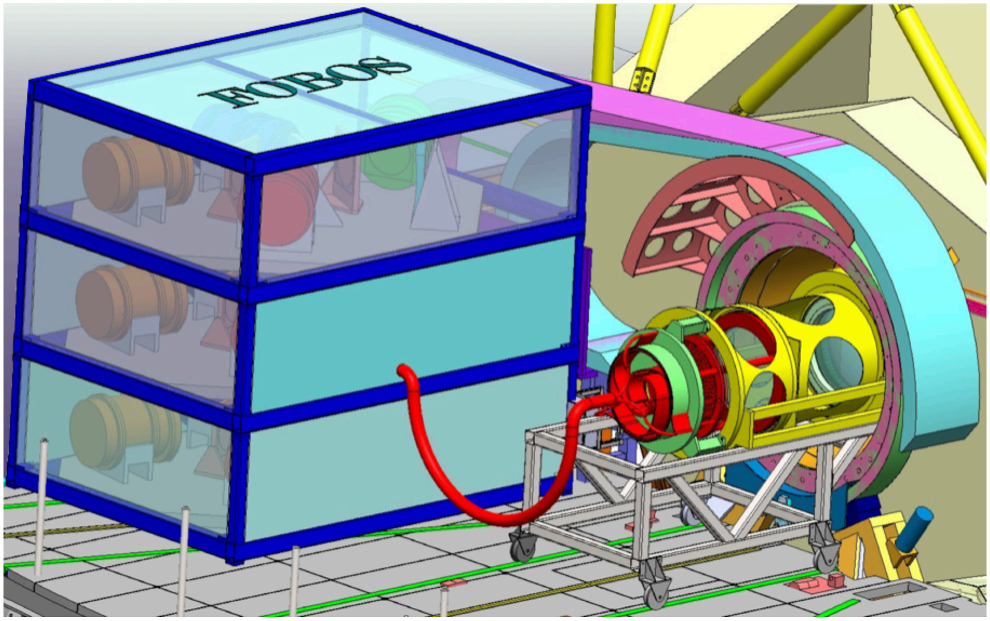

FOBOS: The Fiber-Optic Bench Optical Spectrograph

Keck's next-generation spectroscopic facility

Executive Summary

The 2016 Keck Observatory Scientific Strategic Plan lists highly-multiplexed spectroscopy as a key desirable that would position Keck to take advantage of the coming era of wide-field imaging facilities like LSST, Euclid, and WFIRST. FOBOS[1] addresses this priority via a fiber-based facility that optimizes depth over area, preserving Keck's historical strength in faint-object spectroscopy. The result is a uniquely blue-sensitive, high-multiplex instrument with order-of-magnitude greater sampling density than competitors like Subaru's Prime Focus Spectrograph (PFS). In the LSST era, FOBOS will excel at building the deep, spectroscopic reference data sets needed to interpret vast imaging data. At the same time, its flexible focal plane, including deployable integral-field units (IFUs), enables an expansive range of scientific investigations from the diverse Keck community.

FOBOS will provide $R \sim 3500$ spectroscopy over an instantaneous bandpass of 310-1000 nm for as many as 1800 individual targets across a 17-arcminute diameter field. The instrument is modular and composed of three major components. The focal-plane system includes an atmospheric dispersion corrector (ADC) whose final lens traces the Nasmyth focal surface. This enables flexible target allocation by free-roaming Starbug positioners that "walk" on this surface. When configured in single-fiber mode, each Starbug carries single fiber with a 150 μm diameter core fed by demagnifying fore-optics that yield a 0.9-arcsec diameter on-sky aperture. When configured in IFU mode, FOBOS deploys a different suite of Starbugs in the focal plane that fiber bundles with coupled lenslet arrays that provide finer spatial sampling. A short fiber run (<10 m) through a stress-relief cabling system minimizes throughput losses between the focal plane and an array of three temperature-controlled bench spectrographs mounted on the Nasmyth platform adjacent to the focal-plane system.

