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SCIENCE WITH SKA

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Abstract. Highlights are presented about the science to be done with SKA. as well as state of the art science already done today with its precursors (MeerKAT, ASKAP) and pathfinders (LOFAR, NenuFAR), with accent on the expected breakthroughs.

Keywords: SKA, galaxies, cosmology, pulsars, pre-biotic, molecules

1 The key scientific projects of SKA

Some of the main puzzles of cosmology are the nature of dark matter and dark energy, representing in total 95% of the content of the Universe. The dark energy is presently compatible within the uncertainties with a cosmological constant, but it is paramount to determine with greater precision whether its evolution with time is dynamic, and could be due to a fifth element, a quintessence, and new physics. The tools for making this diagnostic are the same as for many other dark energy probes, either from ithe ground or in space, with Euclid: the BAO (Baryon Acoustic Oscillations), playing the role of a standard ruler, measuring the expansion at differnt redshifts, the Weak Lensing (WL), or Redshift Space Distorsions (RSD), measuring the density and amplitude of large-scale structures to constrain the evolution of Ω and Λ. These tools will be exploited with optical tracers, and the novelty of SKA is to use radio tracers, and the HI-21cm line to identify galaxies. These tracers have different biases than the optical ones, and both studies are very complementary. Optically, the massive galaxies are early-type gathered in galaxy clusters, while the HI-rich galaxies are late-type in the field.

Another key project is to explore the Epoch of Reionization (EoR), likely to extend from z=20 to 6. If it is already possible to have some clues with present searches of galaxies and quasars at z>6, the inter-galactic medium will be uniquely explored by SKA, with the redshifted 21cm-HI line, as it is now with pathfinders and precursors. The large galaxy surveys made over the whole available sky, due to the wide field of view, will serve to determine uniquely the large-scale structures, and the galaxy formation and evolution.

Pulsars will be discovered in a huge number with SKA, exploring the whole Milky Way, while presently they are confined in the solar neighborhood. Milli-second pulsars are extremely precise clocks, which can be used to detect very long wavelength gravitational waves. Strong-gravity will be explored with pulsars and black holes

Cosmic magnetism is another key project, and in particular the formation of primordial magnetic fields will be tackled. Finally, the search for the origin of life, the mapping of the protoplanetary disks, and the search for pre-biotic molecules, will be carried out in synergy and complementarity with ALMA at higher frequencies.

All key projects with SKA have been developed in many whitepapers and conferences, (e.g., Carilli & Rawlings 2004; Carilli 2015).

2 Cosmology and galaxies

2.1 Dark sector and new physics

The state of the art constraints on the dark energy and the dark matter are obtained by combining all available data, from the SNIa standard candels, i.e. the Pantheon sample of 1048 SNIa between redshifts $0.01 < z < 2.3$ (Scolnic et al. 2018), and the 207 SN sample from DES-3yr (Abbott et al. 2019), with the BAO results from SDSS (Alam et al. 2021), and the CMB data (Planck Collaboration et al. 2020). The equation of state of

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the dark energy can be written as the pressure proportional to the density P = w ρ, with w negative, and the variation of w(a)= w_0 + wa (1-a), where a is the characteristic radius of the Universe, a=1/(1+z). Since SNIa are difficult to observe at z>1, Inserra et al. (2021) propose to use and calibrate superluminous supernovae (SLSNe), which will allow to go farther and faster. The first results are promising, putting constraints in the w_0-wa diagram. With the enhanced precision acquired in the recent years, some tension has grown between observations and the standard ΛCDM model, suggesting the necessity of new physics (Smith et al. 2020). In particular the main tension occurs between the Hubble constant H_0= 73.48±1.66 km/s/Mpc measured locally with Cepheids or other indicators (Riess et al. 2018), and the Planck determination of 67.4± 0.5 km/s/Mpc. The discrepancy reaches 3.7σ. In radioastronomy, powerful masers (H_2O, OH..) allow to observe in VLBI the center of external galaxies, and their rotating circum-nuclear disk; measuring the velocities through the Doppler effect and monitoring through VLBI the gradient of maser poition with velocity, results in a precise distance indicator, as shown beautifully by the prototypical example of NGC 4258 (Greenhill et al. 1995). SKA will measure many more masers around AGN at various redshifts, and can give a complementary approach to the problem. Already Pesce et al. (2020) with megamasers confirm H_0 = 73.9±3 km/s/Mpc.

