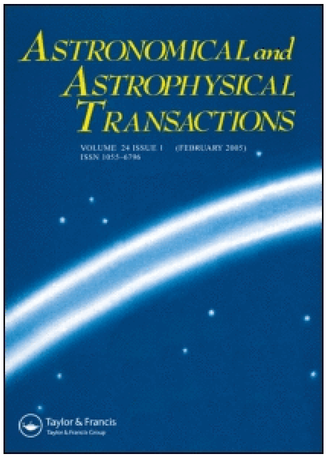

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DARK MATTER IN THE UNIVERSE

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Cosmological arguments proving that the universe is dominated by invisible non-baryonic matter are reviewed. Possible physical candidates for dark matter particles are discussed. Particular attention is paid to non-compensated remnants of the vacuum energy, to the question of the stability of super-heavy relics, cosmological mass bounds for very heavy neutral leptons, and some other more exotic possibilities.

KEY WORDS Invisible dark matter, particles

1 INTRODUCTION

Probably one of the most important discoveries of the 20th century was the discovery that the universe consists mostly of an unknown form of matter. This matter neither emits nor absorbs light and got the name dark (or better to say, invisible) matter. It is observed only indirectly through its gravitational action and, though there are plenty of theoretical hypotheses, the nature of dark matter remains mysterious. The first hints of the existence of dark matter were found more than half of a century ago [1, 2]. The velocity dispersion of astronomical objects was larger than one would expect from observations of luminous matter. The fact that there is more mass than light in the universe got strong support only 40 years later. It was initiated by two groups [3, 4] and stimulated a burst of activity in the field. Now there is a large amount of accumulated astronomical data that unambiguously prove that the universe is dominated by invisible matter or to be more precise there is much more gravity in the universe than all the visible matter could provide.

Very strong arguments in favour of invisible cosmic matter follow from so-called galactic rotational curves, i.e. from the observed dependence of velocities of gravitationally bound bodies on the distance from the visible centre. A very well known example of rotational curves that have led to the seminal discovery of Newton's gravitational law is the distribution of velocities of planets in the solar system (see Figure 1, taken from ref. [5]).

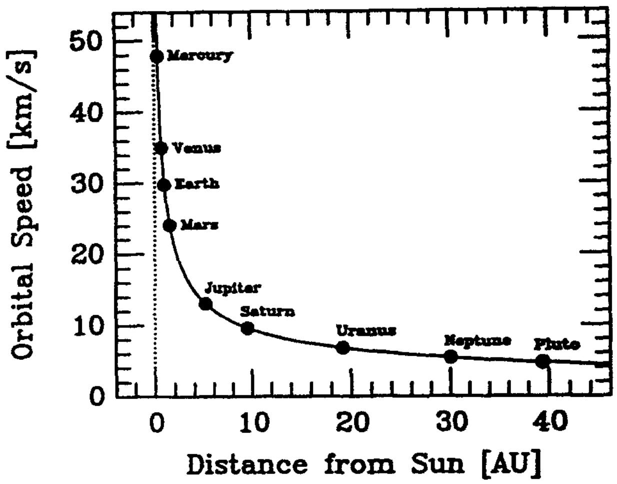

Figure 1 Rotation curve of the solar system which falls off as $1/\sqrt{r}$ in accordance with Kepler's law. The astronomical unit (AU) is the Earth–Sun distance of 1.50×10^{13} cm.

On the basis of this data it was concluded that gravitational forces fall with distance as $F \sim 1/r^2$ and correspondingly, by the virial theorem, $v^2(r) \sim G_N M(r)/r$, so that $v \sim 1/\sqrt{r}$ for a point-like central mass; here $M(r)$ is the mass of gravitating matter inside the radius r. However measurements of rotational velocities of gas around galaxies produce a very different picture; $v(r)$ does not go down to zero with increasing distance from the luminous centre but tends to a constant value, see Figure 2 [6].

To the present day more than 1000 galactic rotational curves has been measured (see e.g. [7]) and they show similar behaviour. It is quite a striking fact that rotational curves are very accurately flat at large distances, $v \to$ const. If such curves had been observed at Kepler and Newton's time one might conclude that the gravitational force did not obey the famous inverse square law but something quite different, $F \sim 1/r$, with the potential $U \sim \ln r$. However, it is very difficult, if at all possible, to modify beautiful general relativity at large distances in such a way that it would give $1/r$ forces. The normal interpretation of flat rotational curves is that there is invisible matter around galaxies with mass density decreasing as

$$\rho \sim \frac{1}{r^2} \tag{1}$$

and correspondingly $M(r) \sim r$. Such a mass distribution could be in a self-gravitating isothermal gas sphere. However, if the dark matter particles do not possess a sufficiently strong self-interaction it is not clear how they would acquire thermal equilibrium.

It is not yet established how far the law (1) remains valid. If it is true up to neighbouring galaxies, the average mass density of this invisible matter would be

