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MASSIVE NEUTRINOS AND THE PROBLEM OF THE DARK MATTER IN SPIRAL GALAXIES

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1. INTRODUCTION

One of the most important characteristics of spiral galaxies, rotation curves (hereafter RCs), do not show Keplerian fall-off thus indicating the presence of invisible mass component (Ashman, 1992). The question of the nature of the dark matter (DM) which dominates the outer parts of spirals, but can also be found in the regions where the ordinary matter is present (Persic, Salucci, Stel, 1995, hereafter PSS), may lead towards the answer to the important questions concerning galaxy formation, cosmology and particle physics. In this paper we made the attempt to show whether massive neutrinos could play the important role in the above mentioned "conspiracy" concerning RCs (Peebles, 1993).

2. NEUTRINO MASS

The question whether neutrinos have masses is still unresolved and we present here the laboratory limits on the neutrino mass that follow purely from kinematics: $m_{\nu_e} \lesssim 5\,\mathrm{eV}$, $m_{\nu_\mu} \lesssim 250\,\mathrm{KeV}$, and $m_{\nu_\tau} \lesssim 23\,\mathrm{MeV}$ (Montanet *et al.*, 1994). Recent measurements that have been done using the LSND (Liquid Scintillator Neutrino Detector) (Athanassopoulos *et al.*, 1995, Hill, 1995) strongly suggest that neutrinos do have masses thus giving us a possibility to determine their place in the universe. The contribution of neutrinos to the cosmological density today (Primack, 1996) is:

$$\Omega_\nu = \frac{\sum_i m_{\nu_i}}{94h^2\mathrm{eV}},$$

where the density parameter $\Omega_\nu = \frac{\rho_\nu}{\rho_{\mathrm{crit}}}$, $\rho_{\mathrm{crit}} = \frac{3H_0^2}{8\pi G} \cong 1.88 \times 10^{-29} h^2 \frac{\mathrm{g}}{\mathrm{cm}^3}$. h is dimensionless parameter used in the parametrization of the Hubble constant H_0, $H_0 = 100\,h\,\frac{\mathrm{km/s}}{\mathrm{Mpc}}$ and $0.4 < h < 1$. According to the well-known cosmological upper limit (e.g., Sarkar, 1996) we have the following constraint:

$$\sum_{i=1} m_{\nu_i} \left(\frac{g_{\nu_i}}{2}\right) \leq 94\text{eV}, \tag{1}$$

where the sum goes over all species that were relativistic at decoupling i.e. $m_{\nu_i} \lesssim 1$ MeV.

3. NEUTRINOS IN GALACTIC HALOS

Perhaps the most noticeable evidence of the existence of the DM came from the measurements of luminosity profiles and RCs of spiral galaxies (Rubin *et al.*, 1985). The case of the spiral galaxy NGC3198 ("everyone's favourite") is very importanrt and could lead us to some important results concerning the problem of the nature of the DM. Van Albada *et al.*, (1985) found that the amount of the DM inside the last point of the rotational curve is at least four times larger than the amount of visible matter. Mass-to-light ratio adjusted to fit the inner part of the rotational curve of this galaxy is:

$$\frac{\mathcal{M}}{\mathcal{L}} = 5.3\ h\ \frac{\mathcal{M}_\odot}{\mathcal{L}_\odot}$$

(Peebles, 1993), where $\mathcal{M}$ stands for the mass, $\mathcal{L}$ for the luminosity, symbol $\odot$ denotes the Sun. While in the central parts of this galaxy there exists good agreement with Newtonian model, in the outskirts, observed velocities do not show Keplerian fall-off. It is assumed that the mass in these outer parts is dominated by low-luminosity material – a dark halo.

This material could be in two forms: baryonic and nonbaryonic. According to Persic and Salucci (1996), (hereafter PS96):

$$\Omega_{\text{bar}}^{\text{gal}} = \Omega_{\text{bar}}^{\text{E}} + \Omega_{\text{bar}}^{\text{S}} = 2 \times 10^{-3},$$

where $\Omega_{\text{bar}} = \frac{\rho_{\text{bar}}}{\rho_{\text{crit}}}$.

PS96 found that spiral (S) and elliptical (E) galaxies contribute the same cosmological stellar mass density. However, recent measurements imply that the density parameter $\Omega_0 = 1$ (with estimated standard error ± 0.2) thus indicating the existence of non-baryonic DM (Kolb and Turner, 1993).

