Title: The Sloan Digital Sky Survey as an Archetypal Mid-Scale Program

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1. How the Decadal Survey Should Use This White Paper

We describe the Sloan Digital Sky Survey (SDSS), to better inform Decadal Panel decisions regarding mid-scale programs by providing one archetypal example. The key insight from SDSS underlying our recommendations is that mid-scale programs need to take advantage of all available resources to reach the highest levels of excellence.

In "Astro2010: The Astronomy and Astrophysics Decadal Survey," mid-scale programs were the second-ranking priority among ground-based activities, to bridge the gap between individual or small group investigations and billion-dollar scale projects. Today, these programs still represent a rich, but underfunded, opportunity. Thoughtfully designed and rigorously executed mid-scale programs can be flexible, scientifically productive, and cost-effective, and support early career training and inclusivity in astronomy. However, Astro2010 did not provide any guidance regarding how mid-scale programs should be structured except for defining their budget scale.

SDSS represents a mid-scale program of long standing that has delivered transformative results and benefited a large fraction of U.S. and international astronomy. Sections 3 through 8 of this document describe the technical, scientific, and organizational aspects of SDSS that underpin this success over the last twenty years, motivating six recommendations that the funding mechanisms for mid-scale programs should encourage.

Midscale programs should:

1. *Adopt inclusive policies and foster the participation of underrepresented groups in their management and science collaboration.*
2. *Adopt early and mid-career training as a specific goal.*
3. *Develop thoughtful and effective collaboration policies to maximize their science output.*
4. *Not only make data public promptly, but also make it easily accessible through powerful and well-documented interfaces.*
5. *Adopt open and competitive planning processes involving broad communities of interest.*
6. *Pursue the full range of funding opportunities, including federal investment, but also foundation and substantial individual institutional investments.*

Our overarching message is that SDSS has been such a continuing and broadly influential success because the approaches outlined above allow it to harness every resource available. Its open planning, public-private partnerships, good collaboration policies, open data, early career training, and inclusive policies are designed to enable all members to contribute in multiple ways. Mid-scale programs that do not adopt these approaches are leaving money, effort, talent, and ingenuity on the table. The funding mechanisms for mid-scale programs therefore need to be designed to ensure the adoption of these recommendations.

2. Overview of SDSS

The SDSS has consisted of a series of projects using a common, evolving set of facilities, managed by the Astrophysical Research Consortium (ARC[1]) and supported by a much broader set of member institutions. As we detail in Section 3, over time funding has come from the Sloan Foundation, federal agencies, and member institutions. **Over the past ten years, the majority of funding has been provided by the member institutions (over 70% in SDSS-IV, from over sixty institutions).**

SDSS has facilities at two observatories. At Apache Point Observatory (APO), the 2.5-m Sloan Foundation Telescope feeds two spectrographs: BOSS, a moderate resolution optical spectrograph, and APOGEE, a high-resolution infrared spectrograph. A plug-plate system allows single fibers and integral field fiber bundles to patrol a 3-degree diameter focal plane. A full-time team of twenty-five observers, engineers, management, and staff operate the telescope full-time for SDSS. At Las Campanas Observatory (LCO), the 100-inch du Pont Telescope feeds a clone APOGEE spectrograph through a similar plug-plate system. Currently, SDSS uses the du Pont Telescope for 100 nights per year, with observers employed by eight Chilean universities. The next SDSS phase plans to operate close to full time on the du Pont Telescope in a manner more closely integrated with the LCO staff. Further support for software and hardware engineering at APO and LCO is provided by ARC and SDSS member institutions.

The ARC Board of Governors allocates the use of the Sloan Foundation Telescope, oversees all SDSS activities, and performs the business management for SDSS. There is no ongoing source of funding for operations, and thus SDSS is planned in separately-funded phases. Each phase of SDSS is treated as its own project, encompassing both construction and observatory operations for a fixed term and with its own management and oversight. Each phase of SDSS also has its own science collaboration, which is distinct from but closely tied to the project team.

