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Science with the Square Kilometre Array (SKA), the mother of all radio telescopes.

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Abstract

The Square Kilometre Array (SKA) project is an international initiative aimed at building and operating two next-generation radio interferometres, called to transform our understanding of the Universe. The SKA project started in the mid 90s as a "Large Hydrogen Array", envisioned to study the evolution of galaxies through the History of the Universe. While this key science project has remained through all these years as one of the main reasons to build the SKA, the scope of the project has broadened so much that it essentially covers all astrophysical areas. The SKA is currently becoming a reality, with funding secured to build the first phase of SKA. Several dishes have been already deployed in South Africa, the location for the SKA-Mid, which will operate in the frequency range from 350 MHz to 15 GHz. Similarly, more than 1000 "Christmas tree" antennas have already been installed in Western Australia, where the SKA-Low (50-350 MHz) will be located. The SKA is expected to make transformational changes in several areas of astrophysics, from the Cosmic Dawn and the Epoch of Reionisation, to pulsars and the cosmic magnetism in our Universe.

This contribution have two main aims: (1) to make the uninformed astronomer familiar with the diversity of science topics where SKA can make transformational changes; and (2) to become acquainted with the opportunities to join SKA. It is precisely now, when a new version of the SKA White book is in preparation, and a general meeting to be held next June 2025, when most of the science to be produced is being discussed, and groups and teams writing those chapters are being formed. This is a once in a lifetime opportunity to get onboard the SKA train, so do not miss it, or you may regret it for the rest of your life.

1 Introduction

Let me start with three important radio astronomical facts. The first one is a very simple, yet extremely relevant: radio emission is not affected by dust, unlike optical and, to a lesser extent, near-infrared emission. This allows to study, e.g., the deeply embedded star formation both near and far, and unveil phenomena that are buried in the nuclear regions of galaxies, and which cannot be adequately studied at other wavelengths.

The second relevant fact is that the (continuum) thermal radio emission from stars is negligible, compared to their emission in the optical, or near-IR. On the contrary, radio is a fantastic tracer of non-thermal continuum radio emission in the universe, which stems from powerful, energetic phenomena, e.g., Active Galactic Nuclear (AGN) activity. Spectral line radio observations are also extremely useful, in particular the emission from the hyperfine transition of neutral hydrogen, the basic brick that makes our universe, which happens at the specific wavelength of 21 cm. The study of neutral hydrogen across a wide range of redshifts, including the epoch where galaxies were at their peak of star formation, can be done in a systematic way with the same telescope. And the study of the Dark Ages, before the optical light of the first generation of stars was even formed, can be studied only in the radio domain.

The third relevant fact is that (single dish) radio observations have a very poor angular, and hence spatial, resolution. For example, the Yebes 40m dish telescope at a wavelength of 1 cm has the same angular resolution that our eye, i.e., about 1 arcminute. This is a much worse resolution than any toy optical telescope, or any pair of binoculars can provide. So radio astronomers have taken advantage for decades of the use of interferometry. By increasing the separation between each pair of dishes, radio interferometry can provide nowadays millarcsecond angular resolution at cm wavelengths, and down to tens of microarcseconds at millimeter wavelengths. This impressive angular resolution allows detailed studies of all sorts of astrophysical objects and, as we know, has resulted in the first image ever of the shadow of a black hole, obtained with the EHT.

2 Why an Square Kilometre Array?

To answer this question, we have to go back to a conference held in 1991, thirty three years ago, where ideas for new, groundbreaking radio astronomy instrumentation were discussed. It was at this conference that the idea of a radio telescope with a collecting area of 1 square kilometre was put forward. Astronomers realized that such a large collecting are would be needed if astronomers wanted to trace neutral hydrogen from our local universe to a redshift of about 10, something unthinkable for optical of near-infrared astronomy, even with the JWST. In addition, the sensitivity of such a collecting area would allow for the detection of a huge amount of pulsars, and other science case, such as the study of the radio luminosity function down to the faintest sources, or the detection of transient sources up to huge distances would become possible. For reference, think of the initial SKA project as “the four ones” project: 1 sq km of collecting area having 1 arcsec angular resolution and a sensitivity of 1 microJy at 1 GHz[1].

