$=1.5\times10^7$ Hz. This implies $\mathcal{E}_g=\hbar\omega_T=9.5\times10^{-20}$ erg. Such a small gap makes sense only because of the large number of electrons involved in motion of the CDW.

The success of the tunneling theory when applied to $NbSe_3$ and TaS_3 suggests the possibility of applying the theory to non-Ohmic conduction observed in other linear-chain compounds.

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Massive Neutrinos and the Large-Scale Structure of the Universe

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If neutrinos dominate the mass density of the Universe, they play a critical role in the gravitational instability theory of galaxy formation. For neutrinos of mass $30m_{30}$ eV, a maximum Jeans mass $M_{\nu m}\approx 4\times10^{15}m_{30}^{-2}M_\odot$ is derived. On smaller scales, neutrino fluctuations are damped, and the growth of baryon fluctuations is greatly inhibited. Structures on scales $>M_{\nu m}$ may collapse, forming galaxies as in Zel'dovich's "pancake" theory.

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The idea that massive neutrinos may solve the missing-mass problem in galaxies and in clusters of galaxies, as well as dominating the mass content of the Universe, has been explored by many authors.[1,2] The recent experimental reports of electron-neutrino mass detection[3] and neutrino oscillations,[4] coupled with the natural appearance of a neutrino-flavor mass spectrum with splittings of order of those between the three leptoquark families in extensions of grand unified theories to SO(10),[5] suggest that we take seriously the astrophysical implications of a neutrino mass. Here, we consider the role of light massive neutrinos in the early Universe and in galaxy formation.

The mean occupation number of the neutrino background in the standard big-bang model as a function of momentum p and time t is $n(p,t) = \{\exp[pc/T_\nu(t)]+1\}^{-1}$, which is valid even in the nonrelativistic (NR) regime, where it is neither Fermi-Dirac nor degenerate. The neutrino "temperature," $T_\nu(t)$, for left-handed neutrinos (ν_L) is now 1.9 K, red shifted from 1 MeV when they decoupled. If right-handed neutrinos (ν_R) couple only as in the Weinberg-Salam model extended to include a neutrino Dirac mass, rates for reactions such as $e^+e^- \to \nu_R\bar{\nu}_L$ [$\sim(m_\nu/T_\nu)^2$ times the $e^+e^-\to\nu_L\bar{\nu}_L$ rate] were always substantially less than the expansion rate.[6] The resulting number ratio of right-handed to left-handed neutrinos is $g-1 \lesssim 10^{-4}$, valid for all ν flavors. Subsequently, however, left and right helicities can mix through deflections in a gravitational field, though spin projection along a fixed axis is conserved.

We then obtain a neutrino plus antineutrino mass density in the NR epoch (in units of the cosmological closure density) of $\Omega_\nu = 0.93\bar{m}_{30}h^{-2}$, where h is Hubble's constant in units of 100 km s^{-1} Mpc^{-1}. (Mpc is 10^6 parsec.) If the average neutrino mass $\bar{m}_{30} = \frac{1}{3}(\sum g m_{30})$ (where the sum is over ν flavors) exceeds $\sim h^2$, the Universe is closed. Here m_{30} is the neutrino mass in 30-eV units. Observations of the deceleration parameter[7] suggest $\Omega_\nu \leqslant 2$, which slightly modifies the well-known constraint on light-neutrino masses,[1] $\bar{m}_{30} \lesssim 2h^2$.

Recent estimates[8] of the mean luminosity density in the Universe imply baryons in galaxies contribute a fraction $\Omega_B = (M/L)_G/2315h \sim 0.004$–$0.007$ to the mean density required for closure. The mass-to-blue-light ratio of a typical galaxy, $(M/L)_G$ (in solar units), due to "conventional" stars probably lies in the range $9h$–$16h$,[9] yielding the above spread. This gives the baryon density in luminous forms of matter, which is smaller than the mass density in neutrinos by the factor $\Omega_\nu/\Omega_B \sim (140\text{–}240)\bar{m}_{30}h^{-2}$. Neutrinos need only have $\bar{m} \geqslant 0.2h^2$ eV to dominate, unless most baryons reside in dark forms of matter, such as very-low-mass stars or black holes.[10]

