PROBING THE NATURE OF DARK MATTER WITH THE SKA

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The Square Kilometre Array (SKA) is the most ambitious radio telescope ever planned, and it is a unique multi-disciplinary experiment. The SKA, in its original conception, has been dedicated to constrain the fundamental physics aspects on dark energy, gravitation and magnetism. However, much more scientific investigation could be done with its configuration: the exploration of the nature of Dark Matter, that we discuss here, is one of the most important additional scientific themes.

1 The SKA

With a collecting area of about one square kilometer, the SKA will be about fifty times more sensitive than the currently most powerful radio interferometer, the Expanded Very Large Array (EVLA). The SKA will continuously cover most of the frequency range accessible from ground, from 70 MHz to 10 GHz in the first (SKA-1) and second (SKA-2) phases, and it will be later extended to at least 25 GHz. The SKA will have an enormously wide field of view, ranging from 200 square degrees at 70 MHz to at least 1 square degree at 1.4 GHz. The speed to survey a large part of the sky, particularly at the lower frequencies, will hence be $10^4$ to $10^6$ times faster than what is possible today.

The SKA is a radio interferometer consisting of many antennas (see Fig.1) which will be spread over a large area to obtain high resolving power. The SKA central region will contain about 50% of the total collecting area and comprises i) separate core stations of 5 km diameter each for the dish antennas and the two types of aperture arrays, ii) the mid-region out to about 180 km radius from the core with dishes and aperture array antennas aggregated into stations distributed on a spiral arm pattern, and iii) remote stations with about 20 dish antennas each one out to distances of at least 3000 km from the core, and located on continuations of the spiral arm pattern. The overall extent of the array determines the angular resolution, which will be $\sim 0.1$ arcsec at 100 MHz and $\sim 0.001$ arcsec at 10 GHz. To meet these ambitious specifications in a sustainable way, the planning and construction of the SKA requires many technological innovations such as light and low-cost antennas, detector arrays with a wide field of view, low-noise amplifiers, high-capacity data transfer, high-speed parallel-processing computers and high capacity data storage units. The enormous data rates of the SKA will require online image production with automatic software pipelines.

The SKA frequency range that is spanning more than two decades cannot be realized with one single antenna design, so this will be achieved with a combination of different types of antennas. Under investigation are the following designs for the low and mid-frequency ranges: i) An aperture array of simple dipole antennas with wide spacings (a sparse aperture array) for
the low-frequency range (~70-450 MHz). This is a software telescope with no moving parts, steered solely by electronic phase delays. It has a large field of view and can observe towards several directions simultaneously.

2) An array of several thousand parabolic dishes of about 15 meters diameter each for the medium-frequency range (~0.45-3 GHz), each equipped with a wide-bandwidth single-pixel feed. The surface accuracy of these dishes will allow a later receiver upgrade to higher frequencies.

As an Advanced Instrumentation Programme for the full SKA, two additional technologies for substantially enhancing the field of view in the 0.5-1 GHz range are under development: aperture arrays with dense spacings, forming an almost circular station 60m across and phased-array feeds for the parabolic dishes.

Technical developments of the SKA project around the world are being coordinated by the SKA Science and Engineering Committee and its executive arm, the SKA Project Office. The technical work itself is funded from national and regional sources, and is being carried out via a series of verification programs. The global coordination is supported by funds from the European Commission under a program called PrepSKA, the Preparatory Phase for SKA, whose primary goals are to provide a costed system design and an implementation plan for the telescope by the end of 2012. A number of SKA Pathfinder telescopes provide examples of low frequency arrays, such as LOFAR (Low Frequency Array) telescope, with its core in the Netherlands, MWA (Murchison Widefield Array) in Australia, PAPER (Precision Array to Probe the Epoch of Reionization), both in South Africa and in Australia, LWA (LongWavelength Array) in the USA. All these low-frequency telescopes are software telescopes steered by electronic phase delays (phased aperture array). Examples of dishes with a single-pixel feed are under development in South Africa (MeerKAT, Karoo Array Telescope KAT-7). Dense aperture arrays comprise up...
to millions of receiving elements in planar arrays on the ground which can be phased together to point in any direction on the sky. Due to the large reception pattern of the basic elements, the field of view can be up to 250 square degrees. This technology can also be adapted to the focal plane of parabolic dishes. Prototypes of such wide-field cameras are under construction in various countries participating the SKA.

