Are sterile neutrinos consistent with clusters, the CMB and MOND?

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29 July 2008

ABSTRACT

If a single sterile neutrino exists such that \( m_{\nu_s} \sim 11\text{eV} \), it can serendipitously solve all outstanding issues of the Modified Newtonian Dynamics. With it one can explain the dark matter of galaxy clusters without influencing individual galaxies, match the angular power spectrum of the cosmic microwave background and potentially fit the matter power spectrum. This model is flat with \( \Omega_{\nu_s} \sim 0.23 \) and the usual baryonic and dark energy components, thus the Universe has the same expansion history as the \( \Lambda\text{CDM} \) model and only differs at the galactic scale where the Modified Dynamics outperforms \( \Lambda\text{CDM} \) significantly.

1 INTRODUCTION

Milgrom’s Modified Newtonian Dynamics (MOND, see Milgrom 1983; Sanders & McGaugh 2002; Bekenstein 2006; Milgrom 2008) as the weak acceleration limit of Einstein’s general relativity is arguably consistent with a wide range of evidence from astronomical systems from the orbits of the planets in the solar system (where Newton’s gravity suffices without dark matter) to dwarf galaxies (Milgrom 1995; Angus 2008) and globular clusters (Angus & McGaugh 2008, in prep) of the Milky Way, tidal dwarf galaxies (Milgrom 2007a; Gentile et al. 2007, see also Bournaud et al. 2007), low surface brightness galaxies (McGaugh & de Blok 1998; Milgrom & Sanders 2007) and high surface brightness galaxies (Famaey & Binney 2005; Sanders & Noordermeer 2007; McGaugh 2008) including giant ellipticals (Angus et al. 2008).

Not only are the dynamics of the galactic systems well matched from the MOND prediction, but they all fall precisely on the Tully-Fisher relation (McGaugh et al. 2000; McGaugh 2005a) which correlates total enclosed mass and the fourth power of the asymptotic velocity, unless they are satellites of a larger galaxy.

The only alternative theory uses cold dark matter (CDM) particles without any experimental motivation in massive, triaxial halos to provide the additional gravity needed to boost the rotation velocities of the systems with an acceleration discrepancy. There are several well-documented and as yet unresolved issues for this framework at the scales of galaxies such as the fine tuning problem of DM halos (Milgrom & Sanders 2005; McGaugh 2005a), the cusp problem (de Blok & McGaugh 1998; McGaugh & de Blok 1998; Gnedin & Zheng 2002; Gentile et al. 2004; Gilmore et al. 2007), the missing satellites problem (Klypin et al. 1999; Moore et al. 1999) and more recently tidal dwarf galaxies (Milgrom 2007b; Gentile et al. 2007; see also Bournaud et al. 2007). Nevertheless, recent studies (Milgrom 2007a; see also Bournaud et al. 2007) have shown that, even under very likely circumstances, a second species of dark matter would be necessary to explain the dynamics of the central 100kpc of clusters and groups of galaxies, which more or less rules them out as good candidates.

Of course, there is no limit on the dark matter being baryonic since the necessary dark matter in clusters of galaxies is at most a few percent of the big bang nucleosynthesis (BBN) baryons, of which only 20% or so are observed at low redshifts (Silk 2007; McGaugh et al. 2007), the remainder is presumed to exist in a warm-hot intergalactic medium (Bregman 2007). This led Milgrom (2007a) to propose the dark matter in clusters to be a cold, molecular gas of \( \sim \) Jupiter mass. These are naturally difficult to detect, but
might have the serendipitous fortune of resolving the cooling flow problem (Fabian et al. 1994).

Unfortunately, even if the cluster dark matter problem were resolved, there remains the issue of cosmological dark matter. Put simply, there is compelling evidence that the Universe consists of a form of dark energy (like a cosmological constant) that forces the expansion of the Universe to accelerate at late times (Perlmutter et al. 1999; Schmidt et al. 1998). However, we have no idea what this dark energy is (Diaferio 2008) from a particle physics point of view, although perhaps the coincidence between $a_o$ and $cH_o$ or $c(A/3)^{1/2}$ is a strong indication (Milgrom 2002; 2008).

