Gamma Rays from Dark Matter Annihilations Strongly Constrain the Substructure in Halos

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To fit recent data, $e^{\pm}$ from dark matter (DM) needs a boosted annihilation rate. This may imply an observable level of gamma rays from nearby galaxy clusters for the Fermi satellite. Using EGRET data, we limit the minimum mass of DM substructures to be about 5×10^3 times larger than for cold DM, meaning a cutoff similar to, e.g., warm DM. We numerically simulate clusters to reliably model the background. If we assume no anomalous boost factor, we find comparable levels of gamma-ray emission from DM and cosmic ray interactions, giving a chance with future data to characterize the DM.

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The identity of the dark matter (DM) in the Universe has been the subject of intense speculation. In particular, the hierarchical formation of structure, as indicated from numerical simulations of cold DM (CDM), agrees very well with observations on scales of galaxy clusters and larger, whereas the small scale behavior on galactic and subgalactic scales is more unsecure. If dark matter particles have weak interactions, one would expect possible signals from annihilations (or decays).

Data from a new generation of cosmic ray detectors have indeed been tentatively interpreted in terms of such signatures of DM. In particular, the positron fraction measured by the PAMELA satellite [1] and the sum of electrons and positrons by ATIC [2] have shown an unexpected excess. Very recent data from Fermi-LAT [3] and H.E.S.S. [4] on the sum of electrons and positrons do not confirm the peak claimed by ATIC, but still indicate an excess compared to the expected background in conventional models. A number of attempts have been made trying to explain the excess due to DM annihilation (for recent reviews, see [5,6]) but also other astrophysical sources such as pulsars have been investigated (e.g., [7], and references therein).

One class of DM models that fits the new data has halo annihilation primarily into muon pairs, which then decay to electrons and positrons. In [8] examples of fits with remarkable quality (which also fit PAMELA [1] and new H.E.S.S. data) were obtained by such DM models. It was pointed out that if the annihilation goes directly into a $\mu^+\mu^-$ pair, a striking signature may be present. This is caused by the direct emission of gamma rays from the final state (final state radiation, FSR), which gives a peculiar energy spectrum, with $E^2 dN_\gamma/dE$ almost linearly rising with energy. The same, but weaker, feature may in fact exist also for the theoretically perhaps more easily motivated models with intermediate spin-0 boson decay, but in this Letter we only treat the somewhat simpler direct annihilation case. In this Letter we show that such DM models face considerable tension with existing gamma-ray limits from clusters of galaxies, systems which will be very interesting to detect and study with coming gamma-ray detectors (Fermi, H.E.S.S., MAGIC, VERITAS, and CTA).

Galaxy clusters constitute the most massive objects in our Universe that are forming today. This causes their DM subhalo mass function to be less affected by tidal stripping compared to galaxy sized halos that formed long ago. The annihilation luminosity of the smooth DM halo component scales as

$$L_{\rm sm} \sim \int dV \rho^2 \sim \frac{M_{200} c^3}{[\log(1+c) - c/(1+c)]^2} \sim M_{200}^{0.83}, \quad (1)$$

where the virial mass M_{200} and the concentration c [see Eq. (3)] are the two characteristic parameters of the universal Navarro-Frenk-White (NFW) density profile $\rho_{\rm NFW}$ of DM halos [9]. Hence, the flux ratio of a nearby cluster (Virgo) to a prominent dwarf spheroidal (Draco) is given by

$$\frac{F_{\rm cluster}}{F_{\rm dwarf}} \simeq \left(\frac{80\ \rm kpc}{17\ \rm Mpc}\right)^2 \left(\frac{2 \times 10^{14} M_\odot}{10^8 M_\odot}\right)^{0.83} \simeq 3.8, \quad (2)$$

