γ-rays from annihilating dark matter in galaxy clusters: stacking versus single source analysis

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ABSTRACT
Clusters of galaxies are potentially important targets for indirect searches for dark matter (DM) annihilation. Here we reassess the detection prospects for annihilation in massive haloes, based on a statistical investigation of 1743 clusters in the new Meta-Catalogue of X-ray Clusters (MCXC). We derive a new limit for the extragalactic DM annihilation background of at least 20 per cent of that originating from the Galaxy for an integration angle of 0.1. The number of clusters scales as a power law with their brightness (boosted by DM substructures), suggesting that stacking may provide a significant improvement over a single target analysis. The mean angle containing 80 per cent of the DM signal for the sample (assuming a Navarro–Frenk–White DM profile) is ∼0.15 (excluding the contribution from the point spread function of any instrument), indicating that instruments with this angular resolution or better would be optimal for a cluster annihilation search based on stacking. A detailed study based on the Fermi-LAT performance and position-dependent background suggests that stacking may result in a factor of ∼2 improvement in sensitivity, depending on the source selection criteria. Based on the expected performance of Cherenkov Telescope Array, we find no improvement with stacking, due to the requirement for pointed observations. We note that several potentially important targets – Ophiuchus, A2199, A3627 (Norma) and CIZA J1324.7−5736 – may be disfavoured due to a poor contrast with respect to the Galactic DM signal. The use of the homogenized MCXC meta-catalogue provides a robust ranking of the targets, although the absolute value of their signal depends on the exact DM substructure content. For conservative assumptions, we find that galaxy clusters (with or without stacking) can probe ⟨σv⟩ down to 10−25–10−24 cm3 s−1 for DM masses in the range 10–100 GeV. For more favourable substructure configurations, ⟨σv⟩ ~ 10−26 cm3 s−1 may be reached.

Key words: astroparticle physics – dark matter – gamma-rays: galaxies: clusters.

1 INTRODUCTION
The annihilation of dark matter (DM) particles into γ-rays has been flagged as one of the most promising channels for indirect detection. Regions of high DM density are of particular interest, making the Galactic Centre the most obvious target (Silk & Bloemen 1987).

However, the Galactic Centre is plagued by a large astrophysical γ-ray background at all angular scales that makes any DM signal difficult to identify (e.g. Aharonian et al. 2004). In that respect, dwarf spheroidal galaxies (dSphs) have the advantage to be essentially background free, relatively close by and with DM density profiles that can be constrained from their internal kinematics. This has made them popular candidates for indirect detection (Evans, Ferrer & Sarkar 2004; Bergström & Hooper 2006; Strigari et al. 2007; Pieri, Lattanzi & Silk 2009; Abdo et al. 2010; Kuhlen 2010; Ackermann et al. 2011; Charbonnier et al. 2011; Sánchez-Conde et al. 2011; Walker et al. 2011).
Somewhat less explored to date, clusters of galaxies are the largest gravitationally bound structures in the Universe, the large DM content of which makes them potentially interesting targets for indirect detection (Colafrancesco, Profumo & Ullio 2006). Although strong constraints have already been derived from X-ray and gravitational lensing studies on the DM distribution in clusters (Pointecouteau, Arnaud & Pratt 2005; Vikhlinin et al. 2006; Buote et al. 2007; Shan et al. 2010; Ettori et al. 2011; Pastor Mira et al. 2011), constraining the inner DM distribution is still a challenging task. Even strong lensing, which likely is the best suited way to pin down the DM distribution at the cluster centre, fails to assemble convincing constraints (see for instance the different conclusions reached by Limousin et al. 2007; Newman et al. 2011; Morandi & Limousin 2012). Estimates of the DM profile and calculations of the $\gamma$-ray flux from clusters are based on X-ray observations, from which Navarro–Frenk–White (NFW; Navarro, Frenk & White 1997) or Einasto (e.g. Merritt et al. 2006) profiles are assumed. For instance, based on the HIFLUGCS catalogue containing 106 objects (Reiprich & Böhringer 2002; Chen et al. 2007), several authors have identified the potentially most luminous objects in DM emission, such as Fornax, Coma or Perseus (Jeltema, Kehayias & Profumo 2009; Pinzke, Pfrommer & Bergström 2011). The non-detection of these favoured targets by Fermi-LAT and H.E.S.S. has resulted in constraints on the DM annihilation cross-section (Ackermann et al. 2010; Yuan et al. 2010; Abramowski et al. 2012), so that the factorization of the spatial and energy-dependent term in equation (1) holds. Actually, depending on the annihilation channel, the ICS contribution can dominate over the prompt one. Considering only the prompt contribution as we do here provides a conservative and robust lower limit on detectability. In this paper, we further restrict ourselves to the $b\bar{b}$ annihilation channel, taken from equation (6) and table XXII in Cembranos et al. (2011). We note that the spectral parameters in Cembranos et al. (2011) are provided for WIMP masses in the range of 50 GeV–8 TeV. Here we assume the spectral parameters for masses below 50 GeV are given by the parameters for a 50 GeV mass, and similarly above 8 TeV. The results are not strongly affected (less than a factor of 1.5 in the sensitivity limits) by the choice of the $\gamma$-ray annihilation channel (apart from the $\tau \tau$ channel).

The $J$-factor represents the astrophysical contribution to the signal and corresponds to the integral of the squared DM density, $\rho^2(l, \Omega)$, over line of sight $l$ and solid angle $\Delta \Omega$:

$$J(\Delta \Omega) = \int_{\Delta \Omega} \int \rho^2(l, \Omega) \, dl \, d\Omega .$$  \hspace{1cm} (2)

We have $\Delta \Omega = 2\pi \cdot [1 - \cos(\alpha_{\text{int}})]$, and $\alpha_{\text{int}}$ is referred to as the ‘integration angle’ in the following. All $J$-factors presented below, including substructures (in the Galaxy or in galaxy clusters), are calculated from the public code $\text{CLUMPY}$ v2011.09 (Charbonnier, Combet & Maurin 2012).

