COLD + HOT DARK MATTER COSMOLOGY

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Abstract

The Cold + Hot Dark Matter (CHDM) cosmological model appears to require about 5 eV of neutrino mass, in order to produce early enough galaxy formation. These neutrinos would constitute hot dark matter accounting for a fraction $\Omega_\nu = 0.2(0.5/h)^2$ of critical density, where $h \equiv H_0/(100 \text{ km s}^{-1} \text{ Mpc}^{-1})$ is the Hubble parameter. Recent experimental data suggests that this neutrino mass may be divided between two or more species of neutrinos. Here we consider the consequences of such neutrino masses for the formation of galaxies and large scale structure in the universe in cosmological models that are spatially flat and in which most of the dark matter is cold. The linear calculations and N-body simulations that we report here indicate that an $\Omega = 1$ CHDM cosmological model with two neutrinos each of mass $\approx$ 2.4 eV (we will call this model Cν^2DM) agrees well with all available observations. However, we find that this is true only if the Hubble parameter $h \approx 0.5$. We also consider Cold Dark Matter (CDM) models with a cosmological constant Λ and show that evidence for hot dark matter raises serious difficulties for low-Ω ΛCDM models.

1 Introduction

The standard Cold Dark Matter (CDM) cosmological model has too much power on small scales when normalized to COBE. Because of the large velocities of the light neutrinos that make up the hot component of Cold + Hot Dark Matter (CHDM), these neutrinos cluster less on small scales than the cold component of CHDM, thereby producing a lower abundance of clusters and smaller pairwise galaxy velocities in better agreement with observations than standard CDM with the same large-scale normalization. Predictions of a CHDM model with a single massive neutrino species and $\Omega_\nu = 0.3$ (corresponding to $m_\nu \approx 7$ eV for Hubble parameter $h = 0.5$) have been shown [1, 2, 3] to agree well with observations, with the possible exception that galaxies may form too late to account for the observations of quasars and damped Lyα systems [4, 5] at high redshifts $z \gtrsim 3$ [6, 7]. The latter observations can be accommodated [8, 9] if the assumed neutrino mass in CHDM is lowered from ~ 7 eV to ~ 5 eV. Lowering the neutrino mass in CHDM also gives a better account of the Void

Probability Function [10] and of the properties of galaxy groups [3],[11]. With one ~ 5 /eV neutrino COBE-normalized CHDM probably overproduces clusters, as we show below, but this can be avoided if the neutrino mass is shared between two or three species of neutrinos.

As we explain in more detail in §2, current experimental hints regarding neutrino masses suggest that the net neutrino mass of ~ 5 eV required for CHDM is shared among two or three species of neutrinos. In particular, if the deficit of atmospheric ν_μ relative to ν_e is due to $\nu_\mu \to \nu_\tau$ oscillations, then the hot component must involve more than one species of neutrino, since because of the long baseline the ν_μ-ν_τ mass-squared difference must then be rather small, $\sim 10^{-2}$ eV^2. This is consistent with the possible detection of $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillations reported by LSND, which if valid requires neutrino mass in the range relevant for hot dark matter. The theory of r-process nucleosynthesis in type II supernovae that currently seems most promising imposes constraints on neutrino mass and mixing patterns, but an inverted neutrino mass hierarchy with ν_e heaviest meets these constraints.

We will first summarize the experimental hints of neutrino masses from the (a) solar and (b) atmospheric neutrino deficits and from (c) LSND. We also summarize recent work [12] showing that if we take seriously CHDM and all the hints (a-c) of neutrino mass, then the r-process nucleosynthesis constraint leads to an essentially unique pattern of neutrino masses and mixings. Then we will consider in more detail the consequences of such neutrino masses for the formation of galaxies and large scale structure in the universe for cosmological models in which $\Omega = 1$ (or $\Omega + \Omega_\Lambda = 1$, where $\Omega_\Lambda \equiv \Lambda/(3H_0^2)$) in which most of the dark matter is cold. We show that $\Omega_\nu = 0.2$ CHDM with the mass evenly shared between two neutrino species — Cν^2DM — agrees better with observations than the one-neutrino version, better indeed than any other variant of CDM that we have considered. We also discuss other variants of CDM, and show in particular that low-Ω ΛCDM is incompatible with light neutrinos with $m(\nu) \gtrsim 2$ eV. The material presented here is an updated version of that in Ref. [13]; among other things, we now use the latest COBE normalization (corresponding to $Q_{\mathrm{rms-PS}} = 20\,\mu$K) for the larger set of cosmological models that we consider.

2 Experimental data on neutrino masses

Evidence for a neutrino mass explanation of the solar ν_e deficit is now fairly convincing, since at least two of the three types of experiments have to be wrong to be compatible with some non-standard solar models [14]. If the solar ν_e deficit is due to MSW $\nu_e \to \nu_\mu$ or $\nu_e \to \nu_s$ neutrino oscillations in the sun, the mass-squared difference between either pair of particles is $\Delta m_{ei}^2 \equiv |m(\nu_e)^2 - m(\nu_i)^2| \approx 10^{-5}$ eV^2. (Here ν_s denotes a "sterile" neutrino, one that contributes negligibly to the width of the Z^o. An example is any right-handed neutrino, which would not participate in standard $SU(2) \times U(1)$ electroweak interactions.)

