Cosmology with the SKA: theoretical prospectives

P. Arnalte-Mur[1], J. M. Diego[2], C. Hernández-Monteagudo[3], D. Herranz[2], R. A. Lineros[4], E. Martínez-González[2] and J. A. Rubiño-Martín[5]

[1] Observatori Astronòmic de la Universitat de València, C/ Catedràtic José Beltrán 2, 46980 Paterna, Spain
[2] Instituto de Física de Cantabria (CSIC-UC), Av. los Castros, s/n, 39005 Santander, Spain
[3] Centro de Estudios de Física del Cosmos de Aragón (CEFCA), Plaza San Juan, 1, Planta2, 44001 Teruel, Spain
[4] Instituto de Física Corpuscular (CSIC-UV), C/ Catedrático José Beltrán, 2, 46980 Paterna, Spain
[5] Instituto de Astrofísica de Canarias, 38200 La Laguna, Tenerife, Canary Islands, Spain

Abstract

We briefly review the context of the SKA in the panorama of modern Cosmology. The SKA will undoubtedly be one of the most powerful tools for Cosmology during the first half of the XXI$^{\rm st}$ century. Many of the fundamental questions of modern Cosmology, such as the nature of the dark energy and dark matter that dominate the dynamics of the Universe, will be answered by SKA-driven science. Moreover, SKA will shed light on many aspects of large-scale structure growth and galaxy formation as well as fundamental Physics regarding the early Universe, inflation and tests of General Relativity.

1 Introduction

One of the remaining challenges in cosmology is to close the observational gap in redshift space between $z \sim 1100$ (when the Universe was roughly 4×10^5 years old and the Cosmic Microwave Background, CMB hereafter, formed) and $z \sim 6$ (when the Universe was about 1 Gyr old and galaxies and quasars were common enough to have reionized most of the intergalactic medium). During most of the intervening period the only light in the Universe was the CMB itself (hence the name of the dark ages that has become popular in the literature). Dark neutral hydrogen (HI) and helium clouds thinned and cooled as the Universe expanded, started collapsing in overdense regions and eventually formed the first (yet unobserved) stars and galaxies. During the so-called Epoch of Reionization (EoR) the light from these first cosmic candles ionized the hydrogen gas in expanding bubbles around isolated galaxies until the bubbles eventually joined and percolated, reaching a state in which most of the hydrogen in the Universe was again ionized. After this moment, a small fraction of neutral hydrogen survived in dense regions in galaxies, where dust clouds are able to block the incoming ionizing radiation. Although this broad picture is almost universally accepted, the details of the cosmic history during the dark ages and the EoR are largely unknown. These unknown elements of the cosmic history contain the key for unveiling some of the most perplexing mysteries of modern Cosmology, such as the nature of Dark Energy and/or the equation of state of the Universe. Reaching the Dark Ages and the EoR is an overwhelming observational and technological challenge for modern cosmologists.

As the most common atomic species present in the Universe, hydrogen is a useful tracer of local properties of the gas. The simplicity of its structure -a proton and electron- belies the richness of the associated physics. The 21 cm line of the neutral hydrogen arises from the hyperfine splitting of the $1S$ ground state due to the interaction of the magnetic moments of the proton and the electron. This splitting leads to two distinct energy levels separated by $\Delta E = 5.9 \times 10^6$ eV, corresponding to a rest frame wavelength of 21.1 cm and a frequency of 1420 MHz. This frequency is one of the most precisely known quantities in Astrophysics having been measured to great accuracy from studies of hydrogen masers. The 21 cm line was theoretically predicted by van de Hulst in 1942 and has been used as a probe of astrophysics since it was first detected by [10]. Due to cosmological redshift, the observed frequency of the line depends on the redshift z of the emitter as $\nu_{obs} = \nu_{em}/(1+z)$. This means that the 21 cm line is redshifted to frequencies $\nu_{obs} \sim 100-200$ MHz for sources in the approximate range of redshifts corresponding to the EoR, $z \sim 6-12$. To this cosmological redshift we must add the Doppler redshift due to the proper motion of the source. The optical depth of this transition is small at all relevant redshifts, yielding a differential brightness temperature of an hydrogen cloud when observed against a background source of light [28]:

$$\delta T_b \approx 27\, x_{HI} \left(\frac{T_S - T_R}{T_S}\right) (1+\delta_b) \left(\frac{\Omega_b h^2}{0.023}\right) \left(\frac{0.15}{\Omega_m h^2}\frac{1+z}{10}\right)^{1/2} \left[\frac{\partial_r v_r}{(1+z)H(z)}\right] \mathrm{mK}, \qquad (1)$$

where x_{HI} is the fraction of neutral hydrogen, δ_b is the fractional overdensity in baryons and the final term arises from the velocity gradient along the line of sight $\partial_r v_r$. The temperatures T_S and T_R are the *spin temperature* of the gas and the *brightness temperature* of the background radiation, respectively. Thus, the differential brightness temperature of the 21 cm is very sensitive to the environment and physical state of the intergalactic medium (IGM), as well as to fundamental cosmology, that enters in the last four terms of Eq. 1.

2 Status of modern cosmology and the role of the SKA

Modern cosmology rests upon the cosmological principle, which states that the Universe is isotropic and homogeneous at the largest scales, and on the validity of Einstein's theory of General Relativity. Both assumptions are roughly consistent with the current status of observations, but a number of observational and theoretical problems indicate that they might not be as solid as we previously thought. An example of observational tension between the cosmological principle and observations are the recently reported statistical anomalies of the

CMB [26]. Regarding the conceptual problems of the relativistic description of the Universe, maybe the most difficult question is about the elusive nature of the 'Dark Energy' that drives the accelerated expansion of the Universe, and whether it can be described or not by the Einstein's equations. The third pillar of modern cosmology is the inflationary paradigm, which poses many interesting open questions by itself.

2.1 The Dark Side of the Universe

The analysis of the CMB allows us to measure the curvature of space and to model the matter and energy content of the Universe [24]. Together with other independent experiments and cosmological probes (supernovae, galaxy and galaxy cluster counts, Lyα forest, large-scale structure [LSS], etc) these recent observations have led to the so called *'Cosmological Concordance Model'*, according to which the Universe is spatially flat, in agreement with the prediction from cosmological inflation. But in this model only 5% of the Universe seems to be made out of atomic matter (and half of it has not been observed in the local Universe yet!). The vast amount in the energy budget of the Universe, about 69%, seems to stem from a 'dark fluid' with negative pressure (the so called Dark Energy) with accelerates the expansion of the Universe, and the remaining 26% is attributed to dark, non-baryonic matter. In other words, 95% of the Universe is made of exotic matter and energy that is not directly observable. One of the foremost challenges of fundamental Physics in the XXIst century is the understanding of this 'dark side' of the Universe [3].

2.1.1 Dark Energy

Some of the possible interpretations of the Dark Energy are the cosmological term Λ in Einstein's equations (the so-called ΛCDM model), a scalar field rolling down its potential and giving rise to the model referred to as *quintessence* (QCDM models, [23]), an even weirder single cosmic fluid with an equation of state that causes it to act like dark matter at high densities and dark energy at low densities(Unified Dark Energy or Unified Dark Matter models, [8, 7]), or a breakdown of the laws of General Relativity (modified gravity theories, see for example [34]). A relatively large number of models have been proposed in the literature, but all of them suffer from conceptual problems that either require severe fine-tuning of fundamental parameters or involve exotic, not well understood physics. Moreover, the current status of observations is not enough to select among these competing models, either due to lack of sensitivity and redshift coverage or to dramatic degeneracy problems. The SKA data will be enough to rule out, or at least constrain, most of these models.

The Dark Energy equation of state (EoS) can be constrained, in principle, by matching existing models with observations at different cosmic times or, equivalently, redshift ranges. Interesting redshift regimes are $100 < z < 1000$ for the early Universe (CMB data), $10 < z < 100$ (linear growth of structures) and $0 < z < 10$ (SNeIa, radio-galaxies, etc). The problem is that for the moment only the low and high z regimes have been explored, while most of the intermediate range of redshifts is still *terra incognita*. The SKA will improve this situation by opening a new window to redshifts up to $z \sim 30$.