We remind that the spatial term $J$ in equation (1) couples to the energy-dependent term $dN_{\gamma}/dE_{\gamma}$ for objects at cosmological distances, because $\gamma$-rays are absorbed along the line of sight (e.g. Cirelli, Panci & Serpico 2010). The redshift distribution of the MCXC catalogue of galaxy clusters (Piffaretti et al. 2011) peaks at $z \sim 0.1$ (see their fig. 1); following Combet et al. (2012), we neglect the absorption for the MCXC galaxy clusters.
2.2 The smooth DM halo and substructures

For the DM halo smooth profile, we use an NFW (Navarro et al. 1997):

$$\rho(r) = \frac{\rho_s}{\left(\frac{r}{r_s}\right) \left(1 + \frac{r}{r_s}\right)^2}, \quad (3)$$

where $r_s$ is the scale radius and $\rho_s$ is the normalization.\(^2\) We note that Einasto profiles give slightly more ‘signal’ than NFW haloes, making our conclusions on detectability conservative.

Cold DM N-body simulations show a high level of clumpiness in the DM distribution (e.g. Diemand, Kuhlen & Madau 2007; Springel et al. 2008). These substructures boost the signal in the outer parts of the DM haloes. In agreement with the analysis of Gao et al. (2012b), we find that the boost in galaxy clusters is larger than the boost obtained for less massive objects such as dSphs. For the latter, boost are $\lesssim 2$ (Charbonnier et al. 2011), whereas we obtain an overall boost of $\sim 10-20$ for galaxy clusters based on conservative assumptions for the substructure parameters (the impact of these parameters is discussed in Section 3.4). The reason is twofold: first, dSphs are less massive so that the mass range of substructures is smaller (the minimal mass is assumed to be the same regardless of the object), hence the number of objects and their overall contribution; secondly, the effective angular size on the sky is larger for dSphs so that current instruments integrating out to 0.5 integrate less substructure signal (see also Gao et al. 2012b).

These boost are obtained from the following configuration – used throughout the paper with the exception of Section 3.4 – for the mass and spatial distribution of the substructures: (i) $dN_{sub}/dM \propto M^{−1.9}$ with a mass fraction $f = 10$ per cent in substructures (Springel et al. 2008), a minimal and maximal mass of $10^{16} M_{\odot}$ and $10^{17} M_{\text{cluster}}$, respectively, and the Bullock et al. (2001) concentration (down to the minimal mass); (ii) the substructure spatial distribution $dN_{sub}/dV$ follows the host halo smooth profile. For this configuration, we checked that the boost is only mildly dependent on this mass by varying the mass from $10^{15}$ to $10^{16} M_{\odot}$. We note that the minimal mass for subhaloes can be as small as $10^{10} M_{\odot}$ depending on the particle physics model (see Profumo, Sigurdson & Kamionkowski 2006, and references therein).

A complete study of the boost should consider different profiles, different parametrizations for the mass–concentration relationship, etc. This will be fully addressed in a future work. However, given the impact it can have on the ($\sigma_{\text{ann}} v$) limit (or detectability for current instruments), a short discussion and general trends are given in Section 3.4.

3 J-FACTORS FOR THE MCXC SAMPLE

The MCXC (Piffaretti et al. 2011) contains 1743 clusters of galaxies detected in X-rays and assembled from publicly available catalogues mainly based on the ROSAT All-Sky Survey or ROSAT serendipitous catalogues. Most observational constraints and predictions are expressed in terms of $\Delta = 500$ or 200. For instance, the mass of a halo, $M_{\Delta}$, can be defined within a radius $R_\Delta$ within which the average density reached $\Delta$ times the critical density of the Universe (at a given redshift). The MCXC provides homogenized quantities for each clusters computed within $\Delta = 500$, e.g. the standardized $[0.1–2.4] \text{ keV X-ray luminosity} L_{500}$, the total mass $M_{500}$, the radius $R_{500}$.

To fully describe the NFW profile parameters (see equation 3) for each galaxy cluster of the MCXC catalogue, we used the provided $M_{500}$ together with a mass–concentration relationship (i.e. $c_\Delta$ is fully determined by the cluster mass $M_\Delta$). This relation is observationally constrained at the cluster scale (Pointecouteau et al. 2005; Buote et al. 2007; Ettori et al. 2010). It has also been shown to depend on the epoch of halo formation by numerical simulations of structure formation (Bullock et al. 2001; Dolag et al. 2004; Duffy et al. 2008; Klypin, Trujillo-Gomez & Primack 2011). Although the data present a large dispersion, a systematic offset remains unexplained (Duffy et al. 2008, 2010). In this study, we assume the Duffy et al. (2008) mass–concentration relation.

For an NFW profile $r_s = R_{\text{A}}/c_\Delta$, and the scale density $\rho_s$ is obtained from the mass measurement. The J-factors for all clusters are then calculated from equations (2) and (3) with CLUMPY.

3.1 Brightest targets

Fig. 1 provides a synthetic view of the J-factor for each galaxy cluster of the MCXC catalogue as a function of their angle $\phi$ away from the Galactic Centre. The integration angle is taken to be $\alpha_{\text{int}} = 0.1$ (left-hand panel) and $\alpha_{\text{int}} = 0.5$ (right-hand panel), the typical range of value for the energy-dependent angular resolution of current $\gamma$-ray instruments such as Fermi-LAT (in the high-energy range above $\sim 10 \text{ GeV}$) and H.E.S.S. Table 1 gathers results for the 20 brightest clusters in the MCXC. From this table, we simply note that J-factors are competitive with those obtained for dSphs (e.g. Walker et al. 2011), confirming that galaxy clusters are valid targets for DM annihilation searches (see also Sánchez-Conde et al. 2011; Gao et al. 2012b). The panels of Fig. 2 show a skymap version of Fig. 1. The top left-hand panel shows the J-factor induced by DM annihilation in the Galactic halo cumulated with all MCXC objects. The top right-hand panel shows the J-factor skymap for all MCXC galaxy clusters only. The bottom panel locates the 20 most promising targets labelled by distance, absolute J-factor value and contrast with respect to the DM Galactic signal.