Its UV sensitivity, high multiplex and sampling density, and aperture flexibility make FOBOS compelling in science areas that are traditional strengths of the Keck Community. These include Local Group archeology studies via resolved stellar spectra at moderate spectral resolution in dwarf galaxies, M31, and the Milky Way halo. At greater distances, FOBOS will probe ultra-diffuse galaxies and the globular-cluster populations of individual galaxies and galaxy clusters like

[1]FOBOS: Fiber-Optic Broadband Optical Spectrograph

Coma. The depth and high sampling density FOBOS provides will open new probes of galaxy clusters and galaxy environment at $z \sim 1$, while its IFU mode will enable kinematic studies of winds, the resolved gas-phase properties and dynamics of star-forming galaxies, and the internal structure of stellar populations for large samples of distant galaxies. FOBOS's capacity for detailed tomographic Ly-α and UV-absorption-line measurements of galaxies and the intergalactic medium at $z \sim 2$–4 will be unparalleled. Cosmological analyses using panoramic deep imaging (e.g., LSST) will greatly benefit from photo-z training by FOBOS, which is ideally suited to required photo-z programs. With a dedicated, fixed IFU always ready, FOBOS can rapidly follow up transient sources while continuing to collect valuable photons on background targets. Its flexible focal plane allows efficient observing strategies that combine multiple programs and can dynamically respond to changing conditions.

1. Science Drivers

[[**this needs some reorganization**]]

1.1. **Unraveling the Formation History of our Local Group of Galaxies.**

Our Local Group of galaxies — the Milky Way (MW), the Magellanic Clouds, Andromeda (M31), Triangulum (M33), and numerous satellite galaxies — allows us to study one realization of the galaxy-formation process in superb detail. In the next decade, LSST and WFIRST will increase the census of stellar streams and halo substructure in these galaxies by a hundredfold. Follow-up *stellar* spectroscopy will constrain stream orbits and the total mass they enclose (Sanderson et al., 2017), as well as the associated age and chemical composition (see below).

[[**Weisz: Dwarf galaxies?**]]

[[**Guhathakurta: M31?**]]

[[**Rockosi: Milkway Halo & DESI connection?**]]

1.2. **A Comprehensive Picture of the Proto-galaxy Ecosystem.**

[[**KG, Joe, X?**]] IGM tomography: Understand the $z \sim 2$ galaxy "ecosystem," including not only the galaxies themselves but their gas-filled environments. The goal is to build a comprehensive picture of the physical processes that fuel proto-galaxy growth, shape their internal structure, and influence their environment.

[[**Cooper?**]] Build SDSS-like statistics for galaxies at this key cosmic epoch. Exploit short spectroscopic exposures in combination with photometry to provide environmental diagnostics for 1M galaxies at z=1–2. Photometric redshifts, while acceptable in large cosmological analyses, wash out information about the local position of galaxies with respect to one another. To characterize a galaxy's local environment and identify its neighbors requires (observationally expensive) spectroscopic redshifts. However, with improved photo-zs available from Challenge **??** and strong priors on spectral types (Challenge **??**), the challenge here is to push machine-learning techniques to deliver *spectroscopic* redshifts (with 300 km s^{-1} accuracy) at the lowest signal-to-noise possible. Reductions by factors of 4–5 in exposure time would enable FOBOS to complete a 1M galaxy environment survey at $z = 1$–2 in just 20-30 nights.

[[**Siana – Clusters?**]]

[[**Westfall, Bundy, Max – Resolved spectroscopy**]]

1.3. **Enhancing Dark Energy Probes via Precision Cosmic Distances.** Enormous worldwide efforts — culminating in LSST, Euclid, and WFIRST — are seeking highly precise measures of cosmic structure to constrain the evolving dark-energy equation-of-state. These measures utilize angular correlations of galaxy positions, their gravitational lensing shear, and the cross-correlation between the two. Unfortunately, photometric distances (via photometric redshifts, or "photo-zs") are significantly less precise than spectroscopic redshifts (spec-zs), introducing significant biases. FOBOS offers spectroscopic validation of photo-zs that is therefore critical to the success of *all* imaging surveys in this respect. It would not only *increase the dark energy figure-of-merit in LSST by 40%* (Newman et al., 2015) but, importantly, provide vital confidence in cosmological results. FOBOS is particularly powerful in this application because it has no "redshift desert" thanks to its unique ability to measure spectroscopic redshifts above $z > 1.5$ via rest-frame UV features. This eliminates the need for expensive, space-based[2] near-IR spectroscopy.

