Active Galactic Nuclei population studies with the Cherenkov Telescope Array


DOI
10.22323/1.395.0887

Publication date
2022

Document Version
Final published version

Published in
Proceedings of Science

License
CC BY-NC-ND

Citation for published version (APA):

General rights
It is not permitted to download or to forward/distribute the text or part of it without the consent of the author(s) and/or copyright holder(s), other than for strictly personal, individual use, unless the work is under an open content license (like Creative Commons).

Disclaimer/Complaints regulations
If you believe that digital publication of certain material infringes any of your rights or (privacy) interests, please let the Library know, stating your reasons. In case of a legitimate complaint, the Library will make the material inaccessible and/or remove it from the website. Please Ask the Library: https://uba.uva.nl/en/contact, or a letter to: Library of the University of Amsterdam, Secretariat, Singel 425, 1012 WP Amsterdam, The Netherlands. You will be contacted as soon as possible.
Active Galactic Nuclei population studies with the Cherenkov Telescope Array

Anthony M. Brown, Atreya Acharyya, Alberto Dominguez, Tarek Hassan, Jean-Philippe Lenain, and Santiago Pita on behalf of the CTA Consortium
(a complete list of authors can be found at the end of the proceedings)

The Cherenkov Telescope Array (CTA) observatory is the next generation of ground-based imaging atmospheric Cherenkov telescopes (IACTs). Building on the strengths of current IACTs, CTA is designed to achieve an order of magnitude improvement in sensitivity, with unprecedented angular and energy resolution. CTA will also increase the energy reach of IACTs, observing photons in the energy range from 20 GeV to beyond 100 TeV. These advances in performance will see CTA heralding in a new era for high-energy astrophysics, with the emphasis shifting from source discovery, to population studies and precision measurements. In this talk we discuss CTA’s ability to conduct source population studies of γ-ray bright active galactic nuclei and how this ability will enhance our understanding on the redshift evolution of this dominant γ-ray source class.
1. Introduction

Over the last 15 years, the current generation of space and ground-based $\gamma$-ray telescopes has revolutionised our view of the high-energy non-thermal Universe. To build upon this success, the international community is now working towards the next generation of ground-based Imaging Atmospheric Cherenkov Telescope (IACT) instruments, the Cherenkov Telescope Array (CTA; [1]). CTA is designed to achieve an order of magnitude improvement in sensitivity with respect to the current generation of IACTs, with unprecedented angular and energy resolution over nearly 4 decades in energy, from 20 GeV to beyond 100 TeV.

The envisaged step-change in performance afforded by CTA will in part be due to CTA's sheer size, and the fact that it will be comprised of three telescope size classes, the Small-Sized-Telescopes (SST), Medium-Sized-Telescopes (MST) and Large-Sized-Telescopes (LST), with each size class optimised to observe a different $\gamma$-ray energy range. The SST component of CTA is primarily responsible for extending the high-energy reach of CTA, predominantly observing $\gamma$-rays with energies from a few TeV up to 100 TeV and beyond. At these extreme photon energies, the limiting factor is not the amount of Cherenkov radiation produced by air showers, but simply the number of $\gamma$-ray induced air showers to observe. As such, the SSTs will be modest in physical size, only 4 m diameter primary mirrors, but there will be a large number of SSTs spread over $\sim 4 \text{km}^2$ [2]. More than two thirds of CTA's southern array telescopes are foreseen to be SSTs. The MSTs will have a diameter of $\sim 12$ m and will dominate the improvement in flux sensitivity in the core $0.2 \leq E_\gamma \leq 10$ TeV energy range. With a diameter of $\sim 23$ m, the LSTs are designed to observe the low Cherenkov photon intensity associated with $20 \leq E_\gamma \leq 200$ GeV photon-induced air showers; however, unlike the SSTs, due to the expected $\gamma$-ray flux in this energy range, there will only be 4 LSTs at the centre of CTA. To allow all-sky coverage, the CTA observatory will consist of two different arrays, one in each hemisphere. The northern array is intended to contain $\sim 20$ telescopes (LSTs and MSTs) spread over about 1 km$^2$, while the southern array is intended to contain $\sim 100$ telescopes (LSTs, MSTs and SSTs) spread over an area of approximately four square kilometres. These improvements in telescope performance will see CTA heralding in a new era for ground-based $\gamma$-ray astronomy, with the emphasis shifting from source discovery, to population studies and precision measurements. During the initial phase of constructing CTA, first arrays of telescopes will enable early scientific observations, with 4 LSTs and 9 MSTs on the Northern site, and 14 MSTs and 37 SSTs on the Southern site, whilst a later construction phase will follow to complete the array. In the following study, this is referred as "alpha configuration", while the full-scope CTA arrays will be referred as "omega configuration".

