Snowmass2021 - Letter of Interest

Enhancing probes of the dark sector with Keck-FOBOS optical spectroscopy

Thematic Areas: (check all that apply ☐/■)

☐ (CF1) Dark Matter: Particle Like
☐ (CF2) Dark Matter: Wavelike
■ (CF3) Dark Matter: Cosmic Probes
■ (CF4) Dark Energy and Cosmic Acceleration: The Modern Universe
☐ (CF5) Dark Energy and Cosmic Acceleration: Cosmic Dawn and Before
■ (CF6) Dark Energy and Cosmic Acceleration: Complementarity of Probes and New Facilities
☐ (CF7) Cosmic Probes of Fundamental Physics
☐ (Other) *[Please specify frontier/topical group]*

Contact Information:

Daniel C. Masters (CalTech) [dmasters@ipac.caltech.edu]
The Keck-FOBOS Science Team: `https://fobos.ucolick.org/`

Authors:

Daniel C. Masters (CalTech)
Kevin A. Bundy (UCSC; FOBOS Primary Investigator)
John O'Meara (WMKO Chief Scientist)
Kyle B. Westfall (UC Observatories; FOBOS Project Scientist)

Abstract:

Over the next decade, dedicated imaging campaigns will survey unprecedented volumes of the Universe, enabling the use of multiple observational probes to study the effects of dark energy on its expansion history and the development of large-scale structure. Accurate galaxy redshifts are key to these studies. Stage-IV cosmology experiments rely on photometric redshifts (photo-zs), typically estimated from $\sim$5-10 broad-band filters, because direct spectroscopic redshift measurements for *all* galaxies imaged by these surveys is not feasible. Instead, specifically tailored spectroscopic samples optimized to improve photo-z training can yield significant gains in the precision and accuracy of cosmological parameters derived from these experiments. Unfortunately, *no current U.S. facility is capable of obtaining the observations to the depths required to capitalize on the* $\approx$*\$4B U.S. investment in these projects*. Here, we briefly introduce the Fiber-Optic Broadband Optical Spectrograph (FOBOS) — a facility-class instrument currently in development for the 10m Keck II telescope — and a key program proposal that meets the well-established spectroscopic need for photo-z training. FOBOS observations would ultimately *increase LSST's dark energy figure-of-merit by* $\sim$*40%*. FOBOS is nearing the end of its conceptual design phase and aims to achieve first light in 2028.

Dark energy science benefits from improved photometric redshifts

Stage-IV cosmology missions — like the Vera C. Rubin Observatory Legacy Survey of Space and Time (LSST), the ESA/NASA *Euclid* mission, and the NASA-led Nancy Grace Roman Space Telescope (Roman) — will obtain multi-band imaging data with unprecedented depth and survey area. Current survey baselines are that LSST will provide *ugrizy* optical imaging of $\sim$18,000 deg^2 with a detection limit 1,000 fainter than the Sloan Digital Sky Survey (SDSS), complemented by deep near-IR imaging by Roman for an overlapping $\sim$2000 deg^2. Measurements drawn from these data of galaxy positions and gravitational shear as a function of distance over vast cosmic volumes will be used to delineate cosmic expansion and the growth of large-scale structure. Critically, the distances used for these measurements must be estimated by photometric redshifts (photo-zs), given the infeasibility of obtaining spectroscopic redshifts (spec-zs) for the expected magnitude distribution of the billions of sources imaged by these surveys (see Figure 1). This reliance on photo-zs has led to significant effort devoted to understanding their influence on the derived cosmological parameters[3,6,13,18]. The consensus of these studies is that improving galaxy photo-z estimates represents one of the most significant gains to be made in the precision of the cosmological parameters.

Observations required to improve photo-zs are well-understood but currently impractical

Limiting uncertainties in photo-z estimates involves improving photo-z **training** and **calibration**[13]. Training focuses on improving photo-zs by, e.g., ensuring that the underlying spectroscopic redshifts used to establish the relationship between galaxy color and redshift sample the relevant parameter space[4,10]. Photo-z calibration involves quantification of the accuracy and precision with which photo-zs map to spec-zs for *all* galaxies used to measure dark-energy parameters of interest. Both pursuits are critical to improving the constraining power of and minimizing the biases in the resulting cosmological parameters[18].

