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# Massive neutrinos and dark halos around galaxies

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**Abstract.** In this paper we investigate the hypothesis that hot massive neutrinos can be the main dark matter component of galactic halos. The consistency of the cosmological $\nu$'s phase space density with the properties of the dark matter halos of dwarf galaxies sets an upper limit to the neutrino mass $m_\nu$ (Tremaine & Gunn 1973; TG). Here we apply the TG argument to a very large sample (1100 objects) of high quality rotation curves of normal spirals, and calculate reliable upper limits to the neutrino mass. Unlike previous works, our estimate is distance independent and holds for different Hubble Types and for the whole luminosity range. We find that, in order to be clustered on galaxy halo scales, $\nu$'s should be so massive as to violate the cosmological constraint $\Omega_\nu \leq 1$. Thus, we conclude that hot neutrinos do not play a relevant role on galactic scales.

**Key words:** dark matter – galaxies: halos – elementary particles

## 1. Introduction

Within the cosmological Hot Dark Matter scenario, the best candidate particle is the ordinary neutrino, with a $O(10\,\mathrm{eV})$ mass. Both accelerator experiments and theory are presently unable to rule out this possibility which, on the other hand, can be tested through its straightforward implications on the structural properties of galaxies.

As is well known, neutrinos remain in thermal equilibrium with the cosmic background radiation field down to $T \sim$ MeV, whereafter they propagates freely, forming a cosmological black body radiation background of temperature $T_\nu \simeq T_\gamma/1.4$ (photons are heated up by $e^+e^-$ pair annihilation). Therefore, the present-day cosmological number of $\nu$'s is fixed ($n_\nu = 112\,\mathrm{cm}^{-3}$), so as their contribution $\Omega_\nu$ to the cosmological density $\Omega$:

$$\Omega_\nu = \frac{m_\nu g_\nu}{(23h_{50}^2\,\mathrm{eV})} \quad (1)$$

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where $1 \leq g_\nu \leq 2$ is the number of helicity states. Within the inflationary paradigm, (1) leads to a strict upper limit to the neutrino mass. More in general, since observationally $\Omega$ does not appear to exceed unity, hot $\nu$'s cannot have a mass larger than $\sim 30h_{50}^2\,\mathrm{eV}$. Notice that for the muon and electron neutrinos, laboratory experiments have set upper limits of $O(100\,\mathrm{keV})$ and $O(10\,\mathrm{MeV})$ respectively, still much higher than the cosmological upper limits.

Obviously, a cosmological scenario must take into account the existence of large amounts of non-luminous matter in galaxies. In particular, a DM component is found to embed every spiral out to several times the optical size (Persic, Salucci & Stel 1996; hereafter PSS). The amount of dark matter in galaxies is such that it most likely cannot be all baryonic: the cosmological mass density of galaxies $\Omega_{\rm gal}$, inclusive of their extended halos, is higher than the baryonic density $\Omega_{\rm b}$, as derived from the primordial abundances of light elements:

$$\Omega_{\rm gal} \geq 0.15 > \Omega_{\rm b} \sim 0.06 \quad (2)$$

(see Salucci & Persic 1995 and Tytler et al. 1996; moreover the main contributor to $\Omega_{\rm b}$ can well be the *intergalactic* gas). On the other hand, the HDM scenario does require that galaxies have a large fraction of non-baryonic DM. In fact, although neutrino perturbations are powerless on these scales and galaxies are formed from the fragmentation of baryon perturbations, however at later times neutrinos are gravitationally dragged into the galaxies where they eventually outgrow the visible mass by a factor of 10 (e.g., Melott 1983).

In the dynamical evolution of collisionless particles such as neutrinos, the microscopic density $f^{\rm micro}$, i.e. the number density in phase space, is conserved along the motion. In an epochal work, this dynamical property has been used to set a lower limit for the HDM neutrino mass, *when this particle is assumed to constitute the halos* of dwarf spheroidals (Tremaine & Gunn 1979; hereafter TG) and dwarf spirals (Lake 1989). In fact, if we extrapolate this lower limit,

$$m_\nu \gg 50\,\mathrm{eV}\ , \quad (3)$$

to every galaxy, we can conclude that light neutrinos cannot be the galaxy DM particle in that the mass limit in (3) violates the cosmological limit (1). However, it should be noted that the contribution to $\Omega$ from dwarf galaxies is uncertain, so we can bypass the TG limit if we take the view that the DM in dwarfs is baryonic, while that in normal galaxies, where (3) is not inconsistent with (1), is exotic, i.e. HDM $\nu$'s (see Sciama 1993). In this paper we will carefully investigate such a scenario of two galactic (hot+ baryonic) dark components.