These proceedings are dedicated to characterising CTA’s ability to observe the population of $\gamma$-ray bright Active Galactic Nuclei (AGN). Considering sources in the fourth Fermi-LAT AGN (4LAC; [3]) catalogue with known redshifts, we use the GAMMAPY software suite [4, 5] with a variety of spectral extrapolation models to higher energies and exposure times, to estimate the number of AGN possibly detectable by both the Northern array and Southern array arrays when accounting for the extragalactic background light (EBL). Importantly, to highlight the impact that the full CTA arrays will have in the context of AGN population studies, we quantify the number

\footnote{Also see Gueta et al. from these proceedings.}
of AGN observed with the full CTA arrays, as well as the smaller total expected with CTA’s initial alpha configuration.

2. The 4LAC catalogue

Since 2008 August 4, the vast majority of data taken by the Large Area Telescope (LAT) on board the Fermi satellite has been performed in all-sky-survey mode, whereby the Fermi-LAT detector points away from the Earth and rocks north and south of its orbital plane, on subsequent orbits. This rocking motion, coupled with Fermi-LAT’s large effective area, allows the LAT instrument to scan the entire γ-ray sky in about a few hours. This observational characteristic, coupled with Fermi-LAT’s long mission lifetime, allows us to construct a deep exposure of the γ-ray sky in the 0.1 – 100 GeV photon energy range.

The 4LAC catalogue lists all γ-ray bright AGN detected by the LAT during the first 8 years of the Fermi mission. In particular, the 4LAC reports the position and best-fit spectral parameters for 2863 γ-ray bright AGN derived from integrating over the entire 8-year data set. The vast majority of the 4LAC AGN are of the blazar class (∼ 98%). Of this 4LAC blazar population, 38% are BL Lac-type objects (BL Lacs), 24% are Flat Spectrum Radio Quasars (FSRQs) and 38% blazar candidates of unknown types (BCUs). Importantly, all AGN currently detected by IACTs are present in 4LAC. As such, the 4LAC catalogue represents a natural starting point from which to quantify the potential of CTA to observe the γ-ray bright AGN population. For this study, we use a subset of the 4LAC catalog revised to only contain sources with a well-known redshift [6]. This target AGN list is then extrapolated to the TeV regime, and prospects of CTA detectability are calculated by using GAMMAPY. A total of 1551 AGN were considered over the whole sky.

3. Extrapolation and computing sensitivity of CTA to the AGN population

3.1 Extrapolating from the 4LAC

Starting with the 4LAC, to quantify CTA’s potential to observe the γ-ray bright AGN population we must extrapolate the 4LAC spectra up across the entire observable energy range expected for CTA. During this extrapolation process, there are several key aspects that need to be considered:

- **Extrapolation scheme:** the functional form of the extrapolation from Fermi-LAT to CTA energies influences the total number of AGN detected. Given our lack of a-priori knowledge of the most appropriate functional form for extrapolation, we use a bracketing approach by assuming both (i) power-law (optimistic) extrapolation (PL) (ii) log-parabola (pessimistic) extrapolation (LP). We note however the LP fits should be taken with caution as existing TeV observations disfavour such an extrapolation of LAT spectra.

- **Extragalactic Background Light:** during propagation from source to Earth, the γ-rays emitted by AGN can interact with the diffuse flux of the Extragalactic Background Light (EBL) creating a positron-electron pair. This interaction will result in an attenuation of the observed γ-ray flux, with the probability of this attenuation being redshift and γ-ray energy dependent. Throughout this study, we describe this probability with the Dominguez 2011
EQL model [7]. Furthermore, due to the redshift dependence of the EQL-attention, this study only considered 4LAC AGN with a well-known redshift\(^2\).

As such, taking these two aspects into consideration, for each AGN, we apply two different extrapolation schemes: (i) Power-law + EQL and (ii) log-parabola + EQL. Given the MeV-GeV energy range over which the 4LAC detects AGN and the fact that the EQL has a minimal impact on \(\gamma\)-rays in the 4LAC energy range, these two extrapolation schemes were applied to the observed 4LAC spectra rather than their EQL-corrected counterparts.

### 3.2 GAMMAPY simulations

For this study, GAMMAPY v0.17 was used with a standard ON-OFF (or aperture photometry) approach. The instrument response functions (IRFs) utilised by GAMMAPY were the final omega array configuration and the proposed initial alpha array configuration, for both Northern sites and Southern sites, from the so-called prod3b-v2 production version\(^3\) [9]. As each of these IRF configurations were simulated for three different sets of zenith distances, depending on each source culmination altitude at each site, the correct IRF was used: 20°, 40° and 60° in zenith IRFs were used for sources culminating below 25°, between 25° to 45° and between 45° to 65° from zenith respectively. Those sources culminating above 65° from zenith on a site were considered un-observable. For each of these array configurations, a 5 hour and 20 hour exposure per source was considered along with five different energy thresholds: 30 GeV, 50 GeV, 100 GeV, 300 GeV, 500 GeV and 1 TeV.

