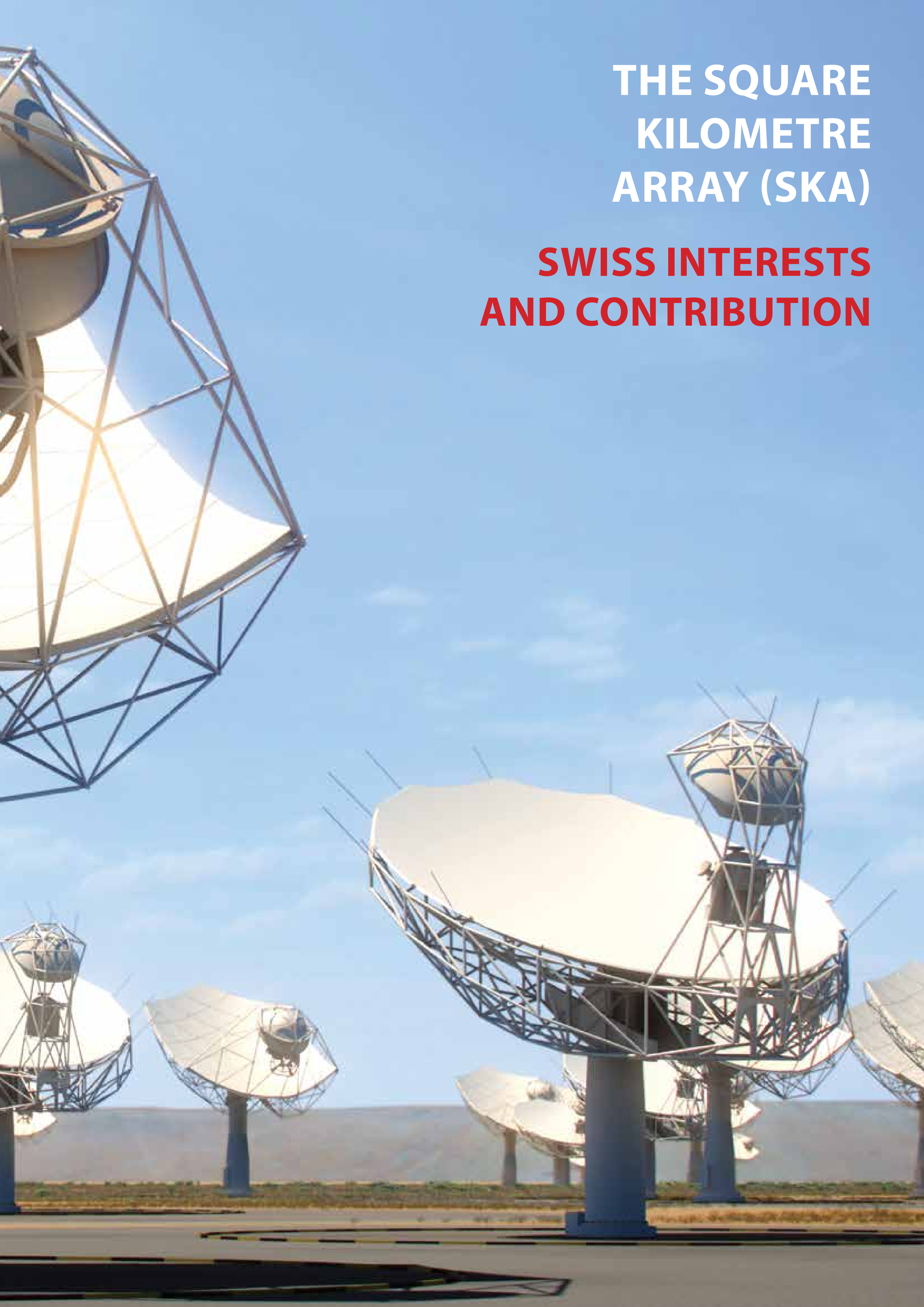
THE SQUARE KILOMETRE ARRAY (SKA)

SWISS INTERESTS AND CONTRIBUTION



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Cover: Artist's rendition of the SKA-mid dishes in Africa showing how they may eventually look when completed. The 15m wide dish telescopes, will provide the SKA with some of its highest resolution imaging capability, working towards the upper range of radio frequencies which the SKA will cover.
Credit: SKA Organisation

The Square Kilometre Array (SKA)

Swiss interests and contribution

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1 observatory, 2 telescopes, 3 continents

The Square Kilometre Array (SKA) is a next-generation radio astronomy facility that will revolutionise our understanding of the Universe and the laws of fundamental physics.

SKA will have a uniquely distributed character: one observatory, operating two telescopes, on three continents for the global scientific community.

A remarkable date for SKA was March 12 2019, when the treaty establishing the Square Kilometre Array Observatory (SKAO), the second inter-governmental organisation dedicated to astronomy in the world, after the European Southern Observatory (ESO), was signed by 7 countries, and celebrated with delegations from a further 8 other countries.

The recently completed SKA Global Headquarters is located at Jodrell Bank near Manchester in the UK, home to the organisation -the SKAO- that oversees development, construction, and operations. The two other SKA sites are radio quiet zones and home to the telescopes themselves: a mid-frequency array in South Africa (SKA-mid), and a low-frequency array in Australia (SKA-low).

In order to take advantage of the development of computing and other innovative technologies of relevance for the SKA programme, the construction of the SKA will be phased. Work is currently focused on the first phase named SKA-1, corresponding to a fraction of the full SKA.

When fully constructed, SKA will be, by several measures, the largest scientific facility built by humankind.

With an expected operational phase of at least 50 years, it will be one of the cornerstone physics machines in the 21st century.

SKA will tackle some of the most fundamental scientific questions of our time. The SKA's science goals are broad and ambitious, looking back into the history of the Universe as far as the Cosmic Dawn, when the very first stars and galaxies formed, in order to seek answers to some of the biggest remaining questions in astrophysics. Among them: How do galaxies evolve? What is Dark Energy and what role does it play in the expansion of the Universe? Can we find and understand where gravitational waves come from? What causes planets to form around stars? Is there life out there? Individually, and working together with other next-generation facilities, SKA will uncover new findings on the Universe.

During its operation, the SKA will collect unprecedented amounts of data, requiring the world's fastest supercomputers to process this data in near real time, before turning these into science products for distribution around the world through a network of SKA Regional Centres located in partner countries. Those data centres will be the final interface with the end users - the scientists - who will turn these science products into information, and finally knowledge.

The SKA is a collaborative international project, with 13 members as of December 2019 (including Switzerland with an Observer status since 2016) and several other prospective members are also involved in many science and engineering activities.

Switzerland has currently an observer position in the SKA project and is considering participation as a full SKAO member from 2021 onwards. As of March 2020, the EPFL in Lausanne will become a special member of the SKA collaboration as the leading house of Switzerland, thus coordinating the various contributions to the SKA project on behalf of the Swiss academic community.

As a leading nation in education and research and with a history of close cooperation with international partners, Switzerland has a strategic interest in contributing to the SKA project. It has a legacy of high-quality research in science and astronomy, as recognized recently by the 2019 Nobel Prize for Physics awarded to two scientists from the University of Geneva for their discovery of the first exoplanets. The December 2019 launch of the Swiss led ESA space mission, CHEOPS (which will study such exoplanets), and the development of instruments for the upcoming Extremely Large Telescope (ELT) in Chile, among others, are examples of Swiss ambition to remain at the forefront of scientific research of the universe.

Swiss membership is expected to be mutually beneficial for the SKA organisation, as it recognises the niche technological expertise of the alpine country's academic institutions and network of industry players. Swiss academic institutions are expected to contribute through research and development in the field of distributed radio frequency systems, high performance computing (HPC), machine learning and artificial intelligence which can be applied to the vast amounts of data that will be generated by SKA.

Swiss SMEs are expected to add value to the project through four identified fields of competence: data processing, system control and supervision, antennas and radio receivers, and precise time management through the use of maser atomic clocks.

On the research perspective, Swiss scientists will lead and participate in the many science projects of the SKA ranging from exo-planet formation around nearby stars to the early moments in the Universe 13.5 billion of years ago with some special focus on galaxy formation and evolution, transients phenomenon, fundamental physics and cosmology, Dark Energy, cosmic magnetism and the cosmic cawn.

Figure 1 Dramatic view of the ASKAP antennas. Credit: SKA Organisation, Rob Millenaar (ASTRON)

1 Sternwarte, 2 Teleskope, 3 Kontinente

Das Square Kilometre Array (SKA), ein Radioteleskop mit einer Sammelfläche von einem Quadratkilometer, stellt eine zukunftsweisende Einrichtung in der Radio-Astronomie dar und wird unser Verständnis des Universums und der Gesetze der Grundlagenphysik revolutionieren.

Das SKA zeichnet sich durch eine einmalige Verteilung über drei Kontinente aus: Eine Sternwarte auf einem Kontinent steuert zwei Radioteleskope auf je einem anderen Kontinent und unterstützt so die weltweite wissenschaftliche Gemeinschaft.

Ein wichtiges Datum für das SKA war der 12. März 2019: Damals wurde der Gründungsvertrag für die SKA-Sternwarte (Square Kilometre Array Observatory (SKAO)) von Vertretern aus sieben Ländern und im Beisein von Delegationen aus weiteren acht Ländern unterzeichnet. Es ist nach der Europäischen Süd-Sternwarte (European Southern Observatory (ESO)) die zweite zwischenstaatliche Organisation im Dienste der weltweiten Astronomie.

Das kürzlich fertiggestellte globale SKA-Hauptquartier liegt in Jodrell Bank in der Nähe von Manchester im Vereinigten Königreich. Hier ist der Sitz der Organisation SKAO. Von hier aus werden Entwicklung, Bau und Betrieb des SKA überwacht. Die beiden übrigen SKA-Zentren befinden sich in radio-leisen Zonen. Es handelt sich um das Mittelfrequenz-Radioteleskop in Südafrika (SKA-mid) und das Tieffrequenz-Radioteleskop in Australien (SKA-low).

Um die Vorteile von Entwicklungen im Computerbereich und anderen innovativen Technologien im Zusammenhang mit dem SKA-Programm ausnützen zu können, erfolgt der Aufbau des SKA zeitlich gestaffelt. Die Arbeiten konzentrieren sich im Moment auf die erste Phase, genannt SKA1, die nur einem Bruchteil des ganzen SKA entspricht.

Wenn das SKA fertig gebaut ist, wird es in verschiedener Hinsicht das grösste je von Menschen errichtete wissenschaftliche Bauwerk sein. Man geht davon aus, dass es während mindestens fünfzig Jahren in Betrieb und damit ein Eckstein unter den physikalischen Forschungseinrichtungen des 21. Jahrhunderts sein wird.

Das SKA nimmt sich einigen der fundamentalsten wissenschaftlichen Fragestellungen unserer Zeit an. Seine wissenschaftlichen Zielsetzungen sind breit gestreut und ehrgeizig, denn es richtet den Blick weit zurück in der Geschichte des Universums auf die "kosmische Morgendämmerung", als die allerersten Sterne und Galaxien entstanden und sucht Antworten auf einige der grössten noch ungelösten Fragen in der Astrophysik. Dazu gehören: Wie entwickeln sich Galaxien? Was ist Dunkle Energie und welche Rolle spielt sie bei der Ausdehnung des Universums? Warum entstehen rund um Sterne herum Planeten? Können wir herausfinden und verstehen, woher Gravitationswellen kommen? Gibt es dort draussen Leben? Allein und in Zusammenarbeit mit anderen zukunftsweisenden Einrichtungen wird das SKA neue Erkenntnisse über das Universum gewinnen.

Während des Betriebes sammelt das SKA bisher nie dagewesene Mengen an Daten, die mithilfe der weltweit schnellsten Supercomputer nahezu in Echtzeit verarbeitet werden. Dann werden sie in wissenschaftlich verwertbarer Form weltweit über ein Netzwerk von regionalen SKA-Zentren in Partnerländern verteilt. Diese Datenzentren sind die letzte Schnittstelle zu den Nutzern, den Wissenschaftlern, die die Daten in wissenschaftliche Ergebnisse und schliesslich in Erkenntnisse und Wissen umwandeln. Das SKA ist ein gemeinschaftliches, internationales Projekt mit dreizehn Mitgliedländern (Stand Dezember 2019), zu denen seit 2016 auch die Schweiz mit Beobachterstatus gehört. Zudem gibt es weitere potenzielle Mitgliedsländer, die in verschiedene wissenschaftliche Tätigkeiten und Ingenieurarbeiten involviert sind.

Die Schweiz hat im Moment im SKA-Projekt Beobachterstatus und behält sich eine Beteiligung mit voller SKAO-Mitgliedschaft ab 2021 vor. Im März 2020 wird die Eidgenössische Technische Hochschule Lausanne ein besonderes Mitglied der SKA-Kollaboration, denn sie ist schweizweit führend bei der Koordination der verschiedenen Beiträge der schweizerischen akademischen Gemeinschaft zum SKA-Projekt.

Als führende Nation im Bereich Bildung und Forschung und mit einer traditionell engen Zusammenarbeit mit internationalen Partnern hat die Schweiz ein strategisches Interesse daran, sich am SKA-Projekt zu beteiligen. Sie hat im Bereich qualitativ hochstehender Forschung in Naturwissenschaft und Astronomie eine lange Tradition, was kürzlich durch die Verleihung des Nobel-Preises 2019 für Physik an zwei Wissenschaftler der Universität Genf für ihre Entdeckung der ersten Exoplaneten eindrücklich bestätigt wurde. Im Dezember 2019 startete die ESA-Raummission CHEOPS, die unter Schweizer Leitung steht und deren Sonde solche Exoplaneten untersucht. Dieses Beispiel, der Bau von Instrumenten für das Europäische Riesenteleskop in Chile und andere zeigen, dass die Schweiz den Anspruch hat, bei der wissenschaftlichen Erforschung des Universums an vorderster Front dabei zu sein.

Man darf davon ausgehen, dass von der Schweizer Mitgliedschaft auch die SKA-Organisation profitieren wird, denn sie zollt den technologischen Nischenkenntnissen der akademischen Institutionen und des Netzwerks der Industriepartner hohen Respekt. Von den akademischen Institutionen der Schweiz erhofft man Forschungs- und Entwicklungsbeiträge in den Bereichen dezentrale Radiofrequenz-Systeme, Hochleistungsrechner (High Performance Computing (HPC)), maschinelles Lernen und künstliche Intelligenz. All dies wird benötigt, um die vom SKA erzeugten gewaltigen Datenmengen zu verarbeiten.

Die Schweizer KMU werden in vier klar definierten Kompetenzbereichen zum Projekt beitragen können: Datenverarbeitung, Systemsteuerung und Überwachung, Antennen und Radio-Empfänger und präzises Zeitmanagement durch den Einsatz von Maser-Atomuhren.

Unter dem Blickwinkel der Forschung werden Schweizer Wissenschaftler an vielen SKA-Projekten führend beteiligt sein. Diese reichen von der Bildung von Exoplaneten um nahegelegene Sterne bis zu den ersten Augenblicken des Bestehens unseres Universums vor 13,5 Milliarden Jahren mit besonderem Fokus auf der Entstehung und Entwicklung von Galaxien, Transienten-Phänomen, Grundlagenphysik und Kosmologie, Dunkle Energie, kosmischen Magnetismus und dem jungen Universum.

1 observatoire, 2 télescopes, 3 continents

Le Square Kilometre Array (SKA) est la nouvelle infrastructure de recherche en radioastronomie qui va révolutionner notre compréhension de l'Univers et des lois de la physique fondamentale.

Le SKA aura un caractère unique : un observatoire, exploitant deux télescopes, sur trois continents pour la communauté scientifique mondiale.

Le 12 mars 2019, le projet SKA prenait vraiment naissance avec la signature, par 7 pays, du traité international établissant l'Observatoire Square Kilometre Array (SKAO), un événement célébré avec les délégations de 8 autres pays participant au projet. SKAO est la deuxième organisation intergouvernementale dédiée à l'astronomie, après l'Observatoire européen austral (ESO).

Le siège mondial du SKA, récemment achevé, est situé à Jodrell Bank près de Manchester au Royaume-Uni, et de là, l'organisation supervise le développement, la construction et les opérations du projet SKA. Les deux autres sites du SKA sont des zones de silence radio et abriteront les deux télescopes: un réseau à moyenne fréquence en Afrique du Sud (SKA-mid) et un réseau à basse fréquence en Australie (SKA-low).

La construction du SKA se fera par étapes afin de tirer parti du développement de l'informatique et d'autres technologies innovantes essentiel pour le programme SKA. Les travaux se concentrent actuellement sur la première phase appelée SKA1, qui correspond à une fraction du télescope SKA final.

Lorsqu'il sera entièrement construit, le SKA sera, à plusieurs égards, la plus grande installation scientifique construite par l'humanité.

Avec une phase opérationnelle prévue d'au moins 50 ans, il sera l'une des machines fondamentales de la physique du XXIe siècle.

Les objectifs scientifiques du SKA sont nombreux et ambitieux. Le champ d'étude du SKA ira de l'histoire actuelle de l'Univers jusqu'au tout début de l'Univers, lorsque les toutes premières étoiles et galaxies se sont formées. Le but est de répondre aux plus grandes questions qui subsistent en astrophysique et cosmologie. En particulier : Comment les galaxies évoluent-elles ? Qu'est-ce que l'énergie noire et quel rôle joue-t-elle dans l'expansion de l'Univers ? Peut-on trouver et comprendre d'où viennent les ondes gravitationnelles ? Qu'est-ce qui provoque la formation de planètes autour des étoiles ? Y a-t-il de la vie dans l'Univers ? Individuellement et en collaboration avec d'autres infrastructure de recherche de nouvelle génération, le SKA révolutionnera notre compréhension de l'Univers.

Lors de son fonctionnement, le SKA collectera des quantités de données sans précédent, nécessitant les superordinateurs les plus rapides du monde pour traiter ces données en temps quasi réel, avant de les transformer en produits scientifiques qui seront distribués dans le monde entier par un réseau de centres régionaux SKA situés dans les pays partenaires. Ces centres de données constitueront l'interface finale avec les scientifiques qui transformeront ces données en informations, et enfin en connaissances.

Le SKA est un projet international, qui en décembre 2019 comptait 13 pays membres (dont la Suisse). Plusieurs autres pays potentiels sont également impliqués dans de nombreuses activités scientifiques et d'ingénierie.

Depuis 2016, la Suisse a un statut d'observateur dans le projet SKA et envisage de participer en tant que membre du SKAO en 2021. A partir de mars 2020, l'EPFL à Lausanne deviendra un membre spécial de la collaboration SKA, coordonnant ainsi les différentes contributions au projet SKA au nom de la communauté académique suisse.

En tant que nation leader dans le domaine de l'éducation et de la recherche et avec une histoire de coopération importante avec des partenaires internationaux, la Suisse a un intérêt stratégique à contribuer au projet SKA. Elle possède un héritage de recherche de haute qualité dans les domaines de la science et de l'astronomie, comme l'atteste l'attribution récente du prix Nobel de Physique 2019 décerné à deux scientifiques de l'Université de Genève pour leur découverte des premières exoplanètes. Le lancement en décembre 2019 de la mission spatiale de l'ESA, CHEOPS (dirigée par la Suisse et qui étudiera ces exoplanètes), et la construction d'instruments pour le Extremely Large Telescope (ELT) au Chile et d'autres sont des exemples de l'ambition Suisse de rester à la pointe de la recherche scientifique sur l'Univers.
L'adhésion de la Suisse devrait être mutuellement bénéfique pour l'organisation SKA, car elle reconnaît l'expertise technologique de niche des institutions universitaires et de son tissu industriel. Les institutions académiques suisses devraient contribuer par la recherche et le développement dans le domaine des systèmes distribués de radiofréquence, du calcul haute performance (HPC) et de l'intelligence artificielle qui peuvent être appliqués aux vastes quantités de données qui seront générées par le SKA.

Les PME suisses devraient apporter une valeur ajoutée au projet par le biais de quatre domaines de compétence identifiés : le traitement des données, le contrôle et la supervision des systèmes, les antennes et les récepteurs radio, et la gestion précise du temps grâce à l'utilisation d'horloges atomiques.

Du point de vue de la recherche, les scientifiques Suisses dirigeront et participeront aux nombreux projets scientifiques du SKA allant de la formation d'exoplanètes autour des étoiles proches aux premiers instants de l'Univers il y a 13,5 milliards d'années, avec un accent particulier sur la formation et l'évolution des galaxies, l'étude de phénomène transitoires, la physique fondamentale et la cosmologie, l'énergie sombre, le magnétisme cosmique et les premiers instants cosmiques.

Swiss interest & contribution in SKA project

Dr. Marc Audard	**UniGE**
Dr. Marina Battaglia	**FHNW**
Prof. René Beuchat	**HES-SO/HEPIA**
Prof. Alexey Boyarsky	**EPFL**
Prof. Camille Bonvin	**UniGE**
Dominique Bovey	**HES-SO/HEIG-VD**
Pascal Coeudevez	**HES-SO/HEIG-VD**
Prof. Francois Corthay	**HES-SO/HEVS**
Prof. Frédéric Courbin	**EPFL**
Prof. André Csillaghy	**FHNW**
Prof. Alberto Dassatti	**HES-SO/HEIG-VD**
Dr. Michele Delorenzi	**CSCS**
Dr. Miroslava Dessauges-Zavadsky	**UniGE**
Prof. Ruth Durrer	**UniGE**
Dr. Jean Favre	**ETHZ/CSCS**
Pablo Fernandez	**CSCS**
Dr. Carlo Ferrigno	**UniGE**
Dr. Gilles Fourestey	**EPFL/SCITAS**
Prof. Anastasios Fragos	**UniGE**
Dr. Claudio Gheller	**EPFL**
Prof. Louise Harra	**PMOD/WRC/ETHZ**
Marc Horat	**Verkehrshaus Luzern**
Michel Hübner	**Swiss ILO (Industry Liaison Office)**
Prof. Pascale Jablonka	**EPFL**
Prof. Philipe Jetzer	**UniZH**
Prof. Jean-Paul Kneib	**EPFL**
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Prof. Martin Kunz	**UniGE**
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Prof. Michele Maggiore	**UniGE**
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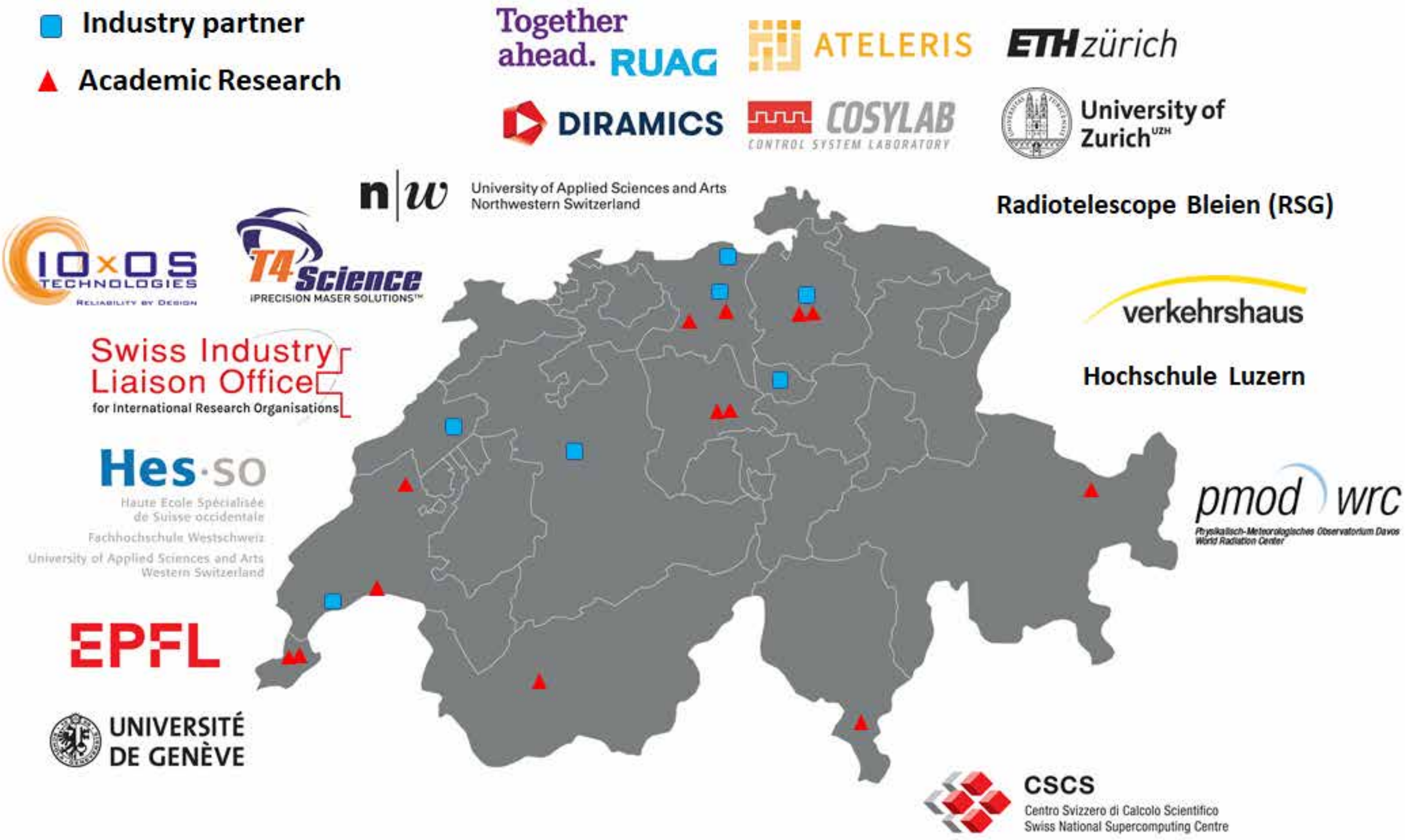
Prof. Martin Vetterli	**EPFL**
Prof. Slava Voloshynovskyy	**UniGE**
Prof. Suzanne Wampfler	**UniBE**
Prof. Yves Wiaux	**EPFL/Herriot-Watt University, Edinburgh**

Figure 2 An all-facing image of the MeerKAT radio telescope, which will be integrated into the mid-frequency component of the SKA phase 1 telescopes. Credit : South African Radio Astronomy Observatory (SARAO)



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1. Science with the Square Kilometre Array

1.1. Searching for life and planets

A fundamental issue in astronomy and biology, and an important question for humankind, is “**Are we alone in the universe?”**

The search for life as we know it is coupled to the hunt for exoplanets. By today, we have discovered thousands of planets outside of our own solar system, some of them being located in the so-called habitable zone. But surprising observations, like the fact that giant gas planets are common in the habitable zone around other stars, unlike in our Solar System, raise many questions, including:

What accounts for the diversity in planetary systems?

Are terrestrial planets in the habitable zone common?

Do giant gas planets form in the inner disk or do they migrate there?

What are the implications for Earth-like planet formation?

Searching for complex molecules in space

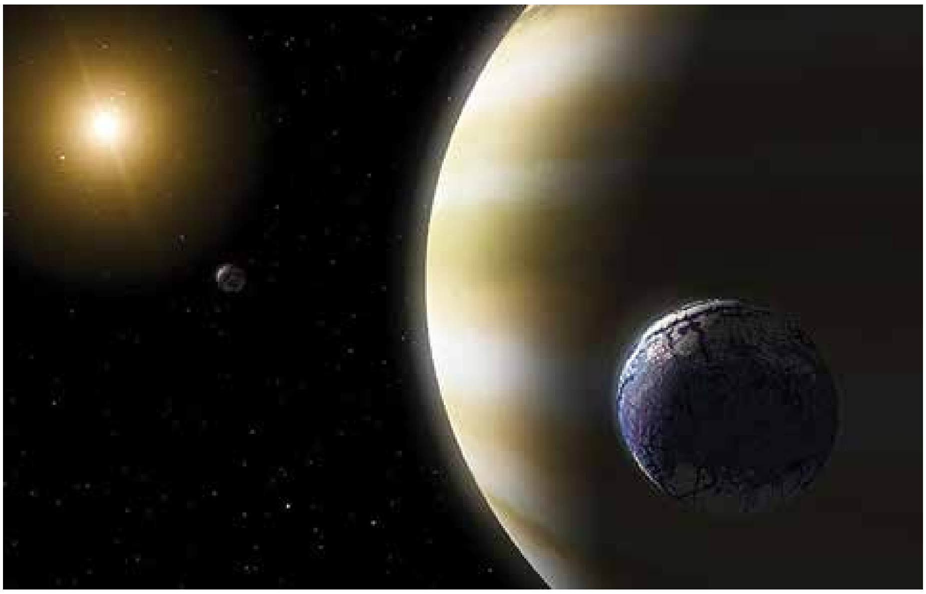
When you mention extraterrestrial life, most people think of little green men and alien invasions! But the science of looking for life on other worlds is a very different story and it is gathering real momentum, with a strong Swiss participation.

The discovery of planets around other stars (nicknamed exo-panets) is a Swiss legacy science since 1995 with the first discovery of a star around Pegasus 51b by Prof. Michel Mayor and Prof. Didier Queloz, who became in November 2019 Nobel Laureates.

The Swiss exo-planets community has developed strongly in the last twenty years in particular through the National Centre of Competence in Research “Planet-S”. A recent milestone took place on 18 December 2019 with the launch of the ESA space mission CHEOPS, led by Swiss scientist Prof. Willy Benz.

Further major progress is taking place through discoveries of complex organic molecules in comets, nebulae and interstellar space, which will form some of the building blocks for life as we know it today. The range of complexity in these organic molecules is vast, and it is leading scientists to speculate more and more that life as we know it could be common in planets within the habitable zones around stars. In particular, astrobiologists will use the SKA to search for amino acids, the building blocks of life, by identifying their spectral signatures at specific frequencies.

Figure 3 Artist’s illustration of an extrasolar planet © NASA



Furthermore, the SKA will be able to detect extremely weak extraterrestrial radio signals if they were to exist, greatly expanding on the capabilities of projects like SETI. Astrobiologists will use the SKA to search for amino acids, the building blocks of life, by identifying their spectral signatures at specific frequencies.