A series of well-formulated observing programs have been developed that address photo-z training and calibration, as summarized in a series of Astro2020 white papers[5,8,12]. However, each of these programs involve significant investment and may require deployment of new instrumentation. In particular, Newman et al.[12],[13] outline an observing program that improves photo-z training via spectroscopy of thousands of galaxies at very faint magnitudes ($i_{\rm AB} \lesssim 25.3$). The combination of sample size and magnitude distribution make this program extremely difficult, if not impossible, with current instrumentation. Although significant efforts *are* underway to fill in underpopulated regions in the color-redshift mapping with targeted Keck spectroscopy to the anticipated Euclid depth[11], a larger-scale effort is needed to reach the fainter galaxies that will dominate the Rubin/Roman samples.

Keck-FOBOS is an ideal instrument for photo-z training

More generally, the need for spectroscopic follow-up of the upcoming vast imaging campaigns is obvious. Indeed, the established and anticipated successes of the Sloan Digital Sky Survey[17] (SDSS) and the Dark Energy Spectroscopic Instrument[7] (DESI) demonstrate the scientific value of coupling panoramic imaging with intensive spectroscopic follow-up. However, an SDSS-like spectroscopic program at LSST imaging depths would require 300 years of observing on the largest telescopes with current instrumentation! Thus, it has long been recognized that a new spectroscopic facility is needed to meet the challenge presented by this new era[15]. Our instrument concept — The **Fiber-Optic Broadband Optical Spectrograph (FOBOS)**, Table 1 — is unique among similar efforts aimed at meeting this need[1,9,16].

Table 1: Top-level FOBOS Specifications

Telescope	10-m Keck II
Patrol Field	$D = 20'$
Total Number of Fibers	1800
Single-Fiber Aperture	$D = 0.8''$
Spectral Range	0.31–1μm
Spectral Resolution	3500
End-to-End Throughput	$\gtrsim$30%
Limiting Magnitude†	r(AB)$\sim$24.5

†To reach S/N$\sim$1 in a 1hr integration.

FOBOS is a facility-class, high-multiplex, fiber-based optical spectrograph for the Keck II telescope at the W. M. Keck Observatory (WMKO), taking advantage of an *existing* telescope infrastructure with a 10m aperture. FOBOS's 1800 fibers are positioned using the Starbugs technology[2] over its 20′ field-of-view, enabling it to observe objects with target densities an order-of-magnitude larger than instruments that emphasize wider fields. Taking advantage of Keck's site and mirror coatings, FOBOS is uniquely sensitive toward the atmospheric limit in the UV and has no "redshift desert" — its blue wavelength coverage allows redshift determination at $1.5 \lesssim z \lesssim 2.5$ via Lyα and/or nearby UV absorption features, such that it reduces the need for expensive, space-based near-IR spectroscopy of galaxies with $z > 1.5$. With Keck's larger aperture and FOBOS's highly efficient design, FOBOS can build spectroscopic samples roughly 1.7 and >3 times faster than Subaru's Prime Focus Spectrograph (PFS) and DESI, respectively. FOBOS builds from and expands on WMKO's traditional strengths by emphasizing deep, sensitive observations, with a calibration system, short fiber run, and stable spectral format that enables ultra-deep integrations of $\gtrsim$50 hours.

FOBOS will be well-suited to provide follow-up spectroscopy of Rubin, *Euclid* and Roman dark energy science imaging data: FOBOS can obtain photo-z training data for sources with spectral features too blue or fluxes too faint for other instruments like PFS, but that dominate by number (Fig. 1). FOBOS can efficiently build photo-z spectroscopic samples by using Starbugs to dynamically reallocate fibers as observations yield successful redshift measurements. FOBOS can efficiently observe sources at declinations $\geq -30°$ ($\sim$60% of the current baseline LSST footprint) and will obtain first-light just before the Rubin Observatory begins to reach the LSST target 5σ point-source depth of $i = 26.8$ (AB) in 2029.

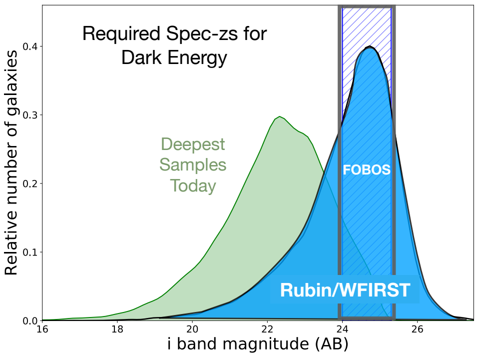

Figure 1: Magnitude distribution of spec-z samples in existing deep fields from, e.g., DEEP2, VVDS, VIPERS, C3R2, and zCOSMOS (*green*), compared with the anticipated distribution of the LSST/Roman weak-lensing sample derived in Hemmati et al.[4], *blue*. Ultra-deep (50hr) exposures with FOBOS are designed to obtain spec-zs for $\sim$15k faint galaxies in the hatched region, representing roughly 50% of the weak-lensing sample of these missions and weakly constrained by current spec-z samples.