Throughout the analysis, we employ detectability conditions as follows: (i) detection significance: \(S > 5\sigma\) (eq. 17 from [10]); (ii) excess required to be larger than 5% the background rate (five times the systematic uncertainty on the background rate) and (iii) excess required to be larger than 10 events. For each AGN, once the two different extrapolations were applied, for each array configuration, exposure time and energy threshold configurations, 100 separate GAMMAPY simulations were performed. Any AGN for which the average of these 100 simulations satisfied the detection criteria, were considered to be detectable by CTA.

### 4. Results

The results of these simulations for the Northern site alpha and omega configurations can be seen in Table 1, whilst the Southern site alpha and omega configuration results can be seen in Table 2. For both arrays, there are significant differences in the number of AGN detected by the predicted sensitivity of the two different array configurations. As expected, the omega configuration performs better than the initial smaller alpha array, showing that we will be able to expand science reach as more telescopes are installed. In some cases, the final omega array detects over double the number of AGN compared to the initial alpha array. This is most notable in the lower energy threshold analysis of the Southern array arrays where the lack of LSTs in the Southern array alpha array has a

\(^2\) CTA has a dedicated ‘redshift working group’ that validates 4LAC redshifts where necessary, as well as organizes observational campaigns to determine the redshifts for CTA AGN candidates that currently do not have a known redshift [e.g. 8]; for example, see also Kasai et al. from these proceedings.

Table 1: Number of AGN detected for Northern array alpha and omega configurations for the different extrapolation schemes, exposures and energy thresholds considered in this study.

<table>
<thead>
<tr>
<th>Northern omega array</th>
<th>30 GeV</th>
<th>50 GeV</th>
<th>100 GeV</th>
<th>300 GeV</th>
<th>500 GeV</th>
<th>1 TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>5 hour - PL</td>
<td>51</td>
<td>84</td>
<td>114</td>
<td>98</td>
<td>83</td>
<td>65</td>
</tr>
<tr>
<td>20 hour - PL</td>
<td>93</td>
<td>171</td>
<td>209</td>
<td>164</td>
<td>135</td>
<td>103</td>
</tr>
<tr>
<td>5 hour - LP</td>
<td>30</td>
<td>50</td>
<td>73</td>
<td>62</td>
<td>54</td>
<td>41</td>
</tr>
<tr>
<td>20 hour - LP</td>
<td>51</td>
<td>101</td>
<td>131</td>
<td>107</td>
<td>87</td>
<td>64</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Northern alpha array</th>
<th>30 GeV</th>
<th>50 GeV</th>
<th>100 GeV</th>
<th>300 GeV</th>
<th>500 GeV</th>
<th>1 TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>5 hour - PL</td>
<td>30</td>
<td>53</td>
<td>76</td>
<td>73</td>
<td>63</td>
<td>49</td>
</tr>
<tr>
<td>20 hour - PL</td>
<td>60</td>
<td>117</td>
<td>154</td>
<td>131</td>
<td>105</td>
<td>84</td>
</tr>
<tr>
<td>5 hour - LP</td>
<td>19</td>
<td>35</td>
<td>45</td>
<td>45</td>
<td>40</td>
<td>27</td>
</tr>
<tr>
<td>20 hour - LP</td>
<td>33</td>
<td>64</td>
<td>96</td>
<td>86</td>
<td>68</td>
<td>56</td>
</tr>
</tbody>
</table>

Table 2: Number of AGN detected for Southern array alpha and omega configurations for the different extrapolation schemes, exposures and energy thresholds considered in this study.

<table>
<thead>
<tr>
<th>Southern omega array</th>
<th>100 GeV</th>
<th>300 GeV</th>
<th>500 GeV</th>
<th>1 TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>5 hour - PL</td>
<td>117</td>
<td>112</td>
<td>90</td>
<td>71</td>
</tr>
<tr>
<td>20 hour - PL</td>
<td>209</td>
<td>173</td>
<td>147</td>
<td>116</td>
</tr>
<tr>
<td>5 hour - LP</td>
<td>68</td>
<td>66</td>
<td>52</td>
<td>45</td>
</tr>
<tr>
<td>20 hour - LP</td>
<td>122</td>
<td>108</td>
<td>92</td>
<td>73</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Southern alpha array</th>
<th>100 GeV</th>
<th>300 GeV</th>
<th>500 GeV</th>
<th>1 TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>5 hour - PL</td>
<td>50</td>
<td>72</td>
<td>72</td>
<td>53</td>
</tr>
<tr>
<td>20 hour - PL</td>
<td>100</td>
<td>124</td>
<td>125</td>
<td>96</td>
</tr>
<tr>
<td>5 hour - LP</td>
<td>30</td>
<td>45</td>
<td>46</td>
<td>39</td>
</tr>
<tr>
<td>20 hour - LP</td>
<td>57</td>
<td>78</td>
<td>74</td>
<td>56</td>
</tr>
</tbody>
</table>

significant impact in the number of AGN detected. It should be highlighted that in both Table 1 & 2, the number of AGN detected doesn’t simply decrease as the energy threshold increases; rather, the number of AGN detected by CTA varies due to the fact that, at the lowest energies there is a large background, whilst at the highest energy, the signal from the AGN becomes statistics limited.

