Future of gamma-ray astronomy: CTA

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THE CHERENKOV TELESCOPE ARRAY

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The Cherenkov Telescope Array (CTA) is a next-generation observatory proposed for very high-energy gamma rays aiming to achieve complete sky coverage, improve sensitivity by about an order of magnitude over current imaging air Cherenkov telescopes (IACTs), cover an energy range of about four decades (from a few tens of GeV to above 100 TeV), and to enhance angular and energy resolutions. CTA will have a large discovery potential in key areas of astronomy, astrophysics and fundamental physics research. These include the study of the origin of cosmic rays and their impact on the constituents of the universe, the investigation of the nature and variety of black hole particle accelerators, and enquiries into the ultimate properties of matter and physics beyond the Standard Model.

1 CTA concept and project

Current IACT instruments and air shower experiments have produced a wealth of exciting results and have demonstrated that very high energy (VHE) phenomena are ubiquitous throughout the universe raising the need of a new generation instrument for a deeper understanding of the underlying phenomena. The mature technology of current Cherenkov telescopes and the high quality of their data open the perspective to build up CTA, a new and highly reliable infrastructure consisting of $O(10^2)$ telescopes of three different sizes, covering an energy range from a few tens of GeV to above 100 TeV and located at two sites in the northern and the southern hemispheres to achieve full-sky coverage.

A formal international collaboration has been set up, which has now over 1000 members from 27 countries from Europe, Asia, Africa and North and South America. In 2010 the CTA Consortium completed a Design Study [Actis et al.[1]] and started a three-year Preparatory Phase which should lead to production readiness of CTA in 2014. The CTA Consortium aims to build a next-generation system with unprecedented sensitivity, spectral coverage, and angular, energy and timing resolutions; and that it will be operated as a true observatory open to the wider scientific community and providing support for easy access and analysis of data.

CTA will be composed of three classes of telescopes: the Large Size Telescopes (LSTs) for the lowest energies, the medium ones (MSTs) for the core energy range and many small ones

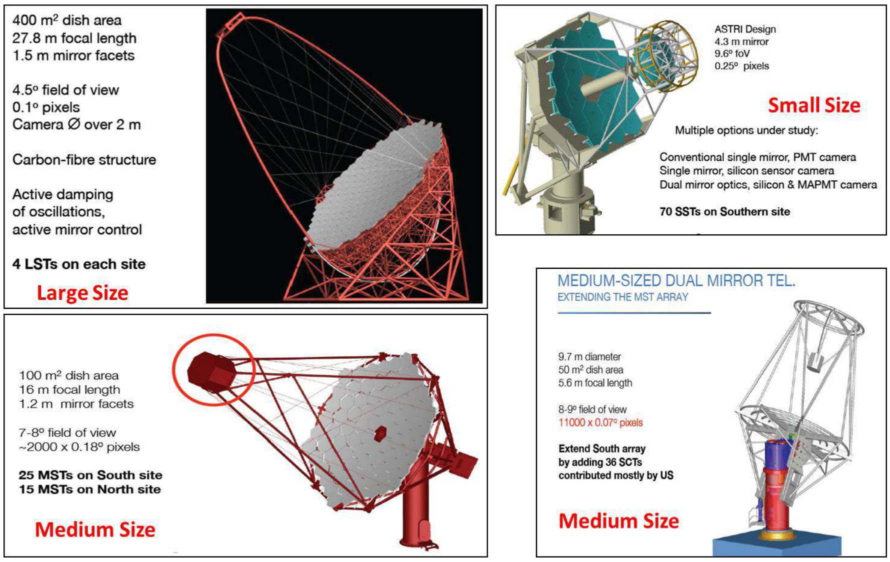

Figure 1: Summary of the three classes (large, medium, small sizes) telescopes parameters and examples of current designs under investigation and optimisation through prototyping phases.