If we want to make the model of a spiral galaxy (for example, NGC3198) we could use the following Richstone and Tremaine (1986) approach for the mass density:

$$\rho(r) = \frac{\rho_c}{(1 + \frac{r^2}{r_c^2})^{\frac{3}{2}}}.$$

where r_c is the core radius. For small values of r, i.e. $r \ll r_c$:

$$\rho = \rho_c(1 - \frac{3}{2}\frac{r^2}{r_c^2} + \cdots).$$

The velocity distribution is isotropic and independent of position, the mass-to-light ratio is independent of radius. In this model there exists a well defined, flat central core. The velocity dispersion is $\sigma =< v^2 >^{\frac{1}{2}}$ in one dimension, the pressure is $p = \rho\sigma^2$ and the pressure per unit volume is $-\frac{\partial p}{\partial r}$. The condition for gravitational equilibrium is:

$$\frac{\partial p}{\partial r} = \frac{3\rho_c \sigma^2 r}{r_c^2} = \frac{GM(r)}{r^2}\rho = \frac{4\pi}{3} G\rho_c^2 r.$$

Thus, one gets the central mass density:

$$\rho_c = \frac{9\sigma^2}{4\pi G r_c^2}$$

(Peebles, 1993, Padmanabhan, 1993).

Schramm and Steigman (1981) considered relic neutrinos with mass $m_\nu \gtrsim \frac{1}{2}$ eV and obtained the same result. According to this paper neutrinos could have collapsed gravitationally during the formation of astrophysical systems whose potential wells are sufficiently deep:

$$\frac{GM(\leq r_c)}{r_c} \approx 3\sigma^2 \gtrsim v_\nu^2.$$

Following Peebles' (1993) reasoning, one can establish a possible model for the present mean distribution of neutrinos in a dark halo via spherically symmetric isothermal form:

$$\mathcal{N}_f = \mathcal{N}_0 e^{-\frac{1}{\sigma^2}(\frac{v^2}{2}+\varphi(r))} \tag{2}$$

where $\mathcal{N}_f$ is defined as:

$$\mathcal{N}_f = \langle \frac{1}{e^{\frac{pc}{kT_\nu}}+1} \rangle, \; T_\nu = (\frac{4}{11})^{\frac{1}{3}} T_0(1+z)$$

where T_0 is the present cosmic microwave background temperature, $T_0 = 2.73 \pm 0.01$ K (Smooth and Other, 1995). In the equation (2) the gravitational potential per unit mass at radius r is $\varphi(r)$, with $\varphi(0) = 0$, $\mathcal{N}_0 \leq 0.5$.

This distribution can be used in order to find the mean density:

$$\rho_\nu(r) = \frac{2m_\nu}{(2\pi\hbar)^3} \int \mathcal{N}_f d^3p = \frac{\mathcal{N}_0 m_\nu^4 \sigma^3}{2^{\frac{1}{2}} \pi^{\frac{3}{2}} \hbar^3} e^{-\frac{\varphi(r)}{\sigma^2}} \tag{2a}$$

(Peebles, 1993).

After solving the Poisson equation for the gravitational potential:

$$\nabla^2 \varphi = \frac{d^2\varphi}{dr^2} + \frac{2}{r}\frac{d\varphi}{dr} = 4\pi G \rho_\nu(r)$$

one obtains, for $r \gg \alpha$, $\alpha^2 = \frac{\pi^{\frac{1}{2}}}{2^{\frac{3}{2}}} \frac{\hbar^3}{G\mathcal{N}_0 m_\nu^4 \sigma}$:

$$\rho_\nu(r) = \frac{\sigma^2}{2\pi G r^2} = \frac{v^2}{6\pi G r^2}. \tag{3}$$

We put in the value for v^2, i.e. the mean square velocity $< v^2 >$, $< v^2 >= 3\sigma^2$ (Padmanabhan, 1993).

It follows from equations (2a) and (3) that the mass is equal to:

$$m_\nu^4 = \frac{1}{6\pi}\left(\frac{3}{2\pi}\right)^{\frac{1}{2}} \frac{h^3}{Gvr_c^2}, \tag{4}$$

where we have assumed that $\frac{\varphi(r)}{\sigma^2} \to 0$ and $\mathcal{N}_0 = 0.5$.

