Dark Matter Gamma-ray searches in Galaxy Clusters: status and prospects

Judit Pérez-Romero[1,*]

[1]Center for Astrophysics and Cosmology, University of Nova Gorica, Vipavska 11c, 5270 Ajdovščina, Slovenia

Abstract. Galaxy clusters are the largest structures in the Universe, being dark matter (DM) dominated objects. For DM decay, they yield the highest expected fluxes with respect to other prime targets. For DM annihilation, clusters can provide fluxes comparable to dwarf spheroidal galaxies, as long as the contribution from substructures is taken into account. We present the analysis of 12 years of *Fermi*-LAT data in the direction of 49 clusters. We modelled the expected substructure population in these objects, providing benchmark models to quantify the uncertainty on their contribution to the annihilation flux. From the combined search, we found a signal of 2.5-3.0σ significance, potentially associated with DM or hadronic induced emission from the intracluster region by cosmic rays. Looking into the future, we discuss the prospects of the Cherenkov Telescope Array Observatory (CTAO), to detect diffuse γ-ray emission from the Perseus galaxy cluster. With its improvement in sensitivy of more than one order of magnitude with respect to current IACTs, we derive the tightest constraints for DM decay scenarios in the TeV range, reaching values of $\tau_{\rm DM} \sim 10^{27}$s.

1 Introduction

Dark matter (DM) is a key element in our comprehension of the Universe, being one of the building blocks of the standard cosmological model. However, its fundamental nature remains unknown, and there exists a large pool of candidates that can fit into the DM shoes (see, e.g, Ref. [1]). Weakly Interacting Massive Particles (WIMPs) are one of the best theoretically motivated models. WIMPs are expected to annihilate/decay into standard model particles in regions of the Universe with high DM density. γ-rays are produced from these interactions and then travel the Universe until they reach our detectors.

Clusters of galaxies are the largest virialized structures in the known Universe. Up to 80% of their mass ($M \sim 10^{14}$-10^{15}M$_\odot$) is in the form of DM, which positions them as excellent targets for γ-ray DM searches, especially for the scenario of decaying DM. To search for this signal, we can use both satellite-based (as *Fermi*-LAT) and ground-based telescopes (as the future Cherenkov Telescope Array Observatory - CTAO), since they are complementary in observational strategy, operational energy range and angular resolution.

In this contribution, we present a summary of the γ-ray DM searches from galaxy clusters that we developed in [2] and [3], described, respectively, in Sec. 3 and Sec. 4. Finally, we assemble some conclusions and future prospects in Sec. 5.

---

[*] e-mail: judit.perez@ung.si

2 Modelling of the dark matter induced gamma-ray emission

In order to build a model for the DM-induced emission from galaxy clusters, we consider that DM is composed by WIMPs in its totality. Then, we can compute the expected γ-ray flux from either the WIMP annihilation or decay as:

$$\frac{d\Phi_\gamma}{dE}(E, \Delta\Omega, l.o.s) = \frac{d\phi_\gamma}{dE}(E) \times \begin{cases} J(\Delta\Omega, l.o.s) \\ D(\Delta\Omega, l.o.s), \end{cases} \tag{1}$$

where $\frac{d\Phi_\gamma}{dE}$ is the DM-induced γ-ray flux. The $\frac{d\phi_\gamma}{dE}$ term is the particle physics term[1], which encodes the spectral features of the WIMPs given by the DM mass (m_χ), the annihilation cross section ($\langle\sigma v\rangle$) or the DM particle lifetime for decay (τ). $J(\Delta\Omega, l.o.s)$ and $D(\Delta\Omega, l.o.s)$ are the astrophysical factors carrying the spatial information of the emission, defined as:

$$J(\Delta\Omega, l.o.s) = \int_0^{\Delta\Omega} d\Omega \int_{l.o.s} \rho^2_{\rm tot}(r) dl; \quad D(\Delta\Omega, l.o.s) = \int_0^{\Delta\Omega} d\Omega \int_{l.o.s} \rho_{\rm tot}(r) dl, \tag{2}$$

where $\Delta\Omega$ is the solid angle and $l.o.s$ the line of sight. $\rho_{\rm tot}(r)$ is the DM distribution within the object. For each cluster, we model $\rho_{\rm tot}(r)$ as the sum of the DM density profile of the main halo and the DM density distribution of the expected population of substructures (subhalos).

For the model of the main halo, we use an NFW ([4]) profile. According to ΛCDM structure formation theory, we expect the existence of a large population of substructures in the main halos. Since $J \propto \rho^2_{\rm tot}$, the annihilation in these subhalos should have a non-negligible contribution to the total J-factor. We model this population factorizing the three main distributions: 1) subhalo radial distribution (location of the subhalo inside the main halo); 2) the subhalo mass distribution; and 3) the subhalo concentration. This parametrization allows us to implement semi-analytical models, following results of N-body cosmological simulations. Still, some of the structural properties of substructures are a matter of debate (see, e.g, Ref. [5]). These uncertainties translate to the computation of the J-factors. To bracket them, we define three benchmark models (MIN-MED-MAX) that reflect the minimum, the state-of-the-art estimate, and the maximum contributions, respectively, of the substructures to the J-factor (for further details about the benchmark models check Tab.I in Ref. [2]).