2.1.2 Dark matter and the growth of the Large-Scale Structure

In the time interval between the formation of the CMB and the present day hierarchical, non-linear Universe populated by stars, galaxies and galaxy clusters, the tiny primordial density fluctuations have evolved due to the combined action of gravity, radiative transfer and cosmic expansion. The small density fluctuations have grown and eventually collapsed to form gravitationally bound structures of enormous extent: the LSS of the Universe. The evolution of the LSS is sensitive to the properties of the dark matter and neutrinos, as well as dark energy and the action of gravity. Going beyond the scales of clusters ($\geq$ few Mpc), the study of the LSS is one of the main observational probes able to provide constraints on the cosmological model (see e.g. [39] for a review). In particular, the main aim of the next generation of surveys (such as eBOSS, J-PAS, DESI or Euclid) is to analyse two features of the galaxy distribution: the Baryon Acoustic Oscillations (BAO), which track the geometrical expansion and its acceleration, and the Redshift Space Distortions (RSD), which provide a measure of the growth of structure able to discriminate between different theories of gravity. In addition, the clustering of galaxies gives us information about the relation between the galaxies and the dark matter haloes hosting them.

There is no doubt that around 80% of the total amount of matter of the Universe is in the form of Dark Matter (DM). Nowadays, the scientific debate is focused on the nature of this DM. Among many proposed particle candidates for DM, Weakly Interactive Massive Particles (WIMPs) are the most popular class of candidates that appear in many models beyond the Standard Model (SM) of particle physics. A main requirement for any candidate is to explain the observed DM relic abundance $\Omega_{\rm DM}h^2 \simeq 0.11$ [25]. A WIMP candidate can fulfill this condition if it is stable, electrically neutral, the thermally averaged cross section is $\langle \sigma v \rangle \simeq 3 \times 10^{-26}\,\mathrm{cm}^3/\mathrm{s}$, and its mass is in the GeV–TeV range.

It is expected that WIMPs, accumulated around galaxies and clusters of galaxies, can annihilate and act as source of cosmic rays and gamma rays. The production and propagation of cosmic rays through galactic magnetic fields leads to the emission of synchrotron radiation which, for cosmic ray electrons in the energy range of 100 MeV to 1 TeV, gives radiowaves in the MHz–GHz frequency range. The frequency dependence of this synchrotron radiation depends on the energy spectrum of the cosmic rays, which in turn depend on the nature of WIMPs, and has a spectral signature that is different to other sources of Galactic synchrotron. Moreover, the angular distribution of this synchrotron radiation will also be rather different to the one corresponding to astrophysical sources such as supernova remnants. The SKA's projected frequency range goes from 50 MHz to 14 GHz, which is in the right ballpark to study galactic WIMP dark matter.

Regarding extragalactic radio signal, SKA will largely contribute to unveil the origin of the isotropic radio background also known as *ARCADE2 anomaly* [12, 15]. This anomaly corresponds to an isotropic component

$$T(\nu) = (1.19 \pm 0.14)/\mathrm{K}\ (\nu/\mathrm{GHz})^{-2.62 \pm 0.04} \tag{2}$$

that cannot be completely accounted by known radio source populations like AGNs and star forming galaxies. This phenomenon is also compatible with the contribution from WIMPs in far galaxies [13, 14] to the radio intensity. Extragalactic WIMP signal would appear like a faint population of radio sources. At 1.4 GHz, this population would emit with intensities $\sim \mu$Jy which one order of magnitud lower that available observations. However, it is expected that SKA1-survey may distinguish sources as faint as $\sim 2\,\mu$Jy after 10000 hours.

2.2 Reionization

We know from the Gunn-Peterson effect [18] and from analysis of the CMB that the Universe is almost fully ionized out to redshifts of about $z \sim 6$, but also that between $z \sim 1000$ and somewhere between 15 to 30 the Universe was filled with neutral hydrogen (the so-called Dark Ages). The history of ionization of the intergalactic medium is a key to reveal the origin of stars, galaxies and active galactic nuclei. We expect that the very first stars and galaxies produce X rays and UV light that eventually reionizes the Universe by a redshift around 10 (the 'Cosmic Dawn' that gives way to the Epoch of Reionization, EoR). However, there might also be other mechanisms of reionization like the injection of energy by annihilation or dark matter particles or by the decay of metastable particles[1].

