Astro2020 Project White Paper
SDSS-V Pioneering Panoptic Spectroscopy

Thematic Areas: Ground Based Project

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1 Key Science Goals and Objectives

1.1 Introduction

SDSS-V, the fifth phase of the Sloan Digital Sky Survey (Kollmeier et al., 2017), will be astronomy's first all-sky, multi-epoch spectroscopic survey, observing the Universe in both the optical and the infrared (IR). Targeting over six million objects, SDSS-V is designed to decode the history of the Milky Way Galaxy, trace the emergence of the chemical elements, reveal the inner workings of stars, seek their black hole companions, and investigate the origin of planets. SDSS-V will also create a contiguous and detailed spectroscopic map of the interstellar gas in the Galaxy — 1,000 times larger than those that exist today — to map the self-regulation mechanisms of galactic ecosystems. Beyond our Galaxy, SDSS-V will chart the growth of massive black holes at the centers of galaxies throughout cosmic time, and illuminate the inner workings of quasars.

Starting in late 2020, SDSS-V will pioneer "panoptic[1] spectroscopy": the first systematic, spectroscopic monitoring across the whole sky. It will reveal changes on timescales from 20 minutes to 20 years and serve as a crucial and timely match to the time-domain *imaging* sky surveys being conducted from the ground and from space. SDSS-V combines several key elements into one unified project: it is (1) a scientific program, (2) a dual-hemisphere facility, (3) an international consortium of institutional partners, (4) a collaboration between individual scientists, and (5) an unprecedented public legacy data set of time-domain, all-sky spectroscopy.

The scope and flexibility of SDSS-V will be unique among both extant and anticipated spectroscopic surveys. Achieving these requires the construction of fiber-positioning robots to obtain near-IR and optical spectra for the black hole and Galactic surveys (§1.3–1.4), plus six DESI-type spectrographs on smaller telescopes to obtain IFU data for the Local Group galaxies survey (§1.5). The rapidly reconfigurable fibers will enable swift sky coverage, high target densities, valuable targets of opportunity, and time-domain monitoring. SDSS-V will be all-sky, with matched survey infrastructures in both hemispheres (at Apache Point and Las Campanas Observatories; APO and LCO).

With a planned start in mid-2020, SDSS-V will be perfectly timed to multiply the scientific output from major space missions (e.g., TESS, Gaia, Spektr-RG/eROSITA) and ground-based projects (e.g., NSF-funded mid/large projects: Zwicky Transient Factory [ZTF], Large Synoptic Survey Telescope [LSST], Laser Interferometer Gravitational-Wave Observatory [LIGO]).

SDSS-V builds on the 25-year heritage of SDSS's advances in data analysis, collaboration spirit and infrastructure, and product deliverables in astronomy. SDSS-V entails a distinct shift in the Sloan Surveys' scientific focus from "large-scale structure with galaxies" to "pioneering panoptic spectroscopy", which will deliver breakthroughs in stellar, black hole, time-domain, exoplanet, *and* ISM astrophysics. The scientific breadth of SDSS-V is enormous as we detail below.

1.2 Pioneering Panoptic Spectroscopy

The ultimate goal and unifying theme of the SDSS-V multi-object spectroscopy (MOS) is to pioneer panoptic spectroscopy, taking spectra across the whole sky all the time. As a pivotal step towarsd this goal, SDSS-V will be the first all-sky, multi-epoch spectroscopic survey comprising

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[1] *panoptic*: presenting a comprehensive or encompassing view of the whole

optical and near-IR data, targeting over six million objects.

The MOS part of SDSS-V is designed to decode the evolutionary history of the whole Milky Way Galaxy, trace the emergence of the chemical elements, understand the structure and evolution of stars, and investigate the origin of planets and stellar remnants. It will map the growth of massive black holes at the centers of galaxies, by identifying and characterizing vast sets of new X-ray sources. It will perform systematic, spectroscopic monitoring across the whole sky, thereby measuring black hole masses, monitoring the growth spurts of black holes, and opening up stellar spectroscopy to large-scale time-domain studies.

