RDS White Paper “Surveys”

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Introduction and Definition

Observing programs that cover large areas on the sky have historically been of tremendous importance for astronomical discovery. In this white paper we summarise the past, present and potential future impact of surveys on German astronomy and give suggestions for future decisions in this field.

To set the scope we first have to define what is meant by a survey. Because all kinds of observing programs are called surveys nowadays it is virtually impossible to come up with an unanimously agreed upon definition. Still it is important to distinguish surveys from other types of observing programs that we will call "PI programs" in the following.

Surveys in this paper refer to programs that cover a significant fraction of the sky or large samples of objects with no or minimal pre-selection and require a statistical approach for the data analysis and scientific exploitation. Typically, these programs also take up a significant fraction of the observing time on a facility. If done properly, surveys are accompanied by well-documented data releases that give easy access to the survey data (raw data as well as higher-level data products) for astronomers in general, also those who are not directly involved in the running of the survey. This ideally leads to multiple use/science cases of the survey data, some of which were not even thought of when the survey was designed. For this to happen a survey typically does not only aim at answering one scientific question but rather open up new areas of parameter space (e.g. in depth, wavelength coverage, angular resolution, or sheer numbers). Such surveys often provide targets for more in depth studies which might then be conducted in dedicated PI programs. In that sense those different modes of observing are tightly connected. These properties usually mean that surveys - unlike PI programs - require a management structure that can coordinate the efforts of a large team in which the technical tasks are divided amongst different specialists.

As mentioned above this definition is not unique and not all surveys described in the following share all these properties. But this definition provides an idea of what this white paper is about and - equally important - what is not covered here.

Surveys have impacted virtually any field in astronomy in the past and it is almost certain this will remain true in the future. From the solar system, to galactic scales, extragalactic objects, the large-scale structure of the Universe, and the Universe as a whole surveys are invaluable due to their inherently statistical approach that allows precise measurements by ensemble/spatial averaging.

Impact and Importance

It is not straightforward to quantify the impact of different types of observing programs. This would be a scientific study in its own right. Here we will just summarise findings of some web-based research on widely-used astronomical surveys that undoubtedly had a large impact. The following table presents google hits as well as the number of papers from ADS that mention a survey for several different projects.

	Google hits	ADS papers
Hipparcos	416k	26k
ROSAT	565k / 121k	30k
SDSS	1.5M / 400k	69k
WMAP	521k / 156k	21k
Kepler	541k	
Planck	889k	

For some surveys this search is unambiguous, and the numbers should be fairly reliable. For other surveys like Kepler and Planck, it is harder to come up with reliable numbers because the survey names carry additional meaning and are used in other contexts.

It can be seen that such big surveys typically lead to hundreds of thousands of google hits and tens of thousands of mentionings in ADS archived papers. This is mainly due to the wide applicability of the data from such projects facilitated by public data releases as already noted above.

There is a trend in astronomy in general for increasingly big projects and more astronomers working in large survey teams than used to be the case. This trend is similar to what happened in particle physics some decades ago and means that surveys will most probably become even more important for astronomical research in the future.

As stressed above, each large survey to-date demands its own management (incl. long-term data management) and technical support structure. Nevertheless, in the long run any public survey data are frequently exploited through diverse archival channels, typically in a multi-wavelength fashion. Hence, surveys undertaken at very different observing frequencies, with different instruments and correspondingly diverse technical challenges, are very fruitfully combined wherever they overlap in sky coverage. In this way even uncoordinated surveys can enable long-term science exploitation by a large scientific community.

While surveys can be planned to insure a common sky coverage, it is generally not predictable which (often times very important) scientific discoveries will result from the joint exploitation of the various data archives. The discovery space enabled through the combination of different overlapping surveys and the associated legacy science enabled by survey activities has already proven to be of great value to the astronomical community. At the same time, associated challenges in supporting the scientific exploitation of these the datasets, given the need of long-term funding for the archives and the growing data rates and volumes, are growing.

SDSS - A Successful Example

In this section we concentrate on one particular survey, the Sloan Digital Sky Survey (SDSS), that had and still has a very wide impact on astronomy ranging from solar system science to cosmology. This project, carried out with a relatively modest (but dedicated) 2.5m telescope, cost less than 100M$ over a lifespan of 10-15 years. This cost is relatively small compared to other major astronomical projects, especially space-based missions.

The success of SDSS can be attributed to a number of factors. It offers a comprehensive and well-matched combination of imaging and spectroscopy over a common survey area with simple pre-selection. This enables an extremely wide variety of studies, because a large number of classes of objects are surveyed by this one project. Another important aspect that is often lacking in other projects was the well-balanced funding for hardware and software that enabled public data releases of unprecedented quality. The combination of these properties led to SDSS being one of the most cited projects for more than a decade.

The expertise built up during the run-time of SDSS is now being transferred to other projects like the Dark Energy Survey (DES) and the Large Synoptic Survey Telescope (LSST) discussed below. This represents another asset of astronomical surveys that is hard to quantify but shouldn't be forgotten.

