

DENSITY FLUCTUATIONS IN THE GALACTIC HALO
AND EXPERIMENTAL SEARCHES FOR DARK MATTER

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Clumping of elementary dark matter in the Galaxy halo may be inevitable. If so, the nondetection of certain dark matter candidates could simply mean that the local halo density is low. Conversely, indirect detection of annihilation products could be facilitated, perhaps to an embarrassing degree.

The interpretation of the results of experiments designed to search for elementary particle dark matter in the Milky Way halo relies on specific suppositions concerning the local mass density and velocity distribution of the unseen particles. Predicted detection rates¹ have all been computed under the assumptions that the halo density profile is smooth, and the velocity distribution is at least approximately Maxwellian, with a one-dimensional velocity dispersion $\sigma = V_c/\sqrt{2} \approx 160 \text{ km s}^{-1}$, where $V_c \approx 220 \text{ km s}^{-1}$ is the Galactic rotation speed. However, an experiment that operates for a time $T \sim 1 \text{ yr}$ only probes a region that extends to a distance $D \sim \sigma T \sim 5 \times 10^{14} \text{ cm} \approx 35 \text{ A.U.}$, which is about the distance to the planet Pluto; for comparison, the distance to the center of the Galaxy is $D_0 \approx 8.5 \text{ kpc} \approx 2 \times 10^9 \text{ A.U.}$. While few would doubt that the halo density may be regarded as smooth on some intermediate length scale, say $\lesssim 0.01 - 1 \text{ kpc}$, there is reason to question whether the halo really ought to be perfectly smooth on length scales of order the size of the inner Solar System, $\sim 10^{-8} - 10^{-6} \text{ kpc}$.

If the halo is clumpy on small scales, then it is possible that presently the Earth is not immersed in a bath of dark matter particles, so that the non-detection of such particles need not imply their absence. As a simple but extreme example, suppose that the dark matter particles are organized into lumps of internal density $\rho_{cl} \gg \bar{\rho}$, where $\bar{\rho} \approx 0.01 M_\odot \text{ pc}^{-3}$ is the mean halo density locally; then the probability that the Earth sits in a dark matter clump is the volume filling factor, $f = \bar{\rho}/\rho_{cl} \ll 1$. If instead the halo contains a continuous mass spectrum of dark matter lumps, so that $\bar{\rho}\psi(M)dM$ is the contribution to the local halo density from clumps of mass M and internal density $\rho_{cl}(M)$, then the volume filling factor of the halo is

$$f = \bar{\rho} \int dM \psi(M) \rho_{cl}^{-1}(M), \quad (1)$$

which may also be very small if the dark matter is concentrated into dense clumps. Consequently, experimentalists searching for elementary particle dark matter in a clumpy halo could simply be unlucky. Conversely, a fortunate experimenter bathed in a dark matter cloud could detect halo particles at an incredibly large rate compared to predictions based on the assumption of a smooth halo.

Although the problem of small scale halo structure is generic, we focus here on a specific case: neutralinos of mass $m \gtrsim \text{GeV}$ whose annihilation is predominantly s-wave.² The cosmology of such particles is governed by m , and a dimensionless parameter, $C = M_{Pl} m \langle \sigma v \rangle$, where M_{Pl} is the Planck mass and $\langle \sigma v \rangle$ is the annihilation rate coefficient for the fermions. Annihilation equilibrium fails at a temperature $T_f \sim m/\ln C$, allowing a significant present day abundance, amounting to a total mass density $\rho_0 \sim m T_0^3 \ln C/C$, where T_0 is an appropriate present day temperature (e.g. about 2°K for neutrinos); at density parameter Ω_0 and Hubble constant $H_0 = 100 h_0 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $C \sim 10^9 m (\text{GeV}) (\Omega_0 h_0^2)^{-1}$. The neutralinos remain in thermal contact with the ambient gas of annihilation products until the temperature falls to $T_K \sim m C^{-1/4}$, after which they decouple completely from the rest of the cosmological soup.³

After T_K , the neutralinos stream freely along straight line paths. Consequently, any fluctuations in the density of dark matter particles will be erased on scales smaller than the free-streaming length, which corresponds to a mass³ $M_{fs} \sim (M_{Pl}^3/m^2) \ln C/C^{5/8} \sim 10^{-4} M_\odot (\Omega_0 h_0^2)^{5/8} / [m(\text{GeV})]^{21/8}$. Moreover, by Liouville's theorem, the microscopic phase space density is preserved after T_K , when its value was $\Lambda_p \sim \ln C/C^{11/8} \sim 10^{-11} [\Omega_0 h_0^2/m(\text{GeV})]^{11/8}$. The coarse-grained phase space density of the halo is $\Lambda_h \sim 10^{-32} / [m(\text{GeV})]^4 \ll \Lambda_p$, which suggests that some fine-grained clustering of neutralinos in the halo is inevitable.

The nature of the clustering is still not certain. One possibility is that dark matter clumps of mass M_{fs} , which are expected to be among the first objects to condense cosmologically, survive intact to the present day and dominate the Galactic halo. Research along these general lines has been reported at this conference by Gurevich and collaborators, who also suggest that non-baryonic clumps may be the MACHOs. Another possibility is that clumps are not permanent but come and go in a dynamical fashion as the result of small scale ‘gravitational turbulence’ in the Galaxy halo: locally space-time dependent density fluctuations with possibly stationary statistical properties.