assuming an early formation epoch of the dwarf galaxy before the end of reionization [10]. Once a satellite galaxy is accreted by our Galaxy, the outer regions are severely affected by tidal stripping. The longer a satellite has been part of our Galaxy, and the closer it comes to the center during its pericentral passage, the more material is removed [11]. In contrast, the substructure in clusters is not affected in the outer regions and may enhance the DM annihilation signal over its smooth contribution considerably as we will see in the following. The FSR feature of DM annihilation may in addition be more easily visible in clusters, as the average intensity of starlight, which may give a masking signal due to inverse Compton scattering of the copiously produced electrons and positrons, is lower than in the Milky Way (MW). For previous work related to dark matter in clusters, see, e.g., [12,13]. All halo masses and length scales are scaled to the currently favored value of Hubble's constant, $H_0 = 70\ \rm km\, s^{-1}\, Mpc^{-1}$. We define the virial mass M_{200} and virial radius r_{200} as the mass and radius of a sphere enclosing a mean density that is 200 times the critical density of the Universe $\rho_{\rm cr}$.

Method.—As our default model for *dark matter annihilation*, we take the Sommerfeld-enhanced (see, e.g., [14,15]) direct muon annihilation mode of [8], i.e., mass $m_\chi = 1600$ GeV and effective enhancement factor 1100 relative to the standard annihilation cross section $\langle\sigma v\rangle_0 \sim 3\times10^{-26}\ {\rm cm^3\,s^{-1}}$. It is nontrivial to rescale this boost to the corresponding value for the cluster environment. This may either give a smaller or larger value, depending, e.g., on the velocity dispersion of bound substructure in the cluster, and whether the Sommerfeld enhancement (SFE) increases down to very small velocities, or if it saturates at some minimum velocity [16]. We choose a simple and generic model for the SFE factor $B_{\rm sfe}(\sigma_v) \approx 0.7c/\sigma_v$ and saturate at $\sigma_{v,\rm min} = 200$ km/s [17]. For a given cluster, we assume a constant velocity dispersion of $\sigma_v = 960\ {\rm km/s}\times(M_{200}/10^{15}M_\odot)^{1/3}$ [18].

Using cluster masses from the complete sample of the x-ray brightest clusters (the extended HIFLUGCS catalogue, [19]) we identify the brightest clusters for DM annihilation. In models with SFE, the DM flux to leading order scales as a power law $F \sim M_{200}^{-1/3}M_{200}^{0.83}/D^2$. The first factor accounts for the SFE and the second one is derived from Eq. (1), using a power-law fit to the mass dependence of the NFW halo concentration derived from cosmological simulations with $M_{200} \gtrsim 10^{10}M_\odot$ [20],

$$c = 3.56\times\left(\frac{M_{200}}{10^{15}M_\odot}\right)^{-0.098}. \qquad (3)$$

Note that Eq. (3) agrees well with [21] for cluster-mass halos after converting the concentration definitions according to [22]. This yields Fornax ($M_{200} = 10^{14}M_\odot$) and Virgo ($M_{200} = 2.1\times10^{14}M_\odot$, [23]) as the prime targets for DM observations and we additionally decide in favor of the well studied cluster Coma ($M_{200} = 1.4\times10^{15}M_\odot$) for comparison.

The differential photon flux from annihilating DM within a given solid angle $\Delta\Omega$ along a line-of-sight (LOS) is given by

$$\frac{dF}{dE_\gamma} \equiv \frac{d^3N_\gamma}{dAdtdE_\gamma} = \int_{\Delta\Omega}\frac{d\Omega}{4\pi}\int_{\rm LOS} dl\, q_{\rm sm}(E_\gamma, r)B_F(\sigma_v, r), \qquad (4)$$

where $q_{\rm sm}(E_\gamma, r)$ is the source function from the smooth halo with contributions from two main processes: DM annihilating to μ^+/μ^- which decay to e^+/e^- pairs that Compton up-scatter cosmic microwave background (CMB) photons (IC) and FSR. The source function of FSR is given by

$$q_{\rm fsr}(E_\gamma, r) = \sum_i \frac{dN_{\gamma,i}}{dE_\gamma}\Gamma_i(r), \qquad (5)$$