Formation of planets

The dusty discs that form around young stars are the sites where planets are made. The birth of a planet is thought to take a million years or more – much longer than a human lifetime – and it is not possible to watch an individual planet appear. Instead, the discs around many young stars must be observed in order to piece together the different parts of the formation process. Fortunately there are hundreds of these young stars within about 500 light years of the Sun, and many thousands more at greater distances.

If placed at 500 light years distance, our own Solar System would be about 1 arcsecond across – roughly equivalent to a thumb-tack seen from a mile away – so observations at high angular resolution are very important.

At radio wavelengths, such resolution is achieved by combining the signals from widely separated antennas. In the SKA, the antennas will be thousands of kilometres apart, enabling us to probe the “habitable zone” of Sun-like protostars, the region where Earth-like planets or moons of gas giants are most likely to have environments favourable for the development of life.

Recent discoveries have shown that giant gas planets (similar to Jupiter) are common around other stars like the Sun. Although there is no conclusive evidence yet for potentially habitable, small, rocky planets like Earth, careful observations with more sensitive telescopes have detected a number of candidate terrestrial-like planets, larger than Earth.

Many scientists believe these habitable worlds, in the so-called “Goldilocks zone” where conditions are just right for life, must exist, and it is only a matter of time before they are detected, either by indirect observations or potentially directly.

Remote sensing of young stars shows they are surrounded by dusty discs which contain the materials needed to form Earth-like planets. Although planets forming in the habitable zone of Sun-like

protostars are currently far too small to be detected directly, the dust from which they form has a lot of surface area that intercepts starlight and converts the energy into heat which can be detected by SKA at short radio wavelengths.

The SKA will visualize the thermal emission from dust in the habitable zone in unprecedented detail. In particular, the SKA will show where dust evolves from micron-sized interstellar particles to centimetre-sized and larger "pebbles", the first step in assembling Earth-like planets.

Images generated by the SKA will display features in discs related to planet formation. The presence of giant protoplanets can open up nearly empty gaps in the disc material, revealing their presence, and they may also drive large-scale spiral waves through the disc.

Because orbital times in the inner disc are short, just a few years, observations made over time can track the evolution of these features. Giant planets may form by the slow growth of dust grains into large rocks that capture gas, or by rapid gravitational instabilities that disrupt the surrounding disc.

The SKA will discern which mechanisms are active, and where in the disc they occur, which will reveal the impact of newborn giant planets on their Earth-like counterparts. When viewed from afar, the signatures of forming planets imprinted on circumstellar dust may be the most conspicuous evidence of their presence.

The gaps in the dust clouds are much easier to detect than the planets themselves because of their much larger surface area. It is akin to seeing the wake of a boat from an airplane when the boat itself is too small to be visible. The SKA may be the only instrument capable of imaging the inner regions of discs where Earth-like planets form.

Radio signals from extraterrestrial civilisations

What about signals from a technologically advanced extraterrestrial civilisation? The SKA will be so sensitive that it will be able to detect signals comparable in strength to television transmitters operating on planets around the closest stars to the Sun out to dozens of light years. The SKA will be able to convingly search for these "leakage" signals from other civilisations for the first time.

The SKA's sensitivity will allow it to expand the volume of the Galaxy that can be searched for intentional beacons by a factor of 1000, using a wider range of frequencies than attempted before. The detection of such extraterrestrial signals would forever change the perception of humanity in the Universe. The search is on, and the SKA will be at the forefront of one of humankind's greatest quests.

Figure 4 Close up artist rendition. Image of the Australian SKA LFAA (Low Frequency Aperture Array) instrument. These dipole antenna which will number in their hundreds of thousands will survey the radio sky in frequencies as low at 50Mhz.
Credit: SKA Organisation/Swinburne Astronomy Productions

Swiss contribution

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1.2. Solar physics

SKA will provide the necessary high-sensitivity, high-cadence, large dynamic range imaging interferometric observations over a large bandwidth with adequate spatial and frequency resolution necessary to answer some of the key science questions in solar physics.

Where and how are particles accelerated in solar flares and how are they transported close to and away from the Sun?

How does the coronal magnetic field change before, during, and after a solar flare and how does it evolve in the quiet Sun?

What are the dynamics and evolution of coronal mass ejections in time and space as they propagate through the interplanetary space?

Observing solar activity at radio wavelengths

The Sun is the main source of energy on Earth in our planetary system. It also hosts a strong dipolar magnetic field, that is maintained by a large-scale dynamo (see section 1.6). Periodically, magnetic energy is released resulting in solar eruptions such as solar flares and coronal mass ejections.

When these solar ejecta reach the Earth they strongly disturb our planet's environment resulting in northern lights (or aurora), electric supply blackouts, satellite damage, and disruption to radio communications, affecting air, and space travel. Over the last decade, the Sun-Earth connection has become a key issue in space research. Understanding solar eruptions therefore is important to mankind as a practical issue.

Radio observations are uniquely suited to study all aspects of solar eruptions as their emissions can be seen across a very broad frequency range, depending on the emission mechanism. The intensity of the radiation depends on the ambient conditions, such as magnetic field strength, plasma density, and temperature.

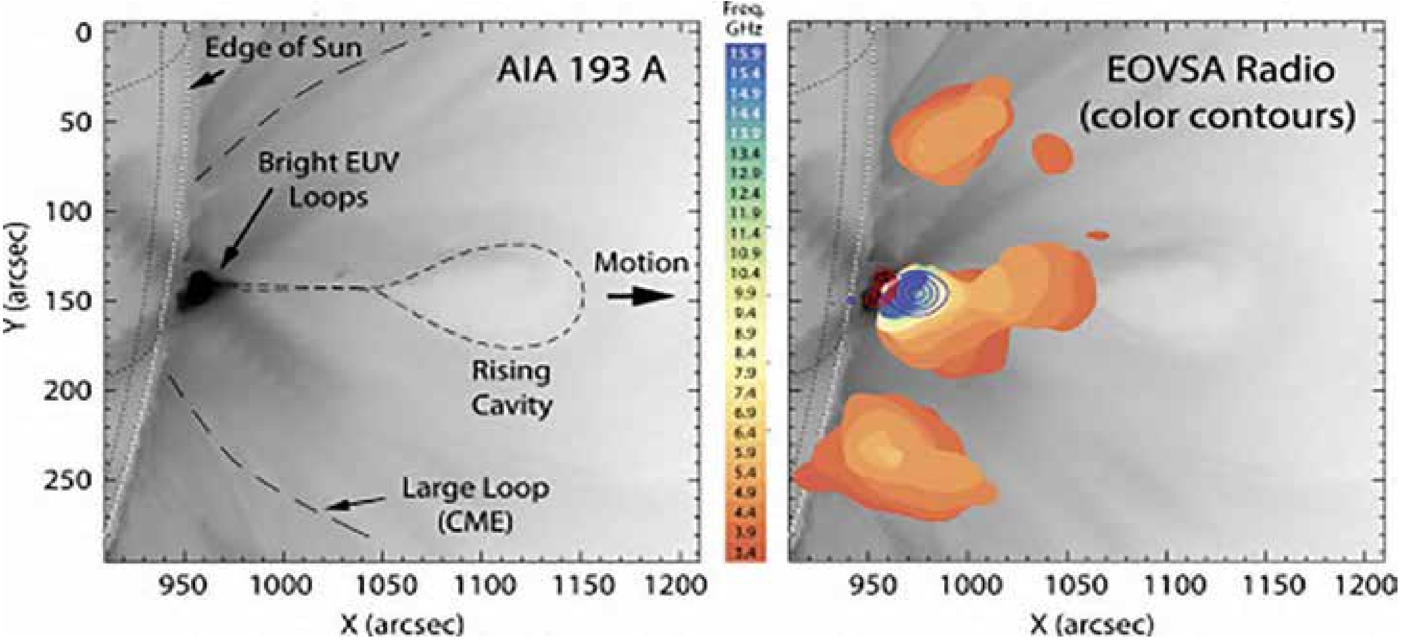
However, the scales of variations in solar radio emission are immense. For example, localized events can be smaller than 1 arcsec, while radio coronal mass ejections (CMEs) can be larger than 1 degree. The contrast in flux density between weak radio bursts (with less than 1 SFU = 10^4 Jansky) and strong flares (typically 10^5 SFU) can be more than 6 orders of magnitude. Lastly, some types of emission can be quite narrow in frequency (a few MHz) and short lived (less than 1 milliseconds) while large scale events like CMEs can be long lasting (10s of minutes) and wideband (100s of MHz).

Location, mechanism, and variability of particle acceleration and transport in solar flares

Energy release and acceleration of particles in solar flares are spatially fragmented processes and it is still unclear where the acceleration site lies with regards to the location of energy release in the corona. Due to the high sensitivity of radio emission to accelerated, suprathermal electrons, it is possible to probe the energy release and acceleration sites in the relatively low density corona.

Radio spectroscopic imaging over a large frequency range allows us to trace the propagation of accelerated electrons in the solar atmosphere and beyond. It also provides diagnostics of nonthermal emission in weak (nanoflare-like) and strong (Type-III like) particle acceleration events not directly associated with major flares.

Figure 5 Left panel: extreme ultraviolet emission from the hot corona observed with the Solar Dynamics Observatory spacecraft. The bright EUV loops mark the location of the solar flare which was associated with a CME. Right panel: the multi-frequency radio contours from the solar dedicated Expanded Owen's Valley Array, with color corresponding to different frequencies according to the color bar between the panels. Red and blue contours indicate X-ray emission from the solar flare. Credit: AAS/SPD, NJIT, https://spd.aas.org/2018_EOVSA_Press_Release



Coronal magnetic field diagnostics

Gyro-synchrotron emission in the solar corona is the most direct means for measuring the coronal magnetic field since this emission strongly depends on the magnetic field strength.

Observations of the gyro-synchrotron emission spectrum as a function of time and space before, during and after a solar flare, in conjunction with careful modelling of gyro-synchrotron emission, is key to understanding the magnetic field changes in the corona that lead to solar flares and the amount of magnetic energy that is transformed in the process.

At the same time modelling of active regions is crucial for understanding quiet Sun heating and provides a magnetic framework needed for flare studies and particle acceleration. SKA's fine solar maps can be used to make self-consistent magnetic field models especially above sunspots and to perform coronal magnetography.

Dynamics and evolution of coronal mass ejections (CMEs)

Radio observations of CMEs have great potential as they are complementary to the traditional white-light observations. Currently, the full potential of radio observations for CME research has not been fully exploited due to lack of spectroscopic imaging capabilities and limited sensitivity of existing instruments.

CME initiation, launch and propagation are important for understanding space weather dynamics. The structures of CMEs are diverse spatially, spectrally and temporally. The SKA will allow us to study the early development of CMEs, investigate the solar flare - CME relationship, and determine the location of CME-related particle acceleration.

SKA high dynamic range spectroscopic images will enable the tracking of fine changes in the structures of CMEs and help investigate the role of coronal shocks and particle acceleration in CMEs.

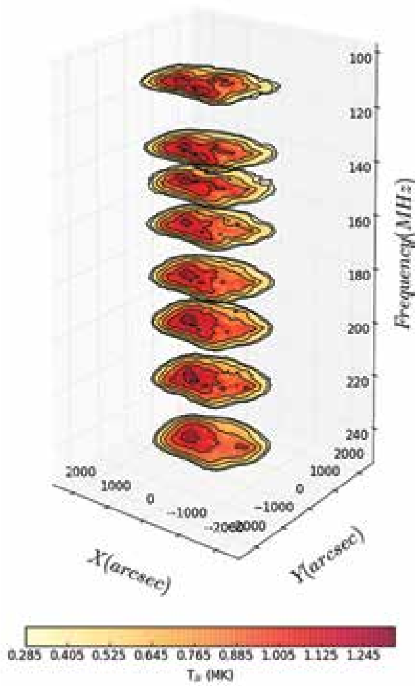


Figure 6 MWA images of the quiet Sun at 9 frequency bands. The images demonstrate the evolution of structures along various coronal heights. The color scales are in brightness temperatures units. Credit: R. Sharma.

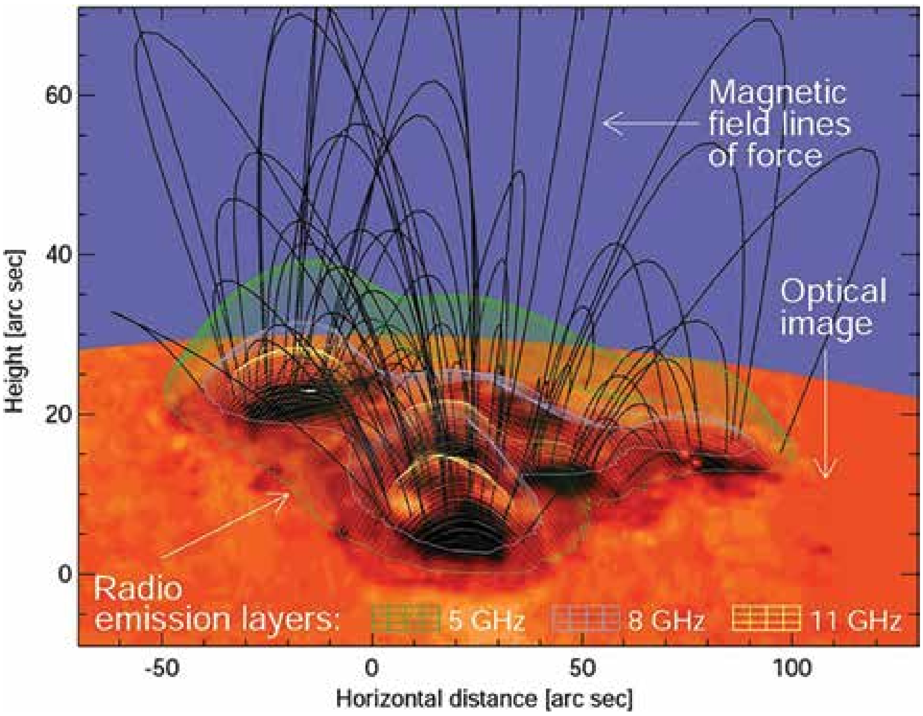


Figure 7 Computed iso-gauss surface for third harmonic of gyrofrequency at 5, 8 and 11 GHz along with the field lines from extrapolated magnetic field for an active region. Credit: Lee (2007)

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1.3. Galaxy evolution

The current standard cosmological model, the so-called ΛCDM model, demonstrated its ability to reproduce the large scale structure of our Universe. However, at small scales, in heavily non-linear regimes, predictions of the ΛCDM model are facing several issues such as the missing satellite or the cusp/core problem. As galaxies are the main tracers of the non-linear evolution of our Universe, a deep understanding of their formation and evolution over cosmic time is mandatory to shed light on those conundrums. Some of the key questions that the SKA telescope will address are:

How do galaxies acquire gas and what is the role of neutral hydrogen in the life-cycle of galaxies?

How is star formation controlled by gas accretion and, in turn, how does feedback from star formation affect the interstellar medium (ISM)?

How is the activity in active galactic nuclei (AGN) connected to neutral hydrogen and how do AGNs affect the gas content of galaxies?

What does the interface between galaxies and the intergalactic medium look like?

What is the role of the environment and of galaxy interactions?

Physics of galaxy evolution

The evolution of galaxies is due to both environmental and internal effects and both affect their stellar and gas content which may be directly observed.

Environmental effects result from the interaction of a galaxy with nearby galaxies or cosmic gas through either gravitational or hydrodynamical processes. A galaxy in a dense environment, like a galaxy cluster, will suffer both tidal stripping and ram pressure stripping.

By stopping the accretion of fresh gas or removing the local cold gas, those effects have a direct impact on its gas content, its star formation and subsequently on their secular evolution and present day properties. Environmental effects are tightly related to the cosmology.

The ΛCDM model predicts the statistical distribution of galaxies to be in filamentary structures with very dense regions: the galaxy clusters at the crossing of filaments, and huge empty regions: the voids. It thus predicts a variety of environments that can directly be probed by studying galaxies.

At the opposite end, internal effects in galaxies are due to local physical processes. The self-gravity is responsible for the formation of peculiar features in the disk of galaxies, like spirals, bars, and warps.

The interstellar gas (interstellar medium, ISM) is at the origin of the formation of stars, which themselves, by their explosion, shape the ISM, setting a feedback-loop.

Understanding and disentangling environmental and internal effects is thus essential to understand the secular evolution of galaxies and bridge them with cosmological models. By its unprecedented ability of tracing gas both in local and high redshift galaxies, the SKA telescope will revolutionize the study of galaxies.

Observing galaxies through cosmic time

Gas in galaxies is present in a multiple variety of phases, with the dominant ones being the neutral hydrogen and the molecular gas. The neutral atomic hydrogen (HI) is an essential tracer of the internal dynamics of galaxies.

Since the seventies, HI observations allow scientists to determine the way galaxies rotate and conclude the presence of large amounts of dark matter, a major ingredient in the ΛCDM model. HI maps also trace large scale spiral structures and impacts of exploding supernovae.

As HI is extended, it is loosely bound and easily stripped in a dense environment, generating HI tidal or cometary tails. As such, HI is also an excellent tracer of the environment.

The neutral atomic hydrogen (HI) is studied via the 21-cm emission hyperfine line at a frequency of about 1400 MHz. Unfortunately, it is a very weak signal that makes it impossible to be detected in distant galaxies with current facilities. The SKA will allow for the first time to study HI at almost all redshift throughout the Universe.

With the first phase (SKA1) HI emission of individual normal galaxy should be obtained for galaxies up to redshift z=0.7. With SKA-2, z=2 is expected. Reaching z=2 is important as it corresponds to a look-back time covering a large fraction of the age of the Universe, up to 3 billions of years after the Big-Bang, when galaxies assemble most of their mass, and therefore will provide significant new insights in galaxy formation and evolution.

The molecular cold gas phase is tightly connected to the formation of stars. Understanding at which rate the stars have been formed on average in the Universe since the Big-Bang (during the past 14 billion years), the so-called cosmic star formation history, requires a detailed knowledge of the molecular phase at different redshift. The molecular phase is mainly traced by the emission of carbon monoxide CO molecule.

Recent observations revealed that the star formation efficiency in galaxies was much higher when the Universe was younger. This could be explained by the presence of large molecular gas reservoirs as traced by millimetre wave observations.

However at high redshift, the CO lines visible at millimeter wavelength can only be detected for high level transitions which do not lead to a reliable determination of the local gas mass, contrary to the fundamental line transition (J=1-0, 115 GHz). With its high sensitivity, the SKA1 will allow for the detection of the CO J=1-0 line transition above z=7.3, which correspond to the first billion years after the Big-Bang. With an improved sensitivity and extended frequency (up to 24 GHz) SKA2 will be an extremely powerful survey machine,

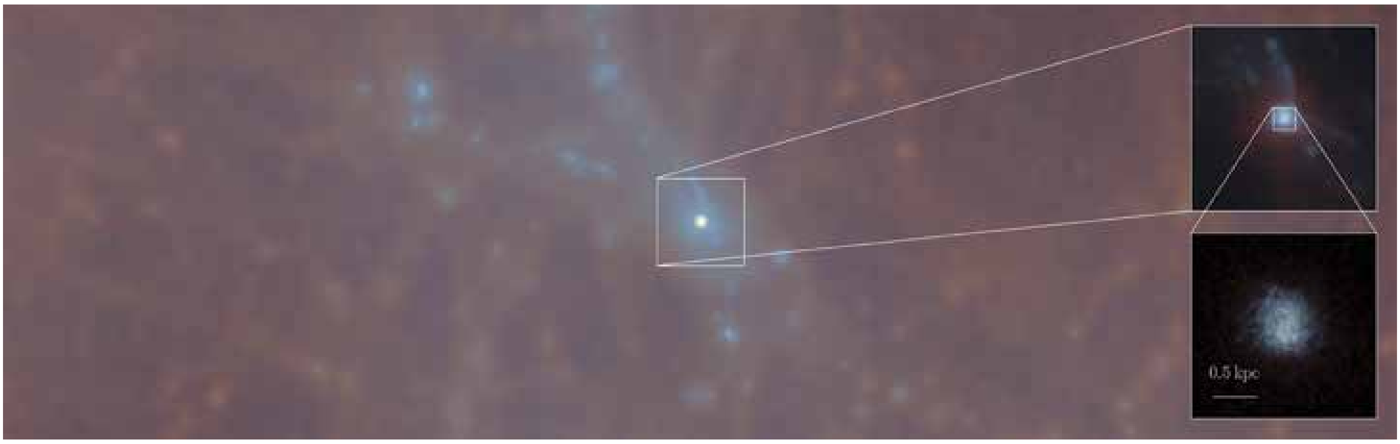


Figure 8 The formation of a galaxy in the cosmic web. The dark matter is represented in red, the gas in blue and the stars in yellow. Credit: Revaz & Jablonka 2018

allowing the detection of up to 40 galaxies per observing hour down to a redshift of 3.8. A major improvement compared to what Swiss scientist are currently observing with the ALMA interferometer (see Figure 9).

In addition to the CO molecular line, other fainter molecular lines like HCN, HCO+ or CS will be observed. Those molecules probe the very dense gas environment and improve the determination of the H_2 hydrogen molecular gas properties, leading to an accurate determination of the gas and temperature density. This is a key information to learn about star formation in the early Universe.

Star formation

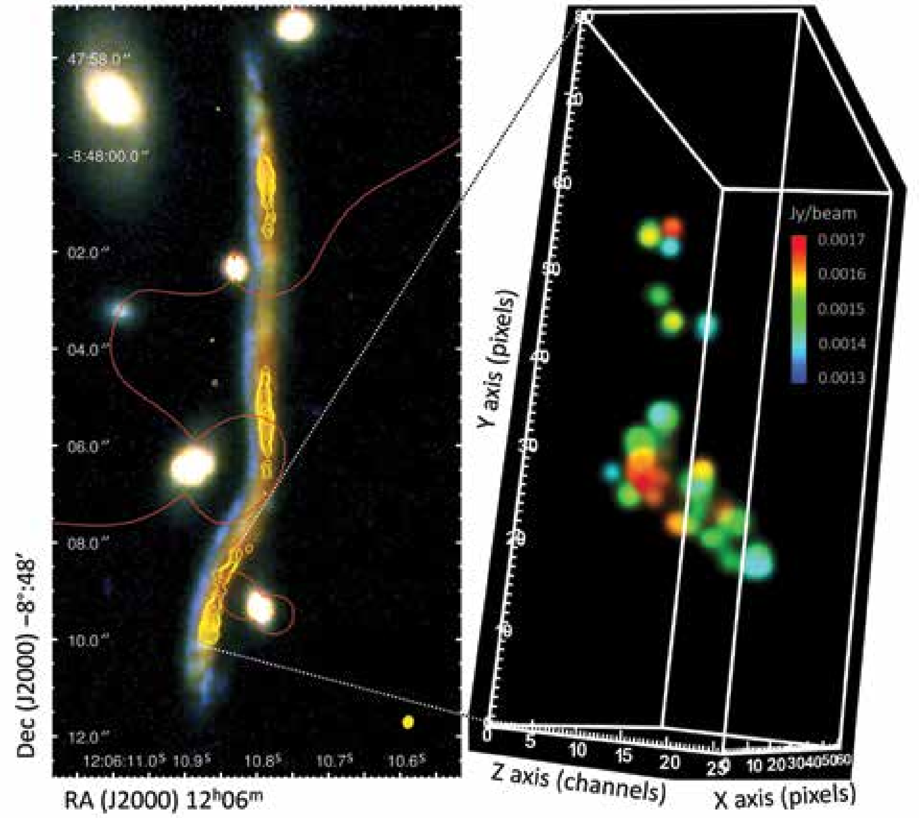
Directly tracing the star formation history of our Universe is essential to probe both the cosmological model and the galaxy formation. While there is a common agreement that the star formation history peaked somewhere between redshift z=1 and z=3, its precise value remains uncertain. Unlike tracers like UV or IR, by observing synchrotron and free-free emission, radio continuum observations give access to the only SFR measurements unaffected by dust attenuation. The SKA telescope will allow for a systematic determination of star formation in galaxies at redshift larger than 3.

Filaments

Filamentary structures are a direct prediction of ΛCDM models. If present in the intracluster medium, they will play an important role for the gas accretion and environment. It has recently been shown that shocks in intracluster filaments are responsible for electron acceleration and magnetic field compression, leading to an observable synchrotron radiation at low frequencies (~ 100 MHz).

The low frequency band of the SKA telescope will then provide a new opportunity to detect through the synchrotron emission the filamentary structure of the Universe.

Figure 9 Example of the ALMA observations of the CO J=4–3 line emission of the strongly lensed Cosmic Snake galaxy at z=1 (left panel). Seventeen individual molecular clouds are detected at scales reaching 30 pc (right panel). They are the seeds of star formation. Credit: Dessauges-Zavadsky et al., Nature Astronomy, 2019



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1.4. Cosmic reionization

Cosmic reionization represents the last major phase transition of the Universe after the Big-Bang, from a neutral to an ionized medium. It is still today a poorly known epoch in the history of the Universe.

From the combination of absorption spectra of high-redshift quasars and the polarization of the cosmic microwave background radiation, cosmic reionization is known to occur within the first 1 billion years of cosmic time.

However, the main sources of ionizing radiation as well as the exact timing of this important process are still unknown. The SKA low-frequency array will allow us to probe the 21 cm line emitted from neutral hydrogen with unprecedented accuracy.

This emission line is seen in absorption or emission against the background as a consequence of different astrophysical processes linked to the very first stars and galaxies. Thanks to SKA, we will be able to address several key questions:

When and how was the Universe ionized?

What were the properties of the ionizing sources, e.g. the first stars and galaxies?

When did the ionizing sources form?

What does the interface between galaxies and the intergalactic medium look like?

21 cm observations

The hyperfine transition of neutral hydrogen at 1-400 MHz or 21 cm has long been proposed as a key tool to study cosmic reionization and cosmic dawn. Indeed, hydrogen is ubiquitous in the intergalactic medium, making up ~75% of the baryonic matter. During the first 1 billion years of cosmic history, the line is redshifted to frequencies smaller than 300 MHz, which is perfectly suited for low-frequency radio telescopes, such as the SKA interferometer in Western Australia.

The 21 cm signal is observed against the CMB background and can either be seen in emission or absorption, at different stages of cosmic history (see Figure 11).

The signal is however affected by the interaction of hydrogen with the ultraviolet light emitted by the first cosmic sources, enabling the investigation of a large variety of aspects from the end of the cosmic dark ages with the formation of the first stars and galaxies down to cosmic reionization where hydrogen was ionized thus erasing the 21 cm signal from the intergalactic medium.

The first generations of galaxies

While great progress has been made over the last few years in identifying early galaxies during the Epoch of Reionization (EoR) in the first billion years of cosmic history, the 21 cm measurements from SKA-Low will provide a completely unique new set of observations into the first generation of galaxies.

In particular, while current optical/NIR imaging surveys are only sensitive to the most massive galaxies, the 21 cm signal will constrain the integrated light emitted by all sources during this time.

If we assume that reionization was driven just by galaxies, we can map out the total star-formation density of the Universe as a function of cosmic time. Additionally, we can constrain the X-ray emission from active black hole accretion through the mapping of the temperature evolution of the intergalactic medium from initially cold to warm.

At even earlier times, we expect the 21 cm signal to be seen in absorption after the emission of the first Lyman-alpha photons from stars and galaxies. Thus, the 21 cm signal uniquely constrains the end of the cosmic Dark Ages and the formation of the very first sources of light in the Universe.

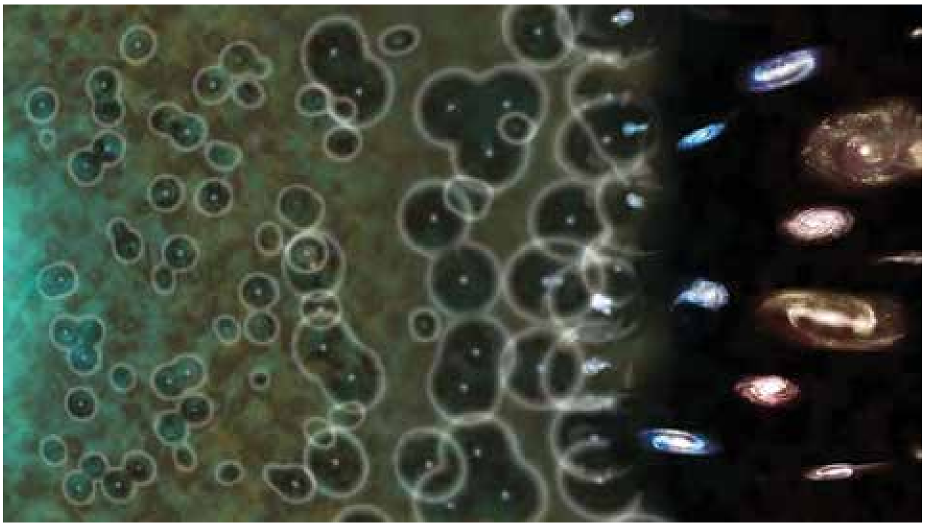

Figure 10 Illustration of the Epoch of Reionization derived by the modeling of the observations - from the Hubble and Chandra space telescopes. Credit: NASA/CXC/M.Weiss

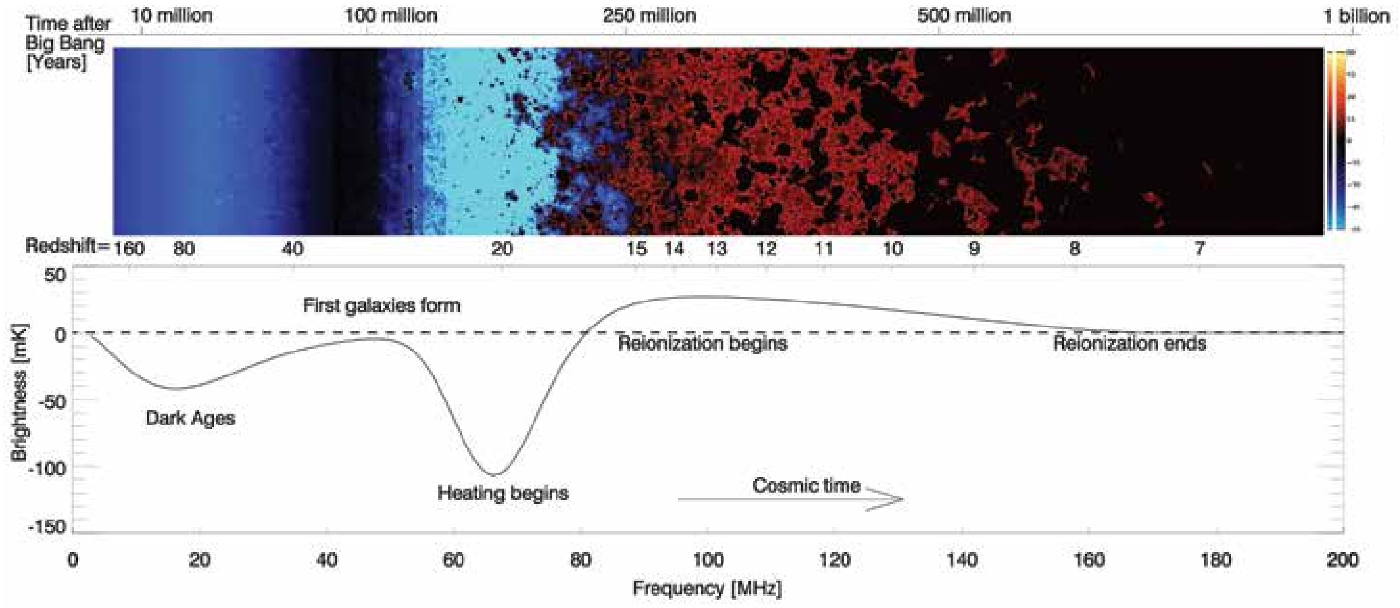

Figure 11   A model of the expected 21 cm signal from the very early Universe. The top panel shows a slice through the 21 cm fluctuations. Due to emission from the first stars and galaxies, the signal transitions from absorption (blue) to emission (red) at different stages of early cosmic history. After reionization ends, the 21 cm signal disappears (black). The bottom panel shows the evolution of the sky-averaged signal as a function of frequency (bottom axis) and redshift (top axis). Figure based on Pritchard & Loeb 2012, from Pritchard 2015, Astronomy & Geophysics, Volume 56, Issue 3

The sources of cosmic reionization.