The suitability of FOBOS for these studies is purposeful, as driven by instrument requirements drawn from our dark-energy "design-reference" program that follows closely programs discussed by Newman et al.[12],[13]. Our dark-energy program calls for observations in 12 FOBOS pointings — arranged evenly in right ascension and chosen to overlap with the LSST, *Euclid*, and Roman footprints — to meet its sample size, field variance, and depth requirements. The observations would build an optimal photo-z *training* sample via ultra-deep, 50-hour integrations of $\sim$15,000 sources at $24 < i_{AB} < 25.3$. Targets will efficiently sample[10,11] the color-magnitude space of the majority of LSST/Roman weak-lensing galaxies, and can be tailored to specific needs discovered (and in light of advancements made) in the first few years of LSST-based cosmology studies. Accounting for FOBOS's expected sensitivity and stability, our exposure-time calculator estimates a continuum S/N$\sim$3.5 (i-band) for the faintest sources at these depths, a level known to be sufficient for $>$ 75% redshift success[11,14]. This program can be achieved with 12.5 dark nights per year.

Additional FOBOS science drivers: As a facility-class instrument, FOBOS has broad science drivers, beyond those described above. In fact, spectra collected for photo-z training also have enormous potential for galaxy-evolution studies, enabling one to fully leverage photometry for billions of faint galaxies. To probe dark matter, FOBOS can quickly obtain spectra for large samples of stars in the dense regions of dark-matter-dominated dwarf galaxies around M31 and the Milky Way. This will enable the highest resolution studies of their chemodynamical structure, including the form of their dark-matter density profiles. FOBOS will also characterize the chemodynamical structure of the disks of M31 and M33. Two additional "design-reference“ programs involve (1) IFU observations of the circumgalactic medium in emission at $z \sim 2$ and (2) spectroscopic follow-up of kilonovae candidates, transients identified by LSST, and transient host galaxies.

References

[1] Ellis, R; Dawson, K. "SpecTel: A 10-12 meter class Spectroscopic Survey Telescope," In *Bulletin of the American Astronomical Society*, v. 51, 2019, p. 45. `https://ui.adsabs.harvard.edu/abs/2019BAAS...51g..45E`

[2] Goodwin, M; Heijmans, J; Saunders, I; Brzeski, J; Saunders, W; Muller, R; Haynes, R; Gilbert, J. "Starbugs: focal plane fiber positioning technology," In *Modern Technologies in Space- and Ground-based Telescopes and Instrumentation*, v. 7739 of *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*, 2010, p. 77391E. `https://ui.adsabs.harvard.edu/abs/2010SPIE.7739E..1EG`

[3] Hearin, AP; Zentner, AR; Ma, Z; Huterer, D. "A General Study of the Influence of Catastrophic Photometric Redshift Errors on Cosmology with Cosmic Shear Tomography," , v. 720(2), 2010, p. 1351–1369. `https://ui.adsabs.harvard.edu/abs/2010ApJ...720.1351H`

[4] Hemmati, S; Capak, P; Masters, D; Davidzon, I; Dore, O; Mobasher, B; Rhodes, J; Scolnic, D; Stern, D. "Photometric redshift calibration requirements for WFIRST Weak Lensing Cosmology: Predictions from CANDELS," *arXiv e-prints*, 2018

[5] Hložek, R; Collett, T; Galbany, L; Goldstein, DA; Jha, SW; Kim, AG; Newman, JA; Perlmutter, S; Perrefort, DJ; Sullivan, M; Verma, A; LSST Dark Energy Science Collaboration. "Single-object Imaging and Spectroscopy to Enhance Dark Energy Science from LSST," , v. 51(3), 2019, p. 369. `https://ui.adsabs.harvard.edu/abs/2019BAAS...51c.369H`