2.3 Tests of inflation

The inflationary paradigm, which is often invoked as a solution to several conceptual 'coincidence' problems in Cosmology (the flatness problem, the horizon problem, the isotropy problem, the problem of the monopoles), is one of the milestones of the Concordance Model. But although the inflationary paradigm is widely accepted in the community, observations have not been yet sensitive enough to choose among the many different scenarios and hypothesis that have emerged in the literature during the last three decades. Conceptually, the mechanism of inflation is similar to many dark energy models: some kind of scalar or tensor potential that during the first instants of the Universe generated an exponential expansion of the scale factor. In principle, inflation models (single-field slow roll, multifields, curvaton, etc.) can be constrained using the same methods described for the EoS (section 2.1.1) and for the CMB: the study of the three-dimensional power spectrum, bispectrum and trispectrum of 21 cm fluctuations, as well as the study the Gaussianity of the same fluctuations, will add very useful information. We expect a significant progress in this topic from the combination of high accuracy and deep extragalactic source surveys achievable with SKA, the three-dimensional power spectrum of matter fluctuations at high z also obtained with the SKA, and the CMB maps provided by *Planck* and from the future CMB missions.

2.4 The role of SKA

With its powerful redshift range ($z_{\rm max} \sim 20 - 30$), large sky area (approximately 2π sr) and broad frequency coverage (50 MHz to 14 GHz), the SKA will revolutionize the panorama of Cosmology. It will have the potential to perform competitive cosmological surveys, complementary to state-of-the-art optical/infrared surveys such as Euclid. One of its main char-

[1] These aspects will be discussed in the next chapter of this White Book.

acteristics is the possibility of covering very large areas, due to the large field of view and the fact that the selection of extragalactic radio sources is not affected by Galactic dust extinction. Together with its sensitivity, this will allow SKA to cover extremely large volumes much faster than any previous facility. As the uncertainties in the next generation of surveys will be dominated by cosmic variance, this represents an important advantage.

Two observation modes will be of interest. On the one hand, SKA will perform surveys using the novel technique of HI intensity mapping (or HI density field mapping) [30]. As the relevant cosmological information comes from very large scales, it is not necessary in this context to identify individual galaxies. One can instead measure the integrated HI emission from all the galaxies in a given pixel in the sky and in frequency, with typical resolutions of $\sim 1^\circ$ and $\sim 5\,\mathrm{MHz}$. This technique will function similarly to how we map the CMB temperature anisotropies. But in contrast to the CMB, the SKA will resolve the HI density field in three dimensions (two angles and a redshift). This will add tomographic information (i.e. time evolution) about the growth of structures in the Universe as well as a direct measurement of the three-dimensional power spectrum $P_{\mathbf{k}}$ of density fluctuations. The 3D power spectrum $P_{\mathbf{k}}$ contains many more modes than the CMB angular power spectrum C_ℓ, and therefore will serve better to discriminate among Dark Energy models. As this HI combined signal is much larger than that of individual sources, this approach allows the mapping of large volumes in short periods of time. This challenging technique has already been tested in small surveys [9, 20], and much research is in progress to address the problems related to foreground removal and calibration (see [30] and references therein). It is feasible, already in the SKA1 phase, to survey an area of $\sim 30000\,\mathrm{deg}^2$ with SKA-MID or SKA-SUR going down to $z \sim 3$ resulting in a volume of up to $V = 700\,\mathrm{Gpc}^3$, although the redshift range will depend on the frequency band(s) used. This SKA1 survey will produce BAO and RSD measurements a factor of 2-3 better than current constraints, and covering a much larger redshift range ($0.05 < z < 3$ if both frequency bands are used). This will be the only survey measuring the properties of the LSS over such a large period of cosmic time. The extremely large volume will make this survey optimal for testing the cosmological model at very large horizon-size scales, in particular measuring the primordial non-Gaussianity parameter f_{NL} with a precision of $\sim 2-3$.

Alternatively, the SKA will perform an LSS survey using as tracers galaxies detected through the 21-cm emission line of neutral Hydrogen (HI) [1]. This is an effective way of obtaining galaxy positions and redshifts over large volumes, and a complementary technique to optical spectroscopic surveys. According to the forecasts of [31, 2], a survey of this type with SKA1 will be able to obtain constraints on BAO and RSD comparable to those of the BOSS survey. The main contribution will arrive with the SKA2 phase, where a 10,000 hours survey with flux sensitivity $\sim 5\mu\mathrm{Jy}$ will be able to cover $\sim 30000\,\mathrm{deg}^2$, and detect $\sim 10^9$ galaxies up to $z \sim 2$. This will be the largest galaxy redshift survey ever performed, covering a volume $V \sim 400\,\mathrm{Gpc}^3$, a factor of ~ 2 larger than Euclid's spectroscopic survey [30]. The HI survey will select star-forming galaxies, which are low bias objects, presenting an additional advantage for RSD, as the signal is inversely proportional to the bias, and at the same time reducing the impact of non-linear effects. Recent works [6, 29] forecast that this survey will measure the BAO scale in redshift slices of $\Delta z = 0.1$ with a precision of $\sim 0.3\%$ in the range $0.4 < z < 1.3$, and constrain RSD to a precision of $< 0.5\%$ in that same range. These constraints are comparable to those predicted for Euclid, while extending to lower redshifts. These two surveys will be complementary, offering a unique opportunity for joint analyses.

