Galaxy Clusters and Dark Matter Properties

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Laboratory experiments, large-scale computer simulations and observational cosmology have begun to make progress in the campaign to identify the particle responsible for gravitationally-inferred dark matter. In this contribution we discuss the dark matter density profiles in the cores of nearby galaxy clusters and estimate the gamma-ray flux expected for MSSM dark matter over a range of neutralino masses.

1. INTRODUCTION

Galaxy clusters are dark matter-dominated objects. Since they are believed to constitute a nearly fair sample of the matter content of the universe [1], WMAP results suggest that they are comprised of roughly 15% baryons and 85% non-baryonic dark matter [2]. Numerical experiments which simulate their formation via the hierarchical assembly of cold dark matter (CDM) halos suggest that their density profiles are adequately described by a pair of power laws and a transition radius [3–5]. Indeed, the dark matter density profile in the centers of relaxed clusters shows power-law behavior to scales as small as ~ 10 kpc [6–8]. If the density profile remains a power law to small enough radius, the central density may become large enough that dark matter self-annihilation produces a gamma-ray flux observable with current instrumentation.

The neutralino is perhaps the leading candidate for the dark matter particle [9]. The observational signal for neutralino annihilations can be quite spectacular. Two of the annihilation channels result in the production of monochromatic gamma rays, unlikely to be confused with other astrophysical processes. Other channels can lead to substantially more gamma rays, although since they produce a continuous spectrum they are more difficult to distinguish from high energy processes such as shock heating.

Most searches for the gamma ray signature of dark matter annihilation have centered on local dark matter concentrations such as the Galactic center [10] and halo [11, 12] and Local Group dwarf spheroidals [13]. However, if the centers of galaxy clusters are cuspy to sufficienty small scale, they too may be observable with the current generation of gamma ray telescopes. In this contribution we calculate the expected annihilation signal from clusters at distances less than ~ 100 Mpc for core density profiles determined through X-ray observations.

2. NEUTRALINO ANNIHILATION

We will assume throughout this contribution that the lightest supersymmetric particle is the neutralino, a linear superposition of the superpartners of the photon, Z^0, and neutral Higgs bosons. and that it provides the bulk of the dark matter in the universe [9, 14]. The neutralino, a Majorana fermion, self-annihilates in the early universe until the annihilation rate is exceeded by the Hubble rate. The neutralino relic density Ω_χ depends upon its exact composition and the presence of resonances, but it can be determined approximately using [9]

$$\Omega_\chi h^2 \simeq \frac{3\times 10^{-27}\,\mathrm{cm}^3\,\mathrm{s}^{-1}}{\langle\sigma v\rangle} \tag{1}$$

where h is the Hubble parameter and $\langle\sigma v\rangle$ is the thermally averaged annihilation cross section. Assuming neutralinos are by far the cosmologically dominant dark matter species, then $\Omega_\chi \simeq (1-f_b)\,\Omega_m$, where f_b is the matter baryon fraction and Ω_m is the total matter density. For $h = 0.67$ and $f_b = 0.15$, the total neutralino annihilation cross section is $\langle\sigma v\rangle = 3\times 10^{-26}$ cm^3 s^{-1}.

Neutralinos can annihilate directly into a pair of monochromatic gamma rays [$\gamma\gamma$], a gamma and a neutral Z boson [γZ^0], or into a gamma continuum through a plethora of hadronization processes [γ(h)]. The dominant "channel" is hadronization, with a resulting gamma ray spectrum conveniently approximated by [12]:

$$\frac{dN_\gamma}{dE_\gamma} = \frac{5}{4m_\chi}\int_{x_{min}}^{1} dx\,\frac{(1-x)^2}{x^{3/2}(x^2-\eta^2)^{1/2}} \tag{2}$$

Here $x = E_\pi/m_\chi$, $\eta = m_\pi/m_\chi$, and $x_{min} = E_\gamma + m_\chi\eta^2/4E_\gamma$. The neutral pion and neutralino masses are m_π and m_χ. The $\gamma\gamma$ and γZ^0 spectra are given by

$$\frac{dN_\gamma}{dE_\gamma} = \frac{2}{E}\,\delta\left(1-\frac{m_\chi}{E_\gamma}\right) \tag{3}$$

and

$$\frac{dN_\gamma}{dE_\gamma} = \frac{1}{E}\,\delta\left(1-\frac{m_\chi(1-(m_{Z^0}/2m_\chi)^2)}{E_\gamma}\right) \tag{4}$$