As explained below, the planning process for each phase begins several years prior to the start of observatory observations, and thus the construction for one project begins during the operations for the prior project. As of this date, there are five phases:

- **SDSS-I** (2000 - 2005): Conducted Legacy Survey: imaging and spectroscopy of nearby galaxies, luminous red galaxies, quasars. Used imager and SDSS spectrograph at APO.
- **SDSS-II** (2005 - 2008): Completion of Legacy Survey, SEGUE-1 survey of Milky Way stars, and SDSS supernova survey. Used imager and SDSS spectrograph at APO.
- **SDSS-III** (2008 - 2014): BOSS large-scale structure survey, APOGEE-1 infrared survey of Milky Way stars, SEGUE-2 optical survey of Milky Way stars, MARVELS planet search program. Used imager, SDSS spectrograph, BOSS spectrograph (upgraded version of SDSS spectrograph), APOGEE spectrograph, and MARVELS spectrograph at APO.
- **SDSS-IV** (2014 - 2020): eBOSS large-scale structure survey, MaNGA integral field spectroscopic survey of galaxies, and APOGEE-2 infrared spectroscopic survey. Uses

[1] ARC: Georgia State University, Johns Hopkins University, New Mexico State University, University of Colorado - Boulder, University of Oklahoma, University of Virginia, University of Washington, University of Wyoming.

BOSS spectrograph (with single fibers and fiber bundles) and APOGEE spectrograph at APO, and APOGEE South spectrograph at LCO.

- **SDSS-V** (2020 - 2025): Milky Way Mapper, Black Hole Mapper, and Local Volume Mapper (see the Kollmeier et al. APC white paper “SDSS-V: Pioneering Panoptic Spectroscopy”). Developing a robotic fiber positioner system to feed APOGEE and BOSS spectrographs at both APO and LCO, and large integral field units on small telescopes to feed new optical spectrographs. This phase is not yet fully funded.

These programs’ data have been used in at least 8000 publications[2]. More than 80% of these publications use the public data; i.e. are not publications written by the collaboration on private data. SDSS imaging provided the deepest, widest, most reliable survey of its time and continues to be used as a reference. SDSS has measured over 90% of known spectroscopic redshifts. SDSS’s local galaxy survey and its integral field survey are each the largest in existence and provide key constraints on galaxy evolution. SDSS established the baryon acoustic oscillation as a standard cosmological tool and has derived from it the most precise distance measurements to date between redshifts z ~ 0.3 to 2.5. SDSS has mapped stellar ages, dynamics, and detailed abundances throughout the Milky Way, including the dust-obscured plane. SDSS discovered the class of ultra-faint dwarf galaxies and numerous other new substructures in the Galactic halo. SDSS has made discoveries too numerous to list individually here that have advanced our understanding of the universe on the scales of planets, stars, galaxies, and cosmology.

3. Inclusiveness in Mid-Scale Programs

Astronomers are not a representative cross-section of the society, which represents an under-utilization of the full pool of talent available. This representation can be improved by creating a more inclusive climate in our community and taking proactive steps to support the participation of underrepresented groups. **All mid-scale programs should have fully integrated efforts to address inclusiveness within the projects themselves and to increase the participation of underrepresented groups in astronomy more generally. SDSS provides both models and lessons in inclusiveness from its history.**

A major issue within SDSS over its history has been the lack of representation of women in the project management. Gender balance in the scientific collaboration, as measured by lead authorship on papers, has tended to track the astronomy population (which is still well below parity). However, within the project itself, leadership at times consisted of as few as one woman within a leadership team of over twenty people. While this imbalance was recognized for a long time and identified in external funding reviews at least as early as 2007, SDSS did not take steps to address and mitigate the issue until the Sloan Foundation identified it during its review of SDSS-IV in 2012. This history illustrates the important role that funding agencies can play in establishing priorities. At the time, SDSS-IV was facing multiple existential threats and therefore, despite a generally positive inclination towards inclusiveness, was not devoting real resources to the issue. The Sloan Foundation made the gender balance and overall inclusiveness of the project and collaboration a truly existential issue that we had to address.

