# COSMOLOGY AND PARTICLE PHYSICS

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## INTRODUCTION

Astrophysicists spend most of their time applying well-established physics to uncertain and ill-understood cosmic phenomena - they are, basically, users of physics who contribute nothing fundamental to that subject in return. But there are some areas of astronomy when the relevant physics is no better understood than the astronomy. The difficulty and uncertainty are then compounded; the credibility of any conclusions is thereby diminished. But astrophysicists then have the psychological compensation that their relationship with fundamental physicists is symbiotic rather than parasitic. In this lecture I shall try to illustrate some ways in which cosmological considerations may permit some (albeit tentative) inferences about particle physics, which cannot be tested by ordinary experimental methods.

This written text is merely a brief summary of the subject. Similar material has been presented by various authors in the proceedings of other recent conferences; the best recent comprehensive review is that of Dolgov and Zeldovich[1].

## COSMOLOGICAL PRELIMINARIES

Cosmological models governed by Einstein's equations evolve in a manner which is controlled by the mean density $\rho$. It is convenient to parameterise the present density of matter $\rho_o$ as $\Omega_o \rho_{crit}$, where

$$\rho_{crit} = (\tfrac{8}{3}\pi G \tau_H^2)^{-\frac{1}{2}} = 4 \times 10^{-30} (\tau_H / 2 \times 10^{10} \text{yr})^{-2} \text{ gm cm}^{-3}.$$

$\tau_H$ is the Hubble time, whose value is still uncertain by a factor $\sim 2$. It is in the range (1-2) x $10^{10}$ yr . If the Universe is describable by a simple Friedmann model, with the cosmical constant $\Lambda$ equal to zero, then it will expand for ever, or eventually recollapse, according as $\Omega \lessgtr 1$. Dynamical arguments seem to favour a value of $\Omega_o$ somewhat less than unity, but the issue is still unsettled. The main contribution to $\Omega_o$ may not necessarily come from baryons. There is direct evidence for a baryon contribution $\Omega_b \gtrsim 0.01$ : this much comes from the stellar content of galaxies, and an intergalactic gas. But the bulk of the mass-energy in the Universe could be in some other form, such as black holes (either primordial, or the endpoints of stars or supermassive objects), or neutrinos of non-zero mass. This last possibility, which I shall discuss later, is of course of particular interest to particle physicists.

All cosmological inferences relevant to particle physics are based on the "hot big bang" model of the early Universe. The primary evidence for this model is the microwave background radiation, with present temperature $T_o \simeq 2.7$K. The data on the spectrum of this radiation, including the recent measurements at millimetre wavelengths (where a Planck curve would peak) are presented by Woody and Richards[2]. The apparently thermal spectrum suggests that this radiation is a relic of a phase when the universe was opaque; the high degree of isotropy implies that, at least since the photons were last scattered, the universe has expanded in close accordance with a Robertson-Walker metric characterised by a single scale factor $R(t)$. The ratio of photons to baryons - a measure of the "entropy per baryon" in the universe - is

$$\mathcal{S} = 1.4 \times 10^{8} \left(\frac{T_o}{2.7K}\right)^{3} \Omega_b^{-1} \left(\tau_H / 2 \times 10^{10} yr\right)^{2}$$

Note that the main uncertainty in this quantity stems from our ignorance of $\Omega_b$. All we can say is that $\mathcal{S}$ lies in the general range $10^8 - 10^{10}$; somewhat more model-dependent considerations based on the physics of the early universe have, however, led many authors to suggest that this range can be narrowed.

The photons make a negligible contribution to $\Omega$ at the present era : this is because at 2.7K, the mean photon energy is only a few times $10^{-4}$eV. However the radiation temperature (or the energy per photon ) varies as $R^{-1}$ as the universe expands, and the radiation energy density varies as $R^{-4}$. But the matter density varies only as $R^{-3}$. At early times, therefore, the expansion was dominated dynamically by radiation. The expansion would be radiation-dominated for $T \gtrsim 3 \times 10^4 \Omega_b$ , and when kT is a few MeV the baryon contribution is quite negligible, basically because photons outnumber baryons by a factor $\mathcal{S}$ . The Friedmann equations, according to which the expansion rate $\dot{R}/R \propto \rho^{\frac{1}{2}}$, then yield the temperature-time relation

$$t = 2 \left(f(T)\right)^{-\frac{1}{2}} \left(\frac{kT}{1 \text{ MeV}}\right)^{-2} \text{ sec.}$$

The quantity $f(T)$ denotes the factor by which the energy density at temperature T exceeds that due to black-body photons alone. At a temperature of a few MeV, when one has $e^+$-$e^-$ pairs and neutrinos,

$$f(T) = {}^{11}/_{4} + {}^{7}/_{8}\, N_\nu ,$$

$N_\nu$ being the number of two-component neutrino species. At higher temperatures still, other heavier species contribute to $f(T)$; but the processes occurring when kT is of order an MeV turn out to be crucial for nucleosynthesis.