[1]Do not worry about the use of microJy and GHz/MHz. Roughly, 1 GHz corresponds to a wavelength of 30 cm, and remember that the crucial spectral line of neutral hydrogen happens at 1.420 GHz, or 21 cm. Regarding the use of microJy, just remember that the best current radio interferometers provide typically 5 microJy sensitivities, so the SKA aims at doing better in terms of sensitivity by about a factor of about five.

2.1 SKA layout

The SKA project will build and operate two next-generation radio interferometres, SKA-Mid, and SKA-Low. The SKA Observatory (SKAO) was established in January 2021 as the Intergovernmental Organisation (IGO), with the mission of building and operating these radio interferometres. The SKAO consists of the Global Headquarters in the United Kingdom, with its two telescopes located in South Africa (SKA-Mid) and Australia (SKA-Low). SKA-Mid will consist of 133 SKA dishes, each of 15 m in diameter, and the 64 13.5m Meerkat dishes at the Karoo site in South Africa, observing at frequencies from 350 MHz (90 cm) up to 15.4 GHz (2 cm). The core of the array will be composed of around 50% of the dishes, randomly distributed within 2 km. There will be three logarithmic spiral arms with a maximum baseline extending out to 150 km. The second telescope will be SKA-Low, which will consist of 131,072 log-periodic dipole antennas distributed across 512 aperture stations of 256 (dipole) antennas each, located in Western Australia. Around 50% of the stations will be located within a 1 km diameter core, with the remaining stations organised in clusters of 6 stations on three modified spiral arms. The maximum baseline length will be around 70 km.

The first SKA-Low antenna was installed in March 2024, and by the time of writing, antennas at four of the telescope's 512 stations have been built, meaning more than 1,000 of its two-metre-tall antennas have been assembled and installed. The first two SKA-Mid dishes were erected in Karoo last July. The pace at which SKA-Mid and SKA-Low antennas are erected will increase from now until 2028, when a call for cycle 0 proposals will be issued.

Specification	**SKA-Mid**	**SKA-Low**
Antenna type	197 steerable dishes	131,072 log-periodic antennas
Number of antennas	133×SKA dishes + 64×MeerKAT dishes	512 stations (each of 256 dipoles)
Frequency range	0.35 – 15.4 GHz	50 – 350 MHz
Maximum baseline	150 km	74 km
Angular resolution	0.3 arcsec at 1.5 GHz	10 arcsec at 100 MHz
Site	Karoo, **South Africa**	Murchison, **Western Australia**

Table 1: Comparison of SKA-Mid and SKA-Low specifications. For detailed and up-to-date information, visit http://www.skao.int.

3 SKA: Sensitivity, survey speed and angular resolution

The sensitivity of the SKA will depend on the observing band, and is expected to give a figure of merit of 2μJy/beam after just 10 min on source in band 2 (from 0.95 to 1.76 GHz). However, for the sake of simplicity, it is easiest to compare the performance of the SKA against that of some of the best current radio inteferometers at similar frequency bands. SKA-Mid will be between 4 and 10 times more sensitive than the Jansky Very Large Array (JVLA), and about 5 to 7 times more sensitive than LOFAR. I recall that an increase of a factor of 5 in sensitivity means a factor of 25 (of reduction) in terms of observing time.

The survey speed of the SKA, i.e., how long does it take to cover a given region of the sky down to a given noise floor, will also outperfom by a factor of between 10 and 100, the current survey speeds of LOFAR, the JVLA, or the uGMRT. This increase in survey speed will allow, e.g., to carry out surveys that would not be feasible with current instrumentation.

Finally, I show in Fig. 1 the angular resolution vs. wavelength/frequency for a number of telescopes, from the HST to SKA and LOFAR. The SKA will actually fill in a gap in resolution that exists in current radio inteferometers. And with the inclusion of VLBI antennas, the angular resolution of the SKA will go down to a few milliarcseconds, basically matching the European VLBI network. This will allow for, e.g., great astrometry and transient localisation.