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[2] As measured by refereed publications with “SDSS” in the abstract.

SDSS has since taken actions on this issue and broader issues of inclusiveness (beyond gender), currently utilizing a standing Committee On Inclusiveness in SDSS (COINS) to develop and execute these ideas. They include:

- Implementing best practices in recruitment in seeking leadership at all levels, including clear definition of roles, fixed duration appointments, open advertisement, and review of candidate lists by the top management. These policies allow “new blood” to join the project management more easily.
- Developing a Code of Conduct and best practice recommendations for conducting teleconferences and meetings, to ensure full participation and a welcoming environment.
- Conducting periodic demographic surveys of the SDSS to track the changes of its population over time and try to identify barriers to participation. These surveys have led to a series of recommendations to the project management over the past few years.
- Reinvigorating the position of Ombudsperson and advertising their role in addressing complaints that the project does not successfully address.
- Conducting collaboration meeting activities, including training sessions, discussion sessions, science discussion activities between senior and junior collaboration members, and in 2014 a site visit and climate review by the American Physical Society Committee on the Status of Women in Physics.

These actions are not radical but are effective in establishing an inclusive climate and in increasing the diversity of the project and collaboration; they also help all collaboration members, not just those in underrepresented groups. Gender balance in the SDSS-IV project management has only modestly improved, due to its very low rate of turnover. However, by adopting best practice recruitment from the beginning of the SDSS-V phase, in terms of gender balance SDSS-V management is representative of the population at large.

To improve the participation of underrepresented minorities in astronomy more generally, SDSS has also established a Faculty and Student Team (FAST) program, focused on students around the point of embarking on a PhD (either while they are undergraduates or early in their graduate career). This program allows groups to join the SDSS as project members and also provides financial support. An initial three-year program supported thirty students in four groups; at least nine of these students are now in Ph.D. programs in the physical sciences. A second three-year program is now underway. This program works by bringing the groups fully into the collaboration and leveraging the broad and positive scientific collaboration to help the teams use SDSS to best address their science interests.

That SDSS did not adopt these policies and programs earlier in its history represents a missed opportunity and means that SDSS was not making the most of its available resources, i.e. people. All mid-scale programs should learn from this lesson and build components like COINS and FAST in from their outset.

4. Early and Mid-Career Training Opportunities

Astronomy is growing in its dependence on mid- and large-scale projects in addition to focused, individual-led or small group-led programs. **SDSS showed that mid-scale programs can provide a training ground for technical and project management experience that students, postdocs, and junior faculty can take advantage of in order to become leaders in both future mid-scale programs and in large-scale programs.**

Collaboration-driven, mid-scale programs like SDSS afford many opportunities to develop project experience that prepare individuals for participation at a higher level and/or in a larger project. These programs are small enough that technical involvement does not have a large barrier to entry or involve large adjustments to adopt the necessary project management protocols. At the same time, they are big enough that individuals acquire the experiences in project management necessary to internalize the importance of budgets, schedules, work breakdowns, interface definition, reviews, and clear lines of communication.

Mid-scale programs can support and encourage this training through:

- Clearly defining both technical and leadership roles and seeking them through open solicitations, with encouragement to promising junior scientists to apply.
- Defining multiple levels of responsibility so individuals can gain experience with greater supervision and lower stakes before rising to higher levels of responsibility.
- Providing explicit education in project management to new project contributors to inculcate the necessary culture within the project.
- Encouraging technical contributors to write up and publish the technical contribution, ideally through a refereed publication.