1.3 The Black Hole Mapper

The Black Hole Mapper (BHM) program is designed to map, model, and understand the growth of supermassive black holes (SMBHs) at the centers of galaxies across the cosmos through two angles unprecedented in spectroscopy: studying hundreds of thousands of black holes selected by X-ray emission (the most robust signature of their mass growth) and studying fluctuating black hole growth rates through time-domain monitoring of large samples.

Quasars are the most luminous objects in the Universe. Powered by accretion onto SMBHs, quasars and Active Galactic Nuclei (AGN) are beacons marking and tracing the growth of SMBHs across cosmic distance and time. The tight correlation between the mass of the central SMBH and the properties of its host galaxy (Kormendy & Ho, 2013) demonstrates a clear connection between the formation of the galaxy's stellar component and the growth of its central BH. Thus, the underlying questions of SMBH growth being addressed by the BHM's quasar studies are closely linked to the galaxy formation and evolution questions being explored by the Milky Way Mapper and the Local Volume Mapper.

Two hallmarks of quasars are their variability across the electromagnetic spectrum on timescales of days to decades and their prodigious X-ray emission, which emanates from the innermost regions around the SMBH (Figure 2[2]). Variability and X-ray emission encode information on the structure, dynamics, and evolution of spatially-unresolved emitting regions. Observational tests of SMBH theory require three primary measurements: precise mass constraints, multi-wavelength Spectral Energy Distributions (SEDs), and detailed characterizations of variability. The BHM program will provide these measurements for a large sample of quasars, adding wide-area, multi-epoch optical spectroscopy to the era of time-domain imaging and the next-generation X-ray surveys (e.g., ZTF, LSST, and *eROSITA*).

Over the past 30 years, reverberation mapping (RM) of the time delay between variability of the continuum and the response of the broad emission line region (BLR) has become a powerful diagnostic of AGN physics (e.g., Peterson, 2014). RM delays measure typical sizes of the BLR and, combined with the velocity width of the broad emission lines (BELs), allow a virial estimate of mass, the most fundamental of all BH parameters. The historical samples of <100 systems comprise predominantly nearby, low-luminosity AGN in the present-day universe. **BHM will measure BH masses for $\sim$1000 quasars directly through RM, across a broad range of luminosity and redshift, characterizing systems that represent the main reservoir of BH growth.** BHM will also definitively characterize the spectral variability of more than 20,000 additional quasars, sampling light-travel, dynamical, and thermal timescales of days to decades, revealing BEL profile

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[2] At `https://www.sdss.org/future/astro2020/`

variations, SMBH binarity[3], outflow constraints, and rare "changing look" events in which quasars turn on or off in just a few years (e.g., Runnoe et al., 2016). These data will shed new light on fundamental questions of SMBH accretion astrophysics and pre-SMBH merger statistics.

Despite the high X-ray luminosity of nearly all AGN, we do not fully understand the physical origin of the tight coupling between the hot X-ray corona and the "cold" accretion disk. This is mostly due to the limited size of X-ray AGN samples compiled with current X-ray telescopes that have the necessary sensitivity but cannot map large swaths of sky (*Chandra*, *XMM-Newton*). However, the imminent launch of *eROSITA* anticipated this year, with both its high sensitivity and large FOV, will discover as many new X-ray sources in its first 12 months as are known today, after more than 50 years of X-ray astronomy. SDSS-V will provide optical spectroscopic measurements, including identifications and redshifts, of $\sim$300,000 *eROSITA* sources detected in the first 1.5 years of the all sky survey (to $i_{AB} \lesssim 21.5$; Merloni et al., 2012). This *eROSITA*-selected sample will comprise mainly AGN and quasars, both obscured and unobscured; but it will also contain X-ray emitting galaxy clusters, X-ray-bright stars (e.g., compact binaries and flaring late-type stars) in the Milky Way and nearby galaxies, extreme and rare objects, transients, and other peculiar variables found in the *eROSITA* survey. Combining X-ray discovery and optical spectral characterization will provide a great leap forward in our description of the X-ray sky, revealing the connections between large, statistical populations of X-ray sources and the cosmic structures in which they are embedded[4].