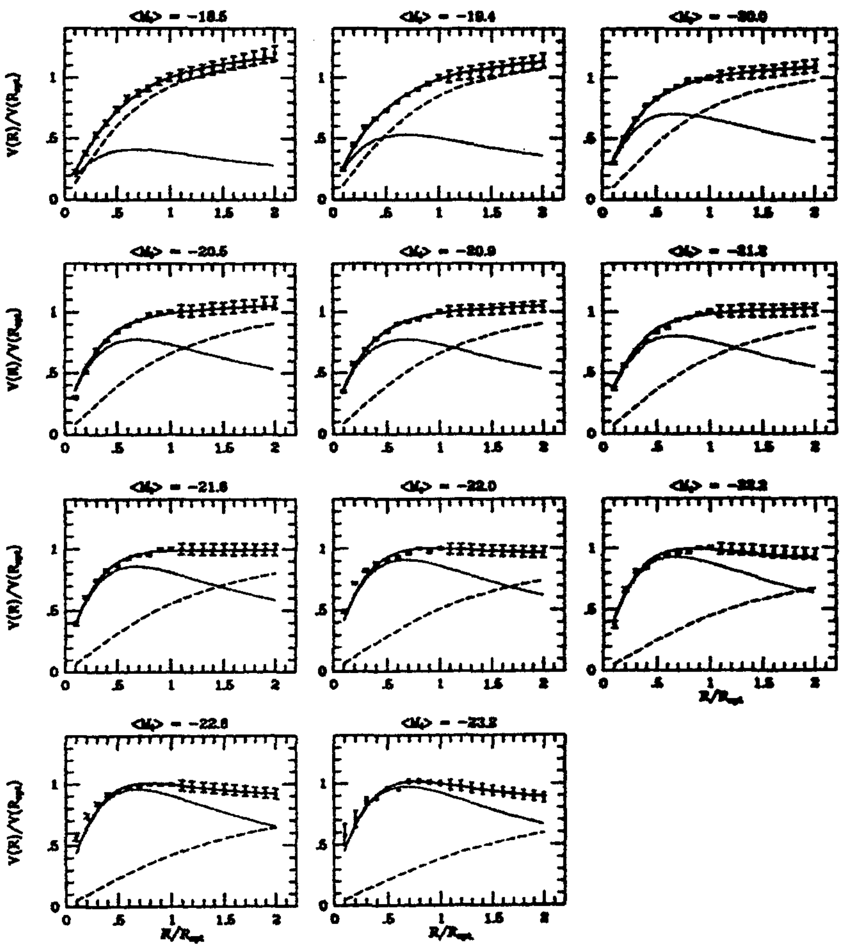

Figure 2 Coadded rotation curves (filled circles with error bars) reproduced by the universal rotational curve (solid line). Also shown are the separate dark/luminous contributions (dotted line: disk; dashed line: halo.)

rather close to the critical one

$$\rho_c = \frac{3H^2}{8\pi G_N} \approx 1.86 \times 10^{-29} h_{100}\ \mathrm{g\ cm^{-3}}, \qquad (2)$$

where $h_{100} = H/100$ km s^{-1} Mpc^{-1} is the dimensionless Hubble constant; by the most recent data [8] $h_{100} \approx 0.7$ with error bars of about 10–15%; for a review see ref. [9].

The contributions of different forms of matter to the cosmological mass/energy density according to the present day data is the following. The visible luminous matter contributes very little to the total density [10]:

$$\Omega_{\rm lum} = \frac{\rho_{\rm lum}}{\rho_c} \leq 0.003 h_{100}^{-1}. \tag{3}$$

There could be many more non-luminous baryons in the form of faint stars, gas, etc. (see below Section 2) but the standard theory of primordial nucleosynthesis does not allow too high a mass fraction of baryonic matter. It is probably the proper time and place to mention that George Gamow [11] made a pioneering contribution to big bang nucleosynthesis. The abundances of light elements are sensitive to the total number fraction of cosmic baryons, more precisely the abundances of light elements depend upon the ratio of the number densities of baryons to photons, $\eta_{10} = 10^{10} n_b/n_\gamma$. Comparing the theoretical predictions with observations one can deduce the value of this ratio at nucleosynthesis. The result crucially depends upon the observed abundance of deuterium since the latter is especially sensitive to η. There are two conflicting pieces of data: high and low deuterium; see the discussion and references in the review [12]. For low ^{2}H regions the limits presented in ref. [12] are:

$$\Omega h_{100}^2 = 0.015\text{–}0.023 \text{ and } \eta_{10} = 4.2\text{–}6.3 \tag{4}$$

while for high ^{2}H:

$$\Omega h_{100}^2 = 0.004\text{–}0.01 \text{ and } \eta_{10} = 1.2\text{–}2.8. \tag{5}$$

Most probably one or other of the above is incorrect and the predominant attitude is in favour of low deuterium. However, it would be extremely interesting if both were true, so that the abundance of primordial deuterium is different in different regions of the universe. A possible explanation of this phenomenon is a large and spatially varying neutrino degeneracy that predicts a large mass fraction of primordial helium, more than 50%, compared to $\sim 25\%$ in normal deuterium regions (which were called 'low' above), and quite low helium, $\leq 12\%$, in the anomalously low deuterium regions [13].

Anyhow, independently of these subtleties, big bang nucleosynthesis strongly indicates that the mass fraction of normal baryonic matter in the universe is quite small (see also the discussion below in Section 2). On the other hand, the amount of gravitating matter, found by different dynamical methods (for a review see [14]), gives $\Omega_m \sim 0.3$. These methods are sensitive to clustered matter and do not feel a uniformly distributed energy/mass density. Theoretical predictions based on the inflationary model give $\Omega_{\rm tot} = 1 \pm 10^{-4}$. This number may be compatible with the above-quoted value for Ω_m only if the rest of the matter is uniformly distributed. The recent indications of a non-zero cosmological constant [15] with

$$\Omega_{\rm vac} \approx 0.7 \tag{6}$$

permit us to fill the gap between 0.3 and 1. It is possibly too early to draw a definite conclusion, since the result is very important and all possible checks should be done. Moreover the SN-data that led to the conclusion of non-zero Λ might be subject to a serious criticism [16]. Still the combined different astronomical data quite strongly suggest that the cosmological constant is indeed non-zero.

The attitude to a possibly non-vanishing cosmological constant from different prominent cosmologists and astrophysicists were and is quite diverse. For example Einstein, who 'invented' the cosmological constant and introduced it into general relativity, considered it as the biggest blunder of his life. The attitude of Gamow was similar; he wrote in his autobiography [17]: 'λ again raises its nasty head'. On the other hand, Lemaitre and Eddington considered Λ very favourably. Moreover, a non-zero Λ (or what is the same, the vacuum energy) should be quite naturally non-zero from a particle physicist's point of view, though any theoretical estimate by far exceeds astronomical upper limits (see the discussion in Section 4).

To conclude, it seems very probable that normal baryonic matter contributes only a minor fraction to the total mass/energy of the universe and we will discuss below possible forms of this yet unknown but dominant part of our world. It is not excluded that there is not a single form of dark matter. The data request several different ones and if it is indeed the case the mystery becomes even deeper. In particular, one has to understand the so-called cosmic conspiracy: why different forms of dark matter give comparable contributions to Ω, while they would naturally differ by many orders of magnitude.

2 BARYONIC DARK MATTER

Since the idea that there is a cosmic ocean of an absolutely unknown form of matter is quite drastic, one is inclined to look for less revolutionary explanations of the data. The first natural question is: could all the dark matter, possibly excluding vacuum energy, be the normal baryonic stuff somehow hidden from observation. The relevant discussion of the cosmic baryon budget can be found in ref. [18].