Helium is much more abundant, and much more uniformly distributed, than the heavier elements. The latter could all be the products of stellar nucleosynthesis. The helium, on the other hand, is commonly attributed to the hot dense early phase of the big bang : indeed, the most compelling reason for taking seriously the earlier phases (t = 1-100 sec) of a big bang is that the simplest assumptions (i.e. homogeneity, isotropy, no "new physics", Einstein's general relativity, etc.) yield a He abundance in gratifying accordance with observations[3,4]. The crucial process that determines the amount of He is the neutron/proton "freeze-out" which occurs when the reactions $p + e^- \rightarrow n + \nu$, $p + \bar{\nu} \rightarrow n + e^+$ become slower than the expansion timescale. In a standard radiation-dominated Friedmann model, the reaction rate goes as $T^5$ (since the particle density goes as $T^3$ and the cross section as $T^2$) and the expansion rate $\sim (G\rho)^{\frac{1}{2}} \propto T^2$. The respective timescales are equal at $kT \simeq 1$ MeV. The neutron/proton ratio is then approximately $e^{-1.5}$, most of these neutrons being subsequently incorporated into D and $^3He$, and then into $^4He$, before they have time to decay freely. The predicted $^4He$ abundance depends only slightly on the matter density - for $\Omega_b > 10^{-2}$ (corresponding to $\mathcal{S} \lesssim 10^{10}$) the density of baryons is high enough to ensure that most of the neutrons which survive at "freeze-out" get incorporated in $^4He$. However, the resulting $^4He$ abundance is sensitive to the expansion rate when $kT \simeq 1$ MeV : if the universe expanded somewhat faster, then the neutron/proton ratio would "freeze out" at a higher temperature, when neutrons were less disfavoured by the Boltzmann factor; the $^4He$ abundance would then be higher.

## LIMITS ON NUMBER OF NEUTRINO SPECIES

Schwartzman[5] pointed out in 1969 that the observed fractional abundance of $^4He$ can be used to place interesting constraints on the number of types of neutrino. This is because the amount of $^4He$ produced depends on the expansion rate (at a given T) and therefore on the number of independent species. One of the main uncertainties in quantifying this line of argument is that we do not know the primordial $^4He$ abundance — all that we can say is that it must be below the lowest reliably-determined abundance in any astronomical object (since stars can make extra helium during the course of galactic evolution). Most astronomers would assess that the primordial $^4He$ must be $\leq 25\%$. This is consistent [4] with $N_\nu = 3$ for $\mathcal{S} > 2 \times 10^9$ (which corresponds to $\Omega_b < 0.08\ (\tau_H/2 \times 10^{10}\,\mathrm{yr})^2$ and permits $N_\nu = 4$ for $\mathcal{S} > 6 \times 10^9$ $(\Omega_b < 0.03(\tau_H/2\times10^{10}\,\mathrm{yr})^2)$. Lower densities are needed, for a given $N_\nu$ and expansion rate, if the primordial fraction of $^4He$ is less than (say) 23% rather than 25%. However, very low values of $\Omega_b$ lead to another inconsistency ; the abundance of $^3He$, and D, intermediate products in $^4He$ synthesis, exceed what is observed[3,6]. These isotopes are both produced in the big bang; D can be burnt into $^3He$ in stars, but the primordial abundance of $(^3He + D)$ is unlikely to have exceeded the presently-observed value of $8 \times 10^{-5}$. This constrains $\Omega_b$ to be $\gtrsim 0.05\ (\tau_H/2\times10^{10}\,\mathrm{yr})^2$ (i.e. $\mathcal{S} < 3 \times 10^9$).