We create DM spatial and spectral templates according to this modelling, using the free software `CLUMPY`[2]. These templates are used to obtain the results shown in Secs. 3 and 4.

3 Search for DM-induced gamma-ray emission with *Fermi*-LAT

For γ-ray DM searches, we are interested in local galaxy clusters, which have been largely observed through X-rays. These observations provide exceptional data to derive the cluster's structural properties. We build a sample of 49 galaxy clusters following the criteria: 1) $z < 0.1$, where z is redshift; 2) virial mass M_{200} obtained from X-ray observations; 3) $|b| > 20$ deg, where b is Galactic latitude; and 4) $s > 2$ deg, where s is the separation between clusters accounting for their extensions. A precise description of the sample can be found in [2].

We analyze 12 years of *Fermi*-LAT data in the direction of the clusters in our sample, from 500 MeV to 1 TeV. The data are fitted using, mainly: 1) fluxes from detected *Fermi*-LAT sources (from 4FGL-DR2 catalog)[3]; 2) interestellar emission template; and 3) DM templates from Sec. 2. The results using this set-up are robust against changes of the analysis choices.

---

[1] We use the results of http://www.marcocirelli.net/PPPC4DMID.html to compute this term.

[2] https://clumpy.gitlab.io/CLUMPY/v3.1.1/

[3] https://fermi.gsfc.nasa.gov/ssc/data/access/lat/10yr_catalog/

The analysis is performed using `FermiPy`[4] and is based on a template-fitting approach, using individual and combined likelihoods. Finally, the significance of the DM hypothesis is computed through the TS vs. the null hypothesis. We define a detection if $TS \geq 25$.

The upper left panel of Fig. 1 shows the TS values assuming the MED model and annihilation to $b\bar{b}$. From the individual analysis, we conclude there is no detection. From the combined analysis, the TS reaches a value of 27, with similar values also for the MAX and decay models, for both $b\bar{b}$ and $\tau^+\tau^-$ channels. If we interpret this emission as a DM signal, we obtain the contours of the TS as a function of m_χ and $\langle\sigma v\rangle$, shown in the upper right panel of Fig. 1. However, the best fit values of $\langle\sigma v\rangle$ are in tension with previous constraints [6].

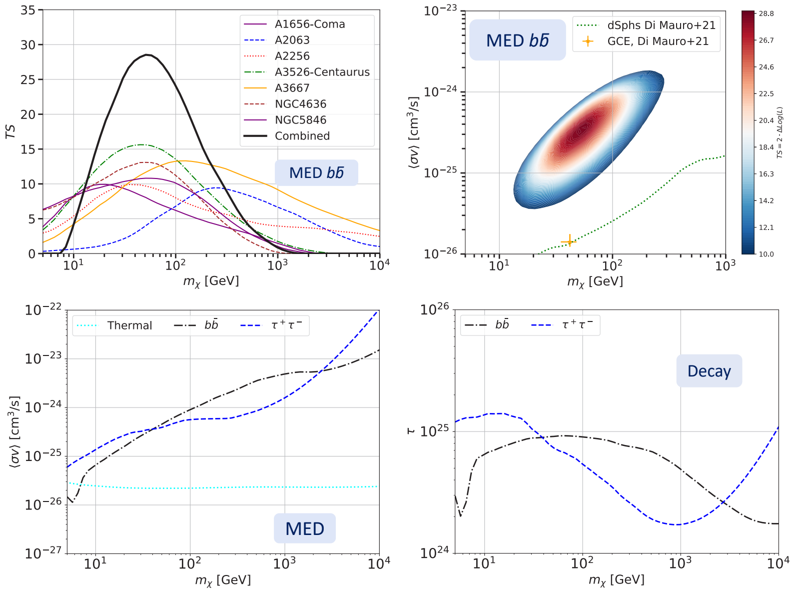

Figure 1. Upper left panel: TS as a function of m_χ from the individual and combined analyses. **Upper right panel:** Contour plot for the TS as a function of m_χ and $\langle\sigma v\rangle$. Both panels correspond to the MED model assuming annihiltion to $b\bar{b}$ channel. **Lower panels:** 95% C.L. upper limits for $\langle\sigma v\rangle$ (**left**) and lower limits for τ (**right**), vs. m_χ, for the annihilation MED model and decay (respectively), and for the $b\bar{b}$ and $\tau^+\tau^-$ channels (from [2]).

To reconcile these results, we recompute the TS distribution using random blank sky directions, to account for deviations in the correspondence between TS and σ significance (deviations from Chernoff theorem). Then, the $TS = 27$ for the MED model is reassigned to 2.7σ, which is below the detection threshold. Thus, we obtain the 95% confidence level (C.L) upper limits for $\langle\sigma v\rangle$ and lower limits for τ vs. m_χ, shown in the lower panels of Fig. 1.