If one inserts the values characteristic for the Milky Way ($v \sim 230\,\frac{\mathrm{km}}{\mathrm{s}}$ and $r_c \sim 8$ kpc), one obtains the following result for the neutrino mass:

$$m_\nu \approx 27\,\mathrm{eV}.$$

This value is the *lower* limit for m_ν, while the *upper* limit is given in the equation (1). The obtained value plays the crucial role in the decaying dark matter (DDM) theory, firstly proposed by Melott (1984) and later developed by Sciama (1990a, 1990b, 1993). According to this theory the mass of the tau neutrino is:

$$m_{\nu_\tau} = 29.21 \pm 0.15\,\mathrm{eV}.$$

Melott *et al.* (1994) while considering decaying neutrinos in galaxy clusters obtained the lower limit for the neutrino lifetime τ_{23} in the units 10^{23} s: $\tau_{23} > (3 \pm 1)(\frac{29\,\mathrm{eV}}{m_\nu})$. Such a decay could be observed (e.g., Samurović and Čelebonović, 1995). Experiment that has been proposed, EURD, will have to prove the existence of a decay line derived from the photons with energy ~ 15 eV.[1]

4. ROTATIONAL CURVES OF SPIRAL GALAXIES

PSS presented the profiles of 134 RCs (references on the measurements can be found therein). We used the equation (4) which after inserting the appropriate values becomes:

$$m_\nu\,[\mathrm{eV}] = \frac{299.0362}{v_{[\mathrm{km/s}]}^{\frac{1}{4}}\, r_{c[\mathrm{kpc}]}^{\frac{1}{2}}}. \tag{5}$$

For the estimation of the core radius, r_c, we used Kormendy's relation (Ashman, 1992) according to which:

$$r_c \approx 5.9\left(\frac{L_B}{10^9 L_{B\odot}}\right)^{0.34}\,[\mathrm{kpc}]. \tag{6}$$

In Table (1) we present the values from PSS together with estimated values for the neutrino mass (most probably of the tau neutrino). Although the most important galactic parameters are not known accurately (Spergel, 1996), one can see that the values of the neutrino mass are gathered within the range $20 \lesssim m_\nu \lesssim 30\,\mathrm{eV}$; the mean value is 22 ± 7 eV. The obtained result could lead to the conclusion that massive neutrinos *could* dominate in the spiral galaxies, but additional measurements of galaxies' parameters and laboratory measurements of neutrino mass are indispensible.

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[1] URL: `http://www.laeff.esa.es/eng/laeff/activity/eurd.html`

Table 1. Values of radius r in kpc, velocity v in km/s and mass of neutrino m_ν for 134 spiral galaxies.

Name	M_B	v $[\frac{\text{km}}{\text{s}}]$	r_c [kpc]	m_ν [eV]	Name	M_B	v $[\frac{\text{km}}{\text{s}}]$	r_c [kpc]	m_ν [eV]
N55	-17.83	80	7.6	36.26	U 3269	-21.01	185	20.58	17.87
N224	-20.81	250	19.33	17.10	U 3282	-21.57	220	24.53	15.68
N247	-17.52	110	6.9	28.62	U 4375	-19.59	190	13.19	22.17
N253	-19.82	215	14.17	20.74	U 11810	-20.39	185	16.95	16.96
N300	-16.83	90	4.29	46.89	U 12417	-19.45	126	12.63	25.12
N598	-18.31	108	8.84	31.20	U 12533	-19.93	210	14.68	20.51
N628	-20.12	200	15.58	20.15	U 12810	-21.45	220	23.62	15.98
N697	-21.16	214	15.77	19.69	27-008	-20.48	171	17.44	19.80
N753	-21.54	215	24.30	15.84	30-009	-21.71	300	25.63	14.19
N801	-21.26	220	22.26	16.46	40-012	...	200	...	...
N891	-20.50	230	17.54	18.33	41-009	...	198	...	...
N925	-19.24	116	11.82	26.50	69-011	...	177	...	...
N1035	-19.04	125	11.10	26.84	71-005	-20.81	240	19.33	17.28
N1085	-21.92	302	27.37	13.71	75-037	-19.06	111	11.18	27.55
N1090	-20.72	173	18.80	19.02	82-008	-21.04	255	20.78	16.42
N1097	-20.71	250	18.74	17.37	88-016	-20.89	215	19.82	16.81
N1114	...	198	...	...	116-012	-17.75	134	7.42	32.28
N1247	-21.07	270	20.97	16.11	121-006	-18.46	129	9.26	29.16
N1365	-20.27	275	16.32	18.17	123-023	-19.62	150	13.32	23.41
N1417	-21.15	245	15.72	19.06	141-020	-21.01	239	20.58	16.76
N1560	-16.80	62	5.5	45.41	141-034	-21.40	277	23.25	15.20
N1832	-20.25	180	16.22	20.27	184-051	-21.40	240	23.26	15.75
N2336	-21.79	250	26.27	14.67	215-039	-20.82	160	19.39	19.09
N2403	-19.24	127	11.82	25.90	235-016	-20.74	202	18.91	18.24
N2558	-20.43	245	17.16	18.24	240-011	-20.53	222	17.71	18.41
N2595	-21.15	300	21.50	15.49	269-019	-20.85	192	19.58	18.16
N2742	-20.10	170	15.48	21.05	282-003	-21.49	198	23.92	16.30
N2841	-21.83	320	26.61	13.71	284-024	-20.45	165	17.27	20.08
N2903	-20.52	206	17.65	18.79	286-016	-20.20	171	15.97	20.69
N2998	-21.16	215	21.57	16.81	287-013	-20.55	167	17.82	19.71
N3109	-16.43	55	4.90	49.58	289-010	-18.88	98	10.56	29.24
N3145	-21.22	275	21.98	15.66	299-004	-20.96	187	20.26	17.96
N3198	-20.17	156	15.82	21.27	306-032	-20.24	179	16.17	20.33
N3200	-21.09	280	21.10	15.91	322-045	-19.35	165	12.23	23.85
N3223	-21.76	253	26.03	14.70	322-076	-20.24	175	16.17	20.44
N3992	-21.67	275	25.31	14.60	346-014	-18.60	98	9.68	30.55
N4013	-19.73	196	13.79	21.53	347-033	-19.84	198	14.27	21.10
N4062	-19.47	160	12.71	23.59	350-023	-21.08	230	21.04	16.74
N4236	-18.74	88	10.11	30.71	352-053	-20.44	250	17.22	18.12
N4258	-20.73	205	18.85	18.20	374-027	-21.35	258	22.89	15.60
N4348	-19.52	188	12.91	22.48	376-002	-20.43	200	17.16	19.19
N4565	-20.86	240	19.64	17.14	379-006	-19.87	169	14.40	21.85
N4605	-16.84	100	5.58	40.04	383-002	-20.54	190	17.77	19.11

