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Multi-frequency dark matter searches in Omega Centauri

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Dark matter remains one of the most pressing gaps in our modern picture of physics. So far, gamma-ray results from Fermi-LAT have ruled out WIMPs, annihilating into b quarks, with masses below 100 GeV as a dark matter candidate. In this paper we examine the potential of the globular cluster Omega Centauri as a target for indirect detection with Fermi-LAT data as well as CTA, HESS, and MeerKAT sensitivity projections. Globular clusters are usually considered largely devoid of dark matter. However, considerable evidence suggests Omega Centauri may be the relic of satellite dwarf galaxy. Using the latest modelling of its dark matter halo we demonstrate that Omega Centauri has the potential to greatly exceed dwarf spheroidal galaxies in its ability to place limits on dark matter models, due both to its proximity to Earth and suggestions of a dense dark matter core. In particular, limits from the three considered frequency bands are able to rule out b quark annihilation in the thermal relic scenario for masses up to 10 TeV in an optimistic case.

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1. Introduction

Indirect searches for Dark Matter (DM) have long favoured gamma-ray frequencies, for various reasons including lower backgrounds leading to more unambiguous signals. Many of these searches have been focussed on either our own Galactic Centre or local dwarf satellite galaxies [1–6]. These approaches still leave a large swathe of viable WIMP parameter space. Thus, it makes sense to consider other potential targets and frequencies. In this work we consider Omega Centauri, a globular cluster suggested to be the remnant of a tidally disrupted dwarf galaxy [7–11]. This would imply a high DM density [12, 13], combined with the short distance to the object, this suggests a large potential for indirect signals [14]. A recent study, however, indicates no significant evidence for a dominant DM component [15]. In this work we determine a J-factor distribution for Omega Centauri, following the halo fitting of [15]. This is used to further the work presented in [16] and provide a more robust examination of the potential of Omega Centauri by including CTA and HESS prospects while updating previously presented results for Fermi-LAT data and MeerKAT sensitivities.

The paper is structured as follows: in section 2 we discuss our computation of the astrophysical J-factor, sections 3 and 4 lay out the formalism for predicting gamma-ray and radio signals from WIMP annihilations, with our results being presented and discussed in section 5. Finally, our conclusions are drawn in section 6.

2. The DM halo of Omega Centauri

In [15], the authors discuss the maximum DM content of a variety of globular cluster targets. This is done via the use of line-of-sight stellar velocities sourced from [17, 18]. The work is similar to that in [12], where the authors make use of optical data sets from the Gaia EDR3 catalogue as well as those from [18, 19], and the Hubble space telescope. Importantly, the results from [15] for the DM parameters in Omega Centauri are in the form of DM halo parameters r_s and ρ_s (for a Navarro-Frenk-White halo [20] but note Burkert is similar). These are displayed in Fig. 1. To formulate a J factor distribution (Fig. 2) we sample r_s between 10^{-8} and 10^{-1} kpc and ρ_s between $\sim$ 10 and 10^{26} $\mathrm{M}_\odot$ kpc^{-3} from the distributions from [15]. It is clear that there is a significant peak in range 10^{17} to 10^{23} GeV^2 cm^{-5}. In fact, this regions contains only 24% of the probability distribution. However, this twice as much as any other similarly sized region. In addition, it contains 95% of the distribution mass for J-factors $\lesssim 10^{23}$ GeV^2 cm^{-5}. Finally, this range contains both the mean ($\approx 10^{21}$ GeV^2 cm^{-5}) and mode ($\approx 10^{20}$ GeV^2 cm^{-5}) of the distribution. Note that this analysis does not include the significant correlation between r_s and ρ_s evident in [15]. The effect of this is not yet known but may enhance the main peak further.

Taking all of this into account, we will concentrate our interest on the 10^{17} to 10^{23} GeV^2 cm^{-5} range. However, we will take pains to acknowledge that a substantial probability ($\sim$ 70%) remains that the J-factor falls below these values. Notably, our preferred range retains some overlap with that of [12], but is substantially less optimistic. Importantly, [15] do not find significant evidence for a dominant DM component in GCs, whereas the opposite conclusion is reached in [12]. The authors of [15] argue that the discrepancy occurs as a result of [12] using fewer free parameters to describe the stellar component. However, it is notable that there are some suggestions [13] of