where the annihilation rate density $\Gamma_i = (\rho/m_\chi)^2\langle\sigma v\rangle_i/2$. The i runs over all gamma-ray producing channels each with the spectrum $\frac{dN_{\gamma,i}}{dE_\gamma}$ and annihilation cross section $\langle\sigma v\rangle_i$. We use the standard photon distribution for the final state radiation from our DM model annihilating directly to charged leptons assuming $m_\chi \gg m_l$ [24]. For the remaining part of this work, the Einasto density profile for DM halos [25] is used, normalized with $\rho_0 = \rho_{\rm NFW}(r_s)/4$ relying on the assumption that 90% of the flux from a NFW density profile and an Einasto density profile originate from within the scale radius $r_s = r_{200}/c$.

The product of enhancement factors from SFE $B_{\rm sfe}(\sigma_v)$ and from substructure enhancement over the smooth halo contribution $B_{\rm sub}(r) = 1 + q_{\rm sub}(r)/q_{\rm sm}(r)$ is denoted by $B_F(\sigma_v, r) = B_{\rm sfe}(\sigma_v)B_{\rm sub}(r)$. High-resolution DM simulations of the Milky Way (MW) suggest an enhancement from substructures of approximately 220 inside r_{200} assuming that the subhalos extrapolate smoothly down from the simulation resolution limit to smallest scales [26], with most of the substructure residing in the outer part of the MW halo. We fit the luminosity $L_{\rm sub} = \int dE_\gamma dV q_{\rm sub}$ from substructures inside a radius r following [27],

$$L_{\rm sub}(<r) = 0.8CL_{\rm sm}(r_{200})(r/r_{200})^{0.8(r/r_{200})^{-0.315}}, \qquad (6)$$

where $L_{\rm sm}(r_{200})$ is the smooth cluster halo luminosity within r_{200}. The normalization $C = (M_{\rm min}/M_{\rm lim})^{0.226}$, where $M_{\rm min} = 10^5M_\odot$ is the minimum subhalo mass in the simulation and $M_{\rm lim}$ the free-streaming mass. While its conventional value is $10^{-6}M_\odot$ [28], we will constrain this quantity by requiring consistency with the nondetection of gamma-ray emission from clusters by EGRET: the smaller $M_{\rm lim}$, the more substructure is present and the larger is the expected gamma-ray signal. This approach of fitting the scaling behavior of $L_{\rm sub}(M_{\rm lim})$ directly from numerical simulations self-consistently accounts for the radial dependence of the substructure concentration [26]. We note that this might result in a slight overestimate of the substructure luminosity if the assumed power-law scaling flattens towards smaller scales although current simulations show no sign of such a behavior which is also not expected since we are approaching the asymptotic behavior in the power spectrum on these scales.

The source function of inverse Compton emission resulting from DM annihilating is given by

$$q_{\rm IC}(E_\gamma, r) = \int dE_e \frac{dn_e}{dE_e}P_{\rm IC}(E_\gamma, E_e), \qquad (7)$$

where $P_{\rm IC}$ is derived by convolving the IC cross-section with the differential target photon number density [12]. Assuming that the spatial diffusion time scale is much larger than the energy loss time scale, the total equilibrium distribution of the electrons plus positrons is given by

$$\left(\frac{dn_e}{dE_e}\right)(E_e, r) = \frac{\Gamma_\mu(r)}{b(E_e, r)}\int_{E_e}^{m_\chi c^2} dE'_e \frac{dN_e}{dE'_e}, \qquad (8)$$

$$b(E_e, r) = \frac{4\sigma_T c}{3(m_e c^2)^2}\frac{B_{\rm CMB}^2 + B^2(r)}{8\pi}E_e^2, \qquad (9)$$

