Are observations of the galaxy cluster Abell 1689 consistent with a neutrino dark matter scenario?

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ABSTRACT
Recent weak and strong lensing data of the galaxy cluster A1689 are modelled by dark fermions that are quantum degenerate within some core. The gas density, deduced from X-ray observations up to 1 Mpc and obeying a cored power law, is taken as input, while the galaxy mass density is modelled. An additional dark matter tail may arise from cold or warm dark matter, axions or non-degenerate neutrinos. The fit yields that the fermions are degenerate within a 430 kpc radius. The fermion mass is a few eV and the best case involves 3 active plus 3 sterile neutrinos of equal mass, for which we deduce 1.51 ± 0.04 eV. The eV mass range will be tested in the KATRIN experiment.

1 INTRODUCTION

The Lambda cold dark matter (ΛCDM) paradigm has been embraced after it was realized that the most natural dark matter candidate, the neutrino, seems incapable to explain the formation of large scale structures like galaxies and galaxy clusters. ΛCDM has been successful in describing the cosmic microwave background and large scale structures. It is adaptable to many other situations, though often not predictive. However, despite decades and dozens of searches, the CDM particle has not been established (Aprile et al 2012), also not at the Large Hadron Collider (Caron 2011), so one may wish to keep an open eye at other scenarios.

It has been put forward by Gibson (1996) that in the early Universe the role of turbulence and viscosity in the protoplasma and after the transition to neutral gas is more important than commonly assumed. Gravitational hydrodynamics alone is capable to explain large scale structure formation without CDM trigger, in a three-step top-down scenario, see also Nieuwenhuizen et al. (2009). First, the plasma undergoes a viscous fragmentation at redshift $z = 5100$, creating voids of 40 Mpc comoving size. After the decoupling of photons the gas condenses in Jeans clumps of 600,000 solar masses and they in their turn fragment in 200 billion micro brown dwarfs of Earth weight. This picture explains a wealth of observations (Schild 1996, Nieuwenhuizen et al 2009, 2012) and motivates to re-open our minds for the possibility of free streaming dark matter, like neutrino hot DM.

The violent relaxation mechanism explains the success of isothermal models in gravitation (Lynden Bell 1967), so it is natural to consider isothermal dark matter fermions. Cowsik & McClelland (1973) model the DM of the Coma cluster as an isothermal sphere of neutrinos, which yields a mass of $\approx 2$ eV. Treumann et al (2000) consider 2 eV neutrinos next to CDM and X-ray gas, all isothermal, and derive density profiles for, e.g., the Coma cluster. Nieuwenhuizen (2009) (N09) applies an isothermal fermion model for a single type of dark matter, cold or not, in addition to the galaxies and the X-ray gas in galaxy clusters. A fit to lensing data of the Abell 1689 cluster works well and yields as best case the neutrino with mass 1.45 eV, below the empirical upperbound of 2.0 eV (Amsler et al 2008). Active neutrinos (left-handed $\nu$, right-handed $\bar{\nu}$) have density $10^2$ cm$^{-3}$ in each of the 3 families (Weinberg 2008), so with 1.5 eV mass they constitute about 10% of the critical mass density. Some 20% can arise if the sterile partners (right-handed $\nu$, left-handed $\bar{\nu}$) have also been created in the early Universe (N09).

As these challenging results from the physics literature have hardly been noticed in the astrophysics community, it is imminent to test them further. Here we shall apply the isothermal model for dark fermions to new data for the gas in A1689 from X-ray observations and recent data for strong lensing (SL) and weak lensing (WL). We also compare to the fit of an NFW profile (Navarro, Frenk and White 1998).

2 DESCRIPTION OF THE DATA

For the strong lensing analysis we refer to Limousin et al (2007) who inferred the 2D mass distribution of A1689 by Hubble Advanced Camera for Surveys (ACS) observations and ground based spectroscopy. They implement a parametric analysis via the Lenstool package (Kneib et al 1996), and determine two large-scale dark matter clumps, one associated with the center of the cluster and the other with a north-eastern substructure. The north-eastern sector of SL and X-ray data is masked out in order to avoid the contribution from this secondary substructure. The 2D mass distribution is rebinned into circular annuli, in order to measure the projected mass profile $\Sigma(r)$ and the covariance matrix $C$ among all the measurements of $\Sigma(r)$.