A SKA-MID survey based on the radio continuum emission will be able to detect 10^8 (10^9) extragalactic sources in SKA1 (SKA2) up to $z \sim 6$, although with no redshift information. The angular distribution of sources at very large scales will contain important cosmological information, such as constraints on the primordial non-Gaussianity, the accurate measurement of the cosmic dipole, and a way of testing the isotropy assumption. Moreover, it will be possible to combine this survey with data from overlapping surveys, either HI SKA surveys or others as Euclid, to use the multi-tracer technique [32, 17] and minimise the effect of cosmic variance, obtaining even tighter constraints on the cosmological parameters.

In addition to these cosmological volume surveys, SKA will be able to perform much deeper surveys over smaller areas. As explained in [5], a deep HI galaxy survey will be able to study the evolution of the clustering of star-forming galaxies up to $z \geq 3$ and its dependence on galaxy properties (in a similar way that optical and infrared surveys do at lower redshift to constrain models of galaxy evolution). In a similar way, deep radio continuum surveys in fields with multi-wavelength coverage will be able to study the clustering of different types of AGNs, providing valuable information to understand its formation and evolution.

Finally, new class of fundamental test will become possible by means of the superb frequency resolution of the SKA, which will allow us to directly see the expansion of the Universe based in the redshift drift of individual objects [21].

2.5 Cosmology with other hyperfine structure lines and SKA

Apart from the hydrogen, other atomic species show hyperfine structure lines that may be useful for cosmological studies with the SKA. This is the case of the hyperfine line of neutral deuterium at $\lambda = 91.6\,\mathrm{cm}$ [33]. Being more challenging to detect than the hydrogen 21 cm line due to its longer wavelenth and also to the smaller abundance relative to H, this line provides the cleanest possible way of measuring the primordial abundance [D/H], free from contamination by structure formation processes at lower z. This measurement provides an excellent indirect determination of the baryon-to-photon ratio $\eta = n_\mathrm{b}/s$. As big bang nucleosynthesis (BBN) [38, 35] is the only known natural production mechanism of deuterium, this in turn provides a measurement of the cosmic baryon abundance $\Omega_\mathrm{b} h^2$.

Another interesting line is the $^3\mathrm{He}^+\ ^2\mathrm{S}_{1/2}\ F = 0$–$1$ transition at $\lambda = 3.46\,\mathrm{cm}$ [36, 4, 22]. Although again the primordial ^{3}He abundance (relative to H) is very small ($\sim 10^{-5}$), in this case the spontaneous decay rate is 680 times larger than the 21 cm, and more importantly, for the same redshift z the radio contamination is much lower because the observed frequencies are larger ($\nu_\mathrm{obs} = 8.666/(1+z)\,\mathrm{GHz}$). Intergalactic $^3\mathrm{He}^+$ absorption can be used as an observable of cosmological helium reionizations, both HeII and HeI. SKA could be used to measure this transition with two main goals. First, to constrain the primordial ^{3}He abundance, providing an indirect measurent of the cosmic baryon abundance. Second, to use the absorption of $^3\mathrm{He}^+$ line along the line of sight of quasars to study the reionization of the first electron of helium, which is thought to occur at the same time as the reionization of hydrogen. This will provide valuable and complementary information to the 21 cm about the ionization state of the IGM and the reionization process.

2.6 Cosmology with SKA in combination with other observables

The 21 cm signal alone encrypts amounts of information that are potentially several orders of magnitude larger than other cosmological observables such as the CMB or the current galaxy surveys. For this only reason the SKA will be one of the most important tools for Cosmology in the first half of the XXIst century. But as it happens in many other fields of Astrophysics, the synergy between 21 cm Astronomy and independent observations in other wavelenghts will help to break degeneracies, remove possible systematic errors, tighten the constraints in cosmological models and lower the size of error bars in fundamental cosmological parameters.