Similarly, evidence for a neutrino mass explanation of the deficit of ν_μ's relative to ν_e's in atmospheric secondary cosmic rays is also increasing, with compatible results from three experiments [15], and especially new information from Kamiokande [16]. The latter includes accelerator confirmation of the ability to separate ν_e and ν_μ events, as well as an independent higher energy data set giving not only a ν_μ/ν_e ratio agreeing with the lower energy data, but also a zenith-angle (hence source-to-detector) dependence compatible with $\nu_\mu \to \nu_e$ or $\nu_\mu \to \nu_\tau$ oscillations with $\Delta m_{\mu i}^2 \approx 10^{-2}$ eV^2. Since almost the entire region of $\Delta m_{\mu e}^2 - \sin^2 2\theta_{\mu e}$ allowed by the Kamiokande data is excluded by data from the Bugey and Krasnoyarsk reactor neutrino oscillation experiments, $\nu_\mu \to \nu_\tau$ oscillations are favored as an explanation of the atmospheric ν_μ deficit. Moreover, the absolute calculated ν_e and ν_μ fluxes — backed by measurements of μ fluxes —agree with ν_e data but show a ν_μ deficit [17]. (Because the mixing angle $\theta_{\mu i}$ must be large to account for the near 50% deficit of atmospheric ν_μ, $\nu_\mu \to \nu_s$ oscillation is disfavored because such large mixing would populate a fourth neutrino species in the early universe, contrary to Big Bang Nucleosynthesis constraints [18].)

The Liquid Scintillator Neutrino Detector (LSND) experiment at Los Alamos has detected an excess of 9 beam-on events of a type for which the most plausible interpretion appears to be $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillations, with a background of only $\lesssim 2.1 \pm 0.3$ events mimicking a $\bar{\nu}_e$, so the probability that the excess is a statistical fluke is $< 10^{-3}$ [20]. These events have both a positron track and a correlated γ-ray consistent with $\bar{\nu}_e + p \to e^+ + n$ followed by capture of the neutron by a proton in the mineral oil filling the LSND tank to form a deuteron. If the LSND events are interpreted as $\bar{\nu}_\mu \to \bar{\nu}_e$, the indicated mixing angle is $\sin^2 2\theta_{\mu e} \approx 3 \times 10^{-3}$. There are several ranges of mass-squared difference $\Delta m^2_{\mu e} \equiv |m(\nu_\mu)^2 - m(\nu_e)^2|$ which are compatible with the KARMEN [22] and BNL E776 [23] experiments, $\Delta m^2_{\mu e} \sim 2$, 6, and 10 eV^2, of which $\Delta m^2_{\mu e} \sim 6$ eV^2 appears to be favored, especially if the excess events LSND has detected of the $\nu_\mu \to \nu_e$ type are also considered [21]. If the ν_e mass is relatively small ($\lesssim 1$ eV, as indicated for Majorana neutrino mass from neutrinoless double beta decay experiments), then $\Delta m^2_{\mu e} \sim 6$ eV^2 implies that the ν_μ mass is $\sim 6^{1/2} \approx 2.4$ eV. This and the $\nu_\mu \to \nu_\tau$ explanation of the atmospheric ν_μ deficit then makes $m(\nu_\mu) \approx m(\nu_\tau) \approx 2.4$ eV. It is this scenario for the hot dark matter in a CHDM cosmology which we will show below gives predictions that appear to be in good agreement with astronomical observations.

However, a possibly disturbing consequence of taking all three hints of neutrino mass seriously is that the three incompatible Δm^2 require a minimum of *four* neutrino species, i.e. a sterile neutrino ν_s in addition to ν_e, ν_μ, and ν_τ [19, 12]. The LSND limit $\Delta m^2_{e\mu} > 0.2$ eV^2 implies that atmospheric ν_μ oscillations cannot be to ν_e so they must be $\nu_\mu \to \nu_\tau$; then MSW solar ν_e oscillations cannot be to ν_μ or ν_τ, so they must be $\nu_e \to \nu_s$.