Ongoing Surveys

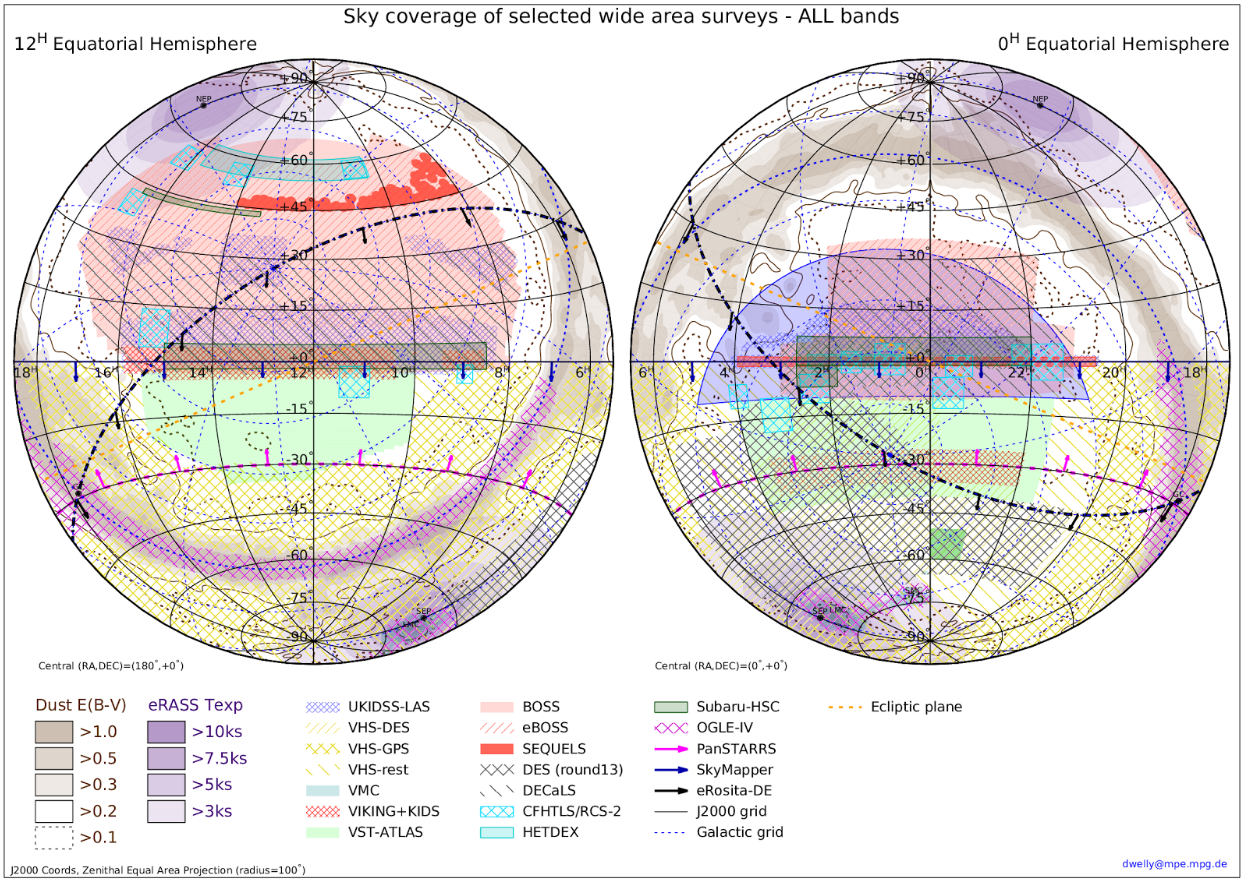

Fig.1 All-sky footprints of some major past, present, and future surveys. Credit: Tom Dwelly, dwelly@mpe.mpg.de

Ground-based optical/near-IR imaging

Advances in CCD and near-IR detector technology have led to increasingly large and sensitive cameras that can cover larger areas on the sky to increasing depth. To fully exploit this potential, a large fraction of the time on telescopes with such wide-field cameras is typically dedicated to survey operations.

The SDSS mentioned above established the prototype of a large optical survey. ESO put in place a plan to build two pure imaging survey telescopes, one for the optical (VST, 2.6m) and one for the infrared (VISTA, 4m), at Paranal in Chile. The community runs 9 public imaging surveys with these two telescopes, some of which have a strong German contribution and are described in the following together with international counterparts.

In the optical the ESO Kilo Degree Survey (KiDS) represents one of the largest extragalactic surveys designed for weak gravitational lensing science. It is complemented by the ESO VISTA Kilo-Degree Infrared Survey (VIKING) which adds images in five infrared bands to the four optical bands of KiDS. Once completed, those surveys will cover ~1500 deg^2 over a wide wavelength range and allow new insights into the physics of the dark universe. Scientists from Bonn are heavily involved in KiDS and VIKING.

The Dark Energy Survey (DES) is another outstanding optical imaging program carried out with one of the largest imaging CCD arrays ever built and mounted on the 4m Blanco telescope at Cerro Tololo, Chile. In Germany, the LMU is involved in this program that otherwise includes scientists from the US, Chile, the UK, Spain, Brazil and Australia. The science drivers for DES focus on cluster cosmology in combination with the South Pole Telescope mm-wave survey, weak lensing studies, galaxy clustering and SNe as probes of cosmic acceleration. While these goals are similar to those for KiDS, the technical approach is somewhat different, trading wavelength coverage and image quality for a much larger solid angle (5000 deg^2) and greater depth, providing a dataset that probes a much larger cosmological volume.

