AS4[1] Executive Summary

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AS4 is the ***first all-sky, time-domain spectroscopic survey***, with observational capabilities that will remain unmatched for the foreseeable future. This unique survey facility is poised to transform broad areas of astrophysics, in particular: understanding the formation of our Milky Way and other galaxies, along with the astrophysics of stars and of supermassive black holes.

In one flagship program, AS4 will provide spectroscopic data for stars across the Milky Way. This survey is unrivaled in its combination of sky coverage, time sampling, and systematic target selection throughout our Galaxy, enabled by dual-hemisphere, wide-field infrared spectroscopy. From this, we will:

- Understand the **genesis of our Galaxy** by acquiring
  - a first **global** picture of Milky Way structure and dynamics, placing our Galaxy precisely in the overall realm of galaxies,
  - comprehensive constraints on the evolutionary processes that shaped our Milky Way and other galaxies, and
  - a map of when and where the broad range of chemical elements were created in our Galaxy.
- Take the understanding of fundamental **stellar physics**, the pillar upon which much of astrophysics rests, to a new level. In combination with the *Gaia*, *Kepler* and TESS space missions, AS4 will transform our understanding of
  - the origin of supernovae,
  - the difference between planet-hosting and non-hosting stars,
  - binary stars across the Hertzsprung-Russell diagram -- as witnesses to star-formation physics, as drivers of stellar evolution and as laboratories to test stellar evolution, and
  - young, massive stars, through a vast sample of (near-IR) spectra.

At the same time, AS4 will open new frontiers in extragalactic astrophysics: it will enable us to understand **quasars as dynamical phenomena** -- through both reverberation mapping and direct black hole mass estimates from multi-epoch spectroscopy that samples time-scales from days to more than a decade. In addition, AS4 will be the only dual-hemisphere spectroscopic complement to the eROSITA mission, unveiling the nature of **X-ray sources** that shine brightly across the sky.

AS4 can deliver these astrophysical breakthroughs because of its unique sky-survey capabilities. AS4 will take spectra with 2.5m telescopes **in both hemispheres**, each with wide-field multi-fiber spectrographs: the APOGEE spectrographs delivering near-IR spectra

[1] AS4 stands for “After SDSS IV”

at R=22,000 and optical spectrographs delivering spectra at R~2,000. AS4 is the **only** existing or planned spectroscopy survey that can do

- **all-sky** high-resolution, high-quality spectroscopy
- all-sky well-sampled **time-domain** spectroscopy
- all-sky (or all-Galactic-plane) dust-penetrating **near-IR spectroscopy**

The current survey plan touches the entire sky multiple times, with heavy emphasis on low Galactic latitudes. With this approach, AS4 can observe approximately 2.5 million targets per year, or ~12.5M targets over a 5-year survey. Combined with earlier SDSS spectroscopy, spectroscopic time-baselines of up to 20 years can be achieved by 2024.

In addition to the AS4 core programs with wide-field, multi-object spectroscopy, we are actively pursuing the implementation of a very **wide-field optical IFU program**, which will enable us to study the physics of the ISM and of the stellar populations' interaction with the ISM, both in the Milky Way and in nearby galaxies. This program builds on the extensive MaNGA scientific expertise, data analysis and software development efforts completed under SDSS-IV.

AS4 will build upon existing data reduction and analysis pipelines. Much of the hardware for AS4 is already in place, including two optical spectrographs and two infrared spectrographs. Hardware development will focus on a set of fiber positioners, the implementation of which is being initiated on the basis of existing technology. The AS4 survey could start as early as late 2019.

AS4 is committed to the exemplary tradition of the SDSS surveys, which executed end-to-end, enables high-impact survey astrophysics in a collegial and open collaboration among its partners.

AS4: The Survey and Its Science

To provide a practical framework, we first lay out some specifics of the overall survey. We then highlight the flagship program, the *Galactic Astrophysics Survey* , and the *Black Hole Astrophysics Survey,* encompassing the main science areas where AS4 can deliver scientific breakthroughs. Finally, we sketch the ultra-wide area IFU survey of nearby galaxies that we aim to include in AS4.

I. Overall Survey Strategy

As in all successful sky surveys to date, the efficient use of a survey facility naturally enables, and therefore invites, the simultaneous exploration of different astrophysical directions. AS4 will deliver transformational data on a wide range of topics, from exoplanets to the physics of supermassive black holes. Its overall layout is centered on its flagship science goal, **mapping our Milky Way as a whole** (and its stars), thereby illuminating our Galaxy's genesis and placing it into the global context of other galaxies.

