FOBOS: A Fiber-Fed MOS for Keck

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Project Justification

The 2016 Keck Strategic Science Plan (SSP) has called for Keck's strengths in faint multiplexed spectroscopy to be maintained and enhanced through the next decade. In particular, WMKO is in pole position to provide unique deep spectroscopic capability in the NUV/blue ($\lambda < 400$nm) to complement JWST, while an enhanced multiplexing will enable efficient follow up of objects identified by upcoming imaging surveys such as LSST, Euclid, and WFIRST. While the SSP suggested achieving these capabilities with a DEIMOS upgrade with a second focal plane and/or a blue spectral channel, recent advances in fiber spectroscopy and sky subtraction now allow these capabilities to be achieved — and indeed significantly surpassed — by building a fiber MOS. We therefore propose the Keck Fiber-Optic Broadband Optical Spectrograph (FOBOS), a 500-object fiber-fed spectrometer sampling the full Keck focal plane, providing medium resolution ($R \sim 2500-5000$) spectroscopy over a large optical range (350-980nm).

Crucially, the importance of massively-multiplexed optical spectroscopy on a 8-10m class telescope has been recognized at the national level by both the NSF [2] and DOE [1]. While multiple concepts are now starting to be proposed for various US facilities, it is unlikely that any of these can get on-sky before the mid-2020s. Keck-FOBOS, on the other hand, leverages the sigificant R&D of the upcoming DESI project and could begin operations near the start of LSST and Euclid science operations in ~ 2022. This makes it a strong contender for national funding for its overall \$12-15M cost (including contingency and overheads), and we request \$45k in funding from WMKO to continue feasibility studies to be used for an external funding request.

Baseline Concept: FOBOS will be a Nasmyth instrument on one of the Keck telescopes, with 500 robotic fiber positioners and mini-IFUs at the focal plane coupling to in-situ spectrographs based on the DESI design[2]. The spectrograph units are designed for a very high throughput averaging 70% (see Fig. 1) over three spectral channels: blue ($\lambda = 350\text{nm} - 560\text{nm}$ at $R \sim 2500$), red ($\lambda = 560\text{nm} - 750\text{nm}$ at $R \sim 4000$) and NIR ($\lambda = 750\text{nm} - 980\text{nm}$ at $R \sim 5000$). We envision the entire FOBOS instrument fitting on the Nasmyth position with a footprint smaller than DEIMOS, where the fiber focal plane+rotator is coupled to the bench-mounted spectrographs via a short fiber run of several meters. This reduces fiber throughput losses while providing the stability of a fixed gravity vector for the spectrographs. We have consulted with M. Kassis (WMKO) regarding space/weight constraints, and have confirmed that the full focal plane/spectrograph assembly would fit in one of the Keck Nasmyth slots. The exact location will depend on the WMKO instrumentation plan for the next decade; options include awaiting the retirement of HIRES after KPF becomes operational, decommissioning DEIMOS, or extending the K2 Nasmyth deck to create a new instrument slot.

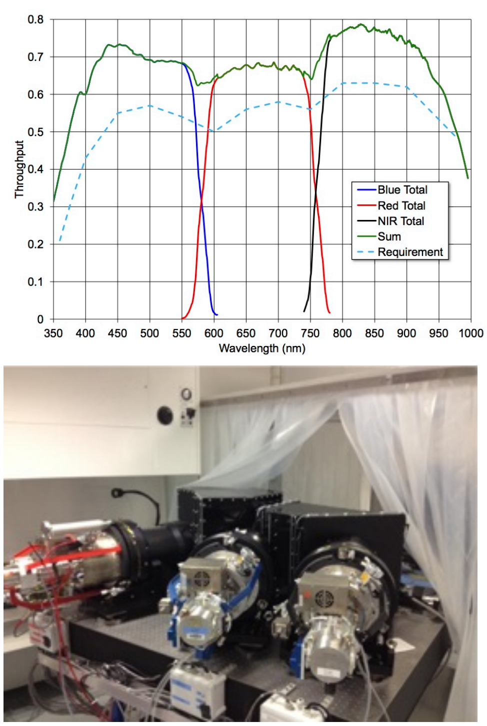

Figure 1: (Top) Design throughputs for the DESI spectrographs, showing the individual spectral channels as well as combined throughput. (Bottom) Photograph of the first DESI spectrograph unit, which was completed in fall 2016 and is currently undergoing testing at Marseille. The overall performance has so far been found to be nominal.