CMB photons interact with hydrogen atoms in three main ways. Firstly, CMB serves as a thermal bath for the hydrogen atoms and a backlight against which the 21 cm signal can act as an absorber or as an emitter according to Eq. 1. Besides, CMB photons interact with the intergalactic medium (IGM) during reionization by Thomson scattering of free electrons or by interactions that may introduce spectral distortions like the Sunyaev-Zel'dovich (SZ) effect [37] or fine structure transitions associated to atomic, ionic and molecular species present in the IGM (resonant scattering collisional emission on the same transitions, and the Wouthuysen-Field coupling in the OI 62.3 μK transition [19]). Moreover, any energy injection process during the dark ages will distort the CMB spectrum at the same time that it will modify the observed 21 cm. Finally, clumps of hydrogen interact gravitationally with CMB photons through the gravitational lensing and ISW effects.

Similarly, and since the SKA will overlap at low redshift with current galaxy and quasar surveys, the joint study of the SKA galaxy redshift survey using the 21 cm line and the SKA continuum radio survey with optical, IR and radio surveys such as the SDSS, WiggleZ, BOSS, 4MOST, LSST, HETDEX, Pan-Starrs, or DES, PAU, J-PAS and Euclid will revolutionize our view of LSS and galaxy formation and evolution.

Other SKA synergies that will contribute to the advance of cosmology include: the radio observation with SKA of Gamma Ray Bursts, that will probe the star formation rate up to very high z; the interdisciplinary study of dark matter annihilation together with X-Ray observatories such as LOFT [11] and particle accelerators; General Relativity tests with precision SKA timing of objects in pulsar catalogues; the study of primordial magnetic fields by measuring the electron density and energy distribution in the direction of LSS features as observed by other experiments, etc.

3 Involvement of the Spanish Cosmology community

Spanish cosmologists have been deeply involved in radio, optical and CMB–related Cosmology for a long time. The Spanish community possesses wide expertise in both theoretical and observational Cosmology as well as in the development of astronomical instrumentation. Several members of our community have participated in both ground-based and space

CMB experiments such as COSMOSOMAS, the VSA, the *Planck* satellite and QUIJOTE. Spanish researchers are a reference in the statistical analysis of temperature and polarization CMB anisotropies and have led relevant projects, such as EPI (Exploring the Physics of Inflation), on microwave instrumentation, component separation, Gaussianity analysis, statistical characterization and the discovery and study of statistical anomalies of the CMB. Our cosmologists are expert on the statistical signal processing of large data sets. Moreover, several members of our community are leading the *Planck* science tasks regarding compact source catalogues, homogeneity and isotropy, cross-correlation with LSS through the integrated Sach-Wolfe effect, galaxy cluster follow-up, primordial magnetic fields and kinematic SZ effect. Spanish scientists are also involved in the preparation of future CMB experiments such as COrE+. All this experience will not only make Spanish researchers very fit candidates to lead SKA-CMB synergy research projects, but also put the Spanish community in a good position to tackle SKA-alone science cases, since most of the techniques, software and statistical tools we have developed for the CMB can easily be exported to 21 cm data.

In addition, Spain has a long tradition in optical, X-ray and radio galaxy surveys. Many members of the Spanish community have participated in most of the big survey projects of the last decades. Moreover, several Spanish researchers are currently leading specifically Cosmology-oriented surveys such as ALHAMBRA, PAU, DESI and J-PAS, and participating in other large current or upcoming surveys such as BOSS, eBOSS, DES, DESI and Euclid. With these surveys we intend to give answer to some of the many questions that plague modern cosmology, such as the kind of equation of state that better fits the observed behaviour of the dark energy.

Finally, Spain has also a deep interest in the theoretical/observational study of dark matter; MultiDark is an excellence project in which most of the Spanish research community working in the field of dark matter is involved. We also are experienced in the management and operation of the kind of supercomputing facilities that will be required by a project such as SKA. All of this expertise and previous work place the Spanish one as one of the most motivated and best situated communities for participating in the SKA.

