as redshifts, stellar continuum fits, and emission line measurements. With a commitment to the public release of such products

[1]LSST: Large Synoptic Survey Telescope. LSST will be begin science operations in 2023.

[2]Euclid is led by the European Space Agency with significant NASA involvement and will launch in 2021. Its primary mission is a 15,000 deg^2 imaging survey in optical and near-IR wavebands.

[3]WFIRST: The Wide Field Infrared Survey Telescope, expected to launch in the mid 2020's.

[4]WMKO: W. M. Keck Observatory operates the two twin 10m Keck Telescopes.

[5]FOBOS: Fiber-Optic Broadband Optical Spectrograph

derived from *all* FOBOS observations, these data products will dramatically reduce the time from observations to science.

As part of the work we propose here, NSF's OIR Lab will solicit additional key program concepts from the U.S. community, host workshops to discuss and refine these concepts, and coordinate proposing teams ahead of a competed selection process to define design-reference programs in support of Preliminary and Final Design.

1.3. **Key Science Goals.** We present three "design-reference" programs that capture FOBOS's primary science goals and drive initial requirements. These programs highlight FOBOS's capabilities in addressing the nature of Dark Energy, the formation of galaxies, and the assembly history of the Andromeda Galaxy system.

1.3.1. *Enhancing Dark Energy Probes via Precision Cosmic Distances.* The quest to understand Dark Energy has motivated billions of dollars of investment in efforts world-wide — culminating in LSST, Euclid, and WFIRST — that seek highly precise measures of cosmic structure to constrain the evolving dark-energy equation-of-state. Delineating cosmic structure requires measurements of galaxy positions and gravitational shear as a function of distance over vast cosmic volumes. For the billions of sources that will be cataloged, distances must be derived from photometric redshifts (photo-zs), whose poor accuracy (among other challenges) can introduce significant biases in cosmological results.

The FOBOS Cosmology Program will play a critical role by training photo-zs from sources that are too faint for other instruments (like PFS) but will dominate the number of galaxies and cosmic volume probed by panoramic deep imaging in the next decade. Complete spectroscopic training to $i_{AB} = 25.3$ will *increase the LSST's dark energy figure-of-merit by 40%* (Newman et al., 2015). FOBOS's strength in this endeavor goes beyond sensitivity. With no "redshift desert," thanks to its unique ability to measure spectroscopic redshifts above $z > 1.5$ via rest-frame UV features, the FOBOS Cosmology Program will dramatically reduce the need for expensive, space-based[6] near-IR spectroscopy.

FOBOS Cosmology Program: For a set of 12 0.1 deg^2 FOBOS pointings arranged evenly in longitude and chosen to overlap with LSST, Euclid, and WFIRST footprints, this program will execute ultra-deep integrations of ∼15,000 $24 < i_{AB} < 25.3$ sources using 1200 single fibers (per pointing) from two of FOBOS's three spectrographs. Fiber-IFUs from the 3rd spectrograph will be used for simultaneous Galaxy Program observations (see below). To maximize the power of the resulting photo-z training sample, we will prioritize rare targets in color-magnitude space, e.g., following Masters et al. (2019), and will dynamically re-allocate fibers to new targets as successful redshifts are obtained (i.e., some fibers will deliver multiple spec-zs). The longest integration times per field will reach 100 hours. Accounting for two-thirds of available fiber-hours, this program would require 23 effective dark nights per year for 5 years.

1.3.2. *Mapping the Baryonic Ecosystem of Early Galaxies at All Scales.* The fueling and regulation of galaxy growth during the peak formation epoch ($z \sim$ 2–3) is critically tied to the turbulent and gas-rich ecosystem in which early galaxies evolve. James Webb Space Telescope and Extremely Large Telescopes will marshal powerful infrared observations to study the stars and nebular gas at the heart of these early galaxies. But to map out their crucial link to the extended gas reservoirs, diffuse halos, and streaming filaments that dominate the mass in these environments requires an instrument like FOBOS. Its deep sensitivity and high sampling density

[6] Ground-based near-IR spectroscopy is too contaminated by sky-line emission to provide spec-zs at the required level of completeness (Newman et al., 2015).

enables comprehensive tomographic reconstruction of the intergalactic medium (IGM) across the largest cosmic structures in a single pointing ($\sim$10 transverse Mpc at $z \sim 2.5$). Its blue sensitivity probes Ly-α across the complete formation epoch ($z = 1.5$–3.5) and opens access to high-ionization transitions that reveal diffuse gas *in emission*, such as O VI (1032 Å). Finally, its ability to combine single-fiber and multiplexed IFU observations allows us to map the density and dynamical state of diffuse gas at all relevant scales from the IGM to the circumgalactic medium (CGM).

