Astro2020 APC White Paper

Towards a Spectroscopic Survey Roadmap for the 2020s and Beyond

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Principal Author: Adam S. Bolton
National Optical Astronomy Observatory
950 N. Cherry Ave Tucson, AZ, 85719
bolton@noao.edu, +1 520-318-8130

Co-authors: Tim Abbott (NOAO), Lori Allen (NOAO), Michael Blanton (NYU), Kevin Bundy (UCO/UCSC), Kyle Dawson (Utah), Arjun Dey (NOAO), Juna Kollmeier (Carnegie), Jennifer Marshall (MSE/TAMU), John Moustakas (Siena), Joan Najita (NOAO), Jeffrey Newman (Pitt)

Abstract: Wide-field survey spectroscopy is essential to realizing the astrophysics potential of LSST and other imaging surveys. This white paper reviews the consistent findings that this capability is a critical scientific need of the US community in the 2020s and beyond, summarizes facilities across a range of apertures and timescales that can address this need, and offers strategic recommendations for the Astro2020 Decadal Survey to enable national scientific progress and leadership in this area in the coming decade.

Key Issue and Overview of Impact on the Field

Wide-field survey spectroscopy in the coming decades holds the potential to deliver breakthrough science for resolved stellar populations, Milky Way structure, the evolution of galaxies and AGN, the physics of dark matter and dark energy, and the signatures of inflation from the early universe. This potential is detailed in numerous science white papers submitted to the Astro2020 decadal survey, as referenced by the following APC white papers describing projects that can address this critical science need:

- *The Sloan Digital Sky Survey as an Archetypal Mid-Scale Program* (Blanton et al.)
- *SDSS-V: Pioneering Panoptic Spectroscopy* (Kollmeier et al.)
- *The Dark Energy Spectroscopic Instrument (DESI)* (Levi & Allen et al.)
- *The MegaMapper: a z > 2 Spectroscopic Instrument for the Study of Inflation and Dark Energy* (Schlegel & Kollmeier et al.)
- *Next Generation LSST Science* (Jha et al.)
- *FOBOS: a Next-Generation Spectroscopic Facility* (Bundy et al.)
- *The Maunakea Spectroscopic Explorer* (Marshall et al.)
- *SpecTel: A 10-12 Meter Class Spectroscopic Survey Telescope* (Ellis & Dawson et al.)

The scientific power of wide-field imaging and spectroscopic surveys in combination has been demonstrated conclusively by the Sloan Digital Sky Survey (SDSS).[1] Without spectroscopy, the classification, radial velocity / redshift, internal stellar and gas dynamics, chemical composition, thermodynamic conditions, and line-of-sight radiative geometry of astronomical objects can only be constrained very approximately. With spectroscopy, all these properties become accessible to quantitative study. Survey-scale spectroscopy is the key to unlocking the astrophysics potential of LSST and other large-scale imaging surveys in the present and planned future.

The need for survey-scale spectroscopy in the LSST era has been well studied and well documented. **Spectroscopy in the era of LSST**[2] was a community workshop hosted by NOAO in 2013 to prioritize science-driven needs for spectroscopic capabilities in the LSST era, as identified in multiple science-area breakout sessions. Many science cases converged on the need for highly multiplexed spectroscopy, as indicated in the final workshop report[3]:

> *"There are many science cases from across the breakout sessions that require spectra of many thousands of objects. Some would like orders of magnitude more. The instruments would be wide field, with a field of view of 1-3 degrees. There would be capacity for hundreds (minimal) to thousands (highly desirable) of spectra in a single observation. These cases focus mainly on optical wavelengths, but IR capability is also important."*

[1] https://www.sdss.org
[2] https://www.noao.edu/meetings/lsst-spec/
[3] https://www.noao.edu/meetings/lsst-spec/files/spectroscopylsst.pdf

The 2015 National Research Council report of Elmegreen et al. on **Optimizing the U.S. Ground-Based Optical and Infrared Astronomy System**[4] also identified the scientific need for spectroscopic survey capabilities complementary to LSST imaging, issuing the following conclusions and recommendation:

> *"CONCLUSION: There is currently no wide-field, highly multiplexed spectroscopic capability on medium- or large-aperture telescopes in the Southern Hemisphere in the U.S. Optical and Infrared (OIR) System.*
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> *CONCLUSION: Wide-field, highly multiplexed spectroscopic capabilities on medium- and large-aperture telescopes in the Southern Hemisphere in the LSST era would be of great benefit to the U.S. OIR System, enabling a wide variety of science including follow-up spectroscopy of LSST targets.*
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> *RECOMMENDATION: The National Science Foundation should support the development of a wide-field, highly multiplexed spectroscopic capability on a medium- or large-aperture telescope in the Southern Hemisphere to enable a wide variety of science, including follow-up spectroscopy of Large Synoptic Survey Telescope targets. Examples of enabled science are studies of cosmology, galaxy evolution, quasars, and the Milky Way."*

Maximizing Science in the Era of LSST[5] was a 2016 community-based study funded by the Kavli Foundation, co-organized by LSST and NOAO, and endorsed by NSF. The goal of the study was to expand on the findings of the OIR System Report of Elmegreen et al. and perform a quantitative flow-down from a representative sample of LSST-era science cases to further establish the highest priority capabilities for the 2020s. The final report of Najita & Willman et al.[6] identified that the single most significant "critical resource in need of a prompt development path" was to:

> *"Develop or obtain access to a highly multiplexed, wide-field optical multi-object spectroscopic capability on an 8m-class telescope, preferably in the Southern Hemisphere."*

Within the DOE-funded high-energy physics community, the **Cosmic Visions Dark Energy** group conducted a study process via meetings and workshops during 2015-16 to identify the most promising future experimental probes of dark energy beyond LSST and DESI. The final science report from the CVDE group[7] concluded that

> *"A Southern spectroscopic survey facility would improve the scientific capabilities of all the probes of dark energy"*

and also that

[4] https://www.nap.edu/catalog/21722/optimizing-the-us-ground-based-optical-and-infrared-astronomy-system
[5] https://www.noao.edu/meetings/lsst-oir-study/
[6] https://arxiv.org/abs/1610.01661
[7] https://arxiv.org/abs/1604.07626

> *"Running DESI in the North past its current expected end date of 2024 [now 2025] is a natural possibility with significant scientific benefit and low cost."*

The **Gemini-Blanco-SOAR (GBS) subcommittee** of the Astronomy and Astrophysics Advisory Committee (AAAC) was created in 2018 at the request of NSF and DOE, and charged with developing an assessment of the scientific utility and priorities for the Gemini, Blanco, and SOAR telescopes during the 2020s. Although not within the strict GBS scope, the subcommittee observed and recommended that

> *"A highly-multiplexed, multi object, wide field of view spectrograph on an 8-10 m class telescope in the southern hemisphere remains missing from the US OIR portfolio… Explore options with international partners to provide access to such a facility, preferably in the Southern hemisphere for the second half of the next decade…"*

and furthermore observed that

> *"The role of the DESI instrument following the end of the DESI survey is of interest as it could also enable significant science goals in a variety of areas."*

Strategic Plan

In consideration of the clearly identified scientific need for highly multiplexed spectroscopy, and the range of projects proposed to address this need (detailed further below), we ask that the Astro2020 Decadal Survey consider the following recommendations to enable the US astronomical community to take a strategic approach during the next decade:

- ***Recognize the critical national importance of wide-field survey spectroscopy in the 2020s and beyond to realizing the full astrophysical science potential of LSST.***
- ***Take a holistic view of the existing, forthcoming, and proposed facilities across a range of apertures that can address this need.*** The success of ambitious future facilities must build upon the scientific, technological, and operational foundation of previous projects. Likewise, data from concurrent projects with complementary strengths can be combined to enable additional science.
- ***Recognize the DESI and SDSS facilities as unique resources for survey spectroscopy for the US community, which will be available for new missions in the mid-2020s.***
- ***Prioritize US community access to an operational 8–12m-class wide-field survey spectroscopy facility by the early 2030s.*** Encourage continued development of US involvement in international partnerships, while also pursuing opportunities for US leadership.
- ***Prioritize US community access to major spectroscopic survey facilities in any international reciprocity agreements during the 2020s.***
- ***Recognize the archival science value of public high-level data products from spectroscopic surveys, and the importance of software systems in delivering this value.*** Providing and maintaining well-supported access to publicly released data sets from

SDSS, DESI, 4MOST, PFS, and other spectroscopic survey facilities will provide significant science opportunity to the US community in the LSST era, even in the absence of new facilities or observing access channels. Likewise, the scientific potential of new spectroscopic survey facilities will depend critically on the provision of accessible data products and access methods.