Several clusters including Virgo, Coma, Fornax, NGC 5813 and Ophiuchus have already been credited to be interesting sources in numerous studies given their masses and distances (Colafrancesco et al. 2006; Jeltema et al. 2009; Pinzke et al. 2011; Sánchez-Conde et al. 2011; Gao et al. 2012b; Han et al. 2012). Other objects, such as 3C 129 and AWM7, were only highlighted from the HIFLUGCS catalogue analysis (Jeltema et al. 2009; Pinzke et al. 2011; Huang et al. 2012). With 10 times more objects, the MCXC gives a more exhaustive list of potential targets including e.g. J0123.6+3315 and J1324.7–5736 (see Table 1 and Fig. 2).

Some differences exist with previous calculations (see Appendix B). These can be partly attributed to a different prescription for the substructures. However, another important difference comes from the fact that almost all previous studies are based on the $M_{500}$ values obtained from the HIFLUGCS catalogue (Reiprich & Böhringer 2002; Chen et al. 2007). In particular, some of ‘brightest’ objects found (e.g. Coma, Fornax, AMW7) have larger masses than those provided in the MCXC catalogue. As discussed in appendix A of Piffaretti et al. (2011), the MCXC relies on a more accurate model for the gas distribution, and many comparisons to
Figure 1. Computed $J$-factors for the MCXC sources (the 10 highest contrast clusters are highlighted, the remaining are shown with a ‘-$-$’ symbol) versus Galactic DM background (total is the sum of smooth, subhaloes and cross-product – see details in Charbonnier et al. 2012). The yellow filled square symbols are evaluated from the cumulative of the cluster signal in different $\phi$ bins: this can be interpreted as a lower limit for the extragalactic DM annihilation signal. Left-hand panel: integration angle $\alpha_{\text{int}} = 0.1$. Right-hand panel: $\alpha_{\text{int}} = 0.5$.

Table 1. 20 brightest galaxy clusters from the MCXC and their contrast $J\alpha_{\text{Gal}}$ for $\alpha_{\text{int}} = 0.1$. The DM Galactic background is evaluated at the position of the cluster (angle $\phi$ away from the Galactic Centre; see Fig. 1).

| Name     | Index | $l$  | $b$  | $\phi$ | $d$  | $\log_{10}\left(\frac{M_{\text{tot}}}{M_{\odot}}\right)$ | $\alpha_{\text{int}}$ | $\log_{10}\left[J(\alpha_{\text{int}})/\left(\frac{M_{\odot}^2}{\text{kpc}^6}\right)\right]$ | $\langle J_{\alpha_{\text{Gal}}} \rangle\left[\text{rank}\right]$ |
|----------|-------|------|------|--------|-----|-----------------------------------------------|----------------------|------------------------------------------------|-----------------------------------------------|
| Virgo    | 884   | 283.8| 74.4 | 86.3   | 15.4| 14.3                                          | 3.3                  | 11.1 11.8 12.6 [2] 4.9 [1]                         |                                                |
| A426     | 258   | 150.6| -13.3| 148.0  | 75  | 15.1                                          | 3.1                  | 10.8 11.5 11.8 [2] 4.5 [2]                         |                                                |
| A3526$^b$| 915   | 302.4| 21.6 | 60.1   | 48.1| 14.5                                          | 1.2                  | 10.7 11.4 11.7 [3] 0.9 [17]                        |                                                |
| NGC 4636 | 906   | 297.7| 65.5 | 78.9   | 13.2| 13.3                                          | 1.7                  | 10.6 11.4 11.8 [8] 1.6 [14]                        |                                                |
| A3627$^{b,c}$| 1231 | 325.3| -7.1 | 35.4   | 66  | 14.6                                          | 0.9                  | 10.6 11.3 11.5 [1] 0.3 [1]                         |                                                |
| Coma     | 943   | 57.2 | 88.0 | 88.9   | 96.2| 14.9                                          | 0.8                  | 10.6 11.3 11.5 [7] 1.6 [8]                         |                                                |
| NGC 5813$^b$| 1147 | 359.2| 49.8 | 49.8   | 21.3| 13.6                                          | 1.4                  | 10.6 11.3 11.6 [7] 0.6 [39]                        |                                                |
| Ophiuchus$^{b,c}$| 1304 | 0.6  | 9.3  | 9.3    | 116.| 15.0                                          | 0.7                  | 10.6 11.2 11.4 [11] 0.2 [2]                         |                                                |
| NGC 5044$^b$| 978  | 311.2| 46.1 | 62.8   | 36.9| 14.0                                          | 1.0                  | 10.5 11.2 11.5 [3] 0.7 [17]                        |                                                |
| AWM7     | 224   | 146.3| -15.6| 143.3  | 72.1| 14.5                                          | 0.8                  | 10.5 11.2 11.3 [5] 2.3 [3]                         |                                                |
| A1060    | 689   | 269.6| 26.5 | 90.4   | 53.1| 14.2                                          | 0.9                  | 10.5 11.2 11.4 [14] 1.3 [11]                        |                                                |
| Fornax   | 285   | 236.7| -53.6| 109.0  | 21.7| 13.5                                          | 1.2                  | 10.5 11.2 11.5 [6] 8.6 [7]                         |                                                |
| A1367    | 792   | 235.7| 73.0 | 99.6   | 89.3| 14.6                                          | 0.7                  | 10.5 11.1 11.2 [12] 1.3 [12]                        |                                                |
| J1324.7−5736$^{b,c}$| 990 | 107.4| 5.0  | 52.8   | 79.5| 14.5                                          | 0.7                  | 10.5 11.1 11.3 [3] 2.3 [1]                         |                                                |
| A0262    | 158   | 136.6| -25.1| 131.1  | 68.4| 14.3                                          | 0.7                  | 10.5 11.1 11.3 [6] 1.7 [6]                         |                                                |
| 3C 129$^c$| 350  | 160.5| 0.3  | 160.5  | 91.7| 14.5                                          | 0.7                  | 10.4 11.1 11.2 [2] 1.8 [4]                         |                                                |
| A2199$^b$| 1249  | 62.9 | 43.7 | 70.8   | 12.4| 14.7                                          | 0.7                  | 10.4 11.0 11.1 [5] 0.6 [38]                        |                                                |
| NGC 1550 | 324   | 191.0| -31.8| 146.5  | 55.2| 14.1                                          | 0.8                  | 10.4 11.1 11.2 [5] 1.7 [5]                         |                                                |
| A3571$^b$| 1048  | 316.3| 28.6 | 50.6   | 159.7| 14.9                                          | 0.5                  | 10.4 11.0 11.0 [19] 0.3 [1]                         |                                                |
| 2A0335   | 286   | 176.3| -35.5| 144.8  | 142.5| 14.8                                          | 0.5                  | 10.4 11.0 11.0 [8] 1.4 [10]                        |                                                |

$^a$Whenever the rank is larger than 50, we use [-].