In detail, the TG argument proceeds as follows. At decoupling, the microscopic Fermi-Dirac distribution function of neutrinos has a maximum given by:

$$f_{\max} = 6g_\nu/2(2\pi\hbar)^3 \tag{4}$$

where the factor 6 is due to the number of neutrino and antineutrino families and $g_\nu$ is the number of spin states. In the HDM scenario, neutrinos are captured by "galaxies" and settle in dark halos. During this process the microscopic distribution function is conserved, and the macroscopic distribution function, defined as the mean of the microscopic one in a small volume of the phase space, never increases. So, we have:

$$f^{\rm macro}_{\max} \leq f^{\rm micro}_{\max} \,. \tag{5}$$

In TG the structural properties of the halo have been assumed as follows: neutrinos have (a) an isothermal spatial distribution and (b) an isotropic gaussian distribution in velocity phase space. Then:

$$M_h(r) = 3G^{-1}\sigma^2 r \,, \tag{6}$$

where $\sigma$ is the halo's 1-D velocity dispersion, and the central density is obtained by $\rho_0 = \lim_{r\to 0}(4\pi r^2)^{-1} dM_h/dr$. The macroscopic phase takes the form of:

$$f^{\rm macro} \propto \exp -\frac{1}{\sigma^2}\left(\frac{v^2}{2} + \phi(r)\right) \,, \tag{7}$$

where $v$ is the velocity of the single neutrino particle and $\phi(r)$ is the spherically symmetric gravitational potential at radius $r$, connected to the density distribution via the Poisson equation. $f^{\rm macro}$ peaks at the center (e.g., Ralston & Smith 1991) with a value:

$$f^{\rm macro}_{\max} = \rho_0 m_\nu^{-4}(2\pi\sigma^2)^{-3/2} \,. \tag{8}$$

Then we have (see TG):

$$m_\nu^4 \geq \frac{\rho_0(2\pi\hbar)^3}{3g_\nu(2\pi\sigma^2)^{3/2}} \,. \tag{9}$$

In dwarf spheroidals, $\rho_0 > 10^5\rho_{\rm c}$ (with $\rho_{\rm c}$ the critical density) and $\sigma < 100\,{\rm km\,s^{-1}}$: the upper limit for the neutrino mass is inconsistent by a factor of 10 with the cosmological limit in (1). A few dwarf spirals (Spergel et al. 1988) provide a similar inequality, $m_\nu > 94 g_\nu^{-1/4}$ eV. Do these results definitely rule out the possibility that a (light) massive neutrino constitutes all dark halos? Actually, the TG argument might be weakened by the following arguments: (a) the isotropic velocity assumption may not be valid; (b) the mass structure of the dark halos, as studied in previous works, is somewhat uncertain: moreover the limiting mass varies as $D^{-1/2}$, where $D$ is the (poorly known) distance to the dwarfs; (c) the assumption that dwarf galaxies and normal ones have the same kind of dark matter may be incorrect, so that any neutrino limit obtained from the dynamics of the former interpreted in terms of the mass properties of the latter is irrelevant. In this section we discuss point (a), while points (b) and (c) will be treated in the next section. Anisotropic distribution functions have been studied (Madsen 1991; Ralston & Smith 1991) by means of the collisionless Jeans equation that allows one to consider the neutrino particles in a mix of radial and circular orbits rather than in the isotropic case. They found that there is an anisotropic solution with a minimum of the density in the center (hollow halo) and with the maximum value of the phase occurring at outer radii, as in a shell-like structure. However, Takahara et al. (1993) have shown that this solution leads to a lower limit to the neutrino mass very similar to the one in (8). Thus, in this paper we will assume an isotropic velocity distribution and we will discard anisotropy as an effective way of relaxing the TG constraint on the neutrino mass.