[[**LBG cosmology: Wilson, White?**]]

[[**Kinematic Weak Lensing: Bundy, Huff, Schlegel, DiGiorgio?**]]

1.4. **FOBOS as an ideal spectroscopic training instrument.** [[**this should point to science drivers in the previous three sections or be integrated there**]]

Radial velocity studies of stars in the MW halo or the M31 disk require observations of up to 10 hours on large telescopes (e.g., Cunningham et al., 2018). This again motivates machine-learning algorithms to extract physical quantities from both multi-band imaging and lower quality spectra (low resolution and S/N) using relatively small, yet high-S/N, training sets. For example, Ness et al. (2015) have developed *The Cannon*, a supervised learning approach that uses spectra with known stellar parameters to label spectra where those parameters are unknown (Fig. 1). Additionally, Ting et al. (2018) have developed *The Payne* which can infer 16 stellar-abundance labels from low-resolution spectra using a neural network and theoretical stellar spectra. Finally, Ting & Rix (2018) have combined Kepler-based astroseismology measurements with APOGEE spectra to determine stellar age to $\sim$25% precision using a neural network. Our proposed effort builds on new lines of inquiry based on these successes.

A nested network of stellar parameter training samples for resolved Milky Way and Local Group studies via extracting maximum information from photometry, in this case stellar parameters. Our goal is to reach magnitudes significantly fainter than the detection limit of current and upcoming spectroscopic surveys of the Milky Way including Gaia, APOGEE,[3] the SDSS-V Milky Way Mapper, planned programs with 4MOST[4] and the Dark Energy Spectroscopic Instrument (DESI) Milky Way Survey, among others. Inferring stellar parameters beyond V$\sim$18 will open up studies of the Milk Way's outer halo, the halo of M31, and stellar populations in local dwarf galaxies.

The immediate challenge is to design an optimized, nested set of training samples that connect data from the surveys above. This nested set will span high-S/N to low-S/N and high spectral resolution to low spectral resolution for sufficiently large, overlapping stellar samples. Subsets will have astroseismology from TESS[5] and PLATO.[6] Using simulated spectra with known input

[2] 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).

[3] APOGEE, the Apache Point Observatory Galaxy Evolution Experiment has observed in both SDSS-III and SDSS-IV.

[4] 4MOST: 4-meter Multi-object Spectroscopic Telescope.

[5] TESS is NASA's Transiting Exoplanet Survey Satellite.

[6] PLATO is ESA's PLAnetary Transits and Oscillations mission.

