Improved Astronomical Limits on the Neutrino Mass

Jes Madsen
Institute of Astronomy, University of Aarhus, DK-8000 Aarhus C, Denmark

and

Richard Epstein
Los Alamos National Laboratory, Los Alamos, New Mexico 87545
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Lower limits for the neutrino mass are obtained if one flavor of neutrino is predominantly responsible for the dark matter in galaxies. From rotation curves of spiral galaxies, it is found that the neutrino mass must exceed $35h^{1/2}$ eV (where h is the Hubble constant in units of 100 km s^{-1} Mpc^{-1}) if the velocity distribution of halo neutrinos is isotropic. If radial dispersion dominates, limits are slightly weakened. These results do not rely on a specific form of the phase-space distribution of halo neutrinos.

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In earlier studies spherically symmetric, equilibrium configurations of neutrino-dominated galaxies were examined. In some of these the coarse-grained phase-space distribution was assumed to be isothermal,[1] completely degenerate,[2] or merely isotropic.[3] In the last study strong lower bounds on the neutrino mass of about 8 eV were obtained. In this Letter we extend this analysis by allowing for deviations from velocity isotropy and by using more demanding data for the mass distributions of galaxies.

Consider a galaxy with a nonrotating, equilibrium, spherical halo of massive neutrinos. The neutrinos exhibit no net velocity flow and no difference between the azimuthal and polar velocity dispersions. In a spherical coordinate system these symmetries can be expressed as

$$\langle v_r \rangle = \langle v_\phi \rangle = \langle v_\theta \rangle = 0$$

and

$$\langle v_\theta^2 \rangle = \langle v_\phi^2 \rangle = (1-\alpha)\langle v_r^2 \rangle ,$$

where the angular brackets denote averages over the neutrino distribution. The neutrinos form a collisionless gas which is described by the "Jeans equations,"[4] which for the present problem give

$$\frac{dP_\nu^{rr}}{dr} + 2\alpha \frac{P_\nu^{rr}}{r} = -\frac{GM_r}{r^2}\rho_\nu, \tag{1}$$

where $P_\nu^{rr} \equiv \rho_\nu \langle v_r^2 \rangle$ is the radial component of the neutrino pressure tensor and M_r is the total mass (baryons as well as neutrinos) interior to radius r.

To explore the effects of velocity anisotropy in the outer parts of the neutrino halo ($r > r_*$), we take α to be a constant and consider upper bounds to the total interior mass and the neutrino density of the forms $M_r(r) < M_r^*(r/r_*)^\beta$ and $\rho_n(r) \leqslant \rho_\nu^*(r/r_*)^{\beta-3}$, where the value of ρ_ν^* is chosen so that the equality holds at $r = r_*$.

If the neutrinos are gravitationally bound in the galactic halo, rather than "held in" by external pressure, then the pressure at large radii can be neglected. If it is also assumed that $\beta < 2-\alpha$, then Eq. (1) can be integrated to give

$$P_\nu^{rr}(r_*) < \frac{GM_r^*\rho_\nu^*}{2(2-\alpha-\beta)r_*}. \tag{2}$$

Because of the constraints imposed by Liouville's theorem, relic neutrinos from the "big bang" have phase-space occupation numbers less than 0.5[1]; in fact, half the neutrinos have occupation numbers less than 0.06.[3] The minimum P_ν^{rr} for a gas of relic neutrinos of mass m_ν, mass density ρ_ν, and anisotropy α is thus obtained by consideration of the limiting case in which the neutrino velocity distribution uniformally fills a velocity ellipsoid with occupation number of 0.5; this gives (for the assumption of one flavor of neutrino and antineutrino, each with one helicity)

$$P_\nu^{rr} \geqslant \frac{3\pi}{5}\left(\frac{4\pi}{3}\right)^{1/3} \frac{\hbar^2 \rho_\nu^{5/3}}{(1-\alpha)^{2/3} m_\nu^{8/3}}. \tag{3}$$

Simultaneously solving inequalities (2) and (3) gives a lower bound on m_ν in terms of the observable properties of galaxies and α:

$$m_\nu > 50\frac{(2-\alpha-\beta)^{3/8}}{(1-\alpha)^{1/4}}\left(\frac{\rho_\nu^*}{10^{-24}\ \mathrm{g\ cm^{-3}}}\right)^{1/4}\left(\frac{r_*}{10\ \mathrm{kpc}}\right)^{3/8}\left(\frac{M_r^*}{10^{10}M_\odot}\right)^{-3/8} \mathrm{eV}. \tag{4}$$

TABLE I. Galaxy data and inferred lower bounds on the neutrino mass.