1.4 The Milky Way Mapper (MWM)

The MWM is designed to fully realize the scientific potential of the MW as the centerpiece of "near-field cosmology", a case study of the path from random initial fluctuations in the universe to a beautiful, intricately and coherently structured galaxy. In addition, MWM will be the first high-quality spectroscopic survey across the entire sky to study the physics of stars—whether they quake, host planets, or orbit black holes.

MWM's primary experiment of "Galactic Genesis" is set apart from existing or planned surveys by its homogeneous, all-sky, dense, contiguous sampling of our Galaxy's full stellar body with dust-penetrating IR spectroscopy, tracing the entire hierarchy of stellar structures within the Galaxy. **It will measure the distribution of ages, precise elemental abundances, and stellar velocities for more than 5 million stars across an unprecedented volume of the Galaxy (with $\sim 10^5$ stars on the far side; Figure 3**[5]).

Studying the Galactic Genesis ultimately relies on knowing and understanding the complete life-cycle of stars, from birth to death, including their interactions with other stars in the same system. There are numerous outstanding questions in stellar physics, spanning *birth*: How efficiently is gas turned into stars, and what processes determine the mass and multiplicity of stellar systems? *Life and evolution*: How does binarity affect the outcome of stellar evolution? What kinds of stars host what kind of planetary systems, and how does this impact planetary formation and evolution?

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[3] Current LIGO detectors are not sensitive to mergers of such SMBHs. But future missions like the Laser Interferometer Space Antenna (LISA) will probe this mass regime in an entirely separate "window on the universe."

[4] While we fully expect a successful *eROSITA* launch, we note that should it be unsuccessful, our program on spectral variability and synergy with the current and future gravity wave observatories—i.e., LIGO and LISA—and current X-ray facilities will be expanded to mitigate the risk to our scientific program.

[5] `https://www.sdss.org/future/astro2020/`

Death: Stars produce heavy elements in their interiors and can expel them as they die, but which stars are responsible for producing which elements, and how are these elements mixed with future star-forming gas to eventually become the building blocks of planets and life? Even the best stellar models used to understand stellar life cycles have major shortcomings that have been revealed by seismic measurements of stellar interiors as well as spectroscopy of stellar surfaces. For understanding stellar physics and models as well as we need to, and to answer these questions, stellar spectra are key. The MWM will therefore produce the quantities that are needed to empirically test models of the most uncertain galaxy formation physics (Rix & Bovy, 2013; Bland-Hawthorn & Gerhard, 2016). It will produce a spectroscopic map like no other survey either existing or planned, measuring elements belonging to five nucleosynthetic families, typically to a precision of <0.1 dex (Fe, C, N, O, Mg, Al, Si, S, Ca, Ti, S, K, Mn, Ni, Cr) or of <0.2 dex (Na, Co, Cu, V, Ce, Nd). Radial velocities will be determined to a precision of <200 m s^{-1}.

The MWM data analysis will harness the data revolution in stellar spectroscopy that is achieving improved stellar parameters (e.g., Jofré et al., 2014; Ness et al., 2015; Ting et al., 2018) via techniques such as data-driven modeling and machine learning to achieve high precision with lower SNR than previously required. Spectroscopic ages and spectroscopic distances precise to $<10\%$ will be derived for red giant stars extending to the far side of the Galaxy (Martig et al., 2016; Ness et al., 2016; Hogg et al., 2018). This will enable us to dissect the Milky Way by age, and explain its chemo-orbital stellar distribution and growth in a cosmological context, by quantifying where stars are born and how they move over time. The multitude of abundances will detail the meso-structure that we can see—for the first time in the nearby disk from *Gaia* (e.g., Antoja et al., 2018; Trick et al., 2019; Sellwood et al., 2019)—across vast spatial extents. This will revolutionize our understanding of the chemical enrichment history and dynamical evolution of the Galaxy.