The DESI design uses 107μm fibers injected at $f/3.9$, which corresponds to a $0.57''$ aperture once matched to the Keck $f/15$ focal plane with microlenses. This is a small aperture for individual fibers, so we have studied combining them into mini-IFUs comprised of $7 \times 0.57''$ hexagonal microlens arrays for each target. The signal from the 7 fibers on each target can be optimally-combined to yield superior S/N and maximize flexibility across all seeing conditions: in good seeing, most of the flux goes through the central fiber with reduced sky background, while in bad seeing the overall 1.71" footprint captures the extended flux. The small size of the individual 0.57" fibers means FOBOS would naturally take advantage of ground-layer AO if it is implemented on Keck in the future. The microlens arrays are the critical R&D item since they underpin the feasibility of the whole project, and thanks to a Mini Grant from UCO we have been able to begin preliminary optical design on the microlens but require more funding to complete this study.

FOBOS in Context: FOBOS will be a powerful and flexible instrument — equally suited for both PI-led science and surveys — that will maintain Keck's proven strength in faint multiplexed spectroscopy established by LRIS, DEIMOS, and MOSFIRE. A natural comparison arises with Subaru-PFS [4], with its ultra-wide FOV (1.3 deg^2) and huge multiplexing (2400).

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[2]Currently being built for the 4m Mayall on Kitt Peak.

While FOBOS will concede the overall FOV and multiplexing advantage, it will be optimized to observe faint objects, with 2× better system throughput than PFS and 1.5× greater telescope collecting area, while the mini-IFUs confer 20% higher S/N, at 0.6″ seeing, over PFS's 1.1″ fibers, equivalent to 1.4× throughput gain. These factors combine into a 4× speed advantage, allowing FOBOS to access sources ~ 1 mag fainter than PFS, thus enabling a complementary set of science goals that will lie beyond the reach of PFS.

Last year's SSC comments requested that we compare FOBOS with possible upgrades of DEIMOS. On paper, FOBOS is clearly superior to an upgraded DEIMOS with a second focal plane (summarized in Table 1). FOBOS's overall FOV would be $\sim 1.8\times$ that of upgraded DEIMOS and would have double the multiplexing. The fibers can be rapidly repositioned (< 1 min) making feasible programs with short (<10 min) exposures that are impractical with DEIMOS, which can only load 10 slitmasks per night. Even if DEIMOS were upgraded with a LRIS-like blue spectral channel, it would offer resolutions comparable to FOBOS ($R \sim 2500 - 5000$ from blue to red) over limited wavelength ranges and discontinuous coverage. The only remaining question was whether sky subtraction on fibers work well enough to manifest these advantages. With the kind permission of the OzDES collaboration [5], we have analyzed the performance data from their deep fiber spectroscopy of $r > 24$ galaxies, to forecast the performance of an analogous instrument on Keck. We find that the S/N-exposure time scaling for fibers should behave roughly Poisson-limited up to $t_{\rm exp} < 3 - 4$hrs on Keck, and indeed shows some throughput advantage compared to slits. With longer exposure times, the fiber S/N improves more slowly than the ideal scaling, but the multiplex advantage makes up for this over upgraded DEIMOS. It is only if very long exposures ($t_{\rm exp} > 15$hrs) are required that upgraded DEIMOS holds the advantage, and even this assumes perfect sky subtraction for slits — which is not certain. This UCO-supported study is appended to the end of this White Paper. This forecast assumes only existing fiber reduction implementations. For long-exposure programs, one may further implement a nod-and-shuffle observing mode at the cost of some multiplexing. We would also explore the use of fiber scramblers or octagonal fiber segments (as being developed by the Keck/KPF project) and "spectroperfectionism" data reduction (as being developed by the DESI project). These techniques would allow FOBOS to more closely approach Poisson-level sky subtraction than assumed in our initial projections.

