

# Community Paper „Dark Energy, Dark Matter, and Large-Scale Structure“

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## Executive summary

Observational cosmology has made dramatic progress over the past decade. The spatially flat cold dark matter (CDM) model with dark energy has been firmly established as standard model of cosmology, and its parameters are being constrained at the few percent level. German researchers and institutes have played a leading role in this endeavor. Nevertheless, the properties of dark energy are still only weakly constrained, and its nature is poorly understood. Thus, the single most important question where we expect decisive advances in the coming decade is: ***What are the properties of dark energy?*** Germany will play leading or major roles in key dark energy experiments. In particular, the ***eROSITA*** and ***Euclid*** experiments will revolutionize observational dark energy science. They will also lead to major advances in the ***characterization of dark matter*** and the ***large-scale structure of the Universe***.

## 1. Introduction

The surprising observation that the Universe is undergoing an accelerated expansion (Nobel Prize in Physics, 2011) likely requires new physics as explanation. **Dark energy**, a form of energy with unusual properties required for driving the cosmic acceleration, remains elusive and poorly understood. Indeed, the solid evidence for a non-zero, yet so tiny (relative to the 'natural' expectation for the quantum field vacuum energy density) value of the dark energy density provides the largest puzzle of fundamental physics. Models currently discussed to explain dark energy span the full range of theoretical physics, including, e.g., a cosmological constant, modifications to General Relativity on large scales, extra dimensions, string theory, or new scalar fields, connecting the Higgs boson with cosmic inflation. Dark energy was discovered by astrophysical observations. The first robust evidence came from observations of supernovae. This evidence was substantiated in particular by observations of the cosmic microwave background, the large-scale structure in the galaxy distribution, the evolution of galaxy clusters, and the gravitational distortion of galaxy images (weak gravitational lensing). Today, the effects we attribute to dark energy are established beyond doubt. The coming

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<sup>1</sup> Deceased Dec 11, 2016.

10-15 years will be decisive for the understanding of dark energy, driven by a large number of dedicated new experiments spread around the globe. We expect that in 15 years we will either have acquired a fundamentally improved understanding of dark energy, or, in case all observations are consistent with a cosmological constant, we may conclude that substantial further progress cannot be achieved in the near term. Astronomical observations are the only means for empirical studies of dark energy since its effects are thought to be important only on the largest scales. Germany leads or has a major role in significant experiments designed to constrain the properties of dark energy.

**Dark matter** was discovered by astronomical observations. Early evidence came from galaxy cluster observations in the 1930s and substantial further evidence in the 1970s through observations of galaxies. Despite the fact that dark matter has been with us for decades, there are good reasons to believe that the next decade will see significant advances in all three promising areas: production at accelerators, direct detection at underground laboratories, and indirect detection through astronomical observations. Weakly Interacting Massive Particles (WIMPs) are an example of heavy particles that are thermally produced and have interaction strengths comparable to weak interactions. Conversely, axions are very light, are produced non-thermally, and have extremely weak interactions. Another, light non-thermally produced candidate are sterile neutrinos, not to be confused with the well-known active neutrinos which cannot make up a significant fraction of matter. Ground-based direct detection experiments that target WIMPs and axions are described in the Eckpunktepapier of the Komitee für Astroteilchenphysik (KAT). Indirect, astrophysical approaches to detect dark matter proceed through gamma-ray, radio, or active neutrino emission (in the case of WIMPs), or X-ray emission (in case of sterile neutrinos or, possibly, axion-like particles) due to decay, annihilation, mixing, or oscillation.

The evolution of **large-scale structure** in the Universe is governed by the initial conditions present in the very early universe, by gravity, and by the expansion history. Therefore, large-scale structure measurements are very sensitive to the properties of dark matter and dark energy, as well as to deviations from general relativity. The baryon acoustic oscillation (BAO) feature in the galaxy correlation function allows for direct measurement of the expansion history. The anisotropy of the correlation function (redshift-space distortions) is sensitive to galaxy velocities and thus probes the growth rate of structure. Similarly, gravitational lensing and the abundance of galaxy clusters provide sensitive measurements of the growth of structure. These measurements allow us to perform stringent tests of interacting dark energy and modified gravity models. While the three known active neutrino species cannot constitute a large fraction of dark matter, as they are not cold, we know they have a nonzero mass. Measurements of the growth of structure on large scales offer the unique opportunity to measure the sum of neutrino masses, complementing ground-based nuclear physics experiments like *KATRIN*. The  $\Lambda$ CDM concordance cosmology, which is completely characterized by only six cosmological parameters, can currently explain a large range of observations from the cosmic microwave background (CMB) to large-scale structure (Fig. 1). However, in the coming years we will test this paradigm with much more rigor.

