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LOW-MASS PHOTINOS AND SUPERNOVA 1987a

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A B S T R A C T

Photinos or higgsinos with mass $O(100)$ eV are not excluded by cosmological considerations, and their radiative decays could be responsible for the surprisingly large ultra-violet background recently detected at a red shift $z \sim 4$. The agreement of the neutrino data from supernova 1987a with standard expectations severely restricts the energy which could have been emitted via such light photinos or higgsinos, and hence constrains the parameters of models in which they appear. In the low-mass photino case, we find that squark masses between ~ 60 GeV and $\sim 2\frac{1}{2}$ TeV are excluded. This together with laboratory limits excludes the range of squark masses generally favoured by naturalness arguments. In the low-mass higgsino case, we exclude much of the range of ratios of Higgs v.e.v.'s favoured by many models.

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The lightest supersymmetric particle (LSP) is expected to be stable in many models, and hence could be present today as a cosmological relic from the Big Bang [1]. If its mass were suitable, the LSP could provide the bulk of the dark matter whose existence is favoured by astrophysical observations and by models of galaxy formation. In the case of the photino $\tilde{\gamma}$ or the higgsino $\tilde{h}$, the cosmological relic density could be near the closure density either if $m_{\tilde{\gamma}}$ or $m_{\tilde{h}} = O(100)$ eV, or if $m_{\tilde{\gamma}}$ or $m_{\tilde{h}} = O(10)$ GeV. Neither of these alternative ranges can be excluded a priori, although there are theoretical reasons disfavouring light photinos - in many models they would be accompanied by light gluinos that have not been seen - and light higgsinos - in many models they would be accompanied by an electroweak axion-like boson that has not been seen.

Even if the $\tilde{\gamma}$ or $\tilde{h}$ is not the LSP, but the gravitino $\tilde{G}$ is lighter so that decays such as $\tilde{\gamma} \rightarrow \tilde{G} + \gamma$ or $\tilde{h} \rightarrow \tilde{G} + \gamma$ occur, the lifetime could be longer than the age of the Universe. In this case the $\tilde{\gamma}$ or $\tilde{h}$ would still be present today as dark matter; additionally, their decay photons may have observable consequences [2]. For example, it has recently been suggested [3] that such photons might account for the surprisingly large ultra-violet cosmological background flux at large red shifts (~ 2 to 4) estimated from observations of the Lyman α forest [4].

The observation of neutrinos from the supernova 1987a, and their agreement with theoretical models based on the conversion of neutron star binding energy, can be used to constrain the numbers, properties and couplings of any species of light neutral particle [5]. For example, the supernova has been used to constrain the number of neutrino species [6], neutrino masses [7] and magnetic moments [8], axions [9], majorons [10] and light scalar particles [11]. We here propose to use the supernova 1987a to constrain models with low-mass photinos^{*)}. If the squark and selectron masses are not much larger than m_W , photino pair-production by nucleon-nucleon bremsstrahlung and e^+e^- annihilation populates the core of the nascent neutron star, and the photinos are thermalized and emitted as black-body radiation from a photinosphere analogous to the neutrinosphere in the "standard" supernova model [13]. The depth and temperature of the photinosphere increase when the photino-nucleon elastic scattering cross-sections are decreased by increasing the squark mass $m_{\tilde{q}}$, resulting in an increase in the photino energy emission rate $Q_{\tilde{\gamma}}$ which may eventually exceed that allowed by the neutrino observations. However, for sufficiently large $m_{\tilde{q}}$ the photinos may stream freely out of the core and $Q_{\tilde{\gamma}}$ may again become acceptably small. Similar arguments may be applied to higgsinos, in which case the model parameter controlling the energy emission rate $Q_{\tilde{h}}$ is the ratio of Higgs v.e.v.'s v_2/v_1 .

*) This proposal was first made in a preprint by D.W.S. [12].