As we have already mentioned in the Introduction a very strong upper limit on the total number of baryons in the universe follows from the big bang nucleosynthesis. However this limit would be invalid if for example electronic neutrinos are strongly degenerate [19, 20]. A charge asymmetry in the electronic neutrinos corresponding to the dimensionless chemical potential $\mu_{\nu_e}/T \sim 1$ could significantly loosen the bound on baryonic mass density and make it close to the necessary $0.3\rho_c$.

However there are some other data that make it very difficult to have a baryon dominated universe. Strong arguments against this possibility come from the theory of large-scale structure formation. In the case of adiabatic perturbations that are characterized by the approximate equality of density and temperature fluctuations, $\delta\rho/\rho \sim \delta T/T$, there is too little time for cosmic structures to evolve. Indeed the perturbations in baryonic matter could arise only after hydrogen recombination that took place rather late at redshift $z \approx 10^3$. After that the perturbations might arise only as the scale factor so to the present time they could at most be amplified by this factor of 10^3. However, it is well known that the fluctuations of the CMB (cosmic microwave background) temperature are quite small, $\delta T/T <$ a few $\times 10^5$.

Hence even today the density fluctuations should be quite small in contrast to the observed developed structures with $\delta\rho/\rho \gg 1$.

For isocurvature perturbations the fluctuations of the CMB temperature are much smaller than density perturbations, $\delta T/T \ll \delta\rho/\rho$, and this permits us to avoid the above objection. However if this were the case, the spectrum of angular fluctuations of the CMB would be quite different from the observed one. In particular, the first acoustic peak would be near $l = 400$, while the data strongly indicates that this peak is close to $l = 200$ in agreement with adiabatic theory (for a recent review and a list of references see e.g. ref. [21]). This argument can be avoided if the shift of the acoustic peak to higher l is compensated by the curvature effects (I thank J. Silk for indicating this point).

Another weighty argument against a baryonic universe is that it is practically impossible to conceal 90% of the baryons. Baryonic matter strongly interacts with light and even if the baryons are non-luminous themselves, they would strongly absorb light. So baryonic matter should be observed either in emission or absorption lines. There is not much space for baryons to escape detection:

1. *Cold gas or dust* does not emit light but can be observed by absorption lines (the Gunn–Peterson test).

2. *Hot gas* is seen by X-rays if it is clumped; if it is diffuse it would distort the CMB spectrum.

3. *Neutron stars or 'normal' black holes*, which were produced as a result of stellar evolution, would contaminate the interstellar medium by 'metals' (elements that are heavier than ^{4}He).

4. *Dust* is seen in the infrared.

According to ref. [18] the total baryon budget is in the range:

$$0.007 \leq \Omega_B \leq 0.041 \tag{7}$$

with the best guess $\Omega_B = 0.021$ (for $h_{100} = 0.7$).

A special search was performed for the so-called MACHO's (massive astrophysical compact halo objects). They may include brown dwarfs, low-luminosity stars and primordial black holes. Such objects are not directly visible and they were looked for through gravitational micro-lensing [22]. The search was pioneered by MACHO [23] and EROS [24] collaborations and at the present time about a hundred such objects have been found in the Galaxy and in the nearby halo. According to the EROS results the mass density of the micro-lenses with masses in the interval $(5 \times 10^{-8}\text{–}10^{-2})M_\odot$ is less than $0.2\rho_{\text{Halo}}$. The MACHO observations permit us to draw the conclusion that the masses of the micro-lensing objects lies in the interval $(0.1\text{–}1.0)M_\odot$ at 90% CL. The mean value of the mass is about $0.5M_\odot$.

Instead of approaching the resolution of the problem of dark matter, these observations made things even more mysterious and more interesting. A large mass of MACHO's suggests that they could be the remnants of the usual stars (white dwarfs?). However it is difficult to explain their relatively large number density and distribution. They could be primordial black holes but in this case they are not necessarily baryonic. An intriguing possibility is that they are so-called mirror or shadow stars, i.e. they are formed from a new form of matter that is related to ours only gravitationally and possibly by a new very weak interaction (see Section 8).

Anyhow, baryons seem to contribute only a minor fraction to the total mass of the universe and some new form of matter should exist. There is no shortage of possible candidates but it remains unknown which one (or maybe ones) is (are) the real dominating entity.

3 NON-BARYONIC (EXOTIC?) DARK MATTER; WHAT IS IT?

For an astronomer the classification of dark matter from the point of view of large-scale structure formation is especially relevant. Independently of its physical nature cosmological dark matter can be of the following three types:

1. Hot dark matter (HDM). For this form of dark matter the structure can be originally formed only at very large scales, much larger than galactic size, $l_{\mathrm{str}} \gg l_{\mathrm{gal}}$.

2. Cold dark matter (CDM). This is the opposite limiting case for which the structure is formed at the low scale, $l_{\mathrm{str}} \ll l_{\mathrm{gal}}$.

3. Warm dark matter (WDM). This is an intermediate case when the characteristic scale of the structures is of the order of the galactic size, $l_{\mathrm{str}} \sim l_{\mathrm{gal}}$.

Somewhat separately there stands a Λ-term or, what is the same, vacuum energy. There are some rather strong indications that for a good description of the observed large-scale structure several different forms of dark matter, including the Λ-term, may be necessary.

Another astronomically important feature of dark matter is its dissipation properties. If dark matter easily loses energy, structure formation could proceed faster. In the opposite case the cooling of dark matter would be less efficient and the structures on small scales would not be formed. So from this point of view there could be two forms of dark matter, *dissipationless* and/or *dissipative*. The dominant part of physical candidates for dark matter particles are weakly interacting and thus dissipationless. However there are some, possibly more exotic, models supplying strongly interacting dark matter particles that could easily lose energy.

There are quite a few physically possible, and sometimes even natural, candidates for dark matter particles. An abridged list of them in order of the author's preference is the following:

1. massive neutrinos;

2. non-compensated remnant of the vacuum energy;

3. new not yet discovered, but theoretically predicted, elementary particles: the lightest supersymmetric particle, axion, majoron, unstable but long-lived particles, super-heavy relics, etc. It is even possible to construct models in which the same kind particles would contribute, e.g. both to hot and warm dark matter;
4. new shadow or mirror world;
5. primordial black holes;
6. topological defects (topological solitons);
7. non-topological solitons;
8. none of the above.