The data from all stations have to be transmitted to a central computer and processed online. Compared to LOFAR - with a data rate of about 150 Gigabits per second and a central processing power of 27 Tflops - the SKA will produce at least one hundred times more data and need much more processing power.

On 25 May 2012 the Members of the SKA Organisation announced that the SKA telescope would be split over Africa and Australia, with a major share of the telescope destined to be built in South Africa. The scheme in Fig.1 shows the distribution of the SKA components across the African and Australian continents (see http://www.ska.ac.za/releases/20120530.php)

The detailed design for low and mid frequencies will be ready by 2013. The development of technologies for the high-frequency band (about 3-25GHz) will start in 2013. Construction of the SKA-2 is planned to start in 2016. In the first phase (until 2019) about 10% of the SKA will be erected (SKA-1) (Garrett et al. 2010), with completion of construction at the low and mid frequency bands by about 2023, followed by construction at the high-$\nu$ band.

Apart from the many expected technological spin-offs, five main science questions (Key Science Projects) have driven the SKA design (see, e.g., Carilli & Rawlings 2004).

- **Probing the dark ages.** The SKA will use the emission of neutral hydrogen to observe the most distant objects in the Universe and probe the Epoch of Reionization. The energy output from the first stars and AGNs started to heat the neutral gas, forming bubbles of ionized gas as structure emerged. The signatures from this exciting transition phase should still be observable with help of the redshifted HI (21-cm) line. The lowest SKA frequency will allow to detect HI at redshifts of up to 20, to search for the transition from a neutral to an ionized Universe, and hence provide a test of our cosmological model.
• **Galaxy evolution, cosmology, and dark energy.** The expansion of the Universe is currently accelerating, a not understood phenomenon, that is often referred to be produced by dark energy (DE). One important method of distinguishing between the various explanations is to compare the distribution of galaxies at different epochs in the evolution of the Universe to the distribution of matter at the time when the Cosmic Microwave Background (CMB) was formed. Small distortions in the distribution of matter (baryon acoustic oscillations) should persist from the era of CMB formation until today. Tracking if and how these ripples change in size and spacing over cosmic time can then constrain the existing models for DE or indicating the way to new possible ideas. Deep all-sky SKA survey will detect HI emission from Milky Way-like galaxies out to $z \sim 1$. The galaxy observations will be sliced in different redshift (time) intervals and hence reveal a comprehensive picture of the Universe's history. The same data set will provide unique information about the evolution of galaxies, how the hydrogen gas was concentrated to form galaxies, how fast it was transformed into stars, and how much gas did galaxies acquire during their lifetime from intergalactic space. HI survey will simultaneously yield information on the synchrotron radiation intensity of the galaxies which is a measure of their star-formation rate, high-E particle content and magnetic field strength.

• **Tests of General Relativity and detection of gravitational waves.** Pulsars are ideal probes for experiments in the strong gravitational field. The SKA can detect almost all pulsars in the Milky Way (see, e.g., Beck 2011) and several 100 bright pulsars in nearby galaxies. The SKA will search for a radio pulsar orbiting around a black hole, measure time delays in extremely curved space with much higher precision than with laboratory experiments and hence probe the limits of General Relativity. Regular high-precision observations with the SKA of a network of pulsars with periods of milliseconds opens the way to detect gravitational waves with wavelengths of many parsecs, as expected for example from two massive black holes orbiting each other with a period of a few years resulting from galaxy mergers in the early Universe. When such a gravitational wave passes by the Earth, the nearby space-time changes slightly at a frequency of a few nHz. The wave can be detected as apparent systematic delays and advances of the pulsar clocks in particular directions relative to the wave propagation on the sky.