This goal inevitably places emphasis on the spectroscopy of stars at low-Galactic latitudes, where most stars live, and on near-infrared (NIR) spectroscopy that can penetrate the otherwise obscuring dust. AS4 has access to wide-field and all-sky (APO in New Mexico & LCO in Chile) spectroscopy in the NIR and optical -- with largely existing hardware in both hemispheres. From this, a number of natural and powerful synergies arise; some are purely scientific: the same type of spectra that teach us about Galactic genesis and the origin of elements also teach us about the stars' companions and planets. Other synergies are practical: the high stellar density at low latitudes requires repeat visits to explore the Galaxy genesis through a sample of 5 million stars, which at the same time enables time-domain spectroscopy (e.g. for binary stars) on an unprecedented scale. The all-year availability of the facility (when the Galactic plane is not up) enables optical (and NIR) spectroscopy across the rest of the sky at higher Galactic latitudes, targeting planet hosting stars, white dwarfs, quasars and X-ray sources.

AS4 has crucial survey capabilities that will remain unique for the foreseeable future:

- Dust-penetrating NIR spectroscopy over a wide enough area to map the entire Milky Way, a key to our flagship science.
- The ability to measure time-variability on scales from 20 min to 20 years (across a good fraction of the sky), due to the combination of survey strategy and SDSS legacy.
- Short exposure times (10-15min) and fiber robots that enable vast sample sizes and contiguous coverage, while repeat visits still allow SDSS-like spectroscopic depth for faint objects.
- The survey facility and strategy provides flexibility for exciting new targets that may arise from the wealth of ongoing photometric surveys, no matter where on the sky these targets are found.

When combined with the SDSS heritage in hardware, software, and collaboration culture, these long-term, unique capabilities hold enormous promise for breakthrough discoveries in our core survey domains, which we lay out next. But if the past is any guide, the science impact will extend far beyond these original goals.

II. Galactic Astrophysics

The Milky Way is the ultimate all-sky structure, as we observe it from within. Our Galaxy's stars, the global distributions of their orbits, ages, masses and element compositions, $p_*(\boldsymbol{r},\boldsymbol{v},t_{age},[X/H])$, provide the observational foundation to reconstructing and understanding the genesis of our Milky Way. Our understanding of stars, both in their fundamental physics and in their role as elementary constituents of galaxies, is currently being transformed by a set of wide-sky, time-domain space missions: e.g, *Kepler-2, Gaia,* and *TESS*, in which ESA and NASA have invested over a billion dollars. These missions provide superb astrometry and photometry, but only very limited stellar spectroscopy. The scientific harvest from these data can be taken to a whole new level (at comparatively modest cost) by comprehensive, systematic, homogeneous spectroscopy that is also all-sky and multi-epoch. By matching our Galactic Astrophysics survey to the complementary information from these space missions, we will reap the full science return on understanding the Galaxy and its stars.

The power of stellar spectra arises from both the wide range and the precision of the physical quantities that can be derived from them: the stars' radial velocities and velocity variations, $\boldsymbol{v}_{los}(t)$ (e.g. central to detecting companions), their fundamental stellar parameters (T_{eff}, log*g*, mass, luminosity, $\boldsymbol{t}_{age}$, rotation velocity, etc.), and their chemical abundances [X/H] for many elements. AS4 will provide stellar spectroscopy across the sky in two set-ups:

- For brighter stars (H<12 mag), R=22,000, S/N>50 near-IR APOGEE spectra can provide ~20 abundances (for FGKM stars), line profiles (for hot or rotating stars stars), and radial velocities for all temperatures to a precision of ~30 m/s.
- For fainter targets (to g=18.5), R=2,000 BOSS-type spectra can provide 5-10 abundances (for FGKM stars at high-S/N), and radial velocities.

Understanding the Milky Way's genesis through the formation memory borne by its stars requires understanding stars precisely from their births to their deaths. The interpretation of fundamental quantities in stellar physics, e.g. the stars' ages, compositions and binarity, in turn requires the Galactic context. AS4 is designed around the close, inexorable interaction of these two fields: it is the only survey to contiguously map much of the Galaxy, ***and*** the only survey to bring spectroscopy for the sake of stellar astrophysics to the same comprehensive and systematic scale that have made extragalactic surveys into milestones of astronomy over the last decades.