Another competing project is the Japanese, US and Taiwanese Hyper SuprimeCam (HSC) survey carried out with the 8m Subaru telescope on Mauna Kea, Hawaii. Similar to DES and KiDS in terms of science goals it exploits the large aperture and unparalleled image quality of the Subaru telescope to go much deeper and measure weak gravitational lensing with larger source densities out to higher redshifts.

These three ongoing extragalactic imaging projects (KiDS-VIKING, DES, HSC) are the major competitors to answer the question about the physical nature of dark energy with weak lensing, clustering, galaxy clusters and SNe that can be measured from images (e.g. galaxy cluster mass function). While German scientists are central players in both KiDS-VIKING and DES, it is clear that relative to other countries of similar size Germany is underrepresented and that there is great potential for scientific growth.

The VISTA Magellanic Clouds (VMC) survey has- due to a relocation of the PI to the AIP - become under German leadership with an accompanying growing German involvement. It provides the deepest, nearly unobscured survey of the stellar populations in the clouds and their surroundings to constrain their star formation histories. Repeat observations also allow for the identification of variable stars and background AGN and, through proper motion measurements, for the determination of the orbits of the Clouds and the internal dynamics of different stellar populations. There is also some German participation in the VMC’s optical counterpart SMASH (Survey of the MAgellanic Stellar History).

The other ESO public surveys have only very limited German involvement.

Ground-based optical/near-IR spectroscopy

Large area spectroscopic surveys tend to be done with fibre-fed spectrographs, redirecting the light from a large field-of-view or bundle of fibres onto the entrance slit of the spectrograph. Some of the ongoing surveys are based on new instrumentation, but many were enabled by upgrading instruments used in earlier surveys or repurposing an existing instrument from PI mode observations into a dedicated survey mode facility.

For extragalactic studies, SDSS remains an important tool for the German community with involvements in the eBOSS, the SPIDERS and the MANGA surveys. The eBOSS survey will make important contributions to tightening the constraints on cosmological parameters using primarily BAO measurements, while the (internal) evolution of galaxies forms the main point of study for MANGA using mini-IFUs to map stellar and gas properties across the galaxies. The SPIDERS survey focuses on X-ray selected AGN and members of X-ray selected clusters. Targets for these surveys originate from earlier SDSS imaging and cover a large fraction of the northern extragalactic sky.

The CALIFA survey performed with the Calar Alto 3.5m telescope, has concluded its observations and data releases, but analysis is still ongoing with strong German involvement. Using the PPAK IFU it provides detailed distributions of stellar and gas properties in 600 galaxies as well as kinematics.

CARMENES, another Calar Alto survey on the 3.5m telescope, is targeting Earth-like exoplanets around 300 M dwarfs by measuring radial velocities with a precision of 1 m/s. First light of this German-Spanish project occurred about a year ago and will last at least another couple of years.

The GAMA galaxy redshift survey using the AAT has also concluded spectroscopic observations, but is still combining data with facilities ranging from the radio to the X-ray. Main aim is the study of galaxy evolution in the full range of environments. It has limited German participation.

For the galactic community the RAVE survey, conducted under German leadership, has completed its observations of ~0.5 million stars and is completing its data releases. Analysis of this rich dataset will continue, especially in combination with the upcoming Gaia data releases.

The near-IR SDSS APOGEE survey is opening up a new window on our Milky Way by observing stars closer to the disk midplane and towards the Milky Way center than ever before. Its relatively high spectral resolution allows detailed studies of the stellar population abundance patterns of many different elements, revealing the formation and accretion history of the different components of the Milky Way. The Gaia-ESO survey aims for similar goals using the UVES and FLAMES instruments at the ESO/VLT, but at optical wavelengths. Both APOGEE and Gaia-ESO have significant participation from several German institutes and will be the key surveys to complement the first Gaia data releases.

Some very limited German participation can be found in the AAT GALAH survey (high resolution spectra of bright stars) and in the Chinese LAMOST Galactic surveys.

Sub-mm, mm and radio

Surveys at longer (mid-IR to radio) wavelengths gained substantial importance for an ever-growing community in the recent past. Roughly half of the integrated background light is emitted at far-IR wavelengths and the condition of the interstellar medium and its (neutral, warm and molecular) baryonic content remain largely inaccessible at shorter wavelengths. It is fair to say that an understanding of key questions in modern astronomy, cosmology and fundamental physics - from galaxy growth to the epoch of reionization, from gravitational waves to dark energy - is only feasible through statistically-sound probes at sufficiently long wavelengths (up to meter waves).

Compared to the optical- to near-IR atmospheric windows, dedicated survey telescopes at such long wavelengths are largely missing, perhaps with the exception of space-based mid- to far-IR observatories (i.e. most recently the Herschel Space Telescope or Planck). Survey science is hence typically conducted throughout regular observing semesters by exploiting the limited hours available for large programs. This is owed to the fact of high observing time pressure through very diverse PI-driven science but also intensive building/operating costs given the partially demanding atmospheric or environmental conditions. Many of the survey-limiting factors arise through the complex technologies involved (e.g. interferometry) or present-day technical constraints (e.g. a limited field of view).