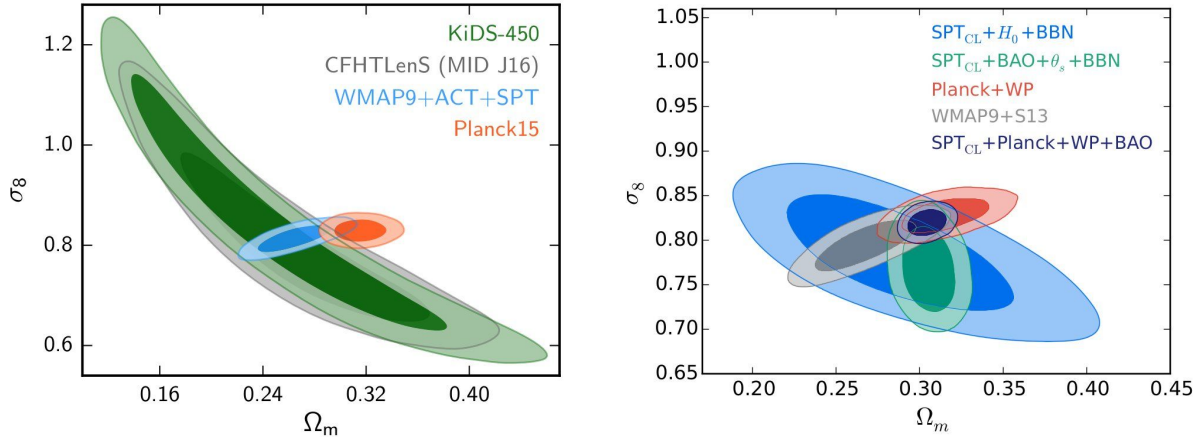


Fig. 1: Constraints on average mass density and amplitude of fluctuations in the Universe from cosmic shear/weak gravitational lensing (left; KiDS/CFHTLenS; from Hildebrandt et al. 2016) and galaxy clusters (right; SPT; from de Haan et al. 2016) compared to CMB measurements (WMAP and Planck). Overall there is good agreement while in detail there are some weak indications for tension between the low-redshift tracers and Planck CMB measurements.

## 2. Key Questions for the Upcoming Decade

The overarching question to be answered on **dark energy** in the coming decade is: what is the physics behind the accelerated expansion? In particular, is the acceleration due to a new form of energy, or a cosmological constant, or does it signal a breakdown of General Relativity on large scales? Further, is there any connection between the current epoch of accelerated expansion and cosmic inflation in the very early Universe? To answer these questions, we first need to constrain the equation of state  $w = p/(\rho c^2)$  of the effective dark energy component by precisely measuring the expansion history of the Universe,  $p$  being the dark energy pressure and  $\rho$  its density. Any value of  $w \neq -1$ , or any indication of a time-varying equation of state, would rule out a cosmological constant. A further important dark energy property is its sound speed  $c_s$ ; if  $c_s$  is much less than the speed of light, dark energy clusters and thus modifies the growth of structure further. A cosmological constant as well as non-clustering dark energy make definite predictions for the growth rate of structure in the Universe. Thus, measuring the growth of structure in conjunction with the expansion history allows for sensitive tests of dark energy and modifications to gravity. Of essential importance are consistency tests between different probes, such as: (i) expansion history and growth-of-structure probes; (ii) low- and high-redshift probes; (iii) large- and small-scale probes; (iv) measurements at different positions on the sky.

In the field of **dark matter**, the key questions concern its properties, in particular, its mass and interaction strength with itself and ordinary matter; as well as its origin, in particular whether it was produced thermally or non-thermally. An additional property of dark matter that is of great consequence for structure formation is its initial velocity dispersion (also loosely referred to as temperature). Large-scale structure observations are consistent with cold dark matter, i.e. dark matter with vanishingly small initial velocity dispersion. Future large-scale structure observations will place tighter limits on the initial velocity dispersion (warm dark matter) as well as dark matter self-interactions that are complementary to ground-based experiments. Constraints on the dark matter self-interaction cross section will be tightened through astronomical measurements, for example via gravitational lensing and X-ray/sub-mm observations of merging galaxy clusters. Germany has access to key instruments for these studies.