(SSTs) for the highest energies (figure 1). For sensitivity at the highest energies, CTA requires a collection area of the order of 10 km^2 which means spreading numerous telescopes over a substantial area. The CTA Consortium is leading an important R&D and prototyping phase aiming to finalise the best design of the telescopes and define the technical implementation details. The light collection capability (i.e. the product of mirror area and the photon collection and detection efficiencies), the field-of-view (FoV), and the camera pixel size, which limits the size of image features which can be resolved, are the main figures of merit characterising the performance of a single Cherenkov telescope. Intensive technical developments in mechanics are being carried out for the: LST, for which the rapid re-pointing for GRB follow-up motivates the choice of a light-weight structure of stiff carbon tubes holding a 23 m diameter reflector [Deleglise et al.[2]], and for the MST and SST in their dual-mirror Schwarzschild-Couder (SC) optical design option with small camera and pixel size, requiring high mechanical stability of the order of few μm. The electronics for signal capture and triggering should provide a bandwidth matched to the length of Cherenkov pulses (of a few nanoseconds). The performance of an array is also dependent on the triggering strategy. Cherenkov emission from air showers has to be separated in real time from the high flux of night sky background photons, based on individual images and the combination of images from several telescopes. Characterisation of new generation photo-sensors, i.e. the Silicon-PM potentially providing higher photo-detection efficiency and reduced single-pixel size [Shayduk et al.[3], Teshima et al.[4]], together with corresponding front-end electronics design are other important and promising development paths followed in every class of telescope sub-project. Figure 1 shows the design of the three classes of telescopes currently under investigation and a summary of main current design parameters. It is worth recalling that the large number of telescopes, warranted to ensure a higher sensitivity than current instruments, will also enable independent operations of sub-arrays which can be pointed at either one source or multiple directions to cover a larger area of the sky.

Determining the arrangement and characteristics of the CTA telescopes in the southern and northern arrays is a complex optimisation problem, requiring a balance of cost against performance in different bands of the spectrum. Figure 2 illustrates the current achievable sensitivity by the southern array (and the contribution to it by the three classes of telescopes sub-arrays) according to the Monte Carlo (MC) simulation study of a potential baseline layout [Bernlöhr et al.[5]]. While at TeV and tens of TeVs energies, background and area extension are respectively the major limiting factors, at lower energy where a core of four LSTs will operate

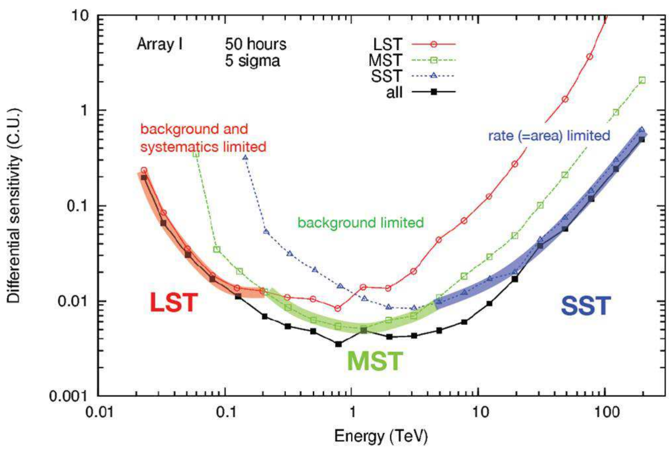

Figure 2: Differential sensitivity (in units of the energy-dependent flux of the Crab nebula) for array I: 4 LSTs, 23 MSTs and 32 SSTs telescopes (50 h, 5 σ, 5% background, 10 events, alpha=0.2).

the systematic effects of the gamma-rays shower evolution are the main constraints. Further expected performance are the angular resolution from 0.3° to 0.02° and the energy resolution from 25% to 5% depending on the energy domain [Hinton et al.[6]].