Simulations show that cosmic reionization was likely very patchy, starting in the first overdense regions of the early Universe. The first sources of light emitted ionizing radiation, which started to create ionized bubbles around them (see Figure 10). As more and more of these sources formed, these bubbles coalesced resulting in a relatively rapid phase transition in the intergalactic medium from neutral to ionized.

During the EoR, the 21 cm signal is seen in emission, with dark spots representing already ionized bubbles. While current measurements from the CMB provide us with an integrated constraint on cosmic reionization, only 21 cm tomography can really reveal the progress of this phase transition, i.e. of the neutral fraction as a function of cosmic time.

So far, the first generation 21 cm telescopes mostly focus on the power spectrum of 21 cm fluctuations and its evolution, due to their limited sensitivity. However, the SKA will completely revolutionize this field. For the first time, we will actually be able to directly image ionized hydrogen bubbles on scales as small as arcminutes.

When connected to galaxy counts and their inferred ionization budget on the same scale and in the same area of the sky, SKA will thus provide a direct and unambiguous answer whether galaxies, black holes, or other, more exotic sources were the main drivers for cosmic reionization.

Furthermore, the direct imaging of individual ionized bubbles with the SKA provides unique new constraints on galaxy formation physics including their star-formation efficiencies in low mass halos.

By combining SKA's 21 cm signal with simulations and observations of the first generations of galaxies from optical/NIR surveys during the same time period, SKA-low will result in the first self-consistent picture of cosmic reionization and galaxy build-up in the early Universe.

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1.5. Radio transients

Some types of astronomical sources appear on the sky only for very short periods of time, on different time scales, from a fraction of a second to years.

These so-called transients are still not well understood. The SKA will help answer some of the open questions:

What is the nature and what are the physical mechanisms of transient multi-messenger sources (electromagnetic and gravitational wave transients)?

What is the source of fast radio bursts?

Hunting for transients with observation alerts

Studies of such sources are possible only if the telescope is pointed toward the source right at the moment when it appears in the sky. A signal detection by a single telescope on a limited time scale of source existence is often not sufficiently detailed for understanding the nature of the source and the physical mechanisms of its activity. Coordinated effort of many telescopes is needed to get insight into the nature of transient sky phenomena.

This coordination becomes possible nowadays due to the availability of multiple astronomical observation "windows" explored by different types of telescopes: from radio to gamma-rays, and possibly across different astronomical "messenger" channels, including gravitational waves and neutrinos.

Such coordinated efforts are enabled by the development of information and communication technology which allows us to synchronize astronomical observations in different bands on very short time scales down to seconds.

The first telescope to detect a transient source performs a fast "on-the-fly" analysis of its data and, in case of detection of a new source, distributes "alerts" to a network of other telescopes through dedicated internet services, such as the Gamma-ray Coordinates Network (GCN), the Astronomer's Telegrams (ATEL) or the Virtual Observatory Events (VOevent).

Observatories receiving these alerts could promptly interrupt their regular observation campaigns to repoint to the transient source and follow up the initial detection, thus complementing the observational dataset with multi-wavelength data.

Gamma-ray bursts, gravitational waves, and optical transients

This practice has initially been adopted by the gamma-ray community to study Gamma-Ray Bursts (GRBs). The nature of these short flashes of gamma-rays, initially discovered by military satellites, has remained unclear until multi-wavelength follow-up coordinated observations have led to the identification of mechanisms which are at least part of the GRBs.

GRB "afterglows" are now detected all across the electromagnetic spectrum, from the radio band up to the highest energy end of electromagnetic astronomical window in the tera-electronvolt energy range, in this case, each photon coming from the gamma-ray burst carries energy comparable to the energies of particles circulating in the most powerful accelerator on Earth, the Large Hadron Collider.

The gamma-rays from GRBs are visible on the sky only for some seconds. Contrary to the GRB event itself, the "trace" of the GRB, or its "afterglow" remains visible on the sky for days following the flash of gamma-rays. Studies of such afterglows across different energy ranges have enabled an understanding of the nature of these explosive events: their "extragalactic" origin and association to the death of massive stars. GRB afterglows are visible in the radio band and analysis of the radio afterglows provides information on the nature and structure of relativistic high-energy particle outflow penetrating through the circumstellar environment created by the dying star.

The extraordinary sensitivity of SKA and its sky survey capabilities superior to all existing radio telescopes will allow us to put the study of radio afterglows of GRBs on a qualitatively new level. In particular, it will enable systematic detection of fainter afterglows tracing the GRB outflows up to the point when they are slowing down to non-relativistic velocity. SKA will most probably also discover phenomenon of "orphan" afterglows, from the GRBs whose gamma-ray emission beam is not aligned along the line of sight toward the Earth.

A sub-population of particularly short GRBs is now known to originate from the merger of compact neutron stars, rather than from the death of a single massive star. In this case the short (several seconds) gamma-ray signal is preceded by a still shorter (milliseconds) gravitational wave burst, as has been recently demonstrated in the "multi-messenger" detection of such an event using a combination of data of gravitational wave detectors LIGO and VIRGO with those of gamma-ray telescopes (INTEGRAL, Fermi GBM).

Similar to the gravitational collapse of massive stars which produce supernovae, the neutron star merger event has initiated an explosive expansion of matter (called "kilonova" instead of "supernova") which left an afterglow which has been visible across different astronomical observation windows, including the radio band.

Only one such "multi-messenger" event has been detected so far, but its study demonstrates the potential of the new

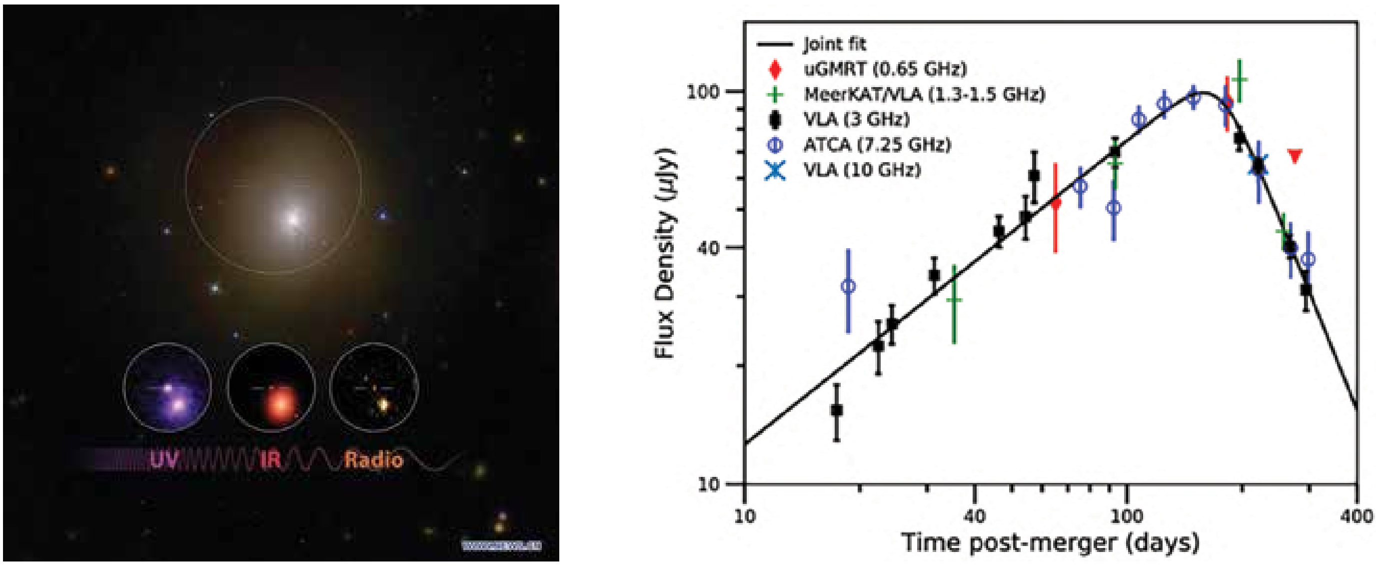

Figure 12 Left panel: Sky region around the neutron star merger event GW170817. The right panel shows the gravitational wave signal in time-frequency representation, the bottom insets show multi-wavelength views. Right panel: Radio lightcurve of the GW170817 afterglow. Credit: National Radio Astronomy Observatory, Socorro, New Mexico 87801, USA Caltec

emerging field of "time domain" multi-messenger astronomy. Properties of the new transient astronomical source population, the neutron star mergers, are still to be uncovered and understood and SKA will be a crucial facility for such a study, providing information on the relativistic outflows which seem to accompany the mergers and subsequent kilonova explosions.

Other types of gravitational wave bursts, associated to black hole – black hole and black hole – neutron star mergers have so far escaped the "multi-messenger" detections, either because of the genuine absence of the electromagnetic signal or its weakness.

Upgrades of the gravitational wave detectors, improved coordination between different multi-messenger observational facilities, and the imminent start of operations of robotic sky surveys in the visible band (LSST) are set to bring discoveries of new types of transient source populations in the sky and also introduce qualitatively new types of information on known types of transients for which the multi-wavelength and multi-messenger data are scarce because of insufficient sensitivity of existing telescopes.

With its superior sensitivity and sky survey capabilities, SKA will be one of the key players in this emerging field of astronomy.

Fast radio bursts

One of the recently discovered transient source types is Fast Radio Bursts (FRBs). These sources appear in the sky on very short, millisecond time scales and only in the radio band. The short time scale of these events (similar to that of the gravitational wave signal from neutron star and stellar mass black hole mergers) suggests that the FRB signals come from compact objects, while their sky distribution suggests an extragalactic origin. In this case, the objects producing the FRB signals generate enormous energy output on extremely short time scales.

Different theoretical models of this phenomenon have been put forward, from "conventional" astrophysical phenomena like giant pulses of young pulsars to evaporation of small black holes.

Progress towards understanding the nature of the FRB phenomenon will be possible via systematic accumulation of a large sample of FRBs and their multi-wavelength and possible multi-messenger follow up, using the approaches recently developed by the "time domain astronomy" community for the study of GRBs and gravitational wave events.

SKA will be an FRB "discovery machine" which will enable such progress, by routinely discovering new FRBs and distributing alerts for the multi-messenger followup observations in the real-time regime.

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1.6. Cosmic magnetic fields

Most of the baryonic matter of the Universe is ionized and therefore magnetic fields can influence astrophysical flows via the Lorentz force. Since modeling the dynamics of magnetized fluids is extremely challenging, there are many open questions left, in particular:

When and how were magnetic fields generated?

How did they evolve in cosmic history?

How do magnetic fields affect the formation of cosmic structures?

What is the shape and strength of the magnetic field in our Milky Way, and how does it compare to fields in other galaxies?

Observations of magnetic fields with radio telescopes

Most of the knowledge about astrophysical magnetic fields comes from radio observations. So-called continuum radio emission plays a crucial role because its largest fraction often is synchrotron radiation emitted by cosmic ray electrons spiraling around magnetic field lines. The observed synchrotron luminosity allows an estimate of the total field strength. Often, synchrotron radiation is linearly polarised and the polarisation plane yields the orientation of the ordered field in the plane of the sky.

Moreover, Faraday rotation of the polarisation plane provides information on the field component along the line of sight (see Figure 13). Hence, a three-dimensional picture of cosmic magnetic fields can be derived from observing radio waves. With its unprecedented sensitivity, SKA will detect extremely faint radio fluxes and thus will be able to probe the history of cosmic magnetism. This makes SKA the next-generation instrument for exploring cosmic magnetism.

Radio measurement techniques probing the weakest magnetic fields in the large-scale structure are complementary to a gamma-ray technique which is based on the observations of extended or delayed emission signal from distant active galactic nuclei.

The Faraday rotation measurements are primarily sensitive to the fields in the filaments and nodes of the large scale structure, while the gamma-ray measurements are sensitive to the fields in the voids. The combination of SKA observation with the gamma-ray detections from the Cherenkov Telescope Array (CTA), which is the next generation ground-based observatory for gamma-ray astronomy, will provide powerful constraints on the intergalactic magnetic fields, thus bringing new insight into the origin and evolution of magnetic fields in the Universe.

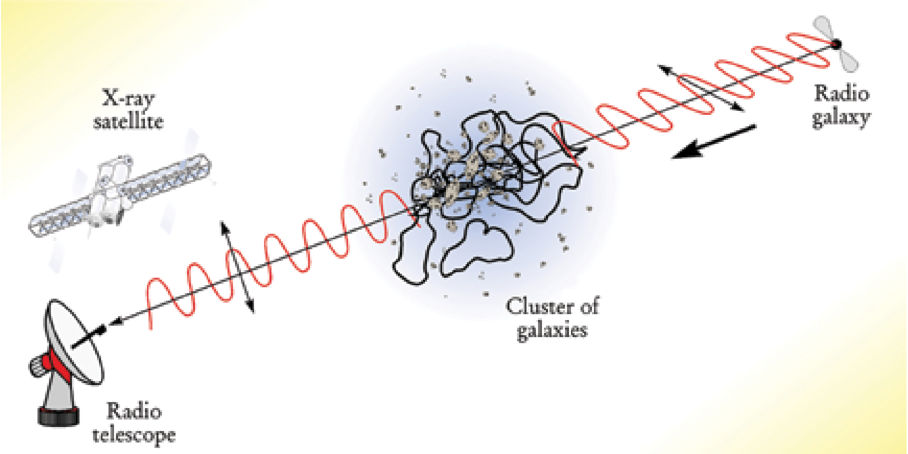

Figure 13 Illustration of the Faraday rotation effect in the magnetic field of a galaxy cluster observed by a radio telescope. The galaxy cluster is observed independently by X-ray satellites. Credit: Philipp P. Kronberg, Physics Today, December 2002, p. 40. Copyright 2002, American Institute of Physics

Origin and evolution of magnetic fields in the Universe

The very first magnetic fields may have already been generated during inflation, the epoch of rapid expansion of the Universe that ended 10^{-32} second after the Big-Bang, or during the quantum electro dynamics (at 10^{-11} second) and quantum chromo dynamics (at 10^{-5} second) phase transitions. Whether these primordial magnetic fields can survive and reach astrophysically relevant scales, and how they affected the evolution of the primordial plasma are highly debated topics in modern cosmology.

But regardless of when exactly magnetic fields have been generated, they are typically very weak and decay continuously due to magnetic diffusion. Magnetohydrodynamical dynamos can bridge the gap between weak magnetic seed fields ($\approx 10^{-20}$ Gauss) to fields observed in today's galaxies ($\approx 10^{-5}$ Gauss) by converting kinetic energy from astrophysical flows into magnetic energy.

Magnetic fields in galaxy clusters

The largest length scales on which magnetic fields can be directly detected by radio emission are galaxy cluster scales. Clusters in which a diffuse radio emission is detected are called radio halos. Their magnetic field seems not to be spatially constant but shows a rather complex structure. In particular, the magnetic field intensity declines with the cluster radius with a rough dependence on the thermal gas density. Moreover, cluster magnetic fields are likely to fluctuate over a wide range of spatial scales with values from a few up to hundreds of kiloparsec.

Thanks to its sensitivity, its broader bandwidth and its resolution, the SKA will allow us to perform complete and accurate studies of magnetic fields in galaxy clusters and help in understanding their origin. SKA-MID will, in principle, even allow the detection of a large fraction of filaments surrounding galaxy clusters with the Faraday Rotation technique.

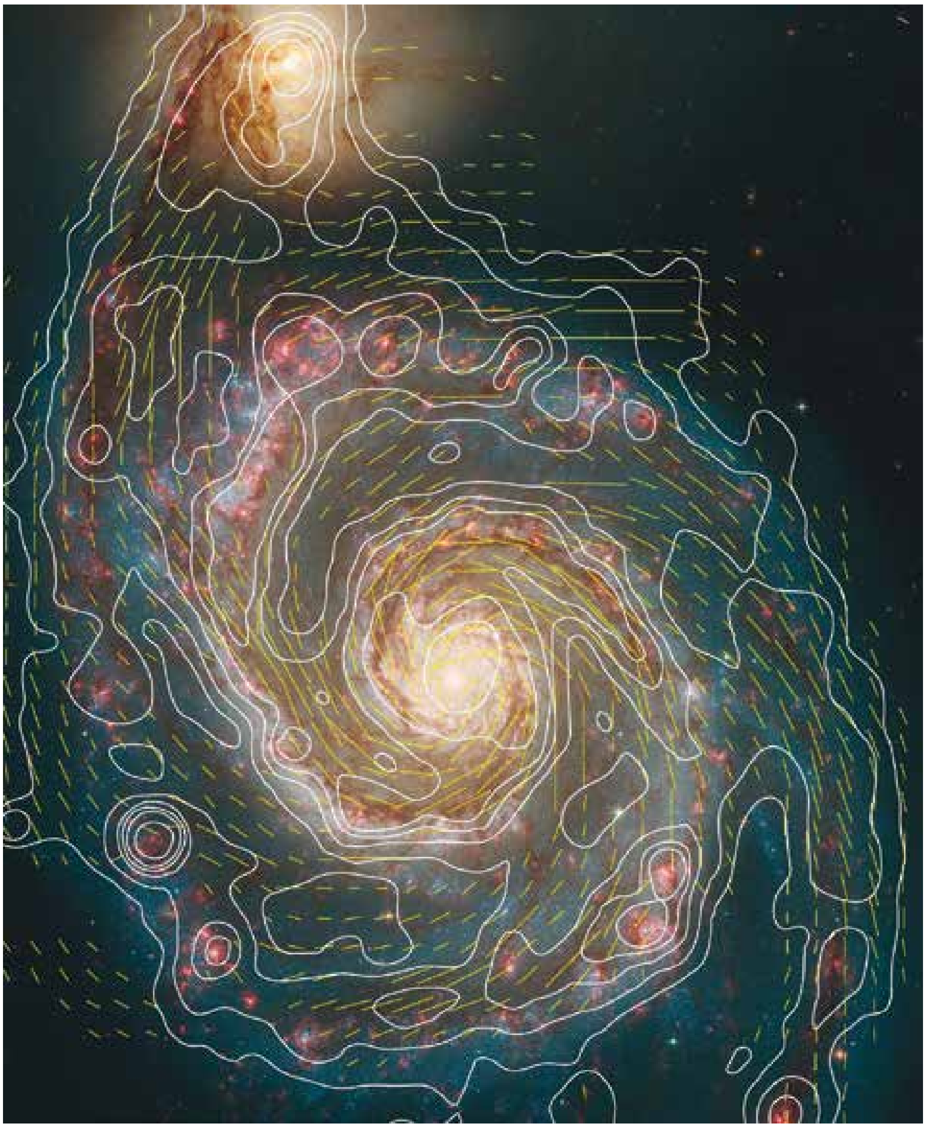

Figure 14 Magnetic field lines (yellow lines) in the spiral galaxy M51 and contours (white lines) of the total radio emission at 6 cm (VLA+Effelsberg) overlaid on a Hubble Space Telescope optical image. Credit: MPIfR (R. Beck) and Newcastle University (A. Fletcher)

Magnetic fields in galaxies

Magnetic fields are a major agent in the interstellar medium of spiral, barred, irregular and dwarf galaxies. They may affect the gas flows in spiral arms, around bars, and in galaxy halos.

The origin of these strong galactic magnetic fields seems to be an efficient α-Ω dynamo that is driven by turbulent motions as well as non-uniform (differential) rotation. It generates large-scale regular fields, even if the seed field was turbulent ("order out of chaos").

The regular field structure obtained in dynamo models is described by modes of different azimuthal symmetry in the disk and vertical symmetry perpendicular to the disk plane. Such modes can be identified from the pattern of polarization angles and Faraday rotation in multi-wavelength radio observations. SKA will allow us to study such magnetic field structures in galaxies at resolutions more than 10 times better than that of current radio telescopes.

Moreover, SKA will be able to observe magnetic fields in galaxies at high redshifts and thereby the evolution of galactic fields can be deducted by comparing galaxies at different cosmic epochs. Thousands of "normal" spiral galaxies at redshift = 2-3 will be detected with the SKA.

At intermediate redshifts, polarised emission from galaxies will often be too faint to be detected directly but the magnetic fields of these sources can be traced by the rotation measures they produce in the polarised background emission. This will allow detailed studies of the magnetic field configuration of individual objects at earlier epochs.

Magnetic fields in the interstellar medium of the Milky Way

The magnetic energy density in the interstellar medium of the Milky Way is comparable to other energy components, like turbulent kinetic, thermal, and cosmic ray energy. Therefore, magnetic fields contribute significantly to the total pressure which balances the interstellar medium against gravity. They may affect the gas flows in spiral arms, around bars, and in galaxy halos. Magnetic fields can be essential for the onset of star formation as they enable the removal of angular momentum from the protostellar cloud during collapse. Energy from supernova explosions is distributed via magnetohydrodynamical turbulence within the interstellar medium, magnetic reconnection is a possible heating source for the Interstellar Medium and halo gas, and moreover magnetic fields control the density and distribution of cosmic rays in the interstellar medium.

Swiss contribution

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1.7. Dark Energy

The observed accelerated expansion of the Universe is caused by the so-called Dark Energy. Even though almost 70 percent of the total energy content of the Universe seems to be in the form of this Dark Energy, it is one of the biggest mysteries in cosmology. The key questions include:

What is the nature of Dark Energy?

How and why has it become that major player in our Universe?

Is Dark Energy the correct explanation of the accelerated expansion of the Universe?

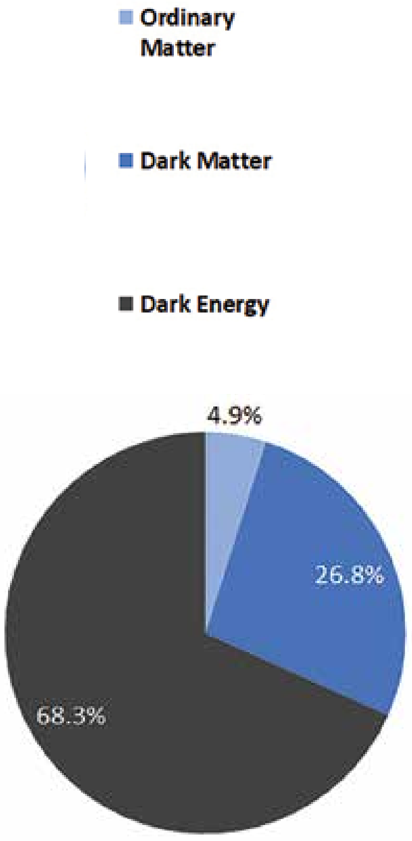

Figure 15 The composition of the Universe determined from analysis of the Planck mission's cosmic microwave background data. Credit: ESA

Cosmology has really come of age in the 20th century, with the development of General Relativity (GR) that finally represented a theory able to model the evolution of the Universe. GR naturally predicted that the Universe should expand, even though researchers tried to build static models, the reason why Einstein originally introduced a cosmological constant into his theory. Lemaitre and Hubble however convincingly showed in 1927 and 1929 that the Universe was indeed dynamic, and the Big-Bang model was born.

Observations at cosmological distances are however difficult. It was realized already in 1933, by Zwicki, that visible matter was not sufficient to explain the velocity of galaxies in the Coma Cluster. This observation was then reinforced by the observation of galaxy rotation curves in the 70's by Rubin, Ford and Freeman, leading to the postulate that there exists an invisible kind of matter, called `Dark Matter'.

Later on, in the 90s, evidence accumulated that the expansion rate of the Universe was accelerating, not decelerating, culminating in two publications in 1998 and 1999 by astronomers measuring distances to supernovae (exploding stars) that received the 2011 Nobel Prize in Physics.

The accelerated expansion of the Universe is a major enigma for fundamental physics: 'normal' matter can only slow down the expansion rate. To increase the expansion rate we need an unknown new component, called `Dark Energy', that possesses a negative pressure. It turns out that the cosmological constant (usually written with the greek letter Lambda) introduced by Einstein possesses this property, and in addition agrees with observations.

This led to the standard model of cosmology, called the Lambda-Cold-Dark-Matter (LCDM/ΛCDM) model, in which about 70% of the current energy density in the Universe is due to a cosmological constant, about 25% is composed of dark matter, and only 5% is due to `normal matter' that we observe on Earth (see Figure 14).

The best current constraints on the model are due to measurements of the cosmic microwave background radiation (CMB) by the ESA Planck satellite. The CMB is the left-over radiation from the Big Bang, and it carries an imprint of the structure of the Universe at an age of only 380'000 years, when the Universe was over 1000x smaller than it is today.

However, the cosmological constant corresponds to an energy density of the vacuum, and if the vacuum can gravitate then naive predictions from particle physics predict a value that is many orders of magnitude too large, so that the Universe should not exist at all. Because of this surprising result, theoretical physicists have tried to come up with alternative models.

One possibility is to replace the cosmological constant by a dynamical field, that leads to the accelerated expansion. Another possibility is to modify Einstein's theory of gravity at large scales, in such a way that gravity itself drives the accelerated expansion of the Universe.

Many of these theories are compatible with current observations, but none of them is completely convincing at the theoretical level. We are therefore at a stage where we need better observations to guide us in this question.

The SKA, as the world's largest radio telescope, is in a unique position to advance our understanding of the nature of Dark Energy and of the theory of gravity. It will indeed measure both the expansion rate of the Universe and the formation of structure on large scales with unprecedented precision. These two measurements are crucial to discriminate between the different theories in play. The SKA will accomplish this with several surveys:

Continuum galaxy survey: Observes galaxies with high resolution based on synchrotron emission from electrons moving the galactic magnetic fields. Measures the shapes and positions of the galaxies but not precise redshifts (distances).

HI galaxy redshift survey: Observes the spectral line from the spin-flip transition between the hyperfine states of neutral hydrogen (HI) at 21 cm. This allows us to map the 3D galaxy distribution and provides very precise redshifts.

HI intensity mapping survey: Using the same observable (the 21 cm line) the intensity mapping survey measures large-scale correlations in the HI emission without detecting individual galaxies.

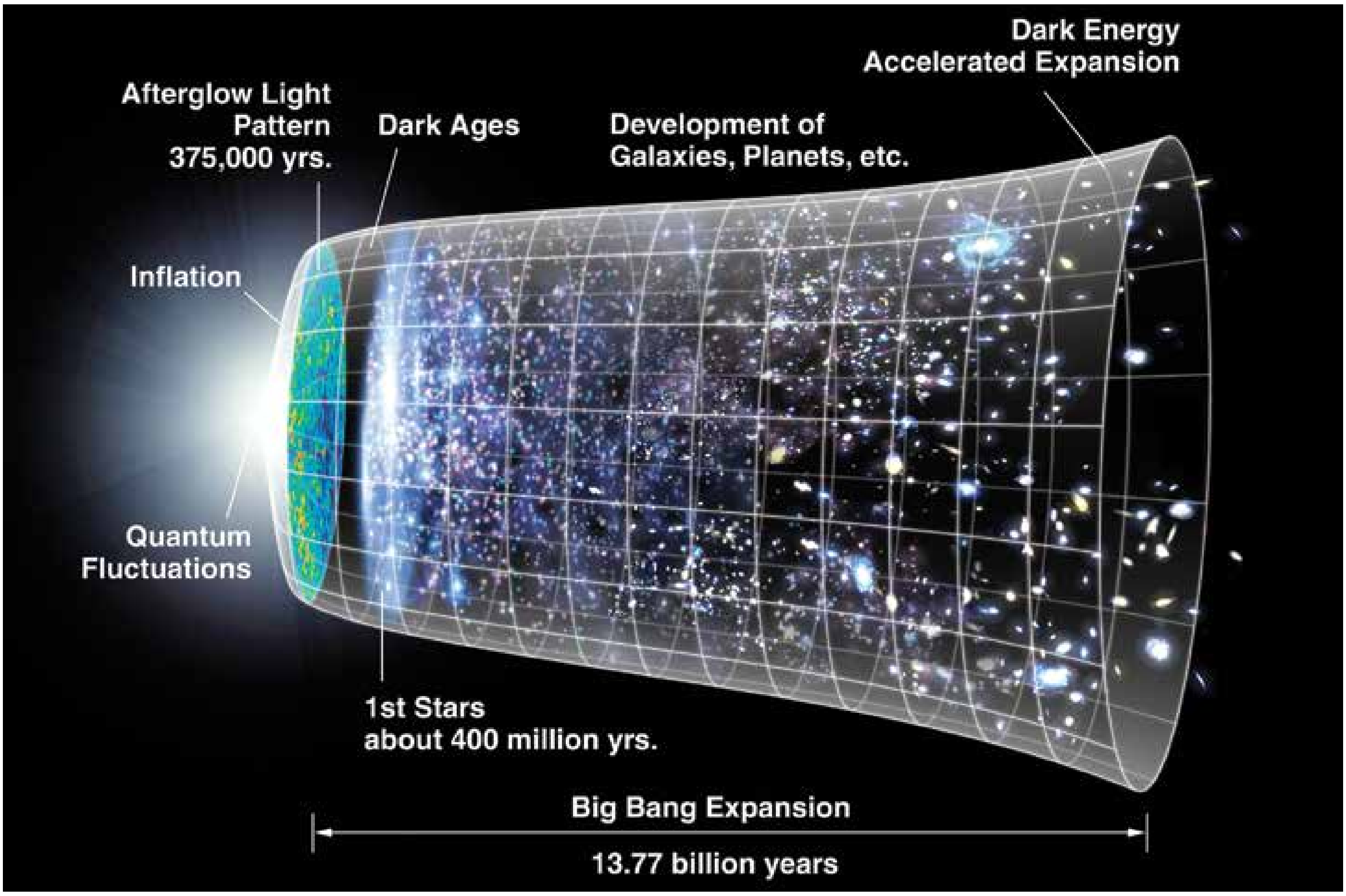

Figure 16 Diagram of evolution of the (observable part) of the universe from the Big Bang (left), the CMB-reference afterglow, to the present. Credit: NASA/WMAP

The shape measurements from the continuum survey allows for a cosmic shear analysis that observes the weak gravitational lensing (bending of light rays) due to the matter fluctuations in the Universe. This allows us to place constraints on the pressure of the Dark Energy (its equation of state parameter w) and to test for modifications of gravity on very large scales.