To achieve some of its key science goals [11], CTA needs to expand the cosmic distances at which blazars are studied. Figure 1 shows the redshift distributions of the simulated and detected AGN for both the alpha and omega configurations of the Northern array and Southern array, for 20 h exposures considering a power-law extrapolation scheme. In both cases, the omega array detects significantly more AGN at large redshifts compared to the alpha configuration. It should be stressed that in this study, we only consider the average 4LAC spectra for extrapolation, integrated over 8 years of the Fermi-LAT data. AGN undergoing $\gamma$-ray flares often exhibit ‘harder-when-brighter’ spectral characteristics (see e.g. [12, 13]), which can facilitate CTA detecting AGN at higher redshifts than those reported here.

The difference in performance of the alpha and omega configurations will also result in differences in the spectral characteristics that CTA will be able to detect from this AGN population.
AGN population studies with CTA

Anthony M. Brown

Figure 1: Redshift distributions of AGN detected by CTA-North (left) and Southern array (right) with 20 h exposures considering a power-law extrapolation scheme. In both cases, the increased sensitivity of the omega array significantly increases the number of AGN detected at larger redshift of the further detected AGN, compared to the alpha configuration. It should be noted that the Southern array comparison considers an energy threshold of 100 GeV, thus negating the major difference between the two array configurations due to the LSTs. As such, this comparison is a conservative one, and we would expect a greater difference.

Figure 2: Flux vs index parameter space for the AGN considered in this study. The grey symbols indicate all AGN simulated, whilst the blue symbols represent the AGN detected by CTA (by either the Northern or Southern array). From left to right, the panels depict the results for the omega and alpha configurations, respectively. This is best seen in Figure 2, which shows the photon index versus integrated flux of all AGN considered in this study. Figure 2 clearly indicates that the omega configuration will increase CTA’s reach across the ‘photon index versus integrated flux’ parameter space compared to the alpha configuration, with CTA being able to detect fainter and/or softer AGN than is possible in its smaller initial alpha configuration.

The results highlight that the CTA will not only multiply the number of sources detected, but also expand the horizons to which we can observe the gamma-ray sky. As described in [14], the detection of high-redshift blazars will enable scientists to explore a range of topics in astronomy, cosmology and fundamental physics. These include the measurement of the gamma-ray absorption by the EBL, investigations of intergalactic magnetic fields, searches for evidence of axion-like particles and multiple tests for Lorentz invariance violation. The increased number of sources will
also provide a basis for a robust reliable estimate of the luminosity function of blazars and help investigate the evolution of the different source populations in this energy regime.

5. Conclusions

With its improved sensitivity, we find that in all analysis configurations considered in this study, the omega configuration performs better than the initial alpha configuration, which shows that we will be able to expand science reach of CTA as more telescopes are installed. In some cases, specifically the Southern array low threshold energy analysis, the difference in the number of AGN detected between the Southern array omega and alpha configurations is greater than 100%. Furthermore, CTA’s omega configuration will detect more AGN at higher redshifts compared to current IACTs, as well as detecting a larger number of fainter and softer AGN compared to the alpha configuration. In addition, multiple propagation studies will already be possible due to the alpha configuration being able to detect sources up to a redshift of \( \approx 1.8 \).

This study shows that even during the construction phase, CTA will already be able to double the number of extragalactic sources detected in the VHE regime, even taking into account that these predictions are most likely conservative, given Fermi-LAT 8-year-averaged spectra are dominated by AGN in low-activity states.

Unfortunately, other \( \gamma \)-ray cosmology studies which require the detection of numerous AGN across a large redshift range, such as attempting to measure the evolution of the EBL across different cosmological epochs or Lorentz invariance violation \([14]\), would greatly profit from the LST component of the omega configuration for the Southern array. This benefit relating to the lower energy threshold is afforded to us by the LSTs, which allow for additional AGN to be detected at large redshifts.

Acknowledgments

We gratefully acknowledge financial support from the agencies and organizations listed here: http://www.cta-observatory.org/consortium_acknowledgments.

References


Gammapy - A prototype for the CTA science tools, in 35th International Cosmic Ray
Conference (ICRC2017), vol. 301 of International Cosmic Ray Conference, p. 766, Jan.,
2017 [1709.01751].

Towards open and reproducible multi-instrument analysis in gamma-ray astronomy, A&A

[6] P. Goldoni, Review of redshift values of bright AGNs with hard spectra in 4LAC catalog,

Extragalactic background light inferred from AEGIS galaxy-SED-type fractions, MNRAS
410 (2011) 2556 [1007.1459].

[2012.05176].

Monte Carlo performance studies for the site selection of the Cherenkov Telescope Array,
Astroparticle Physics 93 (2017) 76 [1705.01790].

317.