2 CTA science cases

CTA will have a large discovery potential in research areas including among others the study of the origin of cosmic rays and their impact on the constituents of the universe, the investigation of the nature and variety of black hole particle accelerators, and enquiries into the ultimate properties of matter and physics beyond the Standard Model, e.g by searching for dark matter and the effects of quantum gravity. With its expected performance CTA opens the path to two major and unique (in the sense that no other instrument has a similar ability in the same energy regime) scientific goals at gamma-ray energies: producing the deepest surveys of the sky (with unprecedented angular and energy resolution, and energy coverage); performing the first sensitive observation of short timescale phenomenology. About the latter, the optimisation of CTA (LST sub-array) particularly in the overlapping energy range 10-100 GeV has taken into account competition and complementarity with Fermi. A first in-depth comparison by Funk et al.[7] of the two sensitivities shows that CTA will perform better thanks to its higher sensitivity although the Fermi-LAT obviously has a huge advantage in terms of field of view. For short-term phenomena (order of minutes) CTA will perform orders of magnitude better than the Fermi-LAT. In the following some examples of selected key science questions addressed by CTA are discussed as well as the critical requirements set-up by them are recalled. For a more complete view on more physics topics see Hinton et al.[6].

2.1 Cosmic-rays origin: population studies of supernova remnants

The expected impact of future observations with CTA for cosmic ray studies relies on its improved sensitivity aiming to increase significantly the number of detected sources making possible population studies of sources like PWNe, SNRs, and molecular clouds. Being able to detect such objects up to the other side of the Galaxy, CTA is expected to provide hundreds of sources and in particular a sample of several tens of TeV-bright young SNRs.

CTA will enable a statistical analysis of the SNR properties in gamma rays through dedicated population studies [Acero et al.[8]]. Only for 5 of the SNRs, that have been detected in TeV gamma rays, their morphology was resolved and they exhibit a clear shell-like morphology: RX J1713.7-3946, Vela Junior, RCW 86 1, SN 1006, and HESS J1731-347. Extrapolating their luminosities

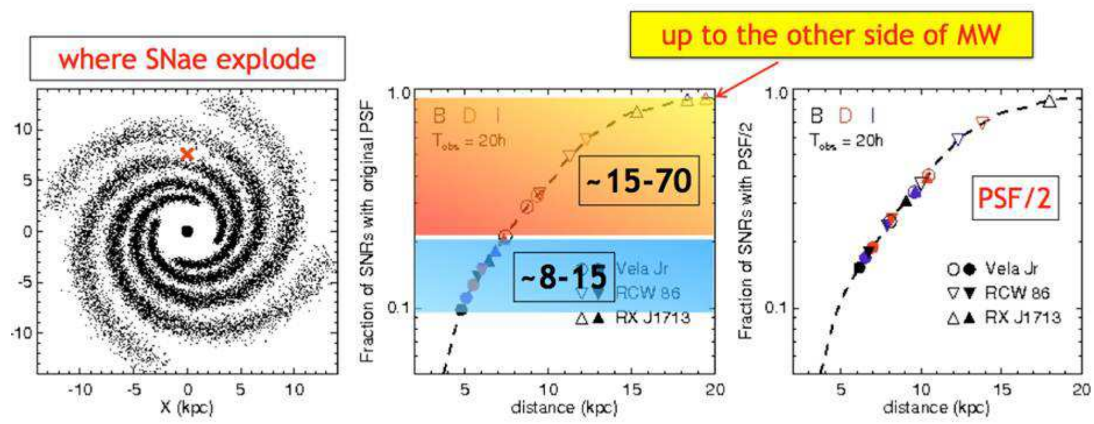

Figure 3: Left: simulated distribution of Galactic SNRs. The Sun and the Galactic centre are depicted by the red cross and the black dot, respectively. Middle: Fraction of SNRs visible as a function of distance from Earth (dashed line). Right: same as middle but with the CTA PSF improved by a factor of 2.