SDSS has had success in preparing individuals for further leadership roles. A recent survey of SDSS Architects from all phases of SDSS found that 50% of respondents had held a leadership role in a project with a budget greater than $10M; although some of those were leadership roles in SDSS itself, about three-quarters of these roles were in projects other than SDSS. Since there are hundreds of Architects over the history of SDSS, this result indicates that a substantial portion of the community leading the next generation of projects has come through SDSS. Mid-scale programs should be designed to continue to provide such training grounds in order to help train succeeding generations of astronomers.

5. Many-Institutional Scientific Collaborations

The SDSS collaboration consists of participants at its member institutions, and ensuring the scientific effectiveness of this collaboration is the product of continuous effort. The ground rules for scientific collaboration are contained in the Publication Policy, which is defined at the beginning of each phase and changed (if ever) only through agreement of the Advisory Council. **A key lesson from SDSS is that its Publication Policy, which emphasizes communication**

within the scientific collaboration and freedom to work on the projects of one's choice, can be highly effective and efficient.

The collaboration is led by the Scientific Spokesperson, an elected position with a three-year term. The Spokesperson chairs the Collaboration Council (CoCo), which represents the scientists at member institutions. The Spokesperson also oversees the Scientific Working Groups, each of which provides a forum for communication and organization around specific scientific topics. The Working Groups have mailing lists and regular teleconferences, at which science results are presented and discussed.

The CoCo leads the development of the Publication Policy in each phase. Although it has evolved through each phase, the Publication Policy is based on principles that have held constant because the science collaboration is satisfied with them. The essential rules are simple:

- All science projects are announced when they are begun.
- All papers based on proprietary data are announced and distributed to the collaboration in final form at least three weeks before submission to a journal or to a preprint archive.

These principles allow different science projects to cover overlapping or even identical topics. Collaboration members may associate themselves with any project, in which case they are updated on the project progress, but do not necessarily earn paper co-authorship. After paper announcements, all collaboration members may comment or request co-authorship, but there is no paper approval process or formal review of the paper itself.

Authorship and authorship order is determined by the lead investigator on the paper. In most cases, co-authorship by SDSS members must be earned due to specific contributions to the paper as determined by the lead investigator. SDSS Architects, those determined to have made at least one FTE-year of contributions to the project, may claim authorship on any scientific paper from the collaboration even without a "direct" contribution to that paper.

Non-members of SDSS may be included as authors in SDSS publications as approved External Collaborators. External Collaborators are approved if their participation benefits SDSS members; for example, their contributions to the paper should not duplicate available effort within the collaboration. This policy allows SDSS members to take advantage of external collaborations without allowing unrestricted access to proprietary data by non-members.

These rules are designed to ensure communication within the collaboration about ongoing activities. When science projects overlap or are reaching conflicting conclusions, the appropriate Scientific Working Group chairs may (and often do) mediate the issue so that the efficiency of the scientific effort is maximized and so that differences are investigated (and if possible resolved) prior to publication. However, the collaboration at large cannot prevent or delay publication of results based on a scientific disagreement. For authorship or other disputes, there are Publication Coordinators and a clearly-articulated mechanism for addressing complaints.

These rules, with minor modifications, have been repeatedly re-adopted after a recommendation by the CoCo through four and soon five iterations of SDSS, which indicates that the collaboration is generally satisfied with them. Nevertheless, issues arise that require the attention of the Spokesperson, CoCo, Working Group chairs, and Publication Coordinator, not always to the satisfaction of all SDSS members. For example, determining what constitutes an authorship-worthy contribution, how and when to protect student Ph.D. theses, how to evaluate External Collaborator requests, and how to conduct large coherent efforts under these rules, all pose important problems that SDSS addresses through active leadership practices and clearly articulated mechanisms. Overall, SDSS provides a compelling model for any broad, diverse, mid-scale or large-scale science collaboration to consider.