Requiring $Q_{\tilde{\gamma}}$ to be less than the total neutrino energy emission rate $N_{\nu} Q_{\nu}$: $N_{\nu} = 3$, we find the constraint

$$m_{\tilde{q}} \lesssim 60 \text{ GeV} \quad (1)$$

in the low-mass thermal "trapping" range, and

$$m_{\tilde{q}} \gtrsim 2\frac{1}{2} \text{ TeV} \quad (2)$$

in the high-mass free-streaming régime. Since accelerator experiments impose the bound $m_{\tilde{q}} \gtrsim 90 \text{ GeV}$ [14], and requiring the natural stability of the mass hierarchy suggests that $m_{\tilde{q}} \lesssim 1 \text{ TeV}$ [15], we conclude that light photinos of the type discussed here are strongly disfavoured if the hierarchy argument is correct. Requiring $Q_{\tilde{h}} < 3 Q_{\nu}$, we find the constraint

$$v_2/v_1 \gtrsim 2 \quad (3)$$

in the thermal range, and

$$0 \leq v_2/v_1 - 1 \lesssim 3 \times 10^{-4} \quad (4)$$

in the free-streaming régime. Since models typically have $1 < v_2/v_1 \lesssim 5$ [15], much of the parameter space for light higgsinos is ruled out but the possibility of a light higgsino cannot be excluded.

In order to study quantitatively energy emission via light photino or higgsino pairs, we need estimates of their pair-emission and elastic scattering cross-sections. Those involving electrons are straightforward to calculate and are given in Ref. [16]. The cross-sections involving nucleons depend on hadronic matrix elements which are not presently calculable from first principles, and must be estimated by appealing to phenomenological ansätze or experiment. The elastic photino-nucleon scattering cross-section which determines the mean free path of the photino and hence the depth of the photinosphere may be written as

$$\sigma(\tilde{\gamma} N \rightarrow \tilde{\gamma} N) \equiv \hat{\sigma}_{\tilde{\gamma}} E_{\tilde{\gamma}}^2 = \frac{24\pi\alpha^2}{m_{\tilde{q}}^4} E_{\tilde{\gamma}}^2 \left(\sum_q Q_q^2 \Delta q \right)^2 \quad (5)$$

Here the Δq are the fractions of the nucleon spin carried by different flavours of quark q ^{*}), which one may estimate either using the Naïve Quark Model (NQM) [18],

^{*}) These hadron structure corrections were not incorporated into the cross-section estimates of Ref. [17].

or from measurements of axial current matrix elements and the European Muon Collaboration (EMC) experiment on polarized deep inelastic μ -p scattering [19]. In the case of $\tilde{\gamma}$ -proton scattering one has

$$\left(\sum_q Q_q^2 \Delta q\right) = \frac{4}{9} \Delta u + \frac{1}{9} \Delta d + \frac{1}{9} \Delta s \quad (6)$$

and one may estimate

$$\Delta u = 1, \Delta d = -0.25, \Delta s = 0 \text{ (NQM) [18]} \quad (7a)$$

$$\Delta u \approx 0.74, \Delta d \approx -0.51, \Delta s \approx -0.23 \text{ (EMC) [19]} \quad (7b)$$

The rôles of Δu and Δd are reversed in the $\tilde{\gamma}$ -neutron scattering cross-section, which is zero in the NQM but non-negligible according to the EMC estimate of the Δq . The formula (5) should be compared with the corresponding formulae for ν -N scattering:

$$\sigma(\nu N) \equiv \hat{\sigma}_\nu E_\nu^2 = \frac{\pi \alpha^2}{2m_w^4 \sin^4 \theta_w} (C_V^2 + 3C_A^2) E_\nu^2 \quad (8)$$

where for elastic neutral current scattering: $\nu N \rightarrow \nu N$

$$\left. \begin{aligned} C_V^N(p) &= \frac{1}{2} - 2\sin^2 \theta_w \approx 0.04, \quad C_V^N(n) = -\frac{1}{2} \\ C_A^N(p) &= \frac{1}{2} (\Delta u - \Delta d - \Delta s), \quad C_A^N(n) = -\frac{1}{2} (\Delta u - \Delta d + \Delta s) \end{aligned} \right\} \quad (9)$$