For the X-ray analysis we refer to Morandi et al (2010), who analyze 2 Chandra X-ray observations with a total exposure time of 150 ks. The vignetting-corrected brightness...
image is extracted from the events 2 files in the energy range (0.5–5.0 keV). The gas density profile is recovered in a non-parametric way by rebinning the surface brightness into circular annuli and via spherical deprojection (Morandi et al. 2007). In order to infer the observed temperature profile, they implement the spectral analysis by extracting the source spectra from circular annuli around the centroid of the surface brightness. Once they assumed an absorbed MEKAL model, the spectral fit is performed in the energy range 0.6–7 keV by fixing the redshift at $z_{A1689} = 0.183$, and the photoelectric absorption at the galactic value. Background spectra, which are free from source emissions, are extracted from regions of the same exposure.

The deprojected temperature is determined through spherical deprojection of the projected temperature profile inferred in the spectral analysis (Morandi et al. 2007).

We take WL data out to 3 Mpc from Fig. 16 of Umetsu and Broadhurst (2008), to be denoted as UB. These authors derive a projected 2D mass map of A1689 by combining lens magnification with distortion of red background galaxies in deep Subaru images. To derive the critical surface density

$$\Sigma_c = \frac{c^2}{4\pi G D_s D_d}$$

(1)

with $D_s$ the distance to the source galaxies, $D_d$ to the deflecting cluster and $D_{ds}$ their mutual distance. UB employ ($D_{ds}/D_s$) = 0.693±0.028 gr cm$^{-2}$ for $h_0 = 1$, $\Omega_M = 0.25$, $\Omega_{\Lambda} = 0.75$ with $z = 0.68$ for the average redshift of the lensed galaxies in the WL analysis.

3 DEGENERATE FERMIONS

We investigate the role of thermal fermions with mass $m$, degeneracy $\bar{g}$, chemical potential $m\nu$ at temperature $T_\nu = m\sigma^2_\nu$, located in a gravitational potential $\varphi(r)$

$$\rho_\nu(r) = \int \frac{d^3p}{(2\pi\hbar)^3} \exp\left[\frac{-\bar{g}m}{2m + m\varphi(r) - m\nu}/T_\nu\right] + 1.$$  

(2)

It is equal to $\bar{g}m\lambda_T^{-3} L_{3/2} \left[\left(\mu - \varphi(r)/\sigma^2_\nu\right)\right]$, with thermal length $\lambda_T = \hbar\sqrt{2/\bar{g}m}$ and a polylogarithmic function $L_{3/2}(x) = \sum_{k=1}^{\infty} k^{-3/2} \left(-1\right)^{k-1} e^{-x} \rightarrow 4x^{-3/2}/3\sqrt{\pi}$ ($x \rightarrow \infty$).

To test the idea we assume spherical symmetry. The density of free electrons is obtained by us in the interval 10 kpc < $r$ < 1 Mpc and presented in Fig. 1. It fits well to a cored power law, better than to a $\beta$-profile. We thus employ

$$n_e(r) = \frac{n^0_e \left(R^0_e\right)^{\alpha_e}}{(r + R^0_e)^{\alpha_e}}, \quad \alpha_e = 2.38 \pm 0.05,$$

(3)

with $n^0_e = 0.073 \pm 0.008$ cm$^{-3}$ and $R^0_e = 124 \pm 7$ kpc. For the 56 data points the fit is good, $\chi^2/\nu = 43.9/53 = 0.827$.

Fixing the H-He ratio at the cosmic value and the metallicity $Z = 0.3$ retrieved by employing the solar abundance ratios from Grevesse & Sauval (1998), we have an average molecular mass $\overline{m} = 0.60 m_N$, with $m_N$ the nucleon mass, and a gas particle density $n_g = 1.852 n_e$, so that

$$\rho_g = \overline{m} n_g = \frac{\rho^0_g \left(R^0_g\right)^{\alpha_g}}{(r + R^0_g)^{\alpha_g}}, \quad \rho_{g0} = 1.11 m_N n^0_e.$$  

(4)

If this would hold beyond the observed range, the gas mass would diverge as $r^{3-\alpha}$. To have only a logarithmic divergence, we model the gas tail by a Burkert (1995) profile,

$$\rho_g(r > r_1) = \frac{\rho_{g0} \left(R^1_g\right)^3}{(r + R^1_g)^3}, \quad r_1 = 1 \text{ Mpc}.$$  