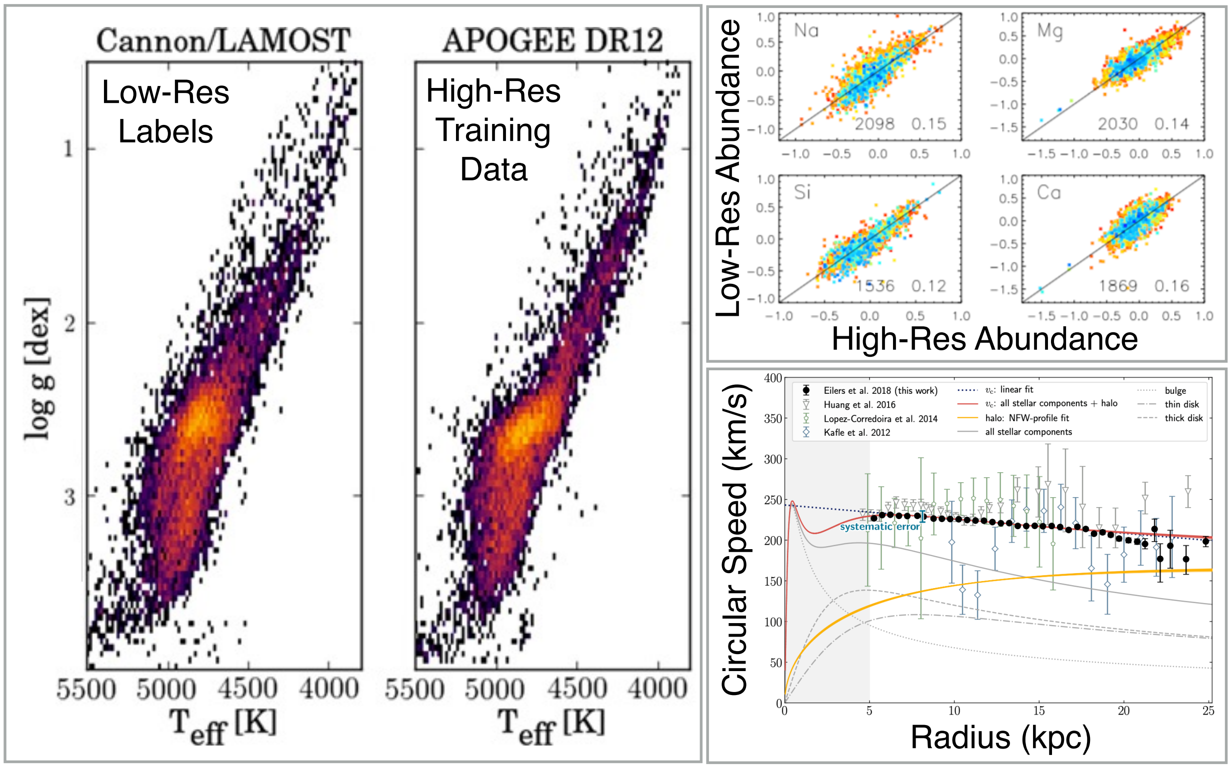

FIGURE 1. *Left*: Validation of *The Cannon* measurements of stellar effective temperature, $T_{\rm eff}$, and surface gravity, $\log g$, using low-resolution LAMOST spectra (left) compared to high-resolution APOGEE measurements (right; Ho et al., 2017). *Top-right*: Recovery of elemental abundances from low-resolution LAMOST spectra compared to high-resolution measurements from GALAH (Xiang et al., in prep). *Bottom-right*: The circular-speed curve of the Milky Way determined using a data-driven model that combines stellar parameters determined from APOGEE spectra with photometry from WISE, 2MASS, and Gaia, yielding the most precise measurements to date (Eilers et al., 2019).

parameters, we will test methods for "label transfer" from information-rich spectra to information-poor spectra as we work down to fainter magnitudes, landing eventually at multi-band photometry alone. Within this nested set, low-resolution FOBOS data will fill in gaps at both high-S/N, where we will be training FOBOS data on higher resolution spectroscopy, as well as lower-S/N where we will be training photometry on FOBOS spectroscopy. The success of this multi-layered label transfer depends not only on the size of the training sets we can access or observe, but on how representative they are. Label transfer to WFIRST imaging of the M31 halo, or Local Group dwarfs in either hemisphere, is a particular concern. We will test it by evaluating label recovery on simulated stellar spectra with cosmologically-informed formation histories for M31 and dwarf galaxies, suitably differentiated from the Milky Way stars that anchor the training network.

Apply deep- learning algorithms to infer physical properties of galaxies at $z{\sim}2$ using using photometry. The range of observed spectral types is well-constrained by broad-band imaging (Figure 2), suggesting a far greater potential for imaging data to reveal physical properties with sufficient training than conventional modeling of spectral energy distributions (SEDs) would suggest. The challenge here is to identify the extent to which machine learning can deliver SDSS-like information — e.g., star-formation histories, stellar-population properties, dust content, inflow/outflow properties, and stellar masses — and determine design parameters for future training sets that will enable such inferences for millions of imaged galaxies at $z{\sim}2$.