as representative of the whole class of SNRs starting from the CTA expected sensitivity one can derive the horizon of detectability: the maximum distance at which a generic SNR would be detected. From the knowledge of the spatial distribution of supernovae in the Galaxy (also simulated in figure 3-left panel), their explosion rate, and the duration of the TeV emission (believed to last a few thousand years) we can obtain the prediction for the number of objects detectable by CTA. Monte Carlo simulations study considering the angular resolution of CTA as a function of size and distance of the sources have been conducted [Acero et al.[8]]. The results enable to estimate (in absence of prior detection of shell-like morphology in other wavelengths, e.g. radio) the CTA horizon of resolvability, defined as the maximum distance up to which the shell of an SNR can be spatially resolved and distinguished from a simple Gaussian shape. In the middle and right panels of figure 3 the fraction of SNRs located within a given distance from the Sun and visible with zenith angle $< 45°$, from the CTA southern hemisphere array, is plotted as a dashed line. The horizon of detectability and of resolvability have been computed for three TeV-bright shell type SNRs: Vela Jr (circles), RCW 86 (downward triangles), and RX J1713 (upward triangles). The horizon of resolvability is indicated with the filled symbols and is defined as the distance up to which the shell-like morphology of those objects would be significantly identified by CTA and favoured at 3σ over the uniform sphere model. The horizon of detectability is indicated by the open symbols and indicates the maximum distance up to which the three SNRs would be detectable by CTA with a peak significance of 5σ, regardless of their morphology. The two horizons have been defined after simulating 100 SNR images per distance bin for an observing time of 20 hours. Different colours refer to three different configurations of the array. If it is assumed that an SNR is bright in TeV gamma rays for $\sim$3000 yr (this is approximately the age of Vela Jr), and we recall that $\sim$2.8 supernovae are expected to explode each century in the Galaxy, one can infer that the number of SNRs currently emitting TeV gamma rays is $\sim$80. One can then use the results from figure 3 to infer the number of SNRs detectable (or resolvable) by CTA. The difference between the middle and the right panel is in the PSF that has been assumed in the calculations.

The CTA improved sensitivity over a large energy range will increase greatly the quality of spectral studies. This will possibly enable the detection of cutoffs or breaks in gamma ray spectra of SNRs, which combined with a competitive angular resolution (e.g. if a goal PSF of about 1 arcmin at 10 TeV is achieved) will also constrain the width of the TeV-counterpart filaments in several energy bands compared to those measured in X-rays. Such spectro-imaging studies could shed light on the nature (leptonic or hadronic) of the VHE emission.

The spectral sensitivity at the highest energies would make it possible the search also for

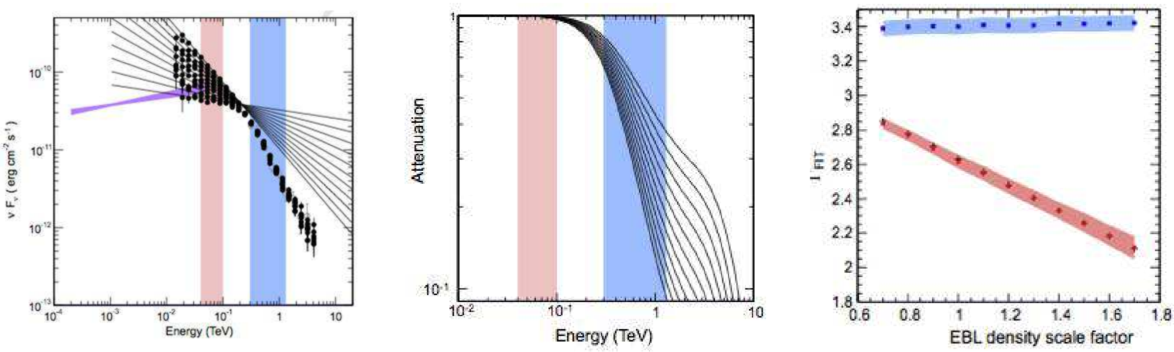

Figure 4: Simulation of CTA measurement of quiescent spectrum of PKS 2155-304 (z=0.116): distinguishing different levels of EBL attenuation effect (see description in the text).

Pevatron candidate within this galactic population. A $> 3\sigma$ excess reachable after 8-10 hours would be followed by deeper observation for discovery confirmation.