**Large-Scale Structure**, which we here define as the clustering of galaxies and other tracers, as well as the abundance and distribution of massive galaxy clusters, has emerged as powerful complementary cosmological probe beyond the CMB. While all large-scale observations are consistent with the standard  $\Lambda$ CDM model and a spectrum of almost scale-invariant adiabatic Gaussian initial perturbations, many key questions remain open: How were these initial perturbations generated? Is there any observable departure from scale invariance, Gaussianity, and adiabaticity? In particular, through the large-scale clustering of galaxies and clusters we are able to place tight constraints on certain types of non-Gaussianity (mode coupling) in the initial conditions, known as “local  $f_{\text{NL}}$ ”. If detected, such a feature of the initial conditions would rule out a broad class of inflationary models, namely “single-field” models where a single degree of freedom is responsible for the accelerated expansion as well as the perturbations (see also the Community Paper on “The Early Universe from Inflation to Reionization”). Further, large-scale structure offers the unique opportunity to map out the history of the growth of structure, parametrized by the amplitude of density fluctuations ( $\sigma_8$ ) and the growth rate  $f = d \ln \sigma_8 / d \ln a$ ,  $a$  being the dimensionless cosmic scale factor. Establishing consistency between large-scale structure constraints on  $\sigma_8$  and CMB constraints provides an important independent cross-check of the cosmological model (Fig. 1). Finally, while most current large-scale structure constraints come from scales less than about 200 Mpc, future surveys such as those performed with *eROSITA* and *Euclid* will probe scales an order of magnitude larger than that. Thus, a further key question is whether the distribution of galaxies and galaxy clusters on the largest scales is found to be consistent with the standard model of cosmology.

Beyond probing the cosmological model itself, large-scale structure surveys will also identify when the first galaxies, groups, and clusters of galaxies formed. One puzzle that awaits solution in the coming decade is the distribution of the total baryonic matter, in particular the fraction of baryons not contained in readily observable stars, cold and very hot gas (the so-called “missing baryon” problem). A key question for our physical understanding of galaxy formation and evolution is the relative importance of stellar (winds and supernovae) and supermassive black hole feedback. Further, this feedback modifies the distribution of the dark matter as well through the gravitational coupling to the baryons. Understanding this effect (as well as galaxy bias, intrinsic alignments, halo structure etc.) is in turn important for the correct interpretation of the measurements of weak lensing and galaxy cluster surveys. Elucidating the chemical enrichment of the intergalactic medium is a further key question for the next decade.

### 3. Key Results of the Previous Decade

Over the past decade, the spatially flat  $\Lambda$ CDM model has been firmly established as the standard cosmological framework, forming the basis for the searches for departures from the standard model described above. Researchers in Germany have contributed key results, a selection of which will be referenced in the following. In the field of **dark energy**, the most important recent results are the constraints on cosmological parameters from the Planck satellite, alone and in combination with other probes (Planck Collaboration 2014). These constraints represent a significant improvement, by a factor of several, in the precision of the cosmological parameters over previous CMB measurements (in particular WMAP), and, in fact, an order of magnitude for the non-Gaussianity parameter  $f_{\text{NL}}$ . In addition, the Planck results enabled a high-significance measurement of gravitational lensing of the CMB (Planck Collaboration 2016), breaking degeneracies present in the primary CMB when taken by itself. Beyond the CMB, key results include improved, unified cosmological analyses of supernova data to constrain the dark energy abundance and equation of state (e.g., Kowalski et al. 2008). Weak gravitational lensing surveys achieved a major breakthrough in the past decade

with the first competitive constraints on the growth of structure and dark energy, in particular in the *COSMOS* (Schrabback et al. 2010), *CFHTLenS* (Kilbinger et al. 2013), and *KiDS* (Hildebrandt et al. 2016) data sets. Finally, the baryon acoustic oscillation (BAO) feature in the galaxy two-point correlation function has emerged as a new geometric probe of the expansion history with precision constraints on the Hubble parameter and curvature reported by the *SDSS*, *WiggleZ*, and, most recently *BOSS* surveys (Grieb et al. 2016; Salazar-Albornoz et al. 2016; Sanchez et al. 2016). This feature, imprinted in the early universe by plasma oscillations, provides a known, extremely robust “standard ruler” which can be used to measure the distance-redshift relation to high precision. On the theoretical side, our understanding of nonlinear evolution, bias and redshift-space distortions in large-scale structure surveys has made significant progress in recent years with notable contributions from German scientists (Salazar-Albornoz et al. 2014; Mirbabayi, Schmidt, and Zaldarriaga 2015).

Interestingly, the most recent results of supernovae, weak lensing, and cluster abundance analyses show some tension with the *Planck* CMB constraints in the context of the flat  $\Lambda$ CDM cosmology (Israel et al. 2014, 2015; von der Linden 2014; Applegate et al. 2016; Hildebrandt et al. 2016). While currently the statistical significance of this tension is only moderate, the potential impact of new physics as possible cause would be enormous. Hence, new results from *KiDS* and the *Dark Energy Survey (DES)* are eagerly awaited.