The South Pole Telescope is a dedicated mm-wave facility that stands as an exception to the situation described above. It has been used to carry out a 2500 deg2 survey at 95, 150 and 220 GHz with ~1 arcmin angular resolution. This survey, with key German participation at LMU, has been successful in producing the first Sunyaev-Zel'dovich selected galaxy clusters. This cluster selection technique produces cluster samples that are approximately mass selected and extend to all redshifts at which the cluster exist. Application of this technique within the SPT-SZ 2500 deg2 survey has produced a sample of over 500 clusters extending to z~1.7 and among the tightest available constraints on cosmological parameters, including those within the dark energy sector. Instrumentation upgrades have allowed more sensitive surveys over 500 deg2 (SPTpol) and the promise of extending this work to even greater depths over the full 2500 deg2 area of SPT-SZ (SPT-3G).

Over all, it must be acknowledged that the German scientific community in particular has been immensely successful over the last decade in capitalising on privileged access to a number of observatories as well as open-sky access permitting even large program science. As far as (sub-)mm science and facilities are concerned, a comprehensive overview of past survey success as well as key instruments used is provided in the dedicated chapter on far-IR/sub-mm facilities. Those include large-area efforts that in most cases provide critical ancillary insights to

SDSS, GAMA etc. (e.g. Herschel-ATLAS, NVSS, VLA-FIRST or the upcoming VLA All Sky Survey). Other applications involve systematic probes of the galactic/extragalactic ISM content and physicals conditions conditions (ATLASGAL, HERACLES, PAWS, EBHIS, THINGS, KINGFISH) as well as cosmological deep field surveys with vast panchromatic ancillary data (PEP, (ALMA-)LESS, PHIBBS(2), (J)VLA-COSMOS).

Space missions

ESA's astrometric mission Gaia, that launched successfully in Dec 2013, will not only be transformational to its core science goal of uncovering the 3D structure of the Milky Way through measuring the locations, distances and velocities of approximately a billion stars, but will also affect nearly all other fields of astronomy by providing unprecedented accuracy to the cosmic distance scale and hence to nearly all physical parameters that require a distance to be deduced. Next to location and velocity, Gaia will with its spectrographs also record the chemical composition for tens of millions of stars, properties that derive from the conditions at the time the stars were born, thus allowing reconstruction of the formation and evolution of the Milky Way. Gaia's unprecedented astrometric and photometric accuracy combined with its repeated scanning of the entire sky enables discovery of many special objects: planets around other stars, asteroids in our Solar System, icy bodies in the outer Solar System, brown dwarfs, and far-distant supernovae and quasars. Germany is deeply involved in Gaia's Data Processing and Analysis Consortium, with leadership roles at ARI (Coordination Unit 3: Core processing) and MPIA (CU8: Astrophysical parameters) and further participation from AIP, DLR, TU Dresden, and ZARM.

Another ESA project that will have a lasting influence on cosmology and astronomy in general is the Planck CMB mission. Although survey operations have finished and the most important cosmological results are published the Planck data will remain a benchmark data set for many years to come. German involvement in this mission sets another positive example for future space projects.

Alongside Planck the Herschel far-IR surveyor has been launched in May 2009. During its lifetime Herschel produced rich data of long lasting legacy value. With substantial German participation the wide area survey HATLAS constitutes a most relevant precursor for future far-IR/sub-mm surveys over cosmological scales. In this context archival data work is actively ongoing to probe average galaxy properties over a large cosmic volume in a panchromatic fashion and to reveal rare populations of distant galaxies in fruitful combination with lower resolution Planck data. Herschel's deep field surveys (PEP, HERMES, GOODS-Herschel) -- some under German leadership, others with strong contributions through German researchers -- set today's standard for our understanding of the dust-enshrouded Universe. Similarly, Herschel mapping efforts within the galaxy and of nearby galaxies produced state-of-the-art chromatic far-IR/sub-mm data that provide unique insights to the physics and composition of the interstellar medium, such as its heating and cooling, chemical networks and molecular or dust grain growth as well as the principles governing the process of star formation.

Launched in 2003 the Spitzer Space Telescope remains operational at mid-IR wavelengths through its warm mission, with guaranteed funding throughout the JWST commissioning phase. While Spitzer survey data products at mid- to far-IR wavelengths still constitute high legacy value and are to-date cornerstones for panchromatic research, recent warm mission surveys mark milestones in the next generation survey landscape or the pre-JWST era. The SPLASH survey -- with active German contributions -- provides an unprecedentedly deep view at the early universe over a representative volume that provides an essential complement to ongoing HSC, VISTA but also deep radio continuum surveys. To name another example, the S4G warm mission nearby-galaxy survey produced key science results (prominently featuring German scientists) for a much improved understanding of galactic structures.