Table 1: Summary of Wide-Field Spectroscopic Options for Keck

Instrument	FOBOS	DEIMOS	DEIMOS (2× focal plane)
Multiplex	500	125	250
Max targets/night	∼30000	1250	2500
FOV (arcmin^2)	~ 300	84	168
Spectral length, $\Delta\lambda$ (nm)	620	260-530	260-530
Resolution FWHM (Å)	1.75	1.1-3.5	1.1-3.5

Finally, at the time of writing, TMT/WFOS is considering fibers to achieve its design goals, with ongoing work to define a fiber reference design in preparation for a downselect in early 2018. This is thus a time-limited opportunity for shared R&D between WFOS and FOBOS especially since WFOS PI K. Bundy is part of our team. The WFOS team will consider innovations that will allow ultra-faint spectroscopy with fibers on TMT, and our teams will work together to exploit the clear synergy between the two projects.

Cost and Risk: The DESI project is in its final stages of construction for a 2018 installation. The contracted build cost for the spectrographs (with WinLight, France) is \$1.5M per unit including testing and validation labor costs. The FOBOS spectrographs would cost $\sim$ \$6M-\$7M for 4 units, with the technical risks having been retired by DESI project. (Retired risks include replacing bonded lens-triplets with oil-coupled lenses, mitigation of a ghost path, and mitigation of vibrational harmonics from the cooling system.)

In DESI, the focal plane array costs $\sim$ \$1k per fiber+positioner (including electronics and mechanicals), so we conservatively estimate \$3.5k per mini-IFU+positioner combination, costing ∼\$1.8M for the full focal plane array. Our concept includes an ADC to enable simultaneous blue-red observations, which can be of similar design as the K1 Cass ADC [3] and should be a straightforward implementation costing $\sim$ \$1.5M. We thus estimate $\sim$ \$10M in hardware costs, translating to a $\sim$ \$12 − \$15M full project cost including R&D, overheads, and contingency.

Another attractive aspect of the FOBOS concept is its modularity, which allows early on-sky testing and phased commissioning to reduce risk. FOBOS could begin operations at partial scope: even with half of its positioners, fibers, and spectrographs, it would be superior to DEIMOS. This could, for example, allow us to pursue funding in stages rather than seeking the full project cost from the outset.

Budget Request

We request $45k in WMKO funding to complete the feasibility study on the FOBOS microlens arrays, which is the critical system to couple the Keck focal plane with the DESI fiber and spectrograph systems. The study will aim to design 7×1 hexagonal microlens arrays that will couple the Keck $f/15$ focal plane to mini fiber-bundles at the $f/3.9$ speed required for injection into the DESI fiber system.

We began this study several months ago with UCO funding, and have been examining modifications of the GMOS IFU epoxy/fused silica microlens arrays to couple Keck with DESI. By the start of WMKO funding in Oct 2017, we expect to have preliminary optical designs in hand, and will begin optimizing the coatings and materials in order to maximize performance, as well as designing the ferrules that will bond to mini-fiber bundles. This will require liaising with possible vendors and obtaining samples for testing.

The cost breakdown for the project is as follows:

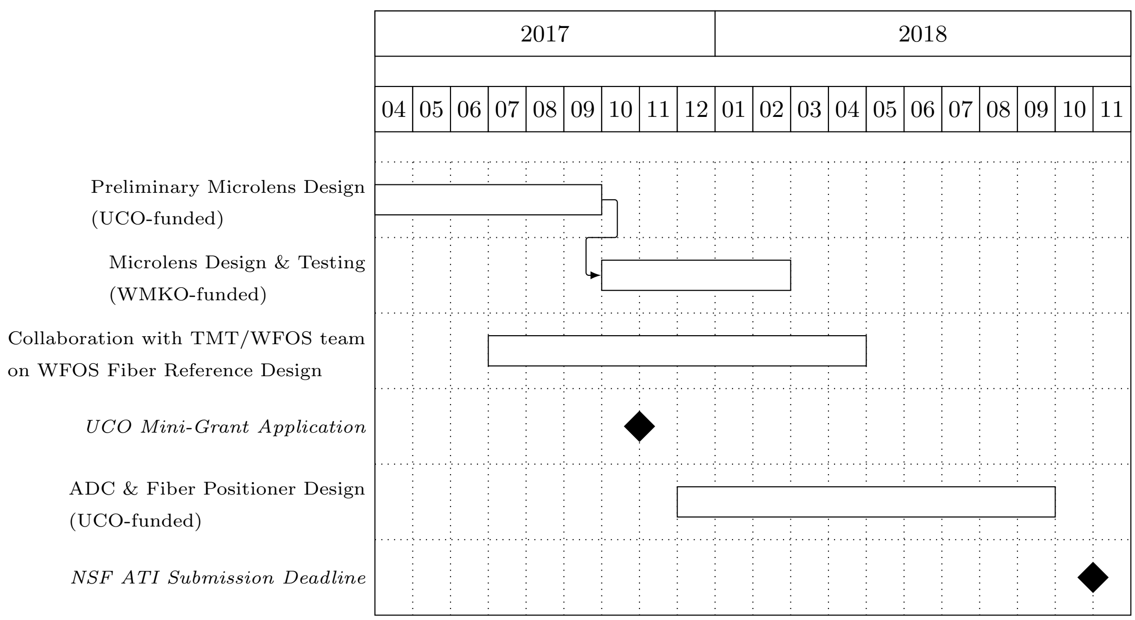
(*i*) **Optical Engineer Time at 0.4FTE $\times$ 12 weeks, $20k**. Tim Miller (UCB/SSL) will continue his work on the microlens design for FOBOS, which was begun this year with support from UCO. He can only provide partial effort due to other commitments to the DESI and Keck/KPF projects.

(*ii*) **Microlens Sample Acquisition and Testing, $20k**. This will allow us to acquire samples for microlens arrays based on our optical design, and carry out optical testing of throughput and PSF performance.

(*iii*) **Optical Fibers and Ferrules, $5k**. For acquiring the fibers and ferrules to physically couple with the microlens arrays, needed to test the optical performance of the latter.

Project Timeline

Our medium-term goal is to demonstrate feasibility in order to apply for a ~ $300k NSF ATI grant in November 2018, to fund the full instrument design prior to a NSF MSIP application for the full project funding. Before then, we hope to apply for the next round of UCO Mini Grants to kickstart our ADC and fiber positioner design work. The following table presents a timeline leading to the NSF ATI proposal.



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Forecasting the S/N-Exposure Time Performance of Fiber-Fed Optical Spectrographs on Keck

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Abstract

The ongoing OzDES redshift survey is observing faint ($r > 24$) galaxies with up to 50hr integrations, using a fiber spectrograph on a 4m telescope. Correcting for seeing and telescope aperture, we use their on-sky S/N results to forecast the likely performance for fiber spectroscopy on Keck. For individual objects, the fibers have slightly better throughput than DEIMOS and provide better S/N for $t_{\mathsf{exp}} < 5$hrs, after which sky-subtraction imperfections make it fall below the Poisson-limited performance assumed for DEIMOS. We also compare the relative spectroscopic survey efficiencies, $\sqrt{N_{\mathsf{spec}}} \times \langle \mathsf{S/N} \rangle$, for a $N_{\mathsf{spec}} = 450$ fiber spectrograph on Keck, vis-à-vis an upgraded DEIMOS with a second focal plane ($N_{\mathsf{spec}} = 250$). We find that the fibers provide better survey speeds for programs that require $t_{\mathsf{exp}} < 15$hrs.