The most recent BAO and RSD results, including 147 000 quasars (Ata et al. 2018), and Lyα absorption surveys (Bautista et al. 2017), are compatible with a flat ΛCDM cosmology, and perfectly compatible with the Planck cosmological parameters (Bautista et al. 2021).

SKA-1 surveys of galaxies in the HI-21cm lines will be complementary and competitive with the optical ones from the ground and in space (Euclid). Surveys where galaxies are detected individually will be most useful for galaxy formation and evolution, they will detect 4 million galaxies up to z=0.2 in the all-sky survey, 2 million galaxies up to z=0.6 in the wide field, and 0.4 million in the deep field survey up to z=0.8 (of 50 square degrees area). For cosmology purposes, HI intensity mapping over 30 000 square degrees, and covering redshifts up to 3 will be more competitive (Maartens et al. 2015). Weak lensing in radio surveys up to redshift z=6 will consider a billion objects. One of the strong advantages of SKA-1 is the much larger volumes sampled, with respect to all other probes (Euclid, DESI, BOSS, Nancy-Grace-Roman...). The second phase SKA-2 will surpass all.

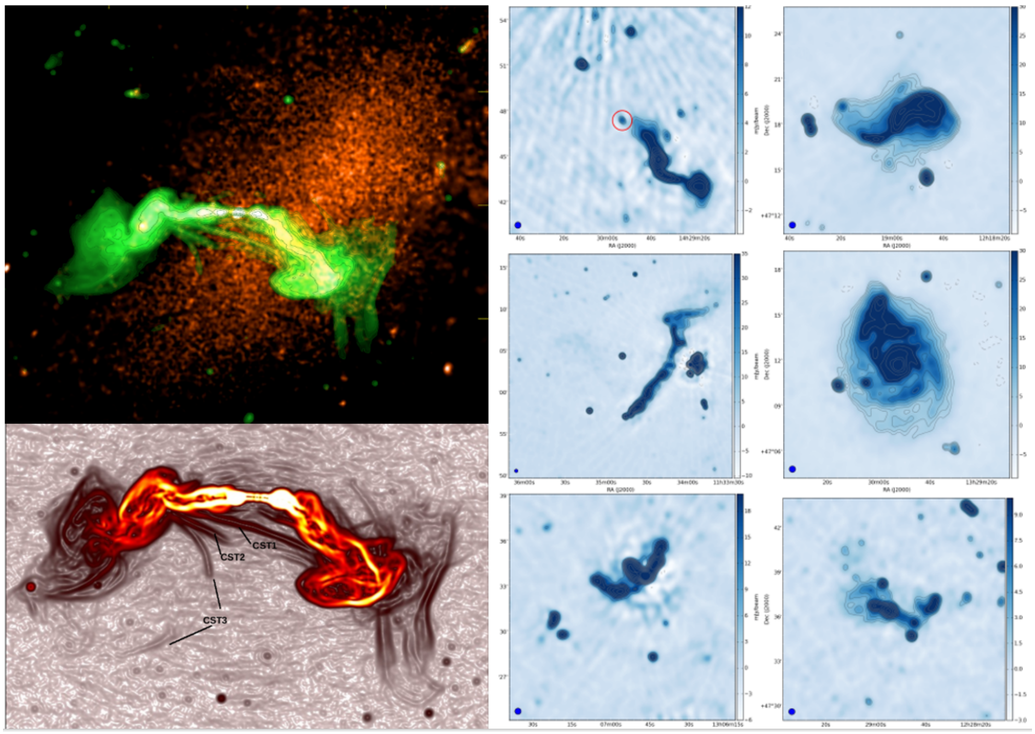

Fig. 1. Left: Radio continuum emission from ESO 137-006 detected by MeerKAT at 1030 MHz. Three collimated synchrotron threads (CSTs) between the radio lobes are indicated. The Sobel filter has been applied to the image, to better show these features (Ramatsoku et al. 2020). The upper panel shows that the galaxy is entering the Norma cluster, and its X-ray gas atmosphere (in red).. **Right:** Some radio images of nearby galaxies from the LOFAR Two-metre Sky Survey (LoTSS) (Shimwell et al. 2019).

2.2 Continuum and HI surveys

Simulations have been performed of wide-field images of the radio-continuum sky with SKA, detecting both the very numerous star-forming galaxies, with synchrtron emission coming from supernovae, and the stronger but less numerous radio AGN, of FRI and FRII types, the latter even less numerous but stronger (Jackson 2004). The AGN radio jets can be used easily as standard rods, constraining the cosmological parameters, by themsleves, and also through weak lensing.