It is quite possible that the last entry may happen to become the first after all.

4 VACUUM ENERGY

The problem of the vacuum energy is possibly the most striking in contemporary physics. Any reasonable theoretical estimate disagrees with the astronomical upper limits on ρ_{vac} by 50–100 orders of magnitude (for a review see refs. [25, 26]. In fact there are practically experimentally proven contributions to the vacuum energy from the known vacuum condensates of quarks and gluons in quantum chromodynamics (QCD). The existence of these condensates is necessary for a correct description of hadron properties. In this sense the existence of these condensates is an *experimental fact*. So we have a fantastic situation: there are well-established contributions to the vacuum energy that are larger than the permitted value by the factor 10^{47}. This may only mean that there is some extremely accurate mechanism that compensates this huge amount practically down to zero. Here 'zero' is in the scale of elementary particle physics; on an astronomical scale the remaining vacuum energy may be quite significant. This compensation should be achieved by something that is not directly related to quarks and gluons because all the light fields possessing QCD interactions are known, while heavy fields cannot make a compensation with the desired accuracy.

It is tempting to assume that the curvature of space-time created by the vacuum energy would generate a vacuum condensate of a new massless (or extremely light) field Φ and the energy of the condensate would cancel down the original vacuum energy in accordance with the famous Le Chatelier principle. It is closely analogous to the axionic mechanism of natural CP-conservation in QCD. Generic features that one should expect from such a compensating (or adjustment) mechanism are quite interesting. First, the compensation is never complete, the amount of non-compensated vacuum energy is always parametrically of the order of the critical energy:

$$\Delta\rho_{\text{vac}} = \rho_{\text{vac}}^{\text{in}} - \rho_{\Phi} \sim \frac{m_{\text{Pl}}^2}{t^2}, \tag{8}$$

but the coefficient of proportionality may be different at different stages of the evolution of the universe (e.g. at the MD- and RD-stages). Another unusual feature is that the equation of state of dark matter corresponding to $\Delta\rho_{\text{vac}}$ may be very much different from the standard ones, $p = \rho/3$ at RD-stage or $p = 0$ at the MD-stage.

So hopefully such a compensating mechanism may be able not only to cut the 'nasty head of λ' (using Gamow's words) but also to extinguish it almost down to nothing with only a small tail remaining. In fact, it is exactly this small tail that induced such a strong negative reaction from Gamow, because it could be 100% cosmologically relevant. This demonstrates two sides of the cosmological constant problem. Astronomers put the question if it is cosmologically important, i.e. if ρ_{vac} is not negligible in comparison with ρ_c. If the answer is affirmative, then another puzzling problem appears: why is the vacuum energy, which remains constant in the course of the cosmological expansion, today close to ρ_c which evolves as $1/t^2$? Particle physicists are more puzzled by the question of why the vacuum energy does not exceed ρ_c by an almost infinite amount. However if this is somehow resolved, then the natural value should be precisely zero. So astronomical indications that ρ_{vac} may be non-vanishing are of prime importance for all members of the astroparticle community.

The compensation mechanism would successfully address both issues: it permits us to compensate ρ_{vac} to a cosmologically acceptable value and gives a non-compensated remnant of the order of ρ_c at any period of the history of the universe. However all these are predictions of a non-existing theory. The original compensating mechanism [27] is based on a massless scalar field with Lagrangian:

$$\mathcal{L}_0 = (\partial\Phi)^2 + \xi R \Phi^2 \tag{9}$$

where R is the curvature scalar. For a certain choice of the sign of the constant ξ the field Φ becomes unstable in a De Sitter background (the term ξR^2 behaves as a negative mass squared) and a vacuum condensate of Φ would evolve. The back-reaction of this condensate on the expansion results in a change from the exponential De Sitter regime to a slower Friedman one, $a(t) \sim t^\alpha$. So far so good, but this change of regime was not achieved by the compensation of the vacuum energy. In fact the energy–momentum tensor of Φ does not have the vacuum form, it is not proportional to the metric tensor $g_{\mu\nu}$. The slowing of the expansion is achieved by the decrease of the gravitational coupling constant with time, $G_N \sim 1/t^2$.

Other possible candidates for the role of the compensating field could be fields with higher spins, vector or tensor ones [28]. More promising seems to be the symmetric tensor field $\Phi_{\mu\nu}$. Even the simplest possible Lagrangian:

$$\mathcal{L}_2 = \Phi_{\mu\nu;\alpha}\Phi^{\mu\nu;\alpha} \tag{10}$$

gives rise to an unstable solution of the equations of motion and to the development of a vacuum condensate that compensates the vacuum energy. In contrast to the energy–momentum tensor of the scalar field considered above, the energy–momentum tensor of $\Phi_{\mu\nu}$ is of the vacuum form, i.e. proportional to $g_{\mu\nu}$. Such a theory possesses a symmetry with respect to the transformation $\Phi_{\mu\nu} \to \Phi_{\mu\nu} + Cg_{\mu\nu}$. This symmetry prevents the quantum generation of the mass of $\Phi_{\mu\nu}$ and may be helpful in some other respects. Still in the simplest versions of the model the gravitational coupling constant evolves with time in the same way as in the scalar field case [29]. Presumably it is related to the breaking of Lorentz invariance by the condensate. The model permits a generalization such that the vacuum field $\Phi_{\mu\nu}$ is proportional to the metric tensor, $g_{\mu\nu}$ so that the condensate is Lorentz invariant. However in any case the cosmology is far from being realistic. Thus, though the compensation mechanism shows some nice features, no workable model giving a realistic cosmology is found at the present day.

Stimulated by the indications that the universe may expand with acceleration, i.e. that $\rho_{\text{vac}} > 0$, a new *constant* parameter w was introduced into the standard set of cosmological parameters [30]. This parameter characterizes the equation of state of cosmological matter:

$$p = w\rho. \tag{11}$$

In the standard cosmology it is assumed that the universe is now dominated by non-relativistic matter, so that $w = 0$. At an earlier stage relativistic matter was dominant and $w = 1/3$. In the case of dominance of the vacuum energy $w = -1$. Two more examples giving a negative w are a system of non-interacting cosmic strings with $w = -1/3$ and also non-interacting domain walls with $w = -2/3$. Since the source of gravity in general relativity (in the isotropic case) is $\rho + 3p$, the universe would expand with acceleration (anti-gravity) if $w < -1/3$.

