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Extragalactic observatory science with the ASTRI Mini-Array at the *Observatorio del Teide*

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The ASTRI Mini-Array is a system of nine imaging atmospheric Cherenkov telescopes to be deployed at the *Observatorio del Teide* (Tenerife, Spain). In a first phase, the instrument will be operated as an experiment, with an observation schedule focused on primary science cases at multi-TeV energies (origin of cosmic rays, cosmology and fundamental physics, GRBs and multi-messenger astrophysics). Afterwards, a guest-observer observatory phase will follow, in which other significant targets will be pointed at. In this contribution, we focus on this second phase, presenting the observational feasibility of the most relevant extragalactic γ-ray emitters (high-synchrotron peaked blazars, Seyfert galaxies, self-interacting dark matter dominated dwarf spheroidal galaxies) and astrophysical processes detectable over long-term time scales that best complement and expand the ASTRI Mini-Array core science. In order to derive our results, detailed simulations have been performed by means of the most up-to-date ASTRI Mini-Array instrument response functions. The prospects of observing extragalactic targets with the ASTRI Mini-Array include the characterization of spectral shape and features of the multi-TeV emission from the considered classes of AGN with short-to-long duration (5 h to 200 h) observations, the detection of sources not yet observed at TeV energies and the improvement of the constraints on the cross section and lifetime of dark matter particles with 100 h observations of best-choice dwarf galaxies, and the possibility to simultaneously observe sources falling in the same field of view (up to a few degrees) with dedicated pointings.

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1. Overview

The ASTRI Mini-Array (ASTRI MA), a system of imaging atmospheric Cherenkov telescopes (IACTs) composed of nine ASTRI small-sized telescopes (SSTs), is under construction at the *Observatorio del Teide* (Tenerife, Canary Islands) [1]. The telescopes are characterized by a large field of view (FoV) of $\sim$10°, and a spatial and energy resolution of a few arcmin and $\sim$10%, respectively, for energies $\gtrsim$1 TeV [2]. The ASTRI MA will start to operate as an experiment and, therefore, will prioritize observations of core-science cases to investigate in detail the origin of cosmic rays, aspects of cosmology and fundamental physics, GRBs and multi-messenger astrophysics [3, 4]. Observations of additional sources will be mostly performed in a subsequent observatory phase. The prospects of galactic astronomy with the ASTRI MA are covered in dedicated contributions [5, 6]; in this document, we aim to highlight the scientific prospects for the observations of extragalactic sources during the observatory phase of the instrument.

The main goals of extragalactic astronomy are short-to-long (from $\lesssim$10 h to $\gtrsim$100 h duration) observations of active galactic nuclei (AGN) at energies $\gtrsim$1 TeV and on cosmology and fundamental physics studies. To reach such an amount of observing time, the large FoV of the ASTRI MA can be fully exploited to perform simultaneous observations of sources located within an angular distance up to $\sim$5° from a given primary target; this choice is motivated by the fact that the ASTRI off-axis performances slowly decrease up to a factor of $\sim$2 lower than the on-axis ones for separations up to 5° [2]. In this way, we can get the simultaneous observation of multiple extragalactic sources in single dedicated pointings. In Fig. 1 we present the sky distribution of optimal ASTRI MA targets, taken from cross-correlations of catalogues of known local or low-redshift objects (e.g., [7]): the fields suitable to be exploited for simultaneous observations are highlighted.

In the following, we provide an overview on the results expected from extragalactic observations at very high energies (VHE) with the ASTRI MA, with a particular focus on:

- the study of the TeV and multi-TeV emission from high-synchrotron peaked (HSP) blazars and Seyfert galaxies;
- the search of γ-ray signals produced by dark matter (DM) annihilation or decay into Standard Model (SM) pairs from halos around the dwarf spheroidal galaxies.

The scientific prospects of the observations of potential ASTRI MA targets have been evaluated using a suitable set of instrument response functions (IRFs). Such IRFs have been extracted from a dedicated Monte-Carlo (MC) production of γ-ray and background (proton and electron) showers that have been analyzed with `A-SciSoft`, the data reduction and scientific analysis software of the ASTRI Project [8].