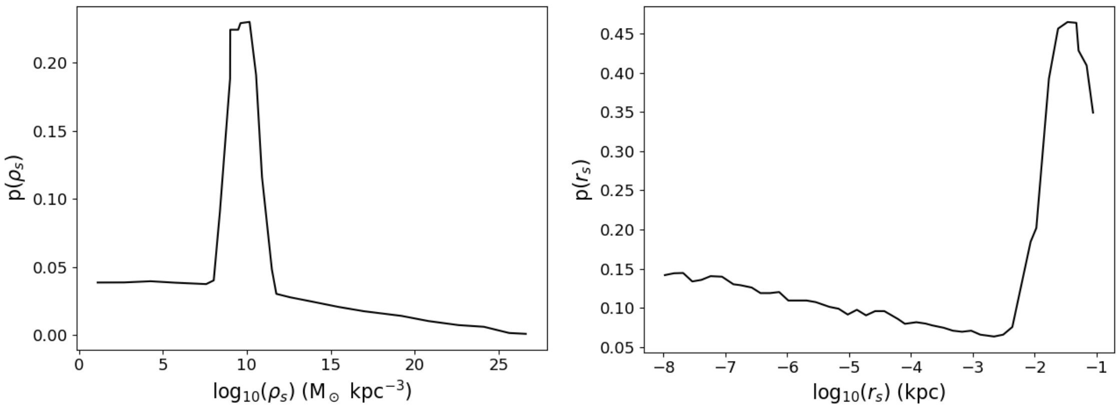

Figure 1: Distributions for DM parameters in Omega Centauri assuming an NFW profile from [15].

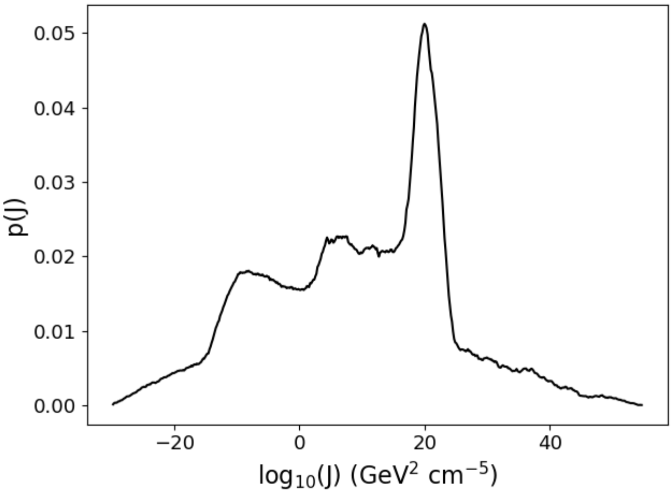

Figure 2: J-factor distribution deduced from DM parameters of [15].

a need for a significant DM component at radii larger than those probed in [15]. This means that, while the conflicting analysis of [15] should caution us against optimistic J-factor values, there is substantial statistical room for Omega Centauri to be strongly DM dominated.

3. DM annihilation: Gamma-ray emission

The DM annihilation within a cone of opening angle $\Delta\Omega$ from the line of sight produces a gamma-ray flux according to

$$S_\gamma(E, \Delta\Omega) = \psi(E) \times J(\Delta\Omega) \; , \tag{1}$$

where the two factors are defined by

$$J(\Delta\Omega) = \int_{\Delta\Omega} d\Omega \int dz \, \frac{r\rho_\chi^2(r)}{2\sqrt{d_L^2 + r^2}} \, , \tag{2}$$

$$\psi(E) = \frac{1}{2}\frac{\langle\sigma v\rangle}{M_\chi^2}\frac{dN_\gamma}{dE}(M_\chi, E) \, , \tag{3}$$

where $d\Omega = 2\pi \sin\theta d\theta$, z is the line of sight coordinate, ρ_χ is the DM density, $d_L = 4.84$ kpc is the halo luminosity distance [21], $r = \sqrt{z^2 + d_L^2 - 2zd_L\cos\theta}$ is the spherical radius, $\langle\sigma v\rangle$ is the thermally averaged DM annihilation cross-section, M_χ is the DM mass, and $\frac{dN_\gamma}{dE}(M_\chi, E)$ are the DM annihilation photon spectra from [22, 23]. The limits of z integration are $z_\pm = d_L\cos\theta \pm \sqrt{r_t^2 - d_L^2\sin^2\theta}$, where $r_t = 43.6$ arcminutes (~ 60 pc at $d_L = 4.84$ kpc) is the tidal radius [24, 25].

4. DM annihilation: radio emission

Radio emission is produced when annihilating DM results in electrons and positrons. These emit synchrotron radiation in the magnetised environment within the host DM halo. The surface brightness a distance R from the centre of the halo is given by

$$I_{\text{sync}}(\nu, R) = \int dl \, \frac{j_{\text{sync}}(\nu, \sqrt{R^2 + l^2})}{4\pi} \, , \tag{4}$$

where l runs over the line of sight. The emissivity j is given by

$$j_{\text{sync}}(\nu, r) = \int_{m_e}^{M_\chi} dE \, \frac{dn_{e^\pm}}{dE}(E, r) P_{\text{sync}}(\nu, E, r) \, , \tag{5}$$

where P_{sync} is the synchrotron power and $\frac{dn_{e^\pm}}{dE}(E, r)$ is the solution of diffusion-loss equation with DM annihilation as a source (for details see [26]). For radio computations we choose two sets of r_s and ρ_s values. First we use 31.6 pc and 7.84×10^{10} $M_\odot$ kpc^{-3} to match $J \sim 10^{23}$ GeV^2 cm^{-5}. Second, we use 31.6 pc and 7.84×10^7 $M_\odot$ kpc^{-3} to match $J \sim 10^{17}$ GeV^2 cm^{-5}. We make use of the median turbulent Milky-Way magnetic field model at Omega Centauri, derived by [27], with a diffusion constant between 10^{26} and 10^{28} cm^2 s^{-1} [27] as well as a flat magnetic field profile (on the 60 pc scale of Omega Centauri) given by $B(r) = 5$ μG [27].