• **Origin and evolution of cosmic magnetism.** Synchrotron radiation and Faraday Rotation (FR) revealed magnetic fields in our Milky Way, nearby spiral galaxies, and galaxy clusters, but little is known about magnetic fields in the intergalactic medium. Furthermore, the origin and evolution of magnetic fields is still unknown. The SKA will measure FRs towards tens of million polarized background sources (mostly AGNs), allowing to derive the magnetic field structures and strengths of the intervening objects, such as, the Milky Way, distant spiral galaxies, clusters of galaxies, and the intergalactic space.

• **The cradle of life.** The SKA will be able to detect the thermal radio emission from centimeter-sized pebbles in protoplanetary systems which are thought to be the first step in assembling Earthlike planets. Biomolecules are also observable in the radio range. Prebiotic chemistry - the formation of the molecular building blocks necessary for the creation of life - occurs in interstellar clouds long before that cloud collapses to form a new solar system. Finally, the SETI (Search for Extra Terrestrial Intelligence) project will use the SKA to find hints of technological activities. Ionospheric radar experiments similar to those on Earth will be detectable out to several kpc, and Arecibo-type radar beams, like those that we use to map our neighbor planets in the solar system, out to $\sim 10$ kpc.

Two out of the five major science goals have been identified that drive the technical specifications for the first phase (SKA-1):
Origins: Understanding the history and role of neutral hydrogen in the Universe from the dark ages to the present-day.

Fundamental Physics: Detecting and timing binary pulsars and spin-stable millisecond pulsars in order to test theories of gravity.

There are however additional science cases for the SKA dealing with new discoveries and opportunities: the search for Dark matter and the understanding of its nature is certainly an important aspect in the exploration of the unknown with the SKA.

2 Probing the nature of Dark Matter with the SKA

Among the viable competitors for having a cosmologically relevant DM species, the leading candidate is the lightest particle of the minimal supersymmetric extension of the Standard Model (MSSM, see Jungman et al. 1996), plausibly the neutralino $\chi$, with a mass $M_\chi$ in the range between a few GeV to a several hundreds of GeV. Information on the nature and physical properties of the neutralino DM can be obtained by studying the astrophysical signals of their interaction/annihilation in the halos of cosmic structures. These signals involve, in the case of a $\chi$ DM, emission of gamma-rays, neutrinos, together with the synchrotron and bremsstrahlung radiation and the Inverse Compton Scattering (ICS) of the CMB (and other background) photons by the secondary electrons produced in the DM annihilation process (see Colafrancesco 2010 for a review). Neutralinos which annihilate inside a DM halo produce quarks, leptons, vector bosons and Higgs bosons, depending on their mass and physical composition. Electrons and positrons (hereafter referred to as electrons for simplicity) are then produced from the decay of the final heavy fermions and bosons. The different composition of the $\chi\chi$ annihilation final state will in general affect the form of the electron spectrum.

Neutral pions produced in $\chi\chi$ annihilation decay promptly in $\pi^0 \rightarrow \gamma\gamma$ and generate most of the continuum spectrum at energies $E \gtrsim 1$ GeV.

Secondary electrons are produced through various prompt generation mechanisms and by the decay of charged pions, $\pi^\pm \rightarrow \mu^\pm\nu_\mu(\bar{\nu}_\mu)$, with $\mu^\pm \rightarrow e^\pm + \bar{\nu}_\mu(\nu_\mu) + \nu_e(\bar{\nu}_e)$ and produce $e^\pm$, muons and neutrinos.

Secondary electrons are subject to spatial diffusion and energy losses. Both spatial diffusion and energy losses contribute to determine the evolution of the source spectrum into the equilibrium spectrum of these particles, i.e. the quantity which is used to determine the multi-frequency spectral energy distribution (SED) induced by DM annihilation. The time evolution of the secondary electron spectrum is described by the transport equation:

$$\frac{\partial n_e}{\partial t} = \nabla [D \nabla n_e] + \frac{\partial}{\partial E} [b_e(E)n_e] + Q_e(E,r),$$