For the all-sky survey at 1.4 GHz, in 2yrs of integration, SKA1 will achieve 3 μJy rms, and detect $\sim$4 galaxies per arcmin^2 (at more than 10σ), (Jarvis et al. 2015). The survey will be made with an excellent quality circular Gaussian beam from about 0.6 to 100", With almost uniform sky coverage of 3π str. This will provide a total of 0.5 billion radio sources, yielding weak lensing and Integrated Sachs Wolfe (WL, ISW) diagnostics. For the wide-field (5000 deg^2), with 2 μJy rms $\sim$6 galaxies per arcmin^2 are expected (at more than 10σ). For the deep-field (50deg^2) with 0.1 μJy rms, $\sim$20 galaxies per arcmin^2 will be detected, at more than 10σ.

Figure 1 shows some examples of radio images from the LOFAR Two-metre Sky Survey (LoTSS), and also how the precursor MeerKAT has discovered new features in typical radio-jets: collimated synchrotron threads, linking the radio lobes from the sides, in parallel to the radio jets, in ESO 137-006. This galaxy is moving inside the wind of the intra-cluster gas, entering the Norma cluster. The radio lobes are distorted and bent, and the threads look like relics of the previous radio jets, in previous episodes of ejection.

In HI-21cm surveys, SKA-1 will allow the imaging of substantial number of high-redshift galaxies for the first time (Staveley-Smith & Oosterloo 2015). While the present instruments are restricted to detect HI in individual galaxies only to the local Universe up to z=0.1, the very deep survey will permit the detection of galaxies at z=2, and even higher for SKA-2. A glance of what intensities could be detected is given by recent stacking to detect only "globally" some remote galaxies. With GMRT deep (117h) field, Bera et al. (2019) have stacked 445 blue galaxies between $0.2 < z < 0.4$, and obtained a detection at 7σ of M(HI) = 5 10 ^{9} M$_\odot$. Stacking the continuum to derive the star formation rate, they derive a depletion time of $\sim$ 9 Gyrs. From GAMA survey, imaged on DINGO-VLA, Chen et al. (2021) have stacked HI cubelets on a sample of 3622 galaxies, and obtained a clear detection, with FWHM of 60km/s.

3 Reionization

Intensity mapping is the only technique able to determine the global quantities searched for in the EoR. Continuum foregrounds are typically 1000 times brighter than the expected cosmological signal. The instrumental responses to bright foregrounds with extended and multiple sidelobes, forming a sea of confused signals, depending on their location on the field of view, are a challenge to understand and subtract away (Santos et al. 2015). The foregrounds to be eliminated produce a perturbing signal, which is not necessarily spectrally smooth (Switzer et al. 2015).