## 2. Dark matter halos: spirals

It is now available a large sample of spirals with high quality rotation curves and good photometry, that permits to obtain, directly from observations, the dark halo mass distribution, regardless of the nature of dark matter (see PSS). The sample covers the whole range of magnitudes, $-17 \simeq M_I \simeq -24$, and of Hubble types, $3 \leq T \leq 6$, of spiral galaxies. About 1100 rotation curves have been coadded in 11 luminosity bins (details are in PSS and references therein). With this procedure we are able to reduce substantially the uncertainties referred in point (b) of the previous section. In fact, we consider the whole family of galaxies, from dwarfs ($M \sim 10^9\,M_\odot$) to giants spirals ($M \sim 10^{12}\,M_\odot$) with an amount of high quality data that allows a careful determination of the structural properties of DM halos. The existence of a Universal Rotation Curve, URC (PSS) for spiral galaxies implies that just a single global parameter (e.g., the luminosity) dictates the rotation velocity at any radius for any object. As a result, an exponential thin disk and a dark matter halo reproduce the URC up to a few percent, when the DM contribution to circular velocity is given by:

$$V_h^2(x) = V^2(R_{\rm opt})(1-\beta)(1+a^2)\frac{x^2}{x^2+a^2} \,, \tag{10}$$

with

$$x = \frac{r}{R_{\rm opt}} \,, \tag{11}$$

$$R_{\rm core} = aR_{\rm opt} \,, \tag{12}$$

$$a = 1.5\left(\frac{L}{L_*}\right)^{1/5} \,, \tag{13}$$

and the fraction of visible matter

$$\beta \equiv \left.\frac{M_{\rm lum}}{M_{\rm tot}}\right|_{R_{\rm opt}} = 0.72 + 0.44 \, \log \frac{L}{L_*} \; ; \tag{14}$$

observationally we have

$$R_{\rm opt} = 13 \left(\frac{L}{L_*}\right)^{0.5} \; {\rm kpc} \tag{15}$$

($L_* = 10^{10.47} L_\odot$ is the knee of the $I$-band luminosity function).

The effective halo density, $\rho(r) = (4\pi r^2)^{-1} dM_h/dr = (4\pi G r^2)^{-1} d(V_h^2 r)/dr$, is:

$$\rho_h = \frac{\rho_0}{3} \frac{x^2+3}{(x^2+a)^2} \; , \tag{16}$$

where

$$\rho_0 = 3v^2(R_{\rm opt})(1-\beta)(1+a^2)(4\pi G R_{\rm opt}^2 a^2)^{-1} \tag{17}$$

$$= 3.5 \times 10^4 (L/L_*)^{-0.7} \rho_{\rm c} \; . \tag{18}$$

The 1-D halo velocity dispersion $\sigma_h$, defined as

$$\sigma_h^2 = \frac{\int_0^{R_{200}} \rho(r) V_h^2(r) 4\pi r^2 dr}{\int_0^{R_{200}} \rho(r) 4\pi r^2 dr} \frac{1}{3} \; , \tag{19}$$

can be computed by using the equations above. Then, the neutrino mass limit becomes:

$$m_\nu \geq \frac{19}{(g_\nu h_{50})^{1/4}} \left(\frac{L}{L_*}\right)^{-0.44} {\rm eV} \; . \tag{20}$$

Let us stress that, given the large amount of data used and the suitable method of mass decomposition, the lower limit in (20) is very precise: the uncertain ties on the DM structural parameters $R_{\rm core}$ and $\rho_0$ are less than 20% (see PSS) and therefore irrelevant in constraining the neutrino mass. Moreover, in spiral galaxies (unlike in spheroidals) the test particles tracing the potential (i.e., gas and stars) have a well identified geometry (disk) and dynamical state (rotation). Finally, notice that (20) is in good agreement with the results of Lake (1989) concerning low-luminosity spirals.

## 3. Dark matter halos: ellipticals and dwarfs

Useful kinematical data are available only for about 20 ellipticals. The information they give is however enough to claim that also these objects are embedded in extended dark halos. The evidence comes both from the kinematics of neutral and ionised gaseous disks, often present in early-type galaxies, and from the temperature and surfacedensity distributions of the X-ray emitting gas which is found around giant ellipticals. Roughly, the DM density distribution is $\propto r^{-2}$ at large radii and $\propto$ constant when $r \to 0$. At a given luminosity, E dark halos are very similar to S dark halos, except that they are denser in the innermost regions. This is likely due to the higher compression caused by the infalling baryonic material that E halos have experienced with respect to the S ones. In detail, we have (see Bertola et al. 1993):

$$\frac{\rho_0^{\rm ell}}{\rho_{\rm c}} = 5.4 \times 10^5 \left(\frac{L_B}{L_*}\right)^{0.3} \left(\frac{r_e}{5\,{\rm kpc}}\right)^{-3} \tag{21}$$

with $r_e$ the de Vaucouleurs radius. (21) shows that the central density of spiral halos is about a factor of 10 lower (PSS). Since from stellar kinematics $\sigma^E$ = 100–300 kms$^{-1}$ $\simeq \sigma^S$, then from (9) we realize that the structure of E halos implies a lower limit to $m_\nu$ higher than that coming from S halos.