where $Q_e(E,r)$ is the $e^\pm$ source spectrum, $n_e(E,r)$ is the $e^\pm$ equilibrium spectrum and $b_e$ (given here in units of GeV/s) is the $e^\pm$ energy loss per unit time $b_e = b_{ICS} + b_{\text{synch}} + b_{\text{brem}} + b_{\text{Coul}}$, with $b_{ICS} \approx 2.5 \cdot 10^{-17}(E/\text{GeV})^2$, $b_{\text{synch}} \approx 2.54 \cdot 10^{-18}B^2(E/\text{GeV})^2$, $b_{\text{brem}} \approx 1.51 \cdot 10^{-16}(n_{th}/\text{cm}^{-3})(\log(\Gamma/n_{th}) + 0.36)$, $b_{\text{Coul}} \approx 7 \cdot 10^{-16}(n_{th}/\text{cm}^{-3})(1 + \log(\Gamma/n_{th})/75)$. Here $n_{th}$ is the ambient gas density and $\Gamma \equiv E/m_e c^2$.

The diffusion coefficient $D$ in eq.(1) sets the amount of spatial diffusion for the secondary electrons: it turns out that diffusion can be neglected in galaxy clusters while it is relevant on galactic and sub-galactic scales (see discussion in Colafrancesco, Profumo & Ullio 2006, 2007). Under the assumption that the population of high-energy $e^\pm$ can be described by a quasi-stationary ($\partial n_e/\partial t \approx 0$) transport equation, the secondary electron spectrum $n_e(E,r)$ reaches

*Neutralino DM annihilation produces several types of particle and anti-particle fluxes, whose complete description is not discussed here for the sake of brevity. We refer the interested reader to Colafrancesco, Profumo & Ullio (2006) for the case of galaxy clusters and Colafrancesco, Profumo & Ullio (2007) for the case of dwarf galaxies.
its equilibrium configuration mainly due to synchrotron and ICS losses at energies $E \gtrsim 150$ MeV and to Coulomb losses at lower energies.

Secondary electrons eventually produce radiation by synchrotron in the magnetized atmosphere of cosmic structures, bremsstrahlung with ambient protons and ions, and ICS of CMB (and other background) photons (and hence an SZ effect, Colafrancesco 2010). These secondary particles also produce heating of the ambient gas by Coulomb collisions with the ambient plasma particles.

**The Spectral Energy Distribution from DM annihilation**

The astrophysical signals of neutralino DM annihilation computed in various DM models can be visible over the entire e.m. spectrum, from radio to $\gamma$-ray frequencies (see Fig. 2).

As pointed by Colafrancesco et al. (2006), the relevant physical properties of DM which determine the features of the emitted radiation are the composition of the neutralino, its mass, and the value of the annihilation cross section.

A large amount of efforts have been put in the search for DM indirect signals at gamma-ray energies looking predominantly for two key spectral features: the $\pi^0 \rightarrow \gamma\gamma$ decay spectral bump, and the direct $\chi\chi \rightarrow \gamma\gamma$ annihilation line emission. Results from Fermi-LAT and other Cherenkov gamma-ray experiments are so far not conclusive and hopes are relegated to the next CTA experiment.

Here we alternatively discuss the impact of radio observations towards DM halos on large scales, i.e. from dwarf galaxies to clusters of galaxies.

**Radio emission**

Secondary $e^\pm$ produced by $\chi\chi$ annihilation can generate synchrotron emission in the magnetized atmosphere of galaxy clusters (as well as galaxies) which could be observed at radio frequencies as a diffuse radio emission (i.e. a radio halo or haze) centered on the DM halo. Observations of cluster radio-halos are, in principle, very effective in constraining the neutralino
mass and composition (Colafrancesco & Mele 2001, Colafrancesco et al. 2006), under the hypothesis that DM annihilation provides a major contribution to the radio-halo flux. Under this hypothesis, a pure energy requirement requires that the neutralino mass is bound to be \( M_\chi \geq 23.4 \text{GeV} \left( \nu / \text{GHz} \right)^{1/2} (B/\mu G)^{-1/2} \) in order that the secondary e± emit at frequencies \( \nu \geq 1 \) GHz, as observed in cluster radio halos (see Fig.7). Soft DM models (bb with \( M_\chi = 40 - 60 \) GeV) are able to reproduce both the overall radio-halo spectrum of Coma and the spatial distribution of its surface brightness, while hard DM models (W+W− with \( M_\chi = 81 - 500 \) GeV) are excluded being the radio spectrum too flat to reproduce the Coma data (see Colafrancesco et al. 2006, 2011).