- ***Keep options open, and plan to evaluate progress and priorities mid-way through the 2020s to determine the most scientifically compelling and technically promising directions for 2025-2030 and beyond.*** The scientific and technical performance of projects operating during 2020-2025 will significantly inform future directions.
- ***Continue to fully exploit experimental synergies between astrophysics and cosmology that can enable inter-agency partnership.***

Organization, Partnerships, and Current Status

Options to meet the US community need for wide-field survey spectroscopy in the LSST era can be generically divided into four categories:

1. Designate an existing US-based spectroscopic survey facility
2. Purchase and/or exchange for US time on an international facility
3. Build a new instrument for an existing US telescope
4. Build a new dedicated US facility

The following is a brief overview of current, forthcoming, and proposed facilities with a potential role in addressing the needs of the US community for large-scale survey spectroscopy in the 2020s and beyond, which together span these four categories of possibility. For definiteness, these are ordered by increasing telescope aperture, with the exception of non-US facilities already in construction, which are grouped together at the end.

Further details for facilities marked with a star (★) are provided by the dedicated Astro2020 APC "project" white papers for each facility referenced near the top of this document.

★ **SDSS:** The Sloan Digital Sky Survey is a long-running spectroscopic survey project, currently in its fourth phase (SDSS-IV) and actively planning for a transition to a fifth (SDSS-V). SDSS currently uses survey spectrographs on the 2.5m Sloan Foundation telescope at Apache Point Observatory in New Mexico and on the 2.5m du Pont Telescope at Las Campanas Observatory in Chile, providing all-sky survey capability. Successive phases of the SDSS are funded through a combination of institutional membership, funding from the Alfred P. Sloan Foundation, and (depending on the project phase) NSF and DOE. Over the past two decades, SDSS has demonstrated consistently high scientific impact through the combination of large and homogeneous spectroscopic surveys, high-quality data products, and accessible public data releases.

★ **DESI:** The Dark Energy Spectroscopic Instrument is a DOE-funded experiment currently being deployed to the 4m Mayall Telescope at Kitt Peak National Observatory, which is operated by NSF's National Optical Astronomy Observatory (NOAO). DESI will use 5,000 robotically positioned fibers feeding ten 3-arm optical spectrographs to conduct a 5-year survey (2020-2025) of over 40 million galaxies, quasars, and stars. The DESI Key Project is designed to deliver precise constraints on the nature of dark energy via measurement of the "baryon acoustic oscillation" feature imprinted within the large-scale structure of the Universe. DESI also incorporates a survey of ~10 million Milky Way stars. Data from DESI will be released publicly at intervals throughout the survey. The DESI+Mayall combination would become available for extended missions in 2025, and has access to more than 1/3 of the LSST footprint from its location at Kitt Peak.

4m Blanco Telescope: There is potential to use the V. M. Blanco 4-m telescope at Cerro Tololo Inter-American Observatory (CTIO) as a massively multiplexed spectroscopy platform, although this would potentially eliminate the availability of the Dark Energy Camera (DECam), which has significant scientific value of its own in the LSST era. Since Blanco is a twin of the Mayall telescope at KPNO, one option would be to deploy a clone of DESI to the Blanco.[8] Alternatively, DECam itself was built to make it possible to exchange its imager for another instrument of a similar envelope. This was explored by the DESpec concept[9], in which a 4,000-fiber positioning unit called MOHAWK[10] would be installed behind the DECam corrector, together with an atmospheric dispersion corrector occupying the current filter and shutter spaces. Such an upgrade would maintain Blanco's multi-purpose capability at both Cassegrain and prime focus. Either a DESI clone or a DESpec are likely to be considerably faster to develop and deploy than a whole new telescope, and thus could capitalize from the south on LSST sooner than a dedicated 8–12m-class facility, albeit with a smaller etendue.