2. Study of the multi-TeV γ-ray emission from AGN

AGN represent the largest sample of γ-ray emitters located outside the Milky Way. Among them, blazars are characterized by emission covering the whole electromagnetic spectrum, and dominated by non-thermal radiation attributed to a relativistic jet of plasma pointing close to our line of sight [9]. They usually show flux variability, and are also considered possible sources of

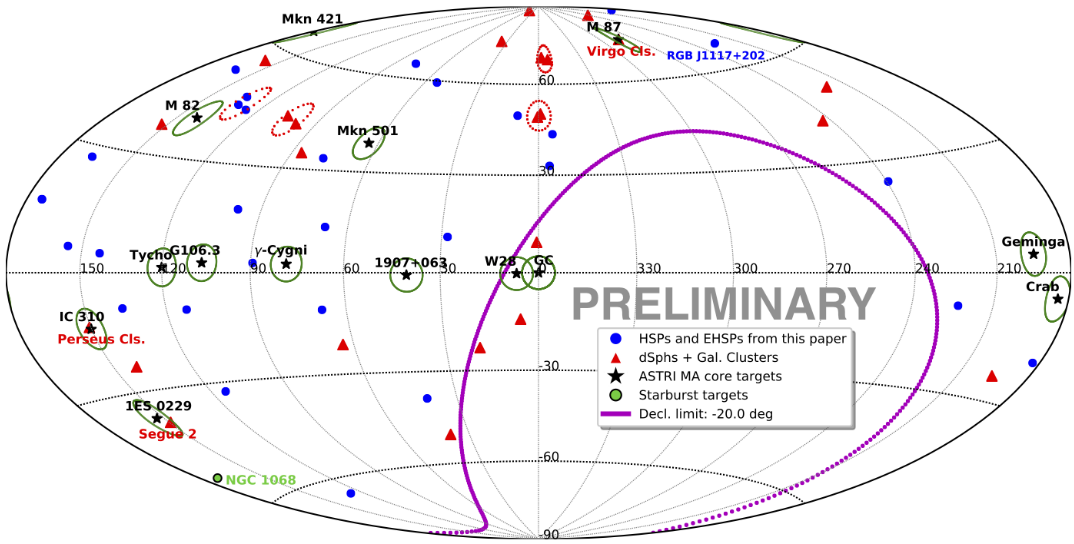
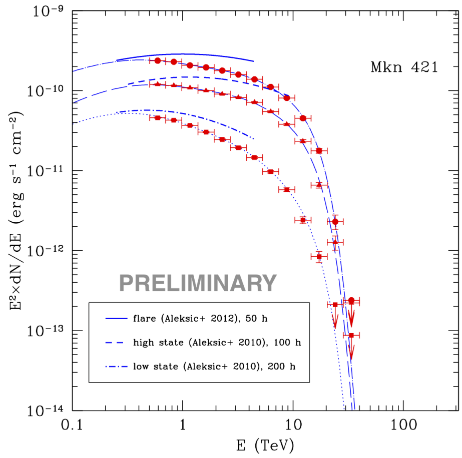


Figure 1: Sky distribution, in Galactic coordinates and Hammer-Aitoff projection, of the ASTRI MA extragalactic targets (see legend). The position in Galactic coordinates of the ASTRI core-science targets (*black stars*) is also shown. A 5° radius circle is drawn around clustered extragalactic targets to be potentially observed in a single joint observation (*red dotted circles*; see text). Core-science targets are also highlighted (*green solid circles*). The assumed limit on source declination for targets visible from the *Observatorio del Teide* (*purple line*) is indicated.

ultra-high-energy cosmic rays and PeV neutrinos [10]. A proposed classification scheme for blazars is based on the position of the synchrotron peak in their spectral energy distribution (SED) that defines low (peak below 10^{14} Hz), intermediate (peak between 10^{14} Hz and 10^{15} Hz) or high-synchrotron peaked (HSP) blazars (peak above 10^{15} Hz) [11]. For the latter, the γ-ray hump also peaks at very high energies (VHE, typically above 100 GeV). Within the class of HSPs, there is an important minority, called "extreme HSPs" (EHSPs), where the synchrotron emission peaks in the 0.1–10 keV X-ray band and the γ-ray hump peaks above $\sim$1 TeV [12].