An additional constraint that should perhaps be imposed on neutrino masses and mixings comes from r-process nucleosynthesis [24], which produces all the heavy chemical elements (e.g. gold). The favored site for this process is in a neutrino-heated "hot bubble" well above the neutron star remnant; this model produces the observed abundance of r-process nuclei without any *ad hoc* parameters or dependence on the messy details of the Type II supernova mechanism. However, matter-enhanced (MSW) neutrino oscillations $\nu_m u$ or $\nu_\tau \to \nu_e$ will lead to a hardening of the ν_e spectrum and too much neutron depletion via $\nu_e + n \to e^- + p$ for successful r-process nucleosynthesis for the LSND-suggested neutrino mass $\delta m^2_{e\mu} \approx 6$ eV^2 and $\sin^2 2\theta \approx 3 \times 10^{-3}$ — unless the mass of the ν_e is higher than that of ν_μ and ν_τ, so that no level crossing can occur. (Level crossing and MSW oscillation then will occur for the antineutrinos, but this appears to be consistent with the SN87A neutrino signal [25].) With the r-process constraint leading to an inverted neutrino mass spectrum, taken together with the previous three experimental hints of neutrino mass and the need to have about 5 eV of neutrino mass for CHDM cosmological models, the neutrino masses and mixings are determined essentially uniquely: $m(\nu_e) \approx 2.7$ eV and $m(\nu_\mu) \approx m(\nu_\tau) \approx 1.1$ eV [12]. While it is remarkable that there actually is a consistent solution, we should also keep in mind the liklihood that not all these hints are right. For purposes of the rest of this paper, we will consider CHDM with either one or two massive neutrinos; if the same total mass were shared by three rather than two neutrinos, the cosmological implications would be very similar.

3 Comparison of cosmological model predictions with observations

COBE observations [26] of fluctuations in the microwave background radiation provide an upper limit (since they include possible tensor gravity wave as well as scalar density wave contributions) on the normalization of the spectrum of density fluctuations in models of structure formation in the universe. When COBE normalization is used for the standard Cold Dark Matter (CDM) model [27] in a critical density ($\Omega = 1$) universe with a Zel'dovich primordial power spectrum ($P(k) = Ak^{n_p}$ with $n_p = 1$) as predicted by simple inflationary models, this fits large-scale data but produces too much structure on smaller scales.

We report (quasi-)linear estimates for CDM and CDM variants in the Table. All models in the Table are normalized to COBE [26, 28] except for the two models marked with an asterisk (*). The first two lines of numbers give our estimates of a variety of observational quantities and the uncertainties in them, from large to small scales. The bulk velocity at $r = 50\ h^{-1}$ Mpc is derived from the latest POTENT analysis [29]; the error includes the error from the analysis but not cosmic variance. However, similar constraints come from other data on large scales such as power spectra that may be less affected by cosmic variance since they probe a larger volume of the universe. We have estimated the current number density of clusters ($N_{\rm clust}$) from comparison of data on the cluster temperature function from X-ray observations with hydrodynamic simulations [30] as well as from number counts of clusters [31]. All recent estimates of the cluster correlation function give fairly large values at 30 h^{-1} Mpc [32]; this also suggests that the zero crossing of the correlation function must exceed ~ 40 h^{-1} Mpc. The linear estimate of pairwise velocities (σ_v) is not an observed value, since pairwise velocities are strongly influenced by nonlinear evolution. However, from previous experience with N-body simulations for various models, we have found that the results from simulations are about a factor of three or four larger than the linear estimate. The limit we quote here is our estimate of the maximum allowed linear value to match numbers derived from redshift surveys, although the statistics on velocities derived from these surveys may not be very robust [33] since they are heavily influenced by the presence of (relatively rare) clusters [34]. To get a better estimate of pairwise velocities in our preferred Cν^2DM model, we have performed N-body simulations, as discussed below. The final column gives the observed density in cold hydrogen and helium gas at $z = 3.0 - 3.5$ from the latest observations of damped Lyman α systems [5].

The next two lines present predictions from the CDM model, and illustrate its problems. The cluster correlation function at 30 h^{-1} Mpc is smaller than observations indicate regardless of CDM normalization, reflecting the fact that the matter correlation function becomes negative beyond $\sim$ 40 h^{-1} Mpc. In addition, CDM normalized to COBE produces more than an order of magnitue too many rich clusters (this problem was emphasized by Ref. [35] when the COBE DMR data first became available) and excessive small-scale pairwise velocities. If CDM is normalized to $\sigma_8 = 0.7$ (or equivalently to linear bias $b \equiv \sigma_8^{-1} = 1.43$), the cluster density problem is avoided, but small-scale velocities are still too large [1],[3],[11], and bulk velocities on a scale of 50 h^{-1} Mpc are probably too low. Even biased CDM is able to account for observations of damped Lyα systems, judging from $\Omega_{\rm gas}$, our Press-Schechter estimate of the amount of gas in collapsed halos at redshift $z = 3 - 3.5$.

CDM is attractive because of its simplicity and the existence of well-motivated particle candidates (lightest superpartner particle and axion [37]) for the cold dark matter; moreover, CDM came remarkably close to predicting the COBE signal. So several variations have been tried to patch up the CDM model. Lowering the normalization (introducing a lot of "bias") or "tilting" the primordial spectrum (assuming $n_p \approx 0.7$) improves agreement somewhat with data on intermediate (~ 10 Mpc, e.g. cluster) scales and small (~ 1 h^{-1} Mpc, e.g. galaxy pairwise velocity) scales, but leads to serious disagreement with larger-scale (30-100 h^{-1} Mpc) measurements of galaxy bulk velocities and power spectra, and galaxy and cluster correlations. Less tilt will lead to serious overproduction of clusters and large galaxy pairwise velocities — e.g. $n_p = 0.9$ with $h = 0.45$ and no gravity waves, as advocated by Ref. [38], predicts $N_{clust} = 2 \times 10^{-6}$ and $\sigma_v = 279$, both calculated as in the Table.