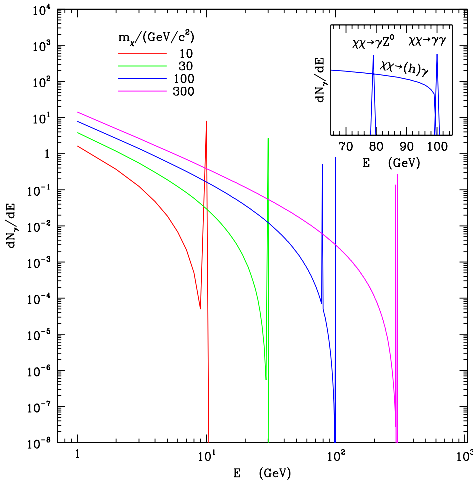

Figure 1: Gamma ray annihilation spectra for four different neutralino masses. The spectra shown are, left to right, for 10, 30, 100 and 300 GeV/c^2. The inset shows the individual contributions from the $\gamma\gamma$, $\gamma\mathrm{Z}^0$ and γ(h) processes.

respectively [15–17]. Estimates for the cross section of these last two channels vary over several orders of magnitude. We use the following values for our analysis: $\langle\sigma v\rangle_{\gamma(\mathrm{h})} = 3\times 10^{-26}$ cm^3 s^{-1}, $\langle\sigma v\rangle_{\gamma\gamma} = \langle\sigma v\rangle_{\gamma\mathrm{Z}^0} = 0.01\langle\sigma v\rangle_{\gamma(\mathrm{h})}$. These spectra are shown in Figure 1 for four values of the neutralino mass.

3. GAMMA RAY LUMINOSITY OF CLUSTERS

The annihilation radiation luminosity of a galaxy cluster is given by

$$L_\gamma = \frac{N_\gamma\langle\sigma v\rangle}{4\pi m_\chi^2}\int \rho^2\, dV \tag{5}$$

where ρ is the matter density of neutralinos, and the integral is taken over the entire cluster volume. For a dark matter core profile following $\rho = kr^\alpha$, this integral diverges toward the center for $\alpha \leq -1.5$. Although astrophysical processes will probably impose a density cut-off, significant gamma ray signatures may still result.

Figure 2 shows the inner logarithmic density slope for a sample of seven relaxed clusters observed with the Chandra X-ray Observatory [8, 18]. The slopes generally span the range $-1 \leq \alpha \leq -2$, suggesting that gamma ray luminosities may indeed be quite high at the center of some clusters.

The largest astrophysically possible neutralino density is determined by the free-fall timescale at the center, with the density determined by equating the free-fall rate

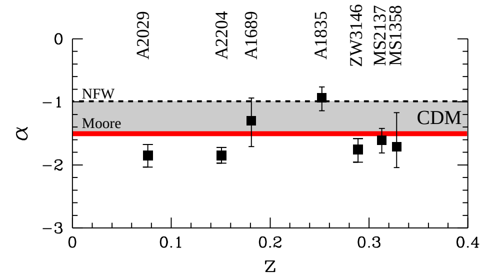

Figure 2: Inner logarithmic density slopes for seven relaxed galaxy clusters [8, 18]. The gray band, bracketed by the NFW and Moore profiles, represents the prediction of standard CDM cosmology.

$$t_f^{-1} = \sqrt{32G\rho/3\pi} \tag{6}$$

to the annihilation rate

$$t_a^{-1} = n_\chi\langle\sigma v\rangle \tag{7}$$

since neutralinos cannot annihilate faster than they are supplied to the high density regions. This implies a free-fall-limited maximum density

$$\rho_{max,f} = 1.2\times 10^{21}\left(\frac{m_\chi}{10\,\mathrm{GeV/c^2}}\right)^2 \mathrm{M}_\odot\,\mathrm{pc}^{-3} \tag{8}$$

However, dynamical heating of neutralinos by the formation of supermassive black hole binaries may reduce this value significantly, to about 10^5 M$_\odot$ pc$^-$3 [19]. (Other processes such as gravitational heating [20] may be less restrictive.) Figure 3 illustrates the peak central density required for a galaxy cluster to be rendered detectable by GLAST and HESS as a function of cluster distance. The cluster central density profile used is $\alpha = -1.5$ to a cut-off radius, where it remains at the limiting density. The horizontal black line indicates a crude estimate of the upper limit of the density imposed by the formation of supermassive black holes during the growth of the central cluster galaxy [19]. This figure shows that *if central densities reach high, but plausible values, then annihilation radiation from neutralino dark matter may be detectable to distances of tens to hundreds of Mpc.* This radiation would carry important information about the very centers of these objects.

