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The Fermi GeV excess: challenges for the dark matter interpretation

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Abstract. One of the most exciting recent results in the field of dark matter indirect searches has been the discovery of an excess emission in gamma rays from the Galactic centre above the standard astrophysical background. We show that current hydrodynamic simulations, namely simulated Milky Way-like galaxies within the "Evolution and Assembly of GaLaxies and their Environments" (EAGLE) project, challenge the possibility to interpret the GeV excess as due to annihilation of dark matter particles in the halo if the Milky Way.

1. Introduction

Since first indications in 2009, several analyses of gamma-ray data from the Large Area Telescope aboard the *Fermi* satellite, *Fermi*-LAT, claimed the existence of an excess above the standard astrophysical background at GeV energies [1, 2, 3, 4]. The excess emission results from analyses of both the inner few degrees of the Galaxy [5, 6, 1, 2] and *higher* latitudes [7, 2], extending up to tens of degrees. Intriguingly, the observed spectral energy distribution and the spatial properties of the *Fermi* GeV excess match the signal expected from weakly interacting dark matter (DM) particles annihilating in the halo of the Milky Way. Nevertheless, astrophysical explanations were put forward as well, as, for example, the emission from a population of point-like sources below the telescope's detection threshold [8, 9, 10, 11], or violent burst events at the Galactic centre (GC) with injection of leptons and/or protons some kilo-/mega-year ago [12, 13], or active star-formation at the centre of the Galaxy [14].

Recently, ref. [3] re-assessed the spectral and morphological properties of this excess emission, robustly characterising the signal against systematic uncertainties related to the high density of cosmic rays (CR), gas, magnetic fields and abundance of point sources within the region $|l| < 20^\circ$ and $2^\circ < |b| < 20^\circ$. The systematic uncertainties due to the Galactic diffuse emission modelling were derived through an innovative method based on a *principal component analysis* of residuals along the Galactic plane (please refer to ref. [3] for more details). The systematic uncertainties are fully encoded in a covariance matrix whose effect in the fit can be interpreted as the result of the variation of slope and normalisation of the Galactic diffuse emission components within the uncertainties allowed by the gamma-ray data (see refs. [3, 15] for more details). The excess properties in light of background model systematics are significantly different from what was claimed before and allow more freedom for models fitting the excess, as it has been shown in ref. [15] in the case of DM models.

In what follows, we set under scrutiny the morphology of the GeV excess data as derived in ref. [3] and we show that the results of current hydrodynamic simulations of Galaxy formation start to challenge the DM interpretation of the GeV excess.

2. Hydrodynamic simulations and dark matter profiles

In [16], we study the spatial distribution of DM particles in Milky Way(MW)-like galaxies simulated by the EAGLE (Evolution and Assembly of GaLaxies and their Environments) project [17, 18], a very recent suite of cosmological, hydrodynamic simulations that reproduces the large-scale properties of galaxies and includes the effect of baryons during structure formation. We are interested in inferring what is the DM density profile predicted by the galaxy formation model used by EAGLE, if there are features of the profile common to all simulated haloes and how well the predicted DM density profile compares with what required to interpret the GeV excess in terms of DM annihilation.

Simulations and Milky Way-like galaxies selection. We use simulations of the EAGLE [17, 18] and APOSTLE projects [19, 20] at different resolutions. APOSTLE, in particular, uses the same code as the EAGLE project but zooms onto regions containing a close pair of DM haloes that could host our MW galaxy and M31 (analogue of the Local Group).

We adopt sets of simulations from three different volumes, which have a different softening length, ϵ (directly related to the resolution limit of the simulation): EAGLE IR (ϵ=700 pc), EAGLE HR (ϵ=350 pc), APOSTLE IR (ϵ=308 pc). The resolution limit is usually taken to be $2.8\times\epsilon$, i.e. 1.96, 0.98 and 0.87 kpc for EAGLE IR, EAGLE HR and APOSTLE IR, respectively. We refer the reader to ref. [16] (and references therein) for more details about the projects and the resolution runs used. We start from the corresponding subsets of galaxies at the centre of haloes with $5 \times 10^{11} < M_{200}/\mathrm{M}_\odot < 1 \times 10^{14}$. The initial sets are composed of 2411, 61 and 24 objects for the EAGLE IR, EAGLE HR and APOSTLE IR simulations, respectively. In order to identify the galaxies that most closely resemble the MW, we define a minimal set of three criteria that the simulated haloes should satisfy. We require that:

(i) The simulated rotation curve fits well the observed MW kinematical data in ref. [21], which represents the largest collection of available data. The observational data are provided as constraints on the angular circular velocity, $\omega_c(R) = v_c(R)/R$, and the galactocentric distance R, where $v_c(R)$ is the circular velocity at distance R. From the simulation, we compute the circular velocity, $v_c(R)$, defined as the velocity of a test particle on a circular orbit at radius R from the GC. Then we compare the measured MW rotation curve with the set of simulated curves and find galaxies that best fit the data through a χ^2 minimisation procedure.