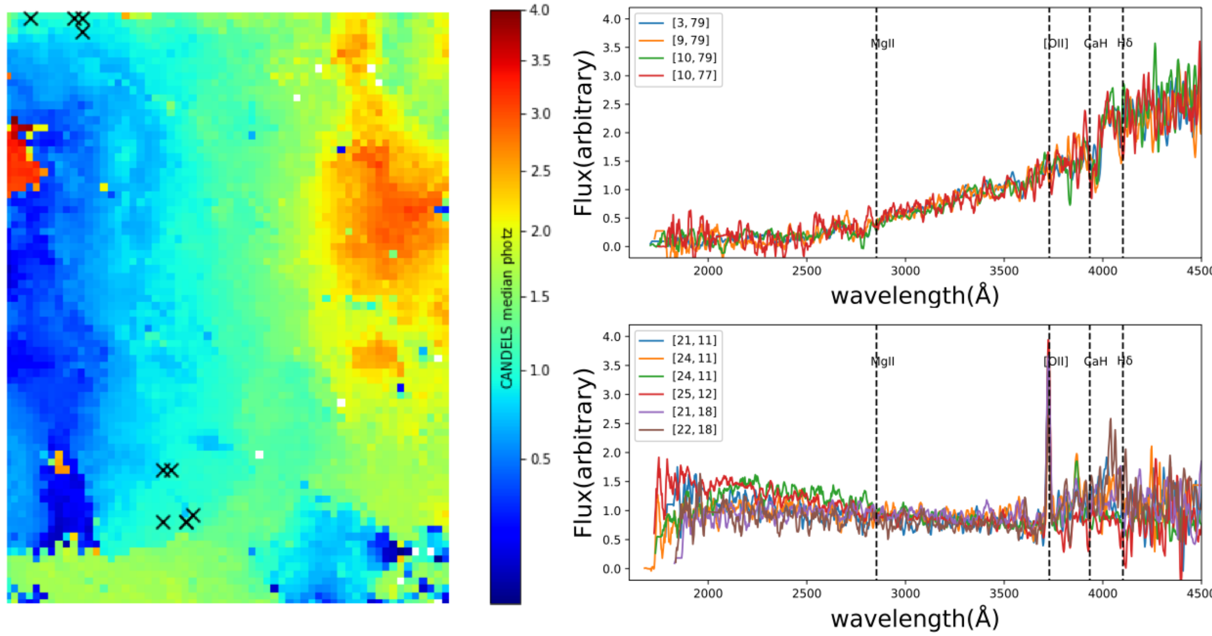

FIGURE 2. *Left*: A Self-Organizing Map (SOM; Kohonen, 1990) from Hemmati et al. (2018) encoding the relation between colors in an LSST+WFIRST-like color space and redshift, z. Position in the SOM is associated with a position in the multi-dimensional broad-band color space of galaxies. Galaxies observed in this space are assigned z values based on the median photo-z of galaxies from the CANDELS survey (color bar; Grogin et al., 2011). Such SOMs can be used to optimally define spectroscopic training samples for use with imaging surveys. *Right*: Galaxy spectra from VVDS (Le Fèvre et al., 2005); black crosses near the top and bottom of the SOM are plotted in the top and bottom panels, respectively. Note the similarity of the high-resolution spectra associated within the SOM, suggesting that a systematic spectroscopic exploration of the LSST color space would have far-reaching benefits to the science return of the mission beyond the photo-z application.

Self-Organizing Maps (SOM, Fig. 2) provide a state-of-the-art representation of a high-dimensional input space in projected 2D grid cells, allowing us to benchmark sampling of the photometric color space under various training set designs. We will use Bayesian Optimization techniques to evaluate the success of simulated training sets against the fidelity of full cosmological analyses that employ them. This will enable extremely rapid exploration of the optimal design space.

2. Instrument Overview

Mounted at the Nasmyth focus of Keck II Telescope at WMKO, FOBOS (Figure **??**) 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 are closely spaced with lateral relative motions enabled by three barrel-mounted actuators. The final CLADC lens surface translates to track focal plane tilt, and it serves as the vertical mounting plate for roaming Starbugs fiber positioners [[**ref**]]. Starbugs patrol a large on-sky area (∼1 arcmin), enabling flexible and dynamic targeting configurations with adjacent fibers as close as 10 arcsec.