Major Future Projects

Ground-based optical/near-IR imaging

One of the most important upcoming imaging surveys will be carried out by the 8m Large Synoptic Survey Telescope (LSST). This facility will rapidly image the whole sky visible from its site in Chile every three nights over a ten year period in six optical and NIR bands. This survey strategy will build up a very deep and wide survey that will surpass every currently running imaging survey in practically all relevant survey design parameters. Perhaps even more importantly, it will open up the time domain by repeatedly observing every position on the sky. This US-led based project is international with important contributions to the camera and data management coming from the French side and, more recently, the move by the UK community to join in the scientific exploitation. Currently, there are a few research groups within Germany that have pursued membership within LSST, but we feel it is crucially important to a wide variety of science areas that the Germany astrophysics community participates in this transformative project. While some of the data products will become public after a proprietary period, it is crucial to fully participate in this survey to gain access to the highest profile science projects that will be carried out during the two year guaranteed proprietary phase.

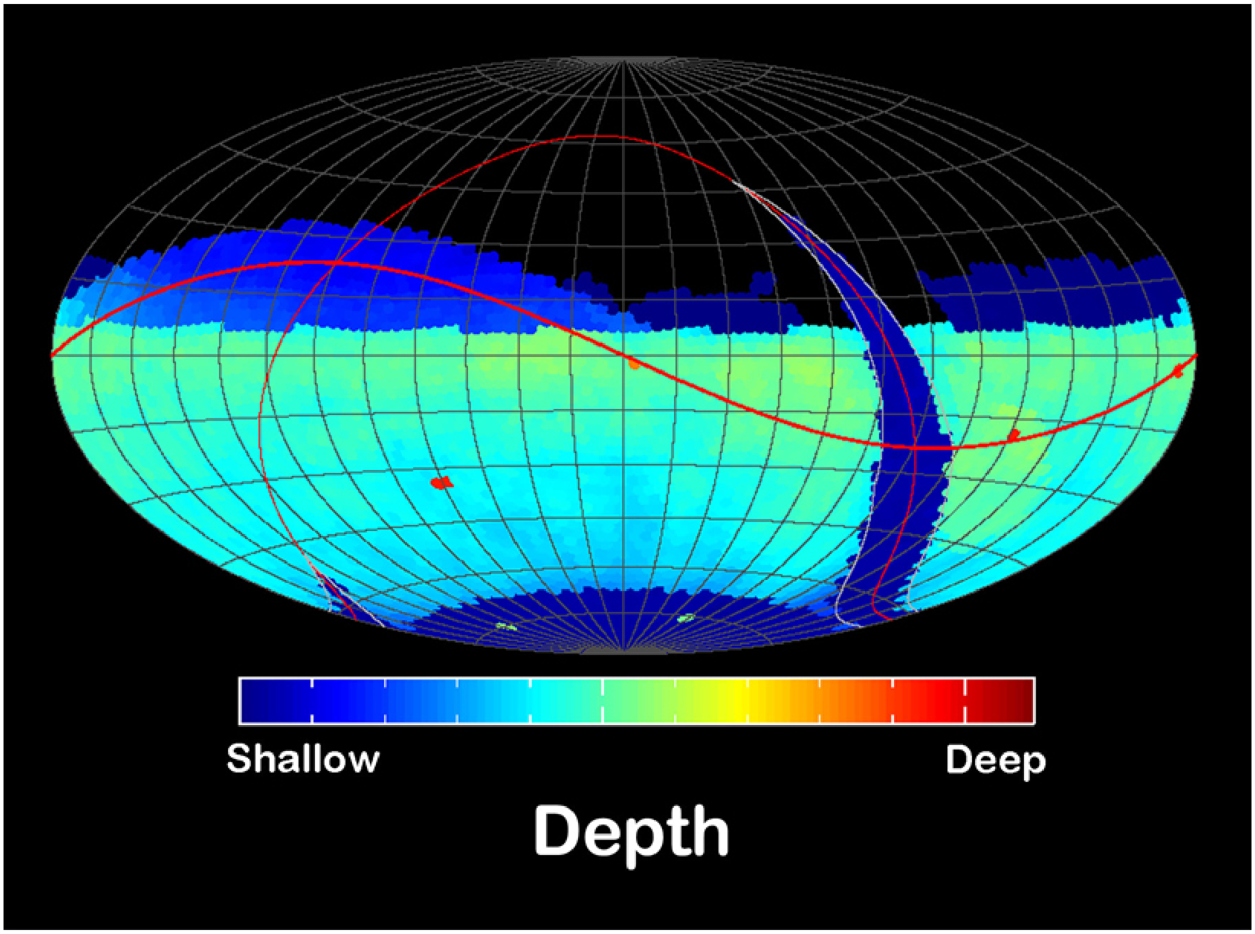

Fig.2: Footprint of LSST covering all of the extragalactic sky in the Southern hemisphere to unprecedented depth. Credit: www.lsst.org

Another important interest of German astronomy is to secure the ground-based follow-up of the Euclid space mission (see below). Euclid relies on ground-based imaging surveys to provide the full wavelength coverage to estimate photometric redshifts for more than a billion of galaxies. While LSST should be able to provide this coverage in the Southern hemisphere the situation in the North is not so clear. Different options are being explored, including a Northern extension of LSST (suffering from high airmass), using existing wide-field imaging telescopes in the North like Subaru, CFHT, or WHT, or building a dedicated facility/camera. Currently these considerations continue with German participation only through our key roles in the Euclid mission.