★ **MegaMapper, a.k.a. "Beast",** is a concept for a dedicated spectroscopic survey telescope with 20,000 fibers and a 2.6 degree diameter field of view mated to a copy of a Magellan 6.5m telescope. This concept is being developed collaboratively between Lawrence Berkeley National Lab and Carnegie Observatories. The design is optimized for cost-effectiveness and wide-field survey speed. The headline scientific goal is to probe inflation and dark energy at high redshift, but the facility would be a powerful platform for other surveys as well (e.g., Milky Way mapping and high-density extragalactic surveys). Concepts for US community access to this facility are not developed, but it would be a US-led project.

★ **Future-LSST:** In April 2019 a workshop was convened at Argonne National Lab to explore potential future missions and next-generation instrumentation for the Large Synoptic Survey Telescope after the conclusion of its 10-year primary mission in the early 2030s. The workshop report by Stubbs and Heitmann[11] explored several scenarios, including the installation of a multiplexed survey spectrograph to take advantage of LSST's unparalleled etendue. The optimal number of fibers in the focal plane for such an instrument was estimated at 40,000 based on the goals of (i) obtaining complete spectroscopy over the LSST imaging footprint for magnitudes $20 < i < 23.5$ over a 10-year spectroscopic survey and (ii) exploiting the etendue advantage of

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[8] The proposal to move the existing DESI from the Mayall to the Blanco should be considered with significant caution, as described in the DESI APC white paper of Levi & Allen et al.

[9] https://arxiv.org/abs/1209.2451 and https://www.noao.edu/meetings/2020decadal/files/BWFS-0.9.pdf

[10] Saunders et al. 2012, Proc. SPIE 8446, 84464W, https://doi.org/10.1117/12.925724

[11] https://arxiv.org/abs/1905.04669

LSST over other planned and proposed spectroscopic facilities. Technical risks identified included the fast input beam to the LSST focal plane, the miniaturization required for fiber positioners, and the lack of an atmospheric dispersion compensator. Conversion of LSST to a spectroscopic facility would also eliminate LSST's imaging capabilities, which will likely remain scientifically compelling beyond the 10-year primary mission.

★ **FOBOS:** The Fiber-Optic Broadband Optical Spectrograph is a proposed instrument for the 10m Keck II Telescope of the W. M. Keck Observatory on Maunakea. FOBOS would be optimized for blue sensitivity, faint objects, high target density, and high throughput at blue wavelengths, with 1,800 fibers over a field of view of 17 arcminutes in diameter delivering simultaneous $R \sim 3{,}500$ spectroscopy over the range 0.31 – 1 micron. The instrument is currently in conceptual design phase. In addition to its science capabilities, FOBOS could serve as a pathfinder for technologies needed to deliver more ambitious dedicated spectroscopic facilities such as MSE or SpecTel (below). Potential models for US community access to FOBOS beyond the Keck partnership would require further exploration.

★ **MSE:** The Maunakea Spectroscopic Explorer is a proposed transformation of the current Canada-France-Hawaii Telescope (CFHT) on the summit of Maunakea in Hawaiʻi. MSE proposes to retain the CFHT structural foundation and footprint, and to replace the existing telescope with a new, dedicated spectroscopic survey telescope with an 11.25m-diameter primary mirror. The dome housing this new telescope would be only slightly larger than the existing CFHT dome. The new telescope would feed 4,332 fibers over a 1.52 deg^2 field of view at prime focus, in turn feeding a combination of low, medium, and high-resolution spectrograph modes. The current baseline schedule calls for a start of science commissioning at the start of 2029. Although MSE would be located in the Northern hemisphere, the relatively low latitude (+19.9 deg) would translate into a significant overlap with the LSST imaging footprint. An international partnership model for MSE construction and operations is currently being developed. In consideration of MSE's responsiveness to the identified scientific needs of the US community, NOAO has promoted US engagement in the MSE Science Team defining the detailed science case and design reference surveys for MSE. NOAO staff currently represent the US through membership in the MSE Science Advisory Group (SAG) and in an observer role to the MSE Management Group.