Galaxy	Type	r_* (h^{-1} kpc)	M_r^* ($10^{10}h^{-1}M_\odot$)	ρ_ν^* ($10^{-24}h^2$ g cm^{-3})	β	$m_{\nu,\min}$ ($h^{1/2}$ eV) $\alpha=0$	$\alpha=0.4$	$\alpha=0.8$
NGC 4800	Sb	2.5	1.9	8.5	1.3	35	29	0
NGC 4605	Sc	2.2	0.50	4.4	1.7	34	0	0
NGC 2844	Sa	4.0	2.4	2.1	1.0	31	29	25
NGC 1035	Sc	3.8	1.6	2.0	1.3	30	25	0
NGC 4062	Sc	4.5	3.0	2.4	1.4	25	19	0
NGC 4448	Sb	5.5	4.7	1.5	1.0	25	23	20
NGC 3067	Sb	4.8	3.0	2.3	1.6	22	0	0
NGC 2742	Sc	6.3	4.5	1.3	1.3	22	18	0
NGC 1087	Sc	7.8	4.0	0.6	1.3	21	17	0
NGC 2608	Sc	7.6	2.9	0.5	1.5	20	12	0
NGC 4682	Sc	9.0	6.1	0.5	1.0	20	19	17
NGC 7537	Sb	9.2	4.8	0.3	1.0	20	19	16
NGC 1357	Sa	7.1	10.9	1.6	1.0	20	19	16
NGC 2715	Sc	10.2	5.7	0.4	1.2	19	17	0
NGC 3672	Sc	9.4	8.0	0.6	1.1	19	17	12
NGC 3898	Sa	7.0	11.9	1.7	1.1	19	17	12

In a detailed investigation of the rotational properties of a sample of sixty Sa, Sb, and Sc galaxies,[5] the rotation curves were obtained out to a large fraction of the optical radius, R_{25} (the distance from the center at which the surface brightness falls below 25 blue magnitudes arcsec^{-2}), and it was found that the rotational velocities were constant ($\beta=1$) or even slightly increasing ($\beta>1$) at the limit of observation for many of the galaxies. At the largest radii measured, the ratio of mass density to luminosity density is characteristically more than an order of magnitude greater than at the center of the galaxies. In these outer regions the mass density is fully dominated by the dark matter and, if it is in fact due to neutrinos, Eq. (4) furnishes limits on the neutrino mass.

Table I gives the relevant data for sixteen galaxies in this sample and the inferred lower limits to the neutrino mass, $m_{\nu,\min}$, for $\alpha=0$, 0.4, and 0.8. The observations allow β to be determined to within 0.2, and the optimal values of M_r^* and ρ_ν^* to be fixed to better than 10%. The radius r_* was conservatively taken to be R_{25}. Choosing a smaller radius would lead to a higher $m_{\nu,\min}$; use of R_{25} thus gives a firm lower limit.

As can be seen from Eq. (4), $m_{\nu,\min}$ is a decreasing function of α when $\beta\geq 1$. The actual value for the anisotropy parameter α is unknown, since we have no independent way of studying the coarse-grained distribution of the halo material. The anisotropies depend on the conditions during halo formation, but some clues are given by collapse simulations of hot[6] collisionless systems.[7,8] In these simulations it is found that the velocity distribution is fairly isotropic (but generally not isothermal[8]) in the central parts, whereas the radial velocity dispersion exceeds the transverse velocity dispersion in the outer regions. This corresponds to α of order zero in the central regions, increasing to $\alpha\sim 0.4$ at the radius surrounding 80% of the total mass.[8] It seems reasonable to assume that the relevant values of α are less than 0.5.

From Table I one sees that the smaller galaxies in general provide the highest values of $m_{\nu,\min}$. This may be a consequence of the smaller size of their optical cores or because the neutrino phase-space density is lower in the larger systems. We conclude that the neutrino mass must exceed $35h^{1/2}$ eV if the velocity distribution is isotropic or mainly transverse ($\alpha\leq 0$). For large radial anisotropies ($\alpha=0.4$), the lower bound is $29h^{1/2}$ eV, and even for an unrealistically high value of $\alpha=0.8$, we can deduce a lower bound on m_ν of $25h^{1/2}$ eV. These limits are the best lower bounds on m_ν now obtainable; higher values for $m_{\nu,\min}$ may be obtained from the same data by the assumption of a specific coarse-grained phase-space distribution, e.g., an isothermal sphere as suggested by Tremaine and Gunn.[1] However, the actual distribution in phase space is not known, and so such limits are not necessarily correct. The present investigation complements earlier methods[1-3] since it is based on different assumptions. It allows a wide range of values for the anisotropy, and it does not demand knowledge of the unobservable coarse-grained phase-space distribution of halo neutrinos.

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[6]Cosmological neutrinos are fairly hot. At a red shift z prior to the formation of significant density inhomogeneities, the one-dimensional rms velocity of a relic neutrino of mass $30m_{30}$ eV is $3.5(1+z)/m_{30}$ km s^{-1}, where the present temperature of the microwave background is taken as 2.7 K.

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