Neutrinos as galactic dark matter in the Ursa Major galaxy group?

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ABSTRACT

We present the analysis of 23 published rotation curves of disk galaxies belonging to the Ursa Major group of galaxies, with kinematics free of irregularities. The rotation curves are analysed in the context of MOND (Modified Newtonian Dynamics). We add an extra component to the rotation curve fits, in addition to the stellar and gaseous disks: a speculative halo of constant density made of, e.g., neutrinos, which would solve the bulk of the problem currently faced by MOND on rich galaxy clusters scales. We find that this additional unseen mass density is poorly constrained (as expected a priori, given that a neutrino halo never dominates the kinematics), but we also find that the best-fit value is non-zero: \( \rho = 3.8 \times 10^{-27} \) g cm\(^{-3}\), and that a zero-density is marginally excluded with 87% confidence; also, the 95% confidence upper limit for the density is \( \rho = 9.6 \times 10^{-27} \) g cm\(^{-3}\). These limits are slightly above the expectations from the Tremaine-Gunn phase space constraints on ordinary 2 eV neutrinos, but in accordance with the maximum density expected for one or two species of 5 eV sterile neutrinos.

Key words: galaxies: kinematics and dynamics - dark matter - galaxies: spiral - gravitation - galaxies: clusters: individual: Ursa Major

1 INTRODUCTION

The current dominant paradigm in cosmology is that galactic dark matter is made of non-baryonic weakly-interacting massive particles, the so-called cold dark matter (CDM). However, on galaxy scales, observations are at variance with a sizeable list of CDM predictions (e.g., Klypin et al. 1999; Gentile et al. 2004, 2005, 2007a, 2007b, 2007c; Simon et al. 2003; Famaey & Binney 2005; Kuzio de Naray et al. 2006), whilst one observes that the gravitational field is closely related to the baryonic distribution in spiral galaxies (e.g., McGaugh et al. 2007; Famaey et al. 2007a) through the modified Newtonian dynamics (MOND) relation of Milgrom (1983): in MOND, for gravitational accelerations \( a \) below \( a_0 \approx 10^{-8} \) cm s\(^{-2}\) the effective \( a \) approaches \((g_N a_0)^{1/2}\) where \( g_N \) is the usual Newtonian gravitational field. This leads to remarkable fits of galactic rotation curves over five decades in mass ranging from tiny dwarfs (e.g., Gentile et al. 2007a, 2007c) through early-type spirals (e.g., Sanders & Noordermeer 2007) to massive ellipticals (Milgrom & Sanders 2003), without resorting to galactic dark matter. MOND also accounts very well for observed scaling relations of galaxies (e.g., Sanders & McGaugh 2002; McGaugh 2004, 2005). Moreover, the mysteriously small but non-zero cosmological constant also finds a natural answer in some co-variant versions of MOND (e.g., Zhao 2007).

However, despite all these successes, MOND fails to completely explain away the mass discrepancy in clusters of galaxies (Aguirre, Schaye & Quataert 2001; Sanders 2003, 2007; Pointecouteau & Silk 2005; Angus, Famaey & Buote 2007a): consequently, these objects still require substantial amounts of non-luminous matter in MOND. The recent weak-lensing observations of the “bullet cluster” (Clowe et al. 2006, Angus et al. 2007b) have moreover constrained this non-luminous component to be collisionless, e.g. dark baryons in some non-dissipative form (MACHOs or small dense clumps of cold gas). Another possibility, suggested by Sanders (2003), is that ordinary neutrinos have a mass of the order of 2 eV (near the present experimental limit), and thus contribute significantly to the mass budget of galaxy clusters. These hot dark matter particles are fermionic and have a maximum phase space density set by equilibrium in the early Universe. Reexpressing this phase space limit from Tremaine & Gunn (1979), and assuming 3 species of ordinary neutrinos of nearly equal mass, Sanders (2003) noted...
that in a relaxed cluster of virialised gas temperature $T$, if the neutrino fluid has the same temperature as the gas, the maximum neutrino density is:

$$\rho_\nu = 4.8 \times 10^{-27} \left( \frac{m_\nu}{2 \text{ eV}} \right)^4 \left( \frac{T}{1 \text{ keV}} \right)^{3/2} \text{ g cm}^{-3},$$  \hspace{1cm} (1)$$

where $m_\nu$ is the ordinary neutrino mass.