[12] A.M. Brown and J. Adams,
High-energy γ-ray properties of the Fanaroff-Riley type I radio galaxy NGC 1275, MNRAS
413 (2011) 2785 [1101.2687].

Multiwavelength variability and correlation studies of Mrk 421 during historically low X-ray and γ-ray activity in

[14] H. Abdalla, H. Abe, F. Acero, A. Acharyya, R. Adam, I. Agudo et al.,
Sensitivity of the Cherenkov Telescope Array for probing cosmology and fundamental physics with gamma-ray jets,
AGN population studies with CTA

Anthony M. Brown

21: INAF - Osservatorio di Astrofisica e Scienze dello Spazio di Bologna, Via Piero Gobetti 93/3, 40129 Bologna, Italy
22: INAF - Osservatorio Astrofisico di Arcetri, Largo E. Fermi, 5 - 50125 Firenze, Italy
23: INFN Sezione di Perugia and Università degli Studi di Perugia, Via A. Pascoli, 06123 Perugia, Italy
24: INFN Sezione di Napoli, Via Cintia, ed. G, 80126 Napoli, Italy
25: INFN Sezione di Roma Tor Vergata, Via della Ricerca Scientifica 1, 00133 Rome, Italy
26: Argonne National Laboratory, 9700 S. Cass Avenue, Argonne, IL 60439, USA
27: Aix-Marseille Université, CNRS/IN2P3, CPPM, 163 Avenue de Luminy, 13288 Marseille cedex 09, France
28: INAF - Osservatorio Astronomico di Roma, Via di Frascati 33, 00040, Monteporzio Catone, Italy
29: INAF - Osservatorio Astrofisico di Catania, Via S. Sofia, 78, 95123 Catania, Italy
30: Grupo de Electronica, Universidad Complutense de Madrid, Av. Complutense s/n, 28040 Madrid, Spain
31: National Astronomical Research Institute of Thailand, 191 Huay Kaew Rd., Suthep, Muang, Chiang Mai, 50200, Thailand
32: Instituto de Astrofísica de Canarias and Departamento de Astrofísica, Universidad de La Laguna, La Laguna, Tenerife, Spain
33: FZU - Institute of Physics of the Czech Academy of Sciences, Na Slovance 999/2, 182 21 Praha 8, Czech Republic
34: Astronomisches Institut der Universität zu Köln, Bögelstrasse 12, 53113 Köln, Germany
35: CCTVal, Universidad Técnica Federico Santa María, Avenida España 1680, Valparaíso, Chile
36: ETH Zurich, Institute for Particle Physics, Schafmattstr. 20, CH-8093 Zurich, Switzerland
37: The University of Manitoba, Dept of Physics and Astronomy, Winnipeg, Manitoba R3T 2N2, Canada
38: Department of Astronomy, University of Geneva, Chemin d’Ecogia 16, CH-1290 Versoix, Switzerland
39: Laboratoire Univers et Particules de Montpellier, Université de Montpellier, CNRS/IN2P3, CC 72, Place Eugène Bataillon, F-34095 Montpellier Cedex 5, France
40: Centro Brasileiro de Pesquisas Físicas, Rua Xavier Sigaud 150, RJ 22290-180, Rio de Janeiro, Brazil
41: Institut de Física d’Altes Energies (IFAE), The Barcelona Institute of Science and Technology, Campus UAB, 08193 Bellaterra (Barcelona), Spain
42: University of Groningen, KVI - Center for Advanced Radiation Technology, Zernikeplein 25, 9747 AA Groningen, The Netherlands
43: School of Physics, University of New South Wales, Sydney NSW 2052, Australia
44: INAF - Osservatorio Astrofisico di Torino, Strada Osservatorio 20, 10025 Pino Torinese (TO), Italy
45: Univ. Savoie Mont Blanc, CNRS, Laboratoire d’Annecy de Physique des Particules - IN2P3, 74000 Annecy, France
46: Department of Physics, TU Dortmund University, Otto-Hahn-Str. 4, 44221 Dortmund, Germany