A simple picture that could lead to a stationary statistical state for the halo would involve binary fragmentation and merger of dark matter clumps in the halo. To be concrete, let us focus on a discrete model in which N_k is the number of clumps of mass $M_k = M_0 2^{-k}$, where k is an integer; in a continuous model, N_k would correspond to $\psi(M)$ in Eq. (1). Suppose that fragmentation of a cloud of mass M_k results in the production of a pair of bound clouds of mass M_{k+1} ; merger of a pair of clouds with equal masses M_k forms a cloud of mass M_{k-1} . The net rate of formation of clouds of mass M_k is then

$$\frac{dN_k}{dt} = -(\nu_k + 2\tilde{\nu}_{k-1})N_k + 2\nu_{k-1}N_{k-1} + \tilde{\nu}_k N_{k+1}, \quad (2)$$

where ν_k is the rate of fragmentation of a mass M_k and $\tilde{\nu}_k$ is the rate of merger to form a mass M_k . If we assume that $\nu_k \sim \sqrt{G\rho_k}$ and $\tilde{\nu}_k = c\nu_k$, where ρ_k is the internal density for mass M_k and c is independent of scale, then Eq. (2) has the steady state solution $N_k \propto M_k^{\log_2 c}$; notice that this is independent of the dependence of density on mass scale, and that the mass spectrum is tilted toward small masses for $c < 1/2$. (This steady-state solution only requires the assumption that $\tilde{\nu}_k = c\nu_k$, not the additional physical conjecture that the characteristic merger and collapse rates are approximately free-fall.) Assuming that the basic physics of collapse and merger is scale free also leads to $\rho_k \propto M_k^{-2\eta}$; if fragmentation tends to leave behind bound pairs, then $\eta < 1$ in general.⁴ The mass spectrum extends down to the ‘Jeans mass’, where the internal phase space density of a lump is $\sim \Lambda_p$; this is generally below M_\odot but above M_{fs} for $m \gtrsim 1\text{GeV}$. The picture outlined above can be generalized to a continuous mass spectrum, and may also apply if fragmentation is replaced by formation of low mass ‘satellites’ in the course of a merger (i.e. if mergers produce, in addition to a large clump comprising most of the colliding mass, smaller ejected sub-lumps), although the value of η could differ in that case. Needless to say, other pictures for the development of fluctuations might be more compelling than the one presented here, but may or may not lead to stationary statistics of the fluctuations.

Although *direct* detection of elementary particle dark matter would be frustrated by clumpiness in the halo, *indirect* detection would be facilitated, perhaps to an embarrassing extent. Let us suppose that annihilation of dark matter particles produces some observable product – e.g. high energy gamma rays – with an efficiency $\zeta(E)dE/E$ for energies near E . Then the (number) flux of observable annihilation products from a single clump of mass M a distance D from Earth is (using $\langle\sigma v\rangle \sim C/M_{Pl}m \approx 10^{-27}(\Omega_0 h_0^2)^{-1}\text{cm}^3 \text{s}^{-1}$)

$$E \frac{dF_{cl}}{dE} \sim \frac{\langle\sigma v\rangle \rho_{cl}(M) M \zeta(E)}{4\pi D^2 m^2} \sim 3 \times 10^{-9} \text{cm}^{-2} \text{s}^{-1} \frac{\delta_{cl} \zeta(E) M/M_\odot}{\Omega_0 h_0^2 [m(\text{GeV})]^2 [D(\text{pc})]^2} \quad (3)$$

where $\delta_{cl} = \rho_{cl}/\bar{\rho}$, and the integrated flux from the halo of our Galaxy is

$$E \frac{dF_G}{d\Omega dE} \sim \frac{\langle\sigma v\rangle \bar{\rho}^2 D_0 \langle\delta_{cl}\rangle \zeta(E)}{4\pi m^2} \sim 3 \times 10^{-7} \text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1} \frac{\langle\delta_{cl}\rangle \zeta(E)}{\Omega_0 h_0^2 [m(\text{GeV})]^2} \quad (4)$$

where $\langle\delta_{cl}\rangle$ is the mean clump density contrast weighted by $\psi(M)$. (For predominantly p-wave annihilation, $\langle\sigma v\rangle \propto \langle v^2\rangle \lesssim 10^{-6}$ and Eqs. (3) and (4) would be correspondingly lower; the admixture of s- and p-wave in $\langle\sigma v\rangle$ is model-dependent.) For comparison,⁵ the excess gamma ray flux above 100 MeV measured by EGRET that is not correlated with Galactic HI column density is $I_{ex} = 1.47 \pm 0.03 \times 10^{-5} \text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1}$, and the isotropic component of this excess is estimated to be $I_{iso} = 1.5 \pm 0.3 \times 10^{-5} \text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1}$. Since the spectrum of the diffuse emission falls with increasing energy,⁶ a halo flux as large as indicated by Eq. (4) could be excessive at photon energies $\gtrsim 1\text{GeV}$ unless $\langle\delta_{cl}\rangle \zeta(E)$ is small. Also, EGRET has apparently found a small number of sources unidentified with any previously known astronomical objects.⁷ These sources have total fluxes $\sim 10^{-7} \text{cm}^{-2} \text{s}^{-1}$ above 100 MeV, and no larger than $\sim 10^{-8} \text{cm}^{-2} \text{s}^{-1}$ above 1 GeV. Although

such fluxes could be consistent with Eq. (3) (depending on the value of $\delta_{ct}\zeta(E)/D^2$) it is probably unlikely that annihilation of multi-GeV particles would produce sub-GeV photons preferentially,⁸ and the mysterious sources could have a more mundane origin than annihilation in neutralino clumps. To the extent that small-scale concentrations of dark matter may be shown to be required physically, the absence of detectable annihilation products could be used to argue against the existence of certain neutralino candidates.

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References

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