It has indeed been shown that galaxy clusters scaling relations, including the luminosity-temperature relation, are then naturally reproduced in MOND (Sanders 2007), while such a non-baryonic component of moderately heavy neutrinos helps fitting the angular power spectrum of the Cosmic Microwave Background in relativistic MOND theories (e.g., Skordis et al. 2006). However, it has recently been shown that such ordinary 2 eV neutrinos would fail to explain the mass discrepancy in X-ray emitting groups of galaxies, where the X-ray temperature falls below 2 keV (Angus et al. 2007a), because the maximum neutrino density would be too low. This notion might be related to the fact that, due to their unrelaxed nature, the temperature of hot gas in groups is not representative of the actual temperature of the neutrino fluid. Alternatively, this could rather hint at the presence of extra baryonic mass in the form of cold dense clumps of cold gas (e.g. Pfenniger, Combes & Martinet 1994; Pfenniger & Combes 1994), or at the existence of one or two species of light sterile neutrinos with masses of a few eV (e.g. Maltoni et al. 2004, Maltoni & Schwetz 2007).

In any case, if neutrinos do contribute significantly to the mass budget of rich galaxy clusters, it is then likely that, in the context of MOND, individual galaxies and galaxy groups possess extensive low-density neutrino halos. These were suggested by Sanders (2007) to possibly affect the weak lensing properties of galaxies on scales of hundreds of kpc. In this Letter, we rather investigate the possible contribution of neutrinos on the rotation curves of individual galaxies residing in groups in the context of MOND. To achieve this, we reanalyse the rotation curves in the Ursa Major galaxy group (Sanders & Verheijen 1998) by adding as a new parameter a constant neutrino density.

2 “MOND + NEUTRINOS” MODELS

In MOND, the transition from the Newtonian regime (where $a = g_0$) to the deep MOND regime (where $a = (g_0 a_0)^{1/2}$) is regulated by an interpolation function $\mu(x)$, where $x = a/a_0$ and $a = g_0 / \mu(x)$. $\mu(x)$ should have the following asymptotic behaviours: $\mu(x) \rightarrow 1$ for $x \gg 1$ and $\mu(x) \rightarrow a_0/a$ for $x \ll 1$. Traditionally the following functional form of $\mu(x)$ was used: $\mu(x) = \left( 1 + \frac{x}{1 + x} \right)^{1/2}$, but recently the preferred form has become the “simple” $\mu(x)$ proposed by Famaey & Binney (2005):

$$\mu(x) = \frac{x}{1 + x}. \hspace{1cm} (2)$$

This form of $\mu(x)$ has been shown to give disk galaxies’ rotation curves fits which are as good as the standard $\mu(x)$, with realistic mass-to-light ($M/L$) ratios (Famaey et al. 2007a). Also, contrary to the standard $\mu(x)$, it gives reasonable disk and bulge $M/L$ ratios in early-type disk galaxies (Sanders & Noordermeer 2007).

To motivate a 2 eV neutrino component in galaxies and galaxy groups, we note that massive neutrinos are hot dark matter (decoupled from electrons and the radiation at relativistic speed), but that these thermal relics have presently cooled to very low speed. Indeed, since their momentum comparable to that of CMB photons today, their speed is expected to be $\sim 30$ km s$^{-1}$ (4/11)$^{-1/3}$ $= 21$ km s$^{-1}$. The factor $(4/11)^{-1/3}$ arises from entropy conservation arguments in the early Universe (e.g. Weinberg 1972). They can however be heated up to 100-1000 km s$^{-1}$ by falling into the gravitational potentials of group and clusters of galaxies.

Eq. (3) could be generalised to situations where the X-ray temperature is unknown or unapplicable. Adopting $T = 1$ keV($\frac{100 \text{ km s}^{-1}}{900 \text{ km s}^{-1}}$)$^2$ from Sarazin (1986), we can convert gas temperature to the 1-dimensional equilibrium velocity dispersion $\sigma$. The Tremaine-Gunn limit for three species of ordinary neutrinos (and their antiparticles) of nearly equal mass can then be recasted as:

$$\left( \frac{\rho_\nu}{4.8 \times 10^{-27} \text{ g cm}^{-3}} \right)^{1/3} \left( \frac{m_\nu}{2 \text{ eV}} \right)^{-4/3} = \frac{\sigma}{400 \text{ km s}^{-1}} \hspace{1cm} (3)$$

Note that $4.8 \times 10^{-27}$ g cm$^{-3} = 7 \times 10^{-5}$ $M_\odot$ pc$^{-3}$.

3 DATA

The Ursa Major group is an ideal example to perform this kind of rotation curve analysis. Galaxy groups are typically dominated by spiral galaxies for which the density profiles can be measured by analysing their rotation curves. Furthermore, such groups are usually diffuse and of relatively low mass. Consequently, the external field effect in galaxy groups is less important than in more massive galaxy clusters (Bekenstein & Milgrom 1984, Famaey, Bruneton & Zhao 2007b, Angus & McGaugh 2007, Wu et al. 2007). The Ursa Major galaxies do not form a rich, “classical” virialised cluster, such as the ones for which 2 eV neutrinos have been invoked (Sanders 2003, 2007) as a solution to the MOND mass discrepancy problem. It is known for a while that such non X-ray emitting groups do not exhibit a mass discrepancy problem in MOND (e.g., Milgrom 2002), but within the uncertainties due notably to the unrelaxed nature of the group, a low density extra mass component cannot be excluded.