4. A TALE OF TWO CLUSTERS

It makes sense, in light of these results, to ask the question: Could any *real* clusters be detected in their

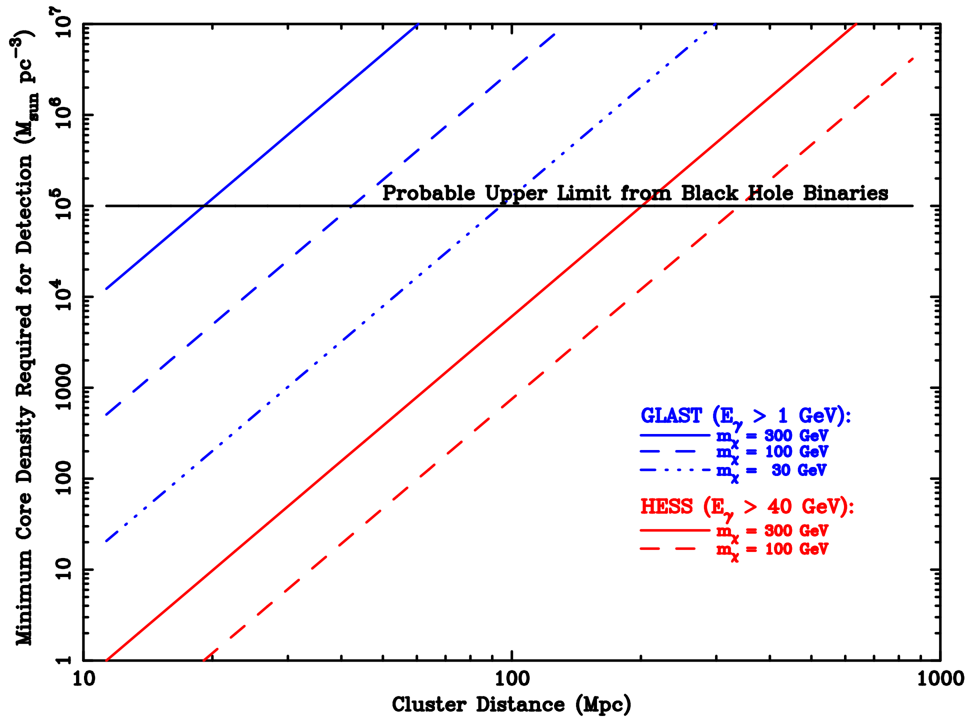

Figure 3: Dark matter central density required for detectability as a function of cluster distance. The upper three diagonal lines represent GLAST sensitivity limits for $m_\chi = 300$, 100, 30 GeV, the lower two for HESS sensitivity limits at 300 and 100 GeV.

annihilation radiation? To address this question we use two examples. The first is the Virgo Cluster at a distance of 17 Mpc, with a central density slope of -1.3 [21]. For the second example we use an Abell 2029-like cluster ($\alpha = -2$; [8]) at a distance of 100 Mpc. The annihilation radiation flux from a cluster, in photons s^{-1} cm^{-2} sr^{-1}, is

$$\begin{aligned} F_\gamma \;&=\; 2.9\times10^{-7}\left(\frac{\langle\sigma v\rangle}{3\times10^{-26}\,\mathrm{cm}^3\,\mathrm{s}^{-1}}\right) \\ &\cdot\left(\frac{m_\chi}{10\mathrm{GeV/c}^2}\right)^{-2}\frac{1}{\Omega}\int_\Omega d\Omega\int_E N_\gamma \\ &\cdot\int_{\mathrm{LOS}}\left(\frac{\rho}{10^{-24}\mathrm{g/cm}^3}\right)^2\frac{dl}{1\,\mathrm{kpc}} \end{aligned} \tag{9}$$