(ii) The total stellar mass of the simulated galaxies is within the 3σ MW range derived from observations, $4.5 \times 10^{10} < M_*/\mathrm{M}_\odot < 8.3 \times 10^{10}$ [22]: 335, 12, and 2 galaxies satisfy this constraint in the EAGLE IR, EAGLE HR and APOSTLE IR simulations respectively.

(iii) The galaxies contain a substantial stellar disc component. In order to verify this we follow the approach of ref. [23], and we characterise the dynamics of each simulated galaxy by looking for evidence of coherent rotation. We use the distribution of angular momentum vectors of individual particles relative to the net angular momentum of the galaxy to discriminate between *discs* (coherent rotation) and *spheroids* (no coherent rotation; comprises bulges and stellar haloes). In the case of the EAGLE IR run the number of galaxies passing the stellar mass *and* disc dominance criteria is 145, while for EAGLE HR only 2 objects survive the this criterion. The 2 galaxies in APOSTLE IR satisfying the dynamical and stellar mass constraints also match the disc requirement.

The three criteria listed above define MW-like galaxies. In particular, applying the first criterion significantly reduces the wide range of variation in the rotation curves from the simulation when considering all objects whose halo mass, M_{200}, lies in the selected MW mass range, $5 \times 10^{11} < M_{200}/\mathrm{M}_\odot < 1 \times 10^{14}$. Moreover, by forcing the haloes to have the correct total stellar mass, the number of good objects is further reduced.

We thus demonstrate that classifying a halo with the correct halo mass as MW-like is a too simplistic criterion, and will often fail to reproduce the MW kinematical data.

Dark matter profiles of Milky Way-like galaxies. We here analyse the DM density profiles of the MW-like analogues in the three sets of simulations. In the following we show results only for EAGLE HR but similar conclusions hold for EAGLE IR and APOSTLE IR and can be found in ref. [16].

In the left panel of figure 1, we show the DM density profile of the final set of EAGLE HR haloes. By construction, we assume spherical symmetry for the distribution of DM, which has been shown to be a good assumption for the APOSTLE simulations [24]. The uncertainty in the density is given by the Poissonian error in the number of particles in each mass shell. The effective resolution limit of EAGLE HR is 0.98 kpc. However, the radius at which profiles can be considered as converged is larger than this value and can be estimated in collisionless simulations using the criterion of [25] that identifies the radius at which the integral in mass is independent on the resolution. The so-called "Power radius" is $R_{\mathrm{P03}} = 1.8$ kpc. A discussion of issues related to convergence in hydrodynamic simulations can be found in refs. [26, 17, 24].

All DM density profiles (also for EAGLE IR and APOSTLE IR) show two common features: (i) The DM density is shallower than what is expected from an Navarro-Frenk-White (NFW) profile in the inner $1.5 - 2$ kpc; (ii) Between about $1.5 - 8$ kpc the effect of baryons results in a steeping of the DM profile. In the right panel of figure 1 we show the radial variation of the local logarithmic slope for our selected MW-like galaxies together with the expectation for the NFW density profile. For EAGLE HR there is a deviation of the slope from -1 (NFW expectation) and a tendency to 0 slightly above the resolution limit. The effect of baryonic contraction is evident in the range $1.5 - 6$ kpc where the logarithmic slope is steeper than -1.