Note that an individual spiral galaxy is expected to be surrounded by a very shallow and extended neutrino halo (Sanders 2007), according to the phase-space contraint which corresponds to a temperature below 0.1 keV (i.e. typically $\sigma \lesssim 120$ km s$^{-1}$ for an individual galaxy, see e.g. Battaglia et al. 2005 for the Milky Way). Such halos, surrounding individual galaxies in a group, would merge with the halo of the group as a whole, for which the equivalent "virialised gas temperature" is $T = 0.14$ keV, corresponding to a dispersion of 150 km s$^{-1}$. However, given that the Ursa Major group is not virialised (Sanders & Verheijen 1998), this value can only be taken as a very rough estimate.

Hereafter, we model the neutrino component around each galaxy as the halo of the whole Ursa Major group, with an isotropic constant density. Given the uncertainties (the actual neutrino temperature, their density profile, the physical distances of the galaxies from the group centre),
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4 RESULTS AND DISCUSSION

We attempted to constrain the neutrino density, using the MOND hypothesis, by fitting the 23 rotation curves discussed in the previous section.

The rotation curves were fitted the usual way in MOND, but adding an extra component in the fits due to the putative neutrino halo. We used the simple $\mu(x)$ function (see Section 2). The global parameters of the fit were $a_0$ and the additional (constant) density $\rho_\nu$: they both were constrained to be the same for all the galaxies of the sample. We note that keeping $a_0$ as a free parameter can compensate any errors on the (fixed) distance. Then, the stellar ($K'$-band) mass-to-light ($M/L$) ratio was left as an additional free parameter, separately for each galaxy. The uncertainties on the fitted parameters were derived from the $\chi^2$ statistics of the global fit performed on the 23 rotation curves of the sample.

We find a 1-$\sigma$ allowed range for $\rho_\nu$ between $0.8 \times 10^{-27}$ g cm$^{-3}$ and $7.4 \times 10^{-27}$ g cm$^{-3}$, the best-fit value being $\rho_\nu = 3.8 \times 10^{-27}$ g cm$^{-3}$. The corresponding best-fit value of $a_0$ is $0.72 \pm 0.09 \times 10^{-8}$ cm s$^{-2}$. In Fig. 1 we plot the confidence levels in parameter space: as shown by Begeman, Broeils & Sanders (1991), fits with variable $a_0$ and fixed distance $D$ are essentially identical to fits with fixed $a_0$ and variable $D$, because the product $a_0D^2$ comes in the computation of the MOND circular velocity. Note that higher distances suggest a lower neutrino density. Also, a negative neutrino density cannot be measured, thus any fit of the density leads to a non-negative value.

As expected a priori, the constraints on $\rho_\nu$ are very weak, as the neutrino halo never dominates the kinematics due to its very low density. Fig. 2 shows the overall effect of adding a neutrino component: at large radii, where the neutrinos contribution is larger, the residuals of the fits become smaller than without neutrinos. In the outer parts, both model rotation curves are below the observations, but the curves with neutrinos are closer to the observations. The wave-like behaviour of the residuals in Fig. 2 will be studied in a future paper: different $\mu$-functions might explain some systematic residual of the rotation curves (Sanders & Verheijen 1998; Milgrom & Sanders 2007). However, using the standard $\mu$-function does not get rid of the wave-like behaviour of Fig. 2. We also note that $\rho_\nu = 0$ is excluded with 87% confidence.

Let us now check whether the neutrino fits are consistent with the Tremaine-Gunn limit and the global observation of Ursa Major. Plugging the 1-$\sigma$ range of our rotation curve-determined value ($0.8 \times 10^{-27}$ to $7.4 \times 10^{-27}$) in the Tremaine-Gunn limit for ordinary 2 eV neutrinos, we predict that $T = 0.3-1.3$ keV. These should be the typical equilibrium dispersion and temperature for characterizing the overall potential which the 2 eV neutrinos are in. This equilibrium velocity dispersion is probably marginally consistent with the global potential of the Ursa Major group: no X-ray emission has been detected, but it is observed to have a galaxy velocity dispersion of $\sigma_{\text{obs}} = 148 \pm 6$ km s$^{-1}$ (Tully 1987). However, Ursa Major is unrelaxed, so $\sigma_{\text{obs}}$ is likely an under-estimate of the potential. On the other hand, the lack of X-ray implies the intergalactic gas in Ursa is most certainly below 1 keV. Adopting $T = 148$ km s$^{-1}$, the data is slightly pushing for a somewhat higher than 2 eV neutrino mass, which could be reminiscent of the fact that ordinary 2 eV neutrinos are not found to explain away the discrepancy in X-ray emitting groups (Angus et al. 2007a).