The past decade has also seen significant progress on constraints on **dark matter** properties. Direct-detection experiments have found no conclusive evidence for dark matter, however the upper limits on the interaction cross section have been improved dramatically over the past decade (see the KAT Eckpunkt Papier for a recent overview). On the astrophysical side, constraints on dark matter self-interaction in galaxy clusters have been obtained from a combination of X-ray and gravitational lensing data, calibrated with simulations (Springel & Farrar 2007; Mastroiello & Burkert 2008). Furthermore, there are searches for X-ray emission lines from galaxy clusters created by dark matter particle decay or annihilation such as sterile neutrinos (e.g., Hofmann et al. 2016). In addition, the cosmological constraints on the sum of the active neutrino masses have been pushed down to levels of 0.3 eV (95% confidence level, de Haan et al. 2016), which are below limits placed by laboratory nuclear physics experiments so far.

The field of **large-scale structure** has seen rapid progress as already shown by several of the results mentioned above. Furthermore, constraints on the non-Gaussianity parameter  $f_{\text{NL}}$  from the large-scale clustering of galaxies and quasars in the *SDSS* survey have been obtained that were competitive with the pre-*Planck* CMB constraints. Moreover, the *Euclid* survey is expected to improve upon *Planck* constraints using this technique. Analysis methods for weak gravitational lensing have advanced significantly, including photometric redshift determination methods (e.g. Hildebrandt et al. 2012) and establishment of lensing magnification as a complementary observable to lensing shear (Hildebrandt et al. 2011, Schmidt et al. 2012). On smaller scales, the discovery of high-redshift galaxy groups and proto-clusters (Capak et al. 2011; Walter et al. 2012) enabled new insights into structure formation, as did constraints on the warm-hot intergalactic medium and filaments with UV, X-ray, and gravitational lensing observations (Richter et al. 2008; Dietrich et al. 2012). First constraints on the gas in the outskirts of galaxies and clusters have been obtained (Reiprich et al. 2009, 2013), and evidence for AGN feedback effects on intracluster gas has been detected (Mittal et al. 2009; Hudson et al. 2010). Concurrently to the progress made in observations on various scales, advances in cosmological simulation techniques have allowed the detailed characterization of the nonlinear regime of structure formation and quantification of baryonic feedback effects within the  $\Lambda$ CDM paradigm (Balaguera-Antolínez & Porciani 2013; Vogelsberger et al. 2014; Bocquet et al. 2016). Additionally, breakthroughs

have been made in the field of self-consistent simulations of non-standard cosmologies, such as coupled dark energy models (Baldi et al. 2010), as well as modified gravity simulations of different models (Schmidt 2009; Winther et al. 2015).

#### 4. Particular Role/Strengths of Research Groups in Germany

Over the past decade, German research groups have contributed significantly to our understanding of cosmology and large-scale structure. Many of the key results mentioned above involved significant contributions by German research groups. This covers both theoretical and observational work, as well as combined efforts. Moreover, German research groups, due their outstanding expertise developed in these fields, play a crucial role in the planning and carrying out of several upcoming large research projects targeting dark energy, dark matter, and large-scale structure.

MPE is leading the *eROSITA* space telescope to study dark energy and dark matter using galaxy clusters and research groups in Bonn and Munich collaborate in the cosmological exploitation. Many research groups at German universities (Bonn, Heidelberg, Munich) and Max Planck Institutes (MPA, MPE, MPIA) are involved in the *Euclid* satellite mission to measure the properties of dark energy, dark matter, and the large-scale structure, e.g., through weak gravitational lensing and galaxy clustering. Both missions will be described in more detail in Sec. 5.

The cosmology group at ITP, U Heidelberg, is among the pioneers in the field of **dark energy**. They recently proposed coupled models which link the epoch of dark energy domination to the mass of neutrinos, and which have attracted significant interest in the community. Important work in the field of massive gravity and parametrized modifications of gravity has been done there as well. The MPA in Garching as well as HITS in Heidelberg are centers for the study of structure formation in standard  $\Lambda$ CDM as well as modified gravity models using N-body simulations as well as semi-analytic methods. Further active groups in these fields exist at Aachen, Bielefeld, Göttingen and at DESY Hamburg.