IIa Galactic Genesis

The formation and evolution of a galaxy is a multi-scale problem: on the largest scales, it is driven by dark matter and hierarchical mass assembly; on scales of 3,000 to 30pc, by the supply of cold gas forming new stars and determining the overall stellar and gas dynamics; and further down, on the scales of star clusters, by the process of star-formation itself (mostly multiple stellar systems) and the resulting core-collapse supernovae. These scales are linked by the gradual, but eventually widespread, dispersal of stars from their birth orbits (e.g., through tidal dissipation and 'radial migration') and by the mixing of the interstellar medium, enriched by preceding supernovae. As all these structures play a linked role, we must obtain a global and contiguous observational picture of the Galaxy. Such a global map is also necessary to rigorously reconstruct what the Milky Way would look like "from the outside", putting it into the context of the overall galaxy population.

Understanding the importance of the various processes at work in the Milky Way, thereby making our Galaxy a model organism for understanding galaxy formation, requires a comprehensive stellar map of the Galaxy, that tells us when stars were born, from what material they were born, and on what orbits they are now. This stellar map needs to:

- encompass much of the Galaxy -- in particular much of its dominant disk and bulge, which requires dust-penetrating, wide-area NIR spectroscopy

- be contiguous to capture the morphological, dynamical, and chemical structures on all scales, which we know must be important
- provide high-quality spectra, to derive not only ages but also many precise abundances, which are direct markers of stellar birth circumstances and
- be densely sampled, because the chances of finding stellar birth siblings in the sample increases as N^2. This is crucial in the context of 'chemical tagging' in order to determine the role of stellar orbit migration in the galaxy (a form of dynamical memory loss) by exploring the range of orbits among stars of indistinguishable element abundances, which may point to similar birth times and places[2].

AS4 will provide stellar spectroscopy that satisfies all of these constraints (Figure 1): contiguous, dense sampling of stars throughout much of the Milky Way. It will do so by obtaining NIR spectra for 5 million stars, drawn from a remarkably simple selection function: H<11 mag and (G-H)>3.5. These are all the stars in the Milky Way that will not have similar information from *Gaia* alone (mostly nearby ones), but will still have *Gaia* proper motions to determine their orbits and are best observed in the NIR. This makes AS4 the only foreseen survey for Galactic genesis that probes our Milky Way as comprehensively as the arguments above demand; no other planned survey even comes close. The AS4 dataset will therefore comprise the ultimate observational benchmark with which models of galaxy formation can be directly compared.

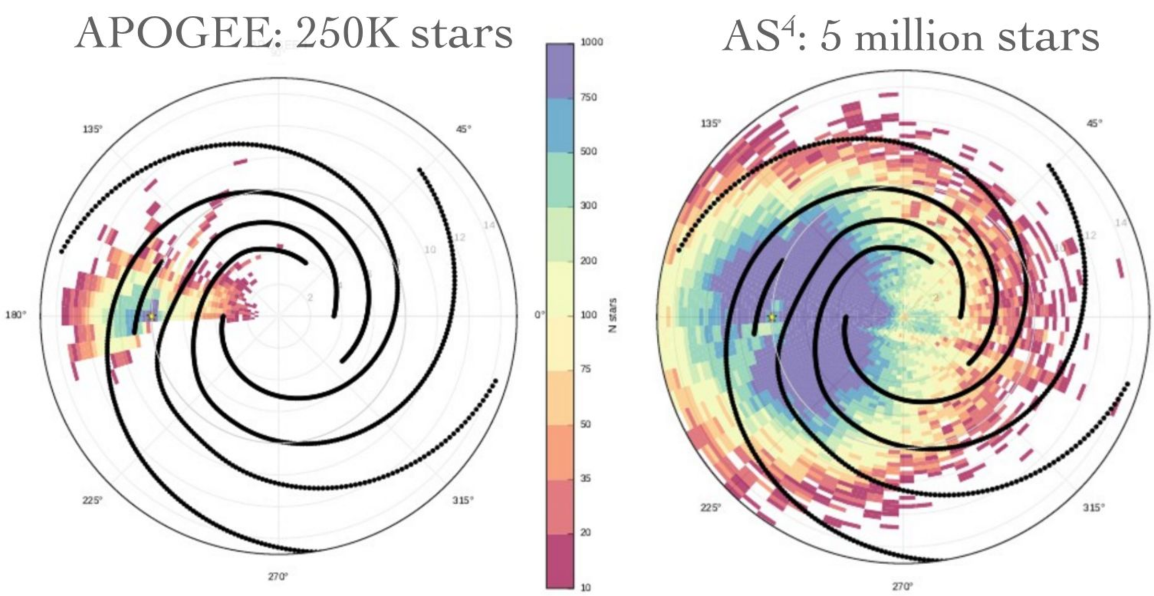

Figure 1: Milky Way Disk footprint of the AS4 stars compared to that of the (transformative and previous-generation SDSS) APOGEE Survey. The black lines indicate the approximate position of the Milky Way's spiral arms, centered on the Galactic Center.