These arguments, based on primordial nucleosynthesis, suggest that $N_\nu \lesssim 4$, and that $\Omega_b$ is of order $0.1\ (\tau_H/2 \times 10^{10}\,\mathrm{yr})^2$. Higher values of $N_\nu$ could be reconciled only with more contrived and inhomogeneous models. If the lepton number for $\nu_e$ and $\bar{\nu}_e$ were non-zero, then the neutron-proton equilibrium ratio would be shifted, thereby affecting $^4He$ production. It is possible in principle to compensate for any speed-up factor in this way and thereby permit a higher value of $N_\nu$ or a higher $\Omega_b$ [3,7]. However, in order to make any difference, neutrino lepton number must be of order the photon number - i.e. $\sim\mathcal{S}$ times larger than the baryon number.

## NEUTRINO MASSES

A straightforward calculation shows that, if neutrinos have no rest mass, the present density, for each two-component species, is $n_\nu = 110\ (T_\gamma/2.7\mathrm{K})^3\ \mathrm{cm}^{-3}$. This conclusion still holds for non-zero masses, provided that $m_\nu c^2$ is far below the thermal energy ( $\sim 10$ MeV) at which neutrinos decoupled from other species and that the neutrinos are stable for a time $\tau_H$. Comparison with the baryon density of $\sim 3 \times 10^{-6}\Omega_b(\tau_H/2 \times 10^{10}\,\mathrm{yr})^{-2}$ shows that neutrinos outnumber baryons by such a big factor ( $\sim\mathcal{S}$) that they can be dynamically dominant over baryons even if their masses are only a few eV[8]. In fact a single species of neutrino would yield a contribution to $\Omega$ of

$$\Omega_\nu = 0.04(m_\nu)_{eV}\ \ (\tau_H/2 \times 10^{10}\,\mathrm{yr})^2.$$

The entire range 100 eV - 3GeV is incompatible with the hot big bang model[9]. (for $m_\nu \gtrsim 3$ GeV, the rest mass term in the Boltzmann factor would kill off most of the neutrinos before they decouple; the number surviving would be $\lesssim n_b$). If a neutrino in this mass range were discovered, it would show that one cannot extrapolate the hot big bang back to kT $\gtrsim$ 10MeV, and that most of the photons must have been generated at later times . Analogous limits can be set on the rest masses of possible right-handed neutrinos[10]. If these neutrinos interact even more weakly than left-handed neutrinos, they would have decoupled at an earlier stage in the hot big bang. Other species that annihilate after the right-handed neutrinos decouple would enhance the number of left-handed neutrinos but not of right-handed. The mass limits on the latter are correspondingly less stringent.

Neutrinos with a mass of a few eV would be dynamically important not only for the expanding universe as a whole but also for large bound systems such as clusters of galaxies. This is because they would now be moving slowly:if the universe had remained homogeneous, their velocities would now be $\sim 200\ (m_\nu)^{-1}_{eV}$ km $s^{-1}$. They would be influenced even by the weak ($\sim 10^{-5} c^2$) gravitational potential fluctuations of galaxies and clusters.

It was conjectured a decade ago[11,12] that neutrinos could provide the "hidden mass" in galactic halos and clusters. In the last two years astrophysicists have explored this possibility in some detail,[13-18] and considered scenarios for galaxy formation in which neutrino clustering and diffusion play a key role. These scenarios have several appealing features, even though they lead to some new problems. If neutrinos indeed have masses of a few eV, then it is an inevitable consequence of the "hot big bang" model that the large-scale structure of the universe should be dominated by gravitationally-bound clusters of neutrinos. The characteristic scales and shapes of these bound systems can be calculated, and future astronomical studies of how galaxies are distributed in space may allow tests of this model. If the three (or more) types of neutrinos have different masses, then the heaviest will obviously be gravitationally dominant, since the numbers of each species should be the same.

We may inhabit a universe where, on the largest scales, the baryons are merely a "tracer" for the distribution of a gravitationally-dominant neutrino sea. Neutrinos of mass $\sim$ 10 eV ($10^{-32}$ gm ) are just one candidate for the unseen mass in the universe: as far as the astronomical evidence goes, the unseen mass could equally well be black holes of up to $10^6$ solar masses ($\sim 10^{39}$ gm). Our level of ignorance is such that there are > 70 orders of magnitude uncertainty in the individual masses of the entities that comprise 90% of the bulk of the universe!