DESY Zeuthen have been heavily involved in the *Supernova Cosmology Project* and the *Nearby Supernova Factory* to measure the expansion history and map the local bulk flows. Groups at MPA and HITS have provided significant insight into the supernova explosion mechanisms, which promises to make them even more accurate cosmological probes. DLR, MPA Garching, and U Heidelberg are part of the *Planck* collaboration, which provided unprecedented constraints on cosmological parameters from CMB observations. MPA and MPE are member institutions of the (e)BOSS surveys mapping the expansion history through the BAO technique. Moreover, within BOSS the MPE group is one of the key leaders of the cosmological analyses, having first-authored 4 of the 11 recent BOSS cosmology papers on BAO and redshift-space distortions. Numerous German groups are involved in large-scale structure surveys in the radio band, in particular LOFAR.

Germany has an especially strong history in the field of gravitational lensing, starting with Jürgen Ehlers. U Bonn hosts one of the leading groups worldwide in theoretical lensing research. Furthermore, scientists at U Bonn and LMU Munich have a leading role in the analysis of several state-of-the-art weak lensing data sets, such as *COSMOS*, *CFHTLenS*, *KiDS/VIKING*, and the *Dark Energy Survey*.

Gamma-ray observations are a key technique to indirectly search for **dark matter** via self-annihilation channels. Germany is leading two state-of-the-art ground-based gamma-ray experiments, *H.E.S.S.* and *MAGIC* (MPIK Heidelberg, MPP Munich, Humboldt University Berlin, DESY Zeuthen, and many others) which have produced important results in this area.



Furthermore, German groups (LMU Munich, MPA Garching, U Heidelberg) have contributed to the interpretation of observations to constrain dark matter self-interaction in merging galaxy clusters with detailed simulations. Colleagues at MPE have studied the constraints on sterile neutrino dark matter candidates obtained from X-ray observations of galaxy clusters. Groups in Munich contributed to constrain the sum of active neutrino masses that have been obtained from studies of galaxy cluster samples.

Germany plays a leading role in the theoretical study of the formation of **large-scale structure**. The preeminent tool in this field nowadays are large numerical simulations which follow the evolution of both ordinary and dark matter, including, besides gravity, the effects of cooling, star formation, as well as supernova and AGN feedback. MPA and HITS host world-leading experts in this area of research, with further strong groups located in Bonn, Munich, and Potsdam. One of the key breakthroughs in this area was the *Millennium* simulation (MPA), which produced a catalog of dark matter halos as well as mock galaxies which are still widely used today. Apart from its unprecedented combination of volume and resolution at the time, one of the reasons for this success was an easy-to-use database interface allowing efficient mining of the results. The recent *Millennium XXL* simulation has yet again broken records in terms of volume and resolution, while the *Illustris* simulation, run by an international collaboration with leading involvement of HITS, has achieved a new milestone in the level of detail of baryonic physics and feedback processes included in a simulation of this size. The *Magneticum* simulations led by LMU Munich have delivered very direct input for connecting observations and theory in terms of structure growth and galaxy cluster mass function. The *EAGLE* and *OWLS* simulations performed by the Virgo consortium, with leading involvement of MPA, have previously set standards in this field.

On the observational side, galaxy cluster studies at basically all wavelengths have been advanced significantly by several groups in Germany (Bonn, Garching, Hamburg, Munich). Key contributions include the cosmological exploitation of surveys and observations based on the *ROSAT All-Sky Survey* (X-rays), the *South Pole Telescope* and the *APEX telescope* (sub-mm/mm), the *Dark Energy Survey* (optical), and *LOFAR* (radio).

## 5. Key Infrastructures needed/relevant for Researchers in Germany<sup>2</sup>

One reason for the strong competitiveness of German groups in the field is the good infrastructure. This includes, in particular: i) Excellent computing facilities, which are essential as much of the science described above relies on detailed simulations. Among these are the large supercomputing centers in Jülich, Stuttgart, and Garching, but also many smaller local facilities at universities and MPIs. ii) Good federal funding opportunities, in particular *SPP*, *SFB/Transregio* and *Exzellenzinitiative*, that allow for close collaborations across institutional boundaries. In the field of cosmology, these were/are in particular, SPP 1177 ‘Witnesses of Cosmic History’, TR33 ‘The Dark Universe’, and the Excellence Cluster ‘Universe’, Munich/Garching. Finally, iii) access to key instruments. The study of dark energy, dark matter, and large-scale structure in particular relies on large dedicated projects around key instruments to make progress on these important questions. The two most important instruments for German groups in the next decade are *eROSITA/SRG* and *Euclid* (Fig. 2).

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<sup>2</sup> Current (<2017) instruments are **not** listed (e.g., ESO surveys [KiDS, ATLAS, VIKING, VHS, GAIA, DES, SPT-Pol, ACT-Pol, PanSTARRS, eBOSS, HETDEX, SNfactory, Fermi, H.E.S.S., MAGIC, ALMA, IRAM, APEX). Important instruments where Germany plays at most a minor role are also **not** listed (e.g., DESI, SPT-3G, Advanced-ACT, ASKAP). Current/planned direct dark matter production/detection physics experiments are also **not** listed (e.g., LHC, XENON1T, CRESST, CDMS, CAST, IAXO).