Seyfert galaxies are another class of AGN that also emit non-thermal radiation in the γ-ray band [13]. The origin of this emission is still undetermined. Potential mechanisms to produce it include the acceleration of relativistic particles by magnetic reconnection in the nuclear region of these sources [14], non-thermal emission from relativistic particles accelerated in the shocks produced by supernova explosions [15], and shocks produced by the interaction of AGN-driven winds with the surrounding interstellar matter [16, 17]. In particular, such shocks are expected to accelerate protons and electrons to relativistic energies with an efficiency that may exceed that of supernova remnants.

To quantify the actual capabilities of the ASTRI MA to detect and study in detail VHE spectral features in different populations of AGN (HSPs, EHSPs, Seyfert galaxies), and to detect sources not yet observed by current IACTs, we investigated simulated observations of the two closest known blazars Mkn 421 and Mkn 501 ($z \sim 0.03$), and of the HSP RGB J1117+202 detected by *Fermi*-LAT [18]. Along with these targets, we also discuss the simulation of the Seyfert 2 NGC 1068. Using the ASTRI MA IRFs, we simulated the observation of the selected blazars for various amounts of



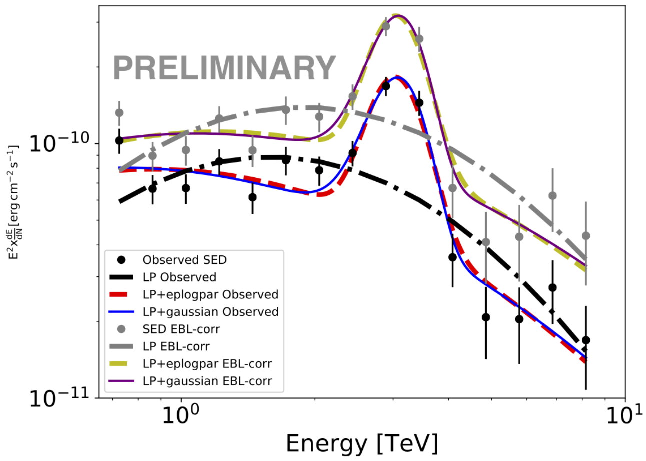


Figure 2: *Left panel:* simulations of different source states of Mkn 421. Depending on the source state, 50 h (*red dots*), 100 h (*red triangles*) and 200 h observations (*red squares*) were simulated respectively, considering the intrinsic source spectra (see legend) convolved with the EBL absorption [19] (*blue dot-long-dashed, long-dashed and dotted lines*). *Right panel:* short-duration (1 h exposure) simulation of the Mkn 501 γ-ray narrow spectral feature in the high state. Both observed and EBL-corrected spectra are shown.

exposure time (from a few hours up to 200 h) coupled with an assumed source state (flare, high state, low state). We show in Fig. 2 that, depending on the source state, the VHE blazar spectra can be studied in great detail beyond the energy cut-off with up to at most ~50 h of observation during flares, with the additional possibility to detect them with high significance and resolve narrow γ-ray features such as emission lines [20] thanks to the ASTRI MA high spectral resolution (~10% at $E_\gamma \gtrsim 1$ TeV). Furthermore, as shown in Fig. 3, long-duration observations (up to 200 h) can unveil the VHE emission of weaker sources, and, in the case of Seyfert galaxies, permit to successfully detect the VHE emission from AGN-driven winds.

3. Indirect dark matter searches in dwarf spheroidal galaxies

DM comprises the largest component of the matter content in the Universe [21]; however, its existence is so far only inferred through indirect evidence of gravitational interaction with baryonic matter. The current frontier of DM searches is represented by the identification of candidate elementary particles outside the Standard Model (SM), in particular cold weakly interacting massive particles (WIMPs). Such particles could annihilate or decay into SM pairs, that can in turn produce final-state VHE photons [22]. Outside the Milky Way, the most DM-dominated sources are the dwarf spheroidal galaxies (dSphs) [23] and the galaxy clusters; due to their relative proximity ($d_\odot \lesssim 250$ kpc) and lack of background emission, the former configure as the best targets for indirect DM searches in the γ-ray domain.