From the viewpoint of agreeing with observations, the best variants of CDM that have been discussed [39] add either a cosmological constant (ΛCDM) or a little hot (neutrino) dark matter (CHDM). The former assumes $\Omega \approx 0.3$ and adds a cosmological constant Λ such that $\Omega_\Lambda \equiv \Lambda/(3H_0^2) = 1 - \Omega$ to preserve flatness (predicted by inflation) as well as improve agreement with data. ΛCDM works best for a larger Hubble parameter $h \approx 0.7$ favored by many observers. It predicts relatively early galaxy formation since at late times structure formation ceases as the universe goes into inflation caused by the positive cosmological constant.

The problem with CDM is that it has too much power on small scales relative to power at large scales. Since the presence of light neutrinos reduces small scale power (because neutrino free streaming causes neutrino perturbations to damp on smaller scales, and this in turn leads to a slower growth rate for the fluctuations in the cold component of CHDM), including a neutrino component improves the agreement of model predictions with observations.

The first version of CHDM to be studied in detail [1],[2] assumed 60% cold, 30% hot (corresponding to a neutrino of mass $94h^2\Omega_\nu \approx 7$ eV), and 10% baryonic matter, with $\Omega = 1$ and $h = 0.5$. This version of CHDM fits galaxy and larger scale structures in the present-epoch universe quite well. The small-scale velocities in this model are almost small enough [1] to agree with the old result $\sigma(1\ h^{-1}\ \mathrm{Mpc}) = 340$ km s^{-1} from the CfA1 survey [36]. However, this result is now known to be in error because of the accidental omission of the Virgo cluster [40]; as we mentioned above, this is not a very robust statistic. A direct comparison of galaxy groups in "observed" CDM and CHDM simulations with identically selected CfA1 groups shows that CDM velocities are much too high, even with biasing, while the velocities in the $\Omega_\nu = 0.3$ CHDM model are in reasonable agreement [3],[11]. However, the fraction of galaxies in groups is slightly too high for $\Omega_\nu = 0.3$ CHDM, while it is significantly too low for CDM. Thus agreement is improved for a lower Ω_ν.

CHDM with $\Omega_\nu = 0.3$ has $\Omega_{\rm gas}$ too small [7],[8] to account for the observed damped Lyα absorption systems [4, 5]. This model forms galaxies too late since the large fraction of free-streaming neutrinos washes out small-scale density fluctuations too effectively. But the small-scale power in CHDM models is a very sensitive function of Ω_ν, and lowering the hot fraction to about 20% solves this problem [8]. However, this model (called 1ν in the Table) may have too much power at intermediate scales and overproduces clusters, especially with the new COBE normalization. In order to avoid this, it should probably to be normalized lower — which we might imagine could reflect some tilt and gravity waves — but the danger is that this would result in too little early structure formation (because $\Omega_{\rm gas}$ is exponentially sensitive to the power spectrum).

These CHDM models have placed the needed neutrino mass in one flavor of neutrino, presumably the ν_τ, whereas if the asmospheric ν_μ deficit is due to $\nu_\mu \to \nu_\tau$ oscillations this cannot be correct. If we take the evidence for atmospheric neutrino oscillations *or* the LSND indications seriously, then the ~ 5 eV mass ought to be shared about equally between the ν_μ and ν_τ. Having two neutrinos of 2.4 eV each, which we call the Cν^2DM model, produces an interesting effect: the ratio of the power spectrum for Cν^2DM compared to that for CHDM with the same total neutrino mass in one species is essentially unity at large and small scales, but it has a dip of about 30% centered at $\sim 10\ h^{-1}$ Mpc. The larger neutrino free-streaming length, resulting from a neutrino mass of 2.4 eV instead of twice that, lowers the abundance of clusters and gives better agreement with observations (cf. also Ref. [41]).

The first Cν^2DM line in the Table gives the results for the first-year COBE normalization $Q_{rms-PS} = 17\mu$K, for which all quantities are in good agreement with the astronomical data. The extra free streaming due to the smaller neutrino mass suppresses cluster formation. The small-scale power in this model is nearly identical to that in the 1ν version, so Cν^2 also produces enough $\Omega_{\rm gas}$. Raising the normalization to the COBE two-year value [26, 28] leads to overproduction of clusters — though it is not as bad as for the 1ν version. But this could be counteracted by introducing a little tilt as shown by the next two lines in the Table, which correspond to COBE-normalized [28] chaotic inflation models with inflaton potentials $V(\phi) = m^2\phi^2$ and $\lambda\phi^4$ respectively, which lead to tilts $n = 0.960$, 0.939 with quadrupole tensor-to-scalar power ratios $(T/S)_2 = 0.126$ and 0.255, which are reduced by about 15% for the $\ell = 11$ multipole [42]. These models are in good agreement with observations, except possibly for the small-scale velocities which must be tested by comparing simulations with data. We note that σ_v is a fairly sensitive decreasing function of both Ω_b and Ω_ν, decreasing nearly 10% if Ω_b is increased from 7.5% to 10% *or* if Ω_ν is increased from 20% to 22%.