In particular, a model with a massless or extremely light scalar field was discussed that could give a negative w. This field received the name 'quintessence'. For a homogeneous scalar field $\phi(t)$ with a self-interaction potential $U(\phi)$ the parameter w is given by:

$$w = -\frac{2U(\phi) - \dot{\phi}^2}{2U(\phi) + \dot{\phi}^2}. \tag{12}$$

If the potential energy is larger than the kinetic energy, w would be negative. However in this model w may be considered as a constant only approximately. A fundamental theory that requires the existence of such a field is missing so this model can be considered as a poor man's phenomenology describing an accelerated expansion, more general than that given just by the vacuum energy. A *raison d'être* for such a field could be the adjustment mechanism discussed above, which predicts the existence of a non-compensated vacuum energy with an unusual equation of state. Simultaneously, as mentioned above, the adjustment mechanism may explain the puzzling fact that the contribution of quintessence to Ω is close to 1.

One can see from Eq. (12) that the lower limit for w is $w > -1$ and this is quite generic for any normal matter. However in ref. [31] even the possibility of $w < -1$ was discussed with the appropriate name 'cosmic phantom'. This really striking equation of state could be realized in models with higher rank tensor fields but it gives rise to a very unusual cosmological singularity (see the discussion in ref. [28]).

5 NEUTRINOS

As a possible candidate for dark matter the neutrino has the following two advantages. First, it is the only one that is definitely known to exist. Second, the neutrino should have a non-zero mass. There are recent indications [32] that at least one neutrino species has a mass of about 0.07 eV. However the second advantage is simultaneously a disadvantage, because the neutrino mass is normally too small for an appropriate description of the large-scale structure of the universe. If cosmic background neutrinos of the a-th flavour have the standard cosmological abundance, $n_{\nu_a} = 3n_\gamma/11 \approx 112\ \text{cm}^{-3}$, then their mass is restricted by the Gerstein–Zeldovich [33] bound:

$$\sum_a m_{\nu_a} < 94\ \text{eV}\ \Omega h_{100}^2. \tag{13}$$

Such light neutrinos decoupled from the cosmic plasma while they were relativistic and they erased all structures by free streaming at the scales below

$$M_{\text{struc}} \sim \frac{m_{\text{Pl}}^3}{m_\nu^2} \approx 10^{15} M_\odot \left(\frac{10\ \text{eV}}{m_\nu}\right)^2. \tag{14}$$

This is a typical example of hot dark matter. (A more accurate estimate gives somewhat smaller M_{struc}.)

On the other hand, the Tremain–Gunn bound [34] demands that the neutrino mass is bounded from below:

$$m_\nu > 50\text{–}100\ \text{eV}. \tag{15}$$

This bound is a striking example of quantum effects on a galactic scale: the Fermi exclusion principle forbids too many neutrinos accumulating in the galactic halo, hence to carry all observed mass they should be sufficiently heavy.

The mismatch between the bounds (13) and (15) does not allow the standard neutrinos to constitute all dark matter in the universe. However, if neutrinos possess a new interaction somewhat stronger than the usual electroweak one, their cosmological number density would be smaller and the limit (13) would be less restrictive. Another possibility is that there are the so-called sterile neutrinos that may be mirror or shadow neutrinos (see Section 8) with mass in the keV range, thus providing warm dark matter [35].

Some time ago a very heavy neutrino with mass in the GeV range was considered as a feasible candidate for cold dark matter. However the combined LEP result [36] of precisely measuring the Z^0 width permits only $N_\nu = 2.993 \pm 0.011$ for all neutral fermions with the normal weak coupling to Z^0 and mass below $m_Z/2 \approx 45$ GeV. So if heavy neutrinos, ν_h, of the fourth generation exist their mass must be higher than 45 GeV. Most probably such particles should be unstable but if the corresponding leptonic charge is conserved or almost conserved and the charged companion of the heavy neutrino is heavier than ν_h they would be stable or very long lived.

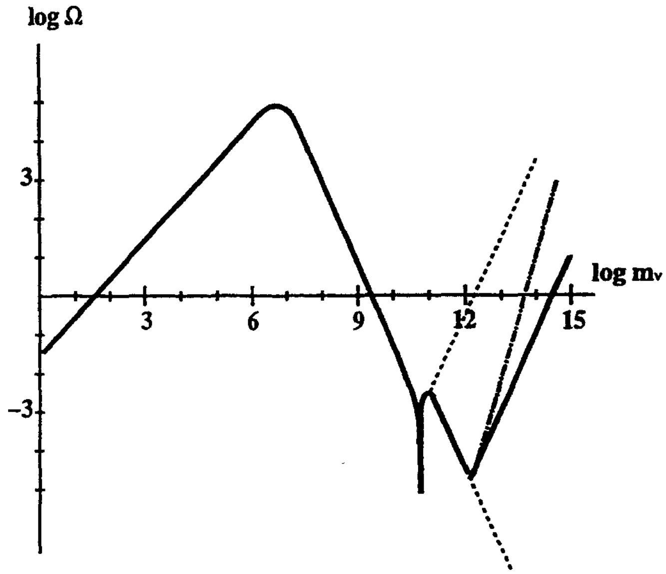

Figure 3 Contribution to the cosmological parameter Ω from a heavy stable neutrino as a function of its mass.

The contribution of ν_h to the cosmological energy density is determined by the cross-section of $\nu_h \bar{\nu}_h$-annihilation and has a rather peculiar behaviour as a function of the ν_h mass. The corresponding Ω is presented in Figure 3.