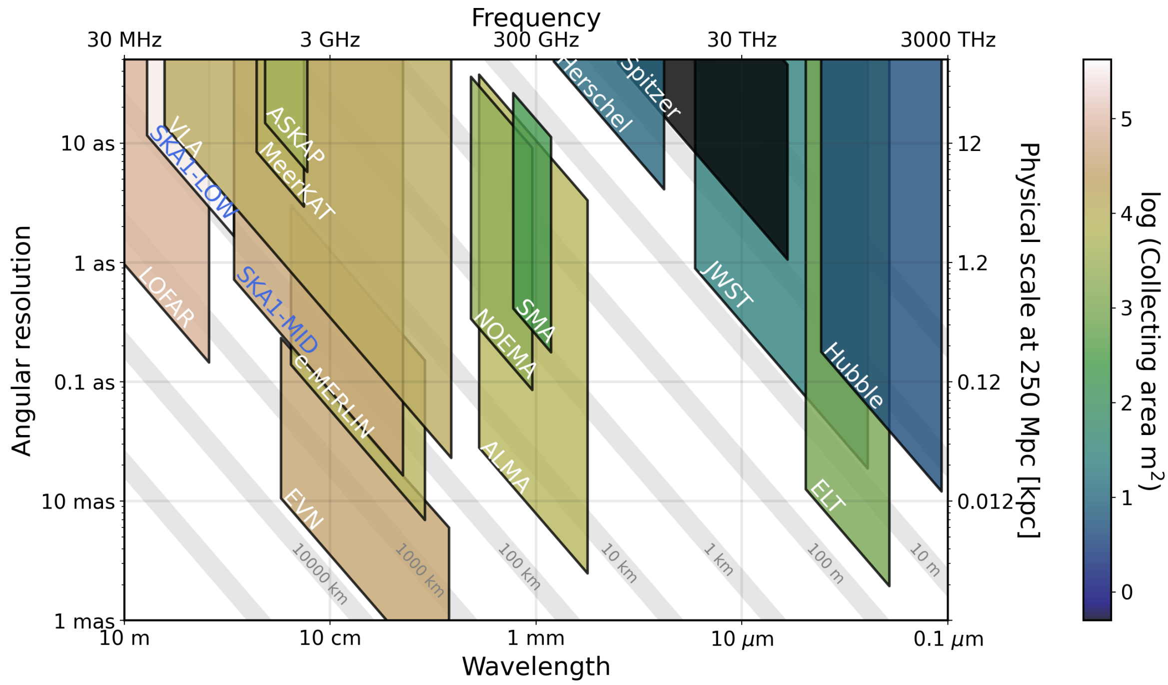

Figure 1: Angular resolution vs. wavelength/frequency plot for current state of the art radio (interferometric) facilities, and other optical and near-IR telescopes, including the future ELT and both the SKA-MID and SKA-LOW. Credit: Javier Moldón (IAA-CSIC).

4 Science with the SKA

There are 14 SKA science working groups (SWGs) as of November 2024, and their science topics cover essentially all astrophysical areas, and currently gather around 1500 members. Each working group has two chairpersons, a limited number of core members, and so far an unlimited number of associate memberships. Chairs are usually changed every two years. Chairs and core members are expected to meet on a regular basis, typically once every month. Membership of in a SKA SWG are open to any researcher that satisfies the criterion of being an accredited researcher in a relevant field of astrophysics. So from PhD students in a relatively advanced stage of their Thesis and up to the most senior researchers are welcome to propose themselves to become members of one ore several SKA SWGs. Therefore, I encourage you to go to the SKA SWG webpage, find out which group does suit your interest most, and contact the chairs to join that group. In the remaining of this section, I give but a flavour of the Key Science Topics that the SKA intends to address, some of which were not initially envisioned. For the most updated information on the SKA science working groups, please visit the above webpage.

Cosmic Dawn and the Epoch of Reionisation - How and when did the first stars, galaxies and black holes form? The first stars and galaxies are difficult to study because they are exceptionally faint. Hydrogen, the most abundant element in the Universe, is the clue that we will use to unlock when the first galaxies began to shine. The SKA-Low telescope will observe neutral hydrogen up to a redshift of 26, so it will date when hydrogen's emissions changed from being electrically neutral to ionised by light photons.

Galaxy evolution - How do galaxies form and evolve across cosmic time? The idea is to trace neutral hydrogen from redshift 0 to redshift of about 6, thus addressing the history of our universe for the last 12.8 billion years. SKA will study the earliest galaxies, and track how they formed over billions of years. SKA scientists will also exploit the SKA sensitivity and angular resolution of both SKA-Mid and SKA-Low to map large-scale structures in the universe and study in enormous detail star-formation and AGN feedback in near and far-away galaxies.

Pulsars - Was Einstein right about gravity? Is General Relativity the ultimate theory of gravitation and, if not, what theory will replace it? A key goal of the SKA is to test Einstein Theory of General Relativity. The sensitivity of SKA will allow to detect tens of thousands of Pulsars. This will lead to the indirec detection of gravitational waves by measuring the distortion of time (rather than space), using Pulsar Timing Arrays (PTAs).