Implications for the GeV excess. Ref. [3] tested several templates for the GeV excess morphology and found that the GeV excess has a spatial distribution $\propto r^{-\gamma}$ with $\gamma = 1.26 \pm 0.15$ (thus corresponding to an inner slope steeper than the standard NFW profile). To test the profiles predicted by hydrodynamic simulations against the GeV excess data, however, we should rely on extrapolation of the DM simulated profile below the resolution limit. For the extrapolation, we adopt a power-law whose steepness is the maximal compatible with the total mass inside the extrapolation radius, namely the maximal asymptotic slope [27]. The asymptotic inner slope is defined as $\gamma_{\max}(r) = 3(1 - \rho(r)/\bar{\rho}(r))$. In order to remove possible numerical effects that still might occur between the resolution limit and the Power radius, we extrapolate the profiles from the Power radius. This is a truly conservative choice since extrapolating from the Power radius guarantees that profiles steeper than the maximal asymptotic slope at the Power radius are not allowed by the simulation data *within the resolution/convergence limit of the simulation.*

The maximal asymptotic slopes for EAGLE HR haloes are 0.94 and 0.98 at R_{P03}= 1.8 kpc. In general, the result of our extrapolation (also for EAGLE IR and APOSTLE IR) indicates

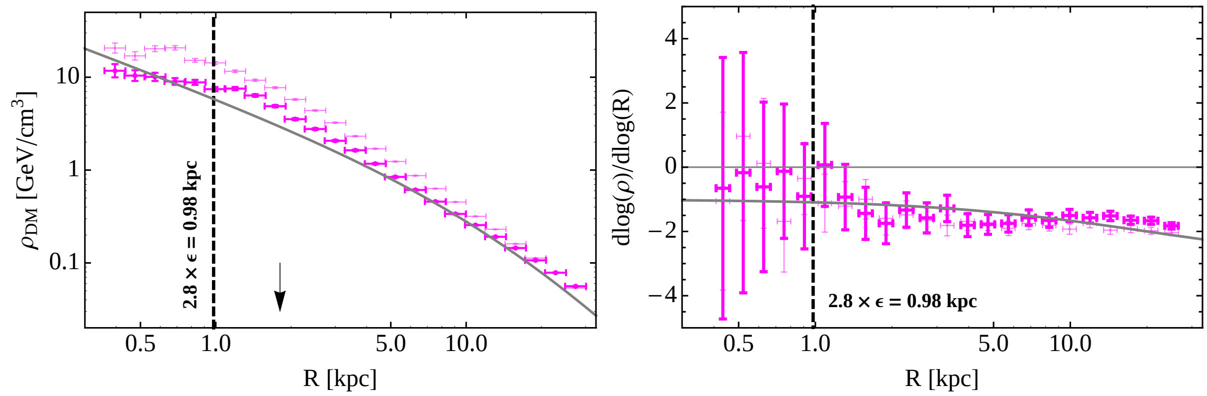

Figure 1. DM density profiles (*left* panel) and radial change of the local logarithmic slopes (*right* panel) of the selected MW-like galaxies in EAGLE HR. The *thick grey line* represents the prediction for an NFW profile with $r_s = 20$ kpc and local DM density $\rho_\odot = 0.4$ GeV/cm^3. In the left panel the effective resolution of the simulation is shown by the *dashed black line*, while the *black arrow* indicates the convergence radius, 1.8 kpc.

that no simulated halo has enough DM mass within the Power radius to support profiles as steep as $r^{-1.26}$ (as required by the data).

We then quantify, through a χ^2 minimisation procedure, how well the *extrapolated* DM density profiles of the EAGLE HR haloes fit the GeV excess data from ref. [3]. The free parameters of the fit are the annihilation cross section $\langle \sigma v \rangle$ and the DM mass. In the case of EAGLE HR (for the best halo) the best-fit parameters are respectively $1.96 \pm 0.14 \times 10^{-26}$ cm^3/s and 46.37 ± 1.37 GeV, with p-value $= 0.34$. These results should be compared with the values preferred by the fit when adopting a DM profile with $\gamma = 1.26$, i.e. $1.71 \pm 0.11 \times 10^{-26}$ cm^3/s, 47.32 ± 1.07 GeV and p-value $= 0.73$. As expected, because of the flattening in the inner region, the fit is worse in the case of a DM density profile drawn from the EAGLE HR galaxies and the best-fit cross section is slightly higher than the best-fit cross section obtained when adopting $\gamma = 1.26$ in the fit.

In conclusion, we find that, even under the very conservative assumption of extrapolating from the Power radius, when performing the fit to the GeV excess data [3], the DM profiles predicted by the EAGLE (and APOSTLE) project fail to reproduce the right morphology of the excess in the innermost regions (within 5° above and below the Galactic plane). The DM density profiles of our selected MW-like galaxies predict gamma-ray fluxes from DM annihilation that cannot fully account for the observed *Fermi* GeV excess. However, this does not exclude the possibility that DM annihilation provides a sub-dominant contribution to the GeV excess.