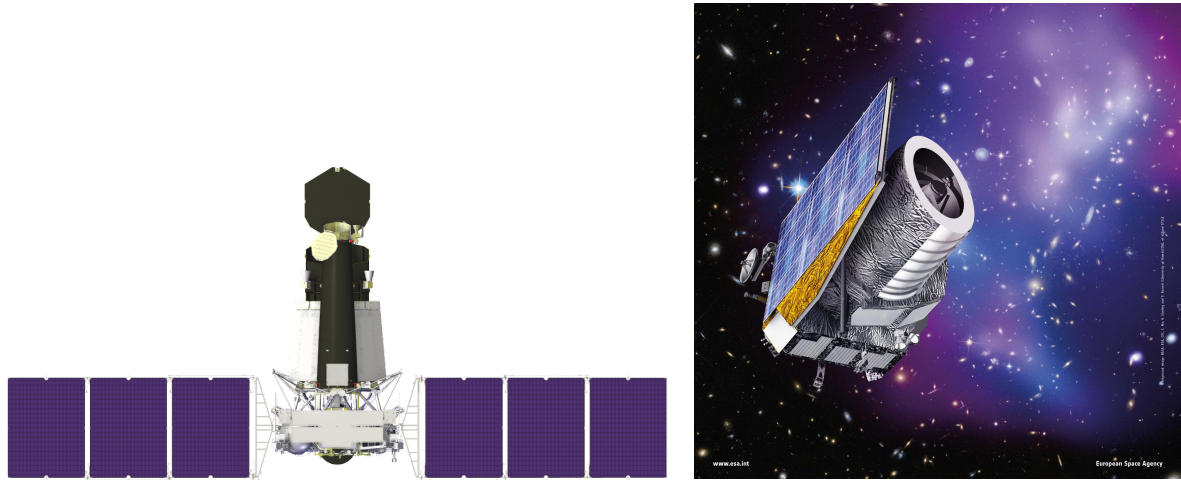


Fig. 2: Left: SRG satellite with the primary instrument *eROSITA* (copyright Lavochkin/IKI/MPE). Right: *Euclid* (copyright ESA).

The X-ray space telescope ***eROSITA*** is led by MPE in Garching (Predehl et al. 2010, 2014) and will perform an all-sky survey. It will enable a broad range of astrophysical science (e.g., Merloni et al. 2012) and many groups in Germany are involved (Bonn, Erlangen, Garching, Hamburg, Munich, Potsdam, Tübingen). Launch is scheduled for end of 2017; the key science driver is the study of dark energy by tracing the large-scale structure with 100,000 galaxy clusters (Pillepich, Porciani, & Reiprich 2012; Borm et al. 2014).

***Euclid*** is a wide-field space telescope working in the optical and infrared whose goal is to constrain the nature of dark energy by employing multiple cosmological probes including cosmic shear, BAO, redshift-space distortions, and galaxy clusters (Laureijs et al. 2011; Amendola et al. 2013, 2016). German institutes, in particular Bonn, Garching, Heidelberg, and Munich, play a major role in the ground segment and scientific exploitation of the data delivered by *Euclid*. Germany will host its own *Euclid* Science Data Center at MPE which will provide easy access to all *Euclid* data products. The current anticipated launch date is end of 2020.

Moreover, Germany has the opportunity to play a significant role in several other key cosmology experiments of the next decade. This includes in particular the ***Square Kilometer Array (SKA)*** and the ***Large Synoptic Survey Telescope (LSST)***. *SKA* is a next-generation low-frequency radio interferometer, building on the current and upcoming LOFAR and LOFAR 2.0 arrays. It provides numerous opportunities to address cosmological science (Carilli & Rawlings 2004, Maartens et al. 2015). *LSST* will use a dedicated 8m optical survey telescope to cover a large fraction of the sky to unprecedented depth. A coordinated involvement in *LSST* would significantly strengthen the German cosmology community, due to the unique complementarity of the *LSST* data set with those of *Euclid* and *eROSITA*, and is thus highly recommended. Further, ESA will most likely participate in the NASA *WFIRST* mission, which targets similar goals as *Euclid* but will provide a deeper survey in the near IR. German involvement in *WFIRST* science exploitation should thus also be encouraged.