In the primordial nucleosynthesis era, the neutrinos are extremely relativistic (ER), and, as discussed above, g is *not* 2, though there are two spin states, but ≈ 1. Thus, light element production remains essentially *unchanged* from the standard picture. This is not true if right-handed neutrinos couple, for example, through weak vector bosons[11] at a strength of $G_R \gtrsim 10^{-3}G_\mathrm{F}$, where G_F is the usual Fermi coupling constant for left-handed neutrinos. The right decoupling temperature is then lower than the temperature at which copious quark-antiquark production occurs. Its red shift then results in the right- and left-handed neutrino temperatures maintaining approximate equality through the nuclear burning era. Thus, $g\approx 2$, which increases the expansion rate, and consequently raises the final helium and deuterium abundances above those of the standard model.[6] To get the observed deuterium abundance in the standard model with $g=1$ requires[12] $0.01 \leqslant \Omega_B h^2 \leqslant 0.02$; to explain low helium measurements may require $\Omega_B h^2$ to be as low as 0.003.[13]

When the red shift falls below $z_\mathrm{NR} \approx 1.8\times 10^5 m_{30}$, the neutrinos go NR. The neutrino distribution function then results in a velocity dispersion of the left-handed background $\langle v^2\rangle^{1/2} = (12\eta_5/\eta_3)^{1/2}T_\nu/m_\nu c \simeq 6m_{30}^{-1}(1+z)$ km s^{-1}, where η_k is the Riemann eta function. This is now smaller than the dispersion in rich clusters (~1500 km/s) and in galaxies (~250 km/s). Assume now that one neutrino flavor carries almost all of the mass[5]; our general conclusions do not depend upon this assumption. A slight modification of the Tremaine and Gunn[2] argument to one neutrino flavor shows that nondegenerate neutrinos cannot form the dark matter in galactic halos unless $m_\nu > 25$ eV. Such a high value is certainly not ruled out by cosmology; therefore it is possible that massive neutrinos are the dark matter in the halos of spiral galaxies and the "missing mass" in clusters. We thus consider the role which neutrinos play in large scale clustering.

The velocity dispersion and the mass density imply a Jeans mass of

$$M_{\mathrm{J}\nu} = M_{\nu m}x^{-3/2}f(x), \quad x = (1+z_\mathrm{NR})/(1+z),$$
$$f(x) = 26.6\left(\frac{x}{24\eta_5}\int_0^\infty \frac{y^4\,dy}{(e^y+1)(y^2+x^2)^{1/2}}\right)^{3/2}\left(\frac{1}{2x\eta_3}\int_0^\infty \frac{y^2\,dy\,(y^2+x^2)^{1/2}}{e^y+1}\right)^{-2}, \tag{1}$$

which peaks at the maximum Jeans mass $M_{\nu m} = 3.9\times 10^{15} m_{30}^{-2}M_\odot$ attained at the red shift $z_m = 42\,900 m_{30}$. The function $f(x)$ involves integrals of the distribution function which we evaluate numerically in the semirelativistic regime. In the ER regime, $f = 0.32x^{7/2}$, and so the Jeans mass rises as $(1+z)^{-2}$ as z

drops. In the NR regime, $f = 26.6$, and the Jeans mass falls as $(1+z)^{3/2}$ through the hierarchy of structural mass scales observed in the Universe until the present epoch, when it is $1.4\times 10^9 m_{30}^{-7/2} \times M_\odot$. (See Fig. 1.)