4 Prospects of detection of DM-induced gamma-ray emission with CTAO from Perseus cluster

The CTAO is the next generation of Imaging Air Cherenkov Telescopes (IACTs). Its sensitivity is expected to improve up to $O(1)$ of magnitude with respect to current IACTs. Among the local galaxy clusters, Perseus is the brightest in X-rays and its position in the sky is optimal for the CTAO Northern Array. We compute CTAO prospects for detecting DM-induced γ-rays from Perseus. Perseus observations have allocated 300h ([7]) and for the analysis we follow the same template-fitting procedure and likelihood method as explained in Sec. 3, using the

---

[4] http://fermipy.readthedocs.io/en/latest/

official CTAO software `gammapy`[5]. As source models we use the DM templates introduced in Sec. 2, a template for the expected cosmic ray (CR) induced signal, the contribution from its two main AGNs (NGC 1275 and IC 310) and CTAO's instrumental background[6]. For the CR-induced signal, we consider the hadronic interactions in the intracluster medium, modelling the CR-proton distribution following the thermal gas (see Ref. [3] for more details). In Fig. 2 we see CTAO's prospected constraints in the case of non-detection. In the left plot we see the key role of the substructure contribution to the DM flux, which can shift up to $\mathcal{O}(1)$ of magnitude the constraints in the $\langle\sigma v\rangle$ vs. m_χ plane. Finally, in the right plot we show that CTAO will be able to explore a new region in the parameter space for decay DM models, reaching $\tau \sim 10^{27}$s at 10 TeV, the best projected constraints in the literature.

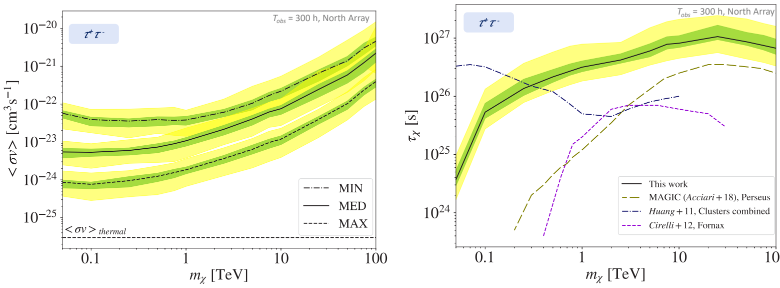

Figure 2. Left panel: 95% C.L. upper limits for $\langle\sigma v\rangle$ vs. m_χ for the MIN, MED and MAX annihilation models. **Right panel:** 95% C.L. lower limits for τ vs. m_χ. Both plots are for the $\tau^+\tau^-$ channel (from [3]).

5 Conclusions

We proved that galaxy clusters are competitive targets for γ-ray DM searches. We found a hint of signal in the analysis of *Fermi*-LAT data, which, if interpreted as due to DM annihilations, it would be in tension with other DM constraints. Work is already ongoing to further investigate this marginal excess in terms of CR-induced γ-ray emission. CTAO has already entered in its construction phase. With its improved sensitivity, we may also be able to shed some light on the *Fermi*-LAT hint, and/or obtain the strongest constraints for DM decay models at TeV energies, from observations of the Perseus cluster.

Acknowledgements

Author is supported by the European Union's Horizon Europe research and innovation programme under the Marie Skłodowska-Curie Postdoctoral Fellowship Programme, SMASH co-funded (grant agreement No. 101081355); and by grant SEV-2016-0597-17-2 funded by MCIN/AEI/10.13039/501100011033 ("ESF Investing in your future"). Work developed with the co-authors in [2] and [3], within the *Fermi*-LAT Collaboration and the CTAO Consortium.

References

[1] L. Bergstrom, Annalen Phys. **524**, 479 (2012), 1205.4882. 10.1002/andp.201200116
[2] M. Di Mauro, J. Pérez-Romero, M.A. Sánchez-Conde, N. Fornengo, Phys. Rev. D **107**, 083030 (2023), 2303.16930. 10.1103/PhysRevD.107.083030
[3] K. Abe *et al.* (CTAO Consortium), JCAP **10**, 004 (2024), 2309.03712. 10.1088/1475-7516/2024/10/004
[4] J.F. Navarro, C.S. Frenk, S.D.M. White, Astrophys. J. **462**, 563 (1996), astro-ph/9508025. 10.1086/177173
[5] S. Ando, T. Ishiyama, N. Hiroshima, Galaxies **7**, 68 (2019), 1903.11427. 10.3390/galaxies7030068
[6] M. Di Mauro, M.W. Winkler, Phys. Rev. D **103**, 123005 (2021), 2101.11027. 10.1103/PhysRevD.103.123005
[7] B.S. Acharya *et al.* (CTAO Consortium), (WSP, 2018), ISBN 978-981-327-008-4, 1709.07997

---

[5] https://gammapy.org/

[6] This research has made use of the CTAO instrument response functions provided by the CTA Consortium and Observatory, see https://www.ctao.org/for-scientists/performance/ (version prod5 v0.1) for more details.