Crucial progress in stellar astrophysics will not come from single snapshot spectra taken with the largest telescopes. What is needed is comprehensive data taking: long-duration, high precision, time-series photometry and spectroscopy of large, well-selected samples of single and multiple star systems. All current spectroscopic survey attempts have either focused on narrow subclasses of stars or had very modest samples, and have rarely had much systematic spectral monitoring, let alone all-sky coverage. MWM will use its infrastructure capabilities for a comprehensive investigation of stellar astrophysics and of stellar system architecture, over a range of 10^4 in the masses of the stars that are part of the binaries, 0.5 hours to >12 years in orbital period, and a few pc to >15 kpc in distance from the Sun. The MWM program is designed to consistently and comprehensively measure mass, age, chemical composition, internal structure, rotation, and the presence of companions for vast samples of stars across the color-magnitude diagram (Figure 3[6]). As such, MWM will be the key to turning the study of early stellar evolution into a precision science.

1.5 The Local Volume Mapper (LVM)

Over the past decades, most aspects of cosmology and structure formation have moved to the "precision regime", in many respects thanks to substantial federal investment in facilities on the ground and in space. However, what currently frustrates that precision, and perhaps deeper cosmological insights, are the *galaxies themselves*. It is clear that feedback from recently formed stars to the surrounding interstellar medium (ISM) must be a central regulatory process in galaxy formation

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[6] At `https://www.sdss.org/future/astro2020/`

(Agertz & Kravtsov, 2015; Silk, 1997). Scores of papers present broad observational evidence for the efficacy of such feedback, which lead to numerous global empirical prescriptions for how to treat this in galaxy modeling. But how these feedback processes fight gravity, and over what time- and length-scales they actually transfer energy and momentum from young stars (and supernovae) to the gas, is inarguably less well-understood than the dark-matter driven hierarchical assembly dynamics of galaxies. The ideal observational basis to tackle this fundamental problem of galaxy formation would be a contiguous and high-resolution map of the gas's physical state and kinematics across an entire galaxy, along with a comprehensive mapping of the individual young and energetic stars. This mapping is what SDSS-V's Local Volume Mapper (LVM) sets out to do for the Milky Way and several Local Group and nearby galaxies. **LVM will directly probe the physical scales from which the global correlations arise, and witness the physics of galaxy formation at the "energy injection scale".**

The temperature and density structures in the warm ionized ISM revealed through strong and auroral emission lines are unresolved in typical Integral Field Unit (IFU) surveys with resolutions of 10s–100s of pc. When probed at pc-resolution, the degeneracy in nebular emission induced by integrating entire H II regions gives way to diagnostics of interior 3D geometry, gas densities and temperatures, and optical depth to radiation. These provide existing methods (established in the LVM wavelength range) the necessary information to make quantitative statements on the impact of all the individual feedback forces. Further, by combining the nebular diagnostics and spectral information, LVM will complement the MWM spectra of individual stars, improving constraints on integrated cluster spectral effective temperatures to within ≈ 0.5 kK.

In practical terms, LVM will take the first step towards a full spectroscopic image of the sky, providing optical IFU data-cubes to resolve, e.g., SF structures, GMCs, H II regions, and young stellar clusters. The LVM will cover the bulk of the MW disk at 0.1–1 pc resolution, the Magellanic Clouds at 10 pc resolution, M31 & M33 at 20 pc resolution, and Local Volume galaxies out to a distance of 4 Mpc at $\sim$100 pc resolution—in total about 1 steradian of sky. To enable this, we will build two clusters of medium resolution ($R \sim 4000$), fiber-fed, IFU spectrographs covering the full optical wavelength range. These spectrographs will be fed by a suite of small-to-medium aperture telescopes with very wide fields of view (FOV) in the northern and southern hemispheres. The range of telescope apertures provides spatial resolution and FOV *tailored* to map large areas across nearby galaxies (Figure 4[7]). The LVM will also provide essential context to the stellar astrophysics MWM programs by providing the ISM context around the targeted young stars. LVM's coverage of $\sim$4000 deg^2 in the Milky Way and $\sim$100 deg^2 in the Magellanic Clouds, the Local Group, and the Local Volume is 10^3–$10^4\times$ larger than any existing IFU dataset. For comparison, SDSS-IV/MaNGA's coverage of 10^4 low-redshift galaxies adds up to only 0.5 deg^2, and all of the single fiber SDSS spectroscopy thus far totals a modest number of square degrees. LVM's coverage of the LMC or M31 will contain as many resolution elements as all of MaNGA's galaxies combined.