(5)

In the central case of Eq. (5): $\rho^1_g = 0.0557 \rho_{g0}$, $R^1_g = 587$ kpc. The galaxy mass density is dominated by the central galaxy (eg). We model it as in Limousin et al (2007), viz.

$$\rho_G(r) = \frac{\rho^0_G R^2_G r^2}{(r^2 + R^2_G)^2}, \quad \rho^0_G = \frac{\sigma^2_G \left(R + R^0_G\right)}{2\pi G R^2_G R^0_G}.$$  

(6)

Finally, we allow a dark matter component $\rho_{dm}(r)$ of the form (c) with parameters $\rho^0_{dm}$ and $R_{dm}$. It is present at all $r$, but mainly relevant in the outskirts. It could stem from cold dark or warm dark matter, axions or from non-degenerate neutrinos. The Poisson equation then reads

$$\varphi''(r) + \frac{2}{r} \varphi'(r) = 4\pi G \rho_c(r), \quad \rho = \rho_G + \rho_\nu + \rho_{dm}.$$  

(7)

For the solution it is advantageous to split off the contributions from $\rho_G$, $\rho_\nu$ and $\rho_{dm}$, that can be treated analytically.

From strong lensing one determines the 2D mass density $\Sigma(r) = \int_{-\infty}^{\infty} dz \rho \left(\sqrt{r^2 + z^2}\right)$. Eq. (5) implies that

$$\Sigma(r) = \frac{1}{2\pi G} \int_0^\infty ds \frac{\cosh 2s}{\sinh^2 s} \left[\varphi'(r \cosh s) - \frac{\varphi'(r)}{\cosh^2 s}\right].$$  

(8)

Averaging it over a disk yields $\Sigma(r) = 2\pi^{-2} \int_0^\infty dr' r' \Sigma(r') = M_2(r)/\pi r^2$, which is equal to (Nieuwenhuizen 2009)

$$\Sigma(r) = \frac{1}{2\pi G} \int_0^\infty ds \varphi'(r \cosh s).$$  

(9)

In weak lensing one determines the shear, which is related to $\Sigma$ and $\Sigma$ as (see Eq. 7 of Umetsu et al. 2011)

$$\gamma(r) = \frac{\Sigma(r) - \Sigma(r)}{\Sigma_{\infty} - \Sigma(r)}.$$  

(10)

We evaluate $\chi^2_{WL} = \sum_i |g_i(r_i) - g^0_{i11} f_{i,1}^2|$, in which we include also the data with $r_i < 400$ kpc, where both $\Sigma$'s in
\[ R \] dispersion \( \sigma \)

Finally, our galaxy cut radius \( R \) terms, as well as to consider working in the Tikhonov regularization, adding a diagonal term \( \sigma^2 \) for error bars, 1 kpc. If we allow them to vary in the fit, they attain large \( \sigma \) values. We adopt the typical value from the diagonal elements, \( \sigma_{SL} = (\sum g_{ij}/12)^{1/2} = 0.0362 \) gr cm\(^{-2} \). Next we minimize \( \chi^2 = \chi_{SL}^2 + \chi_{WL}^2 \) with the FindMinimum routine of Mathematica, speeded up by first searching at \( \sigma = 0 \).

The best fit parameters with linear regression error bars are

\[
\bar{g} \left( \frac{m_{\nu}^2 \sigma^2}{12} \right)^{1/4} = 5.17 \pm 0.58, \quad \mu = (33.6 \pm 1.4) \sigma_{500}^2, \quad (11) \\
M_{\nu} = (3.62 \pm 0.30) \times 10^7 M_{\odot}, \quad R_{\nu} = 7.9 \pm 1.1 \text{ kpc}, \\
\rho_{\nu, dm}^0 = (0.0186 \pm 0.0044) \frac{m_{\nu}}{\text{cm}^3},
\]