With the presence of this dark energy, in order for the Universe not to expand too rapidly, there needs to be some form of matter independent of the well fixed quantity of baryons to endow the Universe with additional inertia. This additional matter serves several purposes: it allows for large redshift relation (expansion history).

The underlying theory of MOND is still unknown, also it is only a classical framework, so a huge effort was made to extend MOND to the relativistic regime. In 2004, a giant leap was made in this direction by Bekenstein (2004) and others have taken to thrashing out the predictions of other MOND inspired relativistic theories (Sanders 2003; Skordis et al. 2006; Zlosnik et al. 2006; 2007; 2008). Sadly, the predictions for cosmology are not clear and there seems to be too much freedom, in contradiction to the absolute predictiveness of MOND in galaxies.

For this reason, I show here the predictions of coupling MOND with sterile neutrino dark matter using the ansatz employed by McGaugh (2004) when matching the CMB with MOND i.e. that no MOND effects should influence the CMB. However, we have no idea what this dark energy is (Diaferio 2008) from a particle physics point of view, although perhaps the coincidence between $a_o$ and $cH_o$ or $c(A/3)^{1/2}$ is a strong indication (Milgrom 2002; 2008).

It is often forgotten when looking at MOND cosmology that no cold dark matter exists in MOND. Therefore, we must relax many of the constraints that are set by CDM cosmology. The most important and obvious one is that there is now a large gap in the energy-density budget since CDM is not present and it is perfectly reasonable to fill this gap with hot dark matter like neutrinos. The constraints on neutrino masses, for which cosmology is still the most stringent, must be reanalysed in light of MOND. Still, the empirical evidence from supernovae data (Schmidt et al. 1998; Perlmutter et al. 1999) strongly suggest the universes expansion is accelerating owed to the existence of dark energy, $\Omega$. Furthermore, the baryon budget is strongly constrained by well understood physics to be around $\Omega H^2 \sim 0.015 - 0.025$ (Boesgaard & Steigman 1983; Burles et al. 2001; McGaugh 2004), but this still leaves a large amount of latitude in the energy budget for DM.

Any DM, however, must be compatible with clusters of galaxies, the well understood lack of DM in galaxies in MOND and the anisotropies in the angular power spectrum of the CMB. The best candidates for such hot DM are neutrinos.

2 NEUTRINOS

2.1 Active Neutrinos

The three active neutrinos ($\nu_e$, $\nu_\mu$ and $\nu_\tau$) from the standard model of particle physics have been shown to mix between flavours by atmospheric and solar neutrino experiments (Ahmad et al. 2001; Asieh et al. 2004). However, the exact masses of the three active neutrinos are not yet known, only their squared mass differences. Nevertheless, the masses of all three are known to be less than 2.2eV from the Mainz-Troitz experiments (Kraus et al. 2005).

The maximum density that a neutrino species can produce after gravitational collapse is given by the Tremaine-Gunn limit (Tremaine & Gunn 1979).

$$\rho_{\nu_{\text{max}}} = \left( \frac{T}{1 \text{keV}} \right)^{1.5} \left( \frac{m_{\nu}}{2 \text{eV}} \right)^4$$

for each of the three species. Thus, the density is greatly dependent on the mass of the neutrinos. However, groups and clusters of galaxies have dark matter that is much denser than can be produced by the active neutrinos even at the maximum mass of 2.2eV (Angus et al. 2008). If the dark matter is indeed a neutrino like species, it must be heavier than 2eV (Angus et al. 2008). There is a further problem with neutrinos at 2.2eV in that the contribution they make to the energy density of the Universe is given by

$$\frac{1}{7} \times 10^{-8} \rho_{\text{crit}} \left( \frac{T}{1 \text{keV}} \right)^{1.5} \left( \frac{m_{\nu}}{2 \text{eV}} \right)^4$$

meaning that at 2.2eV the three neutrinos make a 13.6% contribution to the energy density of the Universe, but the maximum density is relatively low (see Eq 2). Such a huge contribution would be easily detectable in the angular power spectrum of the fluctuations in the CMB as shown for this example in Fig.2. Therefore, the active neutrinos are a very poorly motivated candidate.
2.2 Sterile Neutrinos and the CMB