(I might note parenthetically that neutrino rest masses of $\lesssim$ 1eV would have no important consequences for cosmology or large-scale astronomy. However, if neutrinos have very small rest masses and, in consequence, "oscillate", this may have detailed consequences in (e.g.) supernova explosions; even a mass of $10^{-6}$ eV would permit oscillations of MeV-neutrinos over a path length $\lesssim 10^{13}$ cm, and therefore affect the results of solar neutrino experiments.)

UNSTABLE NEUTRINOS

A new set of considerations apply if neutrinos are unstable. If the lifetimes are $\ll \tau_H$, all primordial neutrinos would have decayed long ago. For lifetimes $< 10^4$ sec, the decays would occur so early that the resultant energy would have been thermalised, leaving no trace except for an increased $\mathcal{S}$ , compared to its value before the decays. (There are, however, other astrophysical constraints on lifetimes $\lesssim 10^4$ sec, from stellar evolution and supernova theory[19].) If the decay time is longer than $10^4$ sec, there would be residual distortions in the microwave background.

If the lifetimes are $\gtrsim \tau_H$, the decay rate per comoving volume will have been essentially constant, and the most conspicuous effect would be a photon background due to decays at recent epochs.[20-22] For masses 10-100 eV, the photons would be in the ultraviolet. The contribution of the ultraviolet background to $\Omega$ is $\lesssim 10^{-8}$; this means that lifetimes between $\tau_H$ and $10^{24}$ sec can be excluded (for $m_\nu > 10$ eV). An even more sensitive limit can be set by considering indirect effects of ultraviolet photons on the intergalactic medium,[22] or (if the resultant photons have energies < 13.6 eV) by sensitive observations of clusters of galaxies in which the neutrino density may be enhanced above its mean value.[23]

## BARYON PRODUCTION

The success of the hot big bang model in relating the origin of the light elements ($^4$He, $^3$He, D) to processes occurring at $t \simeq 1$ sec has emboldened some physicists and astrophysicists to extrapolate back to still earlier times, when the physics is more uncertain and more exotic. Such extrapolation must stop at the Planck time $(G\hbar/c^5)^{\frac{1}{2}} \simeq 10^{-44}$ sec, when $kT \simeq 10^{19}$GeV and quantum gravity effects are crucial. However, if the expansion had indeed followed a Friedmann model (with $p = \frac{1}{3}\rho c^2$) ever since the threshold of "classical" cosmology, the temperature-time relation would be roughly

$$kT \simeq 10^{19}\left(t/10^{-44}\text{sec}\right)^{-\frac{1}{2}} \text{ GeV}.$$

For the first microsecond, kT exceeds a GeV; and during these initial stages the particle energies sweep down through the entire range of interest to theoretical high energy physicists - including, of course, the ultra-high energies unattainable by any feasible terrestrial accelerator.

When $t \lesssim 10^{-36}$ sec the particle energies exceed $10^{15}$GeV, the characteristic mass of the X-boson hypothesised in grand unified theories (GUTs). The consequences of baryon non-conservation may then be crucial : indeed many authors have raised the exciting possibility that the baryon content of the universe - i.e. the value of the parameter $\mathcal{S}$ - may have been imprinted at this era[24-30] (for recent reviews see refs 31 or 32). Provided that C and CP violation occurs, and provided also that the relevant reactions are slow enough relative to the expansion rate to allow non-equilibrium effects to build up, the universe can, as it cools below $10^{15}$GeV, acquire an excess of baryons over antibaryons which is related to the CP-violation parameter. (The <u>non-equilibrium</u> requirement is essential; just as at the much later nucleosynthesis epoch the rapid expansion prevents everything from turning into iron.) Detailed computations show that several GUT schemes lead to an asymmetry of $10^{-9}$; this is the value which would yield $\mathcal{S} \simeq 10^9$, after the baryon-antibaryon pairs annihilate when kT falls below 1GeV. It would be remarkable if GUT theories did indeed account for the baryon content of the universe without needing to impose it as an initial condition. If such a theory could be firmly established, it would vindicate our extrapolation of a Friedmann model - in one bound - almost back to the Planck time. In terms of logarithmic time this is a bigger extrapolation from the nucleosynthesis era than is involved in going to that era from the present time. It would also place constraints on any dissipative processes (arising from viscosity, phase transitions, black hole evaporation, etc) which might occur as the universe cools through the "desert" between $10^{15}$GeV and 100GeV ($10^{-36}$sec - $10^{-10}$sec).