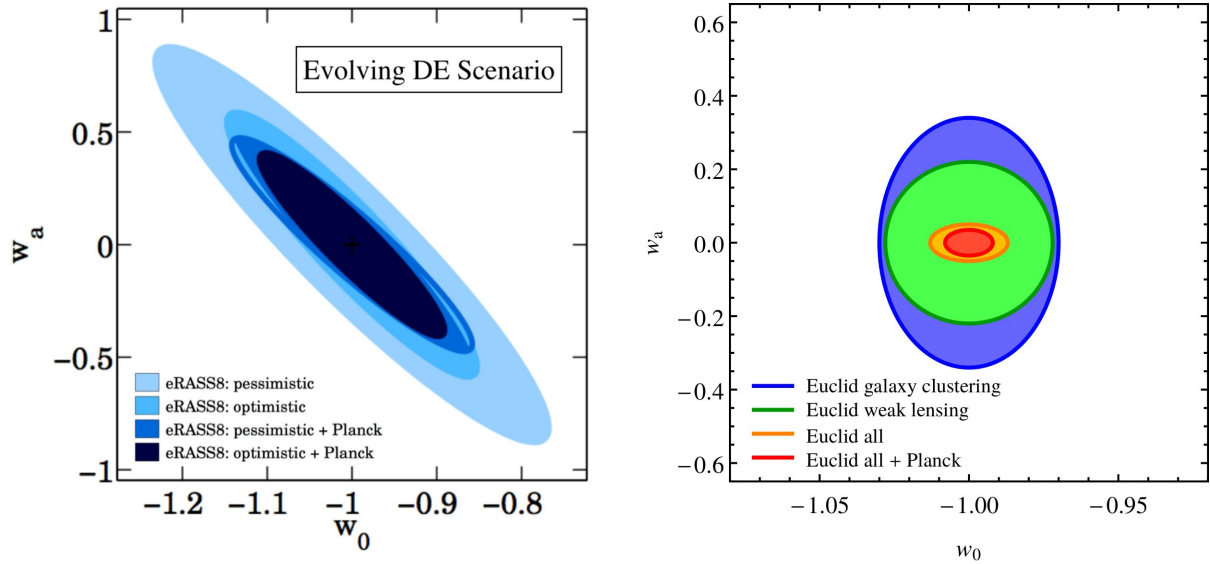


Fig. 3: Expected constraints on evolving dark energy equation of state, parameterized as  $w=w_0+w_a(1-a)$ , from *eROSITA* (left, Pillepich et al., in prep.; Merloni et al. 2012) and *Euclid* (right, adapted from Laureijs et al. 2011).

Germany also plays an important role in several other large experiments in the next decade that, while designed for principal science goals in other fields, will be highly useful for cosmology. This includes, in particular, the *4MOST* spectrograph (led by Potsdam and including Garching, Hamburg, and Heidelberg), the Cherenkov Telescope Array (*CTA*, spokesperson from MPIK and including about a dozen other German institutes), and the *Advanced Telescope for High ENergy Astrophysics* (*Athena*, PI from MPE and including scientists from Bonn, Erlangen, Garching, and Potsdam as working group/panel chairs) with leading roles. German groups play major roles in the *European-Extremely Large Telescope* (*E-ELT*), the *James Webb Space Telescope* (*JWST*), the proposed *CCAT<sup>3</sup>*, *CMB-S4*, and *Core CMB* experiments, hopefully the *Square Kilometer Array* (*SKA*), and in the *evolved Laser Interferometer Space Antenna* (*eLISA*; ESA call for missions expected for 2017, to be launched in 2034 if selected). All of these experiments also address science questions beyond cosmology. Moreover, cosmology research in Germany benefits in multiple other ways from Germany's ESA and ESO memberships.

In order to ensure a successful scientific exploitation of the unprecedented datasets delivered by *eROSITA* and *Euclid* as well as others, an adequate long-term funding scheme for scientist positions is essential. Significant German resources are being invested into the development, construction and operation of hardware and support infrastructure (e.g. satellites, instruments, and data centers) of these missions. Due to their unique impact in the fields of dark energy, dark matter, and large-scale structure, they will potentially yield a very high return on investment in terms of scientific output. This, however, requires scientists that can commit a substantial fraction of their time long-term to these projects to take on leading roles in the scientific exploitation of these missions. A lack of adequate long-term positions in Germany, as is currently the case, (i) diminishes the incentive of young researchers in Germany to engage in these missions whose scientific return will likely arrive well past the end of their current positions; (ii) drains science in Germany of valuable expertise, as highly trained scientists take on academic positions abroad or leave academia; and (iii) reduces the

<sup>3</sup> The *CCAT Pathfinder* (*CCAT-p*) experiment is already approved. The planned large sub-mm survey will enable a measurement of the kinetic Sunyaev-Zeldovich effect from galaxy clusters and the Bonn/Cologne groups expect a leading role in the science analysis.