The LOFAR key project on EoR has observed more than 1000hours on selected clean fields, with the least possible foreground emission. However, even if the nominal sensitivity is reached to detect easily the expected signal, the confusion by foregrounds has prevented to draw any conclusion. Controlling the calibration, and cleaning for the sidelobes down to the low intensity level required is a long process. While in 2017, only 0.5% of data were understood and used (Patil et al. 2017), recently up to 5% of data has been understood and cleaned, resulting in an upper limit of the EoR signal two orders of magnitude above the expected signal. There still remains noise that could be due to residual emission from foreground sources or diffuse emission far away from the phase centre, polarization leakage, chromatic calibration errors, ionosphere, or low-level radiofrequency interference (Mertens et al. 2020)

4 Pulsars, Cosmic magnetism

4.1 Pulsars and gravitational waves

The large number of pulsars to be discovered by SKA, in combination with its exceptional timing precision, will revolutionize the field of pulsar astrophysics. SKA will provide a complete census of pulsars in both the Galaxy and in Galactic globular clusters (Cordes et al. 2004). In the Milky Way, about 30 000 pulsars should be present, and 10 000 milli-second ones. May be 20 000 pulsars will be detectable in the whole Galaxy (while today we know only pulsars in the solar neighborhood). Pulsars and compact objects will allow unique tests of the strong field limit of relativistic gravity and the equation of state at extreme densities.

Through monitoring these pulsars, which are extremely precise clocks, (up to 10^{-15} in relative), gravitational waves of long wavelengths, of the order of light-yrs, could be detected, and pulsars are the only way. The hope is to detect the merger of super-massive black holes, and also the primordial waves, signature of inflation (Janssen et al. 2015). A first preliminary detection has been claimed with present telescopes (Arzoumanian et al. 2020).

4.2 *Fast Radio Bursts*

Since their discovery by Lorimer et al. (2007), our knowledge of Fast Radio Bursts (FRB) have grown considerably: they have been detected in large numbers, especially with the wide-field instrument CHIME: 540 are known, and the occurence has been estimated at 800 per day on the whole sky (CHIME/FRB Collaboration et al. 2019). With SKA-MID, it will be possible to detect 100 FRB/yr, with precise localisation (Keane 2018). The nature of the FRB phenomenon is not yet clarified, although many repeaters have been detected, and one FRB has been associated with a Galactic magnetar, SGR 1935+2154 (Bochenek et al. 2020). Due to their surface magnetic fields larger than 10^{14} gauss, magnetars are the source of high-energy phenomena, where their magnetic energy decays. A florilege of theories have been proposed to explain the phenomena (Platts et al. 2019).

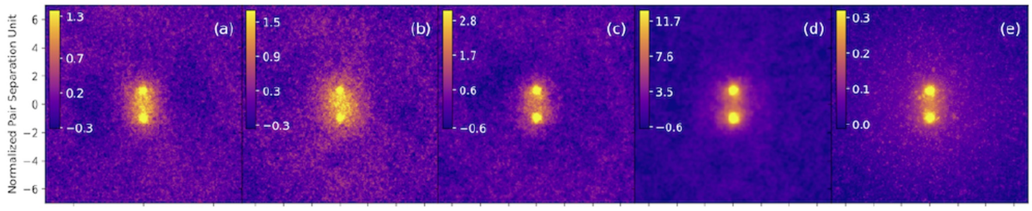

Fig. 2. Stacking radio and X-ray maps, around physically nearby pairs of luminous red galaxies (LRG). From left to right the columns are GLEAM 154 MHz, 118 MHz, 88 MHz, OVRO-LWA 73 MHz, and ROSAT combined band 0.1 -2.4 keV. The colour bars all have units of temperature in K, except the ROSAT maps which are in counts per second per arcmin^2 x10^4. From Vernstrom et al. (2021).