where \( \sigma_{500} = 500 \text{ km s}^{-1} \). These values are taken at the optimal parameters \( \sigma = 0.96 \sigma_{SO9} \), \( R_{\nu} = 564 \text{ kpc}, \) \( R_{\nu} = 129.5 \) kpc. If we allow them to vary in the fit, they attain large error bars, 1.90 \( \sigma_{500} \), 500 kpc, and 260 kpc, respectively, and induce larger errors in (11). However, since the neutrino temperature and velocity dispersion are ill constrained, we may as well consider to work in the \( T_\nu = \sigma = 0 \) limit, or in our optimal case. Next, the scale of the DM tail \( R_{dm} = 0.96 R_{\nu} \) basically overlaps with the scale \( R_{\nu} \) on which the gas decays, as is expected, so there is no reason to consider other values. Finally, our galaxy cut radius \( R_{\nu} \approx R_{\nu}^o \) coincides with the 128.5 \pm 37.0 kpc of Limousin et al (2007), so their analysis constrains it better. Still, their core radius \( R_{\nu, dm} \approx 5.2 \pm 1 \) kpc is somewhat smaller than ours, while their central velocity dispersion \( \sigma_{500} = 370.5 \pm 10.3 \text{ km s}^{-1} \) is well below our \( \sigma_{500} = \sqrt{GM_{\rho}/\pi R_{\nu}} = 619 \pm 25 \text{ km s}^{-1} \), and hence their central mass \( M_{\rho} = 8.8 \times 10^{12} M_{\odot} \) lies below ours, see (11).

The SL fit in Fig. 2 matches the data well, with \( \chi_{SL}^2 = 5.88 \) only, despite the small error bars. The fast decline beyond 400 kpc is absent in the stacking of the SL+WL data with those of 3 other heavy clusters (Umetsu et al 2011). The WL data in Fig. 3 are well matched, also in the regime \( r < 400 \) kpc, where the \( \Sigma \) in the denominator of (11) is relevant, and for \( r > 1 \) Mpc with modelled gas density. The fit has \( \chi_{WL}^2 = 6.77 \) only. For our 12 + 11 data points and 5 parameters we thus have \( \nu = 18 \) and \( \chi^2/\nu = 0.68; \) below 1, the fit may even be “too good”. In Fig. 3 we also show the best fit without DM tail, it has \( \chi^2/\nu = 1.89 \).

The fermion mass emerges in the eV range, likely to be neutrinos. Considering 3 active + 3 sterile neutrinos of equal mass, they have \( \bar{g} \) = 12 degrees of freedom and a mass

\[
m = 1.51 \pm 0.04 \text{ eV}, \quad (12)
\]

which overlaps within 2\( \sigma \) with the 1.45 \pm 0.03 eV of N09.

The average mass density is equal to 200 times the critical density at the cluster redshift for \( r_{200} = 1.98 \) Mpc, where \( M_{200} = (14.6 \pm 1.5) \times 10^{14} M_{\odot} \), of which 28.3 \pm 5.5% is in degenerate neutrinos, 53.5 \pm 7.3% in dark matter, 15.8 \pm 1.6% in gas and 2.4 \pm 0.3% in Galaxies. This can be compared with the estimate \( M_{200} = 14.1 \times 10^{14} M_{\odot} \) (Bardeau, 2005) and (13 \pm 4) \times 10^{14} M_{\odot} (Lemze et al, 2009). At 875 kpc the enclosed mass \( (8.3 \pm 0.4) \times 10^{14} M_{\odot} \) compares well with the Riemen-Sorensen et al (2009) lensing value \( (8.6 \pm 3.0) \times 10^{14} M_{\odot} \). The resulting 18.2 \pm 1.9% of matter in baryons is near the cosmic fraction 4.4/4.4 + 21.4) = 17.4%, as expected. Leaving out the DM tail would imply a too large (~ 26%) baryon fraction, and the larger \( \chi^2/\nu = 1.89 \).

In Fig. 4 we plot the separate components of the mass density. The galaxy density crosses the neutrino density at 41 kpc. The “quantum-to-classical” transition \( E_{\nu}/(\mu - \varphi(r))/\sigma_{\nu}^2 \) = 1 occurs at \( r_{\nu} = 431 \pm 1 \text{ kpc} \); the neutrinos are quantum degenerate for \( r < r_{\nu} \). Due to exclusion principle, their density has no central cusp.