47: University of Zagreb, Faculty of electrical engineering and computing, Unska 3, 10000 Zagreb, Croatia
48: University of Namibia, Department of Physics, 340 Mandume Ndenufayo Ave., Pioneerspark, Windhoek, Namibia
49: Nicolaus Copernicus Astronomical Center, Polish Academy of Sciences, ul. Bartycka 18, 00-716 Warsaw, Poland
50: Universität Hamburg, Institut für Experimentalphysik, Luruper Chaussee 149, 22761 Hamburg, Germany
51: Graduate School of Science, University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-0033, Japan
52: Deutsches Elektronen-Synchrotron, Platanenallee 6, 15738 Zeuthen, Germany
53: Max-Planck-Institut für Kernphysik, Saupfercheckweg 1, 69117 Heidelberg, Germany
54: RIKEN, Institute of Physical and Chemical Research, 2-1 Hirosawa, Wako, Saitama, 351-0198, Japan
55: INFN Sezione di Padova and Università degli Studi di Padova, Via Marzolo 8, 35131 Padova, Italy
56: Escuela POLITÉCNICA Superior de Jaén, Universidad de Jaén, Campus Las Lagunillas s/n, Edif. A3, 23071 Jaén, Spain
57: Department of Physics and Electrical Engineering, Linnaeus University, 351 95 Vaxjö, Sweden
58: University of the Witwatersrand, 1 Jan Smuts Avenue, Braamfontein, 2001 Johannesburg, South Africa
59: Institut für Theoretische Physik, Lehrstuhl IV: Plasma-Astroteilchenphysik, Ruhr-Universität Bochum, Universitätsstraße 150, 44801 Bochum, Germany
60: Faculty of Physics and Applied Computer Science, University of Lódz, ul. Pomorska 149-153, 90-236 Lódz, Poland
61: INFN - Istituto di Astrofisica Spaziale e Fisica Cosmica di Milano, Via A. Corti 12, 20133 Milano, Italy
62: INFN and Università degli Studi di Siena, Dipartimento di Scienze Fisiche, della Terra e dell’Ambiente (DSFTA), Sezione di Fisica, Via Roma 56, 53100 Siena, Italy
63: Center for Astrophysics | Harvard & Smithsonian, 60 Garden St, Cambridge, MA 02180, USA
64: INFN Sezione di Torino, Via P. Giuria 1, 10125 Torino, Italy
65: Finnish Centre for Astronomy with ESO, University of Turku, Finland, FI-20014 University of Turku, Finland
66: Pidstryhach Institute for Applied Problems in Mechanics and Mathematics NASU, 3B Naukova Street, Lviv, 79060, Ukraine
67: Bhabha Atomic Research Centre, Trombay, Mumbai 400085, India
68: Center for Astrophysics and Cosmology, University of Nova Gorica, Vipavska 11c, 5270 Ajdovščina, Slovenia
69: Institut für Astronomie und Astrophysik, Universität Tübingen, Sand 1, 72076 Tübingen, Germany
70: Research School of Astronomy and Astrophysics, Australian National University, Canberra ACT 0200, Australia
71: Department of Physics and Astronomy, University of California, Los Angeles, CA 90095, USA
72: INFN Sezione di Bari and Politecnico di Bari, via Orabona 4, 70124 Bari, Italy
73: Laboratoire de Physique des 2 infinis, Irene Joliot-Curie,IN2P3/CNRS, Université Paris-Saclay, Université de Paris, 15 rue Georges Clemenceau, 91406 Orsay, Cedex, France
74: INFN Sezione di Pisa, Largo Pontecorvo 3, 56127 Pisa, Italy
75: IRFU/DEEDIP, CEA, Université Paris-Saclay, Bat 141, 91191 Gif-sur-Yvette, France
76: INAF - Osservatorio Astronomico di Padova, Vicolo dell’Osservatorio 5, 35122 Padova, Italy
AGN population studies with CTA