[6] Huterer, D; Takada, M; Bernstein, G; Jain, B. "Systematic errors in future weak-lensing surveys: requirements and prospects for self-calibration," , v. 366(1), 2006, p. 101–114. `https://ui.adsabs.harvard.edu/abs/2006MNRAS.366..101H`

[7] Levi, M; Allen, LE; Raichoor, A; Baltay, C; BenZvi, S; Beutler, F; Bolton, A; Castander, FJ; Chuang, CH; Cooper, A; Cuby, JG; Dey, A; Eisenstein, D; Fan, X; Flaugher, B; Frenk, C; Gonzalez-Morales, AX; Graur, O; Guy, J; Habib, S; Honscheid, K; Juneau, S; Kneib, JP; Lahav, O; Lang, D; Leauthaud, A; Lusso, B; de la Macorra, A; Manera, M; Martini, P; Mao, S; Newman, JA; Palanque-Delabrouille, N; Percival, WJ; Prieto, CA; Rockosi, CM; Ruhlmann-Kleider, V; Schlegel, D; Seo, HJ; Song, YS; Tarle, G; Wechsler, R; Weinberg, D; Yeche, C; Zu, Y. "The Dark Energy Spectroscopic Instrument (DESI)," In *Bulletin of the American Astronomical Society*, v. 51, 2019, p. 57. `https://ui.adsabs.harvard.edu/abs/2019BAAS...51g..57L`

[8] Mandelbaum, R; Blazek, J; Chisari, NE; Collett, T; Galbany, L; Gawiser, E; Hložek, RA; Kim, AG; Leonard, CD; Lochner, M; Mandelbaum, R; Newman, JA; Perrefort, DJ; Schmidt, SJ; Singh, S; Sullivan, M; LSST Dark Energy Science Collaboration. "Wide-field Multi-object Spectroscopy to Enhance Dark Energy Science from LSST," , v. 51(3), 2019, p. 363. `https://ui.adsabs.harvard.edu/abs/2019BAAS...51c.363M`

[9] Marshall, J; Bolton, A; Bullock, J; Burgasser, A; Chambers, K; DePoy, D; Dey, A; Flagey, N; Hill, A; Hillenbrand , L; Huber, D; Li, T; Juneau, S; Kaplinghat, M; Mateo, M; McConnachie, A; Newman, J; Petric, A; Schlegel, D; Sheinis, A; Shen, Y; Simons, D; Strauss, M; Szeto, K; Tran, KV; Yèche, C. "The Maunakea Spectroscopic Explorer," In *Bulletin of the American Astronomical Society*, v. 51, 2019, p. 126. `https://ui.adsabs.harvard.edu/abs/2019BAAS...51g.126M`

[10] Masters, D; Capak, P; Stern, D; Ilbert, O; Salvato, M; Schmidt, S; Longo, G; Rhodes, J; Paltani, S; Mobasher, B; Hoekstra, H; Hildebrandt, H; Coupon, J; Steinhardt, C; Speagle, J; Faisst, A; Kalinich, A; Brodwin, M; Brescia, M; Cavuoti, S. "Mapping the Galaxy Color-Redshift Relation: Optimal Photometric Redshift Calibration Strategies for Cosmology Surveys," , v. 813, 2015, p. 53

[11] Masters, DC; Stern, DK; Cohen, JG; Capak, PL; Stanford, SA; Hernitschek, N; Galametz, A; Davidzon, I; Rhodes, JD; Sand ers, D; Mobasher, B; Castander, F; Pruett, K; Fotopoulou, S. "The Complete Calibration of the Color-Redshift Relation (C3R2) Survey: Analysis and Data Release 2," *arXiv e-prints*, 2019, p. arXiv:1904.06394. `https://ui.adsabs.harvard.edu/abs/2019arXiv190406394M`

[12] Newman, J; Blazek, J; Chisari, NE; Clowe, D; Dell'Antonio, I; Gawiser, E; Hložek, RA; Kim, AG; von der Linden, A; Lochner, M. "Deep Multi-object Spectroscopy to Enhance Dark Energy Science from LSST," In , v. 51, 2019, p. 358. `https://ui.adsabs.harvard.edu/abs/2019BAAS...51c.358N`