By prioritizing unprecedented physical resolutions, LVM will quantitatively measure the physics of star formation feedback. LVM is the only optical IFU survey under development that can combine with the MWM's information on young stars in the Milky Way, and with existing HST or ground based photometric surveys of young stars in the the Local Group, to map, model, and understand where the feedback energy and momentum are produced and where they are absorbed, with observations on the critical $\sim$parsec-sized scales.

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[7] At `https://www.sdss.org/future/astro2020/`

2 Technical Overview

MWM & BHM: The centerpiece of SDSS-V's technology development is the robotic positioner focal plane system that will replace the current hand-populated plug-plate fiber system[8] on both telescopes and enable the required high survey rate. The FPS is built by the Department of Astronomy at The Ohio State University, Columbus OH under the experienced leadership of Professor Rick Pogge. We utilize existing developments of robotic fiber positioners for astronomy to adapt a proven solution to satisfy our scientific aims and thereby, we have been able to significantly shorten the research and development cycle. The positioners were designed by the Lausanne AstroRobotics team and will be fabricated by the Swiss micro-precision systems company MPS Faulhaber, with the first article expected to arrive in August 2019. Early verification of key components is crucial for our success oriented schedule to retire risks, hence fiber viewing, as well as guiding and focus cameras have been purchased for early on site engineering test runs and integration into a pre-commissioning instrument, respectively. At the same time, control software design efforts are proceeding in parallel and in close collaboration with the hardware teams. The control software team, under the leadership of Jose Sanchez-Gallegos, has already developed a working prototype for the collision avoidance path planning tool for the positioners. The FPS Preliminary Design Review was held in early November 2018, and the Final Design Review in May 2019.

LVM: The LVM instrument is based around tightly packed, abuttable bundles of fibers (over 3000 in total), drawing and expanding on SDSS's existing MaNGA heritage technologies. The fabrication of the required six modified DESI-like 3-channel spectrographs is underway at Winlight Systems, S.A. Paris, France, who also built the DESI spectrographs. The CCD devices for the detector systmes have also already been ordered. The southern hemisphere version of LVM-i will be commissioned first. At LCO, the enclosure design is in progress and the site has been identified, with construction planned for the southern hemisphere summer in late 2019/early 2020. The telescope designs are in an advanced state, and discussions with various vendors have been initiated as part of the telescope subsystem RFQ. All of these hardware developments use proven technology for rapid implementation by 2021. The LVM-i is led by Dr. Nicholas Konidaris of the Carnegie Observatories.

Data Archive and Access: With its large data set and open public archives, SDSS-V takes advantage of the ongoing revolution in data storage and practices. SDSS has maintained open data archives since 2001 and has established the gold standard of archiving and serving ground-based data to the astronomical community and to the public. Over 8000 refereed papers have used SDSS data, more than 80% of which were written outside of the SDSS collaboration. SDSS data are accessed at rates exceeding 10 TB of downloads and 50 million web hits per month.

The Optical/IR System Roadmap Committee Community Survey[9] found in 2012 that over 30% of U.S. astronomers used SDSS data, making it the 2nd most utilized astronomical facility in the country. **Within the broader field of data science, the open data policies and convenient and efficient data access systems have made SDSS, by some measures, the most important single data set in the field of data science** (Stalzer & Mentzel 2015). These well-established archives, with some expansions, will host and serve SDSS-V data through roughly-annual public data re-

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[8] See a demonstration of plate-plugging in action: `https://www.youtube.com/watch?v=i6ZOUDWRwtg`.

[9] `https://ast.noao.edu/about/committees/system-roadmap`

leases, enabling the data to continue its critical role in the U.S. astronomical data ecosystem. The newest aspects of SDSS-V—specifically, the time domain spectroscopic monitoring and the wide-field integral field data—drive new requirements for data distribution and visualization through the SDSS web applications and data portals.