When neutrinos are ER, but decoupled from matter, perturbations decay on all length scales smaller than the horizon.[14] Further, in the NR regime, neutrinos Landau damp on all scales smaller than the Jeans length,[15] in the same manner as collisionless baryons.[16] We conclude that *all primordial neutrino perturbations will be erased on mass scales smaller than the peak value* $M_{\nu m}$ and on all scales smaller than the associated length $\lambda_{\nu m}(z) \approx m_{30}^{-2}(1+z_m)/(1+z)$ kpc. Neutrino damping does not drive the damping of baryon fluctuations.[14] However, adiabatic perturbations do damp prior to and during the recombination epoch by the viscous coupling of the baryons to the photons on all scales below the Silk mass in baryons,[17,18] $M_{BS} \approx 3\times 10^{13}\,\Omega_B^{-1/2} \times \Omega_\nu^{-3/4} h^{-5/2} M_\odot$, $\sim 10^{15} M_\odot$ for an Einstein–de Sitter universe with $\Omega_B = 0.01$ and $m_{30} = 1$. The maximum neutrino Jeans mass encloses a mass in baryons in our standard case $M_{Bm} \approx (\Omega_B/\Omega_\nu) M_{\nu m}$

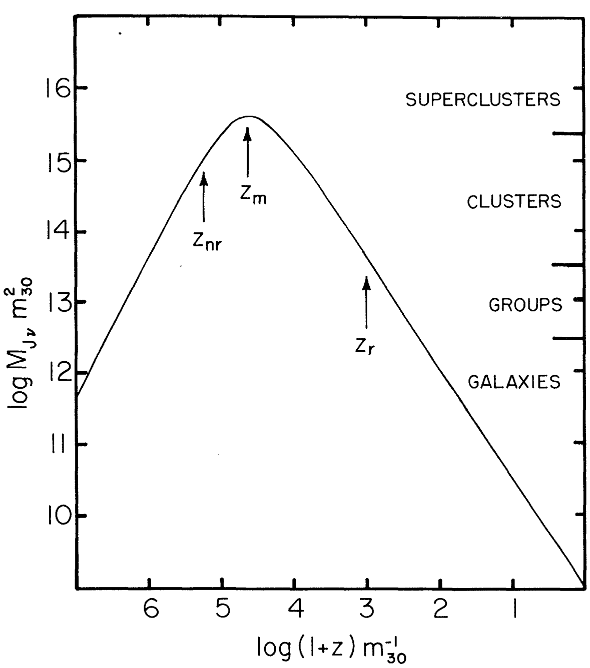

FIG. 1. The Jeans mass in solar mass units for one neutrino flavor vs red shift, along with approximate ranges for various large-scale structures. The neutrino mass in units of 30 eV is m_{30}. Perturbations on scales smaller than the maximum value of the Jeans mass are damped.

$\approx 1.2\times 10^{14} m_{30}^{-3}(\Omega_B h^2/0.01) M_\odot$. Depending upon parameter choice, M_{BS} may be greater or less than M_{Bm}, but they are of same order.

In the conventional picture of galaxy formation,[19] isothermal fluctuations (which do not suffer viscous damping) and all surviving adiabatic fluctuations grow at a rate $\sim(1+z)^{-1}$ in an Einstein–de Sitter universe after photon decoupling. In the presence of massive neutrinos, this result is drastically altered: *Baryon fluctuations smaller than the critical mass* M_{Bm} *grow extremely slowly in the linear regime until they first exceed the instantaneous Jeans mass.* The growth of perturbations of wavelength λ is described by the linearized Einstein field equations perturbed about a Friedmann background. After recombination, these reduce to an equation for the spatial Fourier transform of the fractional baryon and neutrino density fluctuations $\delta_B(\vec{k}, t)$ and $\delta_\nu(\vec{k}, t)$:

$$\frac{d^2\delta_B}{dt^2} + \frac{2\dot{a}}{a}\frac{d\delta_B}{dt} = 4\pi G\rho_T\left(\frac{\rho_B}{\rho_T}\,\delta_B + \frac{\rho_\nu}{\rho_T}\,\delta_\nu\right) \quad (2)$$