Table 1. (continued)

Name	M_B	v $[\frac{\text{km}}{\text{s}}]$	r_c [kpc]	m_ν [eV]	Name	M_B	v $[\frac{\text{km}}{\text{s}}]$	r_c [kpc]	m_ν [eV]
N4682	-19.58	175	13.15	22.67	383-088	-20.04	180	15.19	20.95
N4800	-18.76	172	10.17	25.89	437-030	-20.46	205	17.33	18.99
N5033	-20.67	218	18.50	18.09	439-018	-21.71	245	25.63	14.93
N5055	-20.65	215	18.39	18.21	439-020	-19.91	215	14.58	20.45
N5371	-21.72	240	25.71	14.98	444-047	-19.44	145	12.59	24.29
N5585	-18.47	80	9.29	32.80	444-086	-19.95	210	14.77	20.44
N5673	-20.30	138	16.48	21.49	445-058	-20.72	205	18.80	18.23
N5905	-20.87	235	19.70	17.21	446-044	-19.22	148	11.75	25.01
N5907	-20.69	225	18.62	17.89	481-002	-18.22	119	8.59	30.89
N6503	-18.62	122	9.74	28.83	499-005	-20.84	170	19.52	18.75
N6674	-21.33	255	22.75	15.69	502-002	-20.25	210	16.22	19.50
N7083	-21.27	220	22.33	16.43	507-007	-21.10	263	21.17	16.14
N7331	-20.92	243	20.01	16.93	509-091	-20.03	150	15.14	21.96
N7339	-19.21	170	11.73	24.20	533-004	-19.23	150	11.79	24.89
N7536	-20.18	183	15.87	20.41	543-012	...	174	...	...
N7591	-20.34	200	16.69	19.47	548-032	-17.58	66	7.03	39.57
N7593	-19.61	150	13.28	23.45	555-016	-20.19	222	15.92	19.42
N7606	-21.15	265	21.50	15.98	563-014	...	148	...	...
N7631	-20.18	198	15.87	20.01	564-020	-19.00	92	10.97	29.16
N7793	-17.79	111	7.51	33.62	566-022	-18.91	138	10.66	26.72
I 467	-19.77	150	13.96	22.87	601-009	-21.55	258	24.37	15.11
I 2974	...	230	...	...	M-3-1042	...	148	...	...
U 2259	-16.54	81	5.08	44.24					

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