The continuum survey shows its true strength especially when combined with other surveys, like optical galaxy surveys (e.g. from the upcoming ESA Euclid satellite in which Switzerland is strongly involved).

The HI galaxy redshift survey can probe both the Dark Energy equation of state and the formation of structure on large scales as a function of redshift (distance or age of the universe, as light propagates at a finite speed).

The constraints will be powerful especially at late times, when the Dark Energy becomes the dominant contribution to the energy budget.

The HI galaxy redshift survey can also measure the line-of-sight velocity field, which provides additional tests of General Relativity.

HI intensity mapping (IM) finally is a promising new technique that allows reaching very high redshifts (up to z=6, i.e. an epoch when the Universe was 7x smaller than today) with unprecedented precision. This will allow the IM survey to measure the expansion history and the growth of structure over a large fraction of the history of the Universe. Also the IM survey will gain in power when combined with other surveys.

Such cross-combinations will be crucial to reduce systematic effects in the observations that will become the dominant source of uncertainty in the SKA era due to the high statistical power of the SKA surveys.

The constraints on the very large scales accessible with the SKA IM survey will also allow for uniquely powerful tests of GR on the scale of the cosmic horizon, where deviations are naturally expected to occur if the accelerated expansion is due to a modification of General Relativity.

It should be noted that the SKA surveys will not only probe the nature of Dark Energy, but will constrain cosmological models much more generally, including the primordial universe where a phase of inflationary expansion is thought to have taken place, and particle physics questions like the mass of neutrinos and the nature of dark matter.

Swiss contribution

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1.8. Tests of gravity

In the beginning of the last century Einstein developed the general theory of relativity to describe gravity. The theory has passed many observational tests, but we still do not have the answers to many questions, like for example:

Was Einstein right about gravity?

Can we understand where gravitational waves come from?

Can we map the cosmic evolution of the most massive black holes in the Universe?

Can we measure cosmic acceleration with gravitational waves?

Tests of general relativity

As of today, Einstein's theory of general relativity has been tested in many ways and to high precision has passed every test. Tests have been performed in the solar system, in pulsar systems, on cosmological scales and using the new tool of gravitational waves. Many tests have been done on the equivalence principle, the foundation of general relativity, and are planned in the future. Again all results are in excellent agreement with general theory.

Nonetheless, general relativity being one of the pillars (together with the standard model for particle physics) of modern physics it has to be tested in all possible situations and in particular in the strong field regime. Indeed, when it comes to the problem of unification of the fundamental forces, we will most likely need an extension of the classical theory of general relativity in the domain of quantum physics. We might expect that quantum gravity may produce somewhat different predictions than general relativity.

Alternative theories of gravity that modify general relativity even at scales larger than those at which quantum effects take place, and there are many currently considered by physicists and cosmologists, would also produce potentially measurable deviations.

But how can we measure such tiny deviations? Strong-field tests of gravity that will be carried out using pulsars and the SKA will provide some of the most stringent tests ever made.

A pulsar emits a radio beam along its magnetic axis. As the star rotates it acts like a cosmic lighthouse emitting an apparently pulsed signal when the beam is pointed in our direction – SKA will be able to detect this signal. The observed pulses act as the ticks of a natural clock which can be as precise as the best atomic clocks on Earth. With such an accuracy, SKA will be able to detect the most subtle variations in this and thus to very accurately test general relativity.

Furthermore, SKA will scan for pulsars near to black holes and look at the gravitational influence of these two objects; this will allow us to probe the theory in a completely new regime.

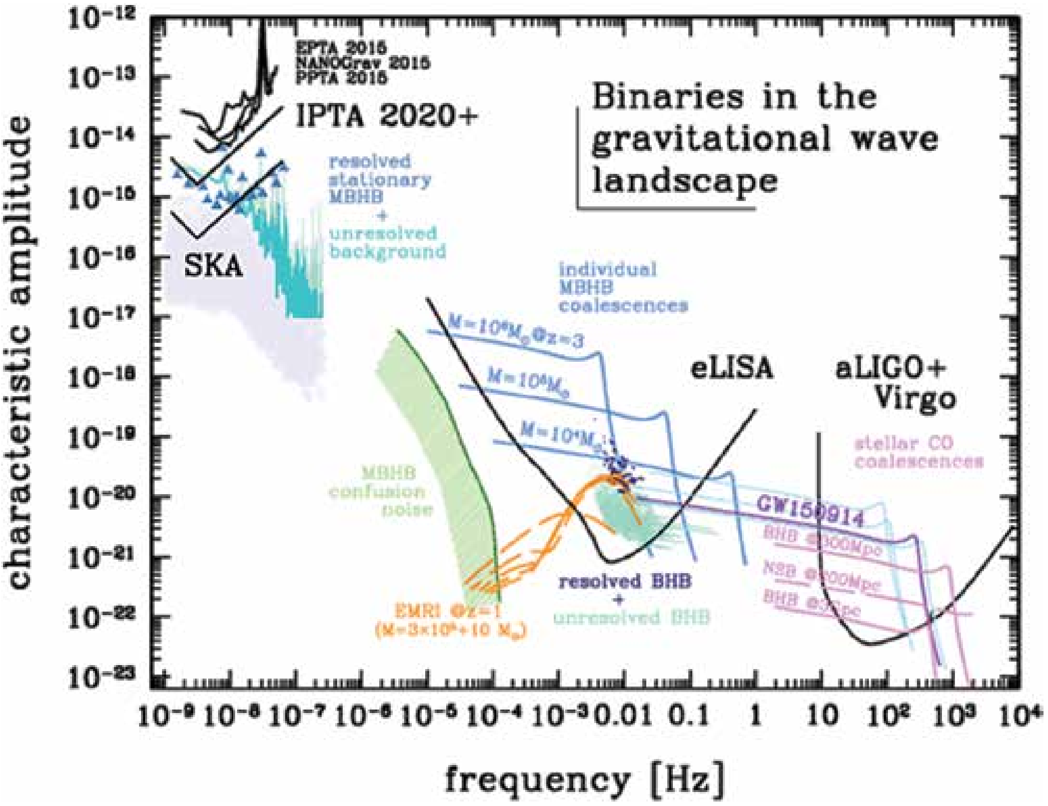

Figure 17 Binaries in the gravitational wave universe. The Figure shows the dimensionless characteristic strain amplitude in Fourier space versus frequency, from black hole binaries of all types, and of neutron star binaries (see review by Colpi & Sesana 2017). Plotted are the sensitivity curves of various existing and planned instruments, including the SKA and LISA. Different types of sources are indicated at the associated frequency range (including already discovered LIGO sources such as GW150914). Credit: "An Overview of Gravitational Waves: Theory Sources and Detection". Edited by G. Auger and E. Plagnol (World Scientific, 2016)

Figure 18 Artist's impression of the possible scientific questions that the SKA may answer, such as the evolution of Protoplanetary Disks. Credit: SKA Organisation/ Swinburne Astronomy Productions

Pulsar timing array: gravitational wave detection at low frequency

The accurate pulsar clocks, distributed throughout our Milky Way, are forming a pulsar timing array (PTA), which SKA telescope plans to monitor in order to discover these extremely low-frequency gravitational waves that no other man-manned gravitational waves experiment will be able to detect.

The SKA will significantly enhance the known pulsar timing array (PTA), by detecting many more millisecond pulsars that is possible with currently available radio telescopes.

Indeed, SKA will allow the pulsars to be timed to very high precision, making them very sensitive to the small space-time perturbations of gravitational waves at frequencies of nHz thereby complementing the much higher frequencies accessible to Advanced LIGO (-100 Hz) and the intermediate frequencies probed by the space-born gravitational detector "Laser Interferometer Space Antenna" LISA, which will work in the mHz range (see Figure 17).

These low-frequency gravitational waves, that SKA will detect, correspond to the merging of supermassive black holes with masses even higher than the ones observable with LISA, namely in the range 10^8-10^{10} solar masses, from the present time up to at least redshift z- ~2 (that is over the last 10 billion years). This will allow us to probe the cosmic evolution of such massive black holes and is complementary to LISA, which can only study black holes with masses below 10^7 solar masses.

The SKA-LISA observatory: cosmological probes with standard sirens

The other important area in which SKA promises to be transformative, and will be highly complementary to LISA, is its use in determining the redshifts of cosmological standard sirens.

Gravitational wave signals have the unique property that they allow us to measure directly the luminosity distance of the emitting source, making them of potential use for cosmology, hence the name "Standard Sirens".

However, from the wave-form one can infer the redshifted mass of the source, but not redshift or mass directly. If redshift can be measured with an independent method, cosmological standard sirens offer a new way to probe directly the cosmic expansion rate and thus test Dark Energy models to much higher redshift and with much smaller uncertainties that is possible now with type Ia Supernovae.

The measurement has already been made successfully using the first neutron star merger detected by AdvancedLIGO in 2017 and followed-up by multiple instruments in the electromagnetic domain. This has yielded a measure of the Hubble constant (H_0) with an error just exceeding 10% based on just one event. For this the SKA and LISA could work in concert.

For a gravitational wave source detected by LISA, the SKA will be used to determine the corresponding redshift by searching for a counterpart signals in the electromagnetic (radio) domain.

The full-SKA with a detection threshold flux of 1 microJansky, will easily detect transient radio bursts and jets just preceding or coincident with a merger by searching into the few degrees sky patch at the location of a gravitational wave black hole in-spiral signal already detected by LISA. We recall that, compared to a single emitting black hole, a binary black hole can yield a much higher radio luminosity because the emitted power is proportional to the cube of the orbital velocity.

Model forecasts show that, over a 5 year observational timeframe, a SKA-LISA observatory could measure the Hubble constant with an error of better than 1% and cosmic acceleration with an error of better than 10%.

Swiss contribution

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1.9. Dark Matter and astroparticle physics

The first clue for Dark Matter came from radio astronomy: The observation of HI emission in galaxies well beyond their optical radius revealed the existence of a large amount of non-luminous matter (see Figure 18 showing the galactic rotation curve). Indeed, ~25 % of the total energy content of the Universe seems to be in the form of Dark Matter. Yet, there is no conclusive evidence for one particular model of Dark Matter. SKA provides the sensitivity and resolution to constrain theoretical models of particle physics and thereby addresses some of the most fundamental questions, like:

What is the mass of the Dark Matter particle and how does it interact?

How is Dark Matter distributed in space and how is it correlated with HI?

What is the mass of neutrinos?

Particle physics is currently at a cross-roads. Indeed, a century long quest to build a closed, complete and self-consistent model of particle physics has resulted in the construction of the Standard Model of particle physics, an extremely successful theory that explains all the plethora of data from accelerator experiments and survived an impressive number of non-trivial tests.

At the same time, we know today that the Standard Model is incomplete as there are observed phenomena it fails to explain. This knowledge comes to a large extent from astrophysics and cosmology and includes

(i) neutrino flavour oscillations,
(ii) matter-antimatter asymmetry of the Universe, and
(iii) Dark Matter

For the first time since many decades we find ourselves in a situation when we know that some new physics must exist but we have no definite predictions where to look for it.

In this situation further input from astrophysics and cosmology plays a unique role.

This, in particular, concerns the nature of dark matter. Clearly, any definite information about its mass, strength of interaction with ordinary matter or self-interaction, primordial properties (such as e.g. initial momentum distribution) would of course disfavour whole classes of particle physics models beyond the standard model.

An important example is given by the properties of dark matter clustering at sub-galactic scales. In the standard cold dark matter model, dark matter distribution is scale invariant down to very small scales.

Many particle physics models imply however that small structures should be suppressed somewhere below (but not so far from) galactic scales.

Such a suppression can be observed in various ways including counting the number of sub-halos of different sizes, studying the distribution of neutral hydrogen in the intergalactic medium (Ly-alpha forest), and gravitational lensing.

A number of observations suggest that small structures are indeed suppressed as compared to larger ones. However, the main challenge for some of these approaches is related to the fact that thermal effects in the gas forming intergalactic medium can imitate the absence of small Dark Matter structures even in the cold Dark Matter model.

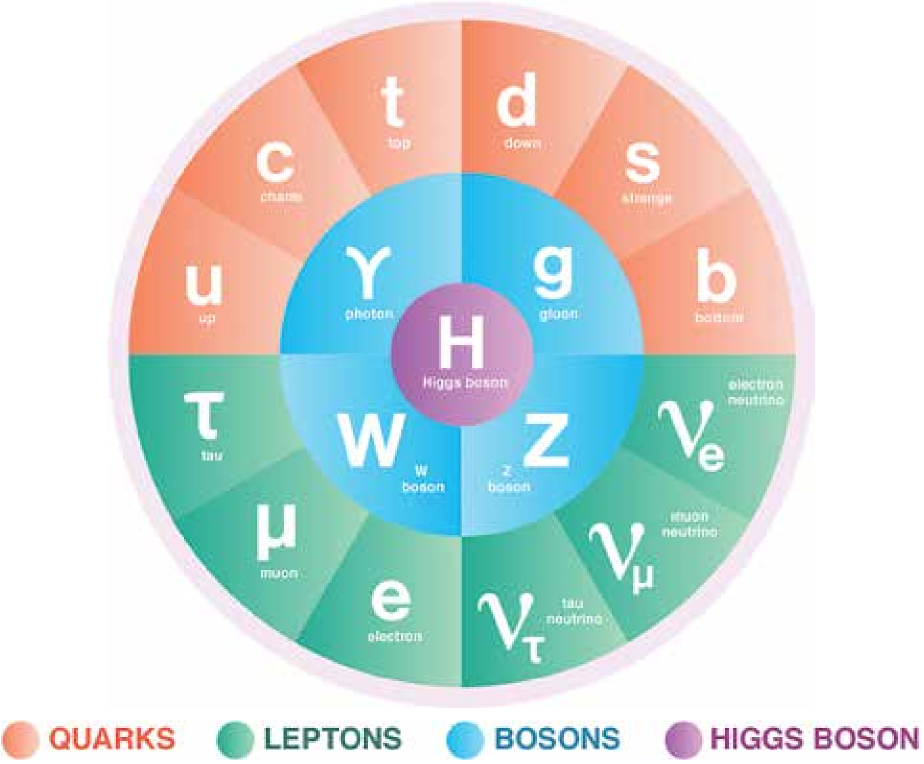

Figure 19 Standard Model of particle physics. Credit: https://www.symmetrymagazine.org/standard-model/

To remove this degeneracy and exclude either cold or a class of non-cold Dark Matter model it is of crucial importance to know in detail the history of re-ionisation and therefore the thermal history of the intergalactic medium at large redshifts. These types of Dark Matter models imply very different experimental strategies for particle physics.

This example demonstrated how with the help of SKA data the direction of development of particle physics can be determined in the next several years. The history of re-ionisation can of course be sensitive not only to dark matter models, but also to other aspects of particle physics.

Another important example is given by the measurement of cosmic magnetic fields (see section 1.6). Detailed maps of magnetic fields in the outskirts of galaxy clusters can not only be important to prove a cosmological origin of the largest-scales magnetic fields in voids, but also to search for the signatures of axions in astronomical data.

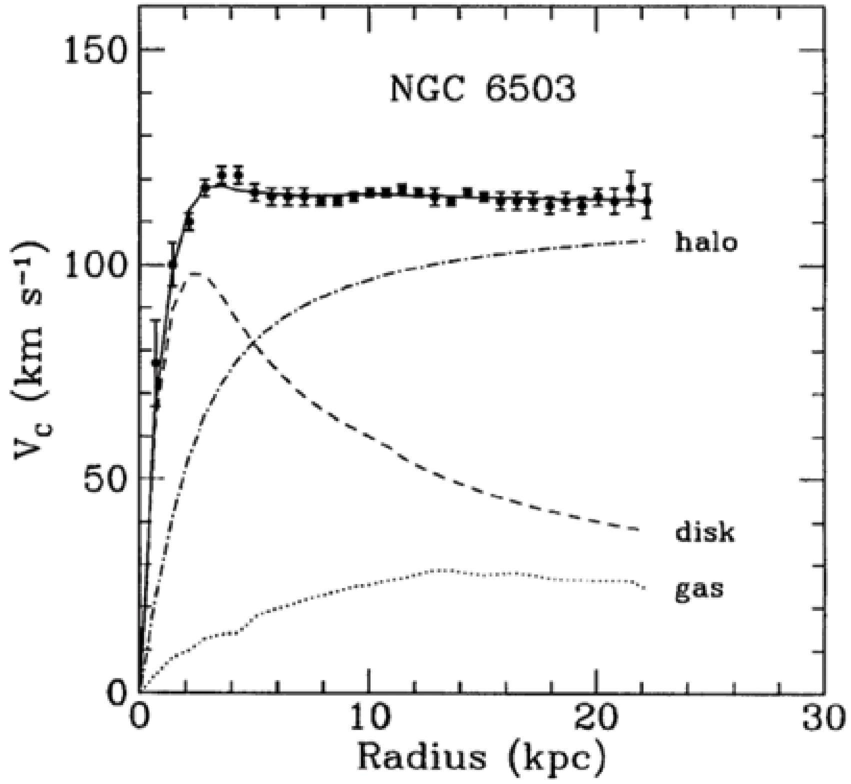

Figure 20 Galactic rotation curve for NGC 6503 showing disk and gas contribution plus the Dark Matter halo contribution needed to match the HI data. Credit: Figure 1 of Freese, "Status of dark matter in the universe", 2017, Original (without labels): Begeman, Monthly Notices of the Royal Astronomical Society, Vol. 249, 523 (1991)

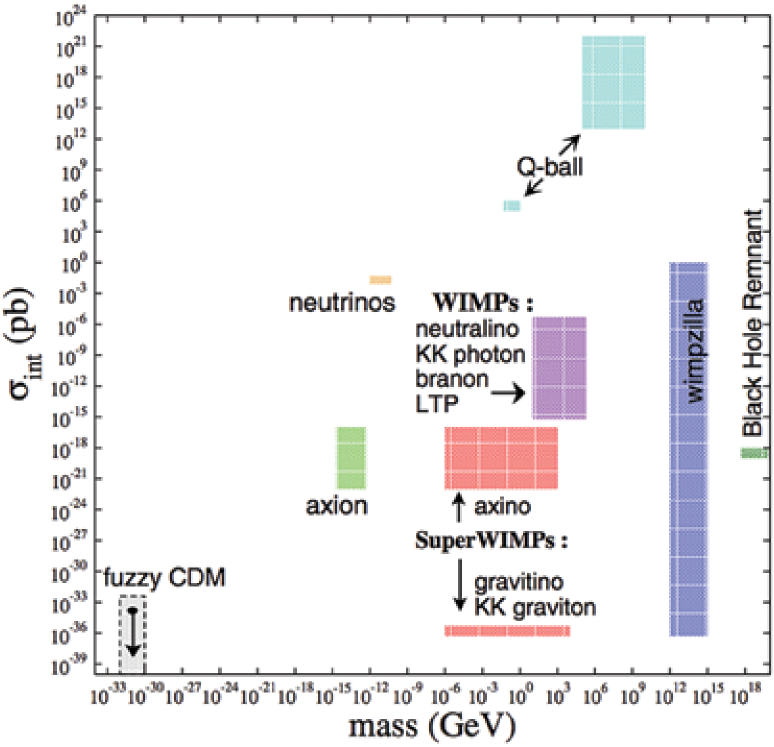

Figure 21 The mass and cross-section sigma_int (in picobarns, where 1 pb = 10^$^{-40}$ m^$^{-2}$) for various Dark Matter particle candidates. Figure taken from Park (2007)

Swiss contribution

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2. The SKA observatory

2.1. Historic perspective

Astrophysics perspective/ multi-wavelength

Unlike in other branches of science, where natural systems can be explored in experiments with adjustable parameters, in astronomy, one can only gain indirect evidence from observing light, e.g. electromagnetic radiation or photons that arrive from outer space in a telescope. Different astrophysical processes produce photons of different energy, but more often one speaks about the photon's frequency (that increases with increasing energy) or its wavelength (which equals the speed of light divided by the frequency, hence it decreases with increasing energy).

The electromagnetic spectrum ranges from very high energies, so-called Gamma rays (with corresponding wavelengths below 0.1 nm), across the optical or visible regime (wavelengths between 400 - 700 nm) and the infrared regime (wavelengths between 700 nm - 1 mm), down to radio wavelengths (wavelengths longer than 1 cm, i.e. frequencies smaller than 30 GHz).

On Earth, large parts of the electromagnetic spectrum are blocked by the atmosphere, as shown in the illustration in Figure 21. This implies that for observations at X-ray, infrared or very long radio wavelengths, the telescopes must operate from space.

One of the two major windows accessible for astronomical observations from the Earth's surface, is the optical window. Historically, most observations have been performed for visible light. However, there is a second, very large window at radio wavelengths, more specifically, the wavelengths between 1 cm and 10 m, or frequencies between 30 GHz and 30 MHz.

Since the 1930s, when the first radio signals from space were detected by Karl Jansky, astronomers have used radio telescopes to explore the Universe by detecting radio waves emitted by a wide range of objects. Our Sun, the nearest star to Earth is seen as a powerful radio emission source, mainly due to its proximity to our planet, but some radio sources, which are millions, even billions of light years away, are truly colossal in terms of their radio flux.

Unlike optical telescopes, which can be hampered by clouds or poor weather conditions on Earth, radio telescopes, working with signals at a longer wavelength, can be used even in cloudy skies. The longer wavelength of radio emissions means that the radio telescopes used to detect them do not have to be as perfectly shaped as their optical counterparts, (but still need to be accurate to around 1 mm in terms of dish surface accuracy) but, to obtain the same level of detail and resolution as their optical cousins, radio telescopes have to be much larger and have a much larger collecting area. The largest radio telescope in the world as a single dish is now the 500 meter FAST telescope, recently completed in China, that has superseded the Arecibo telescope in Puerto Rico.

Radio astronomy progressed through the middle of the last century, with many great discoveries made in radio frequencies such as the discovery of pulsars by Dame Jocelyn Bell Burnell, a postgraduate student working at the

Radio Telescope Bleien

Two historic radio telescopes in Bleien (Aargau) about 50 km south of Zurich areT used for observations of dynamic solar radio flare, radio-monitoring and testing of high frequency components. A third instrument is observing extragalactic radio transients with a horn-antenna and a modern FFT-spectrometer.

The location is a remote area with low radio interference. The location with its instruments got a protection zone of about 1.5 km. The observatory supplies real time data of several environmental sensors here.

The observatory was built in 1979 by the Institute for Astronomy at ETH Zurich. After more than 30 years in 2015 the solar radio burst observations were switched off and instruments were changed for observing cosmological signals at red-shifted hydrogen 21 cm line between 980 MHz and ~1300 MHz.

The Bleien Radio Observatory was the starting point of the international e-CALLISTO network that surveys solar activity and space weather 24 hours per day in radio waves.

SKA will be the next generation radio observatory, reaching unprecedented sensitivity

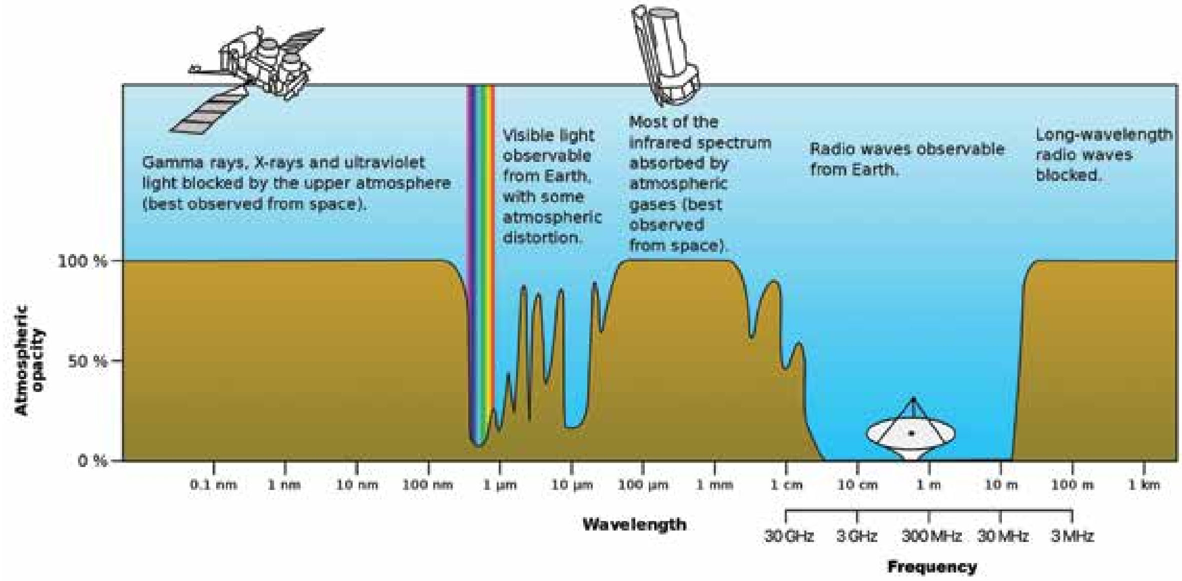


Figure 22 The observation windows in Earth's atmosphere. Credit: wikipedia (original: NASA); frequency scale added for display purposes

University of Cambridge whilst a student under Anthony Hewish, who went on to share the Nobel Prize for Physics with Martin Ryle, another notable radio astronomer in part for this discovery.

SKA development/ international relations

The SKA Project was originally conceived in the early 1990s, and has developed steadily ever since, to the point where it is finalising the pre-construction phase and rapidly approaching the start of construction of SKA1, the first deployment phase of the project.

The current organisational structure of the SKA governance is the Square Kilometre Array Organisation, referred to as "SKA Organisation", a British company established in December 2011, with a mission to carry out SKA design activities preparing for construction of the SKA project.

Following a decision in 2013, the Members of the SKA Board have agreed to working towards the establishment of a dedicated international organisation, known as the SKA Observatory, to implement the SKA project when design has been completed and the project moves to construction and operation phases.

Negotiation of the SKA Convention, supporting Protocols and other key statutory policies, such as Headquarters Agreement, Host Country Agreement, Procurement Policy, Intellectual Property Policy and Access and Operation Policy, etc. began in 2015.

After three and half years of formal negotiations, the SKA Convention was signed on 12 March 2019, a key milestone in the establishment of the SKA Observatory.

The ratification process is currently on-going in the signing countries, and the Convention should enter into force when five countries have ratified it, including the three host countries. The SKA Observatory is expected to be established mid-2020.

Please refer to appendix C for the historical milestones in the evolution of the SKA concept

2.2. Operational phases of SKA

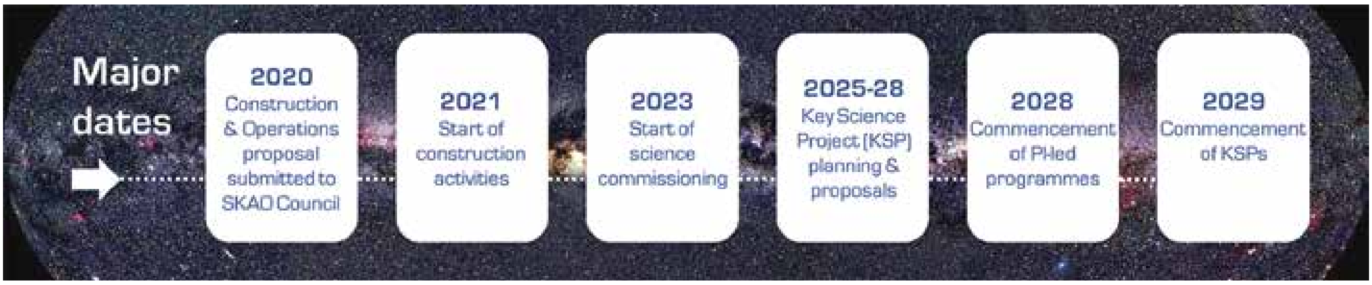


Figure 23 Operational phases of SKA. Credit: SKAO

Observing program

The SKA will be the world's largest observatory in the cm- to m-wavelength range, greatly surpassing the current generation of telescopes in sensitivity, field of view, and survey speed.

The SKA will offer such unique capabilities from the outset, primarily due to the large increase in collecting area over existing facilities, a superior imaging capability, and the opportunity for multiplexing observations. In order to maintain this leading position, a vigorous development programme will be implemented.