2.2 Extragalactic population studies, black holes and star formation history

Thanks to the past and current IACT systems, more than 45 Active Galactic Nuclei (AGN), spread in redshifts from z = 0.0018 to z = 0.536, have been identified in the VHE band; the majority of these sources belonging to the blazar class (presenting continuum emission by a relativistic jet closely aligned with the line of sight). An other class of AGN TeV emitters, more recently detected, are radiogalaxies (e.g. M87 and Cen A). Although these observations already challenge current theories of particle acceleration, to better understand a possible AGN unification scheme, a large statistical population study is demanded and CTA will provide it with hundreds of AGN to be detected. CTA will offer: a large dynamic range well above 10 000 for the studies of bright VHE flaring epochs; sub-minute timing resolution to catch AGN micro-variability; 10% to 15% energy resolution and four orders in magnitude of energy range. These are all crucial figures of merit of CTA to contribute to answer open questions on AGN physics such as the nature of black hole magnetosphere, the formation of jets and the acceleration of particles, the total energy budget, or the prime origins of variability. CTA is expected to firmly detects and studies quiescent stationary VHE states between bright flares of blazars and AGN, consequently leading, through comparison within a larger population, to clarify the validity of the so-called blazar sequence or other tentative unifying scheme [Sol et al.[10]]. A crucial role is expected in this context by the LSTs which, enabling the detection at E>30 GeV, would make possible to detect extragalactic objects at different redshifts, it will therefore clarify the actual distribution of observed photon spectral index versus redshift and to study evolutionary effects at VHE, at least for the blazar class. Furthermore, observing over a large spectral range up to several tens of TeV with a good spectral resolution will make it possible to find out whether the observed cut-offs in the blazar spectra are intrinsic to the source or are induced by the effect of Extragalactic Background Light (EBL) absorption, and to analyze the maximal energies at which particles are accelerated. Meanwhile as already experimented by current telescopes, it would be possible to further indirectly constrain the EBL density and infer the star formation history (SFR), one of the fundamental quantities of cosmology and which is closely linked to structure and galaxy formation. Up to a redshift of 1 to 2 the star formation rate is reasonably well measured (spread of 20-50%). At higher redshifts, data are rare and mostly lower limits are provided. To accurately model the intrinsic parameters of distant sources one requires a simultaneous measurement of the EBL attenuation (at high energies), together with the unattenuated intrinsic spectrum (at the lowest energies). Results of MC simulation study on the capability of CTA are shown in figure 4 where an example of simulated spectra for different EBL densities is proposed [Mazin et al.[11]]. The base spectrum assumed is the quiescence state spectrum of PKS 2155-304. The measured spectrum (grey markers), the simulated spectra for different level of the EBL density (black markers) and the corresponding assumed intrinsic spectra (black lines) are illustrated together; the source spectrum in the GeV energy range as measured by Fermi-LAT is also shown (purple butterfly), and the energy ranges, which are used to determine the slope of the simulated spectrum at low (light red) and high (blue) energies. The CTA high sensitivity in the energy range between 20 and 100 GeV would make possible to sample directly parts of the energy spectrum of a source, which are not affected by the EBL attenuation (red-band in figure 4-middle panel). With the difference between the measured spectrum in the unabsorbed part of the VHE spectrum and in the absorbed part of the spectrum (blue-band in figure 4-middle panel), especially if studied for several sources with good statistics, the strength of the EBL can be derived. Figure 4-right panel shows the measured spectral index of the blazar from the fit of a power law to the low (red) and high (blue) energy range versus the scaling factor of the EBL model. The colour shaded bands denote the error on the spectral index from the fit (RMS of the spectral index distribution). Black crosses mark the intrinsic spectral index that has been utilised. One can notice from these results the level of precision of spectral measurements expected from CTA.

The guaranteed science cases indirectly related to the AGN population study and EBL attenuation measurements concern: reducing uncertainties of the cosmic star formation rate (SFR), traced by the EBL, at higher redshifts; constraining cosmological models and measure the Hubble parameter and cosmological densities though universalising of blazars spectra versus redshifts; probing the properties of early stars and galaxies in the epoch of reionization, by upper limits on the EBL density from spectral cutoffs in sources at very high redshifts ($z > 5$), feasible for Gamma Ray Bursts (GRBs) with CTA. A common expectation is that only GRBs will provide high enough gamma-ray luminosity to detect a source located at high redshifts ($z > 2$): GRB 080916C was the brightest GRB observed by the Fermi/LAT so far. The probability that GRBs with sufficiently high flux will be observed by CTA within its life time has been addressed by several authors finding that CTA, thanks to its low energy threshold of 20-30 GeV and the rapid slewing motion of the LSTs (180° maximum in 20 s) would be able to detect 0.1-0.2 GRBs per year during the prompt phase and about 1 per year in the afterglow phase.