In the region of very small masses the ratio of number densities n_{ν_h}/n_γ does not depend upon the neutrino mass and ρ_{ν_h} rises linearly with mass. This gives the bound (13). For larger masses $\sigma_{\rm ann} \sim m_{\nu_h}^2$ and $\rho_{\nu_h} \sim 1/m_{\nu_h}^2$. This formally opens a window for m_{ν_h} above 2.5 GeV [37, 38]. A very deep minimum in ρ_{ν_h} near $m_{\nu_h} = m_Z/2$ is related to the resonance enhanced cross-section around the Z-pole. Above the Z-pole the cross-section of $\bar{\nu}_h \nu_h$-annihilation into light fermions goes down with mass as $\alpha^2/m_{\nu_h}^2$ (as in any normal weakly coupled gauge theory). The corresponding rise in ρ_{ν_h} is shown by a dashed line. This would give the limit $m_{\nu_h} < 3$–5 TeV [39, 40]. However for $m_{\nu_h} > m_W$ the contribution of the channel $\bar{\nu}_h \nu_h \to W^+W^-$ leads to a rise of the cross-section with increasing mass as $\sigma_{\rm ann} \sim \alpha^2 m_{\nu_h}^2/m_W^4$ [41]. This would permit us to keep ρ_{ν_h} well below ρ_c for all masses above 2.5 GeV. The behaviour of ρ_{ν_h} with this effect of rising cross-section included, is shown by the solid line till $m_{\nu_h} = 1.5$ TeV. Above that it is continued as a dashed line. This rise with mass would break the unitarity limit for a partial wave amplitude when m_{ν_h} reaches 1.5 TeV (or 3 TeV for a Majorana neutrino) [42, 43]. If one takes the maximum value of the S-wave cross-section permitted by unitarity, which scales as $1/m_{\nu_h}^2$, this would give rise to $\rho_{\nu_h} \sim m_{\nu_h}^2$ and it crosses ρ_c at $m_{\nu_h} \approx 200$ TeV. This behaviour is continued by the solid line above 1.5 TeV. However for $m_{\nu_h} \geq$ a few TeV the Yukawa coupling of ν_h to the Higgs field becomes strong and no reliable calculations of the annihilation cross-section have been done in this limit. Presumably the cross-section is much smaller than the perturbative result and the cosmological bound for m_{ν_h} is close to several TeV. This possible, though not certain, behaviour is presented by the dashed-dotted line.

6 SUPER-HEAVY RELICS

Super-heavy quasi-stable particles with mass around 10^{13} GeV were introduced in refs. [44, 45] to avoid the GKZ cutoff [48] for ultra-high-energy cosmic rays. These particles could have been produced at the end of inflation by coherent oscillations of the inflation field (for possible mechanisms of production see e.g. ref. [46, 47]). They may have an interesting impact on structure formation and are discussed in more detail in this conference by H. Ziaeepour. However their meta-stability is rather mysterious. As was argued many years ago by Zeldovich [49], even if the baryonic charge is microscopically conserved, the proton may decay through formation and subsequent evaporation of a virtual black hole. In accordance with his estimate the proton should decay with life-time:

$$\tau_p \approx \frac{1}{m_p}\left(\frac{m_{\rm Pl}}{m_p}\right)^4 \approx 10^{45}\,\text{years}. \tag{16}$$

This estimate can be obtained as follows. The cross-section of the gravitational capture of a particle by the black hole with mass M is equal to its Schwarzschild radius squared,

$$\sigma_{\rm grav} \approx r_g^2 = \frac{M^2}{m_{\rm Pl}^4}, \tag{17}$$

where $m_{\rm Pl} = 1.2 \times 10^{19}$ GeV is the Planck mass. For the virtual black hole state, which is formed in the process of the gravitational decay of a particle with mass m, the mass of the black hole is around the initial particle mass, $M \sim m$. Assuming that all other dimensional parameters are also close to m we obtain the result (16).

We can obtain another (and different) estimate for the proton life-time using the following arguments. The amplitude of the collapse of a particle x with mass m_x into a black hole with the same mass is proportional to the overlap integral:

$$A_{\rm coll} \sim \int d^3r\,\psi_x \Psi_{\rm BH} \tag{18}$$

where ψ_x and $\Psi_{\rm BH}$ are the wave functions of the particle and black hole. The particle wave function is localized on its Compton wavelength, $l_{\rm C} = 1/m_x$, while the black hole wave function is localized at $r_g = m_x/m_{\rm Pl}^2$. Evaluating this integral and assuming again that all other dimensional parameters are close to m_x we obtain

$$\tau_x \sim \frac{1}{m_x}\left(\frac{m_{\rm Pl}}{m_x}\right)^n = 10^{-24+19n}\left(\frac{\rm GeV}{m_x}\right)^{n+1}\,\text{sec}, \tag{19}$$

where the power n is equal to 6, in contrast to $n = 4$ in Eq. (16).

Later on this conjecture was supported by the arguments that quantum gravity effects should break all global symmetries [50], in particular due to the formation of baby universes [51]. The effective Lagrangian which describes these phenomena contains different terms with different powers of the Planck mass, $M_{\rm Pl}^{4-d}$, where d is called the dimension of the corresponding operator. In the examples considered above d was equal to 6 and 7. The very dangerous terms are those with $d = 5$. They would lead to proton decay with life-time $\tau_p \sim 10^{13}$ sec, which is well below existing limits. This makes one believe that the operator with $d = 5$ does not appear in the effective Lagrangian. Note that the simple estimates presented above give $d > 5$. If the particle decay is generated by the operator with dimension d then its life-time is given by the expression (19) with $n = 2(d - 4)$. Thus if we demand that the particle x lives longer that the universe age, $t_U \approx 10^{18}$ sec, then its mass should be bounded from above:

$$m_x < 10^{(19n-42)/(n+1)}\,\text{GeV}. \tag{20}$$

If the Zeldovich estimate [49] is correct then $m_x < 10^7$ GeV. If we use the estimate of the present paper which gives $n = 6$, then $m_x < 10^{10.3}$ GeV. The condition that these particles are heavier than 10^{13} GeV, so that their decays explain the origin of ultra-energetic cosmic rays, demands a rather high value $n > 9$. The dimension of the corresponding operators should be bigger than 8.5.

Of course the arguments presented above are not rigorous but the gravitational decay mechanism still looks very plausible. This mechanism is quite generic and does not depend upon the particle properties but only on their masses. This is related to the universality of gravitational interactions. Of course the presented estimates are rather naive and the unknown non-perturbative dynamics of quantum gravity may significantly change these results. It is possible in particular that the formation of a virtual black hole proceeds as some kind of tunnelling process. In this case the decay probability might be suppressed as $\exp(-cm_{\rm Pl}/m_x)$ (where c is a constant) and the mechanism discussed here would be ineffective.