Ground-based optical/near-IR spectroscopy

A slew of new wide-area, high-multiplex spectroscopic survey instruments is currently being developed driven by the need to complement the astrometric Gaia space mission with spectroscopy to its faintest limits and to conduct massive spectroscopic redshift surveys to address Dark Energy questions.

HETDEX is one of the first new large experiments particularly designed to measure the properties of the accelerating Universe. HETDEX will use the new VIRUS instrument at the Hobby-Eberly Telescope providing 75 integral field units of 50x50 arcsec^2 to survey more than 400 square degrees of the sky over a three year period. The aim is to obtain spectra of nearly 1 million Lyα emitting galaxies with redshifts $1.9 < z < 3.5$. Because HETDEX does a blind area survey, low resolution spectra of millions of other Galactic and extragalactic objects will be obtained as well. HETDEX is expected to start routine observations late 2016 and the German institutes involved are AIP, LMU, MPA, MPE, and the University of Göttingen.

4MOST is the wide-field spectroscopic survey project with the strongest German interests. Starting in 2021, 4MOST will provide a 2.5 degree diameter field-of-view on the 4.1m VISTA telescope, populating it with 2400 fibres feeding resolution R~5000 and R~20,000 optical spectrographs. The 4MOST science projects range from massive redshift surveys of galaxies, clusters of galaxies and active galactic nuclei (massive black holes) to constrain the properties of Dark Energy and Dark Matter and the evolution of galaxies and black holes, through measuring the chemical and dynamical structure of the Milky Way to determine its formation and evolution and the properties of its Dark Matter, to characterising the properties of exo-planet host stars to be discovered by TESS and PLATO. The 4MOST Project is led by AIP, with further important contributions from MPE, MPIA, UHH, and ZAH. However, the entire German community will gain access to this facility through ESO community observing time, making 4MOST a general purpose facility for a large astrophysical community.

Other similar ongoing wide-field, high-multiplex spectroscopic survey development projects have less German involvement. The MOONS facility for the ESO/VLT 8m telescope will provide a 27 arcmin diameter field-of-view with 1000 fibres feeding infrared spectrographs of resolution R=5000 or 20,000. Science drivers are Milky Way structure and evolution, galaxy evolution, and complementing cosmology surveys. MOONS is expected to be operational from 2019 and has some minor participation from LMU, MPA, MPIA. The PFS facility at the 8m Subaru telescope will provide a 1 degree diameter field-of-view with 2400 fibres feeding R~4000 spectrographs. Starting in 2019 its main science goals are galaxy evolution and cosmology, and it is supported in Germany by the MPIA. WEAVE will provide 1000 fibres to a spectrograph with resolution R=5000 or 20,000 at the 4.2m William Herschel telescope at La Palma. Starting in 2019 it will mainly study the evolution of galaxies and the structure and evolution of the Milky Way. A few German individuals are part of the WEAVE science team. Finally, the DESI facility at the the Kitt Peak 4m telescope will have a 3.2 degree diameter field-of-view feeding 5000 fibres to resolution R~3500–5000 spectrographs. Starting in 2019, its science case is almost entirely driven by providing cosmological constraints through redshift measurements of galaxies. It currently has no German participation.

Farther into the future, possibilities are explored to create dedicated 10-15m class wide area spectroscopic survey telescopes. In particular, ESO has created a Working Group on the Future of Multi-Object Spectroscopy and there is an ongoing study to replace the CFHT by the Maunakea Spectroscopic Explorer (MSE). The science cases for such facilities will further expand on the above projects by going to higher spectral resolutions, fainter targets, higher multiplex, and more/larger integral field units. These projects are currently unfunded, but they are potentially very interesting to the German community.

Sub-mm and radio

At (sub-)mm wavelengths it is an arguably expensive common practice to-date to rely on interferometric (continuum and spectroscopic) follow-up of individual regions of interest for a thorough understanding of physical ISM conditions, no matter if galactic or high-redshift science is concerned. Many such follow-up efforts tend to produce large data rates and can be considered data-intensive survey science themselves, particularly drawing on the only recently emerging capabilities provided by ALMA, NOEMA and the expanded VLA.

Detailed follow-up programs will remain very important in the future and profit from the 2030 ALMA upgrade plans, continued IRAM-support as well as continued open-sky policy of the VLA. However, there is a clear need for a next-generation large single dish as dedicated ground-based survey instrument at far-IR/sub-mm wavelengths to complement ALMA. No new space-based far-IR surveyor is on the current agenda for the upcoming decades. Not only this prerequisite renders a dedicated large sub-mm single dish, with access to the highest frequency atmospheric windows most attractive for future survey science, complementing the areal coverage provided by LSST/EUCLID and enabling wide-area galactic/nearby galaxy surveys as well. In fact there is an ongoing vital debate involving the various communities (large-scale surveys targeting key questions in the context of cosmology, galaxy evolution/formation and galactic ecology) supporting a large single dish at or near the ALMA site. Such a project is generally perceived as being highly desirable for the German community and it is strongly supported by the recent ESO users survey as well as the responsible ESO working group. Large field-of-view multi-band, multi-beam imaging and spectroscopic capabilities at sufficiently high angular resolution would allow for an instantaneous characterisation of dust properties across cosmic time for virtually all galaxies in all cosmic environments sampled by surveys like LSST/Euclid and allow for blind redshift searches for highly obscured sources. Such capabilities would also provide us with an immediate constraint on the atomic and molecular ISM content. They would furthermore allow vast galactic surveys at sub-pc resolution to trace the energetics and dynamics in the interstellar lifecycle and capture all relevant dynamic ranges. A novel large sub-mm single dish is also paramount as instrumentation development facility for ALMA as well as future space-based far-IR surveyors.