Simulated energy spectrum of GRB 080916C ($z = 4.3$) if measured with CTA is shown in figure 5-left panel assuming EBL from Dominguez et al.[14]. The duration of the measurement is 45 s as measured with Fermi/LAT. A clear detection can be made and spectral shape can be measured from 30 GeV to 100 GeV. Starting from an assumed source flux of $dN/dE = 1.4 \times 10^{-7}\ (E/\mathrm{TeV})^{-1.85}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}\ \mathrm{TeV}^{-1}$ and simulating the CTA spectral measurement after exposure time of 20 s, the EBL models of Inoue et al.[12] (blue) and Kneiske et al.[13] $best - fit$ (red) can be compared. Due to the lower absorption in case of the EBL model of Inoue et al. the spectral shape of the GRB emission can be measured much better.

It has been suggested that Quantum Gravity effects may induce time delays between photons with different energies travelling over large distances due to a non-trivial refractive index of the vacuum. The observation of very distant, strong flaring blazars will provide the strongest constraints of Lorentz Invariance Violation compared to the current generation of IACTs. In order to constrain LIV effects CTA is required to have very good timing capability: for observations of Mrk 421 ($z = 0.03$) with a sensitivity of 10^{-11} erg cm^{-2} s^{-1} for $E > 10$ TeV photons (30 min obs. at 10 TeV), Planck scale effects would be expected to induce a time delay of ~ 1 s/TeV. This means that CTA needs to resolve flare features of ~ 30 s duration. Higher redshift sources will benefit from the lower energy threshold of CTA [Moralejo[15]].

On the other hand, axions, which are a proposed solution to the strong-CP problem of QCD (or ALPs in general), are also valid candidates to constitute a part or all of CDM. They are expected to convert into photons (and vice versa) in the presence of magnetic fields. In the case of a very distant AGN, the ALP/photon can cause either attenuation or enhancement of the photon flux (in competition with the EBL absorption), depending on the ALP mass [Moralejo[15]].

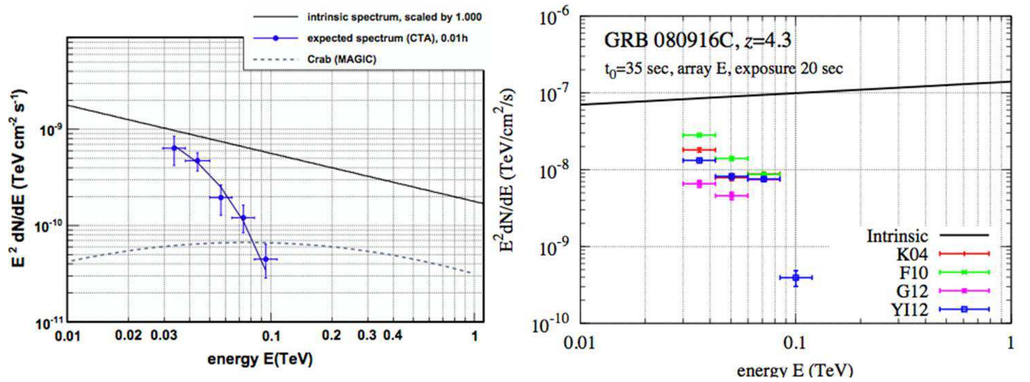

Figure 5: Left) 45 s observation of a bright burst at z=4.3; spectrum determination possible between 50 and 100 GeV (intrinsic spectrum extrapolated from Fermi-LAT). Right) 20 s interval (harder spectrum, higher flux, from Fermi-LAT) allows to distinguish different EBL models.