This programme will provide the observatory with the designs of upgrades to existing capabilities and new capabilities, commensurate with the evolving ambitions of the SKA user community.

The SKA will operate for 24 hours every day to maximise its scientific productivity and provide access to as much of the southern sky as possible throughout the year. The SKA will be operated as a single, integrated observatory running two telescopes, SKA-Low in Western Australia and SKA-Mid in South Africa, without observers present at the telescopes.

Although both telescopes operate over different frequency ranges using different technologies, their science programmes will be closely coupled.

A number of observing modes will be commissioned and supported by the SKA to enable the scientific goals of the observatory and its community to be realised. These observing modes can be differentiated between imaging and non-imaging modes, which are:

- **Imaging**
- **Pulsar Search**
- **Pulsar Timing**
- **Dynamic Spectrum**
- **Transient Search**
- **Very-Long Baseline Interferometry (VLBI)**
- **Calibration**

Furthermore, there will be special observing modes in place to allow fast reaction to targets of opportunity, triggered events, etc.

Several scientific success metrics will be monitored once the observatory becomes operational:

- the over-subscription of observing time is a measure of community demand for access to the facility. This metric will be determined during each time-allocation cycle;
- the number of publications, subject to defined acceptance criteria including peer review, is a measure of the observatory's productivity.

Figure 24 Summary of SKA1 technical details. Credit: SKAO (January 2019)

This metric will be tabulated at least annually through a combination of web searches and manual reviews of the literature;

- the number of citations to publications is a measure of scientific impact. This metric will be tabulated as required, primarily through web services such as the NASA Astrophysical Data System;
- the number of publications or citations per unit cost is a measure of value for money.

And scientific success is intimately linked with operational success with a highly-efficient observatory enabling more science time on the sky.

The operational success metrics will be monitored once the observatory becomes operational which is based on:

- operational availability;
- operational availability of specific capabilities (specific bands and specific observing modes);
- observing efficiency (integration time per unit available time);
- observing project completion;
- system down time due to faults;
- system down time due to unavailability of computational resources;
- system down time due to planned maintenance; and
- safety record.

SKA1

SKA1 refers to the first phase of the SKA, corresponding to a fraction of the full array. SKA1 comprises two telescopes, which differ in design and are complementary by their very nature. Both are interferometers: arrays of antennas which when linked together can act as one enormous telescope, bigger than would ever be possible in a traditional single-dish design.

In South Africa, the Design Baseline for SKA1-Mid comprises 197 dishes, 64 of which are already in situ and form the MeerKAT precursor telescope, itself a world-class facility. In Western Australia, over 130,000 low-frequency antennas will form SKA1-Low, spread across 512 antenna stations.

The telescopes' design is scalable and upgradable, allowing future improvements to maintain their world-leading capabilities, and also to align with available funding. This includes state-of-the art scientific and computing infrastructures, designed to progressively exploit the capabilities of the observatory as computing technology continuously improves over the coming decades. The SKA observatory will facilitate the use of renewable energy as much as is practicable.

Expansion

The project of SKA will develop through phases. The initial phase of SKA is called SKA1. This will be expanded as SKA2 upon once funding becomes available, with a vision of deploying up to ~2000 dishes across 3500 km of Africa, and a major expansion of SKA1-Low to about one million low-frequency antennas across Western Australia.

SKA2 will build on the work of SKA1 to pursue the science drivers in greater depth, as well as being able to follow up new discoveries that emerge from the SKA1 science programme. SKA2 can be expected to use technologies that are currently state-of-the-art for SKA1 but that will have been further developed through a development programme and will build on the experience gained, both technologically and scientifically, from SKA1.

Figure 25 SKA infrastructure and members. Credit: SKAO

2.3. Infrastructure description

SKA headquarters

The SKA's Global Headquarters (HQ) is located next to the iconic Lovell Telescope at Jodrell Bank Observatory, near Manchester, UK. The site has recently acquired UNESCO World Heritage status.

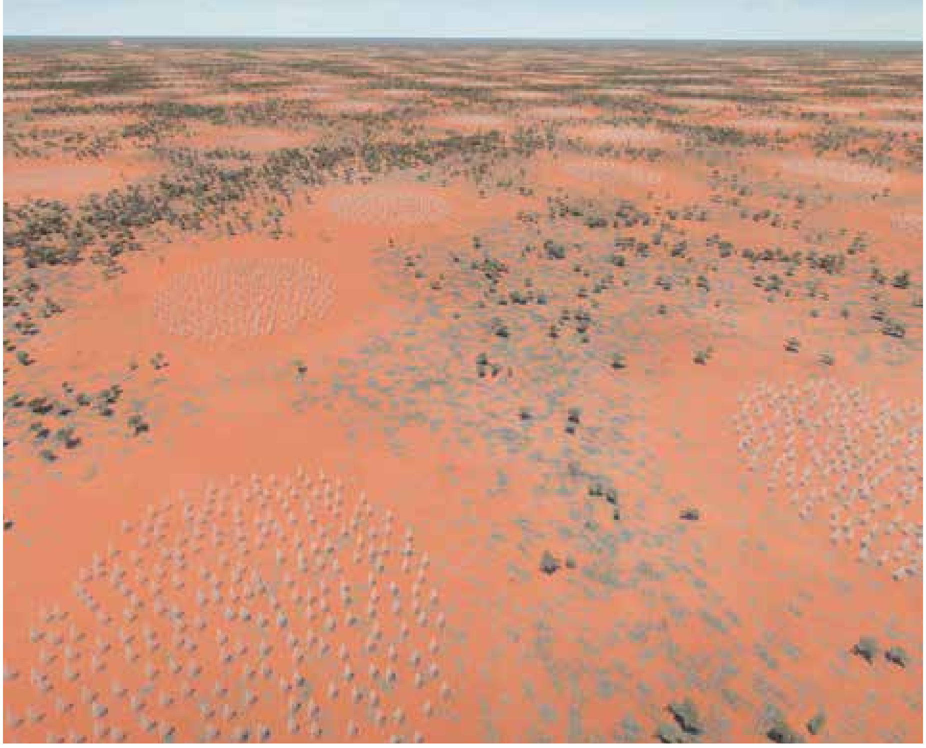
The SKA HQ is home to an international workforce representing over 15 nationalities, and will ultimately accommodate some 150 scientists, engineers, software specialists, policy experts and support staff to lead the delivery and operation of the SKA.

Formally inaugurated in July 2019, the 4,200 square metre facility was funded through the UK Government's commitment to the SKA. It includes a 160-seat auditorium as well as state-of-the-art video conferencing facilities and environmental features including electric vehicle recharging stations and dark sky compliant external lighting. Designed to become a real nexus for radio astronomy in the 21st century, the SKA HQ already welcomes more than a thousand visitors & experts every year.

In 2012, a major decision was taken by the SKA Organisation to co-site the Square Kilometre Array in remote areas of South Africa and Western Australia.

Figure 26 SKA headquarters at Jodrell Bank Observatory, Manchester. Credit: Jean-Paul Kneib

Figure 27 Artist's impression showing a wide field view of how the SKA Low Frequency Aperture Array (LFAA) dipole antennas may look when deployed in the Australian Murchison region. Credit: SKA Organisation



SKA site: Australia

The Australian Radio Quiet Zone of Western Australia (ARQZWA) was established as part of the Radio-communication Act 1992. The ARQZWA consists of circular zones of levels of protection out to 260 km from the core. This comprises the Murchison radio-astronomy Observatory which will eventually host the SKA-Low telescope.

In Western Australia, over 130,000 low-frequency antennas will form the first part SKA-Low, spread across 512 antenna stations, with the range of spectrum covering 50 Mhz – 350 MHz. SKA1-Low will be eight times more sensitive than LOFAR and survey the sky 135x faster.

SKA site: South-Africa

The Karoo Astronomy Advantage Area (KAAA) was established under the protection of the Astronomy Geographic Advantage Act 2007, the Law of South Africa for protection of radio quiet for scientific research. Consisting of a polygonal area of ~500 km by ~300 km at extents, this Radio Quiet Zone provides the area for hosting the site of the SKA-Mid, the middle frequency radio telescope in South Africa.

In South Africa, the Design Baseline for SKA1-Mid comprises 197 dishes, 64 of which are already in situ and form the MeerKAT precursor telescope, itself a world-class facility, covering the range of spectrum from 350 MHz to 14+ GHz. The SKA1-Mid will be 5x more sensitive than the JVLA and survey the sky 60x faster.

Both the large number of stations (512) for SKA1-Low and dishes (197) for SKA1-Mid means that two telescopes will produce exquisitely detailed images of the radio sky.

The SKA will build on science and technologies of the established premier radio facilities, often called pathfinders or precursors for the instruments as testbed for the SKA project to verify technologies capabilities and science strength, such as CHIME (Canada), NenuFAR (France), LOFAR (Netherlands), GMRT (India) and VERA (Japan), in addition to the precursor telescopes already located in South Africa (MeerKAT and HERA) and in Australia (ASKAP and MWA), (see Appendix A for further details).

Figure 28 Aerial shot of the MeerKAT radio telescope before its launch in July 2018. These sunrise shots show the expanse of the telescope, which covers a baseline distance of 8 km.Credit : South African Radio Astronomy Observatory (SARAO)

2.4. Schedule/Partners

On March 12, 2019, ministers, ambassadors and other high-level representatives from over 15 countries gathered in Rome, Italy for the signature of the treaty which establishes the Square Kilometre Array Observatory (SKAO), the intergovernmental organisation (IGO) tasked with delivering and operating the SKA.

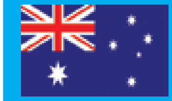
Seven countries signed the treaty on that day, including Australia, China, Italy, The Netherlands, Portugal, South Africa, and the United Kingdom. India and Sweden, who also took part in the multilateral negotiations to set up the SKA Observatory IGO, are following further internal processes before signing the treaty. Together, these countries will form the founding members of the new organisation.

The signature concluded three and a half years of negotiations by government representatives and international lawyers, and kicked off the legislative process in the signing countries, which will see SKAO enter into force once five countries including all three hosts have ratified the treaty through their respective legislatures. It is expected that the SKA Observatory will come into existence mid 2020 with the first Council meeting convened accordingly.

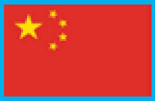
Canada, France, Germany, Spain, Switzerland, Japan and Korea have expressed their strong interests in the SKA project, making their best efforts to prepare the conditions for a future decision of participation of their respective country in the SKA Observatory one way or another as new member, associate member or cooperation partner. These countries are currently the observers to the CPTF, the Council Preparatory Taskforce, attended by all members for preparing the necessary statutory documents that will safeguard the Council's operation when in place.

SKA Observatory will be established as an Intergovernmental Organisation in 2020, taking over from the SKA Organisation. It will undertake the construction and operation of the telescope. As of March 2019, confirmed SKA Observatory members are:

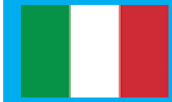
Australia



China

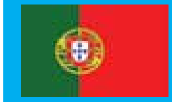


Italy



The Netherlands

Portugal



South Africa

United Kingdom

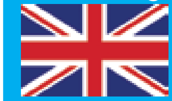
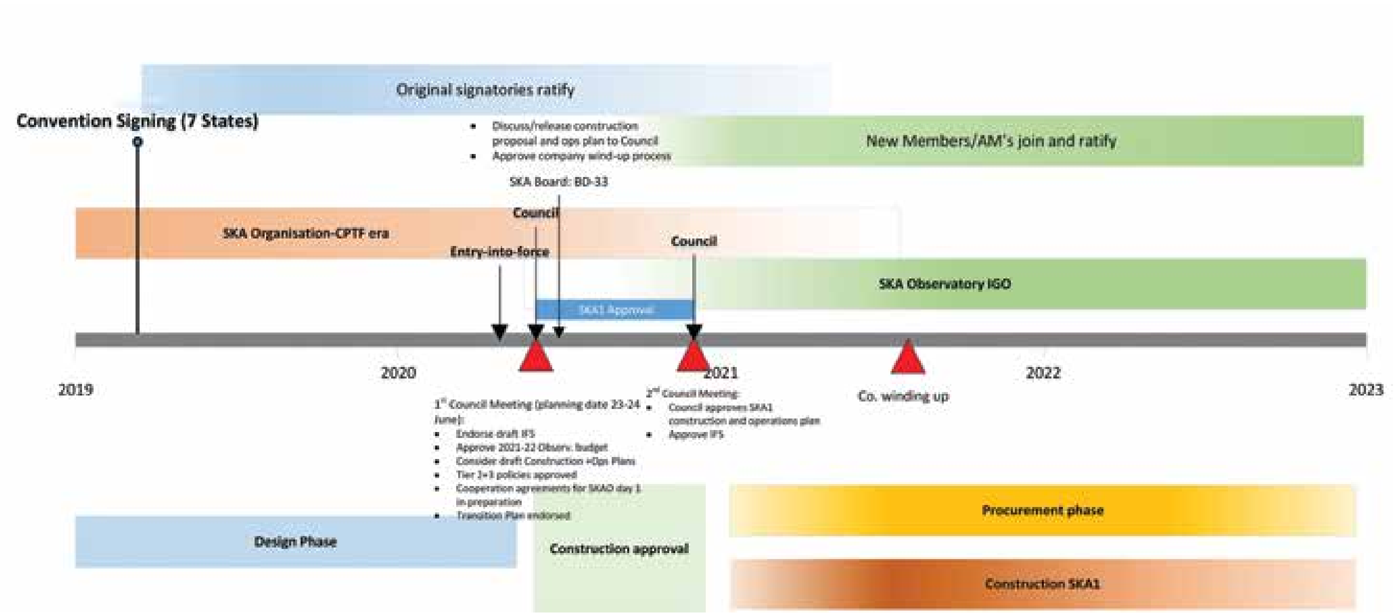


Figure 29 Transition Timeline and Milestones (November 2019). Credit: SKAO



3. The data science challenge of the SKA

3.1. Data science

The challenge facing astronomers in the upcoming decade is not only scientific, but also technological. A flurry of complex data will be delivered by new telescopes such as SKA, LSST or CTA, and this will be difficult to manage with traditional approaches. Data will have to be stored in dedicated facilities, providing the necessary capacity at the highest performance. Corresponding data processing will have to be performed local to the data, exploiting available high performance computing resources. Data reduction and imaging software tools will have to be adapted, if not completely re-designed, in order to efficiently run at scale. Fully automated pipelines will be a compelling requirement for effective software stacks as the richness and complexity of incoming data will inhibit human interaction and supervision.

Current astronomical data have reached the Peta-byte (PB) level (1 PB = 10^{15} bytes).

Recording the data from thousands of dishes and up to a million low-frequency antennas, the SKA telescope will now make the astronomical community enter the Exa-byte (EB) level (1 EB = 10^{18} bytes)! Predictions show that the amount of SKA science archive will grow at a rate of about 300 PB/year, 10 times above the current data stored by CERN. Figure 30 shows that those needs will also excel any storage capacity currently accessible, including giant companies like Google or Facebook.

Figure 31 Future SKA Science Archive needs Credit: SKAO

These tremendous amounts of data will considerably change the manner in which humans explore scientific products. Understanding the nature will foster the development of new analysis approaches relying on massively parallelized interactive tools, machine learning algorithms, and artificial intelligence. It will also open new doors in the data management field, by challenging the long term preservation of large data sets.

The development of Big Data analysis algorithms within the SKA framework will directly impact and benefit other scientific domains, where Big Data is also challenging, like particle and plasma physics, but also geophysics, genomic, and meteorology, to list a few.

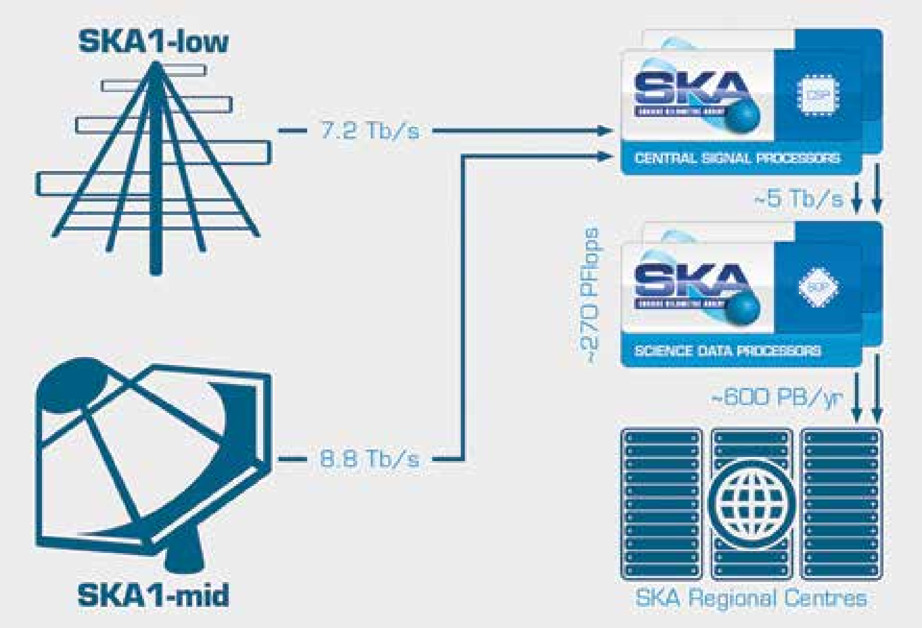


Figure 30 Data transfer rates between the SKA telescopes, processing facilities and regional centres. Credit: SKA Technical Paper (January 2019)

Predictions show that the amount of SKA science archive will grow at a rate of about 600 PB/year. This is larger than the current data stored by giants of the web like Google or Facebook.

Beyond science, SKA will also benefit industry. It will bring opportunities for companies to gain know-how in the management of data of unprecedented amounts. They will be able to rethink current practices and adapt them to these immense dimensions.

This new field opens a multitude of occasions both for new start-ups as well as for established companies to transfer the know-how to industrial applications.

For instance the Bühler group, a major Swiss company and a world leader in food supply and distribution already drastically reduced its production loss, increasing food safety, thanks to a new Big Data management politics.

For such companies, the technological innovation generated by SKA can generate not only a net increase in competitiveness, but also a major step towards sustainable development.

Switzerland already has a long experience of handling large amounts of data, especially coming from scientific instruments. For instance, tens of petabytes coming from the Large Hadron Collider at CERN or the Paul Scherrer Institute are digested by CSCS every year.

3.1.1. Image formation challenge

Aperture synthesis by interferometry in radio astronomy is a powerful technique allowing observation of the sky with antenna arrays with otherwise inaccessible angular resolutions and sensitivities. Image formation is however a complicated problem. Radio Interferometry (RI) measurements provide incomplete linear information about the underlying sky, defining an ill-posed inverse problem for image formation.

Considering non-polarised single-wavelength imaging on small fields of view, the measured visibilities identify an incomplete coverage of the spatial frequency (i.e. Fourier) plane of the 2D image of interest. In this simplified scenario, the data approximately boil down to the convolution of the image with a point spread function with extended sidelobes (called dirty beam) and the inverse problem is essentially a deconvolution problem (see picture in Figure 32).

The celebrated radio-interferometry imaging algorithm CLEAN owes its success to its simplicity and computational speed. Assuming a 2D point source field (pixel domain sparsity signal model) it iteratively (i) removes from the residual map the dirty beam centered at peak value and builds the image by adding a component at the same position (minor cycle), (ii) updates the residual (major cycle) [*Cornwell 2009*].

Wide field multi-scale multi-frequency (3D) evolutions exist *[Rau & Cornwell 2011; Offringa 2014]*, but still crucially lack the versatility to include complex signal models, not to mention that CLEAN often requires user intervention.

Radio-interferometry calibration methods were developed to correct for antenna-based gain errors. First generation methods rely on calibrator sources and account for large gains. Self-calibration algorithms correct for remaining variations by solving a non-linear least squares problem [*Salvini & Wijnholds 2014; Smirnov & Tasse 2015*].

At the target dynamic ranges, direction-dependent effects (DDEs) of instrumental and ionospheric origins complicate the measurement equation beyond the simple Fourier model. DDFacet, one of the most advanced DDE calibration methods still assumes DDEs are constant on image facets and is in practice better suited for point source fields [*Tasse et al. 2018*]. Calibration methods thus also lack versatility, and the convergence properties of the imaging-calibration loop are not established.

A major limitation in radio-interferometry imaging is the absence of techniques enabling proper uncertainty quantification. Are the structures present in the estimated image physical signals or artefacts? Strong conclusions relative to the astrophysical models at stake are impossible until appropriate uncertainty quantification is available. Markov Chain Monte Carlo (MCMC) sampling techniques were in fact recently proposed for radio-interferometry image estimation and uncertainty quantification [*Lochner et al. 2015; Cai et al. 2018*].

Their major drawback is that even the new proximal MCMC algorithms are significantly too computationally expensive, even at moderate image size, making them impractical for radio-interferometry imaging. A variational Bayesian approach was also proposed and formulated in the language of information field theory. It however does not handle DDEs and was only demonstrated on low image sizes [*Junklewitz 2016; Arras et al. 2016*].

The transformational science envisaged from radio-astronomical observations for the next decades ranges from cosmology and the study of dark matter and Dark Energy, to the search for life in the Universe through the study of molecules in other planetary systems or potential radio signals from intelligent civilisations, and to the understanding of the cosmic dawn and the formation of the first stars.

To achieve these scientific goals, the gigantic Square Kilometer Array" telescope is being developed, which will be to radio astronomy what CERN is to particle physics. Its development and use will generate major scientific and economic impact in the world.

The instrument is required to map faint and distant structures, superseding state-of-the-art telescopes by about two orders of magnitude in resolution and sensitivity over wide fields of view. The target high resolution high dynamic range wide field image sizes will exceed a Gigabyte (GB) per frequency channel. When tens of thousands of channels are used wide band image cubes will reach sizes between 1 Tera-byte and 1 Peta-byte.

The associated Fourier data can be multiple orders of magnitude larger than the image cube itself due to the target sensitivity (i.e. low noise) requirements.

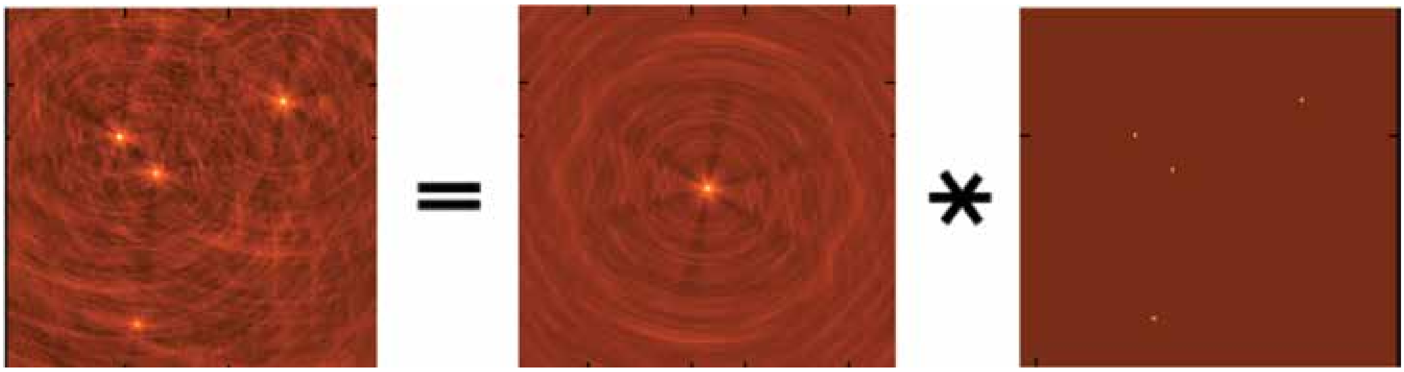


Figure 32 The RI data (left) expressed as the convolution of the dirty beam (middle) with the sought image (right). Credit: casa.nrao.edu

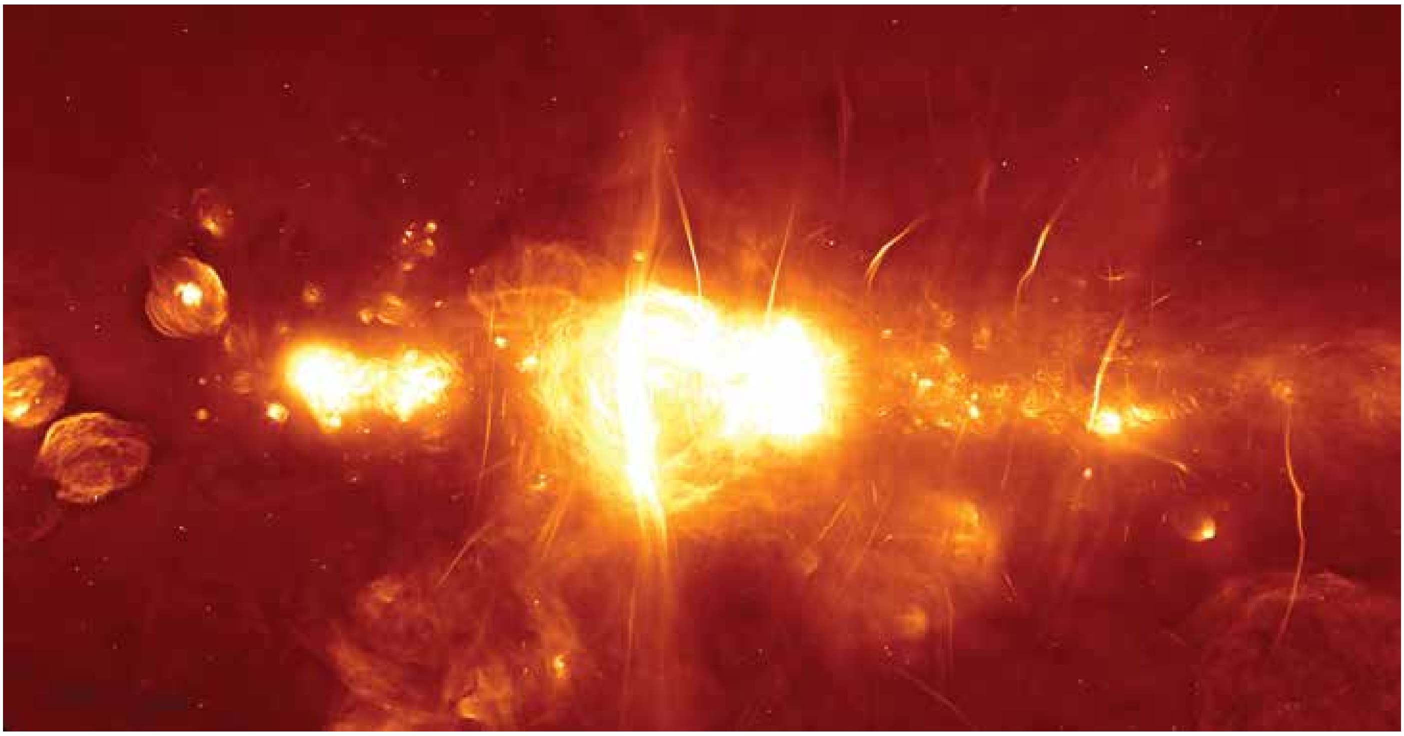


Figure 33 This image, based on observations made with South Africa's MeerKAT radio telescope, shows the clearest view yet of the central regions of our galaxy. At the distance of the galvactic centre (located within the white area near image centre), this 2 degree by 1 degree panorama corresponds to an area of approximately 1,000 light-years by 500 light-years.
The colour scheme chosen here to display the signals represents the brightness of the radio waves recorded by the telescope (ranging from red for faint emission to orange to yellow to white for the brightest areas). This image shows a wealth of never before seen features, as well as a clearer view of previously known supernova remnants, star-forming regions, and radio filaments. MeerKAT's 64 dishes or antennas provide 2,000 unique antenna pairs, far more than any comparable telescope. This design feature contributes critically to making high-fidelity images of the radio sky, including this best view in existence of the centre of the Milky Way. It is also advantageous to observe the centre of the galaxy from South Africa, where it passes overhead and is visible for almost 12 hours each day, unlike from northern hemisphere locations.
Credit: South Africa Radio Astronomy Observatory (SARAO)

The data volumes that SKA will generate are thus unprecedented, reaching Exabyte (EB) scale per image! This will create extreme computational cost and memory requirements for the imaging algorithms.

The expected increase in sensitivity and resolution also implies that future observations are to reveal complex structure distribution across the field of view, in contrast with simple traditional point source fields. Early observations of the SKA precursor MeerKAT in South Africa since 2018 confirm this (see e.g. MeerKAT Milky Way view above, and at ska.ac.za). In this context, imaging algorithms will not only have to cope with large data, but also to leverage complex signal models to produce physical high resolution high dynamic range images.

In conclusion, endowing SKA and others with their expected acute vision requires a new generation of imaging algorithms providing precision (i.e. enabling high resolution and dynamic range), robustness (i.e. including calibration and uncertainty quantification functionalities), and scalability (i.e. able to handle unprecedented image sizes and data volumes).

A decade of research (pioneered in Switzerland by Wiaux and collaborators) suggests that the theory of optimisation can address this challenge *[Wiaux et al. 2009; Carrillo et al. 2012; Carrillo et al. 2013; Carrillo et al. 2014; Pratley et al. 2018; Abdulaziz et al. 2016, 2017; Birdi et al. 2018; McEwen & Wiaux 2011; Dabbech et al. 2017; Wiaux et al. 2009; Kartik et al. 2017; Pesquet & Repetti 2015; Chouzenoux et al 2016; Onose et al. 2016; Onose et al. 2017; Repetti et al. 2017; Birdi et al. 2019; Pereyra, Statistics and Computing 2016; Repetti et al. 2018; Li et al. 2011; Wijnholds et al. 2014; Ferrari et al. 2014; Dabbech et al. 2015; Girard et al. 2015; Garsden et al. 2015; Cai et al. 2018; Pratley et al. 2019; Pratley et al. 2019].*

Swiss contribution

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Prof. Slava Voloshynovskyy (UniGE)

Prof. Yves Wiaux (EPFL/Herriot-Watt University, Edinburgh)

3.1.2. Source identification and characterization with artificial intelligence

Measuring the properties of astronomical sources in images produced by radio interferometers has been successfully achieved for many decades through a variety of techniques. Various automated tools for implementing this approach have been developed. In almost all cases the automatically determined source list requires some level of subsequent manual adjustment to eliminate spurious detections or to include objects deemed to be real but that were overlooked by the automated finder.