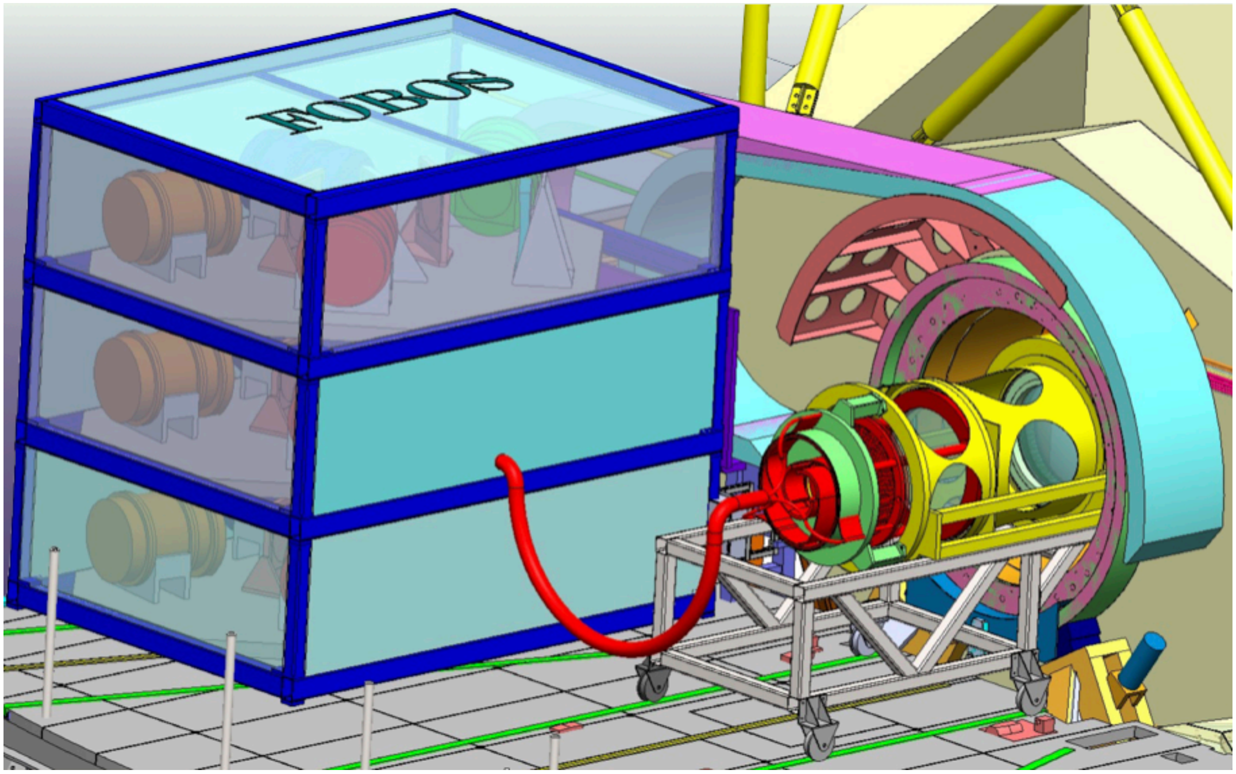

FIGURE 3. [[**Changed figure to get it to compile.**]] *Left*: Rendering of FOBOS focal plane system deployed at the Keck II Nasmyth port. By mounting the FOBOS spectrographs under the Nasmyth platform, other instruments like DEIMOS can maintain access to the telescope. *Right*: Rendering of the ADC and focal surface with Starbugs mounted (red cylinders). *Bottom-left*: Starbugs deployed on the TAIPAN instrument.

A total of 1800 fibers with 150-μm core diameter are deployed at the curved focal plane. Microlens fore-optics convert the f/15 Keck input beam to a faster f/3 focal ratio, which both demagnifies the entrance aperture and allows for better coupling to the fiber numerical aperture by minimizing 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 (a 10m Polymicro Silica fiber transmits $\sim$70% and $\sim$85% of light at 310nm and 350nm, respectively). Special care is given to stress-relief cabling to minimize instabilities (e.g., variable focal ratio degradation) over the fiber run.

Sets of 600 fibers feed each of three identical spectrographs (Fig **??**). Each spectrograph uses a series of dichroics to divide the 259mm-diameter collimated beam into four wavelength channels, providing an instantaneous broad-band 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[7] and recorded by an on-axis 4k$\times$4k CCD mounted at the center of the first camera lens element. Spectrographs are mounted in a permanent temperature-controlled housing on the Nasmyth deck, whereas the focal-plane system can be unmounted and stowed alongside existing Keck instruments. The end-to-end instrument throughput peaks at 60% and is greater than 30% at *all* wavelengths.