We are now in the process of analyzing results from new N-body simulations of Cν^2DM (high resolution 800^3 PM mesh in a 50 h^{-1} Mpc box with 256^3 cold and 2×256^3 hot particles). The case simulated was the first of the Cν^2DM ones in the Table, with the lower first-year COBE normalization ($Q = 17$), though as just discussed we expect that the results will not be very different from those for the higher normalization with a little tilt. We find that the hot particles are much more spread out than the cold ones, because the lower amplitude of the fluctuations in the hot component and their higher velocities even at late times (at $z = 0$, $v_{rms} = 75$ km s$^{-1}(m_\nu/2.4{\rm eV})^{-1}$ from the Fermi-Dirac distribution [1]). This implies that the usual growth rates for an $\Omega = 1$ cosmology should be lowered when velocities are estimated at $z = 0$ for $\Omega = 1$ CHDM since the hot component clusters so much less. Projected pairwise velocities can be estimated from the simulation results by placing an "observer" in the box and measuring relative velocities along the line of sight for given projected separation [1]. The dark matter particle pairwise velocity calculated in this way is $\sigma_v(\text{projected, dark matter}) = 560$ km s^{-1} at 1 h^{-1} Mpc separation. If we conservatively estimate that the velocity bias (the ratio of the rms velocity of the dark matter halos to that of the dark matter particles [43]) is 0.8, this corresponds

Table 1: Comparison of Models — COBE normalization (except for models marked *): $Q_{rms-ps} = 20\mu$K, or $a_{11} = 7.15$ and $a_8 = 9.5$ [28].

Model	Ω_{bar} (%)	Ω_ν (%)	N_ν [a]	m_ν [a]	σ_8 [b]	V [c] 50Mpc	N_{clust} [d] (10^{-7})	ξ_{cc} [e] 30Mpc	r [f] $\xi = 0$	σ_v [g] 1Mpc	Ω_{gas} [h] (10^{-3})
OBSERVATIONS						335	4.0	0.30	> 40	< 200	3.0
uncertainties						80	2.0	0.15			1.0
CDM models, h=0.5 ($t_0 = 13.0$ Gy)											
COBE (Q_{20})	7.5	0	0	0.00	1.28	422	100.	0.12	36	479	39
biased*	7.5	0	0	0.00	0.70	231	1.2	0.08	36	262	14
CHDM models, h=0.5 ($t_0 = 13.0$ Gy)											
KHPR (Q_{20})	10.0	30	1	7.04	0.78	425	16.	0.40	51	117	2.4
1ν (Q_{20})	7.5	20	1	4.69	0.89	423	27.	0.30	52	184	12.
Cν^2DM (Q_{17}*)	7.5	20	2	2.35	0.67	347	2.4	0.35	70	144	4.6
Cν^2DM (a_{11})	7.5	20	2	2.35	0.78	408	11.	0.38	70	169	11.
Cν^2DM$_{n0.96}$	7.5	20	2	2.35	0.69	374	3.7	0.39	71	142	5.5
Cν^2DM$_{n0.94}$	7.5	20	2	2.35	0.63	350	1.5	0.39	72	128	3.3
ΛCDM/ΛCHDM models, $h = 0.7$, $\Omega_0 = 0.3$, and $\Omega_\Lambda = 0.7$ ($t_0 = 13.5$ Gy)											
ΛCDM (a_8)	2.6	0	0	0.00	1.13	362	3.7	0.26	125	71	21.
ΛCHDM (a_8)	2.6	5.3	1	2.44	0.69	342	0.08	0.43	135	29	0.0004
ΛCDM/ΛCHDM models, $h = 0.6$, $\Omega_0 = 0.5$, and $\Omega_\Lambda = 0.5$ ($t_0 = 13.5$ Gy)											
ΛCDM (a_8)	3.5	0	0	0.00	1.25	403	22.	0.29	66	167	27.
ΛCHDM (a_8)	3.5	7.2	1	2.43	0.86	390	3.2	0.50	100	80	3.5