German participation in the science exploitation of these missions, due to a lack of senior scientists able to play leading roles in the exploitation. In contrast, providing sufficient long-term funding for scientist positions connected to these missions greatly enhances the potential to harvest their scientific fruits. It will also significantly enhance the attractiveness of Germany as a destination for leading young researchers in cosmology. Additionally, the successful *eROSITA* and *Euclid* science exploitation will rely on third party-funded (e.g., DFG-funded) scientists in qualification positions (PhD students and postdocs), so availability of such funding should also receive high priority.

We also stress the essential supporting role to both *eROSITA* and *Euclid* played in particular by *4MOST* and *LSST*. For example, *Euclid* will observe more than one third of the full sky with high resolution from space, enabling the accurate measurement of galaxy shapes needed for weak lensing science. These data must be complemented with deep multi-band imaging from ground-based facilities, in order to split the galaxies into tomographic bins via photometric redshifts. In the Southern Hemisphere the combination with deep imaging from *LSST* will thus maximize the science return from *Euclid*. This reinforces the high priority that gaining access to *LSST* data should have for the German community. Similarly, *4MOST* will provide redshifts and velocity dispersions for almost all galaxy clusters detected by *eROSITA* in the Southern Hemisphere.

Where major access to key instruments is still under discussion, in particular for *SKA*, fast progress should be sought. *SKA* will enable cosmological constraints through large-scale structure measurements via neutral hydrogen galaxy surveys and intensity mapping, as well as radio continuum surveys. Its dataset is of a completely different nature than that delivered by optical and near IR surveys, and can thus provide crucial cross-checks.

## 6. Summary and Conclusion

With the advent of unprecedented data sets from new, large surveys, the upcoming decade will mark a decisive epoch in the study of dark matter, dark energy, and large-scale structure. Germany is strongly involved in a number of upcoming relevant missions, including *eROSITA* and *Euclid*, which are the two most important satellite missions in this field in the next 10 years:

- Scheduled to be launched at the end of 2017, *eROSITA*, a German-led space telescope, will produce a large sample of X-ray selected clusters, whose abundance and clustering will allow us to place stringent constraints on dark energy. In fact, *eROSITA* is forecast to be the first Stage IV dark energy probe (Fig. 3, left panel).
- *Euclid* is the major ESA mission to study dark energy and the history of the Universe. To be launched end of 2020, it will combine multiple probes including BAO, galaxy clustering, weak lensing, and optically selected clusters (Fig. 3, right panel). Germany is strongly involved in the exploitation of all four probes.

With its strong involvement in these missions, Germany is well posed to play a leading role in the study of dark energy, dark matter, and large-scale structure in the coming decade. However, certain measures are required to ensure success:

- The strong support to DLR and ESA for the construction and operation of the *eROSITA* and *Euclid* mission has to be continued.
- Adequate funding for the science preparation and exploitation of *eROSITA* and *Euclid* over the entire project periods should be provided. Funding these science tasks (and not just the equipment) is essential, and is expected to yield a science output of exceptional

impact. This applies in particular to state-funded universities but also to federally funded Helmholtz, Leibniz, and Max Planck Institutes. In particular, this should include long term funding for scientist positions who can take on leading roles in the exploitation of these experiments.

- Both *eROSITA* and *Euclid* rely on auxiliary data sets from ground-based telescopes, most notably *LSST* and *4MOST*, providing additional reasons for (continued) support of these facilities. In particular, a coordinated German involvement in *LSST* is strongly recommended, since the *LSST* dataset will be uniquely complementary to those of *Euclid* and *eROSITA*. *SKA* will provide an unprecedented view of large-scale structure in the radio band.

Further, given sufficient science funding, Germany is positioned well to take advantage of the potential of other relevant facilities where Germany plays a significant role, in particular *CTA*, *Athena*, *E-ELT*, *CCAT-p*, *CMB-S4*, *Core*, *JWST*, and *WFIRST*. Along these lines, continued support for the analysis of *HST*, *XMM-Newton*, and *INTEGRAL* data through the Verbundforschung Astronomie/Astrophysik is strongly recommended. This support should be extended to the successor of *HST*, the *JWST*, as well as to the successor of *XMM-Newton*, *Athena*. Further, continued general support for ESA and ESO, with particular emphasis on survey science, remains an important component of the future funding landscape.

Finally, the *SKA* has the potential to be competitive with *Euclid* as a probe of dark energy, dark matter, and large-scale structure. Thus, participation in *SKA* as a major contributor is important to ensure Germany's continued leading role in this research area beyond 2020.

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