Our Galaxy - The main scientific aim of the Our Galaxy SWG is to uncover the ecology of baryons and understand the cycle of matter between the different components of our Galaxy (the Milky Way), from star formation to the replenishment of the ISM with matter and energy released in the last phases of stellar evolution. The galactic centre in the Milky Way harbours the closest supermassive black hole to us, which will allow to study its extreme environment in detail, including its impact on galaxy evolution.

Cradle of Life - This field spans several areas of astronomy, comprising topics such as the formation of planets in disk systems around young stars, exoplanets and complex molecules. SKA-Low aims at directly detecting Jupiter-like exoplanets and measure their magnetic field. Another hot topic is the search for extraterrestrial intelligence (SETI).

Cosmic Magnetism - This project aims at understanding how did the Universe become magnetic? Where and when did it originate, and how has cosmic magnetism evolved through time. The sensitivity and resolving power of the SKA, combined with its wide frequency coverage, makes it ideal for probing magnetism across the Universe through the study of polarized synchrotron emission, its Faraday rotation, and Zeeman splitting.

The Transient Universe - The transients working group aims at exploring what variable and one-off astrophysical signals can teach us about topics ranging from stellar evolution and relativistic astrophysics to cosmology. For example, we have no clue what Fast Radio Burst are made of, although we are already starting to use them as cosmological probes of the universe. SKA will be able to precisely locate large amounts of FRBs, and study in incredible detail the sky transient thanks to its sensitivity and wide freq coverage.

4.1 Advancing Astrophysics with the SKA

The “Advancing Astrophysics with the Square Kilometre Array” conference was held in Giardini Naxos, Sicily, in 2014. Articles were solicited from the community to document the scientific advances that could be enabled by the first phase of the SKA, as well as those pertaining to future SKA deployments. The conference brought together astronomers and astrophysicists from around the world to discuss the latest developments and future prospects of the SKA project. Participants explored various key themes, including the origin and evolution of the universe, dark matter, cosmic magnetism, and the nature of gravity. They also examined the SKA’s potential contributions to, among other topics, understanding the cosmic dawn and reionization, as well as its role in studying pulsars and black holes, which could provide insights into fundamental physics. The conference highlighted the collaborative scientific efforts required to harness the full capabilities of the SKA, emphasizing its expected impact on astrophysics through its unprecedented resolution and sensitivity. The results of this meeting were a two-volume book of over 2000 pages, including 135 chapters, and more than 1200 contributors from 31 nationalities, reflecting the interests of the eight different Science working groups existing at that time. You can access the full proceedings materials in the following link: Advancing Astrophysics with the Square Kilometre Array (AASKA14)

The conference ”Advancing Astrophysics II: Preparing for Science with the SKA”, scheduled to take place from June 16 to 20, 2025, in Görlitz, Germany, is the natural continuation of the first conference, celebrating a decade since the publication of a pivotal book on the scientific advancements possible with the Square Kilometre Array (SKA) telescopes. In the intervening years since the SKA conference in Naxos, antenna designs have reached maturity, construction has begun, and the SKA Organisation has transitioned into an Observatory and intergovernmental organisation spanning five continents and both hemispheres. Meanwhile, observations made using SKA precursor and pathfinder telescopes have shed new light on existing scientific conundrums, and uncovered brand new phenomena. The SKAO is now poised to begin the commissioning of its first test array, with the first science verification data expected to be made publicly available to the community in 2027 and early operations beginning in 2029. At the time of my talk at the SEA meeting in Granada, in July 2024, I announced that SKA was about to issue calls for Expressions of Interest in boock chapters to be contributed to a new version of the SKAO science book, with the aim of providing an up-to-date coverage of the science questions that will be addressed by the SKA telescopes. The updated book will be written against a mature set of telescope specifications with a suite of tools and documents based on detailed design work and site characteristics of the SKA telescopes. It will capture both updates to existing science cases and brand new ideas.

The conference will be hosted at the new German Center for Astrophysics, and the event will not only focus on the SKA's capabilities but also on the expected synergies with other instruments and the enhancement of scientific outcomes beyond initial expectations. At the time of writing those proceedings, the call for proposing new chapters has been formally ended, but contributing to an already approved chapter is still possible. Since book chapters are being coordinated through the SKAO SWGs, the best way to contribute is to get in contact with the relevant chairs.