FOBOS Galaxy Ecosystem Program: This program consists of two parts that integrate into and build upon the FOBOS Cosmology Program. Additional IGM mapping of the 12 Cosmology pointings will expand the sampled area of each field to 0.5 deg^2 (5 pointings each) at a depth of 3 hours. This depth ensures sufficient Ly-α absorption mapping with a sightline density of $\sim$1600 per FOBOS pointing across absorber redshifts, $z = 1.5$–3.5 (see Lee et al., 2016). Field selection will take advantage of quasar-quasar pairs at certain redshifts. The number of fields and mapped area will capture the largest modes of large-scale structure while beating down sample ("cosmic") variance. This program component requires a total of 26 nights, spread over 5 years.

The second component of this program runs in parallel with the ultra-deep Cosmology Program. With two-thirds of fibers allocated to photo-z training in that program, the remaining third will be configured into 16 fiber IFUs, each composed of 37 fibers spanning 5.6 arcsec. With 100-hour integrations, these will map emission lines from the CGM on 5 kpc scales out to $r < 23$ kpc for $z \sim 2$ galaxies spanning a range of M_* and SFR. The final sample of nearly 200 direct CGM maps will link the buildup of the CGM through heating and gas flows to the cosmic web on large scales (mapped via IGM tomography) as well as the internal structure of the galaxies themselves (as observed by JWST and and at high resolution by ELT instruments). This component utilizes the equivalent of 11 nights of dark time per year for 5 years.

1.3.3. *Assembly of Andromeda's Disk and Satellite Galaxies.* Facilities like Gaia and APOGEE are probing the assembly history of the Milky Way and its halo by mapping their chemo-dynamical structure in unprecedented detail. In the next decade, a major goal is to building toward this level of understanding for the Andromeda Galaxy, its halo, and its satellite galaxies. Instruments like PFS with degree-scale fields of view that span 20 kpc or more at M31 distances are well suited to characterizing M31 halo structure. But FOBOS's much higher sampling density is critical for breakthrough data sets of stellar tracers in the M31 disk, M33, and Andromeda's major satellites. High S/N FOBOS spectra will map patterns of [Fe/H] and [Mg/Fe] and link these chemical tags to the underlying dynamics with unprecedented statistical power. Combining these FOBOS observations with integral-field data from the SDSS-V Local Volume Mapper and PFS surveys of halo structure, a complete picture of the Andromeda system's formation history will address key questions about disk evolution, dwarf galaxies, and substructure that have so far been limited to Milky Way and its surroundings.

FOBOS Andromeda Program: This program will survey 100,000 primarily RGB stars in the M31 disk, 10,000 stars in M33, and a further 15,000 stars in the central regions of Andromeda's major satellites: NGC 185, NGC 147, and And II. Accounting for a 60% rejection rate (see Dorman et al., 2012) due to crowding of ground-based RGB catalogs ($i_{Vega} < 22.5$), on-sky densities of 6 pointings in the PHAT[7] region between 5–20 kpc average 1 isolated source every $10''$, suitable for 10 independent fiber assignments per pointing. Two disk pointings beyond 20 kpc will be visited once. With order-of-magnitude longer integrations than SPLASH[8], total

[7] Describe and reference PHAT.

[8] Describe and reference SPLASH.

integrations of 10 hours per visit provide S/N $\approx$ 20 per resolution element for the faintest targets, a spectral quality sufficient for [Fe/H] with 0.1 dex precision and kinematic fits. For the "sweet-spot" of RGB tracers at $i_{Vega} = 21.5$, S/N $\approx$ 50, enabling [Mg/Fe] with 0.1 dex precision. Outside of M31, 6 10-hour visits will cover M33 and 3 visits each are assigned to NGC 185, NGC 147, and And II. This program requires 23 nights per year for 5 years.

2. Technical Overview

To meet the substantial spectroscopic needs of the U.S. astronomy community (Section **??**), we propose three coordinated activities: 1) Organizing and evaluating the results of a community-wide effort to address a series of data-science challenges; 2) Completing preliminary design for the FOBOS instrumentation, informed in part by refining requirements as a result of (1); 3) Designing the operational modes, planning tools, data analysis software, and platforms necessary to deliver public training data that address these challenges. We focus our current request on the Preliminary Design Phase (PDP) of FOBOS development, following the the overall project plan and final deliverables outlined below. Anticipating progress in all three activities, we will request NSF MSRI-2 funding in 2021 to build and deploy FOBOS at WMKO, with observations and publicly served training data to follow. FOBOS would see first light in 2027 and carry a total cost of \$32M (without contingency in 2019 dollars).