Acknowledgments

The authors acknowledge partial support from the Spanish MINECO through projects AYA2013-48623-C2-2, AYA2007-68058-C03-01, AYA2010-21766-C03-02, AYA2012-30789 and the Consolider-Ingenio projects CSD2010-00064 (EPI: Exploring the Physics of Inflation) and CSD2009-00064 (MultiDark), and from the Generalitat Valenciana through grants PROMETEOII/2014/060 and PROMETEOII/2014/084. RAL acknowledges the Spanish grant FPA2014-58183-P. CHM acknowledges the support of the Ramón y Cajal fellowship RyC 2011 148062 awarded by the Spanish MICINN and the Marie Curie Career Integration Grant CIG 294183.

References

[1] Abdalla, F. B., Rawlings, S. 2005, MNRAS, 360, 27

[2] Abdalla, F. B., et al. 2015, AASKA14, eprint arXiv:1501.04035

[3] Albrecht, A. et al., 2006, *Report of the Dark Energy Task Force*, eprint arXiv:0609591
[4] Bagla, J. S., & Loeb, A. 2009, eprint arXiv:0905.1698
[5] Branchini, E. et al. 2013, in *Italian SKA White Book*, eds. L. Feretti, E. Prandoni
[6] Bull P. et al., 2015, in AASKA14, eprint arXiv:1501.04088
[7] Capozziello, S. et al., 2006, Phys. Rev. D, 73, 043512
[8] Cardone, V. F., Troisi, A. & Capozziello, S., 2004, Phys.Rev. D, 69, 083517
[9] Chang T.-C., Pen U.-L., Bandura K., Peterson J. B., 2010, Natur, 466, 463
[10] Ewen, H. I. & Purcell, E. M., 1951, Nature 168, 356
[11] Feroci, M. et al., 2012, Experimental Astronomy, 34, 415
[12] Fixsen, D. J. et al. 2009, eprint arXiv:0901.0555
[13] Fornengo, N. et al. 2011, Physical Review Letters, 107, 271302
[14] Fornengo, N. et al. 2012, J. Cosmology Astropart. Phys., 3, 033
[15] Fornengo, N. et al. 2014, J. Cosmology Astropart. Phys., 4, 008
[16] Furlanetto, S. R., 2006, MNRAS 371, 867
[17] Gaztañaga, E., Eriksen, M., Crocce, M., et al. 2012, MNRAS, 422, 2904
[18] Gunn, J. E. & Peterson, B. A. 1965, ApJ, 142, 1633
[19] Hernández-Monteagudo, C., Rubiño-Martín, J. A., & Sunyaev, R. A., 2007, MNRAS, 380, 1656
[20] Kerp J. et al., 2011, AN, 332, 637
[21] Klöckner, H. R. et al., 2015, in AASKA14, eprint arXiv:1501.03822
[22] McQuinn, M., & Switzer, E. R. 2009, Phys. Rev. D, 80, 063010
[23] Padmanabhan, T., 2003, Phys.Rept., 380, 235
[24] Planck Collaboration, 2014, A&A 571, A16
[25] Planck Collaboration 2014, A&A, 571, A19
[26] Planck Collaboration, 2014, A&A 571, A23
[27] Pritchard J and Loeb A., 2010, Nature 468, 772
[28] Pritchard, J. R. & Loeb, A., 2012, Rep. Prog. Phys. 75, 086901
[29] Raccanelli A., et al., 2015, in AASKA14 eprint arXiv:1501.03821
[30] Santos, M. G., et al. 2015, in AASKA14, eprint arXiv:1501.03989
[31] Santos, M. G. et al. 2015, in AASKA14, eprint arXiv:1501.03990
[32] Seljak, U. 2009, PRL, 102, 021302
[33] Sigurdson, K., & Furlanetto, S. R. 2006, Physical Review Letters, 97, 091301
[34] Starobinsky A.A., 1980, Phys. Lett, B, 91, 99
[35] Steigman, G. 2007, Annual Review of Nuclear and Particle Science, 57, 463
[36] Sunyaev, R.A. 1966, Astronomicheskii Zhurnal, 43, 1237
[37] Sunyaev, R. A., & Zel'dovich, Y. B., 1972, Comments on Astrophysics and Space Physics, 4, 173
[38] Wagoner, R. V., Fowler, W. A., & Hoyle, F. 1967, ApJ, 148, 3
[39] Weinberg, D. H., Mortonson, M. J., Eisenstein, D. J., et al. 2013, Phys. Rep., 530, 87