$^b$Weakly contrasted clusters are probably not the best targets.

$^c$Clusters close to the Galactic plane are notfavoured targets.

Numerical simulations indicate that any systematic uncertainties are now $\lesssim 15$–20 per cent (Piffaretti & Valdarnini 2008).

3.2 Galactic and extragalactic DM background

Galactic DM provides a ‘diffuse’ DM emission $J_{\text{Gal}}$ that can drown the point-like emissions we are looking for. The value of the local DM density is still loosely constrained in [0.2–0.4] GeV cm$^{-3}$ by several techniques (Sofue, Honma & Omodaka 2009; Catena & Ullio 2010; Salucci et al. 2010; Garbari, Read & Lake 2011; Iocco et al. 2011). We assume here $\rho_{\odot} = 0.3$ GeV cm$^{-3}$. The value for $J_{\text{Gal}}(\phi > 20^{\circ})$ is also very sensitive to the Galactic subhalo distribution. The Galactic signal is thus uncertain by a factor of a few. We calculate in Table 1 the contrast, i.e. the ratio between the cluster signal and the DM Galactic signal. As shown in Figs 1 and 2, the DM Galactic signal has a shallow latitudinal dependence except towards the Galactic Centre ($\theta > 5^{\circ}$) where the signal is maximal. Several of the brightest sources are close to the Galactic centre, namely Ophiuchus, A3626 (Norma) and J1324.7−5736. Although they exhibit a large $J$-factor, their contrast is low, and they are not favoured. Indeed, the contrast indicates when a point-like observation strategy becomes less promising than a strategy based, e.g., on the detection of a gradient for smooth Galactic halo towards the Galactic Centre (as done in Abramowski et al. 2011). Away from the
Galactic Centre, we have $J_{\text{Gal}} \propto \alpha_{\text{int}}^2$. This is illustrated by the left- and right-hand panels of Fig. 1, where the value of $J_{\text{Gal}}$ is multiplied by 25 moving from $\alpha_{\text{int}} = 0.1$ to 0.5. However, the corresponding signal from each cluster is only marginally increased, meaning that the contrast is worsened for large integration angles.

The diffuse extra-Galactic DM signal constitutes another background, the level of which has been estimated from $N$-body simulations (see e.g. fig. 4 of Pieri et al. 2011). It is not considered here. However, by averaging in each $\phi$ bin the signal from all clusters and correcting for the solid angle element, we derive a first ‘data-driven’ estimate of this extragalactic contribution, and we find $J_{\text{extragal}} \gtrsim J_{\text{Gal}}/5$ (yellow filled squares in Fig. 1). Larger samples of galaxy clusters are required to refine this figure.

The five brightest sources in Table 1 are located far from the Galactic Centre and plane, and therefore have the ‘best’ contrast with respect to the diffuse DM and astrophysical emissions (located mostly in the disc). These sources are also amongst the closest targets and have the largest angular size. As we will show in the next sections, this will prove crucial for the detection prospects once the astrophysical background and the angular response of the instruments are taken into account.

### 3.3 Distribution of $J$-factors and $\alpha_{90\text{ per cent}}$ for the cluster sample

Most of the galaxy clusters in the MCXC are faint objects (see Fig. 1). A stacking analysis is appealing if the slope of $\log N - \log J$ is steeper than $-1$, indicating that the number of sources increases more rapidly than the brightness of those sources diminishes.

The $\log_{10}(N) - \log_{10}(J)$ distribution is shown in the top panels of Fig. 3. We note that the double-peaked structure found is an indication that the MCXC is neither complete nor uniform at high redshift. The top left-hand panel emphasizes the importance of substructures for $\alpha_{\text{int}} = 0.1$: in their absence (dotted blue line), we have $N_{\text{no subs}} \propto J^{-1}$ such that there are $\gtrsim 20$ times more objects each time $J$ is decreased by a factor of 10. With substructures (dashed red line) the prospects for stacking are improved; $N_{\text{subs}} \propto J^{-2.0}$ such that there is now a factor of 100 increase in the number of target objects for the same factor of 10 $J$ decrease. The lower left-hand panel of Fig. 3 shows the $\log_{10}(N) \log_{10}(\alpha_{90\text{ per cent}})$ distribution, where $\alpha_{90\text{ per cent}}$ is the integration angle for which 80 per cent of the total $J$-factor is included. The quantity $\langle \alpha_{90\text{ per cent}} \rangle$ is of importance as it corresponds to the desired point spread function (PSF) in order to include most of $J$ in the majority of sources. This plot again emphasizes the role of substructures. The mean for the $\alpha_{90\text{ per cent}}$ distribution moves from $\sim 0.03$ (dotted blue line) to $\sim 0.15$ when the contribution of substructures is taken into account. This is more favourable for current observatories, the angular resolution of which being at best is $\sim 0.1$.

The choice for the integration angle also impacts on the $\log_{10}(N) - \log_{10}(J)$ distribution. The top right-hand panel shows that larger integration angles have an impact only for haloes not fully encompassed, i.e. for the closest/brightest ones. Indeed, objects whose $\alpha_{90\text{ per cent}} < \alpha_{\text{int}}$ do not have significantly more signal when $\alpha_{\text{int}}$ is increased. For the bigger objects, the interplay between the different...
angular dependence of the smooth and substructure contributions shapes the $\log_{10}(N)$–$\log_{10}(J)$ distribution. The distribution of boost (for different integration angles) shown in the bottom right-hand panel of Fig. 3 illustrates this interplay. For very small $\alpha_{\text{int}}$ (e.g. 0.01, dot–dashed grey line), the signal from the smooth dominates and the distribution is strongly peaked around 1 (no boost). As the integration angle is increased (0.5, solid red line), the distribution is broadened, asymmetric and reaches a maximum of $\sim 20$.