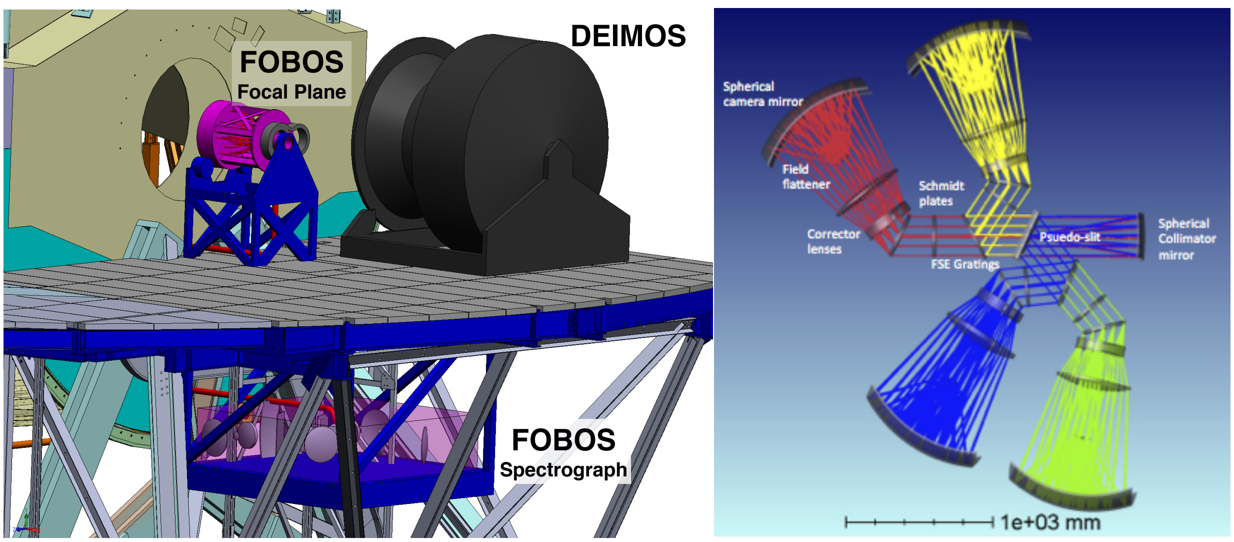

Figure 1. *Left*: Rendering of FOBOS instrument systems deployed at the Keck II Nasmyth port. By mounting the FOBOS spectrographs under the Nasmyth platform, other instruments like DEIMOS can maintain access to the telescope. *Right*: Rendering of one of the three four-armed FOBOS spectrographs.

2.1. **FOBOS Instrument Concept.** Mounted at the Nasmyth focus of Keck II Telescope at WMKO, FOBOS (Fig 1) will be one of the most powerful spectroscopic facilities deployed in the next decade. FOBOS includes a compensating lateral atmospheric dispersion corrector (CLADC, not pictured) to ensure that target light from all wavelengths falls on allocated fibers while also correcting image aberrations at the edges of the 20 arcmin diameter Keck field. Each of the CLADC lenses is 946 mm in diameter, the first two closely spaced with lateral relative motions enabled by three barrel-mounted actuators. The final CLADC lens surface serves as the vertical mounting plate for roaming Starbugs fiber positioners. It translates to track focal plane tilt. Starbugs patrol a large on-sky area ($\sim$1 arcmin), enabling flexible and dynamic targeting configurations with adjacent fibers as close as 10 arcsec.

A total of 1800 150-μm core diameter fibers are deployed at the curved focal plane. Fore-optics on the front end of each fiber demagnify and speed up the beam (from f/15 to f/5) for better coupling to the fiber numerical aperture and to minimize losses from focal ratio degradation. The focal plane plate rotates and translates to follow image positions as the telescope tracks across the sky. The fiber run is kept at less than 10m to maintain high throughput at UV wavelengths. Special care is given to stress-relief cabling to minimize variable focal ratio degradation over the fiber run.