References

[1] Abazajian K, Canac C, Horiuchi S, and Kaplinghat M 2014 *Phys.Rev.* **D90** 023526
[2] Daylan T, Finkbeiner D, Hooper D, Linden T, Portillo S et al 2014 *Preprint* arXiv:1402.6703
[3] Calore F, Cholis I, and Weniger C 2015 *JCAP* **1503** 038
[4] Fermi-LAT Collaboration, Murgia S 2014 *Talk given at the 2014 Fermi Symposium, Nagoya, Japan, October 20-24*
[5] K. N. Abazajian K and Kaplinghat K 2012 *Phys.Rev.* **D86** 083511
[6] Gordon C and Macias O 2013 *Phys.Rev.* **D88** 083521
[7] Hooper D and Slatyer T 2013 *Phys.Dark Univ.* **2** 118
[8] Hooper D, Cholis I, Linden T, Siegal-Gaskins J, and Slatyer T 2013 *Phys.Rev.* **D88** 083009
[9] Calore F, Di Mauro M, and Donato F 2014 *Astrophys.J.* **796** 1

[10] Cholis I, Hooper D and T. Linden T 2014 *Preprint* arXiv:1407.5625
[11] Petrovic J, Serpico P and Zaharijas G 2014 *Preprint* arXiv:1411.2980
[12] Carlson E and Profumo S 2014 *Phys.Rev.* **D90** 023015
[13] Petrovic J, Serpico P and Zaharijas, G 2014 *JCAP* **1410** 052
[14] Gaggero G, Taoso M, Urbano A, Valli M, and Ullio P 2015 *Preprint* arXiv:1507.06129
[15] Calore F, Cholis I, McCabe C, and Weniger C 2014 *Preprint* arXiv:1411.4647
[16] Calore F, Bozorgnia N, Lovell M, Bertone G, Schaller M, Frenk C, Crain R, Schaye J, Theuns T and Trayford J, 2015 *JCAP* **1512** 053
[17] Schaye J, Crain R, Bower R, Furlong M, Schaller M, TTheuns T, Dalla Vecchia C, Frenk C, McCarthy I, Helly J, Jenkins A, Rosas-Guevara Y, White S, Baes M, Booth C, Camps P, Navarro J, Qu Y, Rahmati A, Sawala T, Thomas P and Trayford T 2015 *MNRAS* **446** 521
[18] Crain R, Schaye J, Bower R, Furlong M, Schaller M, Theuns T, Dalla Vecchia C, Frenk C, McCarthy I, Helly J, Jenkins A, Rosas-Guevara Y, White S and Trayford J 2015 *MNRAS* **450** 1937
[19] Sawala T, Frenk C, Fattahi A, Navarro J, Bower R, Crain R, Dalla Vecchia C, Furlong M, Helly J, Jenkins A, Oman K, Schaller M, Schaye J, Theuns J, Trayford J and White S 2015 *Preprint* arXiv:1511.01098
[20] Fattahi A, Navarro J, Sawala T, Frenk C, Oman K, Crain K, Furlong M, Schaller M, Schaye J, Theuns T and Jenkins A 2015 *Preprint* arXiv:1507.03643
[21] Iocco F, Pato M, and Bertone G 2015 *Preprint* arXiv:1502.03821
[22] McMillan P 2011 *Mon.Not.Roy.Astron.Soc.* **414** 2446
[23] Scannapieco C, White S, Springel V, and Tissera P 2009 *Mon.Not.Roy.Astron.Soc.* **396** 696
[24] Schaller M et al 2015 *Preprint* arXiv:1509.02166
[25] Power C, Navarro J, Jenkins A, Frenk C, White S et al 2003 *Mon.Not.Roy.Astron.Soc.* **338** (2003) 14
[26] Schaller M, Frenk C, Bower R, Theuns T, Jenkins A, Schaye J, Crain R, Furlong M, Dalla Vecchia C and McCarthy I 2015 *MNRAS* **451** 1247
[27] Springel V, Wang J, Vogelsberger M, Ludlow A, Jenkins A, Helmi A, Navarro J, Frenk C and White S 2008 *Mon. Not. Roy. Astron. Soc.* **391** 1685