This manual adjustment step, again, has remained unchanged since the earliest days of radio source measurement. As radio surveys become deeper and wider, and the number of sources in the automated catalogues increases, such manual intervention is progressively less feasible and finally, with facilities like SKA, impossible.

A big effort, hence, has to be dedicated to design new source detection pipelines able to produce catalogues with a high degree of completeness and reliability, together with well-defined and characterised measurement accuracy. Furthermore, such tools are required to: make effective use of hardware in order to run in near-real time on huge data volumes, integrate with a range of software ecosystems, and have the flexibility to support a range of science goals.

Artificial Intelligence (AI) based solutions can represent a viable, innovative approach to tackle the challenges posed by huge and complex data. Besides providing effective solutions for extracting knowledge from the data, AI based approaches can efficiently use large supercomputing systems, exploiting, in particular, parallelism and accelerators, managing problems of "any" size at high performance. Furthermore, they offer fully automated methods, requiring no human intervention or control, a paramount requirement to cope with such enormous data sets.

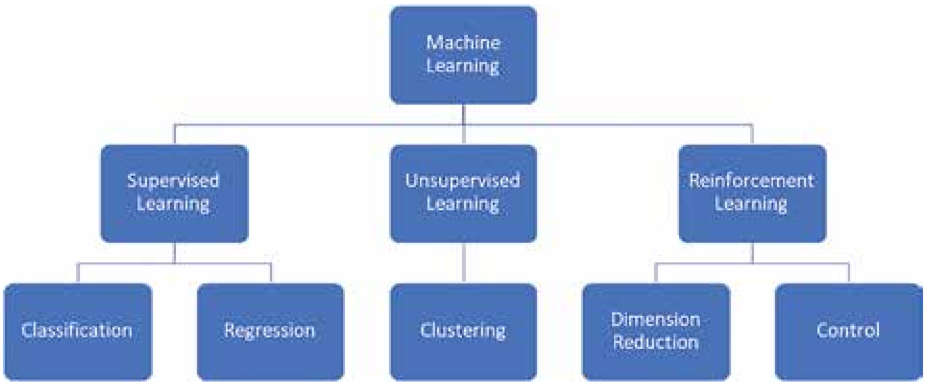

Figure 34 Classification of Machine Learning techniques

> Swiss competence is well established in many areas of Machine Learning. Image classification is particularly significant for radio astronomy images. It represents one of the most successful areas of application of supervised Machine Learning in the last decade, thanks in particular to two concurrent factors: the availability of enough computing power to cope with complex, multi-layered neural networks, and the availability of enough data to perform the training.

More specifically, Machine Learning, a branch of AI already successfully used in astronomy and cosmology, can be adopted in a broad spectrum of applications, providing different algorithmic solutions suitable for the specific problem under investigation. Figure 34 summarizes the different classes of Machine Learning approaches and their main applications.

The SKA poses additional challenges to standard image processing tools, represented by the presence of high noise and artifacts in the images, their large size (order of 10000x10000 pixels) and their enormous volume, which requires supercomputing resources to cope with.

Among the various Machine Learning approaches, a number of specific solutions for automated classification can be explored. Deep Learning provides outstanding performance for tasks relating to computer vision, text analysis, speech recognition. It can be used to detect and classify astronomical sources with no human intervention in the images coming from the SKA, strongly facilitating the work of the scientist preselecting even the faintest signals with high precision and accuracy.

Unsupervised Machine Learning has a huge potential in tasks like image segmentation, denoising, clustering, dimension reduction. For instance Deep Convolutional Denoising Autoencoders currently represent among the most advanced AI based solutions for image cleaning, removing noise and artifacts minimizing the loss of information, enabling further processing by sophisticated data analysis tools that, cannot effectively operate with low signal to noise data. Autoencoder algorithms can act also as effective dimension reduction algorithms, capable of projecting a complex dataset in a low dimensionality space whose parameters condense the essential information characterizing the data under investigation.

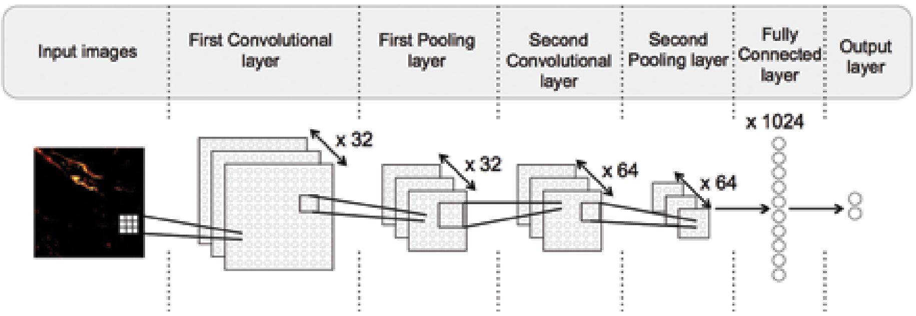

Figure 35 A typical Deep Learning architecture (Convolutional Neural Network) for automated image classification. Credit: Gheller, Vazza & Bonafede, 2018

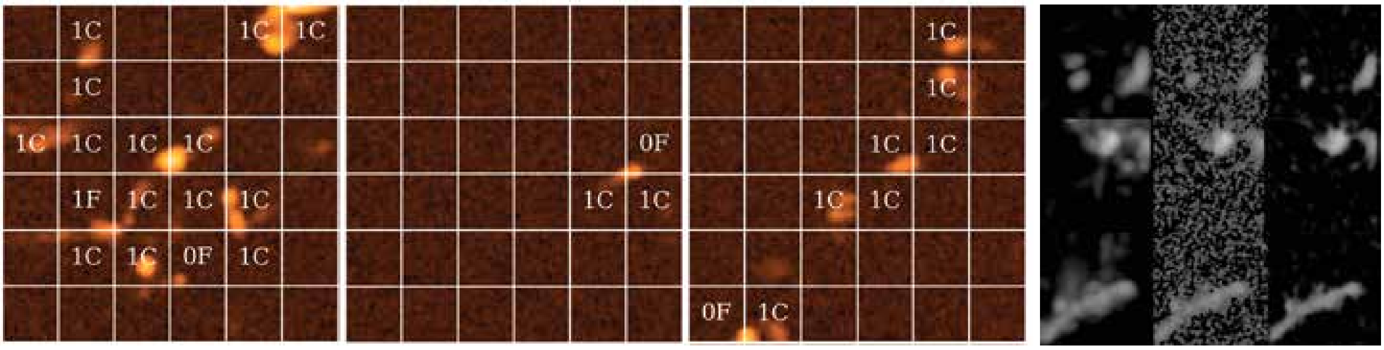

Figure 36 An example of automated image classification through Deep Learning (left panel) and of image denoising through Deep Denoising Autoencoders (right panel). Credit: Gheller, Vazza & Bonafede, 2018, Gheller & Vazza (2019)

A further promising approach is represented by Reinforcement Learning solutions, which build on the top of traditional Machine Learning algorithms further enhancing the level of "intelligence" of the AI tool. In perspective, they can be used for real-time control software of instruments and data analysis pipelines.

The role of novel AI methods is also crucial not only for the identification and characterization tasks but also for high resolution imaging, compression and optimal experiment planning under time/resource limited setups.

The novel AI methods can also largely contribute to the solution of inverse problems in imaging considered in section 3.1.1. The training data can be efficiently used for the development of new regularization techniques based on generative models such as GANs (Generative Adversarial Networks) and VAEs (Variational AutoEncoders) for those situations when the imaging operator is known. Alternatively, when the imaging operator is only partially known or even unknown due to various factors, one can design end-to-end trained systems providing the best "blind" restoration.

Additionally, the AI systems might be of interest to provide the direct identification from the observed data, thus avoiding the restoration stage, that is essentially of interest for providing automatic identification in view of Big Data constraints.

Finally, a single image super-resolution AI methods can provide valuable insights about the phenomena of interest from the precursor measurements or from the limited time or limited spatial spectrum sampling observations.

A no less important domain for the application of AI methods is the development of new methods for efficient data compression yet preserving all necessary information for successive restoration, identification or other image analysis tasks considered above. The novel lossy compression is of great importance for the whole SKA. If implemented properly, the compressed representation can be efficiently used for fast indexing problems and data analysis in the compressed domain.

Finally, the optimal experiment planning such as a selection of array configurations and observations under the limited number of antenna array elements and time for the investigation of targeted physical phenomena represents a great interest allowing to solve many problems based on limited data thus leading to storage, computation and energy saving in general.

The first attempts to design the learnable compressive sensing algorithms scalable to various types of data and sizes indicate very promising results (see Figure 35).

> Many Swiss partners have an extended know how in this domain. It is worth mentioning that the AI methods can benefit a lot from the training data generated by existing simulators where several Swiss partners have a significant record of achievements.

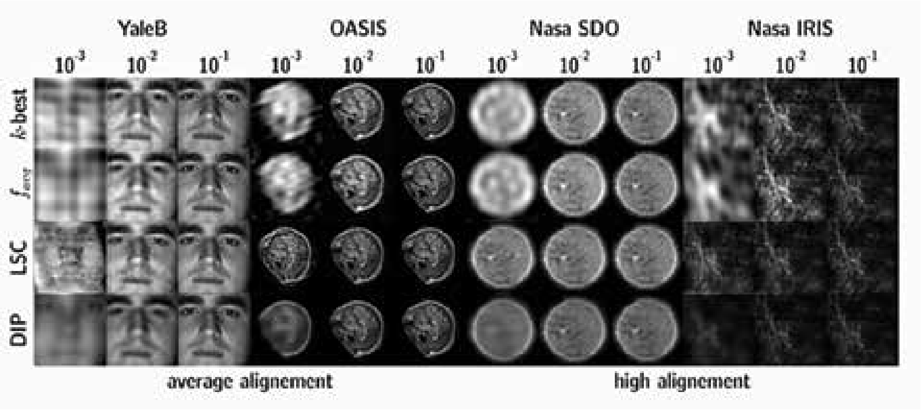

Figure 37 An example of learnable compressing sampling allowing to sample 2 order of magnitude less data in the Fourier domain and to restore data based on trained low complexity decoders. The method is quite generic and can be scaled to various data. Credit: M. Ferrari, O. Taran, T. Holotyak, K. Egiazarian, and S. Voloshynovskiy, "Injecting Image Priors into Learnable Compressive Subsampling," in Proc. 26th European Signal Processing Conference (EUSIPCO), Rome, Italy, 2018

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Prof. Alexandre Refregier (ETHZ)

Prof. Slava Voloshynovskyy (UNIGE)

3.1.3. HPC computing

The pinnacle of modern HPC performance is being achieved through many-core and hybrid computing, and looking at the trends over the past decade it is likely some form of hybrid computing will continue to be prevalent in emerging HPC systems.

In the last TOP500 ranking, detailing every six months the 500 most powerful supercomputers in the world, issued in November 2019, six of the first ten systems are based on hybrid, accelerated, architectures. In the GREEN500 ranking, evaluating supercomputers worldwide by energy efficiency (addressing sustainable supercomputing), eight of the first ten systems are heterogeneous.

The ability to fully exploit new hybrid and many-core architectures is of paramount importance towards achieving optimal performance on modern HPC systems.

On the other hand, with the increasing size and complexity of data produced by observations and in particular by the SKA, it is of primary importance for scientists to be able to exploit all available hardware in emerging HPC environments to achieve maximum computational throughput and efficiency.

For instance, the size of the Australian SKA Pathfinder, ASKAP, spectral-line data cubes (typical size 3600 x 3600 pixels x 16,384 channels, or nearly 800GB) will not fit in memory for a single processor.

The ASKAP continuum data, being single channel images (at least, the images that result from the multi-frequency synthesis imaging), will fit in memory, but the large field of view results in more than 70,000 sources per ASKAP field, so that parallel processing is required to meet the performance goals of the pipeline. In general, splitting up the data set allows it to be processed in parallel, utilizing multiple CPUs or GPUs, dramatically decreasing the processing time and potentially allowing a number of different approaches, or more computationally-intensive analyses to be used.

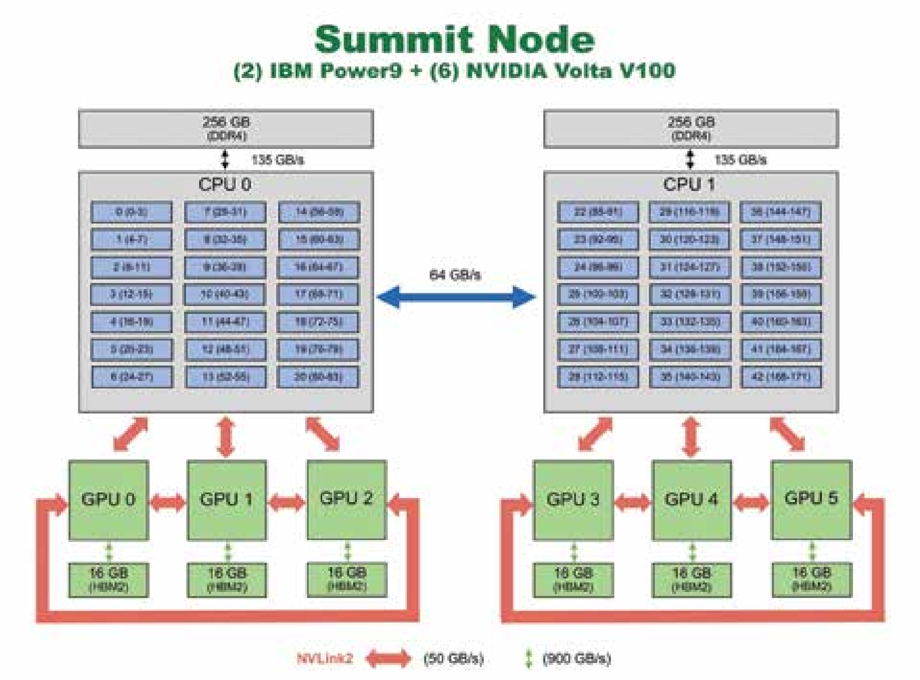

Figure 38 The hybrid computing node of the Summit supercomputer at the Oak Ridge National Laboratory in the USA, ranked N.1 in the TOP500 list on November 2018. Credit: Oak Ridge National Laboratory

HPC is also essential for numerical experiments, with sophisticated codes running complex physical models which help reproducing and interpreting data and bridge the gap between theory and observations. Numerical simulations require the most advanced and capable supercomputers to guarantee the accuracy and precision necessary to cope with high-quality data like those produced by the SKA.

Finally, real-time supercomputing is becoming an essential component of acquisition systems, with real-time process control, on-the-fly data compression and reduction, data exploration and verification through multi-dimensional visualization tools.

Exploiting these emerging hybrid architectures is non-trivial however, due to the challenges presented by mixed hardware computing and the increasing levels of architectural parallelism. New algorithms and numerical and computational solutions are required.

Switzerland is at the forefront of research and development in the field, involving both academic sites and various institutions and centers, like the Swiss National Supercomputing Center (CSCS).

The Swiss Data Science Center (SDSC) is currently operating one of the most powerful and technologically advanced supercomputers in the world.

Its mission is to accelerate the use of state-of-the-art data science and machine learning techniques within scientific disciplines, and SWITCH, providing advanced computing services to academic research and education.

Swiss contribution

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Dr. Gilles Fourestey (EPFL/SCITAS)

Dr. Claudio Gheller (EPFL)

Prof. Thomas Schulthess (ETHZ/CSCS)

3.1.4. Visualisation

Visual exploration and discovery represent invaluable tools to understand scientific data. They provide scientists with prompt and intuitive insights enabling them to identify interesting characteristics and thus define regions of interest within which to apply time-consuming methods. Additionally, they can be a very effective way in discovering and understanding correlations in data patterns, or in identifying unexpected behaviours, thus saving valuable resources, e.g. by terminating promptly ongoing numerical simulations producing unreliable results. Visualization tools can also provide effective means for communicating scientific results not only to researchers but also to members of the general public.

Traditional visualisation tools, however, cannot meet the requirements of data of increasing complexity and size as that produced by the SKA. Innovative techniques and solutions have to be explored and implemented, representing a challenge both from an algorithmic and from a technological point of view:

1. Effective visual data representation techniques must be studied and developed, capable of extracting and highlighting relevant information. For instance, standard volume rendering or isosurfaces based approaches are not suitable to 3D radio data cubes. On the other hand, traditional "2D slicers" tend to lose information on the third dimension.
2. The volume of big scientific data can make data processing slow, or even unfeasible. The use of parallel and distributed computing resources can enable visualisation of data larger than the typical memory of a user machine, however requires research into topics such as parallel visualisation pipelines, distributed visualisation algorithms, data management and distribution, image compositing techniques, hardware optimisation (e.g. optimised rendering algorithms for GPUs)
3. Due to the sheer volume, data transfer becomes impossible and data has to be processed where it is stored, so at the data center. Remote, in-situ and in-transit visualisation approaches are absolutely necessary. In order to be useful to the scientist, such approaches must enable interactive use within the context of the modern web-enabled research environment. This requires understanding the general remote approaches for HPC applications, and integrating such approaches with web technologies

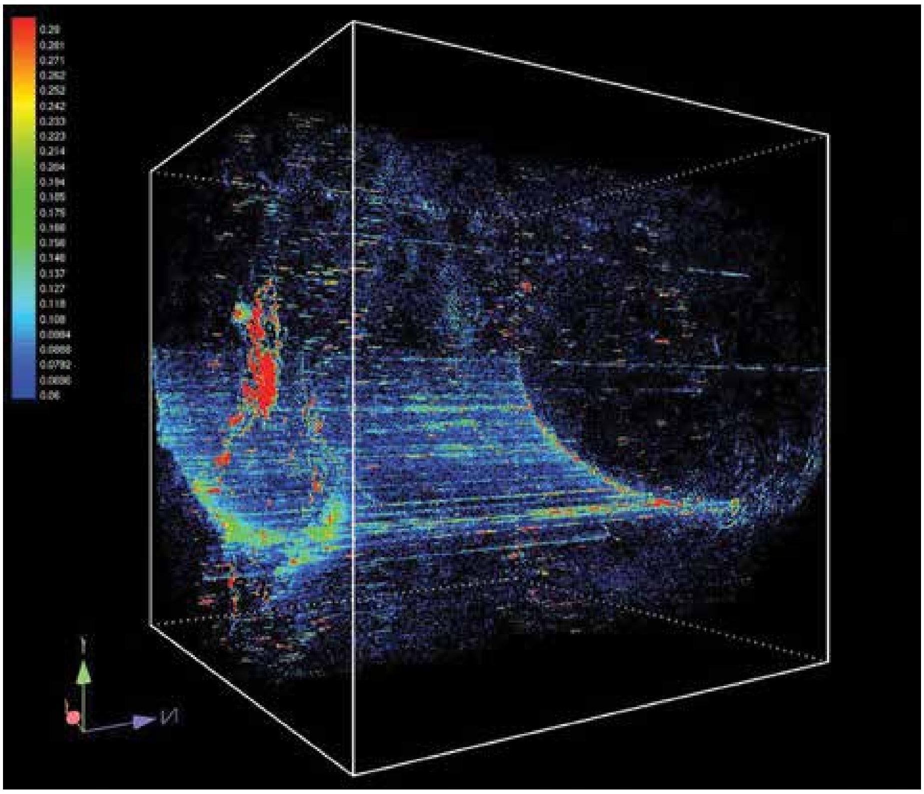


Figure 39 Giant HIPASS cube of the whole southern sky made by Russell Jurek (ATNF) from the existing set of 387 original southern HIPASS cubes. 3D Visualisation by Amr Hassvan (Swinburne University of Technology)

The Imaging@EPFL initiative was launched in January 2019 by EPFL President Martin Vetterli with the goal of promoting interdisciplinary expertise and cutting-edge research in imaging at EPFL.

Swiss contribution

Dr. Jean Favre (ETHZ/CSCS)

Dr. Claudio Gheller (EPFL)

Dr. Yves Revaz (EPFL)

3.2. Swiss competence centers

3.2.1. SDSC

The Swiss Data Science Center (SDSC) is a young infrastructure created in 2017, with the aim of fostering the use of data science and machine learning techniques within academic disciplines of the ETH Domain, the Swiss academic community at large, but also the industrial sector.

Currently, SDSC regroups a team of about 30 professionals, a majority of data and computer scientists, spread over both the ETH and EPFL campus. The team is multi-disciplinary, covering a variety of domains such as personalized health and medicine, earth and environmental science, social science, digital humanities as well as economics. Its multi-disciplinary approach fosters the collaboration between both academic and industrial projects.

In addition to its contribution to the development of analysis algorithms and data reduction tools, SDSC aims to foster the accessibility of data, sharing it, but also ensuring its long-term storage, as well as guaranteeing the reproducibility of published results.

For this purpose, SDSC developed RENKU, an open platform that addresses these problems. RENKU supports versioning of data and code; RENKU tracks which results were produced by whom and when. RENKU makes it possible to have greater trust in results and acknowledge the contributions of all those involved, regardless of whether their contribution was to implement the solution, provide the data, or ask the right questions.

With its multidisciplinary skills in data science, SDSC will be a strong support for the SKA project.

3.2.2. CDCI

In Switzerland, coordinated activities on the multi-messenger studies of transient sources are developed at the University of Geneva, in the framework of the **Common Data Centre Infrastructure (CDCI)** for astronomy, astroparticle and cosmology, in collaboration with the team of INTEGRAL Science Data Centre (ISDC) which has large experience in distributing the GRB alerts in real time to the astronomical community over the 16 years of operations of the INTEGRAL telescope.

It is a new growing infrastructure from the Department of Astronomy of the University of Geneva. It aims at providing the community with a service to support data management activities for space-based and ground-based observational facilities dedicated to astrophysics at large, i.e. including astroparticle and cosmology.

CDCI supports an online data analysis platform which combines data and analysis results on detections and follow up observations of different types of transient sources (including GRBs, gravitational wave events, tidal disruption events, FRBs, diverse optical transients discovered in robotic sky surveys) within a coordinated and coherent “multi-messenger” analysis framework.

The CDCI is building on 20 years of experience in astronomical data management which includes the INTEGRAL Science Data Centre in Geneva that is responsible for the processing, archiving and distribution of data of the INTEGRAL space observatory, a Data Processing Unit of the GAIA telescope, responsibilities in the ground segments of next generation space missions EUCLID, Athena, LISA.

CDCI also develops an “added value” multi-instrument data analysis platform, **Online Data Analysis (ODA)** which provides the possibility of on-the-flight data processing of telescope data “as a service” using cloud computing approach.

This approach is set to become more and more important in the future especially in the upcoming era of astronomical “big data” which could not be moved toward the users and instead the data analysis would have to be deployed remotely on computing facilities colocated with data archives. Such an approach will most probably be implemented for a range of SKA-generated data.

The CDCI will provide support to any Swiss scientist interested in leading data center activities, in particular by contributing directly to the early phase of a project’. A major goal of the CDCI is to ensure the long-term preservation of the data and of the specific data analysis expertise after the mission is terminated, in particular through the deployment of web services.

3.2.3. Institute for Data Science

The FHNW Institute for Data Science (I4DS) supports research and development of data-driven algorithms and processes. It is dedicated to the transfer of technology from science to industry. It therefore runs projects with a high level of application potential.

As a result, it covers a wide range of activities, including on the science side astroinformatics, and on the industry side manufacturing, financial, and internet applications.

In the context of the SKA, the institute sees its role as a hinge between the academic research as described in the sections above and the operative implementation that is necessary to make sure that the data processing infrastructure continuously runs as expected. This in concordance with Swiss software companies whenever possible.

The competencies of the institute relevant to SKA include:

- **Machine learning:** classification and regression models, predictive modelling, time series analysis, recommender systems, deep learning;
- **Exploratory data science:** descriptive statistics, data visualization, graph analysis;
- **High performance computing:** parallelizing on distributed systems, efficient optimization for GPUs, hybrid computing;
- **Data pipelines:** construction of processing software infrastructures for scientific data analysis, workflows;
- **Image analysis and processing:** image reconstruction and segmentation, object recognition, data compression, dimension reduction.

Projects at I4DS include the development of a key component of ESA's Euclid spacecraft ground segment infrastructure. It also designs the data analysis software for ESA's Solar Orbiter X-ray instrument. It is involved in the image processing of the soft X-ray instrument on the ESA/Chinese spacecraft SMILE.

For the Dark Energy Survey Camera, it is involved in software engineering aspects. In the radio astronomy domain, it has extensive experience in solar radio observations (see also the corresponding section above). With colleagues from the University of Geneva, as part of the Swiss National Science Foundation national research program on big data, it uses machine learning techniques to predict solar flares, in line with its former EU FLARECAST project which pioneered the use of machine learning in this area.

The institute has also experience in generating public outreach programs, and can contribute to the communication with a larger public, for instance with information and informal learning materials that can attract interested citizen scientists, maybe even involve some of them in specific aspects.

3.2.4. The University of Applied Sciences and Arts Western Switzerland

The University of Applied Sciences and Arts Western Switzerland (HES-SO) is a collegiate university consisting of a central Rectorate and 28 schools in 7 cantons. The HES-SO, with about 21'000 students organized into 6 faculties, is the second largest higher educational institution in Switzerland. It offers a large variety of education programs: 46 Bachelor degrees, 21 Master degrees and 255 continuing education courses.

The Engineering and Architecture faculty strongly supports the development of space technologies related to seven key areas: Advanced Materials, Communication Systems, Micro- and Nano-technology, Fluid Mechanics, Robotics, Software, and System Engineering. Education and research are strongly oriented towards practical applications. HES-SO is anchored into the regional economy, and collaborates closely with SMEs, industries and research institutes.

The HES-SO plans to contribute to the SKA project in several fields of competencies: Radio-frequency and microwave, signal processing (DSP and FPGA-based), Data science, as well as contributing to the construction of the instruments (mechanical and thermal design).

The Yverdon campus of the HES-SO/HEIG-VD is a leader in Microwave Software Defined Radio (SDR) which allows building receivers that can operate flexibly on a very wide frequency range (up 30 GHz) while offering a bandwidth of several GHz. Two institutes, REDS (embedded systems) and IICT (information and communication technologies) are collaborating on such receivers in the frame of an ESA project.

The antenna signal passes through a Low Noise Amplifier and band-pass filtering front-end, then is directly digitized at sampling rates of 8 to 12GHz, as allowed by current technology. Nyquist subsampling, also called bandpass sampling, is used to sample frequency bands above the given frequency. The operating range is limited only by the performance of the sample and hold stage of the receiver, potentially allowing operation at more than 30 GHz, with a maximum bandwidth of half the sampling frequency.

Digital down conversion and/or direct band-pass filtering could allow production of several distinct data streams on several frequency sub-bands if needed. Currently, in the SKA1-MID, there are 3-4 single-band receivers, mechanically selected at the focal point of the antenna. A single flexible SDR-based receiver could be used instead, with frequency bands switched by SW control, thus simplifying the antenna design.

The digital processing required for such a receiver must be performed in FPGA, a strong competency where institutes of three engineering schools of the HES-SO: HEIG-VD/REDS (Vaud), HEVS/ISI (Institute of Industrial Systems, Valais) and HEPIA/CoRES (Communicating embedded systems, Geneva) have a track record of successful FPGA projects in digital processing functions such as filtering, decoding, error correction, and for various applications (up to industrial stage) such as digital TV transmission and reception, satellite communications, quantum cryptography, and adaptive optics. This expertise can be readily applied to the design of high-speed correlators.

Data Science and machine learning is a strong competency at HES-SO: HEIG-VD/IICT, HEIG-VD/REDS, have done projects in applications as diverse as signal identification, data mining, and bio-signal and image analysis.

HES-SO is performing applied research and development, in daily collaboration with industrial partners. The TRL (technology readiness level) of deliverables out of the labs can be up to 6, and more when the industrial partner is involved. The partners within HES-SO can deliver fully functional instruments, incorporating mechanical and thermal design for extreme environments and cryogenics, a field of expertise of HES-SO/HEPIA/CMEFE (Geneva campus, fluid mechanics).

3.2.5. Swiss National Supercomputing Centre (CSCS)

The Swiss National Supercomputing Centre (CSCS) develops and operates cutting-edge high-performance computing systems as an essential service facility for Swiss researchers. These computing systems are used by scientists for a diverse range of purposes – from high-resolution simulations to the analysis of complex data.

CSCS has a strong track record in supporting the processing, analysis and storage of scientific data, and is investing heavily in new tools and computing systems to support data science applications. For more than a decade, CSCS has been involved in the analysis of the many petabytes of data produced by scientific instruments such as the Large Hadron Collider (LHC) at CERN. Supporting scientists in extracting knowledge from structured and unstructured data is a key priority for CSCS.

User Lab
On behalf of the Swiss Confederation, CSCS runs a User Lab, where researchers in Switzerland can apply for computational resources that are free at the point of use. A transparent review process by independent experts ensures that all deserving projects receive the computing resources they need to accomplish their aims.

Computational Services for Science
Swiss scientists, research institutions and projects with their own funding can access the computational resources at CSCS as contractual partners. The environment provided is either shared with the User Lab, or a dedicated solution can be deployed, depending on specific needs.

3.2.6. SCITAS

SCITAS is the scientific computing technology platform of EPFL. Its main mission is to provide researchers at EPFL and its partners access to scientific equipment and service expertise in high-performance computing that is efficient and customer-oriented.

The subsidiary mission is to contribute, through its own research and development activities, to advancing the technology of the platform for the benefit of its users.

SCITAS has around 15 members and is composed of two distinct groups: operations and application support:

- the operation group takes care of the HPC clusters that are available for production as well the daily administrations of the different hardware services,
- the application support group is in charge of setting up and maintaining high performance software environment necessary to the users. It also provides a high level software optimization service in order to efficiently use HPC resources that are available to EPFL researchers.

Finally, SCITAS is also involved in basic and advanced scientific computing/HPC courses, in particular for Masters and Ph.D. students.