3.4 Impact of varying substructure parameters

As already underlined, several ingredients for the DM distributions (smooth and subhaloes) can affect the results above. For instance, physical processes involving baryonic matter [such as active galactic nucleus (AGN) feedback] may produce a core distribution (Martizzi et al. 2012). This could decrease the total $J$-values. However, for galaxy clusters, a dominant part of the signal comes from substructures for $\alpha_{\text{int}} \gtrsim 0.05$ (as seen in bottom right-hand panel of Fig. 3), the distribution of which impacts the results significantly. First, the smallest protohalo mass remains unknown, and it strongly depends on the details of the DM candidate microphysics at the kinetic decoupling (e.g. Green, Hofmann & Schwarz 2005; Profumo et al. 2006; Bringmann 2009; Gondolo, Hisano & Kadota 2012). Secondly, the subhalo spatial distribution is found to be less concentrated than the smooth halo one, and consistent with Einasto profiles in the recent Aquarius (Springel et al. 2008) and Phoenix (Gao et al. 2012a) simulations. In the latter, the mass distribution slope $dM/d\log M \propto M^{-\alpha}$ is also found to be steeper and close to 2, leading to a larger fraction of substructures in clusters than in galaxies. When the slope is close to 2, the contribution to the signal of small subhaloes becomes as important as that of larger ones, which can strongly boost the overall signal depending on the chosen $c_\alpha$–$M_\alpha$ (concentration–mass) relation.

Many studies have focused on the characterization (e.g. mean and variance, environment effects) of this relation, but are limited by the mass resolution of currently available numerical simulations. The state-of-the-art studies on galaxy clusters apply down to a minimum halo mass $\sim 10^{10} M_\odot$ (Wechsler et al. 2002, 2006; Zhao et al. 2003, 2009; Neto et al. 2007; Gao et al. 2008, 2011; Macciò, Dutton & van den Bosch 2008; Giocoli et al. 2010; Muñoz-Cuartas et al. 2011; Klypin, Trujillo-Gomez & Primack 2011). Extrapolations to the smallest subhalo mass are provided in a very few studies only. For instance, almost all analyses of the DM annihilation signal are based on two different parametrizations (Bullock et al. 2001; Eke, Navarro & Steinmetz 2001). Giocoli, Tormen & Sheth (2012) recently provided a new parametrization of $c_\alpha$–$M_\alpha$; at $z = 0$, it is consistent with the Bullock et al. (2001) parametrization in the $\lesssim 10^{10} M_\odot$ range, but its redshift dependence is different.
Given the variety of results found in the literature and the uncertainties on some parameters, we only select a few configurations below.

(i) \( \frac{dP}{dv_{\text{Phoenix}}} \): uses spatial distribution and scale radius as provided by the Phoenix project (Gao et al. 2012a), instead of following that of the smooth profile (all other parameters as in Section 2.2).

(ii) \( \frac{dP}{dv_{\text{Phoenix}}} \) and \( \alpha_M = 1.98 \): uses a steeper slope for the mass distribution as found in Phoenix (Gao et al. 2012a) instead of 1.9 (note that \( \alpha_M = 1.94 \) in Springel et al. 2008).

(iii) \( \frac{dP}{dv_{\text{Phoenix}}} \) and \( \alpha_M = 1.98 \) and \( f = 0.3 \): uses a DM mass fraction as found in Phoenix (Gao et al. 2012a) instead of 0.1 (as found in Springel et al. 2008).

(iv) \( \frac{dP}{dv_{\text{Phoenix}}} \) and \( \alpha_M = 1.98 \) and \( f = 0.3 \) and \( (c_N - M_\Delta)_{\text{ENS01}} \) or \( (c_N - M_\Delta)_{\text{G12}} \): uses a mass–concentration relation from Eke et al. (2001) and Giocoli et al. (2012), instead of using Bullock et al. (2001).

The impact is shown in Fig. 4 for the \( \log_{10}(N) - \log_{10}(J) \) (top panel) and the \( \log_{10}(N) - \log_{10}(\text{Boost}) \) (bottom panel) distributions for \( \alpha_{\text{int}} = 0.1 \). Taking an Einasto profile for the spatial distribution of subhaloes has only a minor effect (solid thin black versus dashed black line). A major impact is that of the value of the parameter \( \alpha_M \) (solid thin black versus dotted black line). It increases the boost (and thus the signal) by about one order of magnitude. This increase can be larger if a smaller minimal mass for the subhaloes is chosen, but it can also be decreased by a factor of 10 if the minimal mass allowed is \( 10^3 M_\odot \). Although the Phoenix and Aquarius simulations tend to prefer values close to 2, the result is intrinsically limited by the mass resolution of the simulation, and this slope can still be smaller at lower masses. Moreover, Elahi et al. (2009) argue that this slope could be overestimated, even in the simulation mass range. Another obvious effect is from the mass fraction \( f \) in substructures (thin versus thick solid black line). Finally, the two red curves show the impact of the \( c_N - M_\Delta \) parametrization (thin and thick red lines) compared to using Bullock et al. (2001) parametrization (thick solid black line). Choosing Giocoli et al. (2012) gives slightly less signal, whereas using Eke et al. (2001) washes out the boost completely. To conclude, we see that the main source of uncertainties corresponds to the slope of the mass function, the minimal mass of the subhaloes and the concentration. Unfortunately, these are also the least-constrained parameters from the available numerical simulations.

Our reference configuration gives a conservative estimate of the signal expected from galaxy clusters. We underline that the shape of \( \log_{10}(N) - \log_{10}(\text{Boost})(\alpha_{\text{int}}) \) is only weakly impacted by choosing other configuration (and the ordering of the best targets – not shown – also remains mostly unaffected). Therefore, the conclusions that will be reached below for the stacking analysis using the reference configuration hold regardless of this choice. However, the consequences of a larger boost would be the following: (i) a larger signal and a better \( \sigma_v \) limit set from non-detection, (ii) an increase of the 80 per cent containing angle and (iii) an enhanced contrast with respect to the Galactic background resulting in an increased extragalactic to Galactic signal ratio.

4 HALO STACKING AND RESULTS

There are two primary considerations for the MCXC stacking analysis: how to order the sources, and how many sources to stack. This is discussed for different situations before moving to the detection prospects for the stacking strategy.