A possible way to avoid gravitational decay is to assume that the particle in question is the lightest in the family of particles possessing a conserved charge, which is associated with a local (gauge) symmetry (similar to electromagnetic $U(1)$). However this would imply that this particle is absolutely stable. To avoid that, one would have to assume that the corresponding gauge symmetry is slightly broken in such a way that the gauge boson(s) acquires a tiny but non-zero mass. It is well known that black holes may have hairs which are related to the long-range forces which in turn are associated with zero mass of the particles which transmit interactions. For example the Coulomb field of an electrically charged black hole is maintained outside the gravitational radius only because the photon is strictly massless. In the case that the photon has a non-zero mass, a black hole would not have electric hairs even if electric charge is strictly conserved. A limiting transition from the case of a strictly massless photon to that with a small mass there is a long disappearance time of the hairs. This time should be inversely proportional to the mass. So in principle there may exist very heavy and very long lived particles if they possess a conserved charge but the corresponding gauge symmetry is slightly broken so that the gauge boson acquires a tiny mass. The charge may remain strictly conserved but the particle would be unstable in the same way that the proton becomes unstable due to collapse into a black hole, despite conservation of baryonic charge in particle interactions without gravity. A possible way to realize such a model is to assume a non-minimal and gauge non-invariant coupling of gauge bosons to gravity, for example in the form $A_\mu^2 R$ or $A_\mu A_\nu R^{\mu\nu}$, where R is the curvature scalar and $R^{\mu\nu}$ is the Ricci tensor.

Barring this highly speculative possibility we have to conclude that either the explanation of the highest energy cosmic rays by decays of ultra-heavy long-lived particles is impossible, because such particles should undergo fast ($\tau_x < \tau_U$) decay, or that the gravitational breaking of global symmetries is not as strong as we assumed above.

7 LIGHTEST SUPERSYMMETRIC PARTICLE (LSP)

Low-energy supersymmetry has at least two attractive features for a solution of the dark matter problem. First, the theory predicts the existence of new stable particles that could constitute cosmological dark matter. Second, with a natural scale of supersymmetry breaking around 1 TeV, the theory predicts that LSP would give $\Omega_{\rm LSP} \approx 1$ without any fine tuning. The third feature, which makes this hypothesis especially attractive for experimentalists, is that for a large range of parameters of supersymmetric models these new stable particles are within the reach of sensitivity of different existing and planned methods of search. This subject was recently reviewed in great detail in ref. [52, 53], so I will be very brief here.

There are several possible candidates for the role of dominating supersymmetric matter in the universe: neutralino (a mixture of gauginos, $\tilde\gamma + \tilde Z$, and higgsinos, $\tilde h_1 + \tilde h_2$); sneutrino (a heavy supersymmetric partner of the neutrino); gravitino (the supersymmetric partner of the graviton, with spin 3/2); axino (the partner of the axion), messenger fields related to a hidden sector of the theory, ... Such particles (at least some of them) can be searched for directly by a registration in low-background detectors (Ge, NaI, Xe, ...) through the reaction: $N + \text{Nuclei} \to \text{recoil}$. There are also indirect methods based on a search for the products of their annihilation in the Earth or in the Sun, producing high-energy muons. At the present day only upper limits on the annihilation cross-section are established, though there are indications of an annual modulation effect [54] that may be a signature of dark matter.

A very interesting feature of neutralino annihilation in the galactic halo is the production of antimatter: not only anti-protons [55] but also a noticeable fraction of anti-deuterium may be created. According to the calculations of ref. [56] the flux of $\bar D$ at low energy, below 1 GeV, would be much larger than the flux of the secondary $\bar D$, produced by normal cosmic ray collisions. The AMS mission could either register anti-deuterium from neutralino annihilation or exclude a significant fraction in the parameter space of the low-energy SUSY models. There are also promising ways to register neutralino annihilation through observation of energetic positrons or gamma rays (see ref. [52] for the details).

A low-energy supersymmetric extension of the minimal standard model is very natural from the particle physics point of view. It supplies possibly the best candidate for dark matter particles. In most versions of the model these particles would form weakly interacting cold dark matter, though in some cases warm dark matter is also possible. There is a lot of experimental activity in search of supersymmetric particles and hopefully in the next few years they will be discovered or, if Nature is not favourable, a large part of the parameter space will be excluded but the mystery of dark matter will still remain.

8 MIRROR/SHADOW WORLD

The idea that our world is doubled and there exists a similar or exactly the same world coupled to ours only by gravity, was suggested long ago [57] in connection with conservation of parity, P, or combined parity, CP. Subsequently it was developed and elaborated in several papers [58]. Its popularity greatly increased after it was found that superstring theories have a $G \times G$ internal symmetry group and the two identical worlds, corresponding to two groups, communicate only through gravity [59]. The considered models, however, were not confined to this simplest option. In addition to gravity a new super-weak (but stronger than gravity) interaction was introduced between our particles and mirror particles. Moreover, different patterns of symmetry breaking in these two worlds were considered, so that the physics in our world and in the mirror world or in this case better to say in the shadow world, became quite different.

At first sight the existence of a whole new world with the same or similar particle content would strongly distort the successful predictions of the standard big bang nucleosynthesis (BBN) theory. The latter permits no more than one additional light fermionic species in the cosmological plasma at $T \sim 1$ MeV (see e.g. [12]). The completely symmetric mirror world would give slightly more than seven. However, as was argued in ref. [60] the temperature of the mirror matter after inflation could be smaller than the temperature of the usual matter and thus the energy density of mirror matter during nucleosynthesis could be safely suppressed. Concrete mechanisms that could create a colder mirror world if the symmetry between the worlds was broken, were considered e.g. in refs. [35, 61]. Another possible way to escape a conflict with BBN by the generation of lepton asymmetry through neutrino oscillations was discussed in ref. [62].