Sets of 600 fibers feed each of three identical spectrographs (Fig 1). Each spectrograph uses a series of dichroics to divide the 259 mm diameter collimated beam into four wavelength channels with combined, instantaneous coverage from 0.31–1 μm. Fused-silica etched (FSE) gratings provide mid-channel spectral resolutions of $R \sim 3500$ at high diffraction efficiency in each channel. The dispersed light is focused by an f/1.1 catadioptric camera[9] and recorded by an on-axis 4k×4k CCD mounted at the center of the first camera lens element. Spectrographs are mounted in a temperature controlled housing installed under the Nasmyth Deck to allow space for other Keck instruments above. The end-to-end instrument throughput peaks at 60% and is greater than 30% at all wavelengths

FOBOS includes observatory level systems for precise instrument calibration using dome-interior screen illumination, a metrology system for accurate fiber positioning, and guide cameras for field acquisition and guiding. The instrument design envisions future upgrades including alternate collecting modes that deploy multiple fiber bundles, feeds to other fiber-based spectrographs at different wavelengths or spectral resolutions, and the ability to support and benefit from image corrections with Ground-Layer Adaptive Optics.

2.2. **FOBOS Instrument Design Effort.** FOBOS will complete its current conceptual design phase in fall 2019. Funding from this proposal will support the next phase of Preliminary Design. A schedule of milestones and additional information is provided in the Project Execution Plan (PEP). Major components of the Preliminary Design effort are described below.

Atmospheric Dispersion Compensator (ADC): The opto-mechanical design, tolerancing, lens cell design, motion systems, and software-control design of the ADC will be completed.

Focal Plane System: Mechanical design, including flexure analysis and the selection of drive mechanisms and potential vendors will be completed. This system also defines one of the interfaces to the Keck II Telescope and must comply with WMKO space envelopes, servicing needs, and other requirements. The focal plane system also includes the guide cameras.

Starbugs fiber positioners: Starbugs are a positioning technology developed and deployed by the Australian Astronomical Observatory (AAO), which has partnered with our team to generate a conceptual design for use of Starbugs by FOBOS. Design requirements for Starbugs in FOBOS are more relaxed than the currently on-sky TAIPAN instrument thanks to the larger physical plate scale at Keck.

Fiber System: We will complete the optical design and processing plan for affixing forward optics lenses to each fiber head. A micro-lens array solution will be developed for a central, fixed-position 4.5-arcsec diameter IFU for fast source acquisition. This work package also includes the stress-relief cable system and fiber termination hardware and processing.

Spectrographs. The optical systems and components (slit, collimator, dichroics, gratings, and camera), an analysis of acceptable tolerances and performance, their mechanical supports,

[9] Based on the camera design for the Multi-Object Optical and Near-infrared Spectrograph (MOONS) on the Very Large Telescope (VLT).

software controls, and the overall enclosure will all be advanced through Preliminary Design. Detectors, cryostats, read-out electronics and systems for thermal management will be designed.

2.3. **Addressing Data Science Challenges and Designing FOBOS Training Sets.** Our team includes leading experts on data science applications to astronomy and, specifically, LSST. We will also use our established connections to LSST's Informatics and Statistics Science Collaboration (ISSC) to advertise, recruit, and coordinate efforts to tackle the Data Science Challenges described in Section 1.3. Our proposal request includes two community workshops to motivate progress and discuss results. At the end of the proposal period, we will publish the results and developed software packages.

Our data-science challenges require work on simulated imaging+spectroscopic data sets where input physical properties (e.g., redshift) can be compared to output recovered values. Simulated imaging data (e.g., from LSST and WFIRST) are in-hand, while mock spectroscopy will be provided by a FOBOS instrument simulator, an initial version of which has already been developed. Further advances to be supported by this proposal include improved error modeling and simulating systematic effects from detector artifacts, image quality aberrations informed by the emerging detailed optical design, and variable observing conditions.

The resulting success in addressing each data-science challenge will define a level of readiness and set requirements on desired FOBOS training sets, including number of sources, pointings, magnitude limits, signal-to-noise thresholds, and observing conditions. Preliminary observing design and a description of required operational modes to efficiently observe these training sets will begin with this proposal. Operational modes will set requirements on target aggregation and prioritization systems, field acquisition speed, field rotation range, zenith avoidance zone, reconfiguration time, calibrations, read-out time, quick-look reduction software and processing rates. We will develop integrated program concepts that efficiently combine required observations. Detailed survey and execution plans will be completed in the next phase of this project (MSRI-2). Roughly 20% of Keck observing time is open to the public, and as in previous federally-funded projects, we fully expect that Senior Personnel at Keck institutions will be successful in collaborative efforts to secure significant amounts of additional telescope observing time to enable rapid, public release of FOBOS training data (e.g., Newman et al., 2013).