These improvements will ensure that astronomical researchers at all levels, including undergraduate/graduate student researchers and astronomers at institutions without their own telescope access, can work at the frontier of astronomical science. This data access is a key benefit of SDSS-V to the U.S. community.

3 Technology Drivers

Each of our mapper programs makes use of existing technologies to do something new and scientificially groundbreaking. In the case of each of our mapper programs, the regime we reach with our technology improvements is area and rapid survey speed. These do not require new technological development, but rather innovative deployment of known technologies.

4 Organization, Partnerships, and Current Status

The SDSS-V program emerged from an extensive review process in which white papers were solicited from the international astronomical community. The program is crafted from that review process and presented to public and private foundations as well as individual institutions for funding.

The SDSS-V Project is governed under the auspices of the Astronomical Research Corporation (ARC). An overview of the relationships between the various organizational structures and the top survey management is shown on our Figure website. The Board has delegated the oversight and management of SDSS-V to the Advisory Council (AC). Advisory Council actions are governed by the Principles of Operation-V (PoO-V[10]). The PoO-V has been approved by the Board of Governors and has been agreed to by all institutions joining SDSS-V. Amendments to the PoO-V must be approved by the Board of Governors on the recommendation of the AC by processes described in the PoO-V.

The SDSS-V Project is organized into groups ("Groups"). Each Group has a leader who is responsible for managing that Group's work. Groups report to the Director in the Central Project office or her delegate. The distribution of work within the Project is defined by a Work Breakdown Structure (WBS). The WBS captures all of the tasks of the Project for each of the 15 Groups, and it serves as the base for defining the Project Schedule and Master Budget.

The Advisory Council transmits the Director's budgets along with its recommendations to the Board for approval.

SDSS-V currently has signed Memoranda of Understanding with 30+ institutions globally and is iterating on drafts with another ~10 institutions[11].

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[10] `https://www.sdss.org/wp-content/uploads/2017/11/SDSS-V-Principles-of-Operation.pdf`

[11] The current institutional partnership can be viewed here: https://www.sdss.org/future/astro2020/

5 Schedule

SDSS-V is proceeding in two phases: Instrumentation development and survey planning, and survey operations. The Project Schedule (Fig. 1) is tied to the WBS tasks for each Group and is constrained by the approved Project duration and funding arrangements. The CPO manages the schedule with input from the Groups.

6 Cost Estimates

SDSS-V's funding model is dominated by support from institutional members, plus contributions from private foundations and individual donors The project is currently 65% funded.

The budget was constructed bottom-up from each of the 15 WBS groups. Some WBS elements of the program are well-constrained; others include a substantial instrument development component. The CPO carries contingency to account for uncertainty in budget elements. As our project has matured through the planning phase, we have gotten high-fidelity vendor quotes for much of the hardware procurement. We show in Figure 5 on the website the SDSS-V budget divided among the major elements of the program.

7 Conclusions

The SDSS-V program is primed to make great scientific strides for the entire astronomical community in the 2020–2030 timeframe. Should we succeed in carrying it out, we will have a time-domain spectroscopy machine that is scientifically innovative, constructively managed, efficient, and available to the *entire astronomical community*. While there are many far larger programs seeking the attention of the National Academy, we request your consideration and endorsement for a visionary project that has an excellent track record and a sensible cost. The return on investment will be truly extraordinary.