which is valid in the linear regime, $\delta_B \ll 1$, $\delta_\nu \ll 1$, when matter pressure is neglected. Here, $a(t)$ is the Robertson-Walker scale factor and $\rho_T = \rho_\nu + \rho_B$. This is coupled to an integral equation for δ_ν obtained from the linearized Vlasov equation for the collisionless neutrino distribution function describing growth for $\lambda \geq \lambda_{J\nu}$ and damping for $\lambda \leq \lambda_{J\nu}$, where $\lambda_{J\nu}(z)$ is the instantaneous Jeans length.[15] Growth of neutrino density fluctuations occurs on scales $\lambda > \lambda_{\nu m}$ for $z < z_m$, but is suppressed in the radiation-dominated era.[20] Not until the epoch of photon decoupling can the baryons respond to the neutrino perturbations. Prior to recombination, no growth of baryon or photon fluctuations occurs on scales below the photon Jeans length, which is approximately the horizon size. After decoupling, δ_B rapidly responds to the neutrino perturbation (even if $\delta_B = 0$ initially), until $\delta_B \approx \delta_\nu$ on scales $\lambda > \lambda_{\nu m}$. Growth continues until $\delta_\nu \sim (1+z)^{-1}$ exceeds unity, when the enhanced self-gravity enables the first structures of mass $\sim M_{\nu m}$ to condense from the expanding background.

To consider scales $\lambda \leq \lambda_{\nu m}$, we take δ_ν to be zero below $\lambda_{\nu m}$ as our initial condition. For wavelengths $< \lambda_{J\nu}(z)$, we find the solutions in the Einstein–de Sitter case: $\delta_B \sim t^{p_\pm}$, where $p_\pm = \pm\frac{1}{6}[(1 + 24\rho_B/\rho_T)^{1/2} \mp 1]$. Only the p_- mode grows. If baryons dominate the mass density, $p_+ = \frac{2}{3}$, yielding the usual growing mode. If neutrinos dominate, p_+ is very small, $\sim\frac{1}{20}$ for $\Omega_B h^2 = 0.01$, and

$m_{30}=1$: Growth is negligible.

The growing part of the solution for $\lambda_{J\nu}(z) \leqslant \lambda \leqslant \lambda_{J\nu}(z_r)$ yields the fluctuation spectrum $\delta\rho_B/\rho_B(z) = \frac{3}{5}[\delta\rho_B/\rho_B(z_r)](\Omega_B/\Omega_\nu)[M/M_{J\nu}(z)]^{2/3}$. We write the fluctuation spectrum at z_r as $\delta\rho_B/\rho_B(z_r) = \delta\rho_B/\rho_B(z_m) = (M_c/M)^{n/6+1/2}$ which corresponds to a Fourier power spectrum $|\delta_B|^2 \propto k^n$. Note that the mass spectrum flattens by $M^{2/3}$ at $M < M_{J\nu}(z_r)$, which corresponds to a power spectrum $|\delta_B|^2 \propto k^{n-4}$. If $n<1$, fluctuations on scale $M_{\nu m}$ are the first to condense after the recombination epoch.

We now show that condensation of galactic or subgalactic masses requires that either galaxies were formed in the nonlinear neutrino regime, $\delta_\nu \gtrsim 1$, or the baryon fluctuations were substantially nonlinear on galactic scales, $\delta_B \gtrsim 1$, at recombination. The nonlinear evolution of neutrino structures of mass $M_{\nu m}$ is likely to resemble a variant of Zel'dovich's "pancake" theory of galaxy formation from adiabatic fluctuations.[21] According to this theory, the generic type of collapse is asymmetric, with preferential collapse along one axis occurring at red shift $z_{\rm nl}$. The Zel'dovich theory faces a serious constraint due to the relatively large amplitudes required for the initial adiabatic fluctuations: $\delta_B \gtrsim 10^{-3}(1+z_{\rm nl})$ at decoupling. Since neutrino fluctuations grow between z_m and z_r, the value of δ_B at decoupling is reduced to $\sim\delta_\nu(z_m) \lesssim 5\times10^{-5}(1+z_{\rm nl})m_{30}^{-1}$. The associated temperature fluctuations in the cosmic background radiation are[18] $\lesssim\frac{1}{3}\delta_B(z_r) \approx \frac{1}{4}\delta_\nu(z_m)$ over scales $\sim\lambda_{\nu m}$ and are below recent observational upper limits ($\Delta T/T \lesssim 2\times10^{-4}$ over scales $\sim 4'$).[22]