★ **SpecTel** is a proposed dedicated spectroscopic survey facility in the Southern hemisphere, with an 11.4m mirror, a 4.9 deg^2 field of view, a multiplex capability of 15,000, and wavelength coverage from 360 – 1330 nm. The SpecTel concept draws on the outcomes of an ESO study into science drivers and telescope designs for massively multiplexed spectroscopy.[12] While still in pre-conceptual design, SpecTel represents one of the most ambitious options for survey spectroscopy currently under discussion, and one of the most responsive to the scientific aspirations of the US community. Any realistic timescale would not see a SpecTel in science operations before 2030. This timescale nevertheless allows for (i) timely large-scale spectroscopic follow-up over the full LSST imaging footprint and informed by the full 10-year depth of the LSST imaging survey, and (ii) coordinated operation with an extended LSST imaging

[12] https://arxiv.org/abs/1606.06494, https://arxiv.org/abs/1701.01976, and https://arxiv.org/abs/1708.03561

mission. The intervening years would allow for partnership development (e.g., US plus ESO) and refinement of the science case and technical design based on precursor facilities.

In considering potential sites for new US-led Southern facilities, we note that the NSF-supported infrastructure of CTIO/NOAO-South, soon to be NCOA-South, offers a mature and comprehensive environment for development and operations. While the wider CTIO complex already hosts the many telescopes of Cerro Tololo and Cerro Pachon, there remains an abundance of sites for potential further development. The location is easily accessible, is fed by all the necessary utilities including the ultra-high-bandwidth internet required by LSST, and possesses an extensive and seasoned pool of human expertise, making it an obvious and desirable choice for new facilities. Of the vast unoccupied holdings, only one as-yet undeveloped site has been surveyed for astronomical purposes (Cerro Morado, several decades ago.) Hence, a new campaign of site testing could be of value.

WEAVE, 4MOST, PFS, and MOONS are four spectroscopic survey facilities currently being constructed internationally without US participation or access (except for some US institutions in the case of PFS):

- WEAVE[13] is a ~1,000 fiber, medium- to high-resolution optical fiber spectroscopic instrument with a 2 degree diameter field of view being built for the 4m-class William Herschel Telescope at the Roque de los Muchachos Observatory on the island of La Palma in the Canary Islands of Spain.
- 4MOST[14] is a 2,436 fiber instrument with a 2.5 degree diameter field of view feeding medium- and high-resolution spectrographs, currently being constructed for the European Southern Observatory's 4m-class VISTA telescope at Paranal Observatory in Chile with an anticipated start of science operations in 2022.
- The Subaru Prime Focus Spectrograph (PFS)[15] is a 2,394-fiber low- to medium-resolution spectrograph with a 1.3 degree diameter field of view and continuous wavelength coverage from 380nm to 1260nm, currently being constructed for the National Astronomical Observatory of Japan's 8.2m Subaru Telescope on the summit of Maunakea, with an expected start of science operations in 2022.
- The Multi-Object Optical and Near-infrared Spectrograph for the VLT (MOONS)[16] is a 1,000 fiber instrument with a 500 arcmin^2 field of view offering moderate spectral resolution over 0.65 – 1.80 microns and high resolution spectroscopy over 0.77 – 1.64 microns, which is expected to begin science operations on ESO's Very Large Telescope UT1 at the end of 2020.

Although they do not currently offer US community access, these four instruments (i) define the current international landscape of forthcoming spectroscopic survey facilities, (ii) represent potential resources for negotiated reciprocal access in exchange for access to US resources, (iii)

[13] https://ingconfluence.ing.iac.es:8444/confluence//display/WEAV/The+WEAVE+Project
[14] https://www.4most.eu/cms/
[15] https://arxiv.org/abs/1608.01075 and https://pfs.ipmu.jp
[16] https://www.eso.org/sci/facilities/develop/instruments/MOONS.html

can be expected to deliver survey data sets that will become public and available to the US community, and (iv) will provide scientific and technical lessons to inform the development and operation of new facilities and surveys in the late 2020s and beyond.

Conclusion

While there is currently no definitive single road to meeting the needs of the US community for survey-scale spectroscopy in the LSST era, the projects above illustrate that there are in fact many possible roads. By recognizing the critical importance of this capability, the Astro2020 Decadal Survey can enable US astronomers to prioritize and pursue these roads in serial and parallel with the goal of maximizing and diversifying the scientific return on LSST and other major investments of the present and future.

Schedule

See individual project APC white papers. Collectively, the variety of these projects allows for progressive development through the decade to achieve the spectroscopic survey science goals of the US community.

Cost Estimates

Cost estimates can be found in individual project white papers, and range from “medium” to ”large”. Considered alone, incorporation of spectroscopic survey data sets into existing data archives and data services would likely be of “small” cost.