4.1 Strategy for a ‘perfect’ instrument

4.1.1 Signal-limited regime

The top panel in Fig. 5 shows the cumulative distribution of \( J \) for integration angles of 0.05 (solid green stars), 0.1 (open black squares) and 0.5 (solid red circles) as well as \( \sigma_{80\%} \) (open blue circles). The numbers denote the number of MCXC contributing to the cumulative, and the ordering in a given \( J \) bin. The MCXC sources are naturally ordered by \( J \) in this plot. Sources within 20’ of the Galactic Centre are excluded. The cumulative \( J_{\text{Gal}} \) is also shown (dashed lines). As mentioned in Section 3.2, the contrast \( (J_{\text{source}}/J_{\text{Gal}}) \) is related to the detectability of an object if we are only limited by the amount of signal available. In such a regime, a stacking analysis remains valid as long as we add sources with a contrast larger than 1. The boxed numbers indicate at what point this occurs: for an integration angle of 0.5, the optimum number of objects to stack in this regime is 21. The wealth of sources in the MCXC becomes more useful for smaller integration angles, with an optimum of 1224 objects at 0.05. For the
AGN (hosting a supermassive black hole) often found at the cluster.

Three integration angles are shown: 0°, 0.1°, and 0.5°. The open blue circles correspond to an integration signal and associated Galactic DM background are represented by an arrow.

The lower panel of Fig. 5 shows \( \sum J_i(>J)/\alpha_{\text{int}} \sqrt{N} \) as a function of \( J \), again for integration angles of 0° (solid green stars), 0.1 (open black squares) and 0.5 (solid red circles). The peak in these ‘signal-to-noise ratio’ curves indicates the optimum number of sources to stack in the background-limited regime, and are highlighted as 1224, 713 and 21 for 0°, 0.1 and 0.5, respectively.

In this plot, sources are ordered by increasing \( J \)-values, and therefore only ‘signal-to-noise ratio’ curves can be included for fixed integration angles. For variable integration angles, such as \( \alpha_{\text{80\%}} \), the signal-to-noise ratio of each source in the catalogue will depend on the integration angle as well as \( J \), and therefore the stack must be ordered by \( J/\alpha_{\text{80\%}} \). In this case, the optimum number of sources is close to the full stack size, though we will see in the following section that these optimum values change drastically when the angular response of the instrument is considered. Examining the list in detail, it is apparent that when ordering by \( J/\alpha_{\text{80\%}} \) rather than \( J \), only a few sources high up the list swap places. The sources falling somewhere in the ‘top’ 20–30 remain consistent.

The conclusions drawn from Fig. 5 are only valid for an instrument with a perfect angular response. In reality, the angular response of an instrument – typically characterized by the PSF which we take here to mean the 68 per cent containment radius – must be combined with the integration angle in quadrature before considering the amount of background contamination in an observation. In deciding which integration angle to use, we consider that, for a small fixed angle, the cumulative \( J \) is reduced since some signal from angularly large sources is neglected. For a large fixed angle (e.g. 0°), the cumulative \( J \) increases slowly, implying that angularly large sources are also bright, and located near the top of the list. Further down the list, where sources are angularly small, large amounts of galactic contamination and astrophysical background are included unnecessarily. Therefore, a different integration angle for each source, such as \( \alpha_{\text{80\%}} \), may be optimum, and is used in the remainder of the analysis.

4.2 Strategy for a ‘real’ (PSF-limited) instrument

The upper panel of Fig. 6 shows the cumulative signal-to-noise ratio as a function of the number of sources stacked for different values of the PSF. As the PSF worsens from 0° to 3°, the relative signal-to-noise ratio drops and the peak position shifts towards a smaller stack size. The peak position indicates the optimum number of sources to stack, and is shown in the lower panel of Fig. 6 as a function of PSF for an all-sky instrument. For a fixed integration angle of 0° (dashed line), the optimal number is constant with the PSF. When \( \alpha_{\text{80\%}} \) is considered, the optimal number of sources drops as the PSF of the instrument increases. For a PSF of 0°, 1200 sources
4.3 Detection prospects

In this section, we assess the DM detection prospects for the stacking of sources from the MCXC for the Fermi-LAT all-sky $\gamma$-ray satellite, and the envisaged array of Imaging Atmospheric Cherenkov Technique CTA. Whilst the design of CTA is still evolving, performance curves for several configurations have been released. Here, we use the so-called array layout ‘E’, which is described in CTA Consortium (2011). For the Fermi-LAT, the one-year point-source performance curves for a high-latitude source are used (Rando et al. 2009). The diffuse galactic and extragalactic background models given by the template files gal_2yearp7v6_v0.fits and iso_p7v6source.txt, respectively, which are available from the Fermi-LAT data server, are used to obtain the background within the integration angle for each source position on the sky. A toy likelihood-based model, as used in Charbonnier et al. (2011), is used to obtain the sensitivity of these instruments to the DM galaxy cluster signal.

The top panel of Fig. 7 shows the sensitivity of Fermi-LAT and CTA to the three sources from the MCXC that result in the highest $J$ and $J/\alpha_{80\,\text{per cent}}$ (‘signal-to-noise ratio’) in the context of this work for PSFs smaller than 1°: Virgo, A426 and A3526 when considering an integration angle of $\alpha_{80\,\text{per cent}}$. All curves represent a 5σ significance. The Fermi-LAT curves are computed for 5-yr exposure, whilst the CTA curves assume 1000 h observation of each source. Whilst it is unrealistic to expect pointed observations on all three of these sources for this duration, an equal exposure is useful in comparing the potential targets. Virgo dominates the sensitivity for both detectors. Individual curves were produced for the 10 brightest sources, and it was found that the top three sources shown here provide the best individual sensitivity.
A spectrum of photon energies is associated with each DM mass. Most sensitivity is contributed by the photon energy range close to the peak in $E^2 \, dN/dE$, which lies one order of magnitude below the DM mass for our assumed annihilation spectrum. Very low energy photons (several orders of magnitude below the DM mass) contribute little to the sensitivity due to the relatively hard signal spectrum and overwhelming background. In our analysis, we exclude photons with energies less than 1/200 the DM mass (providing this cut lies below 10 GeV). We consider this to be a realistic approach in practice to avoid source confusion problems due to the very poor PSF of Fermi-LAT close to threshold. At 100 MeV, for example, the Fermi-LAT PSF is some 6° in radius, a region that is likely to include several additional Fermi sources.