Major Milestones	Target Date
SDSS-IV ends at APO	June 2020
SDSS-IV ends at LCO	September 2020
APO SDSS-V Corrector (ASC)	November 2020
Preliminary Design Review	October 2018
Critical Design Review	June 2019
Build	September 2020
Integration	October 2020
Shipment to APO	November 2020
On-Telescope Testing	November 2020
Focal Plane System (FPS)	January 2021
Preliminary Design Review	November 2018
Critical Design Review	April 2019
Build Phase	October 2020
Commissioning Instrument (CI)	June 2020
LCO LAIT	July 2020
LCO Ship & Commissioning	October 2020
APO LAIT	November 2020
APO Ship & Commissioning	January 2021
APO Hardware Activities	September 2020
BOSS removal	July 2020
APOGEE BPR & Servicing	August 2020
APOGEE Fabry-Perot APO	September 2020
BOSS Upgrade Prototype and Build	July 2020
BOSS Upgrade integration	July 2020
LCO Hardware Activities	April 2021
Du Pont Upgrades	December 2019
BOSS installed at LCO	September 2020
APOGEE BPR and Servicing	October 2020
APOGEE Fabry-Perot LCO	April 2021
Control Observatory Software	May 2021
SW Framework	August 2019
Targeting and scheduling	May 2021
Input for MOS targeting database	October 2019
FPS control SW	October 2019
Guiding and Acquisition SW	February 2020
Field Viewing Camera	May 2020
Testing with FPS CI at LCO	February 2020
Testing with FPS CI at APO	June 2020
LCO BOSS Spectrograph SW	February 2020
Macro actor	August 2020
Servers	May 2020
Reduction Pipelines	July 2020
Quick Data Reduction Pipeline	May 2020
Science Data Reduction Pipeline	June 2020
Observer Interfaces	October 2020
Plate operations updates	March 2020
LCO SW Commissioning	October 2020
APO SW Commissioning	January 2021
Survey Operations	December 2025
Science Survey Observations	June 2025
Plate Observations at APO	November 2020
Robotic Observations at LCO	June 2025
Robotic Observations at APO	June 2025
Data Releases	December 2025
Data Release 18	December 2021 *(tentative)*
Data Release 19	December 2022 *(tentative)*
Data Release 20	December 2023 *(tentative)*
Data Release 21	December 2024 *(tentative)*
Data Release 22	December 2025 *(tentative)*

Figure 1: **SDSS-V High-Level Schedule.**

References

Agertz, O., & Kravtsov, A. V. 2015, ApJ, 804, 18

Antoja, T., Helmi, A., Romero-Gómez, M., et al. 2018, Nature, 561, 360

Bland-Hawthorn, J., & Gerhard, O. 2016, ARA&A, 54, 529

Hogg, D. W., Eilers, A.-C., & Rix, H.-W. 2018, arXiv e-prints, arXiv:1810.09468

Jofré, P., Heiter, U., Soubiran, C., et al. 2014, A&A, 564, A133

Kollmeier, J. A., Zasowski, G., Rix, H.-W., et al. 2017, ArXiv e-prints, arXiv:1711.03234

Kormendy, J., & Ho, L. C. 2013, ARA&A, 51, 511

Liu, X., Shen, Y., Bian, F., Loeb, A., & Tremaine, S. 2014, ApJ, 789, 140

Martig, M., Fouesneau, M., Rix, H.-W., et al. 2016, MNRAS, 456, 3655

Merloni, A., Predehl, P., Becker, W., et al. 2012, ArXiv e-prints, arXiv:1209.3114 [astro-ph.HE]

Ness, M., Hogg, D. W., Rix, H.-W., Ho, A. Y. Q., & Zasowski, G. 2015, ApJ, 808, 16

Ness, M., Hogg, D. W., Rix, H.-W., et al. 2016, ApJ, 823, 114

Pei, L., Fausnaugh, M. M., Barth, A. J., et al. 2017, ApJ, 837, 131

Peterson, B. M. 2014, Space Sci. Rev, 183, 253

Rix, H.-W., & Bovy, J. 2013, The Astronomy and Astrophysics Review, 21, 61

Runnoe, J. C., Cales, S., Ruan, J. J., et al. 2016, MNRAS, 455, 1691

Sellwood, J. A., Trick, W. H., Carlberg, R. G., Coronado, J., & Rix, H.-W. 2019, MNRAS, 484, 3154

Sharma, S., Bland-Hawthorn, J., Johnston, K. V., & Binney, J. 2011, ApJ, 730, 3

Silk, J. 1997, ApJ, 481, 703

Stalzer, M., & Mentzel, C. 2015, ArXiv e-prints, arXiv:1503.08776 [cs.DL]

Ting, Y.-S., Conroy, C., Rix, H.-W., & Cargile, P. 2018, arXiv e-prints, arXiv:1804.01530

Trick, W. H., Coronado, J., & Rix, H.-W. 2019, MNRAS, 484, 3291