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[2] Note that this N^2 scaling of the scientific figure of merit with sample size is a marked contrast with many other cases, where it improves merely as $N^{1/2}$.

IIb Transforming Stellar Astrophysics with AS4

Stars are the fundamental macroscopic entities in the cosmos. As such, much of astrophysics relies on a thorough understanding of the physics of stars. Yet, many crucial questions in the stars' life cycle are still open or have only very incomplete answers:
Birth: What regulates the star/stellar system-formation efficiency? How, and how quickly, is the mass of the resulting star set? Most stars are born as multiple systems: what does it tell us about star formation, and how does it affect their subsequent evolution?
Life/Evolution: Which stars end up hosting planetary systems, which do not, and why? What are the missing physical ingredients in the state-of-the-art models of stellar structure and evolution? How precisely can we age-date stars?
Death: Which stars produce how much of which (metal) elements? What are the distributions of compact binary remnants that stars leave behind? What are the progenitors of Type Ia supernovae that are both the essential producers of iron in the cosmos and unmatched cosmological probes?

While an overall picture of stellar physics and stellar evolution has long been established, a number of recent developments make this a topic of vast scientific promise and intense interest in the near future: *asteroseismology*, made possible by the ultra-precise light-curves of the space missions *Kepler/K2*, *CoRoT*, and soon *TESS*, provides a direct probe of stellar interiors: this is now telling us qualitatively new stellar properties, such as ages, but it is also telling us that we do not really understand stellar structure. And by now understanding the *Galactic genesis* is becoming severely limited by what we do not yet understand well enough about stars, especially their ages and the heavy element yields.

The data from these space missions call, in particular, for a comprehensive spectroscopic survey across the entire sky, to measure the missing pieces of information: the basic stellar parameters, the precise abundances of many elements. And we need to understand the multiple companion systems in which most stars live: most massive stars live in close binaries with comparably massive objects; for other stars the companions range from equal-mass companions to planets.

A number of AS4 aspects come together to make it unique: the ability to visit any point in the sky repeatedly; the radial velocity precision of 30 m/s; the combination of AS4 survey strategy and SDSS heritage, which provides observational baselines from 20 minutes to 20 years; and AS4's timing with respect to the emergence of *Kepler*/*K2*, *Gaia* and *TESS* data. No competing project on the horizon combines these necessary qualities.

The possibilities of breaking new astrophysical ground in stellar astrophysics with AS4 are rich, and therefore also wide ranging. But a number of them stand out as highlights:

- Understanding the origin of Type-Ia supernovae; by determining the incidence of very close binary white dwarfs

- Understanding the structure and evolution of massive stars, which dominate the overall energetics[3], by combining asteroseismology with AS4 spectroscopy.
- Understanding the differences between stars that do and do not host planets, through comprehensive spectroscopy of all targets of the exoplanet mission *TESS*
- Drawing up a comprehensive picture of stellar binarity across all stellar evolutionary phases and birth environments; this will quantify how star formation, stellar evolution and multiplicity are related
- Exploiting white dwarfs as precision clocks in the Galaxy
- Providing a census of stellar-mass black holes
- Providing a platform for spectroscopic follow-up of unanticipated discoveries from these space missions

AS4's stellar astrophysics survey is a class apart in terms of its scope and comprehensiveness as compared to other spectroscopic efforts in stellar astrophysics. It can answer these and other questions, and it will raise our understanding of internal structure and evolution of single and binary stars to a new level.

III. AS4 Black Hole Astrophysics

Quasars are the Universe's most persistently luminous objects, revealing the astrophysics of actively accreting supermassive black holes (SMBHs) and tracing their mass growth and coevolution with host galaxies over >90% of cosmic time. AS4 will characterize quasars as variable phenomena through multi-epoch spectroscopy, provide the best way to measure their black hole masses at earlier epochs, and produce a powerfully-complete and unbiased census of another ~10^5 X-ray emitting quasars from eROSITA, the premier next generation of X-ray sky surveys.

IIIa Accretion Physics and Precision Mass Estimates

Quasars are dynamic phenomena that show accretion-driven variability over a wide range of scales, which encodes critical information about their nature and physics.

Spectroscopic variability in quasars can quite directly measure SMBH masses, accretion disk properties, accretion rate changes, dynamical changes in the broad emission line region, rare binarity signatures, and outflow properties that may help regulate aspects of host-galaxy evolution.