The lower panel of Fig. 7 shows the sensitivity of Fermi-LAT and CTA when stacking the optimum number of sources determined from the lower panel of Fig. 6 for PSFs of 0.1 (1200), 0.5 (90) and 1° (17). The brightest source, Virgo, is shown individually. Again, the Fermi exposure is taken as 5 yr. As Fermi is an all-sky instrument, each source in the stack receives this exposure regardless of the stack size.

At DM masses below $\sim 100$ GeV, the majority of photons are collected in an energy range where the Fermi-LAT PSF is worse than a degree. Here, the analysis falls into the background-limited regime. Therefore, stacking does not help, and just adds background, making the sensitivity worse than Virgo alone, for example $\sim 3.5 \times 10^{-25}$ to $\sim 2.5 \times 10^{-23}$ cm$^2$ s$^{-1}$, respectively, at $\sim 2$ GeV. Searching for WIMP masses above $\sim 100$ GeV, photons begin to be included that are seen by Fermi-LAT with a better PSF. In this mass regime, the amount of signal collected becomes important, and the stacking helps. The analysis eventually becomes signal limited, and stacking improves the sensitivity by a factor of up to 1.7, from $\sim 3 \times 10^{-23}$ to $\sim 1.8 \times 10^{-23}$ cm$^2$ s$^{-1}$ at $\sim 1$ TeV. This is roughly equivalent to the improvement in signal-to-noise ratio shown in the upper panel of Fig. 7 for a PSF representative of the energy range in question. For example, at a mass of 2 TeV, photons are included down to 10 GeV, corresponding to a PSF always better than 0.25°. Even at masses where an improvement with stacking is found, beyond a stack size of 17 sources the improvement is negligible. This is simply because the instrument PSF varies with energy and therefore taking the optimum number of sources for a fixed PSF is only an approximation.

In the case of CTA, we assume that a total exposure of 1000 h is available, and since CTA requires pointed observations, this is reduced to $\sim 60$ h per source when 17 objects are stacked, $\sim 12$ h per source when 90 objects are stacked, and $\sim 0.8$ h per source when 1200 objects are stacked. This effect dominates any gain in sensitivity due to stacking, and confirms the finding of the previous section that for an instrument requiring pointed observations, only the brightest source should be targeted. Note that systematic effects are not included, and will limit the accuracy of a 1000 h observation.

5 DISCUSSION

A stacking analysis of galaxy clusters may provide better limits for indirect detection of DM than the analysis of any single object, at least for all-sky instruments. However, this improvement is likely to be modest for the case of annihilating DM. Stacking is more promising in the case of decaying DM (Combet et al. 2012). For instruments requiring pointed observations such as CTA, observing the most promising source until the observation is systematic limited and then moving to additional sources is a reasonable strategy. Such an approach also mitigates against the uncertainty in the properties of individual haloes.

Limits placed on the velocity-averaged cross-section depend on the determination of $J$ not only for studies relying on known detector sensitivities (such as this work), but also for works making use of real data, e.g. the Fornax observation by H.E.S.S. (Abramowski et al. 2012). We checked that, given the same $J$ for a given source, we obtain a very similar sensitivity to that estimated in previous studies (see Appendix B). In our analysis, Virgo has the highest astrophysical factor ($J$) and best signal-to-noise ratio, followed by A426. Several authors have suggested (based on cluster properties given by the HiFLEUR catalogue) that Fornax is the most promising galaxy cluster for DM annihilation. However, as discussed above, the MCXC provides homogenized values for $M_{500}$ based on a more accurate gas density prescription that typically results in lower $J$ for the brightest clusters (but note that there is no systematic trend when all galaxy clusters are compared; see Piffaretti et al. 2011). The differences between these two catalogues are large enough to significantly change the conclusions of studies on the sensitivity of current and future instruments to DM annihilation, for example the detectability (or not) of DM with the annihilation cross-section expected for a thermal relic in this class of objects. In that respect, the ranking we provide from the MCXC catalogue should be robust, although the $J$-values calculated in this paper may still change depending on the level of clumpiness, exact mass–concentration relation, etc.

For all-sky instruments and in particular for Fermi-LAT, the improvement in sensitivity obtained by stacking is at best a factor of 1.7; MCXC sources with the 1200 largest values of $J$ or $\Delta J / \Delta J_{\text{80\%}}$ should be included to obtain this improvement. Additional sources do not improve the sensitivity, as further background is integrated without significant additional signal. This implies that the benefits of stacking are limited by the PSF of the available all-sky $\gamma$-ray instruments. Indeed, the PSF of Fermi-LAT at low energy is several degrees, whereas the majority of MCXC targets are distant and hence subtend small angles, with a typical $\Delta J_{\text{80\%}}$ of $\sim 0.15$ (when substructures are considered); an all-sky instrument with a PSF approaching $\Delta J_{\text{80\%}}$ at all energies would benefit from the stacking of all sources in the MCXC. In this case, sensitivity would then be limited only by the available signal, and an extended catalogue – as should be provided in a few years from now by the eROSITA mission (Predehl et al. 2011) – including even fainter objects would be needed to reach a cumulative $J \sim 10^{11}$–$10^{12}$.