Anthony M. Brown

126: National Centre for Nuclear Research (Narodowe Centrum Badań Jądrowych), Ul. Andrea Sołtan 7, 05–400 Otwock, Świerk, Poland
127: Enrico Fermi Institute, University of Chicago, 5640 South Ellis Avenue, Chicago, IL 60637, USA
128: Institut für Physik & Astronomie, Universität Potsdam, Karl-Liebknecht-Strasse 24/25, 14476 Potsdam, Germany
129: Department of Physics and Astronomy, Iowa State University, Zaffarano Hall, Ames, IA 50011-3160, USA
130: School of Physics, Aristotle University, Thessaloniki, 54124 Thessaloniki, Greece
131: King’s College London, Strand, London, WC2R 2LS, United Kingdom
132: Escola de Artes, Ciências e Humanidades, Universidade de São Paulo, Rua Arlindo Bettio, CEP 03828-000, 1000 São Paulo, Brazil
133: Dept. of Astronomy & Astrophysics, Pennsylvania State University, University Park, PA 16802, USA
134: National Technical University of Athens, Department of Physics, Zografos 9, 15780 Athens, Greece
135: University of Wisconsin, Madison, 500 Lincoln Drive, Madison, WI 53706, USA
136: Astronomical Observatory of Taras Shevchenko National University of Kyiv, 3 Observatorna Street, Kyiv, 04053, Ukraine
137: Department of Physics, Purdue University, West Lafayette, IN 47907, USA
138: Unitat de Física de les Radiacions, Departament de Física, and CERES-IEEC, Universitat Autònoma de Barcelona, Edifici C3, Campus UAB, 08193 Bellaterra, Spain
139: Institute for Space-Earth Environmental Research, Nagoya University, Chikusa-ku, Nagoya 464-8601, Japan
140: Department of Physical Science, Hiroshima University, Higashi-Hiroshima, Hiroshima 739-8526, Japan
141: Department of Physics, Nagoya University, Chikusa-ku, Nagoya, 464-8602, Japan
142: Friedrich-Alexander-Universität Erlangen-Nürnberg, Erlangen Centre for Astroparticle Physics (ECAP), Erwin-Rommel-Str. 1, 91058 Erlangen, Germany
143: Santa Cruz Institute for Particle Physics and Department of Physics and Astronomy, University of California, Santa Cruz, 1156 High Street, Santa Cruz, CA 95064, USA
144: IRFU/ DIS, CEA, Université de Paris-Saclay, Bat 123, 91191 Gif-sur-Yvette, France
145: INFN Sezione di Trieste and Università degli Studi di Trieste, Via Valerio 2, 34127 Trieste, Italy
146: School of Physics & Center for Relativistic Astrophysics, Georgia Institute of Technology, 837 State Street, Atlanta, Georgia, 30332-0430, USA
147: Alikhanyan National Science Laboratory, Yerevan Physics Institute, 2 Alikhanyan Brothers St., 0036, Yerevan, Armenia
148: INAF - Telescopio Nazionale Galileo, Roche de los Muchachos Astronomical Observatory, 38787 Garafia, TF, Italy
149: INFN Sezione di Bari and Università degli Studi di Bari, via Orabona 4, 70124 Bari, Italy
150: University of Split - FESB, R. Boskovicova 32, 21 000 Split, Croatia
151: Universidad Andres Bello, República 252, Santiago, Chile
152: Academic Computer Centre CYFRONET AGH, ul. Nauki 11, 30-950 Cracow, Poland
153: University of Liverpool, Oliver Lodge Laboratory, Liverpool L69 7ZE, United Kingdom
154: Department of Physics, Yamagata University, Yamagata, Yamagata 990-8560, Japan
155: Astronomy Department, Adler Planetarium and Astronomy Museum, Chicago, IL 60605, USA
156: Faculty of Management Information, Yamashita-Gakuen University, Kofu, Yamanashi 400-8575, Japan
157: Department of Physics, Tokai University, 4-1-1, Kita-Kaname, Hiratsuka, Kanagawa 259-1292, Japan
158: Centre for Astrophysics Research, Science & Technology Research Institute, University of Hertfordshire, College Lane, Hertfordshire AL10 9AB, United Kingdom
159: Cherenkov Telescope Array Observatory, Saupfercheckweg 1, 69117 Heidelberg, Germany
160: Tohoku University, Astronomical Institute, Aoba, Sendai 980-8578, Japan
161: Department of Physics, Rikkyo University, 3-34-1 Nishi-Ikebukuro, Toshima-ku, Tokyo, Japan
162: Department of Physics and Astronomy and the Bartol Research Institute, University of Delaware, Newark, DE 19716, USA
163: Institut für Astro- un Teilchenphysik, Leopold-Franzens-Universität, Technikerstr. 25/8, 6020 Innsbruck, Austria
164: Department of Physics and Astronomy, University of Utah, Salt Lake City, UT 84112-0830, USA
165: IMAPP, Radboud University Nijmegen, PO. Box 9010, 6500 GL Nijmegen, The Netherlands
166: Josip Juraj Strossmayer University of Osijek, Trg Ljudevita Gaja 6, 31000 Osijek, Croatia
167: Department of Earth and Space Science, Graduate School of Science, Osaka University, Toyonaka 560-0043, Japan
168: Yukawa Institute for Theoretical Physics, Kyoto University, Kyoto 606-8502, Japan
169: Astronomical Observatory, Jagiellonian University, ul. Orla 171, 30-244 Cracow, Poland
170: Landessternwarte, Zentrum für Astronomie der Universität Heidelberg, Königstuhl 12, 69117 Heidelberg, Germany
171: University of Alabama, Tuscaloosa, Department of Physics and Astronomy, Galalee Hall, Box 870324 Tuscaloosa, AL 35487-0324, USA
172: Department of Physics, University of Bath, Claverton Down, Bath BA2 7AY, United Kingdom
173: University of Iowa, Department of Physics and Astronomy, Van Allen Hall, Iowa City, IA 52242, USA
174: Anton Pannekoek Institute/GRAAPPA, University of Amsterdam, Science Park 904 1098 XH Amsterdam, The Netherlands
175: Faculty of Computer Science, Electronics and Telecommunications, AGH University of Science and Technology, Kraków, al. Mickiewicza 30, 30-059 Cracow, Poland
176: Faculty of Science, Ibaraki University, Mito, Ibaraki, 310-8512, Japan
177: Faculty of Science and Engineering, Waseda University, Shinjuku, Tokyo 169-8555, Japan
AGN population studies with CTA