As mentioned above, the three active neutrinos are known to have mass. Another oddity arising from this is that the active neutrinos are solely left handedly chiral, whereas all other fermions are ambidextrous. The easiest way to incorporate this into the standard model of particle physics is to introduce a right handed “sterile neutrino”. In addition, they are not simply aesthetically pleasing, the introduction of a single sterile neutrino was preferred from analysis of the Miniboone experiment by Giunti & Laveder (2007) (see also Aguilar et al. 2001; Maltoni & Schwetz 2007) with a mass in the range 4eV-18eV to explain the disappearance of electron neutrinos from the beam at low energies.

In the simplest model, if the mixing angle of the sterile neutrino is low enough, then thermalisation in the early Universe can balance the abundance of the sterile and active neutrinos. In this case, the cosmological density is exactly related to their mass, as for the active ones (Eq 1). With the hypothesis that all the DM in MOND comes from a single sterile neutrino, we used the freely available CMB anisotropy code CAMB (Lewis et al. 2000) and incorporated it into a χ² minimisation routine comparing with the data from the WMAP5 data release (Dunkley et al. 2008) and the ACBAR 2008 data release (Reichardt et al. 2008). We allowed variation of Ω_0, n_s, d_n_s/d ln k, τ, H_0 and fixed the Universe to be flat meaning Ω_L = 1 − Ω_b − Ω_cdm.

Obviously, in this MOND inspired model there is no CDM by definition, but since the CDM model works well at producing the CMB anisotropies, we began the search by simply transferring Ω_cdm to Ω_0. Furthermore, the 3 active neutrinos are taken, for simplicity, to be massless. As discussed later, it is not feasible to have a pair of very massive (> 0.5eV) sterile neutrinos because splitting the Ω_0 between two or more neutrinos reduces the available mass to each neutrino thus detrimentally lowering its Tremaine-Gunn limit (ρ_v^max ∝ m_v^4) and thus the gravity available to drive the collapse of the baryons prior to recombination on small scales like the third acoustic peak. This is highlighted in Fig 2 where the comparison is made between one sterile neutrino and two.

The parameters for the best fit are given in table 1 which also contains the parameters for the WMAP5 fit from Dunkley et al. (2008) and a comparison of the two fits are shown in Fig 1. All parameters are consistent with experimental bounds and are not significantly different to the ΛCDM model, which is sensible since the ΛCDM model of the CDM anisotropies is a good one.

The mass of the sterile neutrinos inferred from the best fit value of Ω_0 ν_0, h² = 0.117 is m_ν_0 ∼ 11eV. This mass range of sterile neutrino has never before been considered in the literature because it is excluded by cosmological data if we assume Newton’s law are correct (Dodelson et al. 2006; Seljak et al. 2006) since they cannot influence galaxy rotation curves because they would have a free streaming scale (cf. Sanders 2003) of more than R_c = 1.3 (m_ν_0 / 3 eV) 1/3 (500 km s⁻¹) / c = 50kpc in a Milky Way type galaxy, for V_c = 200 km s⁻¹. The total mass this would create within 8kpc is ∼ 5 × 10^9 M_☉ which is about 10% of the total mass and would actually help MOND fits to the Milky Way’s rotation curve (Famaey & Binney 2005; Gentile et al. 2003; McGaugh 2008).

In particular, it would have a similar contribution to the energy density as required from cold dark matter fits to the CMB (Ω_0, h² = 0.117; Ω_cdm h² = 0.108) and leave the matter power spectrum at large scales (> 50h⁻¹Mpc) unaltered. This is shown in Fig 3 which compares the observed matter power spectrum with that predicted by the sterile neutrino model here, but with Newtonian instead of MONDian gravity. At scales smaller than ∼ 50h⁻¹Mpc the computed power spectrum drops many orders of magnitude below the observed one.