[a] N_ν is the number of ν species with mass. If $N_\nu \geq 1$, each species has the same mass m_ν.
[b] $(\Delta M/M)_{rms}$ for $R_{top-hat} = 8h^{-1}$ Mpc.
[c] Bulk velocity in top-hat sphere of radius $50h^{-1}$ Mpc.
[d] Number density of clusters $N(> M)$ in units of $10^{-7}\,h^3$Mpc^{-3} above the mass $M = 10^{15}h^{-1}M_\odot$, calculated using Press-Schechter approximation with gaussian filter and $\delta_c = 1.50$.
[e] The cluster-cluster correlation function amplitude at $30h^{-1}$ Mpc, computed using linear theory [39: HP93] and assuming a unit bias factor for the dynamical contribution.
[f] Zero crossing ($\xi(r) = 0$) of the correlation function in units of h^{-1} Mpc.
[g] Linear estimate of pairwise velocity at $r = 1h^{-1}$ Mpc: $\sigma_v^2 = 2H_0^2\Omega^{1.2}\int dk\,P(k)(1 - \sin kr)/kr$.
[h] Mean density of collapsed baryons at $z = 3$–3.5 in units of 10^{-3} of critical density, calculated using $\Omega_{gas} = (\Omega_b/\Omega_c)\,\mathrm{erfc}(\delta_c/\sqrt{2}\sigma)$, with $\delta_c = 1.4$ [8], and σ computed for mass $5 \times 10^{10}h^{-1}M_\odot$ using gaussian smoothing and assuming all gas is neutral. Since some gas may be ionized or removed by star formation, Ω_{gas} for the various models should be at least as high as the observations.

to 450 km s^{-1} for galaxies, consistent with current observations (and, as expected, about a factor of 3 larger than the linear estimate in the Table). As already mentioned, the Void Probability Function from these simulations is in excellent agreement with the PPS and CfA2 data [10].

It is remarkable that, with the experimentally suggested neutrino masses, only cosmological models with $h \approx 0.5$ match observations. As we discussed in Ref. [13], for $h = 0.7$ — favored by many observers — CDM ($CDM_{0.7}$) is an even worse fit to the data than for $h = 0.5$ because the larger h makes matter-dominance ($\propto \Omega h^2$) occur earlier and thus moves the bend in the CDM spectrum to smaller scales, giving more intermediate and small scale power for a given large scale normalization. Adding two 2.4 eV neutrinos only slightly improves the situation, because this only gives $\Omega_\nu \sim 0.1$ for $h = 0.7$, so the spectrum is not modified very much. Of course, with large h, $\Omega = 1$ models also lead to too short a time since the big bang: $t_0 = 2/(3H_0) = 6.52\,\mathrm{Gy}/h = 9.3$ Gy for $h = 0.7$.

A larger age is obtained for an open universe; in order to be consistent with inflation, we assume a positive cosmological constant. The maximum value of Λ allowed by the COBE data is $\Omega_\Lambda \equiv \Lambda/(3H_0^2) \approx 0.78$ [44], and the maximum allowed by quasar lensing statistics is $\Omega_\Lambda \approx 0.7$ [45]. For a flat ($k = 0$) universe with $\Omega_\Lambda = 0.7$ and $\Omega = 0.3$, $h = 0.7$ corresponds to $t_0 = 13.5$ Gy. ΛCDM with these parameters is a good fit [46] to the data. However, this model becomes much worse if even one neutrino of 2.4 eV is added, seriously underproducing clusters and $\Omega_{\mathbf{gas}}$ because of the excessive fraction of hot dark matter suppressing small-scale structure. Consequently, low-Ω_0 models have serious problems if any neutrinos have significant mass. Raising Ω_0 to 0.5 gives enough cold dark matter to counteract the poisoning of structure formation by a single neutrino species of 2.44 eV mass, but this model must have a lower Hubble parameter to be consistent with $t_0 \geq 13$ Gy ($h \geq 62.5$ for $\Omega_0 = 0.5$).

A similar situation occurs for $\Omega = 1$ Cν^2DM with $h = 0.4$, for which $\Omega_\nu = 0.32$ with two 2.4 eV neutrinos. (Recall that for given $m(\nu)$, Ω_ν scales as h^{-2} since critical density is $\propto h^2$.) Because the bend in the CDM spectrum moves to larger scales as h decreases, there is less intermediate and small scale power for given large scale normalization; adding hot dark matter further decreases small scale power. We find that even with only one 2.4 eV neutrino, there is just not enough power to generate the observed number of clusters or high-redshift objects.

4 Conclusions

Ever since the early 1980s there have been hints [47] that features on small and large scales may require a hybrid scenario in which there are two different kinds of dark matter. Preliminary studies of the CHDM scenario were carried out in 1984 [48] and it was first worked out in detail only in the last two years [1],[2],[3] with one massive neutrino. We have shown here that the Cν^2DM model, with Hubble parameter $h = 0.5$ and both neutrinos having a mass of 2.4 eV as suggested by ongoing experiments, gives a remarkably good account of all presently available astronomical data. New data on CMB, large scale structure, and structure formation will severely test this highly predictive model. Results expected soon from ν-oscillation experiments will clarify whether indeed $m(\nu_\mu) \approx m(\nu_\tau) \approx$ 2.4 eV. The Table shows the implications of such neutrino masses for a variety of popular CDM-type cosmological models. If even just the ν_μ has a mass of 2.4 eV, as suggested by preliminary results from the LSND experiment, flat low-Ω CDM models are disfavored.

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References

[1] A. Klypin, J. Holtzman, J.R. Primack, and E. Regős, *Astrophys. J.* **416**, 1-16 (1993).