Examples of services provided by CSCS to contractual partners are the analysis of data from the Large Hadron Collider (LHC) at CERN, the archiving of data from the X-ray laser SwissFEL for the Paul Scherrer Institute and the provision of computational resources for the numerical weather forecasts of MeteoSwiss.

Figure 40 View of the machine room at the CSCS with cooling islands and the Piz Daint supercomputer on the right. Credit: CSCS

4. Innovation and industry participation

There is a long tradition in Switzerland for cooperation between industry and large research facilities at national or international level. International research facilities, such as the newly settled SKAO, are looking for specific high end niche technology bricks and world class engineering solutions. Swiss industry, with a culture of innovation and reliability, performs above average on this demand.

The **Swiss ILO Office,** established in 2015, informs industry about business opportunities, promotes the Swiss technology within all large scale infrastructures in which Switzerland is a member and reports on contracts obtained (CERN, ITER, ESO, ESS, etc.).

For the future SKA project, the Swiss ILO Office has identified four fields of competence where there exists differentiated added value towards international competition.

Several Swiss SMEs, having an international export profile and superior technology know-how to offer, are showing strong interest to participate.

4.1. Time Management

Time management devices are recognized worldwide as an indisputable asset of the Swiss industry. In the last two decades highly precise atomic clocks have been developed and commercialized by a few Swiss enterprises for the telecom market. T4Science and Spectratime are the most representative companies in this market. Typically T4 science hydrogen based atomic clocks are on board all European Galileo navigation satellites.

T4Science

Founded in 2006 in Neuchâtel, Switzerland, T4Science is a leading designer and manufacturer of a full range of advanced, cost-effective and high-performance MASER CLOCK solutions. Its products are used in a wide variety of scientific applications and in the time and frequencyv industry.

The company is a world leader in designing, manufacturing, and marketing the next generation of high-performance, cost-effective, high-quality and compact maser products with smart functionality. It also offers a complete line of critical services for total customer satisfaction. T4Science products are used in a wide variety of scientific applications such as Telecom, space, navigation, scientific and VLBI network.

The SKA telescope will make synchronous observations with antennas at diverse locations. This requires very precise timing. The local clocks used in these systems have to be very stable in order to minimize signal loss and mistiming of data during integration in the local correlators, as well as for calibration purposes.

The stability requirements are dependent on the observing frequencies, but at the highest frequencies foreseen for the SKA, clock stabilities of the order of Pico (10-12) seconds in 1 second will be required. Time synchronization transmission over the SKA network in the sub-picosecond time domain could be realized with optical links.

T4 Science
iPRECISION MASER SOLUTIONS™

4.2. System control and supervision

As a prominent machine tool export country, Swiss industry owns all engineering competences to drive and control complex automatized electro-mechanical systems. SME expertise can be found in the whole machine supervision value chain, from sensor/ actuators front ends up to the application software.

Some companies have focused their expertise exclusively towards activities arising from research facilities with an extremely complete and consistent roadmap. This is for instance the business model of Cosylab and IOxOS Technologies.

Cosylab Switzerland

Cosylab Switzerland is a branch of Cosylab supporting large scientific infrastructures like the SwissFEL project, by providing distributed control system development, software engineering, system integration and tight time synchronization.

Since 2001, Cosylab is addressing challenges similar to SKA in different experiments. It was the sole contractor of the ALMA Common Software development, so far the largest operational radio telescope in the world, and is now providing similar services to E-ELT, the largest optical telescope under construction, and CTA, the next generation ground-based observatory for gamma-ray astronomy at very-high energies. Cosylab not only took care of the synchronization and time distribution of many large experiments, but also contributed to the White Rabbit project supported by CERN, GSI and other institutes.

The capability of handling long-duration projects carried on by large international collaborations is also proved by ITER, the nuclear fusion project for which Cosylab is developing the control system framework (CODAC) since 10 years. Finally, Cosylab has proven experience of the TANGO distributed control system framework, which has been selected for SKA: Cosylab has successfully integrated the complete control system for the SOLARIS synchrotron in Poland and for the NICA ion collider facility in Russia, and provided various subsystems for the MAX IV synchrotron in Sweden and for the ONERA wind tunnels in France.

IOxOS Technologies

IOxOS Technologies, founded in 2007 in Gland (Switzerland), is an electronic design company offering innovative solutions to system integrators in Big Science, Mil/Aero and Transport industries.

It combines its hardware design expertise with engineering, consulting and training services covering both hardware and software, with the aim of meeting the customer's needs from the initial specification to the final implementation, validation, verification and system integration.

IOxOS Technologies offers a comprehensive line of FPGA centric products, including IP Cores, FPGA based System on Chip (SoC) and Network on Chip (NoC) solutions, FPGA design kits and board design, all of them targeting the most extended form factors in the industry (such us MicroTCA.4, VME64x, Compact PCI Serial, PXI and VXI).

IOxOS Technologies, has consolidated its position as a provider of high-end electronic systems for data acquisition, real-time control, monitoring and safety applications for some of the most relevant scientific research facilities such as the European Spallation Source (ESS) in Sweden, CERN and the Paul Scherrer Institute (PSI) in Switzerland, the CEA Saclay in France and the Science and Technology Facilities Council (STFC) in the UK among others.

The company is working together with all these research institutes, providing a full range of electronic modules and FPGA firmware for the development of critical systems such as Low Level RF (LLRF) controllers, Beam Position Monitors (BPM), Beam Loss Monitors (BLM), Local Protection Systems of RF sources (RF-LPS) and Fast Beam Interlock Systems (FBIS).

The common denominator of its products and services is the use of high-end FPGA devices combined with high-performance communication protocols ensuring the flexibility, reliability, long-term availability and performance required by large-scale and highly sophisticated projects, such as the SKA.

4.3. Antenna & radio receivers

The knowledge for radio transmission systems is available thanks to the heritage of the former large telecom firms established in Switzerland (Ascom, Hasler, Autophon, Siemens) and to defence industries (Contraves, Oerlikon).

Beside these historical players, SMEs have emerged from the academic centers serving specific niche markets, such as the ones using innovative antenna concepts (ViaSat, Mirad, Swissto12).

These SMEs are able to offer strong R&D resources for one specific custom demand and provide rapidly automated processes for the production of high end products.

Moreover, the Swiss companies qualified in the space industry for the integration of larger parts (Ruag Space, APCO Technologies) have the industrial skills to manufacture and test Antennas for the SKA project, as the requirements on size and assembly complexity are similar.

In the domain of radio receivers, a promising contribution to SKA may come from Diramics, which presents a new state of the art Low Noise Amplifier (LNA) technology. This technology is worthy of being benchmarked against other LNA options currently under evaluation by SKAO.

Ruag Space

RUAG is a dynamic international group that combines outstanding technological expertise with a high degree of foresight and responsibility. RUAG Space is the leading supplier of products for the space industry in Europe and has a growing presence in the United States and in the rest of the World as well.

Experience, outstanding reliability, customer focus and a comprehensive, clearly structured product portfolio make RUAG Space the partner of choice for manufacturers of satellites and launchers throughout the world.

With thirteen production sites in six countries, RUAG Space specializes in components for use aboard satellites and launch vehicles. Its capabilities fall into four areas: structures and separation systems for launch vehicles, structures and mechanisms for satellites, digital electronics for satellites and launch vehicles, and satellite communication equipment.

RUAG Space precision mechanisms are highly regarded by renowned space customers throughout the world, in particular when it comes to the precise positioning and motion control within payload instrument mechatronics, solar generators, thrusters and antennas.

RUAG Space Switzerland, Product Unit Mechanisms (PU-M) is also well established in the non-space business for high-end commercial and institutional mechanism products, and has the clear strategy to enhance the non-space business with projects at research large scale facilities (ESO, ITER, SKA, etc.) and selected industrial partners.

Together ahead. RUAG

Diramics

Diramics was founded in 2016 as a spin-off from ETH Zurich to commercialize the InP HEMT technology developed there. InP HEMTs are a transistor technology that is specialized and optimized for ultra-low-noise applications.

The products are being used by radio-astronomy observatories, ESA and NASA for deep-space communications, defense applications, as well as many other more commercial applications such as Satcom or radar.

Diramics' technology is leading in terms of noise performance. In addition to the discrete transistors, Diramics will also offer integrated circuit low noise amplifiers, which are currently in the prototyping phase. This will simplify integration into systems and allow for a broader adoption of the technology.
Low noise amplifiers are one of the key components determining the sensitivity of the SKA antenna array. Reducing the noise figure of the LNA, which is present in each antenna, will reduce the overall system noise and allow for shorter observation times, higher resolution images, or for a cheaper way to build radio-astronomy antenna arrays such as the SKA.

CALTECH uses Diramics devices to build low noise amplifiers around 1.4 GHz with a noise temperature well below 10K without cryogenic cooling. These will be used in their DSA (Deep Synoptic Array) and improve sensitivity of the array by 20%.

DIRAMICS

4.4. Data processing

The strength of the Swiss academic centers in computer science has fostered the creation of commercial companies to address various private sector requirements when it comes to handle massive computer data (insurance, telecom).

For scientific big data analysis, similar engineering skills in statistical tools handling, algorithmic and machine learning are needed. These competences are available among several SMEs in Switzerland.

Close to the academic centers, and in combination with the national computing center (CSCS), multidisciplinary teams can quickly be formed to serve complex physics-oriented projects such as SKA.

Ateleris is pioneering in such a role by honoring private contracts as well as serving the scientific community through several EU or national funded projects.

Ateleris

Ateleris GmbH was founded in 2016 as a University of Applied Sciences Northwestern Switzerland FHNW spin-off. Ateleris is an accredited start-up at the TECHNOPARK Aargau in Brugg, Switzerland.

Ateleris is a software development and technology consulting company with special expertise in data analytics and optimization. The team at Ateleris has specialists from the field of applied computer science with extensive experience in the execution of applied research projects for industry and public partners, especially in international projects.

Ateleris is active in multiple technological and topical domains: their experts have worked in international and interdisciplinary projects and have developed flight software and algorithms for satellites, built scientific tools for ground-based data analysis, developed algorithms and smart applications for industry customers, and built data analytics solutions for data exploitation by business clients. The Ateleris team has a proven track record in the field of astroinformatics and scientific data processing.

The know-how and experience Ateleris has built-up in scientific data exploitation can be transferred and applied to SKA to help scientists, the public sector and private businesses to find, enhance, combine and analyze the data collected by this powerful instrument.

Ateleris sees its main area of support in building software tools that improve later processing steps – closer to the end user – by developing data refinement, data combination, data visualization and data exploitation software, using (semi-) automated information extraction and enhancement techniques based on machine learning.

ATELERIS

Swiss contribution

Michel Hübner (Swiss Industry Liaison Office)

5. Swiss stakeholders and preparations for SKA

5.1. Current status

Switzerland is actively working towards membership of the SKA Organisation, which is being discussed in the framework of the national roadmap for infrastructure 2017-2020.

Swiss scientists are at the forefront of many fundamental science questions which will be addressed with the SKA, the most important topics already mentioned in previous sections.

Swiss scientists are part of the main science working groups which prepare and organise the science which will be done with the SKA.

The Swiss scientific community is intensively carrying out multi-wavelength observations with the world's leading facilities and satellites covering the vast electromagnetic spectrum from high energies to the radio domain. Swiss scientist are already using interferometric observations, and are using several SKA precursor projects.

Research groups in Switzerland are also among the world leaders in numerical simulations for astrophysics, a fundamental topic for future experiments such as the SKA.

Academia and industry carry out important research and development on cutting-edge technology is being carried out by Swiss academic institutions and industry partners, which is crucial to meet the challenges of the SKA. This includes hardware (e.g. large capacity memories, fast analog-digital converters), data compression and extraction techniques, signal and image processing, machine learning, and other big data developments.

Swiss SKA activities are led by a consortium in which more than 50 scientists are participating from different research institutes throughout Switzerland (see map at the beginning of this document for further details).

5.2. Swiss SKA days

2016

EPFL, Lausanne

2017

EPFL, Lausanne

2018

FHNW, Brugg-Windisch

2019

University of Bern

2020

June 2-3

University of Zürich

The Swiss community has already organized four annual "Swiss SKA days", meetings with national and international participation, where scientists from different fields, industry, government, SKA representatives, and the press meet. These meetings also include exchanges with the general public.

5.3. International collaboration

Switzerland/South Africa

There are currently two bilateral collaborations relevant for the SKA.

The collaboration "Wide-band Imaging in the SKA era" (led by Jean-Philippe Thiran at EPFL and Oleg Smirnov of Rhodes University) is currently funding new algorithm and software developments for radio-imaging in the context of the MeerKAT project, the South African SKA precursor.

The second collaboration, "Addressing the big data challenge: developing transferable technologies and methodologies in the astronomy domain" (lead by Martin Kunz at the University of Geneva and by Kavilan Moodley, HIRAX PI at UKZN), is more generally focused on a framework to analyse large data sets. While it focuses on HIRAX as a key case study, the techniques developed will also be useful for the SKA.

Furthermore, the University of Geneva, ETHZ and EPFL are participating member of the Hydrogen Intensity and Real-time Analysis eXperiment (HIRAX). This experiment led by the University of Kwazulu-Natal (Durban, South-Africa) is a novel HI mapping facility that will be installed within the SKA site in South-Africa in 2020. This project is funded in Switzerland by the Swiss National Foundation and by the universities.

Finally, Swiss scientists will further develop collaboration with South-African scientists, as now the MeerKat interferometer has started to conduct scientific observations.

Switzerland / Australia

In the last few years, some active development of the Australian SKA Pathfinder (ASKAP) software ASKAPsoft have been conducted in interaction with Swiss HPC scientists. This collaboration is no further developing to conduct common astrophysics project in particular in the context of the WALLABY and EMU surveys that will start observation in 2020.

Switzerland/China

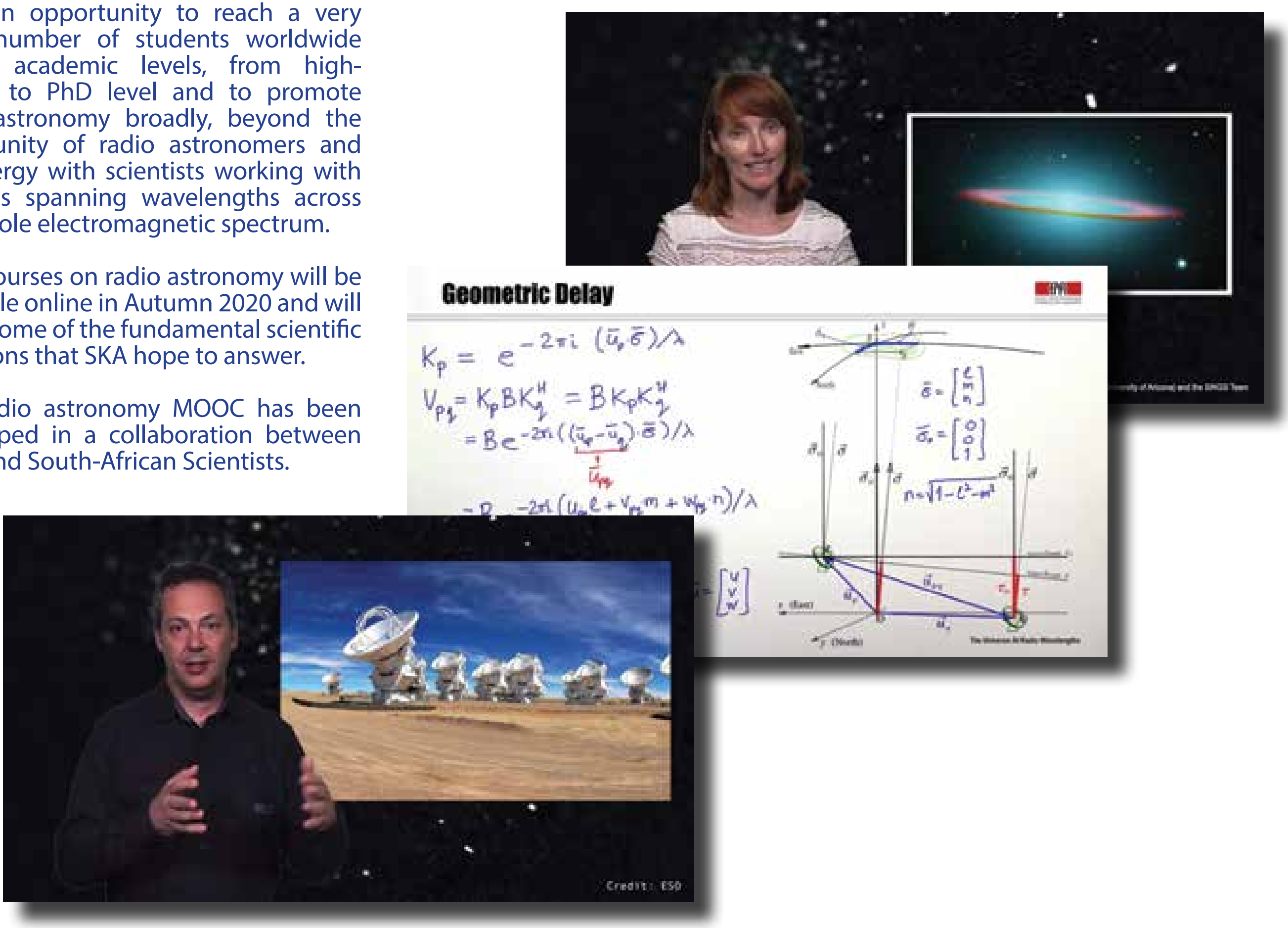
As follow-up discussion initiated during the 2019 Swiss SKA Days, where a Chinese delegation presented their participation in the SKA project, some strong interest have developed between Swiss and Chinese scientists. Although, these interests are yet to be consolidated, it could take the form of talents exchanges, and collaborative scientific projects on the topics of Astrophysics but also Big Data analysis. These could benefit from the SNF Sino-Swiss Science and Technology Cooperation Scheme.

5.4. MOOC on radio astronomy

Massive Open Online Courses (MOOCs) offer an opportunity to reach a very large number of students worldwide at all academic levels, from high-school to PhD level and to promote radio astronomy broadly, beyond the community of radio astronomers and in synergy with scientists working with facilities spanning wavelengths across the whole electromagnetic spectrum.

EPFL courses on radio astronomy will be available online in Autumn 2020 and will cover some of the fundamental scientific questions that SKA hope to answer.

The radio astronomy MOOC has been developed in a collaboration between EPFL and South-African Scientists.



5.5. Public outreach

Visualisation is an effective instrument to introduce the general public, especially young people, to even the most complicated and innovative aspects and concepts of science.

The opportunity to use 3D digital visualisation and Virtual Reality facilities, further enhance the impact for the communication and divulgation and push toward a new approach to the cultural and scientific heritage.

The availability of tools to visualise scientific data in a comprehensible, self-describing, rich and appealing way is therefore crucial for researchers and for the public, both for creating knowledge and disseminating it.

It represents an outstanding way of promoting and spreading SKA discoveries to the general public, but also to specialists.

5.5.1. Virtual Reality

The emergence of a broad variety of Virtual Reality (VR) devices, from plug-and-play devices to sophisticated interactive environments, is opening new avenues for the visualization and communication of scientific datasets. Undoubtedly, exploring the potential of VR for astrophysics is a timely venture.

The potential of VR for astrophysics has already been identified, be it in the form of immersive and interactive experiences. For outreach purposes, VR technology can provide the general public with a highly enticing means to apprehend complex astro-physical datasets and concepts.

EPFL established a new laboratory in 2017 for experimental museology (eM+), exploring the convergence of aesthetic practice, visual analytics and cultural data, and exploiting innovative technologies, in particular VR. Leveraging the experience of eM+, novel contents will be produced, based on the data and the results produced by the SKA.

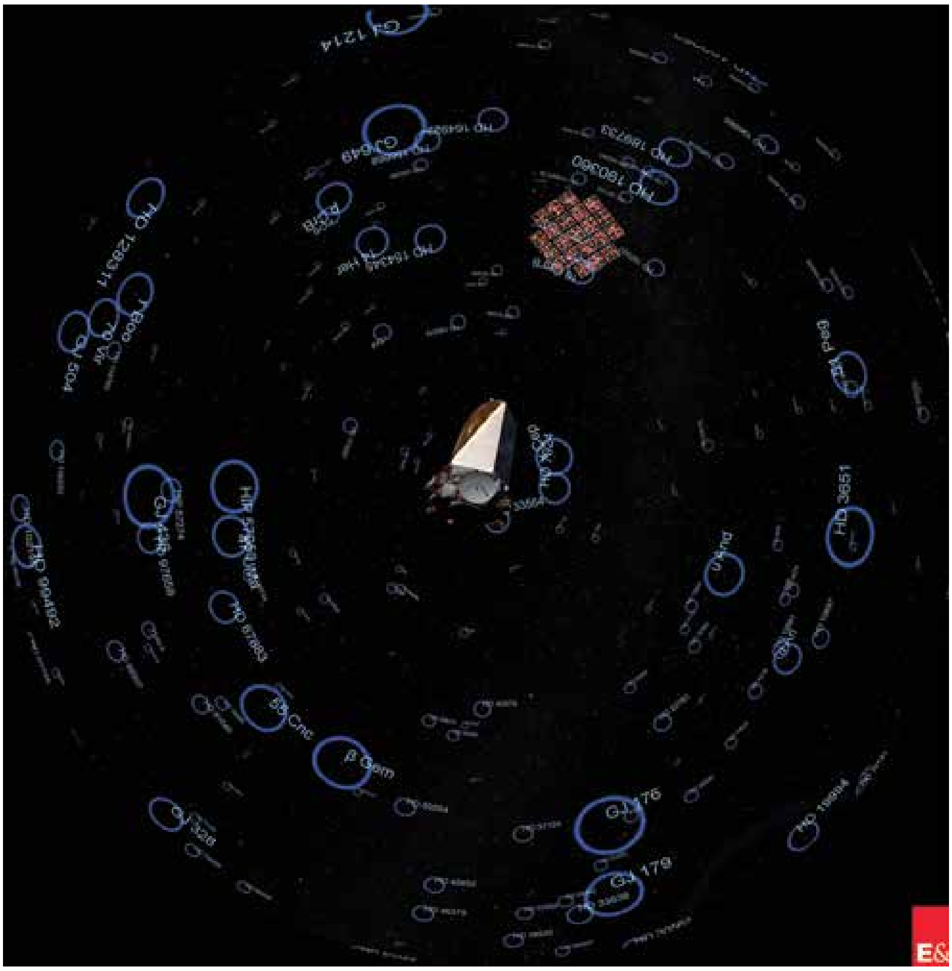


Figure 41 Visualization of two exoplanet position datasets along with a 3D model of the Kepler Space Telescope in the Planetarium. Credit: Verkehrshaus der Schweiz, produced with Digistar by Evans & Sutherland

Figure 42 The Planetarium at the Verkehrshaus in Lucerne is the largest platform for scientific outreach in Astronomy, Astrophysics and Earth sciences in Switzerland. Credit: Verkehrshaus der Schweiz, produced with Digistar by Evans & Sutherland

5.5.2. Planetaria

The only large planetarium in Switzerland, is located at the Verkehrshaus der Schweiz (The Swiss Museum of Transport) in Lucerne. With its 18m dome, 246 seats and daily shows it is the largest platform for public scientific outreach in the topics of Astronomy, Astrophysics and Earth Sciences.

With a state of the art digital planetarium technology (resolution 33Mpx) it is able to display large datasets like the ones to be expected from SKA and even interact with them. Therefore, it would be a significant platform for national research institutions like EPFL to connect with the Swiss public and present their work regarding SKA.

Additionally, the Planetarium in Lucerne is well connected to other institutions and especially planetaria around the world so it can provide assistance for additional outreach activities by providing SKA data over cloud based systems and involving e.g. the International Planetarium Society (IPS Science & Data Visualization Task Force) to reach planetarium domes worldwide.

An interesting opportunity would be the **Data to Dome initiative**, a global project involving some of the world's leading planetarians as well as the European Southern Observatory (ESO) which specializes in converting and providing access to large scientific datasets for use and presentation in planetaria.

Appendix A: SKA precursors

Radio telescope	Site	Number of antennas	Wavelength coverage (Frequency coverage)
Millimeter Interferometers			
ALMA	Chajnantor Plateau, Chile	54x12-meters + 12x7-meters	0.32 - 3.6 (8.6) mm (84 - 950 GHz)
NOEMA	Plateau de Bure, France	10x15-meters	9.4 - 37.5 mm (8 - 32 GHz)
Low-Frequencies Arrays			
LOFAR	Europe (Center: Netherlands)	51 stations with in total 8.000 antennas	1.3 - 30 m (10 - 240 MHz)
MWA	Shire of Murchison, Australia	128 phased tiles (each with 16 dipoles)	1 - 4.3 m (70 - 300 MHz)
21 CMA	Tianshan Mountains, west China	81 tiles with 127 log-period antennas for each, deployed along two perpendicular arms of 6+4 km in length	1.5 - 6.0 m 50 to 200 MHz
Mid-Frequency arrays			
JVLA	Plains of San Aqustin, USA	27x25-meters	0.6 - 410 cm (73 MHz - 50 GHz
MeerKAT	Karoo Radio Astronomy Reserve, Northern Cape, South Africa	64x13.5-m	3 - 30 cm (1 - 10 GHz)
ASKAP	Shire of Murchison, Australia	36x12m	0.17 - 0.43 m (700 MHz -1.8 GHz)
HI mapping			
CHIME	near Penticton, BC, Canada	four 20m x 100m cylindrical reflectors (each with 256 dual-polarization antennas)	0.37 - 0.75 m (400 - 800 MHz)
HERA	Karoo Radio Astronomy Reserve, Northen Cape, South Africa	Currently 19 x 14 m non-tracking dishes (18 more currently under construction, to be 350 when completed)	1.2 - 6.0 m (50 – 250 MHz)
BINGO	Serra do Urubu, Brazil	Single dish	0.24 - 0.31 m (960 MHz -1260 MHz
HIRAX	Karoo desert, South Africa	1024 x 6m dishes	0.37 - 0.75 m (400 - 800 MHz)
Tianlai project	Hongliuxia village, Balikun(Barkol) town, Xinjiang, China	Currently 3x15x40m cylinders (each with 96 dual-polarization receiver units) and 16x6m dishes	0.37 - 0.43 m (700 - 800 MHz)

Figure 43 Composite image bringing together the two SKA sites under a shared sky. Pictured here are some of the SKA precursor telescopes, South Africa's KAT-7 and MeerKAT telescopes on the left and Australia's ASKAP telescope on the right. Credit: SKA Organisation

Milimeter interferometers

ALMA

Mars-like scenery on the Chajnantor Plateau at an altitude of 5000 meters in northern Chile, the driest place on Earth, where the **Atacama Large Millimeter/submillimeter Array (ALMA)** is located. This radio telescope made up of an ensemble of 66 12- and 7-meter diameter antennas is the largest millimeter telescope in the world.

With antennas spread across 16 kilometers, ALMA reaches milliarcseconds maximum resolution, equivalent to a basketball hoop on the Moon. Working at short wavelengths from 8.6 mm to 0.32 mm, the coldest and most hidden Universe snaps into focus.

Using ALMA, astronomers are able to probe the birth of stars and planets, glimpsing the initial phases of these objects. ALMA is also able to see distant galaxies with similar details as contemporary galaxies, and able to detect the first galaxies that emerged from the cosmic Dark Ages billions of years ago.

The European Southern Observatory membership countries, including Switzerland, have shared 37.5% of the ALMA's construction cost. Swiss astronomers from several institutions (e.g. UniGE, EPFL, ETHZ, UniBE, UniZH) have obtained competitive access to this unique facility, obtained important results, and also acquired significant experience with interferometry using ALMA.

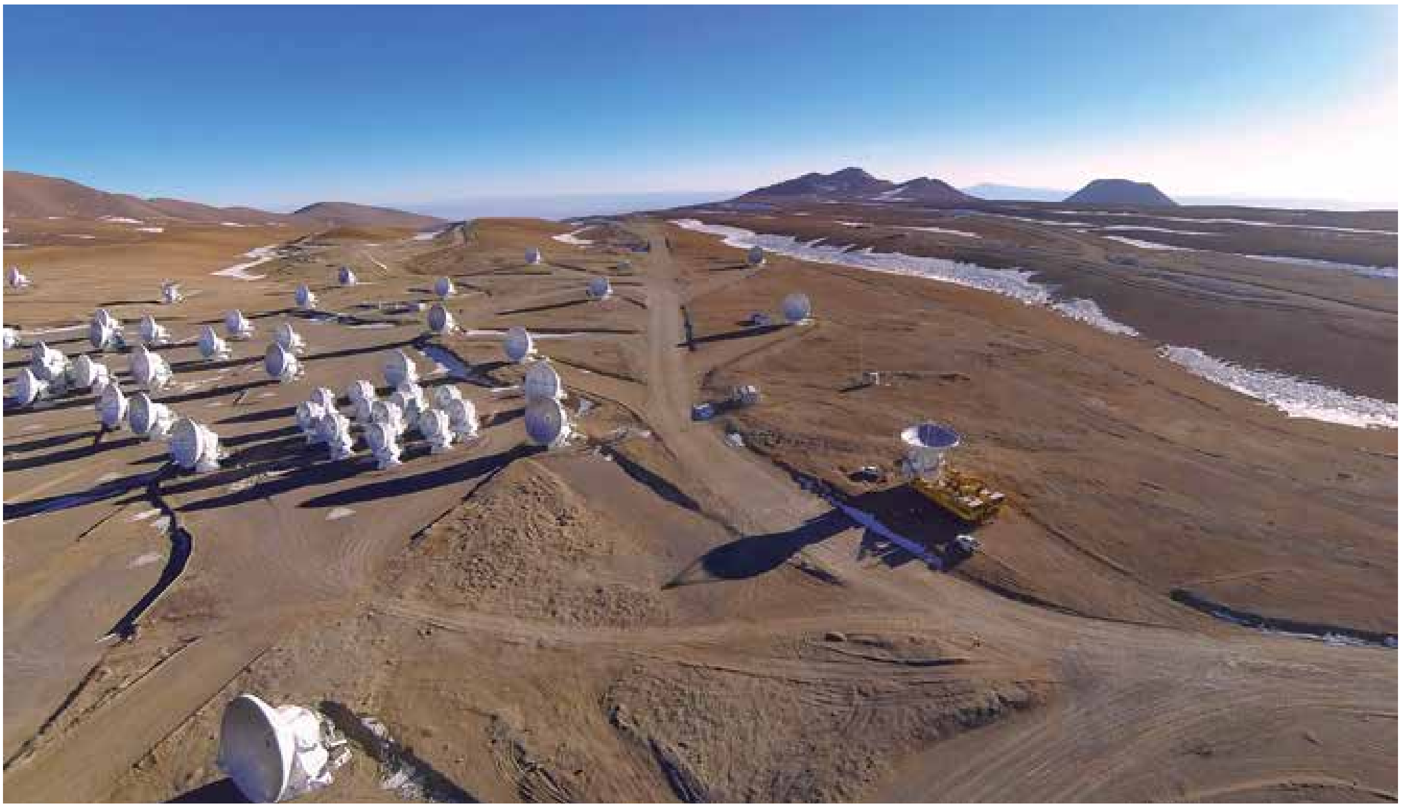


Figure 44 The final antenna for the Atacama Large Millimeter/sub-millimeter Array (ALMA) project is here seen arriving to the high site at the ALMA Observatory, 5000 metres above sea level. Its arrival completes the complement of 66 ALMA antennas on the Chajnantor Plateau in the Atacama Desert of northern Chile — where they will in future work together as one giant telescope. Credit: A. Marinkovic/X-Cam/ALMA (ESO/NAOJ/NRAO)

NOEMA

The **Northern Extended Millimeter Array (NOEMA)** on the Plateau de Bure at an altitude of 2500 meters in the French Alps is the ALMA counterpart in the northern hemisphere. Although achieving weaker sensitivity and angular resolution, the cutting edge technology of the millimeter instrumentation mounted on the NOEMA 10 15-meter diameter antennas makes this radio telescope very competitive and complementary to ALMA. Switzerland is accessing NOEMA observing time through open time or scientific collaborations with researchers from the NOEMA partner countries (Germany, France, Spain).