Let us finally note that a possible effect on all these results is the external field effect (EFE), discussed in Section 2: galaxies in clusters are embedded in an external field much higher than the typical value of $0.01a_0$ in which the Milky Way is embedded (Famaey et al. 2007b, Wu et al. 2007), so even when their internal acceleration is much smaller than $a_0$ they are actually not in a MOND regime. However, as argued in Sanders & Verheijen (1998), the EFE is expected to be of order 0.02$a_0$ in the Ursa Major group, meaning that we can neglect it as a first order approximation.

5 CONCLUSIONS

We analysed 23 rotation curves of disk galaxies with regular kinematics belonging to the Ursa Major group of galaxies, presented by Sanders & Verheijen (1998). The rotation curves are fitted within the MOND (Modified Dynamics, Milgrom 1983) context, where traditionally only the visible matter (gas and stars) is needed to fit rotation curves. However, given that MOND shows a mass discrepancy in rich galaxy clusters which can be mainly solved by adding a halo of 2 eV ordinary neutrinos (Sanders 2003), we add a third
component to the MOND fits, with the same constant density for all galaxies of the sample. It is however important to bear in mind that this extra mass component in our fits does not necessarily have to be ordinary neutrinos.

The fits give a rather unconstrained best-fit value of the additional constant density: $\rho_\nu = 3.8^{+3.6}_{-3.0} \times 10^{-27}$ g cm$^{-3}$. Such weak constraints are to be expected since a neutrino halo is never the dominant component in the kinematics. However, a zero additional density is marginally excluded, with 87% confidence. These results show that neutrino (or any other dark matter) effects are worth being modelled in MOND in the future, with better data and larger samples.

We however comment that there is a slight tension between the rotation curve-determined neutrino density and the Tremaine-Gunn limit for three species of ordinary 2 eV neutrinos, assuming that the velocity dispersion is a good estimator of the neutrino fluid temperature (which is unsure in such an unrelaxed cluster). Indeed, from Eq.(1), and for $T = 0.14$ keV, the maximum neutrino density for UMa should be $2.5 \times 10^{-28} (m_\nu/2eV)^4$ g cm$^{-3}$. For ordinary 2 eV neutrinos, this density is a factor 15 smaller than our best-fit value. A similar tension is observed in fitting weak-lensing data of high-z X-ray clusters (Takahashi & Chiba 2007, Angus et al. 2007b), temperature profiles of X-ray emitting groups (Angus et al. 2007a), and velocity dispersions of galaxies at the center of rich clusters (Richtler et al. 2007). This means that the narrow window of ordinary neutrino mass of 2-2.2 eV is presently tightly squeezed by opposite constraints from astronomical data and particle physics experiments. Actually, this tension could rather hint at the existence of one, two or three species of light sterile neutrinos (Maltoni & Schwetz 2007). For three species of sterile neutrinos with a 5 eV mass (and ordinary neutrinos with a negligible mass), a mass $m_\nu = 5$ eV can be directly plugged in Eq. (1). In the case of two species of sterile neutrinos, the maximum density must then be divided by a factor 1.5, and in the case of one species by a factor 3. This means that for two species of 5 eV sterile neutrinos, the maximum density for a temperature of 0.14 keV is $6 \times 10^{-27}$ g cm$^{-3}$, and for one species $3.25 \times 10^{-27}$ g cm$^{-3}$, densities much closer to our rotation curve-determined values. These one or two species of 5 eV sterile neutrinos could additionally solve the problem of the MOND missing mass at the center of high-z X-ray clusters (Takahashi & Chiba 2007, Angus et al. 2007b), in X-ray emitting groups (Angus et al. 2007a), and in individual galaxies at the center of clusters (Richtler et al. 2007).

Lastly, we note that doing similar rotation curve work in the much hotter Virgo and Coma clusters might reveal a stronger effect of the neutrinos, expected to be 100 times denser in Coma than in Ursa Major. It is thus of interest to fundamental physics to push for accurate resolved kinematic data of galaxies in the Virgo and Coma clusters.

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Figure 2. Residuals of the fits. Top: all the data. Bottom: data binned in radial bins of 2 kpc; the errorbars are derived from the uncertainty on the mean in each bin. Full circles represent the fits with neutrinos, empty circles are the fits without neutrinos.

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