A new burst of interest in mirror/shadow matter arose after MACHO collaboration announced that the mass of the micro-lenses they observed is close to the solar mass (see Section 2). The natural idea that these objects may be built from mirror matter immediately attracted a lot of attention [35, 61, 63–65]. In the case of exact symmetry between the worlds the properties of the stellar objects would be the same but the process of structure formation could be quite different by the following two reasons. First, since the mirror matter is colder than the usual matter, the mirror hydrogen recombination would be considerably earlier and the structures might start forming earlier too. Second, baryon asymmetry in the mirror world might be different from ours and it would have an important impact on the primordial chemical content of the universe and galactic and stellar formation [66]. The cosmological mass fraction of mirror baryons is unknown but most probably they do not constitute all dark matter in the universe. There is one peculiar feature of this matter that it is strongly interacting and can easily lose energy through emission of mirror photons. Structure formation with this kind of dark matter would be very different from the normal scenario with dissipationless cold dark matter. The cooling mechanisms, that are very essential for structure formation, could be either stronger or weaker. In particular, in the world with a very large fraction of mirror ^{4}He molecular cooling would be considerably less efficient.

There would be even more differences between cosmology and astrophysics of our world and the mirror world if the mirror symmetry is broken [35, 61]. There could be the case that there are no stable nuclei in the mirror world and thus there could not exist mirror stars with a thermonuclear active core. If the mirror electrons are heavier than the usual ones, the mirror hydrogen binding energy would be larger and this would be another reason for earlier recombination. To study the history of stellar formation and evolution in such a distorted world would be a very interesting exercise that could reveal essential features of the underlying physics. Except for a different astrophysics and new stellar-size invisible bodies, the mirror world could provide sterile neutrinos that might explain the observed neutrino anomalies though the oscillations between our neutrinos and sterile ones. In particular, among these sterile neutrinos there could be rather heavy ones with mass in the keV range that might be excellent candidates for warm dark matter.

9 MISCELLANEA

Because of lack of space and time I could not discuss many other interesting forms of dark matter. One of the favourites, the axion, is discussed at this conference by Yu. Gnedin. Topological and non-topological solitons may also be quite interesting options. Though the measurements of the angular fluctuations of the CMB seemingly exclude cosmic strings as a dominant part of cosmological dark matter, they may still give some contribution to the total mass of the universe. Non-topological solitons, Q-balls, recently attracted renewed attention [67, 68]. Primordial black holes with a log-normal mass spectrum [69] still remain an interesting possibility. There are some even more exotic candidates that are discussed in the literature; among them are such objects as superstrings giving super-heavy dark matter [70], domain walls with an 'anti-gravitating' equation of state, $p = -(2/3)\rho$ [71], or even liquid or solid dark matter [72].

Unstable dark matter remains attractive, and though it was proposed in 1984 [73], the main burst of activity was in the 1990s [74]. The basic idea of introducing unstable but long-lived particles into consideration was to increase the horizon length at the time of equality between matter and radiation and to increase by that the power at large scales. Recently this idea was revived in another attempt to save the model of structure formation with pure cold dark matter [75]. The model looks quite natural from the particle physics point of view if there exists a light scalar boson, familon or majoron so that a heavier neutrino, which may violate the Gerstein–Zeldovich bound, could decay into this boson and lighter neutrino. It is also possible that a massive scalar boson decays into two light neutrinos. A very interesting scenario in the former case is that the scalar bosons are massive and their spectrum is two-component: energetic bosons coming from the decay and non-relativistic ones formed during a phase transition similar to axions. In this case the same particle may form both cold and hot (or warm) dark matter. A slightly different mechanism was proposed in ref. [76] in the framework of string cosmology. It was argued there that weakly interacting non-thermal relics may be produced in the course of dilaton-driven inflation with the double peak spectrum that could simultaneously give cold and hot dark matter.

A very interesting form of dark matter is self-interacting. One possible example of the latter is given by a mirror or shadow world discussed above. A few more models of self-interacting dark matter with particles belonging to our world were considered in the literature; they were either light bosons [77], e.g. majorons or familons, or neutrinos with an anomalous self-interaction [78]. Observational evidence in favour of self-interacting dark matter was recently analysed in ref. [79].

10 CONCLUSION

As we have seen, a set of independent arguments unambiguously proves that the main part of matter in the universe is not visible and, moreover, this invisible matter is not the matter that consists of known elementary particles such as e.g. protons or neutrons, or neutrinos. The existence of this unknown form of matter is strong evidence in favour of new physics beyond the minimal standard $SU(3)\times SU(2)\times U(1)$-model (MSM). Possibly a low-energy supersymmetric extension of MSM solves the mystery of dark matter with the lightest supersymmetric particle (LSP) that quite probably could be stable. However astronomical data indicate that one form of dark matter is not enough and except for cold dark matter, which might be provided by LSP, there is a very strong quest for hot and/or warm dark matter. Moreover detailed description of rotation curves at small distances indicates that dark matter may be dissipative. Quite possibly there is one more ingredient of dark matter, related to the vacuum energy, that makes the situation even more mysterious.

Even if there is only one form of dark matter, the cosmic conspiracy, namely the close values of $\Omega_{\rm baryon}$ and $\Omega_{\rm DM}$, is quite puzzling. It demands quite a strong fine-tuning in fundamental particle theory and at the present day no reasonable understanding of the phenomenon exists. The problem of the cosmic conspiracy becomes tremendously deeper if there are several (> 2) forms of invisible matter with similar contributions to Ω.

An answer to an often asked question, what is the best bet for dark matter particles, reflects not so much our knowledge of the subject but a personal attitude of the respondent. Seemingly most votes would be given to LSP and possibly the next one is the axion. An advantage of these two is that neither were invented *ad hoc* but were predicted by particle theory independently of cosmology. By similar arguments mirror or shadow matter is also in good shape. However other candidates based on more complicated models may have better chances just because their properties are chosen in accordance with cosmological demands.

Ten years ago at one of the 'Rencontre de Moriond' meetings P. Peebles in his summary talk arranged a public opinion poll about how many dark matter candidates would survive to the end of the century. The stakes were up to double digit numbers. I have to admit that I voted for one dark matter candidate, the only real one that 'would be surely known'. It was an extremely over-optimistic point of view and today we have even more possible candidates than ten years ago (none of the old ones have been removed from the list and quite a few new ones came into being) and we still do not know what is/are the correct one(s).

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