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

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. [[**make the following consistent with what we say in the summary**]]. Initial deployment of the focal-plane will focus on a single-fiber format, with a secondary deployment of multi-format fiber bundles to follow. Additional instrument upgrades include integration of fibers that feed additional spectographs — these spectrographs could provide increased multiplex capacity, higher spectral resolution, and/or observe different spectral regions — and additional front-end sensing equipment that fully support and benefit from image corrections with Ground-Layer Adaptive Optics.

3. Recent and Ongoing Progress

FOBOS development over the past year has focused on (1) engaging the scientific and instrumentalist communities in discussions about the FOBOS design, particularly with regard to science cases and instrument feasibility, (2) initial development of an instrument simulator and exposure-time calculator, (3) advancing the optomechanical designs of the focal-plane and ADC systems, (4) consolidating development of Fiber-WFOS for TMT and repurposing much of the design for FOBOS at Keck, (5) working with Keck instrument scientists and engineers toward a practical integration plan, and (6) developing a detailed project execution plan, schedule, and budget. Many of these activities were enabled by funds provided in response to our previous white-paper submission.

Visits to Keck-user institutes have been particularly helpful in building interest around the instrument and refining its specifications. As of this writing, Bundy, MacDonald, and/or Westfall have visited UCR (also joined by Michael Cooper from UCI), UCLA, Keck observatory, LBNL, and UCSB. We plan to continue these visits, hoping to visit UCB, UCD, and CIT before the end of the year.

Three specific ways the instrument conceptual design has been affected by these conversations are the emphasis on the flexibility of the focal-plane sampling, the "first-light" multiplex capacity, and sensitivity toward the UV. Although the capabilities of PFS are a common comparison for FOBOS, many of the science goals now enumerated in Section 1 require target densities and/or wavelength coverage that PFS will not provide; in the overlapping wavelength range between the two instruments, FOBOS's survey speed is [[**x**]] times larger than PFS's. Given both this and the SSC's own assessment of the need for multiplex at Keck, our current design includes 1800 single-fiber apertures over the current (17') FOV, yeilding a target density of $\sim$8 arcmin^{-2} (approximately the target density of DEEP2), but able to meet a maximum target density of $\sim$30 arcmin^{-2} in patches of the focal-plane given the flexibility of the Starbugs positioning system. Although this mode is our first-light capability, a strong message from Keck users was that a large-format monolithic IFU and many deployable IFUs were both highly desirable. These provided a secondary motivation for FOBOS's large pseudo-slit capacity in that it provides for front-end upgrade paths that yield a monolithic IFU with a FOV comparable to VLT/MUSE and 15-100 smaller deployable IFUs. Finally, Keck remains unique in its throughput toward the atmospheric limit. No other current or planned [[**check this again**]] spectrograph for 10m-class telescopes provides sensitivity below $\sim$380nm, providing FOBOS with a unique capability among the landscape of forthcoming instrumentation.

An identified risk of the front-end design of FOBOS is in the coupling of the microlens fore-optics to the fiber and the coupling of the microlens entrance aperture with the Keck II focal plane. It is critical that both of these couplings minimize losses. Using funds provided by a UCO mini-grant, we will address and begin to mitigate these risks via prototype fiber builds that are tested in the fiber labs at UCO and LBL [[**confirm that**]] and perform on-sky tests that verify the lab results. Lab tests have already begin with imaging the near- and far-field input and/or output beams of bare fibers. We have optomechanical designs of the microlens-fiber coupling, and have ordered hardware to be begin fabrication. We plan to propose for experiments to be performed during engineering time at Keck by the end of the year [[**check this**]].

Finally, with the permission of the SSC, we proposed for instrument-design funds from the NSF via its new Mid-scale Research Infrastructure scheme. Although the proposal was ultimately unsuccessful, preparation of the proposal led to a ground swell of development in our project planning and science development, much of which is included in this submission.

4. Proposed Work

4.1. **Instrument Design Work.** FOBOS will complete its current conceptual design phase in fall 2019 [[**check this**]]. 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 optomechanical 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 inputs 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 inputs 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, 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.

4.2. **MAISTRO: Target Allocation with Artificial Intelligence.** [[**keep this?**]] 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,[8] 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

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

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.

4.3. **Automated Data Products.** [[**edit this**]] 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).

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