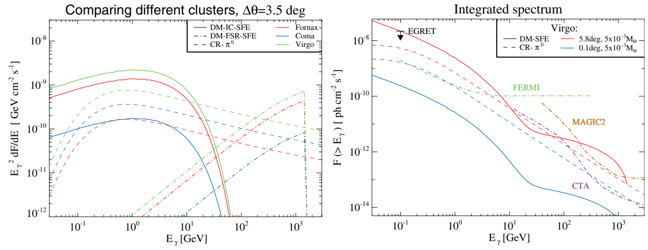

FIG. 1 (color). Left: differential spectra for 3 different clusters observed within a solid angle of radius $\Delta\theta = 3.5$ degree (neglecting the contribution of the MW's halo). We show the IC emission from DM annihilations (solid) as well as FSR (dashed-dotted). We include SFE and the enhancement from cluster substructures down to a limiting substructure mass of $M_{\rm lim} = 5 \times 10^{-3} M_\odot$. We show the pion decay emission of our conservative model without galaxies with dashed lines. Right: we contrast the integrated spectrum of Virgo for the EGRET angular resolution, $\Delta\theta = 5.8$ (red), with that of imaging air Čerenkov telescopes, $\Delta\theta = 0.1$ (blue), and compare those to the point source sensitivity curves on the 5σ level of Fermi (2 yr all-sky survey) as well as MAGIC2 and CTA (50 hours). We choose $M_{\rm lim} = 5 \times 10^{-3} M_\odot$, so that the resulting flux is just consistent with the EGRET upper limit [37]. This reduces the substructure boost from ~220 to 50.

where $\frac{dN_e}{dE_e}$ denote the differential number of electrons plus positrons resulting from an annihilation event, $B_{\rm CMB} = 3.24(1+z)^2\ \mu$G denotes the equivalent field strength of the CMB, and we parametrize the magnetic field of the galaxy cluster by $B(r) = 3\ \mu{\rm G}[n_e(r)/n_e(0)]^{0.7}$, which follows from flux frozen magnetic fields.

To address the problem of source confusion by *astrophysical backgrounds*, we perform high-resolution, cosmological simulations [29] of a sample of 14 galaxy clusters [30]. They span over one and a half decades in mass and follow radiative gas physics, star formation, supernova feedback. In particular, we use an updated version of the cosmic ray (CR) physics that is capable of following the spectral evolution of the CR distribution function by tracking multiple CR populations—each being described by its characteristic power-law distribution with a distinctive slope that is determined by the acceleration process [31]. We compute the dominating gamma-ray emission signal from decaying neutral pions that result from hadronic CR interactions with the ambient gas following [32]. We find that it obeys a universal spectrum and spatial distribution (details will be presented in [31]). This allows us to reliably model the CR signal from nearby galaxy clusters using their true density profiles as obtained by x-ray measurements [33] that we map onto our simulated density profiles. We compute gamma-ray luminosity-mass scaling relations of our sample [34] and use these to normalize the CR induced emission of all clusters in HIFLUGCS [19]. In our optimistic CR model, we calculate the cluster's total gamma-ray flux within a given solid angle while we cut the emission from our individual galaxies and compact galactic-sized objects in our more conservative baseline model [35].

Results and discussion.—In Fig. 1, we find that, given our assumptions, the DM annihilation signal in Fornax and Virgo should be clearly visible by Fermi. It dominates over the CR induced signal for both of our CR models. The annihilation signal within 3.5 deg is similar for Fornax and Virgo—these are clusters with a comparable distance but the latter being twice as heavy: the larger signal of Virgo due to its larger mass is counteracted by the larger substructure boost of Fornax for the same angular extent. Using the standard assumptions for the limiting mass of substructures within DM halos of $10^{-6} M_\odot$, we show that the resulting annihilation flux from Virgo is already in conflict with the EGRET upper limit. This allows us to place a lower bound on the limiting mass $M_{\rm lim} = 5 \times 10^{-3} M_\odot$ and hence to constrain the free-streaming scale in the linear matter power spectrum to

$$k < \frac{6\pi}{16}\left(\frac{4\pi}{3}\frac{\Omega_m \rho_{\rm cr}}{M_{\rm lim}}\right)^{1/3} \simeq 35\ {\rm kpc}^{-1}. \qquad (10)$$