6. Open Data Policies and Scientific and Community Impact

SDSS has, since its beginning, provided regular, well-documented, and high functionality public data releases, while still succeeding in funding a project with a majority of contributions from member institutions. **A key lesson from SDSS is that such public data releases increase the scientific impact of the data by a factor of five (as measured by publications), that they have ancillary benefits to the collaboration members, and that they do not prevent funding the project primarily from institutional contributions.**

While a complete review of SDSS's history of data releases is beyond our scope, the following important features are critical to their success:

- Data is released within one or two years of its acquisition.
- All data and software is released, including raw data, meta-data, and intermediate results, not only the final resulting images, spectra, and catalogs. Doing so enables better traceability and better investigations of reproducibility of scientific results, and also allows for unanticipated analyses which require the intermediate data.
- Data is thoroughly documented, including file formats and data structure, but also including reduction software, methods, and example use cases. There is a helpdesk that responds to hundreds of queries per year.
- Several avenues to data access are available, from just flat files (available through several methods, like rsync, Globus, or http), to interactive interfaces to spectra and images, to programmatic APIs, to server-side SQL notebooks and Jupyter notebooks.

Providing this data access has a cost (above what would be necessary to serve data to the collaboration alone) that is a substantial fraction of the survey budget, probably between 5-10%. However, over 80% of publications involving SDSS are based on public data. This fact implies that a properly designed data release can increase the project impact on science by around a factor of five, which is an excellent return on investment.

In addition, public data releases provide several benefits to the collaboration:

- The commitment to the data releases serves to guarantee to the collaboration a regular cadence of well-organized, coherent, and fully-documented data sets.
- Data releases are a platform for distributing Value Added Catalogs that survey members create and may want to make available to the public in an integrated form with the SDSS data (or in fulfillment of data management requirements of their individual grants).

- The data releases enable education and outreach activities, from large scale programs like Galaxy Zoo, SDSS Voyages, and SDSS Plates For Education, to smaller scale incorporation of data-oriented activities in individual faculty's courses.
- The large impact of the data releases is impressive to foundations and agencies and helps to get non-member institutions familiar enough with SDSS data to consider joining, both of which help ultimately to fund the project long-term.

All mid-scale programs should support public data releases with full documentation and useful access methods, which greatly multiply the project impact. Although providing a fully-fledged data release comes at some cost, it also provides tangible benefits, and SDSS has demonstrated that doing so does not prevent a funding model based on data access prior to public release.

7. Scientific Planning Processes Within SDSS

The original SDSS facility was designed for the specific purposes of SDSS-I. Starting with SDSS-II, ARC has decided upon the use and development of these facilities through a competitive process described below. This process has guided the facilities development and the scientific goals of the series of major survey programs. **A key lesson from SDSS is that for private mid-scale facilities, an open competitive process for the selection of dedicated scientific programs is effective, can raise the quality and breadth of the science, and can engage and attract new scientific and technical experts.**

From SDSS-II through SDSS-V, the facilities have been allocated in three- to six-year increments and dedicated to a small number of major survey programs. Planning for each phase typically has begun two to four years prior to the anticipated start of its observing, with a proposal process led by ARC. Members of the SDSS and the broader community have been invited to submit proposals for new programs, either to use the existing facilities or to build new capability. The proposals have been sent for external reviews and considered for approval by a Futures Committee consisting of both existing ARC or SDSS members and non-members. Futures Committees have sought to construct overall programs that justify raising tens of millions of dollars; they have always considered the possibility seriously that no program is sufficiently compelling and that the facility should be closed. For each phase, the futures committee recommended a broadly-defined scientific plan, which ARC then approved. ARC then appointed a Director of the project, who led the definition of science requirements, the project construction and operations, and fund-raising.

This process differs from those typical for both private and public facilities:

- Unlike most private facility planning processes, the SDSS planning process has been open to outside proposers. The considered and accepted proposals have not been limited to those submitted by ARC institutions or by already-existing SDSS members.

- Unlike most public facility time allocation or grant allocation processes, the ARC futures committee takes a direct and active hand in shaping the final proposals. For example, the committee engages in direct communication with the proposers, to better understand or to influence the proposals. The committee would also at times recommend alterations of or combinations of proposals. As a very successful example, the BOSS program in SDSS-III was the product of two different large-scale structure proposals.