4.3 *Magnetic Fields*

Polarisation of radio emission, and Faraday rotation have been used intensively to determine the intensity and orientation of the magnetic field in spiral galaxies, at various depths according to the various wavelengths: either from the halo, or the disk, and different distributions have been obtained with respect to the spiral arms (Kierdorf et al. 2020). Turbulence due to star formation in spiral arms paradoxically reduces alignment, and frequent field reversals in the vertical direction contribute to distortions that are not yet well understood. LOFAR has been used in combination with VLA to determine the spectrum of the emission, separate thermal and non-thermal components, the magnetic field strength and the cosmic ray electron losses (Mulcahy et al. 2018).

All-sky survey of Faraday rotation will measure inter-galactic magnetic field, as well as inside galaxies. The mechanisms to generate the field are not yet settled, from inflation, phase transitions in the early Universe, and batteries to amplify the seeds. Normally the field is frozen in the ionized gas, but should dilute away in the expansion. When structures collapse, the field is amplified again (Johnston-Hollitt et al. 2015).

Searches have been done in diffuse filaments connecting clusters, at the cosmic web (15Mpc) scale, combining X-ray hot gas with eRosita with radio data from ASKAP/EMU Early Science (Reiprich et al. 2021). Missing baryons are searched for by studying the warm-hot gas in cluster outskirts and filaments. The bridge between two clusters is detected; it may contain known galaxy groupis, but not accounting for all the emission There are several clumps of warm gas falling into the clusters, compatible to what is observed in simulations.

LOFAR has also detected synchrotron emission in filaments between merging galaxies, with possible shocks re-accelerating the electrons (Govoni et al. 2019; Botteon et al. 2020), but these were only short scales. Now with GLEAM (the MWA survey), it is possible to search for longer filaments (see Figure 2). These are traced by Luminous red galaxies (LRGs), which are massive early-types residing in the center of galaxies clusters or groups. The first large-scale filament detection, has revealed a magnetic field of 30-60 nG, of intensity higher than previously believed, with electrons subject to more efficient shock acceleration (Vernstrom et al. 2021).

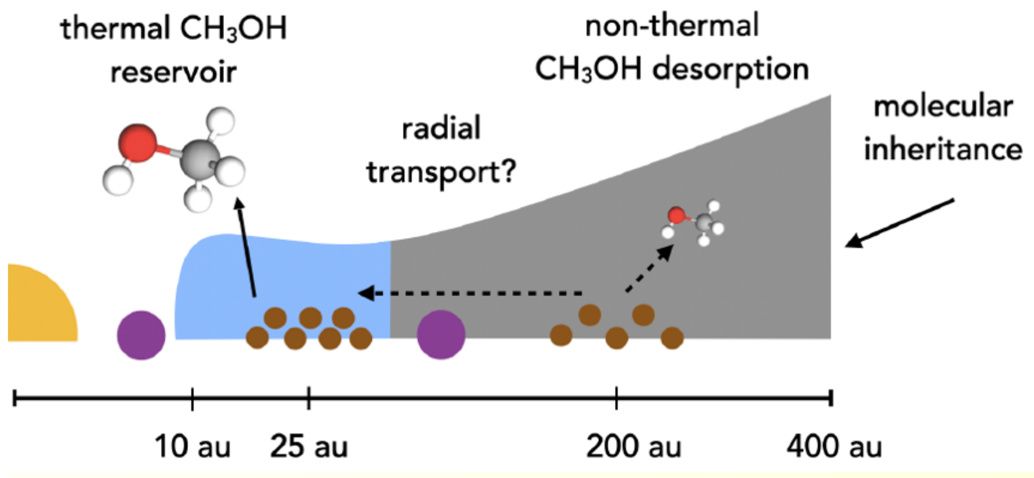

Fig. 3. Cartoon of a protoplanetary disk (HD 100546) showing the regions where CH_3OH is detected and the different physical and chemical mechanisms proposed (Booth et al. 2021).