The purpose of this document is to empirically estimate the probable spectral S/N performance as a function of exposure time for fiber-fed optical spectrographs on Keck, in comparison with a hypothetical upgraded DEIMOS with a second focal plane. We will extrapolate from the on-sky performance of the ongoing OzDES Survey (Yuan et al., 2015), a deep spectroscopic campaign using the 2dF-AAOmega fiber spectrograph (Sharp et al., 2006) on the 4m AAT, which has been successfully obtaining spectroscopic galaxy redshifts down to $r > 24$. To obtain redshifts for such faint galaxies with a 4m telescope, OzDES aims to accumulate up to 50hrs integrations on some targets. Their S/N performance can therefore help determine whether fibers are an acceptable solution for Keck.

The data used in this study is based on the OzDES first data release, with up to 40hrs of exposure time on some objects with the 4m AAT. The paper describing this data (Childress et al, submitted) is not yet public at the time of writing, but we have the kind permission from the survey PIs (C. Lidman, AAO, and A. Kim, LBNL) to use the relevant scaling and plots for this study.

We organize this document as follows: Section 1 will describe our assumptions for rescaling the OzDES S/N results to Keck, while Section 2 will describe our assumptions for 'Double DEIMOS', i.e. DEIMOS augmented with a second focal plane. We then compare the relative performance and survey efficiencies in Section 3. This study ignores differences in spectral resolving power or wavelength coverage, nor questions of cost.

1 Scaling OzDES Fiber Performance to Keck

From the OzDES First Data Release draft, we reproduce their plots for spectral S/N vs r-magnitude and noise vs exposure time (Fig.1). The left panel of Fig.1 shows that with the 2dF-AAOmega spectrograph on the 4m AAT, they achieve

$$\mathsf{S/N} = 0.2 \text{ per } \text{Å} \tag{1}$$

on a r=24.0 source with their individual 40 min exposures, which are subsequently co-added to build up integration time. We modify this single-exposure S/N to Keck in two ways: (a) To exploit superior seeing, a fiber spectrograph on Maunakea can be designed with smaller fiber diameters than the $2''$ used by OzDES, e.g. the $1''$ fibers on Subaru PFS (Sugai et al., 2015). Assuming the noise is sky-dominated and there are no aperture losses, $1''$ fibers leads to a $2\times$ improvement in S/N over the fiducial OzDES value. (b) We account for the $6.25\times$ difference in telescope collecting area to reduce the corresponding exposure time, such that 6.4 mins of integration would yield the same S/N on a 10m compared to the fiducial 40 min OzDES single exposures. We thus find $\mathsf{S/N} = 0.4$ per Å on a $r = 24.0$ source with 6.4 min exposures on Keck using

$1''$ fibers, assuming the same instrumental throughput as OzDES.

The noise scaling with exposure time (Fig.1, right panel), on the other hand, is found in OzDES to be best-fit by

$$N \propto \frac{t^{-0.6} + 0.1}{1.1}, \quad (2)$$

which is slower noise reduction than the ideal $N \propto t^{-0.5}$ scaling, reflecting imperfect sky subtraction.

Assuming OzDES-like fiber performance on Keck, we combine the above to find the following S/N scaling for a $r = 24.0$ source:

$$\langle \mathrm{S/N} \rangle (t_{\mathrm{exp}}) \approx \frac{0.4}{(9\, t_{\mathrm{exp}})^{-0.6} + 0.1} \mathrm{\AA}^{-1} \quad (3)$$

where t_{exp} is the exposure time in hours. Note that this is a conservative estimate toward fibers, since future improvements in fiber sky subtraction are quite possible. Also, the throughput assumed here is effectively that of the 2dF-AAOmega instrument used for OzDES, which could probably be better with FOBOS. For example, FOBOS will have a much shorter fiber run with correspondingly less fiber losses, and will have far better stability at Nasmyth than the prime focus sampled by OzDES.

For the fiber multiplexing, we adopt $N_{\mathrm{spec}} = 450$, which is the number of targets observable with a 500-fiber spectrograph assuming 50 fibers have been allocated for calibration.