Qualitatively, this discrepancy is owed to the fact that structures on these small scales have formed with the assistance of MONDian gravity. For instance, following the argument of Eq 1 the redshift by which scales as large as 50h⁻¹Mpc are deep in the MOND regime (i.e. g ∼ 2H) is roughly

\[ z \sim \left[ \frac{2g}{3H_0^2 \Omega_{cdm}} \right]^{1/3}, \tag{4} \]

which for 70Mpc is z ≈ 100. Certainly many authors (Sanders 2008; Nesser 2002; Knebe & Gibson 2004) have shown that structures can form very quickly in MOND even without CDM and galaxy size objects can be in place as early as z ≈ 10.

The tools to perform the full matter power spectrum analysis are currently not available for MOND (nor standard dynamics), since they crucially depend on hydrodynamics. Assuming that including the modified dynamics enables a match to the matter power spectrum at all scales, the only conceivable ways of distinguishing between MOND and ΛCDM (if missing satellites, the lack of cusps in DM halos and tidal dwarf galaxies are ignored) is in the complex modelling of galaxy formation, or the unambiguous detection of the hot or cold DM particles.
As discussed in Angus et al. (2008) there appears to be galaxies where MOND requires dark matter of some form. The maximum density of the DM in groups and clusters of cold dark matter were necessary to show the CDM halos are a poor match to observed galaxies (de Blok & McGaugh 1998; McGaugh & de Blok 1998; Gnedin & Zhao 2002; Gentile et al. 2004; Gilmore et al. 2007) which show that no dark matter is necessary to explain the detailed dynamics of relatively low mass groups of galaxies and systems smaller. This is expected for sterile neutrino dark matter because it would have a free streaming length greater significantly larger than a typical galaxy (∼50kpc) for the Milky Way. However, just as numerical simulations of clusters of cold dark matter were necessary to show that the CDM halos are a poor match to observed galaxies (de Blok & McGaugh 1998; McGaugh & de Blok 1998; Gnedin & Zhao 2002; Gentile et al. 2004; Gilmore et al. 2007), the equilibrium distribution of the sterile neutrino DM must be checked to be consistent with groups and clusters of galaxies (see Sanders 2007).

On the other hand, the three active neutrinos should probably have masses well below 0.5eV. Otherwise it will become difficult to match the CMB power spectrum because the angular scale of the peaks prefers \( \Omega_{\nu}h^2 = 0.117 \) while \( \Omega_{\nu} \propto m_{\nu} \). Increasing the mass of another neutrino reduces the mass of the sterile neutrino and the amplitude of the third peak of the CMB diminishes due to the rapidly decreasing maximum density \( \rho_{v,\text{max}} \propto m_{\nu}^3 \).

Certain analyses of neutrino mixing experiments seem to require an additional, sterile neutrino with a mass in the range \( 4eV < m_{\nu_s} < 18eV \). Here I took the ansatz that there is a fourth, sterile neutrino of 11eV mass and that MOND effects are not important at cosmological scales. I showed that its contribution to the dynamics of galaxies would be negligible, but that it could solve all problems MOND has with the dynamics of clusters of galaxies and it can match the angular power spectrum of the CMB. The matter power spectrum needs to be recalculated because MOND gravity is crucial to the formation of these smaller structures and because of the increased dominance of baryons at these scales over DM, hydrodynamics cannot be avoided as in CDM simulations. If experiments can indeed pinpoint the existence of a sterile neutrino with mass ∼11eV this would be a significant advance for the Modified Newtonian Dynamics.

Even if collider experiments detect a CDM candidate with mass of 300GeV, this will give us virtually no information about the cosmological abundance and therefore brings us no closer to solving the dark matter problem. The great thing about sterile neutrinos is that if we can find the mass from laboratory experiments then this effectively fixes the cosmological abundance AND the contribution the neutrinos can make to clusters of galaxies can be strictly constrained.
Henceforth, it would be possible to run structure formation simulations in MOND with all the ingredients.

4 ACKNOWLEDGMENTS

GWA’s research was supported by an STFC travel grant and an STFC studentship.