5 Craddle for life

ALMA has made a breakthrough in the domain of the formation of planets and protoplanetary disks, in imaging with superb resolution resonant rings and gaps (Andrews 2020). Disks are formed first with gas and small-size dust grains, the latter agglomerating progressively in mm- and cm-sized grains before becoming planetesimals. These grains emit at longer and longer wavelengths, and SKA-1 will be the prefered instrument to detect cm to m-sized dust. At high resolution with 40mas beam, the nearest systems will be mapped with 4AU resolution, sufficient to determine the snow line (Hoare et al. 2015). Large exoplanets, of Jupiter-size, could be detected with their magnetic fields (Zarka et al. 2018). In synergy with ALMA, the detection of complex organic molecules (COM) could be carried out, such as the methanol CH_3OH, with deuterated species CH_2DOH, methanethiol CH_3SH, formamide NH_2CHO, and heavier pre-biotic molecules in Band 5, such as amino acids and sugars. In 1000h SKA1-mid could detect clearly α-alanine, with a hundred of lines, for a column density of 10^{13} cm^{-2} (Hoare et al. 2015).

Methanol has been detected in protoplanetary disks, and is thought to come from hydrogenation of CO on icy grains (cf Figure 3). Complex organic molecules have now been detected, which are key to form amino-acids, and pre-biotic molecules (Booth et al. 2021). These COM cannot form in situ, but must come from ices formed previously in dark interstellar clouds.

6 Conclusions

SKA-1 will help to tackle the main puzzles of cosmology: the nature of dark matter and dark energy, by using the common tools (BAO, WL, RSD) with high precision, and with tracers with different biases than optical surveys (radio continuum, HI in galaxies). With extragalactic masers, it will be possible to bring a complementary constraint to the H_0 problem, suggesting new physics.

With redshifted HI-21cm line, SKA will have a unique contribution to the Epoch of Reionization, and the birth of the first galaxies. With the timing of millisecond pulsars, SKA will make a breakthrough in probing strong ggavity, and detecting gravitational waves in the very low frequency regime (nanoHz), to search for primordial waves.

Our knowledge of magnetic genesis will considerably improve. SKA will work in synergy with ALMA to determine the physics of protoplanetary disks, and detect pre-biotic molecules.

All these key projects have begun to be tackled at very low frequency with the NenuFAR pathfinder in Nançay, where the first large programs are ES1: Cosmic Dawn; ES2: Exoplanets & Stars; ES3: Pulsars; ES4: Transients; ES5: Fast Radio Bursts; ES6: Planetary Lightning; ES7: Joint Jupiter studies; ES8: Cluster of galaxies & AGNs; and ES9: Cluster Filament & Cosmic Magnetism.

References

Abbott, T. M. C., Allam, S., Andersen, P., et al. 2019, ApJ, 872, L30

Alam, S., Aubert, M., Avila, S., et al. 2021, Phys. Rev. D, 103, 083533

Andrews, S. M. 2020, ARA&A, 58, 483

Arzoumanian, Z., Baker, P. T., Blumer, H., et al. 2020, ApJ, 905, L34

Ata, M., Baumgarten, F., Bautista, J., et al. 2018, MNRAS, 473, 4773

Bautista, J. E., Busca, N. G., Guy, J., et al. 2017, A&A, 603, A12

Bautista, J. E., Paviot, R., Vargas Magaña, M., et al. 2021, MNRAS, 500, 736

Bera, A., Kanekar, N., Chengalur, J. N., & Bagla, J. S. 2019, ApJ, 882, L7

Bochenek, C. D., Ravi, V., Belov, K. V., et al. 2020, Nature, 587, 59

Booth, A. S., Walsh, C., Terwisscha van Scheltinga, J., et al. 2021, Nature Astronomy

Botteon, A., van Weeren, R. J., Brunetti, G., et al. 2020, MNRAS, 499, L11

Carilli, C. 2015, in Advancing Astrophysics with the Square Kilometre Array (AASKA14), 171