A stack of the top 1200 objects excluding Virgo results in a sensitivity only $\sim 15$ per cent worse than the same stack size including Virgo. In this case, the improvement in sensitivity between the brightest source alone (A426) and the stack of 1200 objects is nearly a factor of 3 above masses of 100 GeV. The advantage is that the large number of clusters stacked is expected to wash out individual uncertainties on the halo properties (e.g. the dispersion of mass–concentration relationship). One viable strategy might therefore be to use Virgo as an independent confirmation of the signal established through the stacking of other clusters. Virgo contains the known $\gamma$-ray emitter M87 (Belicke, Götting & Tłuczykont 2004; Abdo et al. 2009). The $\Delta J_{\text{80\%}}$ of Virgo is $\sim 0.3$ for a smooth halo, comparable to the Fermi-LAT PSF at the highest photon energies, but $\sim 3°$ when substructure is considered. Disentangling the point-like emission from M87 from any extended DM emission may therefore be possible. Very recently, Han et al. (2012) have claimed evidence at the $\sim 4\sigma$ level for diffuse DM-like emission from Virgo; they use photon energies detected by Fermi-LAT above 100 MeV and a full likelihood fit to a template versus a point source. Further
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APPENDIX A: THE RELATIONSHIP BETWEEN J AND α_int

There exists a simple parametrization to calculate \( J(\alpha_{\text{int}}) \) for any \( \alpha_{\text{int}} \), given the DM profile (Combet et al. 2012). Indeed, we can assume that all galaxy clusters share the same DM profile. Given the mass range span by the MCXC, we can approximate at first order their concentration parameter to be the same. For an NFW profile, \( c(M) = R_{\text{vir}}/r_s \) and we take \( c(10^{14} M_\odot) \approx 5 \) (Duffy et al. 2008). Defining

\[
\alpha_s \equiv \tan^{-1}\left( \frac{r_s}{d} \right), \quad \alpha_{\text{max}} \equiv \tan^{-1}\left( \frac{5r_s}{d} \right),
\]

(A1)

\[
x \equiv \frac{\alpha_{\text{int}}}{\alpha_s} \quad \text{and} \quad x_{\text{max}} \equiv \frac{\alpha_{\text{max}}}{\alpha_s} \approx 5, \quad \text{(A2)}
\]

there is a universal dependence of the fraction of the smooth and substructure contributions (Maurin et al. 2012),

\[
\mathcal{F}_J(x) \equiv \frac{J(x \cdot \alpha_s)}{J_{\text{max}}},
\]

where we parametrize to be (valid only for an NFW)

\[
\mathcal{F}_{\text{smooth}}(x) = \begin{cases} 
3x^{0.93} & \text{if } x \leq 10^{-2}, \\
1 & \text{if } x \geq 5,
\end{cases}
\]

(A3)

and

\[
\mathcal{F}_{\text{subs}}(x) = \begin{cases} 
1 & \text{if } x \geq 5, \\
\exp[-0.086+0.17 \ln(x)-0.092 \ln^2(x)+0.011 \ln^3(x)] & \text{if } x \leq 10^{-2}, \\
\exp[-1.174+1.06 \ln(x)-0.17 \ln^2(x)-0.015 \ln^3(x)] & \text{if } 10^{-2} < x < 5,
\end{cases}
\]

(A4)

The ‘signal’ \( J \) can then be calculated for any integration angle, using

\[
J_{\text{int}}(\alpha_{\text{int}}) = J_{\text{smooth}}(0.1) \times \mathcal{F}_{\text{int}}(\alpha_{\text{int}}/\alpha_s) + J_{\text{subs}}(0.1) \times \mathcal{F}_{\text{subs}}(\alpha_{\text{int}}/\alpha_s).
\]

(A5)

Hence, as shown in Maurin et al. (2012), for DM annihilation, one needs three quantities (available for all clusters in the Supporting Information – ASCII file – submitted with the paper, short sample in Appendix C), i.e. \( \alpha_s \), \( J_{\text{smooth}}(0.1) \) and \( J_{\text{subs}}(0.1) \).

This parametrization describing the fraction of the signal in a given angular region is valid down to \( \mathcal{F}_J = 10^{-3} \).

APPENDIX B: A COMPARISON OF THE VALUES OF J OBTAINED HERE TO OTHER WORK

DM annihilation in galaxy clusters has been studied in several papers including Jeltema et al. (2009), Ackermann et al. (2010), Sánchez-Conde et al. (2011), Pinzke et al. (2011), Gao et al. (2012b), Huang et al. (2012), Ando & Nagai (2012) and Han et al. (2012). Below, in Table B1, we provide a comparison with some of these studies, whenever the \( J \)-factor was available.

The calculations of the present work are consistent with those of Sánchez-Conde et al. (2011), Pinzke et al. (2011) and Gao et al. (2012b). Our results for the boost values are also in agreement. Our \( J \)-values are also broadly consistent though systematically lower (respectively systematically larger) than those of Ackermann et al. (2010) and Huang et al. (2012) without (respectively with) the substructure contribution. In any case, the uncertainties quoted in these two papers (third line in the table) are probably underestimated. Note that all the three studies rely on the HIFLUGCS catalogue based on ROSAT and ASCA X-ray observations (Chen et al. 2007).

The main difference is for Fornax, which is a factor of 10 larger (though the difference is less significant if we compare with the results of Sánchez-Conde et al. 2011). This is due to the lower mass we infer for this cluster from the MCXC 500, and \( R_{500} \) values, which are based on a better modelling of the gas in the cluster (Piffaretti et al. 2011).
APPENDIX C: J TABLE OF THE MCXC CATALOGUE

In Table C1, the J-values of the first five objects of the MCXC catalogue are given.

We provide, as Supporting Information with the online version of the paper, the full table for the 1743 MCXC catalogue objects.

Table C1 column descriptions are as follows:

(i) Name: cluster name (from MCXC);  
(ii) Indice MCXC: indice of the cluster row in the MCXC catalogue (see Piffaretti et al. 2011);  
(iii) l: Galactic longitude in degree (from MCXC);  
(iv) b: Galactic latitude in degree (from MCXC);  
(v) d: angular diameter distance in kpc (from MCXC);  
(vi) $\alpha_s$: arctan($r_s/d$) in degree ($r_s$ is the scale radius of the cluster);  
(vii) $J_{sm}(0:1)$: astrophysical annihilation term (from smooth halo) in ($M_\odot$ kpc$^{-5}$) for $\alpha_{int} = 0:1$;  
(viii) $J_{sub}(0:1)$: astrophysical annihilation term (from substructures) in ($M_\odot$ kpc$^{-5}$) for $\alpha_{int} = 0:1$;  
(ix) $\alpha_{80\text{per cent}}$: angle in degree containing 80 per cent of the total $J$;  
(x) $J_{80}$: value of annihilation signal for $\alpha_{int} = \alpha_{80\text{per cent}}$.

SUPPORTING INFORMATION

Additional Supporting Information may be found in the online version of this article:

Table C1. J-values for the 1743 MCXC catalogue objects.

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