PHASE TRANSITIONS

In grand unified theories such as SU(5) or SO(10), there would be a phase transition at a temperature of order $10^{15}$GeV; there would also be a phase transition at the electro-weak unification energy of $\sim 10^2$GeV.[33] One of the phases will in general have a lower energy density than the other; a first-order transition would occur, involving the creation (via quantum fluctuations) of "bubbles" of new-phase in a medium that is elsewhere in the old phase. Each new-phase bubble will expand until it collides with another. The differing energy densities of the two vacua would be equivalent to different values of the cosmical constant ( or $\Lambda$-term).

The $\Lambda$-term is now very small (corresponding to a mass-energy density of $\lesssim 10^{-30}$gm cm$^{-3}$; or, in other units, to $\lesssim 10^{-44}$GeV$^4$). One would expect the change in the effective $\Lambda$-term associated with symmetry-breaking to be of order the energy density at the "grand unified temperature, i.e. $\sim 10^{60}$GeV$^4$. Why things should be "fine tuned" to a precision of $\lesssim$ 1 part in $10^{100}$, so that the post-transition $\Lambda$-term is so small, is still a mystery (but see ref (34)).

If the dynamics of the very early universe are effectively dominated by a $\Lambda$-term, then R(t) inflates exponentially (the "de Sitter cosmology"). The idea of an exponential growth phase has some appealing consequences[35,36]. In particular, it suggests an answer to the problem of why the universe is so large — why the curvature radius of the hypersurfaces of homogeneity in the Robertson-Walker metric is $\gtrsim 10^{30}$ times the comoving scale of the horizon at the Planck time. If R grows by (say) $e^{100}$ during this phase, the large scale of the universe, or its "flatness", could be accounted for.

The main difficulty of this scheme centres on whether the universe can expand by a gigantic factor and still, afterwards, achieve a "graceful exit" from its exponential growth - whether there can be a transition to a Friedmann phase where $R \propto t^{\frac{1}{2}}$. (For a discussion of this, see ref (37)). Note that, for this scheme to work, the heat released during the phase transition must raise kT above $m_x c^2$ so that baryon synthesis can occur after the exponential phase. Optimists might hope that this model could not only account for the universe's overall homogeneity, but also generate fluctuations (needed to give galaxies and clusters) from microscopic effects.

The "inflationary" universe can perhaps (if its other difficulties can be overcome) account for the scale of our universe; but it offers no explanation for why the early universe should have been so isotropic - describable by the Robertson-Walker metric.

A major uncertainty in quantifying the cosmological consequences of phase transitions arises from the unknown rate at which bubbles are nucleated. Recent work[38] suggests that the thermalisation and homogenisation would be slow and inefficient. Collisions between bubble walls could lead to formation of black holes. Any black holes formed at the "grand unified" era would quickly evaporate; but those formed after a phase transition at the Salam-Weinberg temperature would have planetary masses and would survive to the present day. The more the phase transition is delayed, the greater is the boost given to the entropy - for instance, if the electro-weak transition, releasing $\gtrsim 10^5$GeV$^4$ of energy density, was delayed until kT had fallen to a few hundred MeV, $\delta$ would be enhanced by up to $\sim 10^6$, thereby destroying the apparent concordance between the GUT predictions and the photon/baryon ratio observed today.

The production of magnetic monopoles is expected whenever the symmetry of an initial non-Abelian group is spontaneously broken, and the unbroken symmetry group contains the Abelian U(1) in its decomposition[39,40]. If this leads to even one monopole per horizon volume, and the monopole mass is $\sim 10^{15}$GeV, then the resultant monopoles would exceed by $10^{10}$ the number needed to yield[41] $\Omega = 1$; the discrepancy is even greater when one takes into consideration the stringent constraints on the monopole density implied by the existence and persistence of large-scale cosmic magnetic fields. Some mechanism for suppressing or diluting the monopole density far below this naive estimate is obviously needed.

Symmetry-breaking may lead also to the formation of "domain walls" or "strings". The former can probably be ruled out, on the grounds that the effective mass-energy of the walls would be incompatible with present-day cosmological constraints. One-dimensional singularities - "strings" - cannot however be excluded[42]. It is not clear whether the topology of the strings would allow them to contract and disappear, or whether on the other hand they are stretched as the universe expands. In the latter case, they could contribute $\Omega \simeq 10^{-4}$ even at recent epochs, and might be the "seed" fluctuations that trigger galaxy formation[43,44].