Anthony M. Brown

178: Institute of Astronomy, Faculty of Physics, Astronomy and Informatics, Nicolaus Copernicus University in Toruń, ul. Grudziądzka 5, 87-100 Toruń, Poland
179: Graduate School of Science and Engineering, Saitama University, 255 Simo-Okubo, Sakura-ku, Saitama city, Saitama 338-8570, Japan
180: Division of Physics and Astronomy, Graduate School of Science, Kyoto University, Sakyo-ku, Kyoto, 606-8502, Japan
181: Centre for Quantum Technologies, National University Singapore, Block S15, 3 Science Drive 2, Singapore 117543, Singapore
182: Institute of Particle and Nuclear Studies, KEK (High Energy Accelerator Research Organization), 1-1 Oho, Tsukuba, 305-0801, Japan
183: Department of Physics and Astronomy, University of Sheffield, Hounsfield Road, Sheffield S3 7RH, United Kingdom
184: Centro de Ciências Naturais e Humanas, Universidade Federal do ABC, Av. dos Estados, 3001, CEP: 09.210-580, Santo André - SP, Brazil
185: Departamento de Física e Astronomia, Sezione Astrofisica, Università di Catania, Via S. Sofia 78, 1-95123 Catania, Italy
186: Department of Physics, Humboldt University Berlin, Newtonstr. 15, 12489 Berlin, Germany
187: Texas Tech University, 2500 Broadway, Lubbock, Texas 79409-1035, USA
188: University of Zielona Góra, ul. Licealna 9, 65-417 Zielona Góra, Poland
189: Institute for Nuclear Research and Nuclear Energy, Bulgarian Academy of Sciences, 72 boulevard Tsarigradsko chaussee, 1784 Sofia, Bulgaria
190: University of Białystok, Faculty of Physics, ul. K. Ciołkowskiego 1L, 15-254 Białystok, Poland
191: Faculty of Physics, National and Kapodestrian University of Athens, Panepistimiopolis, 15771 Ilissia, Athens, Greece
192: Universidad de Chile, Av. Libertador Bernardo O’Higgins 1058, Santiago, Chile
193: Hiroshima Astrophysical Science Center, Hiroshima University, Higashi-Hiroshima, Hiroshima 739-8526, Japan
194: Department of Applied Physics, University of Miyazaki, 1-1 Gakuen Kibana-dai Nishi, Miyazaki, 889-2192, Japan
195: School of Allied Health Sciences, Kitasato University, Sagamihara, Kanagawa 228-8555, Japan
196: Departamento de Astronomía, Universidad de Concepción, Barrio Universitario S/N, Concepción, Chile
197: Charles University, Institute of Particle & Nuclear Physics, V Holešovičkách 2, 180 00 Prague 8, Czech Republic
198: Astronomical Observatory of Ivan Franko National University of Lviv, 8 Kyryla i Mephedora Street, Lviv, 79005, Ukraine
199: Kobayashi-Maskawa Institute (KMI) for the Origin of Particles and the Universe, Nagoya University, Chikusa-ku, Nagoya 464-8602, Japan
200: Graduate School of Technology, Industrial and Social Sciences, Tokushima University, Tokushima 770-8506, Japan
201: Space Research Centre, Polish Academy of Sciences, ul. Bartycka 18A, 00-716 Warsaw, Poland
202: Instituto de Física - Universidade de São Paulo, Rua do Matão Travessa R Nr.187 CEP 05508-090 Cidade Universitária, São Paulo, Brazil
203: International Institute of Physics at the Federal University of Rio Grande do Norte, Campus Universitário, Lagoa Nova CEP 59078-970 Rio Grande do Norte, Brazil
204: University College Dublin, Belfield, Dublin 4, Ireland
205: Centre for Astro-Particle Physics (CAPP) and Department of Physics, University of Johannesburg, PO Box 524, Auckland Park 2006, South Africa
206: Departamento de Física, Facultad de Ciencias Básicas, Universidad Metropolitana de Ciencias de la Educación, Santiago, Chile
207: Núcleo de Formação de Professores - Universidade Federal de São Carlos, Rodovia Washington Luís, km 235 CEP 13565-905 - SP-310 São Carlos - São Paulo, Brazil
208: Physik-Institut, Universität Zürich, Winterthurerstrasse 190, 8057 Zürich, Switzerland
209: Department of Physical Sciences, Aoyama Gakuin University, Fuchinobe, Sagamihara, Kanagawa, 252-5258, Japan
210: University of the Free State, Orange, Bloemfontein, 9300, South Africa
211: Faculty of Electronics and Information, Warsaw University of Technology, ul. Nowowiejska 15/19, 00-665 Warsaw, Poland
212: Rudjer Boskovic Institute, Bijenička 54, 10 000 Zagreb, Croatia
213: Department of Physics, Konan University, Kobe, Hyogo, 658-8501, Japan
214: Kumamoto University, 2-39-1 Kurokami, Kumamoto, 860-8555, Japan
215: University School for Advanced Studies IUSS Pavia, Palazzo del Broletto, Piazza della Vittoria 15, 27100 Pavia, Italy
216: Aalto University, Otakaari 1, 00076 Aalto, Finland
217: Agenzia Spaziale Italiana (ASI), 00133 Roma, Italy
218: Observatoire de la Côte d’Azur, Boulevard de l’Observatoire CS34229, 06304 Nice Cedex 4, France