5 Awaiting for SKA: Precursors and pathfinders

If you are already a radio astronomer believer, and or you think it might be useful to enter the SKA, think about using one or more of those precursors and/or pathfinders. They have regular calls, once or twice per year, and if you are really quick, after this talk you can still try to reach the deadline for SKA precursor MeerKAT and the SKA pathfinder GMRT. In Table 2, you can see the figures of merit for some of the most relevant SKA precursors and pathfinders in the world. For specific and precise values of those figures of merit, you should visit the website of the relevant interferometer and use their sensitivity calculators, but I hope the Table will be useful for then non radio astronomer, and will help you guide in taking the decision of which radio interferometer is most suitable to reach your science goals.

Table 2: Non-thorough instrument guide for non-radio astronomers

Scope	Frequency	Resolution (arcsec)	Sensitivity (μJy)	Radio facility
Low freqs	40-80 MHz	~15	~1000	LOFAR
	100-200 MHz	~few tens	~80	LOFAR
	80-300 MHz	~100-300	~1000	MWA
	150-900 MHz	$\sim 1.5 - -10$	20-100	GMRT
Sensitivity & Fidelity	1-3 GHz	~5-10	~1-5	MeerKAT
Mid freqs & Fidelity	1-15 GHz	~0.1-30	3-10	VLA
High resolution	1-6 GHz	0.06-0.15	~20	e-MERLIN
	1.4-8.4 GHz	~0.002-0.01	~3-10	EVN
	1.4-15 GHz	~0.002-0.01	~10	VLBA
High freqs	15-40 GHz	0.1-0.05	~20-40	VLA
	15-40 GHz	~0.001-0.02	~10	VLBA

Table 3: This table should be considered as a poor-man's (i.e., non-radio astronomer) guide, so you can quickly get an idea of which current radio facility, or facilities, can be of use to you. The sensitivity is not given for the same on-target time, but rather based on standard time allocations for a point-like detection with the VLA or MeerKAT (typically 10-30 min), up to the few hours (4-10 hr) needed to obtain an adequate image with close to milliarcsecond angular resolution, using very long baseline arrays.

6 Spain in SKAland

Spain has contributed to the SKA project since its inception. SKA Spain started as an initiative of a number of researchers to promote the entrance of Spain in the SKA consortium, with the financial support of our Ministery of Research and Innovation. A cornerstone in the scientific promotion of the SKA was reached in 2015, The Spanish Square Kilometre Array White Book was published. The book had 30 chapters, which span most of the topics covered by the existing SKA Science working groups at that time, and included contributions from 120 researchers of many Spanish institutions. In June 2018, Spain became one of the members of the SKA Organisation (the entity in charge of the design and pre-construction activities of the two telescopes, SKA-Mid and SKA-Low). In January 2021, the SKAO was established as an Intergovernmental Organisation with the mission of building and operating SKA-Mid and SKA-Low, Finally, in April 2023, after more than a decade of relentless efforts, Spain became the 9th member of the SKA Observatory. At the time of writing, 65 Spanish researchers participate in 12 out of the 14 existing SKA SWGs.

SKA Spain has now its own webpage, SKA-Spain, and has the main mission of coordinating the Spanish participation in the SKA project. The Spanish SKA coordination team, together with the Spanish community and members of committees, working groups and the SKAO Council, addresses the main objective of maximising the return to the Spanish astronomical community during the development, construction and scientific operation phases of the SKAO by supporting both the scientific and technological Spanish communities. This also involves supporting the preparation of the scientific community for positioning in the Key Science Projects (KSP), the development of Open Science within the context of the project, and the preservation of leadership in core activities of impact for the community.

The development of a network of SKA Regional Centres (SRCNet) is one of those core activities of high impact for the community, where SKA Spain is particularly active. The amount of data generated by the SKA will be humongous. Currently we're already facing a troubling computing situation in radio astronomy, with telescopes such as the JVLA, MeerKAT, and especially LOFAR. But when SKA comes online, things will be much worse, with about 700 Petabytes of data being generated every year. To manage such an "astronomical" amount of data, a new paradigm is needed. The data produced by the SKAO will be distributed to the SRCNet. Each of the SRCs will provide access to the data, computational and storage resources, as well as support during scientific analysis. There are key aspects in this new paradigm First, there will be no raw-data, but science-ready data products, similar to what ALMA does, so those products are more accessible to radio astronomers; second, the data analysis will be also non-local, but will instead use a global science platform, which should result in better tools for collaborative work; third, the SKA archive will be fully aligned with Open Science principles, thus maximizing the science output. Those three aspects will be managed by different SKA regional centres, which will form a network of such centres: SRCNet.