Ever since the paper by Lin & Faber (1983), it has been well known that dwarf ellipticals set a very high lower limit to $m_\nu$. In these galaxies typical central overdensities are of the order of (2–8)$\times 10^7$, while typical 1-D dispersion velocities of the order of 10 km s$^{-1}$. These values imply:

$$m_\nu > 800 h_{50}^2 \, {\rm eV} \; , \tag{22}$$

which rules out the possibility that these systems can host hot neutrinos.

## 4. A lower limit to $m_\nu$

First, we take spirals to represent also S0 and E galaxies, in that the earlier Hubble types give even higher lower limits to $m_\nu$. We estimate the cosmological mass density of galaxies whose dark halos do not host neutrinos, because otherwise their macroscopical phase density will exceed the microscopical one: in spirals this happens when $\lambda \equiv L/L_* \sim 0.4$, in ellipticals at higher $\lambda$, and in other galaxies never). From a Schechter-like luminosity function and the halo mass-to-light ratio given in PSS, we obtain (see (2)):

$$\Omega_{E,S}^{\nu\;\rm free} \simeq 0.15 \frac{\int_{0.01}^{0.4} \lambda^{-0.5} \exp(-\lambda) d\lambda}{\int_{0.01}^{4} \lambda^{-0.5} \exp(-\lambda) d\lambda} \; , \tag{23}$$

that is:

$$\Omega_{E,S}^{\nu\;\rm free} \simeq 0.12 \; . \tag{24}$$

Then the cosmological amount of dark matter detected in galaxies, which cannot be in the form of light massive $\nu$'s [see (1)], is:

$$\Omega^{\nu\;\rm free} = \Omega_{E,S}^{\nu\;\rm free} + \Omega_{DW} \; , \tag{25}$$

where $\Omega_{DW}$ is the contribution from dwarf halos, which is difficult to pinpoint in the broad range $10^{-2}$–$10^{-1}$.

We compare $\Omega^{\nu\;\rm free}$ with the density of dark baryons $\Omega_{{\rm b}_\bullet}$. This quantity, of course, cannot exceed the primordial nucleosynthesis limit,

$$\Omega_{{\rm b}_\bullet} < \Omega_{BBN} \simeq 0.06 \; . \tag{26}$$

Moreover, part of nucleosynthesised baryons are locked in visible stars, in the IGM, in Ly $\alpha$ clouds, and cannot contribute to a halo dark component. Thus we realize that $\Omega^{\nu\;\rm free}$ exceeds $\Omega_{{\rm b}_\bullet}$ by a factor of 2–3: we need a nonbaryonic DM component able to cluster on the kpc scale. Dark baryons (e.g., machos) cannot be the only DM constituents of galaxy halos.

## 5. Conclusions

The great majority (80%–90%) of galaxies cannot host HDM neutrinos in that these could have clustered around galaxies, forming the observed DM halos, only if their mass were so large ($> 40$ eV) that their contribution to the background density would exceed unity. This extends the results of previous works concerning a limited number of dwarf galaxies.

The halos around the most luminous galaxies (a small fraction of the total number, 10%–20%) might in principle be made of hot neutrinos with $m_\nu < 29 h_{50}^2 (1 - \Omega^{\nu \text{ free}})$ eV. Notice however, that this hypothesis would imply the contemporaneous presence, on galactic scale, of two different exotic DM components.

More definitely, being $\Omega_{\rm gal}^{\nu \text{ free}} > \Omega_{\rm b_\bullet}$, the possibility that in an $\Omega = 1$ standard-BBN Universe neutrinos plus BDM can account for the whole DM content of galaxies is ruled out by our present results.

Notice that the structural properties of dark halos (central density and core radius) correlate smoothly and continuously with luminosity along the whole galaxy luminosity sequence (see PSS). Therefore a scenario, in which BDM and massive $\nu$'s are relevant in the halos of, respectively, low and high luminosity galaxies, requires a detailed as well as unexplained fine-tuning between the elementary properties of neutrinos and the astrophysics of the formation of dark baryonic objects (i.e., machos). We conclude by claiming that neutrinos may only play a cosmological role in structure formation within a mixed H+CDM scenario, in which a CDM component clusters on galactic scale, and an HDM component clusters on larger scales with $m_\nu \simeq 27 \Omega_\nu / \Omega$ eV.

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