In simple words one may conclude that the relation between a large sub-mm single dish and ALMA is for far-IR/mm astronomy what SDSS/LSST surveying combined with detailed HST/JWST follow-up is for optical/near-IR astronomy.

A vast range of future science applications will demand dedicated survey instruments with sufficient collecting area operating at longer wavelengths through the meter wave regime: From the molecular ISM at the highest redshifts, baryonic large scale structure probes through the epoch of reionization (from neutral hydrogen) to fundamental physics in the context of dark energy or gravitational waves (from precision pulsar surveys in the time domain). Other applications include an in-depth probe of magnetic fields or a census and large scale impact of active galactic nuclei throughout cosmic time.

These highly diverse science areas where German researchers already play leading roles demand next generation radio observatories as envisioned for the the two phases of the Square Kilometer Array (SKA) and a next generation VLA. The SKA will be built in South Africa (high frequencies) and Australia (low frequencies). It will be the world's largest radio telescope and surpass all existing radio telescopes by large factors in terms of resolution, sensitivity, and especially survey speed. German researchers are involved in the ongoing MeerKAT (SKA precursor in South Africa) and LOFAR (SKA Pathfinder in Europe) projects preparing for SKA. But surprisingly for many scientists, Germany pulled out of SKA project in 2014. We feel that - similar to the case of LSST - it is crucially important to reconsider this decision and for Germany to become at least an associated member in SKA. Otherwise a lot of the most interesting science in the radio domain as well as panchromatic science over the next decades will happen without German participation.