The gas temperature data, presented in Fig. 5, can be viewed in the light of an hydrostatic equilibrium (HE). With pressure \( p_{\varphi} = n_{\varphi} T_{\varphi}, \) the HE condition \( \rho_{\varphi} = -p_{\varphi} \) implies

\[
k_B T_{\varphi}(r) = \frac{\pi}{\rho_{\varphi}(r)} \int_r^\infty dw \rho_{\varphi}(w) \varphi(w). \quad (13)
\]
4 NFW MODELLING OF THE DATA

Cold dark matter can be modelled by the NFW profile, which involves the critical mass density $\rho_c = 3H_0^2/8\pi G$,

$$\rho_{\text{NFW}}(r) = \frac{200c^3\rho_c}{3[\log(1+c) - c/(1+c)]} \frac{r_s^3}{r(r+r_s)^2}$$

The galaxy and gas densities should be added to it. However, a competition between the central peaks of the NFW and of the galaxies yields bad fits, $\chi^2 \approx 700$, for reasonable values of $R_{\text{vir}}$, $R_{\text{g}}$, and $M_{\text{g}}$. Hence we continue with describing all matter by NFW. $\Sigma$ and $\Sigma_{\text{HE}}$ thus follow from (14) with $\phi' = GM(r)/r^2$. The fit to SL alone yields $\chi^2_{\text{SL}} = 6.5$, $r_s = 626$ kpc and $c_{200} = 4.4$, while the fit to WL alone yields $\chi^2_{\text{WL}} = 6.4$, $r_s = 179$ kpc and $c_{200} = 11.0$, the latter in accord with UB. These known discrepancies (see, e.g., UB; Lemze et al 2009) cast a shadow on the combination of SL + WL. Indeed, this brings a dominance by the small SL errors, viz. $\chi^2_{\text{SL}} = 19.8$, $\chi^2_{\text{WL}} = 26.1$, $r_s = 433$ kpc and $c_{200} = 5.48$. Its goodness-of-fit is only 0.0013, while its $\chi^2/\nu = 45.8/19 = 2.18$ exceeds our previous 0.68 by a factor 3.

The NFW temperature prediction is obtained by inserting $\phi' = GM(r)/r^2$ in (13). The result is depicted in Fig. 5. It exceeds the measured temperatures even at 1000 kpc, so it is neither a reasonable fit, showing once more that the HE problem is not solved within NFW modelling.

5 DISCUSSION

This Letter presents new data for the electron density and temperature in the X-ray gas of A1689. Combined with strong lensing data of Limousin et al (2007) and weak lensing data of Umetsu and Broadhurst (UB, 2008), this allows to test the isothermal fermion model of Nieuwenhuizen (2009), upon adding a DM tail. Based on partly old data, it achieved to model the cluster dark matter as isothermal fermions. The model could easily have been inadequate at the new level of information, but it appears that the previous finding is mainly reproduced. Both the strong and weak lensing data are well described.

On the other hand, the NFW profile of cold dark matter, which performs well for SL and WL separately, appears to perform less well when both data sets are combined. This contrasts to UB, who used older SL data. Not only is $\chi^2/\nu$ about 3 times larger than for neutrinos, the quality of the NFW fit is also lower due to systematic deviations for WL.

The reason why isothermal neutrinos work well may lie in the fact that their temperature-to-chemical-potential ratio is small, $T_e/\mu = \sigma_\nu^{\mu}/\mu = 0.027$, so that essentially one considers quantum degenerate $T_e = 0$ neutrinos, a “neutrino star”, of 0.86 Mpc in diameter.

In the present work the gas density of A1689 is taken from observations up to 1 Mpc. After general indications for this possibility (Kull et al. 1996), it was predicted that in A1689 the $\nu$DM is more localised in the centre than the gas (Nieuwenhuizen 2009). This partial segregation between DM and gas is reminiscent of the situation in the bullet cluster. It is confirmed in the present approach, see Fig. 4, where the neutrino core is more localised than the gas and DM.

Observations of galaxy clusters generally suggest them to contain fewer baryons (gas plus stars) than the cosmic
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fraction. This “missing baryon” puzzle is particularly relevant for massive clusters, like A1689, as they are expected to represent the cosmic matter content (baryons and dark matter). It has recently been solved. For a relatively large sample of groups and clusters of galaxies the gas fraction has been measured within $r_{500}$ and it is concluded that the “missing” baryons are present as X-ray gas located in the outskirts of the clusters (Rasheed et al 2011). Our gas data have allowed an extrapolation which confirms this picture.

Other support for the neutrino picture may come from the “cosmic train wreck” galaxy cluster Abell 520, where a lot of DM is located in the centre with the X-ray gas, both separated from the galaxies that are out of the center (Jee et al 2012, Clowe et al 2012). While this is hard to explain within LCDM, cores made up of quantum degenerate matter that undergo a central collision may coalesce in the center.