The Fermi sensitivity will allow us to place an even more stringent limit of $M_{\rm lim} > 10^3 M_\odot$ which is approaching the upper limit $M_{\rm lim} < 2 \times 10^8 M_\odot$ derived from Ly-α power spectrum measurements [36]. The contribution of the smooth DM halo component towards high galactic latitudes within 3.5 deg amounts to $F(>100\ {\rm MeV}) \simeq 9 \times 10^{-9}\ {\rm ph\,cm^{-2}\,s^{-1}}$ which should be easily detectable by Fermi, especially considering an enhancement factor of a few from the substructure in the MW halo. This allows us to finally scrutinize the DM models motivated by the recent Fermi, H.E.S.S., and PAMELA data. Assuming SFE, the next generation of imaging air Čerenkov telescopes have good prospects of detecting the DM annihilation signal while it will be very difficult without an enhancement. We show in Fig. 2, that the DM annihilation flux is substantially boosted due to substructures in clusters as well as in the MW's halo that has a smooth angular emission characteristic but is expected to have the same spectral behavior. This provides hope that even in the absence of SFE, the DM annihilation flux is of the same order of magnitude as our conservative model of CR induced gamma-ray emission. The very distinctive spectral properties of the DM-induced gamma rays and the universality of the CR spectra suggest that spectral subtraction techniques could be applied to detect the annihilation signal and characterize the properties of DM.

Conclusions.—The DM models motivated by the recent Fermi, H.E.S.S., and PAMELA measurements require an anomalous boost factor of 1100. Assuming that SFE entirely accounts for this boost, this necessarily predicts large annihilation fluxes from nearby galaxy clusters even in the case of somewhat reduced SFE due to the larger velocity dispersion of clusters. Using standard assumptions for the limiting mass of substructures within DM halos, we find a violation of the EGRET upper limit in Virgo. The lighter a DM particle, the larger the induced free-streaming scale in the power spectrum and the higher the mass cutoff for the

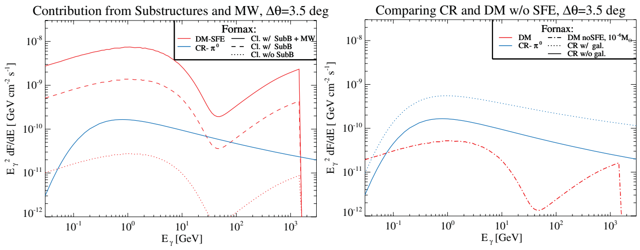

FIG. 2 (color). Studying separately the contribution from substructure and the SFE to the differential spectra of Fornax within a solid angle of $\Delta\theta = 3.5$ degree. Left: the DM annihilation spectra with SFE and $M_{\mathrm{lim}} = 5 \times 10^{-3} M_{\odot}$ (red) is compared to the pion decay spectrum from CR interactions (blue). We show the pure contribution from the smooth cluster halo (dotted, $B_{\mathrm{sfe}} = 490$, $B_{\mathrm{sub}} = 1$), to which we add substructures (dashed, $B_{\mathrm{sfe}} = 490$, $B_{\mathrm{sub}} = 50$), and to which we additionally add the line-of-sight contribution due to the Milky Way's halo towards Fornax (solid). Right: we compare the hadronically induced pion decay spectrum to the DM annihilation signal *without SFE*. The pion decay spectrum shown with (dotted) and without (solid) the contribution due to galaxies and dense point sources. The substructure boosted DM annihilation signal including the MW contribution (dash-dotted), but assuming a standard value for the limiting substructure mass of $M_{\mathrm{lim}} = 10^{-6} M_{\odot}$.

smallest structures: since the DM interpretation fixes the DM particle mass this locks in a minimum substructure mass. Hence, a nondetection of gamma rays at the predicted level by Fermi would provide a serious challenge for the standard assumptions of the CDM power spectrum, or call for a new dynamical effect during nonlinear structure formation that wipes out the smallest structures. The resolution may of course also be that the rising positron ratio measured by PAMELA and the electron plus positron excess seen by H.E.S.S. and Fermi is caused by local astrophysical sources, e.g., pulsars, and is unrelated to DM.

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