REFERENCES

Aguilar A., Auerbach L. B., Burman R. L., Caldwell D. O., Church E. D., Cochran A. K., Donahue J. B., Fazely A., 2001, Phys. Rev. D, 64, 112007
Ahmad Q. R., Allen R. C., Andersen T. C., Anglin J. D., Bühler G., Barton J. C., Beier E. W., Bercovitch M., 2001, Physical Review Letters, 87, 071301
Angus G. W., 2008, MNRAS, 387, 1481
Angus G. W., Famaey B., Buote D. A., 2008, MNRAS, 387, 1470
Angus G. W., Famaey B., Tiret O., Combes F., Zhao H. S., 2007, ApJ, 654, L13
Ashie Y., Hosaksa J., Ishihara K., Itow Y., Kameda J., Koshio Y., Minamino A., Mitsuda C., 2004, Physical Review Letters, 93, 101801
Bekenstein J., 2006, Contemporary Physics, 47, 387
Bekenstein J. D., 2004, Phys. Rev. D, 64, 112007
Boesgaard A. M., Steigman G., 1985, ARAA, 23, 319
Boesgaard A. M., Auerbach L. B., Burman R. L., Caldwell D. O., Aguilar A., 2002, MNRAS, 331, 909
Boehm G., Barton J. C., Beier E. W., Bercovitch M., 2001, Phys. Rev. D, 64, 112007
Bournaud F., Duc P.-A., Brinks E., Boquien M., Amram P., Lisenfeld U., Keribalski B. S., Walter F., Charmandaris V., 2007, Science, 316, 1166
Bregman J. N., 2007, ARAA, 45, 221
Burles S., Nollett K. M., Turner M. S., 2001, ApJ, 552, L1
Clowe D., Bradaˇ c M., Gonzalez A. H., Markevitch M., Randall S. W., Jones C., Zaritsky D., 2006, ApJ, 648, L109
de Blok W. J. G., McGaugh S. S., 1998, ApJ, 508, 132
Diaferio A., 2008, ArXiv e-prints, 802
Dodelson S., Melchiorri A., Slosar A., 2006, Physical Review Letters, 97, 041301
Dunkley J., Komatsu E., Nolta M. R., Spergel D. N., Larson D., Hinshaw G., Page L., Bennett C. L., Gold B., Jarosik N., Weiland J. L., Halpern M., Hill R. S., Kogut A., Limon M., Meyer S. S., Tucker G. S., Wollack E., Wright E. L., 2008, ArXiv e-prints, 803
Fabian A. C., Johnstone R. M., Daines S. J., 1994, MNRAS, 271, 737
Famaey B., Binney J., 2005, MNRAS, 363, 603
Gentile G., Famaey B., Combes F., Kroupa P., Zhao H. S., Tiret O., 2007, Astron. Astrophys., 472, L25
Gentile G., Salucci P., Klein U., Vergani D., Kalberla P., 2004, MNRAS, 351, 903
Gentile G., Zhao H. S., Famaey B., 2008, MNRAS, 385, L68
Gilmore G., Wilkinson M., Kleyna J., Koch A., Evans W., Wyse R. F. G., Grebel E. K., 2007, Nuclear Physics B Proceedings Supplements, 173, 15
Giunti C., Laveder M., 2007, ArXiv e-prints, 707
Gnedin O. Y., Zhao H., 2002, MNRAS, 333, 299
Klypin A., Kravtsov A. V., Valenzuela O., Prada F., 1999, ApJ, 522, 82
Knebe A., Gibson B. K., 2004, MNRAS, 347, 1055
Kraus C., Bornshein B., Bornshein L., Bonn J., Flatt B., Kovalik A., Ostrick B., Otten E. W., Schall J. P., Thummler T., Weinheimer C., 2005, European Physical Journal C, 40, 447
Lewis A., Challinor A., Lasenby A., 2000, Astrophys. J., 538, 473
Maltoni M., Schwetz T., 2007, Phys. Rev. D, 76, 093005
McGaugh S. S., 2008, ArXiv e-prints, 804
McGaugh S. S., 2004, ApJ, 611, 26
McGaugh S. S., 2005a, Physical Review Letters, 95, 171302