Figure 45 The NOEMA observatory in the French Alps: Equipped with cutting edge technology, the NOEMA antennas scan the universe for prebiotic molecules, among other cosmic objects. © DiVertiCimes/IRAM

Low-frequency arrays

LOFAR

LOFAR, the **"Low Frequency Radio Array",** is a pan-European radio telescope. It consists of an interferometric array of dipole antenna stations distributed throughout the Netherlands and in several countries in Europe. These stations have no moving parts and due to the all-sky coverage of the component dipoles, give LOFAR a large field-of-view.

The astrophysical goals of LOFAR is to advance our understanding of the formation and evolution of galaxies, clusters and active galactic nuclei.

LOFAR offers a transformational increase in radio survey speed compared to existing radio telescopes, as well as opening up one of the few poorly explored regions of the electromagnetic spectrum. It is tuned to explore the low-frequency radio sky through several surveys.

The LOFAR Surveys Key Science Project (LSKSP; Röttgering et al. 2011, JApA, 32, 557) has planned a survey strategy with three tiers of observations. Tier-1 is the widest tier. It includes low-band (LBA) and high-band (HBA) observations across the whole 2π steradians of the northern sky.

Figure 46 Image showing the various locations of the international LOFAR Telescope sites in Europe. Credit ASTRON

The LOFAR HBA (120-168 MHz) survey is referred to as the LOFAR two-meter Sky Survey (LoTSS, Shimwell et al, 2017, A&A, 598, 104). The first data release is presented in Shimwell et al, 2018, special edition of A&A, volume 622.

The LoTSS survey is a long-term project, but over 2000 square degrees of the northern sky have already been observed and additional data are continuously being taken.

The survey was initially designed to detect radio galaxies at z>6, and diffuse radio emission associated with the intra-cluster medium galaxy clusters at z>0.6.

LoLSS (LOFAR LBA Sky Survey) is the ultra-low-frequency counterpart of LoLSS at 40-70 MHz. The survey records data only from the Dutch station and it is currently ongoing.

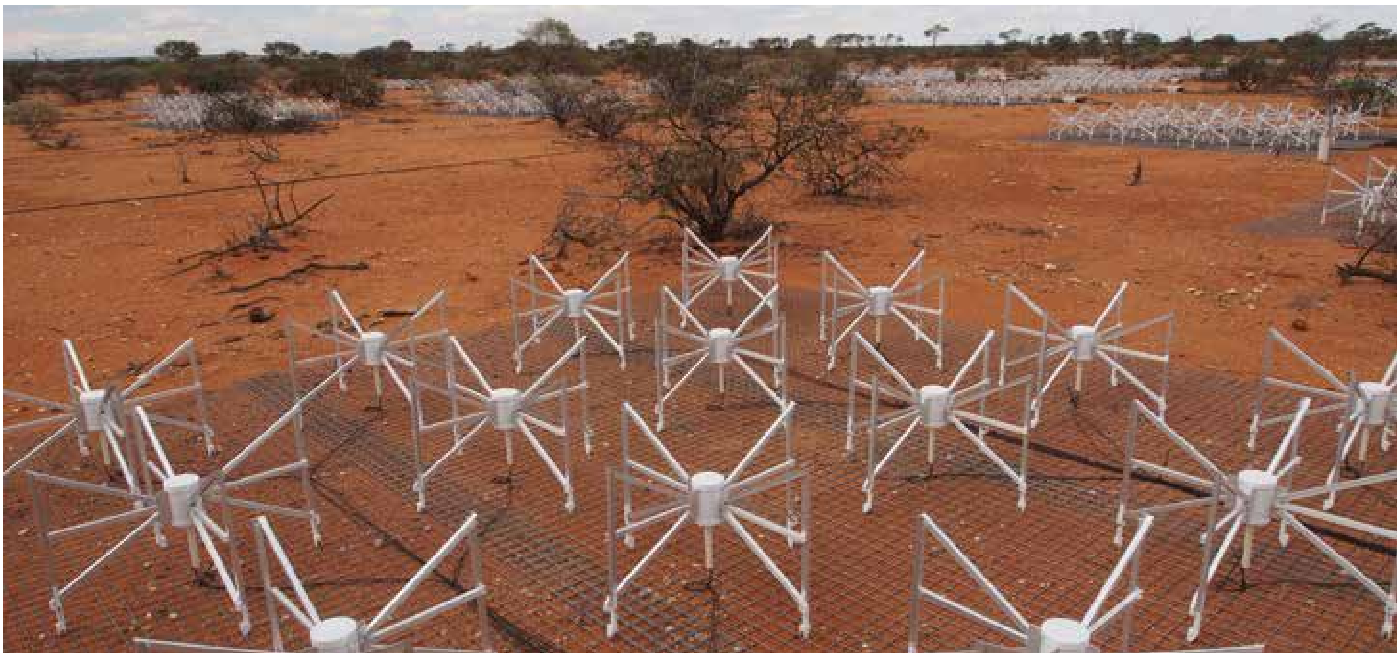
The Deeper Tier-2 and Tier-3 observations will cover smaller areas, focussing on fields with the highest quality multi-wavelength datasets available across a broad range of the electromagnetic spectrum.

Figure 47 An aerial photograph taken of the LOFAR radio telescope and the Chilbolton site. Credit: Dr. G B Gratton/STFC

MWA

The Australian Murchison Widefield Array (MWA) Phase I was completed in 2013 and includes 128 phased tiles, each of which consists of 16 crossed dipoles covering the frequency range 70–300 MHz. The Phase II of MWA was completed in April 2018 and has doubled the number of tiles, but quadrupled the size of the area they are distributed across.

Figure 48 The Murchison Widefield Array (MWA) telescope is the low frequency precursor telescope to the SKA. Credit: SKA Organisation, William Garnier (SKAO)



21CMA

The 21 CentiMeter Array (21CMA), sited in Tianshan Mountains, west China, is a ground based meter-wave interferometric array designed to probe the 21cm radiation of neutral hydrogen from the cosmic dawn and the epoch of reionization at redshift z=6 to 27.

The array, constructed from August 2005 to July 2006 and upgraded by July 2010, consists of 81 tiles with 127 log-period antennas for each, which are deployed along two perpendicular arms of 6+4 km in length.

A field of 10-100 square degrees centered on the North Celestial Pole is imaged 24 hours per day in a low frequency range from 50 MHz to 200 MHz with a resolution of 24 kHz. Coherent uv data at each frequency channel are being accumulated to meet the desired sensitivity of statistical detection of the cosmic 21cm signal, and advanced RFI and foreground removal techniques have been correspondingly developed.

21CMA is a unique low-frequency radio interferometer that serves as SKA pathfinder in China.

Figure 49 The Wulasitai Observing Station. Copyright © National Astronomical Observatories, Chinese Academy of Sciences

Mid-frequency arrays

JVLA

The **Jansky Very Large Array** (JVLA) is one of the world's premier astronomical radio observatories. It consists of 27 radio antennas in a Y-shaped configuration on the Plains of San Agustin fifty miles west of Socorro, New Mexico.

Each antenna is 25 meters in diameter. The data from the antennas is combined electronically to give the resolution of an antenna 36km across, with the sensitivity of a dish 130 meters in diameter.

Figure 50 The Very Large Array (VLA) is a collection of 27 radio antennas located at the NRAO site in Socorro, New Mexico. Each antenna in the array measures 25 meters (82 feet) in diameter and weighs about 230 tons. Credit Alex Savello / National Radio Astronomy Observatory

MeerKAT

The South African MeerKAT radio telescope is a precursor to the Square Kilometre Array (SKA) telescope and will be integrated into the mid-frequency component of SKA Phase 1.

Inaugurated in July 2018 and located in the Karoo desert, MeerKAT consists of 64 x 13.5-m dishes working at centimeter wavelength.

A Swiss National Science Foundation (SNF) bilateral project with South Africa "Wide-band Imaging in the SKA era" (led by Jean-Philippe Thiran at EPFL and Oleg Smirnov of Rhodes University) is currently funding new algorithm and software developments for radio-imaging in the context of the MeerKAT project.

Figure 51 Aerial shot of the MeerKAT radio telescope before its launch in July 2018. These sunrise shots show the expanse of the telescope, which covers a baseline distance of 8 kilometres. Credit : South African Radio Astronomy Observatory (SARAO)

ASKAP

The Australian SKA Pathfinder (ASKAP) consists of 36 x 12-m dishes, forming a 6-km diameter telescope array, which is expected to be fully operational in 2019.

Each dish is equipped with a wide-field Phased Array Feed, delivering 30 square degree field-of-view at 700 - 1800 MHz. ASKAP has been designed to be a fast hydrogen (HI) survey instrument with high dynamic range.

The ASKAPsoft pipeline, developed at CSIRO and operating on the Pawsey Supercomputing Centre in Australia, has also been deployed and tested on the CSCS's PizDaint GPU computer cluster.

It has been shown during the CSCS-led Hackathon that improving and speeding up existing algorithms (e.g., imaging and CLEANing) was feasible (a collaboration between Koribalski and Gheller at EPFL). M. Böhlen at Uni-ZH is also developing stream processing of the ASKAP pipeline with Koribalski using their expertise in HPC.

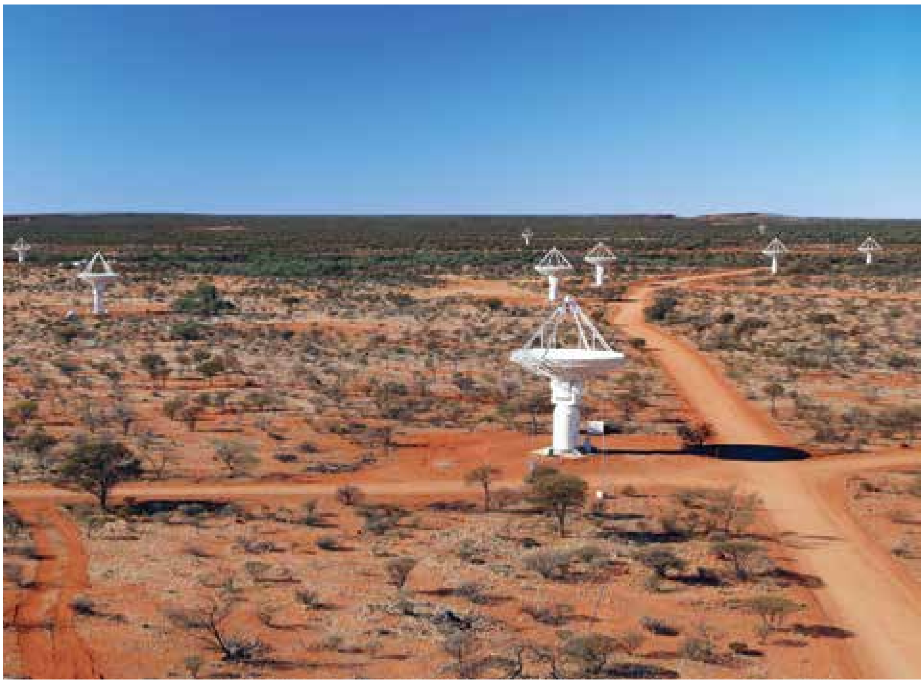


Figure 52 CSIRO's ASKAP antennas at the Murchison Radio-astronomy Observatory in Western Australia, installed with innovative phased array feed (PAF) receivers at the apex of the antenna. Credit: CSIRO.

Figure 53 ASKAP antennas under a starry night sky. Credit: Alex Cherney/terrastro.com

HI mapping

Figure 54 Image of the 4 cylinders and 1024 dual-polarized antennas of the CHIME telescope located at the Dominion Radio Astrophyscial Observatory (DFAO), a national facility for astronomy operated by the National Research Council of Canada. Credit: chime-experiment.ca

CHIME

CHIME is a Canadian-led North American radio telescope which started its observation end of 2017. The telescope covers the frequency range 400-800 MHz and will map the sky to build the 3-dimensional map of hydrogen density (HI) to measure the expansion history of the universe.

Figure 55 HERA site in South Africa. Credit: South Africa Radio Astronomy Observatory (SARAO)

HERA

The Hydrogen Epoch of Reionization Array (HERA) is a radio telescope dedicated to observing large-scale structures during and prior to the epoch of reionization.

What makes the telescope unique is the fact that it is constructed out of PVC piping, chicken mesh wire and tarred poles.
The University of California, Berkeley, leads the experiment in collaboration with partner teams from the USA, UK, Italy and South Africa.

Participating South African institutions include Rhodes University, the University of KwaZulu-Natal, the University of the Western Cape, the University of the Witwatersrand and SKA South Africa.

BINGO

BINGO is an international project, including participation from ETHZ, and should be operational in 2019. This single-dish radio telescope aims at mapping neutral gas on large angular scales.The frequency coverage is 960-1260 MHz, which corresponds to a mean redshift of neutral hydrogen of z~0.3.

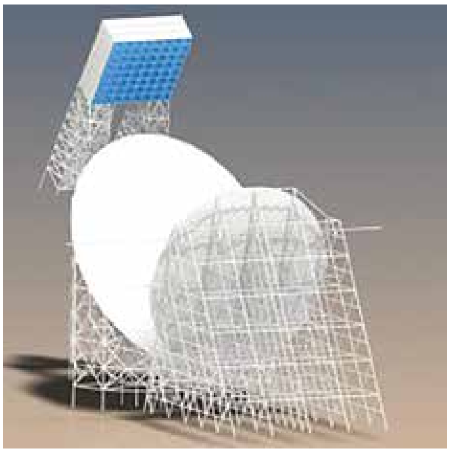


Figure 56 Preliminary BINGO telescope design. Credit: bingotelescope.org

HIRAX

HIRAX is a South-African led international project, including participation of ETHZ and the University of Geneva. It will eventually consist of 1024 6m dish antennas in a compact array configuration that will observe the southern sky in the frequency range 400-800 MHz (like CHIME). Construction of a 128 dish pathfinder on the SKA site in the Karoo desert in South Africa will start in early 2020.

The Swiss HIRAX activities are supported by a FLARE grant for the digital correlator and a bilateral grant for Swiss - South African joint research activities, in addition to personal grants of groups at ETHZ, EPFL and the University of Geneva.

Figure 57 Artist impression of the 1024 dishes in to be constructed at the SKA site. Credit: UKZN

Tianlai project

The Tianlai project is an experiment aimed at detecting Dark Energy by measuring the baryon acoustic oscillation (BAO) features in the large scale structure power spectrum, which can be used as a standard ruler.

The basic plan of the experiment is to make an intermediate redshift (0<z<3) 21cm intensity mapping survey. The experiment will use a parabolic cylindrical telescope array.

The cylindrical reflector is placed in the north-south direction, with receiver units placed along its focus line, and a number of such cylinders in parallel will form the whole array. The estimated size of the full array is about 120m x 120m, with about 2000 dual-polarization receiver units.

Currently, the Tianlai collaboration includes scientists and engineers from China, Canada, France, and the USA.

Figure 58 Tianlai project site located at Hongliuxia in Balikun county in the eastern part of Xinjiang, at an elevation of about 1500m above sea level. The surrounding environment is a sparsely populated steppe with little artificial radio interference. Credit: Cosmic Dark Energy and Dark Matter Research Group, © National Astronomical Observatories, Chinese Academy of Sciences

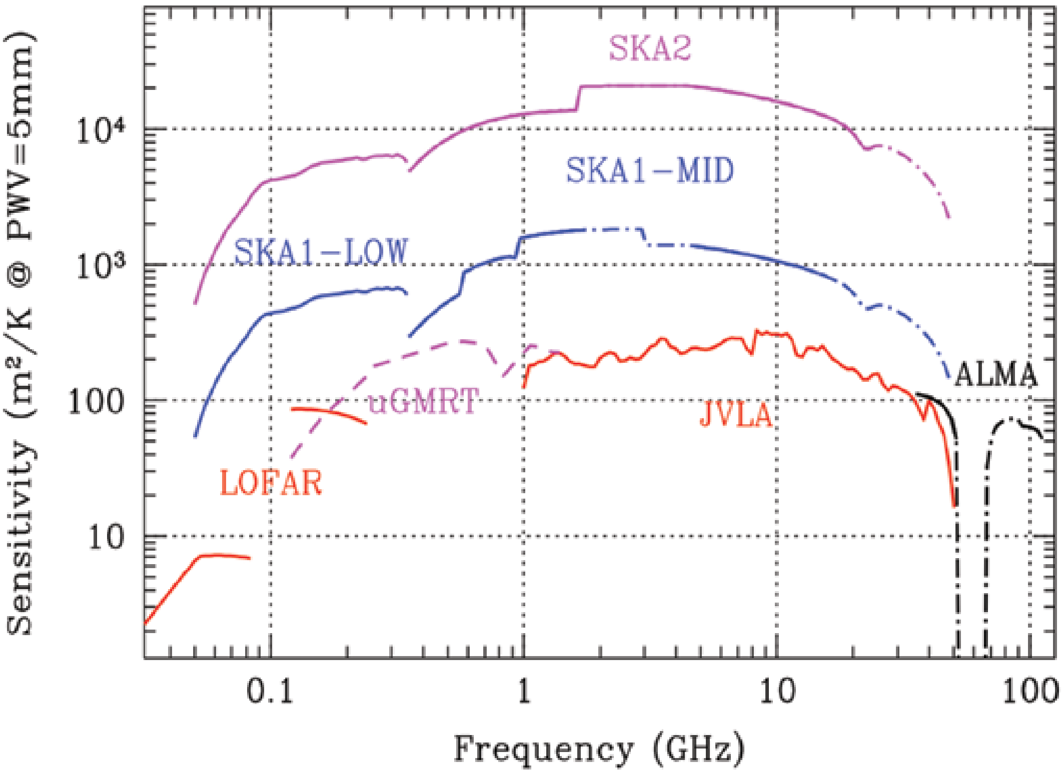


Figure 59 SKA anticipated sensitivity. The dot-dashed lines indicate upgrade paths for SKA1, to be confirmed. Credit: SKA Organisation

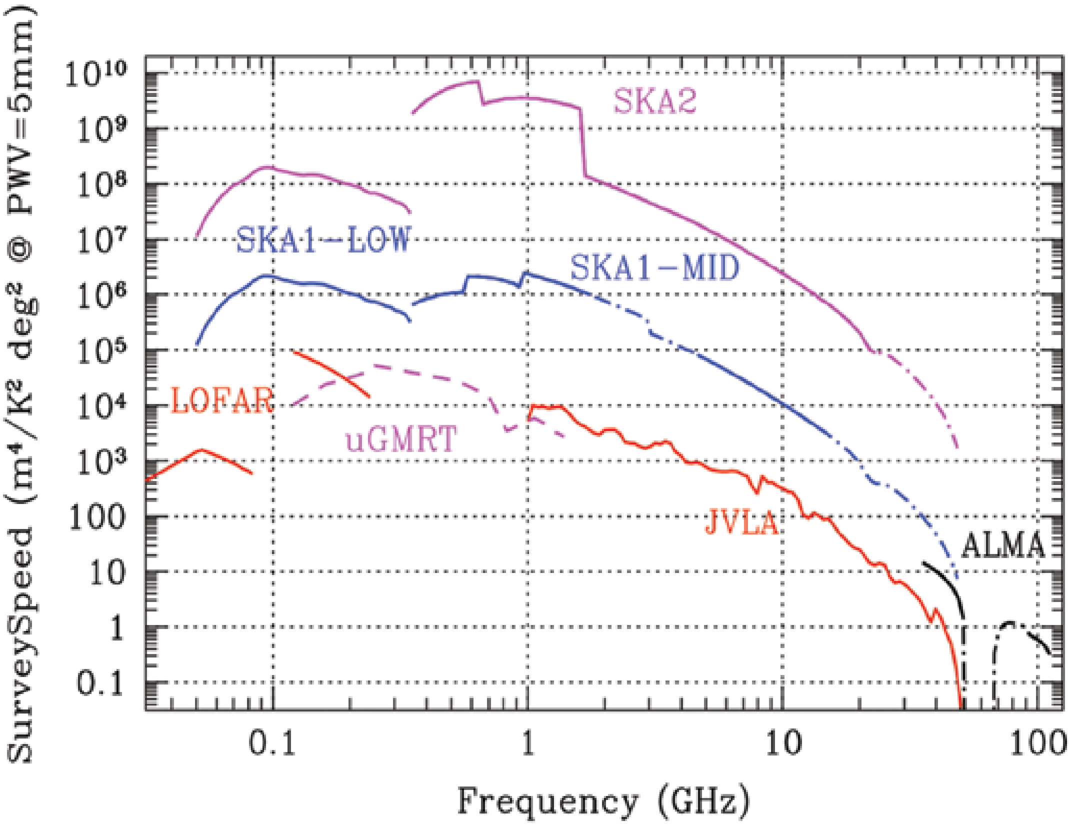


Figure 60 SKA anticipated survey speed. The dot-dashed lines indicate upgrade paths for SKA1, to be confirmed. Credit: SKA Organisation

Nominal frequency	110 MHz	300 MHz	770 MHz	1.4 GHz	6.7 GHz	12.5 GHz
Range [G Range [GHz] Hz]	0.05-0.35	0.05-0.35	0.35-1.05	0.95-1.76	4.6-8.5	8.3-15.3
Telescope	Low	Low	Mid	Mid	Mid	Mid
FoV [arcmin]	327	120	109	60	12.5	6.7
Max. Resolution [arcsec]	11	4	9.5	0.3	0.06	0.03
Max. Bandwidth [GHz]	0.3	0.3	1	1	4	5
Cont. rms, 1hr [mJy/beam]	26	14	4.4	2	1.3	1.2
Line rms, 1hr [mJy/beam]	1850	800	300	140	90	85
Resolution range for Cont. & Line rms [arcesec]	12-600	6-300	1-145	0.6-78	0.13-17	0.07-9
Channel width (uniform resolution across max. bandwidth) [kHz]	5.4	5.4	15.2	15.2	61.0	79.3
Spectral zoom windows x narrowest bandwidth [MHz]	4 x 4.0	4 x 4.0	4 x 3.125	4 x 3.125	4 x 3.125	4 x 3.125
Finest zoom channel width [Hz]	244	244	190	190	190	190

Figure 61 Key parameters of the two SKA1 telescopes and their expected performance. Credit: SKA Organisation

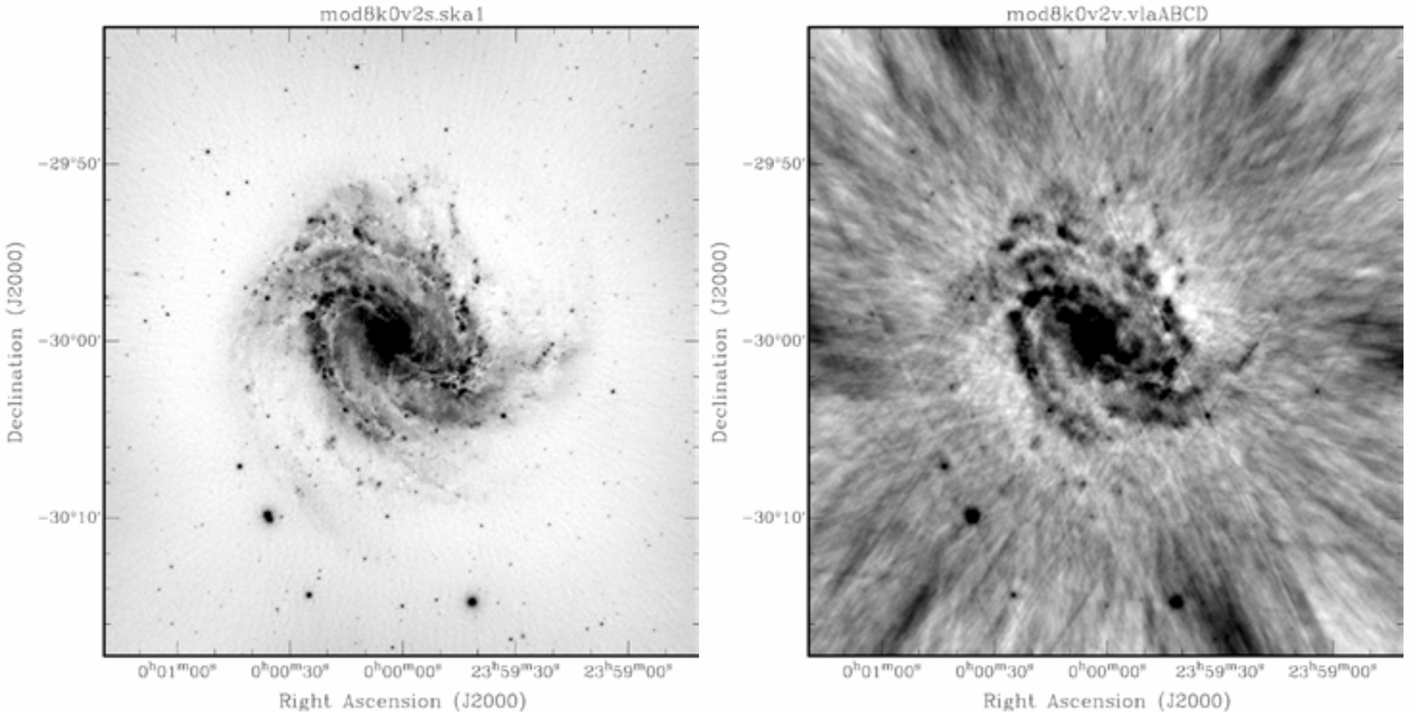


Figure 62 Simulated image reconstruction of face-on spiral galaxy by single SKA1-Mid snapshot compared to combination of snapshots in each of VLA A+B+C+D. Credit: SKAO

Appendix C: SKA historical milestones

Milestones in the Development of the SKA Concept (Credit: SKAO)	
1991	Concept
1993	International Union of Radio Science (URSI) established the Large Telescope Working Group
1997	Memorandum of Agreement signed by eight institutions from six countries. "Memorandum of Agreement to Cooperate in a Technology Study Program Leading to a future Very Large Radio Telescope"
2000	Memorandum of Understanding signed at the International Astronomical Union in Manchester to establish the International Square Kilometre Array Steering Committee (ISSC)
2004	Memorandum of Agreement to Collaborate in the Development of the Square Kilometre Array, this collaboration agreement also made provision for the establishment of the International SKA Project Office (ISPO)
2007	Proposed expansion of the ISPO with the ISSC calling for proposals to host the project office International Collaboration Agreement fo the SKA Program drawn up, establishing the SKA Science and Engineering Committee (SSEC) as a replacement to the ISSC Further agreement drawn up. Memorandum of Agreement to establish the SKA Program Development Office (SPDO)
2008	Project office selected and moved to University of Manchester
2011	SKA Organisation established to formalise relationships between the international partners and centralise the leadership of the project
2012	Site selection of the SKA sites, Australia and South Africa Project office relocated to Jodrell Bank Observatory
2013	International Engineering Consortia to design the SKA formed
2015	Start of negotiations towards establishing SKA Observatory as an Intergovernmental Organisation (IGO)
2016	System-wide Preliminary Design Review concluded
2018	Start of Critical Design Reviews
2019	Signature of the SKA Convention following the conclusion of the IGO negotiations Opening of the SKA Global Headquarters at Jodrell Bank System-wide Critical Design Review

Appendix D: Useful links

The SKA organisation

https://www.skatelescope.org/ska-organisation/

EPFL Leading House for Swiss collaboration with SKA

https://www.epfl.ch/labs/lastro/scientific-activities/ska/

The Swiss Data Science Center (SDSC)

https://www.epfl.ch/research/domains/sdsc/

Common Data Centre Infrastructure (CDCI)

https://www.astro.unige.ch/cdci/

CDCI online Data Analysis

https://www.astro.unige.ch/cdci/astrooda_

FHNW Institute for Data Science (I4DS)

https://www.fhnw.ch/en/about-fhnw/schools/school-of-engineering/institutes/institute-for-data-science

I4DS Astroinformatics and Heliophysics

https://astro-helio.ch/

The Swiss National Supercomputing Centre (CSCS)

https://www.cscs.ch/

University of Applied Science and Arts Western Switzerland

https://www.hes-so.ch/

SCITAS (Scientific IT and Application Support

https://www.epfl.ch/research/facilities/scitas/

Swiss Industry Liaison Office for International Research Organisations

https://www.swissilo.ch/