## CONCLUSIONS

In the last two decades, the hot big bang model has "matured' from the somewhat speculative concept introduced by Lemaitre, and by Alpher, Gamow and Herman : it still is not dogmatically established, in that there exist alternative (though somewhat contrived) models that are compatible with the sparse relevant data; but it is much more plausible than any specific alternative. If the "hot big bang" is accepted, we can infer the following:

(i) There are unlikely to be more than 4 species of 2-component neutrinos.

(ii) No (left-handed) neutrinos have masses in the range 100 eV - 3 GeV.

(iii) Some astrophysical considerations actually favour a neutrino mass $\sim$ 10eV Neutrinos, and not baryons, could then be gravitationally dominant in large systems of galaxies in the expanding universe.

(iv) There are astrophysical constraints on neutrino lifetimes if they are unstable.

While there are "escape clauses" which render these inferences less than compelling, they can validly be cited as relevant evidence by particle physicists. These inferences depend on extrapolating back to $\lesssim 10^{-2}$ sec (kT $\gtrsim$ 10MeV), but the agreement between the predicted primordial nucleosynthesis and the observed helium and deuterium abundances give us some confidence in the validity of this.

The consequences of other recent ideas in particle physics require a further extrapolation backward towards the singularity - indeed, the consequences of GUTs require us to go back 35 more orders of magnitude in time. It would be exciting if such theories could account for the unexplained parameter $\mathcal{S}$; but at the moment this topic is at the same speculative stage that the era $10^{-2}$-1 sec was before the microwave background had been discovered. One could however be more optimistic, and claim the "prediction" of $\mathcal{S}$ as one of the few empirical tests of grand unified theories.

If indeed this optimism is justified, it throws into sharper focus the problem of why the universe resembles an isotropic Friedmann model. The solution to this problem should perhaps be sought at the Planck time; it must await a theory of quantum gravity.

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## Discussion

B. Kayser, SLAC and VS-NSF: There are experiments searching for heavy but "left-handed" neutrinos emitted together with electrons in $\pi$ decay a small percentage of the time. Such neutrinos could have masses in the (10-100) MeV range. What do cosmological considerations say about the possibility of such neutrinos?

M. Rees: There is no difficulty if the mass is so high that it exceeds $kT$ when the neutrinos decouple. The neutrinos are then killed off by the Boltzmann factor, and the surviving density can be much less than the photon density (or even less than the baryon density). In simple models, this requires $\gtrsim$ 2 GeV, however.

H. Faissner, TH Aachen: Would you mind about an axion existing, with half-weak coupling, a mass near 250 KeV, and a lifetime close to 10 msec?

M. Rees: I don't think this would have a drastic effect on cosmology, because the decay would occur prior to nucleo-synthesis. However, some constraints can be set from supernova theory. Supernovae ejection only involves $\lesssim 10^{51}$ erg, whereas the energy released when a neutron star forms may be $\sim 10^{53}$ erg. This excess energy "goes to waste" as neutrinos or gravitational waves, and does not give kinetic energy to the envelope. However, if too many axions decayed before escaping the envelope, they would boost its kinetic energy to an unacceptably high value. On the other hand, there is a theoretical problem in getting model supernovae to explode at all - in this connection, an energy boost due to axions which decayed in a few milliseconds would be helpful!

E. Gabathuler, CERN: In your talk you mentioned possible mass-limits on right-handed neutrinos from cosmology. Would you care to comment?

M. Rees: These limits can be set, but are less stringent than for ordinary neutrinos. This is because if the right-handed neutrinos interact even more weakly, they will decouple from other species earlier, when $g'$ may still be high. The extra energy input when $g'$ falls then boosts the number of left-handed neutrinos, but not necessarily that of right-handed neutrinos. Since they are less numerous they are allowed to be individually more massive. For Majorana right-handed neutrinos, up to 1 KeV would be permissible.

M. E. Peskin, Cornell University: I think it worth mentioning a more speculative idea about the dark matter of the universe. Many authors have proposed that the effects which you ascribe to massive neutrinos could be explained in supersymmetry theories by the presence of massive supersymmetric partners of familiar particles. In particular, in the class of models studied by Fayet and Farrar, the fermionic partner of the photon, the "photino", has a small mass which might well be of the required size. Thus we not only don't know the type of object which comprises this dark matter, we don't even know if it is made of particles which have been experimentally recognized.