2.3 Dark Matter

A large number of observations from Galactic to cosmological scales support the explanation that Dark Matter (DM) would be composed by a new type of particle although its nature remains unknown. The proposal of Weakly Interacting Massive Particle (WIMP) predicted by theories beyond the Standard Model of particle physics provides a relic abundance accounting for the inferred amount of DM. The WIMP search is conducted in three ways: by particle production at the LHC, probing the theories of Standard Model extension; by searching for nuclear recoils signals experiments, probing the WIMP scattering cross section; by indirect search looking for a signal in secondary products of WIMP annihilation or decay, probing the annihilation cross section.

Joint observations and complementary investigations along the three different approaches work together to better constrain model parameters. In particular the indirect search conducted through different channels: neutrinos, antimatter cosmic-rays and gamma rays and the overlap of experimental observations can increase confidence in the interpretation of signals, especially because of poorly understood astrophysical backgrounds.

These considerations apply in particular to the gamma-ray based indirect searches for dark matter. Potential spectral signatures in gamma-rays can be classified in mainly strong spectral features and ambiguous signals. The first class is due, for instance, to direct annihilations into $\gamma\gamma$ or $Z\gamma$ producing a sharp line spectrum with a photon energy depending on the WIMP mass (in the SUSY neutralino hypothesis). Unfortunately, these processes are loop-suppressed and therefore very rare. In some extent more ambiguous are signals due to continuum emission from pion decay resulting from the WIMPS annihilations in pairs of leptons or quarks. The number of gamma rays finally originated by WIMP annihilation depends on the DM density along the line of sight of the observer. This motivates a number of promising targets for indirect DM searches, namely those with known density enhancements, foremost the Galactic Centre and close-by dwarf galaxies and galaxy clusters. More specifically, assuming the ΛCDM cosmological model, the hierarchical collapse of small over-densities are formed by DM structures which may also host smaller satellite structures and it has been proposed that dwarf spheroidal galaxies may have formed within some of these sub-halos hosted in the larger Milky Way dark matter halo.

By observing the region around the Galactic Centre, and by adopting dedicated observational strategies [Doro et al.[16]], CTA will reach the canonical velocity-averaged annihilation cross-section of $\sim 3 \times 10^{-26}$ cm^3 s^{-1} in only 100 h observation DM mass above 300 GeV. This will be the first time for ground-based IACTs to reach this sensitivity level. Together with the constraints from Fermi-LAT for DM lighter than a few hundred GeV, this can seriously constrain the WIMP paradigm for CDM in case of no detection. Models with a large photon

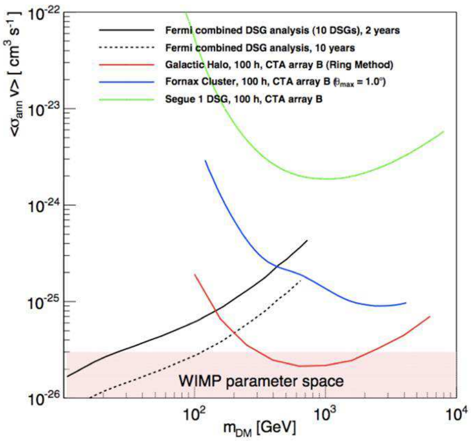

Figure 6: Dwarf spheroidal galaxies are interesting objects for DM search but not the strongest science case for CTA. Galactic halo and (ex. Fornax) galaxy cluster are more promising.

yield from DM annihilation will be constrained to even smaller cross-sections. In conclusion, the WIMP scenario, either through detection or non-detection will be significantly affected by the first years of operation of CTA. Overall, the CTA prospects for detection of the expected dark matter annihilation signal are best for the Galactic halo, followed by galaxy clusters and then dwarf spheroidal galaxies. Comparison of exclusion curves of Fermi-LAT in 24 months and expected for 10 years (rescaled with the square root of time) are shown in figure 6 [Doro et al.[16]]. The exclusion curves for the various targets studied in this contribution are also reported for the bb-annihilation channel: for the dwarf satellite galaxy Segue 1 (green curve), for the Fornax galaxy cluster in case only DM-induced gamma-rays are considered (blue line) and for the ring-method of observation of the Galactic Centre vicinities.

Acknowledgments

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