A difficulty appears in the galaxy distribution where significant power would be expected over large scales, corresponding to M_{Bm}. The two-point galaxy correlation function[19] has the form $\xi(r) = (r_0/r)^{1.8}$ with $r_0 \approx 4h^{-1}$ Mpc, whence the mass scale below which clustering is nonlinear is $M_{B\rm nl} \approx 5\times10^{14}\Omega_B h^{-1}[r_0 h/(4\text{ Mpc})]^3 M_\odot$. There is, however, tentative evidence for larger-scale nonlinear structure.[23] If we require $M_{B\rm nl}$ to exceed M_{Bm}, we require $m_{30} > 2.9[(4\text{ Mpc})/r_0]$. This requires $\Omega_\nu h^2 \sim 1$ and $M_{Bm} \approx 4.6\times10^{12}(\Omega_B h^2/0.01)M_\odot$. This mass scale corresponds to a group of ~ 80 galaxies.[19]

The mass limit deduced using the correlation function disagrees with the neutrino mass inferred from measured mass-to-light ratios if we assume that the luminous baryonic matter has not segregated from the dark neutrino matter. Since $M_{\nu m}/M_{Bm} \approx 800(M/L)^{-1}m_{30}h^{-1}$, and $M/L \approx 500h$ for rich clusters, we require $m_{30} \approx 0.6h^2$ and hence $M_{\nu m} \approx 10^{16}h^{-4}M_\odot$. The problem is still more severe in the case of groups of galaxies, where $M/L < 500h$. We conclude that substantial dissipation on cluster scales is required in order to segregate the luminous matter from the neutrinos. We cannot rule out this possibility. Since in such a picture, galaxy formation occurs after the collapse of the pancake, it is difficult to see how galaxy halos composed of neutrinos could form given the high velocity dispersion expected of this cluster material [$\sim 1300 m_{30}^{-1}(1+z_{\rm nl})$ km/s].

The alternative possibility that $\delta_\nu \sim 0$ initially constrains the initial amplitudes of isothermal baryon density fluctuations. To achieve $\delta\rho_B/\rho_B \sim 1$ now on scales $\sim M_{B\rm nl}$, we infer that $\delta\rho_B/\rho_B \sim 0.02(0.01/\Omega_B)[(4\text{ Mpc})/r_0 h]^2 m_{30}^{-2}[M_{B\rm nl}/M_B]^{n/6+1/2}$ at z_r on scales corresponding to a mass in baryons of M_B. Hence, on galactic scales $\delta\rho_B/\rho_B \approx m_{30}^{-2}$ for $1 \lesssim n \lesssim 4$. A value of n in this range is required for isothermal fluctuations to account for the galaxy correlation function.[19] Such a theory seems unattractive (galaxies exist because galaxies have always existed).

In summary, the ratio of right- to left-handed neutrinos is likely to be $\ll 1$ and thus primordial nucleosynthesis is unaffected by the presence of a neutrino mass in the standard big-bang model. To avoid conflict with q_0 determinations implies that $m_\nu \lesssim 190$ eV, otherwise $\Omega_\nu > 2$. If the dominant mass density of the Universe is in massive neutrinos (e.g., $m_\nu > 1$ eV if $\Omega_B h^2 \sim 0.01$), the gravitational growth of density fluctuations is inhibited in the linear regime on mass scales $< M_{\nu m}$. Moreover, the large-scale structure displays a prominent feature at $M_{\nu m} \sim 4\times10^{15}m_{30}^{-2}M_\odot$, in which case comparison with the galaxy distribution requires $m_\nu > 85$ eV. Alternatively, nonlinear structure on galaxy scales must be present in the very early Universe. We conclude that confirmation of a neutrino mass will require a significant revision of the gravitational instability theory of galaxy formation as outlined here.

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ERRATUM

FIRST OBSERVATION OF THE GROUND-STATE HYPERFINE-STRUCTURE RESONANCE OF THE MUONIC HELIUM ATOM. H. Orth, K.-P. Arnold, P. O. Egan, M. Gladisch, W. Jacobs, J. Vetter, W. Wahl, M. Wigand, V. W. Hughes, and G. zu Putlitz [Phys. Rev. Lett. 45, 1483 (1980)].

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