[2] M. Davis, F. Summers, and D. Schlegel, *Nature* **359**, 393 (1992); D. Schlegel, M. Davis, F. Summers, and J.A. Holtzman, *Astroph. J.* **427**, 512 (1994). Y.P. Jing, H.J. Mo, G. Börner, and L.Z. Fang, *Astron. Astroph.* **284**, 703 (1994).

[3] Nolthenius, R., Klypin, A., & Primack, J.R. *Astrophys. J. Letters* **422**, L45-48 (1994).

[4] K.M. Lanzetta, *Publ. Astron. Soc. Pacific* **105**, 1063 (1993); K.M. Lanzetta, A. Wolfe, D.A. Turnshek, Preprint (1993).

[5] L. Storrie-Lombardi, R.G. McMahon, M.J. Irwin, and C. Hazard, in *Proc. ESO Workshop on QSO Absorption Lines*, in press (1995).

[6] M.G. Haehnelt, *Mon. Not. Roy. Astron. Soc.* **265**, 727 (1993). D.Yu. Pogosyan and A.A. Starobinsky, *ibid.* **265**, 507 (1993). A.R. Liddle and D. Lyth, *ibid.* **265**, 379 (1993).

[7] H.J. Mo and J. Miralda-Escude, *Astroph. J.* **430**, L25 (1994); G. Kauffmann and S. Charlot, *Astroph. J.* **430**, L97 (1994); C.P. Ma and E. Bertschinger, *Astroph. J.* **434**, L5 (1994).

[8] A. Klypin, S. Borgani, J. Holtzman, J.R. Primack, *Astrophys. J.*, **444**, 1 (1995).

[9] C.-P. Ma, in *Dark Matter* Proc. 5th Ann. Astrophys. Conf. in Maryland, October 1994, eds. Stephen S. Holt and Charles L. Bennett (American Institute of Physics, 1995), in press.

[10] S. Ghigna, S. Borgani, S. Bonometto, L. Guzzo, A. Klypin, J.R. Primack, R. Giovanelli, and M. Haynes, *Astroph. J. Lett.* (1994). We have found the VPF predicted from our new $C\nu^2DM$ simulations to be in excellent agreement with observations (work in prep.).

[11] R. Nolthenius, A. Klypin, J.R. Primack, *Astrophys. J.* in press (1995).

[12] George M. Fuller, Joel R. Primack, and Yong-Zhong Qian, Preprint astro-ph/9502081, *Phys. Rev.* in press (1995).

[13] Joel R. Primack, Jon Holtzman, Anatoly Klypin, and David O. Caldwell, *Phys. Rev. Lett.*, **74**, 2160-2163 (1995).

[14] J.N. Bahcall, at Neutrino94, in *Nucl. Phys. B*, Proc. Supp. **38**, 98 (1995); V. Berezinzky, G. Forentini, and M. Lissia, *Phys. Lett. B* **341**, 38 (1994); P.I. Krastev and A.Yu. Smirnov, *Phys. Lett. B* **338**, 282; S.P. Rosen, *27th Int. Conf. on High Energy Phys.*, Glasgow (1994); N. Hata and P. Langacker, *Phys. Rev. D* **50**, 632 (1994).

[15] K.S. Hirata et al., *Phys. Lett.* **B280**, 146 (1992); R. Becker-Szendy et al., *Phys. Rev.* **D46**, 3720 (1992); P.J. Litchfield, in *Proc. Int. Europhys. Conf. on High Energy Phys.*, eds. J. Carr and M. Perrottel (Ed. Frontières, Gif-sur-Yvette, France, 1993).

[16] Fukuda, Y. et al., *Phys. Lett. B* **335**, 237 (1994). K. Inoue, at Moriond'95.

[17] G. Barr, T.K.Gaisser, and T. Stanev, *Phys. Rev. D* **39**, 3532 (1989); W. Frati et al., *Phys. Rev. D* **48**, 1140 (1993); D.H. Perkins, *Astropart. Phys.* **2**, 249 (1994).

[18] Z. Shi, D.N. Schramm, B.D. Fields, *Phys. Rev. D* **48**, 2563 (1993), and refs. therein.

[19] D.O. Caldwell, in *Perspectives in Neutrinos, Atomic Physics, and Gravitation*, ed. J. Tran Thanh Van et al. (Ed. Frontieres, Gif-sur-Yvette, France, 1993). D.O. Caldwell, and R. Mohapatra, *Phys. Rev. D* **48**, 3259 (1993). J.T.Peltoniemi and J.W.F. Valle, *Nucl. Phys. B* **406**, 409 (1993).

[20] C. Athanassopoulos et al. (LSND), rev. preprint submitted to *Phys. Rev. Lett.* (June 9, 1995). Also I. Stancu, Moriond'95.

[21] D.O. Caldwell, in *Trends in Astro-particle Physics* Stockholm, 1994, eds. L. Bergstrom, P. Carlson, P.O. Hulth and N. Snellman, *Nucl. Phys. B*, Proc. Suppl. (in press).