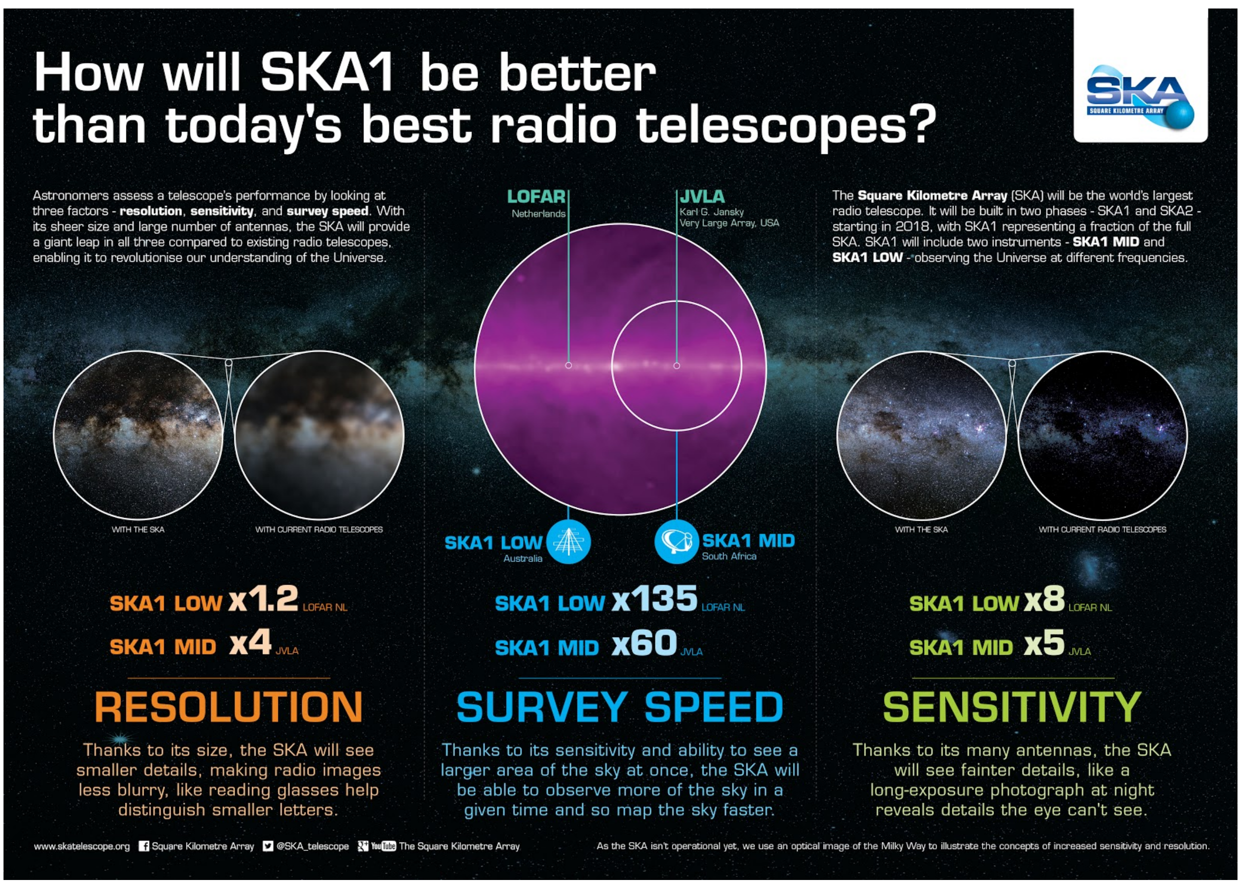

Fig.3: Main characteristics of the Square Kilometre Array in comparison to existing telescopes. Credit: www.skatelescope.org

Space missions

A number of planned space missions will conduct large area surveys at various wavelengths, depths, resolution, and cadence intervals. They all will have legacy value beyond their core science mission.

Exoplanet missions TESS (NASA) and PLATO (ESA) aim to discover new planets around bright stars using the transit technique, enabling massive spectroscopic follow-up from the ground for planet characterization. Whereas TESS only observes most areas of the sky for 1-2 months, PLATO will stare at certain areas of the sky for several years thus allowing discovery of Earth twins with orbital periods of more than a year. Both missions will obtain very precise, high-cadence (~minute time scale) photometry of bright stars, enabling not only discovery of planet transits, but in the process also obtain astro-seismology measurements that enable accurate determination of masses and ages of hundreds of thousands of stars. PLATO is a DLR led mission with strong further German interests at many institutes. Rapid follow-up observations of interesting sources from PLATO will require their own dedicated survey effort that is crucially important for the full scientific exploitation of the mission. The identification and characterization of the exo-planet candidates found by PLATO with high-resolution spectrographs requires a concerted effort where German astronomers can play a key role with the CARMENES instrument at Calar Alto and HARPS and ESPRESSO at ESO.

The ESA/NASA Euclid mission will take high-resolution images of the full extragalactic sky in one broad optical band and three infrared bands. These will be used to measure the shapes and approximate redshifts of more than a billion galaxies to be used for an extremely powerful weak gravitational lensing survey. Additionally, Euclid will take slitless spectra in the infrared yielding precise redshifts for 50 million galaxies that will be used to measure the galaxy power spectrum and the baryon acoustic oscillation scale. Together these two probes will revolutionise our understanding of the accelerating expansion of the Universe. Germany has a strong role in Euclid and is responsible for several key parts of the project. Relative to our financial contribution to the mission, German astronomers are underrepresented in numbers andin leadership roles. This is partly due to the fact that such a very long-term, space-based project requires a continuous commitment that is typically only possible for scientists with a permanent research position. Given the relatively small number of permanent staff members at German institutes, especially universities, compared to other countries it is challenging to make a stronger impact here.

eROSITA is a German/Russian X-ray mission that will be launched in late 2017 to conduct a full-sky survey at X-ray energies from 0.5 to 8 keV.. The main science driver for this mission is the determination of the dark energy equation of state through the X-ray selection of a sample of ~100k clusters of galaxies and the measurement of the redshift evolution of their mass function. Furthermore, eROSITA will provide an unprecedentedly large catalogue of galactic and extragalactic X-ray sources that will enable breakthroughs in our understanding of the the populations of compact sources in our galaxies and the evolution of the AGN population over cosmic time.

No future CMB space mission has secured funding yet. Given the timescales of such missions it is foreseeable that such projects will not launch within the next decade. So these mission concepts are beyond the scope of this white paper and are not discussed here. However, it is clear that a strong German participation in potential future mission for this crucial cosmological probe is very desirable.

Conclusions and Recommendations

Surveys will continue to shape the future of astronomical discovery. It is conceivable that their importance will even increase because many of the complicated questions asked by astronomers nowadays can only be answered by massive statistical studies that require large scale observing programs. This will probably lead to more and more astronomers working in increasingly large survey collaborations.

One aspect that should not be forgotten is the multi-wavelength nature of many astronomical research projects. Again it is probable that this trend will gain importance in the future. While in this white paper we examined the different wavelength regimes independently, we would like to stress that some of the most interesting science will only be done by researchers with access to survey data spanning a range of wavelengths and that necessarily originate from many facilities.

We believe that a unified effort within the German astronomy community is necessary to enable German scientists to take on leading roles in future survey projects. Such a unified strategy is also necessary to help in establishing and maintaining a balance between universities and non-university research institutes. In particular we recommend the following points:

- All possible efforts should be taken to ensure full access and participation of German astronomers (universities as well as non-university institutes) in LSST.
- German participation in SKA should be revived and at a least an associated membership should be assured.
- The panchromatic surveyor landscape should be complemented with a large sub-mm single dish under German participation
- Survey operations in general should be coordinated on a national level as in many other countries to avoid different classes of access to survey data, which limits the impact of German astronomy in such projects.
- Career paths for astronomers like tenure-track should be created that allow long-term dedication to multi-decade surveys, an area where Germany lags behind many other countries.