In order to assess the capabilities of the ASTRI MA to search for DM in dSphs, we considered three best-choice targets observable from the Northern hemisphere: Ursa Minor (UMi), Coma Berenices (CBe), and Ursa Major II (UMa II). Such dSphs have been selected for being hosted in massive DM halos [24]. Taking advantage of the ASTRI MA IRFs coupled to a full-likelihood method [25] implemented into the analysis pipeline, we studied the response of the instrument to

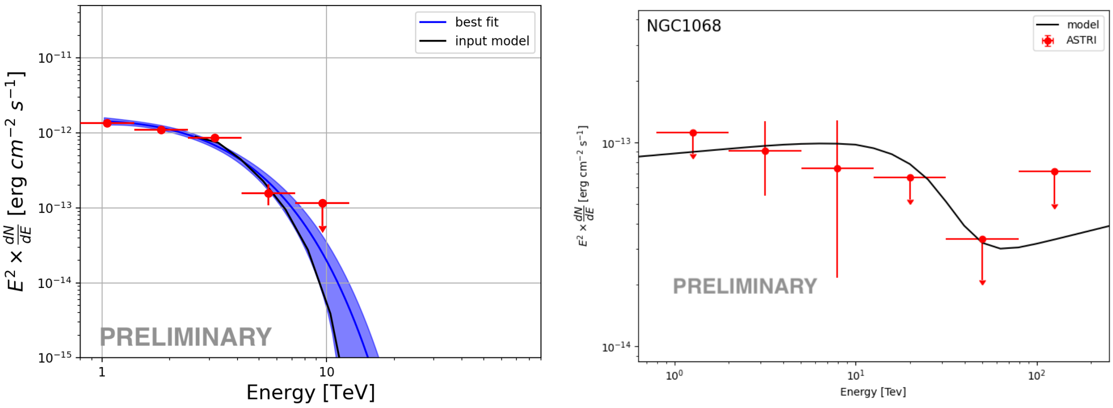


Figure 3: *Left panel:* spectrum of RGB J1117+202 for 200 h observations. The adopted source spectral model (*black line*) is shown superimposed to the corresponding uncertainty of the reconstructed emission profile (*blue line and shaded area*) and the observed spectrum (*red dots*). *Right panel:* simulated γ-ray spectrum of NGC 1068. The observed signal after 200 h of observation (*red dots*) is shown superimposed to the spectrum predicted by the AGN wind model (*black line*) [16, 17].

signals produced by the annihilation of SM pairs produced by DM self-interaction: in particular, we focus on the $b\bar{b}$, $\tau^+\tau^-$, W^+W^- (continuous spectra) and $\gamma\gamma$ channels (monochromatic lines) [26]. We then simulated event lists for 100 h observations of UMi and CBe, and for both 100 h and 300 h in the case of UMa II, assuming point-like sources. Since such simulations provided no evidence of γ-ray signals, we derived constraints on the interaction parameters of the DM particles – cross section $\langle\sigma_{\rm ann}v\rangle$ and particle lifetime $\tau_{\rm dec}$ – as a function of the DM particle mass m_χ in the range $0.55 \div 100$ TeV. Such constraints are computed both for the case of UMa II observed alone for 300 h, and for the 100 h observations of the three selected targets stacked together.

We present in Fig. 4 the final ASTRI MA sensitivity curves at 300 h to DM annihilation cross sections and decay lifetimes for the $\tau^+\tau^-$ channel, both in the case of single-target (UMa II) and stacked observations of dSph halos (UMi, CBe and UMa II). At $m_\chi \gtrsim 10$ TeV, a comparison with the existing literature shows that $\gtrsim$300 h observations of extragalactic DM halos with the ASTRI MA may provide constraints on the properties of DM particles at multi-TeV energies that are at the same level of or better than those available from other VHE searches available in the literature. Coupled with observations of the Galactic center and halo, the search of γ-ray signals at multi-TeV energies from DM-dominated extragalactic sources is a science topic for which the ASTRI MA may give interesting contributions.