Carilli, C. L. & Rawlings, S. 2004, New A Rev., 48, 979

Chen, Q., Meyer, M., Popping, A., & Staveley-Smith, L. 2021, MNRAS, 502, 2308

CHIME/FRB Collaboration, Amiri, M., Bandura, K., et al. 2019, Nature, 566, 230

Cordes, J. M., Kramer, M., Lazio, T. J. W., et al. 2004, New A Rev., 48, 1413

Govoni, F., Orrù, E., Bonafede, A., et al. 2019, Science, 364, 981

Greenhill, L. J., Jiang, D. R., Moran, J. M., et al. 1995, ApJ, 440, 619

Hoare, M., Perez, L., Bourke, T. L., et al. 2015, in Advancing Astrophysics with the Square Kilometre Array (AASKA14), 115

Inserra, C., Sullivan, M., Angus, C. R., et al. 2021, MNRAS, 504, 2535

Jackson, J. C. 2004, J. Cosmology Astropart. Phys., 2004, 007

Janssen, G., Hobbs, G., McLaughlin, M., et al. 2015, in Advancing Astrophysics with the Square Kilometre Array (AASKA14), 37

Jarvis, M., Bacon, D., Blake, C., et al. 2015, in Advancing Astrophysics with the Square Kilometre Array (AASKA14), 18

Johnston-Hollitt, M., Govoni, F., Beck, R., et al. 2015, in Advancing Astrophysics with the Square Kilometre Array (AASKA14), 92

Keane, E. F. 2018, Nature Astronomy, 2, 865

Kierdorf, M., Mao, S. A., Beck, R., et al. 2020, A&A, 642, A118

Lorimer, D. R., Bailes, M., McLaughlin, M. A., Narkevic, D. J., & Crawford, F. 2007, Science, 318, 777

Maartens, R., Abdalla, F. B., Jarvis, M., & Santos, M. G. 2015, arXiv e-prints, arXiv:1501.04076

Mertens, F. G., Mevius, M., Koopmans, L. V. E., et al. 2020, MNRAS, 493, 1662

Mulcahy, D. D., Horneffer, A., Beck, R., et al. 2018, A&A, 615, A98

Patil, A. H., Yatawatta, S., Koopmans, L. V. E., et al. 2017, ApJ, 838, 65

Pesce, D. W., Braatz, J. A., Reid, M. J., et al. 2020, ApJ, 891, L1

Planck Collaboration, Aghanim, N., Akrami, Y., et al. 2020, A&A, 641, A6

Platts, E., Weltman, A., Walters, A., et al. 2019, Phys. Rep., 821, 1

Ramatsoku, M., Murgia, M., Vacca, V., et al. 2020, A&A, 636, L1

Reiprich, T. H., Veronica, A., Pacaud, F., et al. 2021, A&A, 647, A2

Riess, A. G., Casertano, S., Yuan, W., et al. 2018, ApJ, 861, 126

Santos, M., Bull, P., Alonso, D., et al. 2015, in Advancing Astrophysics with the Square Kilometre Array (AASKA14), 19

Scolnic, D. M., Jones, D. O., Rest, A., et al. 2018, ApJ, 859, 101

Shimwell, T. W., Tasse, C., Hardcastle, M. J., et al. 2019, A&A, 622, A1

Smith, T. L., Poulin, V., & Amin, M. A. 2020, Phys. Rev. D, 101, 063523

Staveley-Smith, L. & Oosterloo, T. 2015, in Advancing Astrophysics with the Square Kilometre Array (AASKA14), 167

Switzer, E. R., Chang, T. C., Masui, K. W., Pen, U. L., & Voytek, T. C. 2015, ApJ, 815, 51

Vernstrom, T., Heald, G., Vazza, F., et al. 2021, MNRAS, 505, 4178

Zarka, P., Marques, M. S., Louis, C., et al. 2018, A&A, 618, A84