Combined with legacy SDSS spectroscopy since ~2000 that provides a long time-baseline, AS4 multi-epoch spectroscopy of ~10^5 quasars will sample timescales from mere days to over two decades, thereby probing otherwise spatially unresolvable SMBH region

[3] In another remarkable linkage of astrophysical fields, massive *binary* stars now appear possibly to play a crucial role in effecting cosmic reionization, the last important phase transition in the Universe.

size-scales, and providing information otherwise unavailable even in the flourishing era of photometric time domain imaging surveys. AS4 time-domain spectroscopy simultaneously resolves variability from the continuum emission regions of the accretion disk, from the broad emission line regions on both photoionization and dynamical timescales, and from absorption lines that probe powerful kinetic outflows near the nucleus. In this combination of sample size and time sampling, AS4 will be orders of magnitude ahead of existing or imminent quasar surveys. AS4 will reveal dramatic “changing-look quasars" that abruptly switch off (and on?), transitioning from active quasar to more docile galaxy in just a few years. AS4 will definitively measure the masses of ~10^3 SMBHs, providing orders of magnitude progress in measuring the most fundamental of all black hole parameters.

IIIb Spectroscopy for the eROSITA X-ray sky

The next-generation eROSITA all-sky X-ray survey (a German-Russian mission, to be launched in 2018) will reveal the energetic universe at hard X-rays, where active galactic nuclei dominate the emission. The X-rays arise from a compact, high-temperature inner disk corona, in the immediate vicinity of the event horizon. Energetic X-rays successfully penetrate the accretion-related tori and disk structures near the SMBH, the quasar host-galaxy, intergalactic media and our own Milky Way interstellar medium, eventually reaching us relatively unaltered -- and providing a far less biased census than optical data do.

eROSITA will scan the entire sky multiple times in X-rays at spatial resolutions of a few arcseconds, with sensitivity an order of magnitude deeper in soft X-rays than the ROSAT All-Sky Survey, and X-ray spectral information up to hard X-rays. But eROSITA, like all X-ray surveys, absolutely needs optical spectroscopy for its science goals, in particular for redshifts and for source identification/diagnosis.

An initial thousand square degrees, accessible from the North, of eROSITA sky coverage will be surveyed in SDSS-IV under the current SPIDERS program; but the bulk of the eROSITA sky area led by the German collaboration is in the South, making this a prime opportunity for an AS4 extension of optical spectroscopy to Las Campanas. AS4 spectra will provide ~10^5 optical counterpart identifications -- mainly quasars -- of eROSITA sources discovered in the first ~1.5 years of X-ray observations, and before later, deeper, identification programs (e.g., 4MOST) begin. Additional eROSITA/AS4 science will encompass late-type flaring stars and CVs, and innovative cluster physics and cosmological studies from ~10^4 galaxy clusters (far exceeding the number in any current survey) emitting strongly in X-rays, and spectroscopically surveyed in AS4.

IV: Mapping The Local Volume at the Star Formation Scale

AS4 is also pursuing an integral-field spectroscopic (IFU) survey, on unprecedented angular scale, aimed foremost at covering the entirety of the Milky Way's most important neighbours, M31, M33 and the Magellanic Clouds. Disk galaxy formation is a multi-scale problem, where star and cluster formation (few pc) from molecular cloud complexes (20-50 pc) is linked to feedback and overall galaxy dynamics on >1 kpc scales. This calls for overlapping maps of the stellar populations, kinematics and the ISM covering (much of) the galaxies at a physical resolution resolving the above scales. By pushing IFU spectroscopy to an unprecedented wide-area regime, the AS4 Local Volume Mapping (LVM) Program promises to deliver such information for the first time.

Scientifically, this links the population of present-epoch galaxies -- where SDSS has had truly transformational impact (including the MANGA IFU program) -- to the comprehensive study of the Milky Way for understanding stellar and galactic astrophysics, the core program of AS4. The AS4 LVM will fill the vast gap between the crude (kpc scale) information on very many galaxies, as well as the extremely detailed information on just one: ours.

While scientifically linked, the hardware requirements for this program are relatively distinct: IFUs of ~2500 fibers feeding a substantive number of new spectrographs. To achieve the necessary physical resolution (1 pc in the MW, 10 pc in the LMC/SMC, and 10-25 pc on M31/M33), the fiber/spectrograph systems could operate on telescopes of apertures of 20cm, 1m and 2.5m, setting the plate scale, possibly telescopes at APO and or LCO, and potentially elsewhere. Depending on fundraising success, a stage-wise implementation may be necessary and feasible.