2 Assumptions for "Double-DEIMOS"

The other possible upgrade path for multiplexed spectroscopy on Keck is to add a second focal plane to DEIMOS, which we dub "Double-DEIMOS" here. This would allow a total multiplex of $N_{\mathrm{spec}} \sim 250$, and is assumed to have the same throughput as DEIMOS.

To estimate the scaling with exposure time, we simply assume perfect sky subtraction in the Poisson limit (S/N $\propto t^{0.5}$) and normalize the S/N relation to DEIMOS using the DEEP2 survey results, i.e. Fig. 28 from Newman et al. (2013). On $r = 24.0$ sources, they achieve $\langle \mathrm{S/N} \rangle = 0.87$ per Å with 1hr integrations. The S/N-exposure time scaling for $r = 24.0$ sources for DEIMOS is then:

$$\langle \mathrm{S/N} \rangle (t_{\mathrm{exp}}) = 0.87\, t_{\mathrm{exp}}^{0.5}\, \mathrm{\AA}^{-1} \quad (4)$$

where t_{exp} is again the exposure time in hours.

3 Results

The S/N per object, as a function of exposure time, is shown in Fig. 2 for both OzDES-like fiber throughput on Keck, and DEIMOS, i.e. Eq. 3 and 4. For exposures of several hours ($t \lesssim 3-5$hrs) we find a similar trend for both fibers and slits, and indeed a better performance for the fibers indicating higher throughput. On longer exposures, the perfect sky subtraction assumed for DEIMOS leads to a better per-object performance.

To account for differences in multiplexing, we also plot in Fig. 3 the 'spectrograph efficiency', $\sqrt{N_{\mathrm{spec}}} \times \langle \mathrm{S/N} \rangle$, which describes the relative survey speed of achieving a given S/N over a large number of spectra. The result shows that the greater multiplexing with fibers provides better overall efficiency over "Double-DEIMOS" for most reasonable integration times on Keck, even well into the $t_{\mathrm{exp}} > 5$hrs regime where the individual source S/N with fibers drop below those of the slits. It is only if integration times of $t_{\mathrm{exp}} > 17$hrs per pointing are required to achieve high-S/N (e.g. S/N > 2.5 per Å on $r \sim 24$ sources, that the perfect sky subtraction assumed for "Double-DEIMOS" makes it more efficient for surveys than a fiber instrument on Keck. However, we reiterate that the fiber performance assumed here reflects the *current* state of fiber spectral reduction, and it is likely that further gains are possible with future work to improve fiber performance on long exposures, for example with a nod-and-shuffle observing mode or using optical elements to improve PSF stability.

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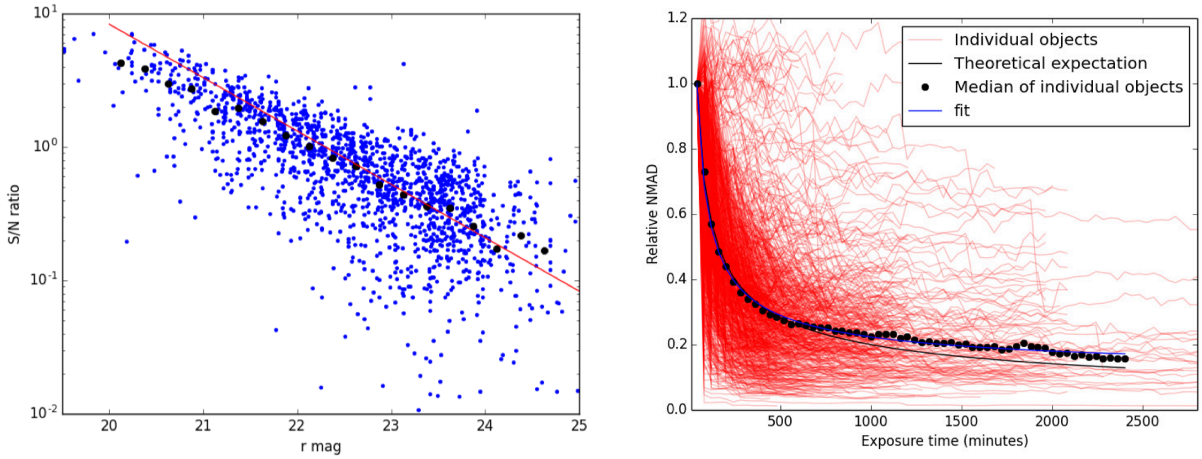