where Ω is the beam size. Figure 4 shows the expected annihilation radiation flux from each object as seen by GLAST (for $30 \le m_\chi \le 300$ GeV/c^2) and HESS (for $100 \le m_\chi \le 300$). The GLAST and HESS detection thresholds are shown for comparison, as is the tentative HESS detection of Sgr A* [22]. In both cases we have adopted $\rho_{max} = 10^5$ M$_\odot$ pc^{-3}. The fluxes have been calculated from the surface brightness integral over a beam size of 10^{-5} sr. GLAST may detect an annihilation signal from a steep-core cluster if the neutralino mass is low; HESS may be able to detect it for a wider range of distance and particle mass.

5. CONCLUSION

We have shown that, for plausible values of the central dark matter slope and for sensible astrophysical constraints on the peak density, neutralino annihilation radiation from the centers of galaxy clusters may be detectable using current and near-future gamma ray telescopes. These signals would not only provide spectacular, if indirect, evidence for the existence of dark matter, but they would also carry information about conditions at the centers of galaxy clusters.

Acknowledgments

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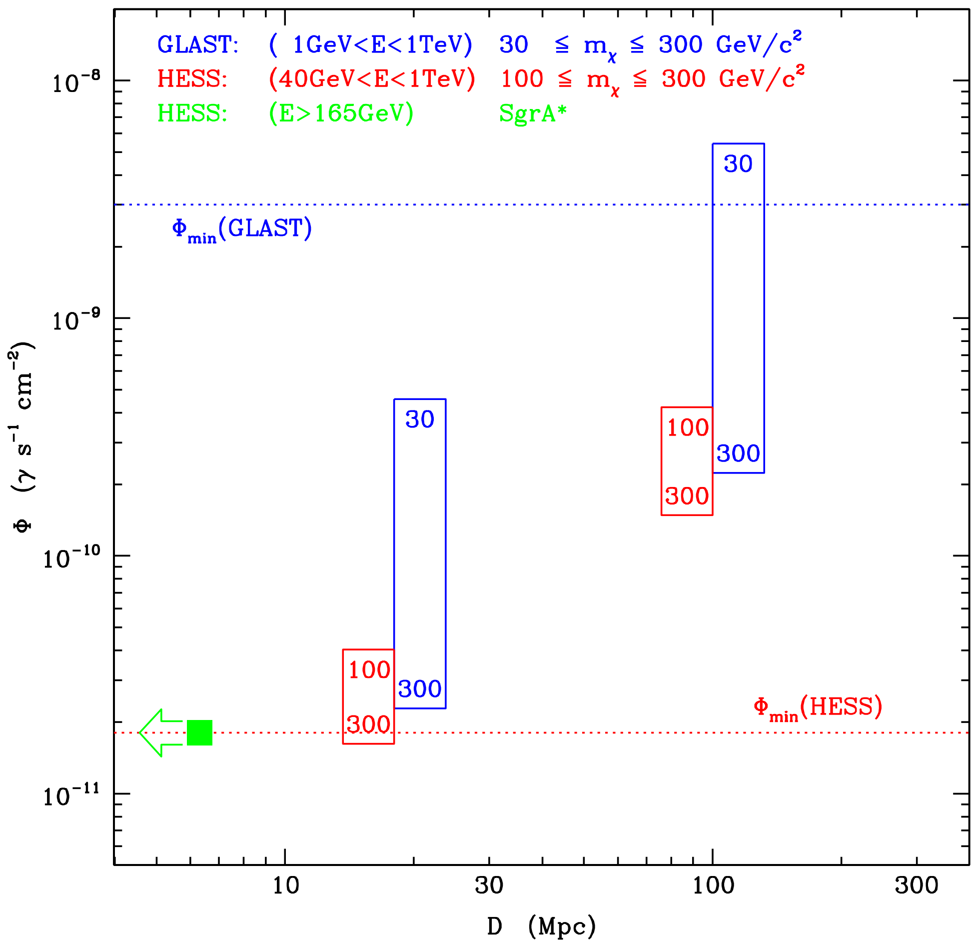

Figure 4: Expected gamma ray fluxes from Virgo (left at 17 Mpc) and a more distant, but steeper-profiled, cluster at 100 Mpc. For reference the GLAST and HESS detection thresholds are shown, as is the recent detection of Sgr A* [22].

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