In dwarf galaxies, radio emission is strongly affected by propagation effects. Fig.3 shows that for a propagation set up (Diff. set #1) with a Kolmogorov spectrum \( (D \propto E^{1/3} B^{-1/3}_\mu) \) there is a depletion of the electron populations with a significant fraction leaving the diffusion region, while for a propagation set up (Diff. set #2) with a steeper spectrum \( (D \propto E^{0.6} B^{0.6}_\mu) \) they are more efficiently confined within the diffusion region but still significantly misplaced with respect to the emission region. As a consequence, also the spectral shape of the radio flux of Draco is affected by diffusion effects which produce a steeper spectral slope when the electron populations are more efficiently confined within the diffusion region (i.e. Diff. set #2) with respect to the case (i.e. Diff. set #1) where there is a depletion of the electron populations with a significant fraction leaving the diffusion region (see Colafrancesco et al. 2007 for details).

Predictions for the SKA

Deep observations of radio halos in DM halos are not yet available, and this limits in fact the capabilities of the available radio experiments to set relevant limits on DM models. Our program of deep search for DM radio emission in a sample of local dwarf galaxies has been recently approved with the ATCA observatory and the results of our analysis will be soon available to the community. The limits on \( \chi DM \) radio signals obtainable with the available radio telescopes will be surpassed by far by the next coming large radio experiments like SKA and its precursor MeerKAT (in South Africa).

For the case of a typical dwarf galaxy, like e.g. Draco, the constraints on a typical DM model that has been already investigated will be at least a factor 100 more constraining than the limits obtained by Fermi-LAT in the gamma-rays (see Fig.3). This is mainly due to the unprecedent sensitivity of the SKA, even considering the decrease in the peak signal of DM-induced radio emission produced by the spatial diffusion effects. These limits scale with the value of the B field in dwarf galaxies following the SED behaviour shown in Fig.2. Analogous searches for radio emission in large cosmological volumes of DM halos are being planned with the SKA and with the MeerKAT precursor. In this framework the SKA will be also able to set a reliable estimate of the magnetic field in the dwarf galaxy region by using both polarization measurements and Faraday Rotation measurements of background radio sources. In addition, the possibility to have an extended frequency coverage of the SKA in its Phase-2 reaching at least 25 GHz will allow to use both radio synchrotron observations and Inverse Compton observations of the same DM-produced secondary electrons to fully disentangle the magnetic field vs. electron degeneracy present in the synchrotron radio emission and thus determine at the same time both the magnetic field and the DM particle properties contributing

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\(^b\)For the diffusion coefficient we consider here the case of a Kolmogorov form \( D(E) = D_0 / B^{1/3}_\mu (E/1 \text{ GeV})^{1/3} \) with \( D_0 = 3 \cdot 10^{28} \text{ cm}^2 \text{ s}^{-1} \), in analogy with its value for the Milky Way (here \( B_\mu \) is the magnetic field in units of \( \mu G \)). The dimension of the diffusion zone is, consistently with the Milky Way picture, about twice the radial size of the luminous component, i.e. \( \approx 102 \) arcmin for Draco (Diff. set #1). An extreme diffusion model in which the diffusion coefficient is decreased by two orders of magnitudes down to \( D_0 = 3 \cdot 10^{26} \text{ cm}^2 \text{ s}^{-1} \) (implying a much smaller scale of uniformity for the magnetic field), and with a steeper scaling in energy, \( D(E) = D_0 (E/1 \text{ GeV})^{-0.6} \) (this is the form sometime assumed for the Milky Way) is considered for comparison (Diff. set #2)
to the diffuse radio emission in a DM halo. This possibility offered by the SKA will further allow to use radio observations of DM halos to probe the distribution of DM halos up to quite high redshifts (see Colafrancesco & Marchegiani 2012) and in principle up to the redshift range in which there is not a major content of baryons in DM halos associated with primordial galaxies (thus excluding the possibility to produce radio emission by other kind of mechanisms, like e.g. cosmic ray emission or HI line emission) but leaving the DM-induced radio emission like the minimum guaranteed source of radio emission (in the DM models we are considering here).

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