McGaugh S. S., 2005b, ApJ, 632, 859
McGaugh S. S., de Blok W. J. G., 1998, ApJ, 499, 66
McGaugh S. S., de Blok W. J. G., Schombert J. M., Kuzio de Naray R., Kim J. H., 2007, ApJ, 659, 149
McGaugh S. S., Schombert J. M., Bothun G. D., de Blok W. J. G., 2000, ApJ, 533, L99
Milgrom M., 1983, ApJ, 270, 365
Milgrom M., 1995, ApJ, 455, 439
Milgrom M., 2002, ApJ, 577, L75
Milgrom M., 2007a, ArXiv e-prints, 712
Milgrom M., 2007b, ApJ, 667, L45
Milgrom M., 2008, ArXiv e-prints, 801
Milgrom M., Sanders R. H., 2003, ApJ, 599, L25
Milgrom M., Sanders R. H., 2005, MNRAS, 357, 45
Milgrom M., Sanders R. H., 2007, ApJ, 658, L17
Moore B., Ghigna S., Governato F., Lake G., Quinn T., Stadel J., Tozzi P., 1999, ApJ, 524, L19
Nusser A., 2002, MNRAS, 331, 909
O'Sullivan E., Sanders A. J. R., Ponman T. J., 2007, MNRAS, 380, 1409
Perlmutter S., Aldering G., Goldhaber G., Knop R. A., Nugent P., Castro P. G., Deustua S., The Supernova Cosmology Project 1999, ApJ, 517, 565
Pointecouteau E., Silk J., 2005, MNRAS, 364, 654
Reichardt C. L., Ade P. A. R., Bock J. J., Bond J. R., Brevik J. A., Contaldi C. R., Daub M. D., Dempsey J. T., Goldstein J. H., Holzapfel W. L., Kuo C. L., Lange A. E., Lueker M., Newcomb M., Peterson J. B., Ruhl J., Runyan M. C., Staniszewski Z.., 2008, High resolution CMB power spectrum from the complete ACBAR data set
Romanowsky A. J., Douglas N. G., Arnaboldi M., Kuijken K., Merrifield M. R., Napolitano N. R., Capaccioli M., Freeman K. C., 2003, Science, 301, 1696
Sanders R. H., 2003, MNRAS, 342, 901
Sanders R. H., 2005, MNRAS, 363, 459
Sanders R. H., 2007, MNRAS, 380, 331
Sanders R. H., 2008, MNRAS, 386, 1588
Sanders R. H., McGaugh S. S., 2002, ARAA, 40, 263
Sanders R. H., Noordermeer E., 2007, MNRAS, 379, 702
Schmidt B. P., Suntzeff N. B., Phillips M. M., Schommer R. A., Clocchiatti A., Kirshner R. P., Garnavich P., Challis P., 1998, ApJ, 507, 46
Seljak U., Makarov A., McDonald P., Trac H., 2006, Physical Review Letters, 97, 191303
Silk J., 2007, in Papantonopoulos L., ed., The Invisible Universe: Dark Matter and Dark Energy Vol. 720 of Lecture Notes in Physics, Berlin Springer Verlag, Galaxy Formation and Dark Matter, pp 101–+ Skordis C., Mota D. F., Ferreira P. G., Boehm C., 2006,
Physical Review Letters, 96, 011301
Tegmark M., Blanton M. R., Strauss M. A., Hoyle F.,
Schlegel D., Scoccimarro R., Vogeley M. S., Weinberg
D. H., Zehavi I., Berlind A., Budavari T., Connolly A.,
Eisenstein D. J., Finkbeiner D., 2004, ApJ, 606, 702
Tremaine S., Gunn J. E., 1979, Physical Review Letters,
42, 407
White M., Scott D., Silk J., 1994, ARAA, 32, 319
Zlosnik T. G., Ferreira P. G., Starkman G. D., 2006, Phys.
Rev. D, 74, 044037
Zlosnik T. G., Ferreira P. G., Starkman G. D., 2007a, Phys.
Rev. D, 75, 044017
Zlosnik T. G., Ferreira P. G., Starkman G. D., 2007b,
ArXiv e-prints, 711