The result is that at various stages the SDSS program has accreted key partners and grown its scope and its base of institutional support. For partners, joining SDSS is not an indefinite commitment to a particular facility. There are a number of examples of institutions entering the SDSS collaboration and becoming key financial or technical contributors because their staff could be participants in the proposal process and could lead programs within SDSS, despite not being associated with ARC. With regard to developing new instrumentation or functionality, the process has allowed new expertise and technical capabilities to enter the program over time.

This open planning process represents a robust model for any existing mid-scale facility that seeks to serve a large scientific community. It has allowed SDSS to successfully and coherently adjust to a changing science and community landscape for over twenty years.

8. Funding Model for SDSS

SDSS has been supported at different times by the Sloan Foundation, the National Science Foundation (NSF), the National Aeronautics and Space Administration (NASA), the Department of Energy (DOE) Office of Science, and individual institutions. The federal funding component has been critical in seeding the project, and federal support has been leveraged into increased institutional membership contributions. **Over the past decade, the majority of financial support has been provided by the institutional members (70% in SDSS-IV, from over sixty institutions). SDSS provides a model for how high-quality scientific programs can and should leverage federal agency and foundation resources by raising substantial private funds, allowing them to pursue the most ambitious possible programs at a given level of agency or foundation investment.**

Over its history, the funding model of SDSS has slowly evolved. The Sloan Foundation has always provided around 25% of its support. The relative fraction of federal and institutional contributions has shifted over time. For SDSS-I construction and operations, the remainder after the Sloan Foundation contribution was paid by federal grants and institutional contributions in approximately equal measure. In SDSS-IV, the total federal investment was around 4% (from the DOE Office of Science) and the remainder (~ 70%) was from institutional contributions. This shift was not by the choice of the SDSS management. At the beginning of SDSS-IV construction in 2012, NSF was not accepting unsolicited mid-scale proposals; when MSIP was established in late 2013, SDSS-IV sought but did not obtain funding from the NSF over two MSIP cycles. SDSS-V has been denied funding in one MSIP cycle and is currently seeking funding through the NSF MSRI and MRI programs.

The institutional membership model is defined at the beginning of each project under rules that are consistent throughout its lifetime, though in principle subject to change by the membership. For Full Institutions, all employees of the institution have survey membership. For Associate Institutions, a fixed number of faculty and postdocs have survey membership; the price per "slot," which is a faculty member plus a postdoc (plus students) is ⅛ that of a Full Institution. The price for a Full Institution has grown slowly between each phase (at a rate comparable to inflation) and is $1,150,000 for SDSS-V, payable over about six years. The project also accepts in-kind contributions towards membership, if those contributions offset the project budget.

Institutions' motives for contributing to the survey vary, but include the following:

- Assuring the success of the project.
- Influencing the scientific goals of the project.
- Participating in the scientific collaboration.
- Access to survey data prior to its public release.

That the survey provide the last three benefits is critical to assure that enough institutions contribute financially. Data access prior to public release is a tangible benefit, but membership in SDSS provides also the ability to influence project plans and to join a large and supportive science collaboration. For many members, these benefits are primary and alone are enough to motivate membership. This fact underscores the importance of good collaboration policies to encourage institutional memberships.

SDSS is a proof-of-concept that mid-scale programs do not need and should not expect to have full, or even majority, support by federal funding agencies. Rather, its models of leveraging modest federal and private support through extensive institutional buy-in has proven highly successful.

9. Summary

The SDSS experience as a mid-scale project should inform how other similar-sized projects set their ambitions and how they approach their technical, management, collaboration, and fund-raising challenges. SDSS policies in all of these areas are designed to harness all the resources available to it, through inclusiveness, through training of personnel, through open science and data policies, through open and competitive planning processes, and by drawing heavily on institutional investment (not just federal and foundation investment) to finance the projects. We hope that these policies will serve as a model to other mid-scale programs in the coming years.