There are currently 17 initiatives from 17 different countries collaborating with the SKAO to develop the SRCNet. The Instituto de Astrofísica de Andalucía currently hosts the Spanish Prototype of an SKA regional centre, the espSRC. The goals of the espSRC are to maximize the scientific return and participation in SKA Key Science Projects, facilitate preparatory SKA science. The espSRC provides computing support to carry projects similar to future projects with SKA early science. It does also provide software support, trains people and promote community capacity building and a collaborative framework. Definitely, it would be extremely useful for our astrophysic community that Spain hosts an SKA regional centre. The espSRC currently provides support to more than ten research projects, encompassing Galactid and Extragalactic Science with SKA precursors and Pathfinders, including e-Merlin, EVN, GMRT, JVLA, LOFAR, MeerKAT, and WSRT/Apertif. In you need to apply for access to the espSRC, you can go to the following webpage: https://spsrc-user-docs.readthedocs.io/.

7 SKAO major dates

I summarize in Table 4 the SKAO major dates in the timeline of the SKA-Mid and SKA-Low. The will be pre-science verification of the data, using a test array (AA0.5 in the table), which will last for the whole year 2025. During 2026, the science comissioning phase will take place. Those two phases will give users an opportunity to assess the data quality and become familiar with the data, using a small amount of dishes and stations. Science verification will start during 2027, and the amount of dishes and stations will be already comparable, or better than any currently available at that time. During this phase, data will be public immediately after observations, and SRCNet resources will be available to the community. The early operations are expected for the end of 2028, early 2029, with shared-risk, PI-led science programmes. A call for Key Science Projects (KSP) will be issued sometime between 2027-2029. While I agree this is a too wide time range, the intention is that the start of the observations of KSPs is expected for 2030, when all 197 SKA-mid dishes and all 512 SKA-low stations should be fully operational. Therefore, if you are interested in the SKA, you should definitely start to get familiar with the data as soon as it is available.

To help you get ready with the SKA, and with the writing of the chapters to the conference in Görlitz of next June 2025, the SKAO has prepared a number of tools, including sensitivity calculators for both SKA-Mid and SKA-Low, and a number of SKA subarray templates. Demos are likely to happen, and you can contact the SWG chairs for details.

8 Summary

I hope you have read this contribution from its beginning to this point. But in case you have not done so, let me remind you of the take-away messages.

1. SKA prospects for making transformational science with the SKA look great, thanks to the unrivaled sensitivity that SKA-Mid (350 MHz - 15 GHz) and SKA-Low (50 - 350 MHz) will provide.

2. Continue (or start) using the SKA precursors and pathfinders, since SKA will not outperform arrays like MeerkAT until around the end of 2027.

Milestone Event (earliest)		Timeline	
		SKA-Mid	**SKA-Low**
Test Array Operations		**2025**	**2025**
AA0.5	4 dishes 4 stations	2025 Q4	2024 Q4
Science Commissioning		**2026**	**2025**
AA1	8 dishes 18 stations	2026 Q3	2025 Q4
Science Verification begins		**2027**	**2027**
AA2	64 dishes 64 stations	2027 Q3	2026 Q4
Early Operations (Shared Risk)		**2029**	**2029**
AA*	144 dishes 307 stations	2028 Q2	2028 Q1
Design Baseline		TBD	TBD
AA4 (Design Baseline)	197 dishes 512 stations	TBD	TBD

Table 4: Milestones for SKA-Mid and SKA-Low

3. Test array operations and science comissioning will start in 2025 and 2026, respectively. Do not procrastinate, but join as soon as possible the SKA science working group that suits you best, and think about preparing radio proposals for SKA pathfinders and precursors.

4. The espSRC is fully operational and provides computing resources, as well as scientific and technical support for users. It is the perfect place to get involved in the preparatory science for the SKA.

5. Get involved in the chapter writing for the science case, or cases, of interest to you, and do not miss the Görlitz meeting of next 16-20 June 2025, where the science discussed in those chapter will be presented and discussed.

I guess the bottom message is “Do not miss the SKA train”.

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