4. Conclusions

The detailed exploration of the scientific prospects of extragalactic astrophysics at multi-TeV energies that are in reach of the next-generation IACT system ASTRI MA, to be deployed at the *Observatorio del Teide*, has been focused on:

- the characterization of the spectral shape and features – e.g., cut-offs and emission lines – of the multi-TeV γ-ray emission from extreme blazars (HSPs and EHSPs);

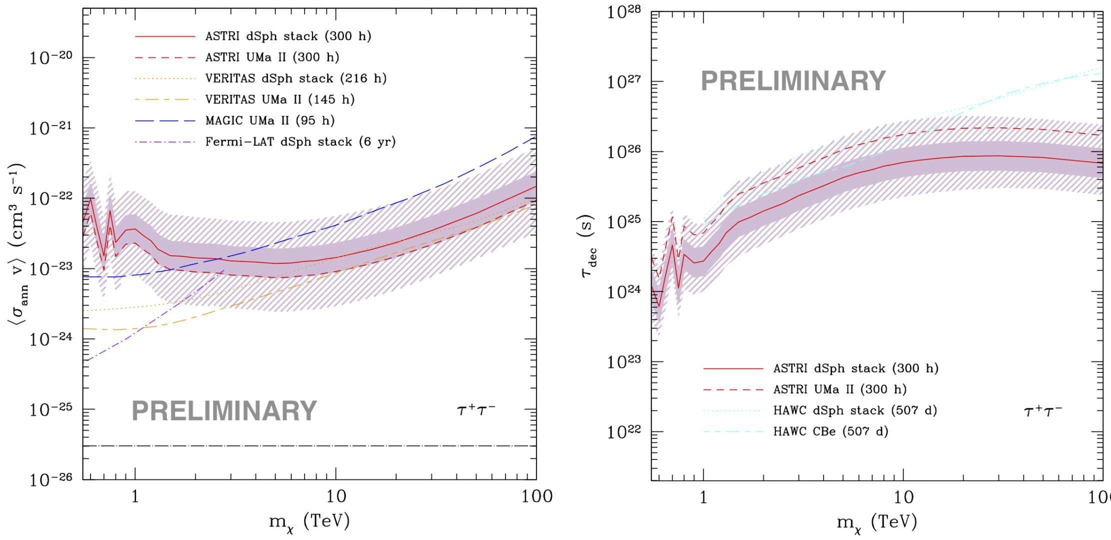


Figure 4: Comparison between 300 h ASTRI MA sensitivity limits to DM particle cross section (*left panel*) and lifetime (*right panel*) for the $\tau^+\tau^-$ channel (*red solid and dashed lines*), and the corresponding limits obtained by existing space- and ground-based facilities for γ-ray observations (see legends for color and line-style codes). Error bands at 68% probability on the parameters due to photon statistics (*pink shaded areas*) and to uncertainties on the DM amount in the dSph halos (*pink hatched areas*) are indicated. The velocity-averaged thermal relic cross section $\langle\sigma v\rangle \sim 3 \times 10^{-26}$ cm^3 s^{-1} for DM annihilation [27] (*black dot-dashed line*) is indicated.

- the detection at TeV energies of new blazars, not yet observed with current IACTs;
- the study of the γ-ray emission from AGN-driven outflows in Seyfert galaxies;
- new independent long-duration observations of dSphs aimed at detecting hints of DM signatures, or improving the constraints on the cross section and lifetime of particle DM self-interacting into SM products, particularly in the multi-TeV mass range.

Such observations may greatly benefit from an almost uniform instrument response up to $\sim 5°$ off-axis: due to this characteristic, an observing strategy optimized to take full advantage of the ASTRI MA capabilities may be foreseen to point at clustered extragalactic targets at once, in order to increase the number of observed sources without requesting large amounts of dedicated exposure time.

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