[13] Newman, JA; Abate, A; Abdalla, FB; Allam, S; Allen, SW; Ansari, R; Bailey, S; Barkhouse, WA; Beers, TC; Blanton, MR; Brodwin, M; Brownstein, JR; Brunner, RJ; Carrasco Kind, M; Cervantes-Cota, JL; Cheu, E; Chisari, NE; Colless, M; Comparat, J; Coupon, J; Cunha, CE; de la Macorra, A; Dell'Antonio, IP; Frye, BL; Gawiser, EJ; Gehrels, N; Grady, K; Hagen, A; Hall, PB; Hearin, AP; Hildebrandt, H; Hirata, CM; Ho, S; Honscheid, K; Huterer, D; Ivezić, Ž; Kneib, JP; Kruk, JW; Lahav, O; Mandelbaum, R; Marshall, JL; Matthews, DJ; Ménard, B; Miquel, R; Moniez, M; Moos, HW; Moustakas, J; Myers, AD; Papovich, C; Peacock, JA; Park, C; Rahman, M; Rhodes, J; Ricol, JS; Sadeh, I; Slozar, A; Schmidt, SJ; Stern, DK; Anthony Tyson, J; von der Linden, A; Wechsler, RH; Wood-Vasey, WM; Zentner, AR. "Spectroscopic needs for imaging dark energy experiments," *Astroparticle Physics*, v. 63, 2015, p. 81–100

[14] Newman, JA; Cooper, MC; Davis, M; Faber, SM; Coil, AL; Guhathakurta, P; Koo, DC; Phillips, AC; Conroy, C; Dutton, AA; Finkbeiner, DP; Gerke, BF; Rosario, DJ; Weiner, BJ; Willmer, CNA; Yan, R; Harker, JJ; Kassin, SA; Konidaris, NP; Lai, K; Madgwick, DS; Noeske, KG; Wirth, GD; Connolly, AJ; Kaiser, N; Kirby, EN; Lemaux, BC; Lin, L; Lotz, JM; Luppino, GA; Marinoni, C; Matthews, DJ; Metevier, A; Schiavon, RP. "The DEEP2 Galaxy Redshift Survey: Design, Observations, Data Reduction, and Redshifts," , v. 208, 2013, p. 5

[15] NRC. *Optimizing the U.S. Ground-Based Optical and Infrared Astronomy System*, The National Academies Press, Washington, DC, ISBN 978-0-309-37186-5, 2015

[16] Schlegel, D; Kollmeier, JA; Ferraro, S. "The MegaMapper: a z¿2 spectroscopic instrument for the study of Inflation and Dark Energy," In *Bulletin of the American Astronomical Society*, v. 51, 2019, p. 229. `https://ui.adsabs.harvard.edu/abs/2019BAAS...51g.229S`

[17] Strauss, MA; Weinberg, DH; Lupton, RH; Narayanan, VK; Annis, J; Bernardi, M; Blanton, M; Burles, S; Connolly, AJ; Dalcanton, J; Doi, M; Eisenstein, D; Frieman, JA; Fukugita, M; Gunn, JE; Ivezić, Ž; Kent, S; Kim, RSJ; Knapp, GR; Kron, RG; Munn, JA; Newberg, HJ; Nichol, RC; Okamura, S; Quinn, TR; Richmond, MW; Schlegel, DJ; Shimasaku, K; SubbaRao, M; Szalay, AS; Vanden Berk, D; Vogeley, MS; Yanny, B; Yasuda, N; York, DG; Zehavi, I. "Spectroscopic Target Selection in the Sloan Digital Sky Survey: The Main Galaxy Sample," , v. 124(3), 2002, p. 1810–1824. `https://ui.adsabs.harvard.edu/abs/2002AJ....124.1810S`

[18] The LSST Dark Energy Science Collaboration; Mandelbaum, R; Eifler, T; Hložek, R; Collett, T; Gawiser, E; Scolnic, D; Alonso, D; Awan, H; Biswas, R; Blazek, J; Burchat, P; Chisari, NE; Dell'Antonio,

I; Digel, S; Frieman, J; Goldstein, DA; Hook, I; Ivezić, Ž; Kahn, SM; Kamath, S; Kirkby, D; Kitching, T; Krause, E; Leget, PF; Marshall, PJ; Meyers, J; Miyatake, H; Newman, JA; Nichol, R; Rykoff, E; Sanchez, FJ; Slosar, A; Sullivan, M; Troxel, MA. “The LSST Dark Energy Science Collaboration (DESC) Science Requirements Document,” *arXiv e-prints*, 2018, p. arXiv:1809.01669. `https://ui.adsabs.harvard.edu/abs/2018arXiv180901669T`