2.4. **MAISTRO: Target Allocation with Artificial Intelligence.** Powered by Starbugs fiber positioners, FOBOS will enable fast, dynamic reallocation of fibers. To efficiently determine the best options given a wide range of possible targets and desired observing outcomes, we will develop a preliminary design for MAISTRO[10] an "artificial intelligence" (AI) targeting system that will learn optimization strategies for assigning targets from a database of overlapping observing programs with pre-defined priorities. The AI package will aggregate data quality using a quick-look reduction package, science-driven performance metrics, *and real-time assessments of the observing conditions* to make dynamic targeting recommendations. For example, if conditions are slightly less than optimal, MAISTRO would reconfigure Starbugs to brighter objects in a field or implement a different program prioritization. MAISTRO will incorporate updated target lists and priorities from the active observer and could easily be over-ridden at any time. Fractions of the full FOBOS multiplex might also be reserved "manual targeting" as required by the program PI.

[10] MAISTRO: Modular Artificial Intelligence System for Target Reallocation and Observing.

2.5. **Publicly Available Automated Data Products.** While the FOBOS data simulator is required for our data-science challenges, it also forms the basis of a delivered data reduction pipeline (DRP) for this instrument. This software will provide both the quick reduction assessments needed for dynamic targeting, as well as full reductions for scientific analysis. In the proposal period, we will also develop a preliminary design for a data analysis pipeline (DAP). Unique among Keck instruments, the FOBOS DAP will take advantage of the fixed spectral format and common target classes to provide high-level data products, including Doppler shift, emission-line strengths, and template continuum fits (cf., Westfall et al.; SDSS-IV MaNGA DAP). The DAP will also produce results from relevant machine-learning applications (e.g., redshifts at low-S/N).

Raw data, reduced spectra, and high-level DAP science products will be publicly delivered via user-friendly platforms built on the Keck Observatory Archive. After associated proprietary periods, data will be served for *all* FOBOS observations, creating a rich legacy data set for the astronomical community. Both program PIs and the larger community will be encouraged to develop the DRP and DAP to meet the needs of specific science applications. These software packages will be open source and publicly served (e.g., using GitHub).

3. Broader Impacts

3.1. **Akamai: Training the next generation of Hawaiian STEM professionals.** Led by the Institute for Scientist and Engineer Educators (ISEE) at UCSC, the Akamai Internship Program is aimed at advancing college students from Hawai'i into the STEM workforce. Almost 400 students have participated to date, of which 24% are Native Hawaiian and 38% are women. A longitudinal study of Akamai outcomes indicated that 87% were still in STEM, either in the workforce or continuing STEM studies (Barnes et al., 2018). ISEE and the Akamai program already have deep connections to WMKO; 45 interns have worked on projects related to instrument development and observatory operations over the past 15 years. Our funding request includes support for two Akamai interns.[11] One intern will develop aspects of the FOBOS instrument simulator and use this simulator to develop performance metrics for the Preliminary Design. The second will build machine-learning tools for Data-Science Challenge **??**, specifically for obtaining spectroscopic redshifts at low S/N.

3.2. **Investing in future educators.** Also via the ISEE, we will support three graduate students to participate in the Professional Development Program (PDP) that build teaching skills through collaborative design of an inquiry activity. The PDP team conceives, develops, and tests the activity which culminates in a lab exercise run with undergraduates. The program emphasizes inclusive and equitable learning environments. Specifically, our team of graduate students will develop a lab unit related to FOBOS instrument development aimed at incoming community college transfer students enrolled in UCSC's highly-successful Lamat Program. In addition to enriching graduate student training, these efforts will positively impact 25 undergraduates from California community colleges, a large fraction from underrepresented minority groups.

3.3. **Student Training.** UCSC's **Astro 9** course introduces scientific research methods to 1st-year students by engaging small student teams on actual research projects supervised by graduate students, postdocs, and staff. The **Science Internship Program** (SIP) creates a similar environment for high-school students over a 10 week summer program. We will design projects for both programs focused on simulating data sets and introducing machine learning concepts

[11] At UCO, an Akamai intern during Summer 2018 helped build a fiber test-bench at UCSC.

used in our Data Science Challenges. Both PI Bundy and co-PI Westfall have served as research mentors in these programs.

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