Figure 1: Spectral S/N performance from the OzDES fiber spectroscopic survey, reproduced from Childress et al. 2017 (submitted). (Left) The points show the S/N in the $6500\,\text{Å} < \lambda < 8500\,\text{Å}$ range from 40 min exposures on the 4m AAT, evaluated as a function of r-magnitude. We use their results for $r = 24.0$ sources to anchor our estimates (Eq. 1) . (Right) The red curves show the trends in spectral noise from individual objects as additional integrations are accummulated. The black dots show the median of the sources, while the blue curve shows the best-fit to the median (Eq. 2). The black, lower, curve shows the theoretical curve assuming Poisson-limited scaling ($N \propto t^{-0.5}$).

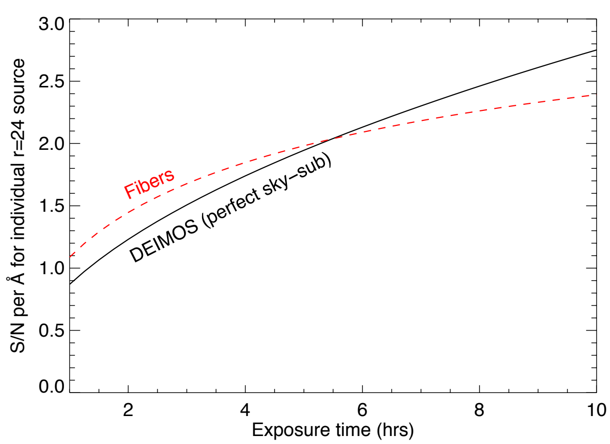

Figure 2: Comparison of per-object S/N of DEIMOS (black curve) with the OzDES results rescaled for Keck (red dashed curve), as a function of exposure time for a $r = 24$ source. The scaling for fibers is comparable to the Poisson limit for integrations of up to several hours and is indeed slightly better reflecting better throughput, but imperfect sky subtraction lead to a slower improvement in S/N with long exposure times. Future developments in fiber spectral reduction could lead to better performance in the long exposure regime.

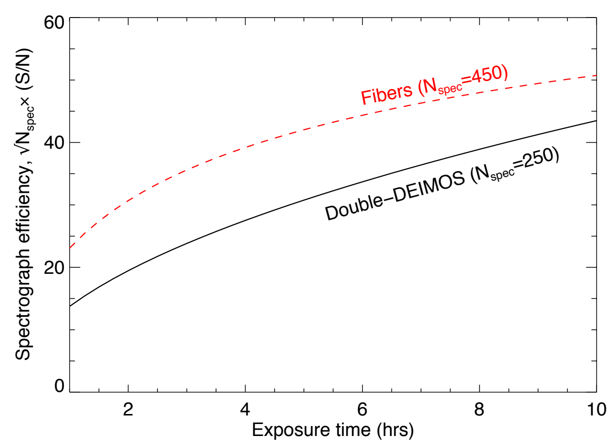

Figure 3: The relative spectroscopic survey efficiency, $\sqrt{N_{\rm spec}} \times \langle \mathrm{S/N} \rangle$, for "Double-DEIMOS" with a second focal plane (black curve) compared with a 450-object fiber spectrograph on Keck assuming the throughput performance of OzDES (red dashed curve), as a function of exposure time. The multiplex advantage of fibers leads to a better survey efficiency unless exposure times of $t_{\rm exp} > 15$hrs are required, at which point "Double-DEIMOS" becomes dominant if it can achieve perfect sky subtraction.