[22] G. Drexlin, *Prog. in Part. and Nucl. Phys.* **32** (in press, 1994); J. Kleinfeller, Moriond95.

[23] L. Borodovsky et al., *Phys. Rev. Lett.* **68**, 274 (1992).

[24] Y.-Z. Qian et al., *Phys. Rev. Lett.* **71**, 1965 (1993); Y.-Z. Qian, Ph.D. thesis, UCSD (1993).

[25] Y.-Z. Qian and G. M. Fuller, *Phys. Rev. D*, in press (1995).

[26] K.M. Gorski et al., *Astrophys. J. Lett.* **430**, L89 (1994); C.L. Bennett et al., *Astrophys. J.* (in press, 1994); E.F. Bunn, D. Scott, and M. White, *Astrophys. J.* **441**, L9 (1995); R. Stompor et al., *Mon. Not. Roy. Astr. Soc.* (in press, 1995).

[27] G.R. Blumenthal, S.M. Faber, J.R. Primack, and M. Rees, *Nature* (1984); M. Davis, G. Efstathiou, C. Frenk, and S.D.M. White, *Nature* (1992); J.P. Ostriker, *Ann. Rev. Astron. Astrophys.* **31**, 689 (1993).

[28] We actually normalize the models not to $Q_{\mathrm{rms-PS}} = 20$ but rather to the "pivot points" $a_{11} = 7.15$ for the $C\nu^2$DM models, or $a_8 = 9.5$ for the ΛCDM models, as recommended by Stompor et al., Ref. [26].

[29] A. Dekel, *Ann. Rev. Astron. Astroph.* **32**, 371 (1994) and private communications.

[30] G. Bryan et al., *Astroph. J.* **37**, L5 (1994).

[31] We have increased the cluster masses in N. Bahcall and R. Cen, *Astroph. J.* **408**, L77 (1993) by a factor of 1.4; the results are then in rough argreement with those of A. Biviano et al., *Astroph. J.* **411**, L13 (1993) and S.D.M. White, J.F. Navarro, A.E. Evrard, and C.S. Frenk, *Nature* **366**, 429 (1993).

[32] See e.g. S. Olivier, J. Primack, G.R. Blumenthal, and A. Dekel, *Astroph. J.* **408**, 17 (1993); A. Klypin and G. Rhee, *Astroph. J.* **428**, 399 (1994); and refs. therein.

[33] H.J. Mo, Y.P. Jing, and G. Börner, *Mon. Not. Roy. Astron. Soc.* **264**, 825 (1994); W.H. Zurek, P.J. Quinn, J.K. Salmon, and M.S. Warren, *Astroph. J.* **431**, 559 (1994). Cf. also Refs. [3] and [40].

[34] R. O. Marzke et al., CfA preprint (1995).

[35] G. Efstathiou, J.R. Bond, S.D.M. White, *Mon. Not. Roy. Astron. Soc.* **258**, P1 (1992).

[36] M. Davis, P.J.E. Peebles, *Astrophys. J.* **267**, 465 (1983).

[37] See e.g. J.R. Primack, D. Seckel, and B. Sadoulet, *Ann. Rev. Nucl. Part. Sci.* **38**, 751 (1988).

[38] D. Scott, J. Silk, and M. White, *Science*, **268**, 829 (1995).

[39] J. Holtzman, *Astroph. J. Suppl.* **81**, 1 (1989); J. Holtzman and J.R. Primack, *Astroph. J.* **405**, 428 (1993). A.R. Liddle and D.H. Lyth, *Phys. Rep.* **231**, 1 (1993).

[40] R. Somerville, J.R. Primack, R. Nolthenius, and M. Davis, in prep. (1995).

[41] D. Pogosyan and A.A. Starobinsky, in Large-Scale Structure in the Universe, eds. J.P.Miicket, S.Gottlöeber, V. Müller, (World Scientific, 1995), in press.

[42] M. S. Turner, *Phys. Rev. D*, **48**, 3502 (1993); M. S. Turner, M. White, and J. E. Lidsey, *Phys. Rev. D*, **48**, 4613 (1993).

[43] R.G. Carlberg and H.M.P. Couchman, *Astroph. J.* **340**, 47 (1989).

[44] E. Bunn & N. Sugiyama, preprint astro-ph/9407069 (1994).

[45] D. Maoz and H.-W. Rix, *Astroph. J.* **416**, 425 (1993). C. Kochanek, *Astroph. J.* **419**, 12 (1993), UCLA Conference, ed. D. Cline (1995), in press, and private communication.

[46] G. Efstathiou, W.J. Sutherland, S.J. Maddox, *Nature* **348**, 705 (1990); R. Cen, N.Y. Gnedin, and J.P. Ostriker, *Astroph. J.* **417**, 387 (1993).

[47] A. Dekel, *Astron. Astrophys.* **101**, 79-87 (1981); Dekel, A. *Astroph. J.* **284**, 445-456 (1984).

[48] See the historical references in Ref. [1].