For neutrinos all $g = 12$ left- and righthanded states are available in the cluster. Alternatively, this hints at 3 + 3 families of nearly equally massive Majorana neutrinos. This implies a mass $m = 1.51 \pm 0.04\,eV$ and a cosmic DM fraction $\Omega = 9.8\%$ for active neutrinos, and if the sterile ones with this mass are also generated in the early Universe, $\Omega = 19.5\%$. This may be achieved by a Majorana mass matrix with meV entries, next to a Dirac matrix with the $\sim 1.5\,eV$ mass eigenvalues (Nieuwenhuizen 2009). It will also produce neutrino-less double $\beta$-decay, with $m_{\nu_e} \sim 1\,meV$.

In the early Universe neutrinos maintain the quasi-relativistic Fermi-Dirac distribution $[\exp(pc/k_B T_e) + 1]^{-1}$ with $T_e(z)$, until the neutrinos condense (“$\nu e$”) on the baryons in the galaxy cluster (Nieuwenhuizen 2009). This happens when the “Hubble force” $H(p_{\nu_e}) = 3.151\,H k_B T_e / c$ equals Newton’s $G m_\nu (M_{H_{200}}^\odot + M_{gas}^\odot) / r_{H_{200}}^2$. The corresponding redshift is $z_{\nu e} \sim 7$, below the estimate of Nieuwenhuizen (2009). The neutrino mass contained at $z_{\nu e}$, $\sim 2.65\,Mpc$ can be estimated from the cosmic DM density, $(4\pi / 3) 0.2 \rho_c (z_{\nu e} + 1)^3 r_{H_{200}}^3 = 11 10^{14} M_\odot$c, near the $M_{gas}^\odot + M_{H_{200}}^\odot = (4.1 + 7.8) 10^{14} M_\odot$c captured according to our model. This supports the possibility that the DM tail consists of neutrinos as well. The $T_e = 45\,mK$ in A1689 lies below the would-be free streaming momentum temperature of 1.95 K but, as it should, above the related 0.96\,meV kinetic temperature (Nieuwenhuizen 2009).

Gravitational hydrodynamics is a top-down scenario where cosmic voids and proto-clusters are formed early on in the plasma and it is consistent with neutrino hot dark matter (Nieuwenhuizen, Gibson & Schild 2009). Neutrinos would be localised near the centre of the Virgo supercluster to which the Local Group belongs, and hardly occur in the Galaxy. Galactic dark matter would be baryonic, constituted by “missing” baryons, for which direct and indirect indications exist (Nieuwenhuizen et al 2010, 2012).

The mass of the electron antineutrino will be searched in the 2015 KATRIN experiment from the present upper bound of $2\,eV$ down to 0.2\,eV. The uncertainty is $\Delta m^2_{\nu_e \mathrm{sys}} = 0.017\,eV^2$ (Weinheimer 2009). If a mass near 1.5\,eV exists, this implies $\Delta m_{\nu_e \mathrm{sys}} = 6\,meV$ or $\Delta m_{\nu_e \mathrm{sys}} / m_{\nu_e} = 0.4\%$, well below our 2.5% statistical inaccuracy. The average neutrino mass is much larger than the oscillations, so they play no role: the solar value $\Delta m_{\nu_e}^2 = (2.43 \pm 0.13) 10^{-3}\,eV^2$ implies $\Delta m_{\nu_e}^2 / m_{\nu_e} = 0.048\%$.

If in KATRIN a mass of 1 eV is indeed observed, this will rule out the LCDM picture. Its supposed exclusion of neutrinos as the dominant non-baryonic dark matter can then be traced back to the assumption of CDM. Structure formation then has to start out nonlinearly and be top-down, welcoming very early galaxies and large scale structures like the axis of evil (Nieuwenhuizen et al 2010).

In conclusion, we model the strong and weak lensing of the galaxy cluster A1689. The NFW profile performs moderately for the combined data sets. A central core of quantum degenerate neutrinos combined with a dark matter tail performs well and confines the neutrino mass. This dark matter tail may be composed of the usual suspects, cold or warm dark matter, axions, or ... non-degenerate neutrinos. To explain the gas temperature remains an outstanding problem.

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