5. DM constraints

In Fig. 3 we display the 95% confidence interval limits on $\langle\sigma v\rangle$, for annihilation into $b\bar{b}$ and $\tau\tau^-$, from Fermi-LAT data [14], HESS [28], MeerKAT [29], and CTA alpha configuration[1] sensitivities. The CTA computations are done using the `gammapy` [30] package with additional tools[2]. For comparison we also plot limits from dwarf spheroidal galaxies with Fermi-LAT [31].

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[1] https://www.cta-observatory.org/science/ctao-performance/

[2] https://github.com/peroju/dmtools_gammapy

These results are plotted for $J = 1.65 \times 10^{21}$ GeV^2 cm^{-5}, this being the mean of the J-factor distribution from Fig. 2. Each of the sensitivities used assumes 20 hours of observing time. The shaded area for MeerKAT indicates the uncertainty on the diffusion constant (this dominates over the factor of ~ 4 uncertainty from the magnetic field strength [27]). Whereas, for CTA it is that from the variance in simulated observations, made using `gammpy`, while assuming a point-source target.

The displayed results indicate how strong the potential of Omega Centauri is for DM indirect limits, even with the less optimistic analysis of the DM halo from [15]. Notably, even the most pessimistic diffusion assumptions allow MeerKAT to compete with Fermi-LAT dwarf galaxy results. Interestingly, the CTA $\tau^+\tau^-$ limits come close to the thermal relic value (using only 20 hours of observation time) for the mean J-factor value at masses above a few hundred GeV. The more significant uncertainty is, of course, the J-factor itself. As a value of 10^{17} GeV^2 cm^{-5} would make neither the Fermi-LAT nor MeerKAT limits competitive with those from dwarf galaxies (the limits scaling roughly as J^{-1}). J-factor values of around 10^{22} GeV^2 cm^{-5} would be needed to make the MeerKAT potential competitive with recent radio work [32, 33]. Notably, the CTA limits provide an excellent complement to those from radio and Fermi-LAT, with $J \sim 10^{22}$ GeV^2 cm^{-5} allowing CTA to probe the thermal relic cross-section for masses in the range 1 to 10 TeV, while Fermi-LAT and MeerKAT would do so up to 1 TeV.

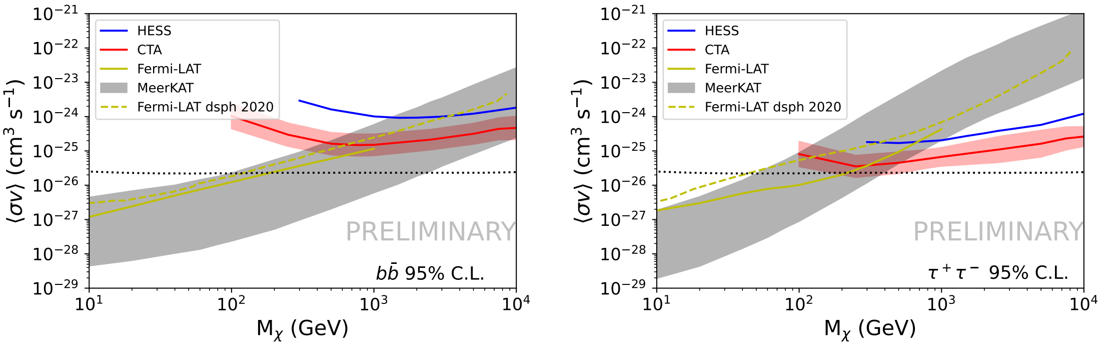

Figure 3: Constraints on $\langle\sigma v\rangle$ at 95% confidence interval for $J = 1.65 \times 10^{21}$ GeV^2 cm^{-5}. Left: annihilation into b quarks. Right: annihilation into τ leptons.

6. Conclusions

In this work we provide preliminary indications that, despite the more pessimistic Omega Centauri halo analysis from [15], there is plenty of room for the resulting multi-frequency indirect DM limits to greatly advance upon the existing literature. It is notable that J-factors that would make Omega Centauri limits insignificant are still reasonably probable. This might change with a full analysis that accounts for correlations between the DM halo parameters (as these favour the peak values of the J-factor distribution). However, the smallest J-factor around the main peak of the distribution ($\sim 10^{17}$ GeV^2 cm^{-5}) would still make the Omega Centauri indirect limits insignificant at all frequencies. In contrast, the most optimistic J-factors would allow combined radio and gamma-ray limits from Omega Centauri to probe below the relic level for WIMP masses up to 10

TeV. Further analysis of the halo structure of Omega Centauri will be needed to more precisely establish whether Omega Centauri will be a new frontier in indirect DM detection.

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