and for inelastic charged current scattering: $\bar{\nu}_e p \rightarrow e^+ n$

$$C_V^C(p) = 1, \quad C_A^C(p) = \frac{1}{2} (\Delta u - \Delta d) \quad (10)$$

Taking the ratio of the elastic $\tilde{\gamma} N \rightarrow \tilde{\gamma} N$ and total $\bar{\nu}_e N \rightarrow X$ cross-sections, we find

$$\begin{aligned}
 \frac{\sigma(\tilde{\gamma}N \rightarrow \tilde{\gamma}N)}{\sigma(\tilde{\nu}_e N \rightarrow X)} &= \frac{\hat{\sigma}_{\tilde{\gamma}} E_{\tilde{\gamma}}^2}{\hat{\sigma}_{\tilde{\nu}_e} E_{\tilde{\nu}_e}^2} \\
 &= \frac{E_{\tilde{\gamma}}^2}{E_{\tilde{\nu}_e}^2} \cdot \frac{48 \sin^4 \theta_w m_w^4}{m_{\tilde{q}}^4} \times \\
 &\times \left[\frac{Y \left(\frac{4}{9} \Delta u + \frac{1}{9} \Delta d + \frac{1}{9} \Delta s \right)^2 + (1-Y) \left(\frac{1}{9} \Delta u + \frac{4}{9} \Delta d + \frac{1}{9} \Delta s \right)^2}{Y \left[\left(\frac{1}{2} - 2 \sin^2 \theta_w \right)^2 + 1 + \frac{3}{4} (\Delta u - \Delta d - \Delta s)^2 + \frac{3}{4} (\Delta u - \Delta d)^2 \right] + (1-Y) \left[\frac{1}{4} + \frac{3}{4} (\Delta u - \Delta d + \Delta s)^2 \right]} \right] \quad (11)
 \end{aligned}$$

where Y is the proton number fraction. The ratio (11) is equal to the inverse ratio of mean free paths:

$$\frac{\sigma(\tilde{\gamma}N \rightarrow \tilde{\gamma}N)}{\sigma(\tilde{\nu}_e N \rightarrow X)} = \frac{\lambda_{\tilde{\nu}_e}}{\lambda_{\tilde{\gamma}}} \quad (12)$$

In a similar way, one can calculate the ratio of nucleon-nucleon bremsstrahlung cross-sections

$$\frac{\sigma(nn \rightarrow (\tilde{\gamma}\tilde{\gamma}) + nn)}{\sigma(nn \rightarrow (\tilde{\nu}\nu) + nn)} = \frac{48 \sin^4 \theta_w m_w^4}{3 m_{\tilde{q}}^4} \left(\frac{\frac{1}{4} \Delta u + \frac{4}{9} \Delta d + \frac{1}{9} \Delta s}{\frac{1}{2} (\Delta u - \Delta d - \Delta s)} \right)^2 \quad (13)$$

(and analogously for the np and pp processes) which equals the ratio of energy emission rates in a free-streaming régime.

A similar analysis can be made for light higgsinos, leading to the results

$$\begin{aligned}
 \frac{\sigma(\tilde{h}N \rightarrow \tilde{h}N)}{\sigma(\tilde{\nu}_e N \rightarrow X)} &= \frac{\hat{\sigma}_{\tilde{h}} E_{\tilde{h}}^2}{\hat{\sigma}_{\tilde{\nu}_e} E_{\tilde{\nu}_e}^2} = \frac{3}{4} \cdot \frac{E_{\tilde{h}}^2}{E_{\tilde{\nu}_e}^2} \times \cos^2 2\alpha \times \\
 &\times \left[\frac{Y (\Delta u - \Delta d - \Delta s)^2 + (1-Y) (\Delta u - \Delta d + \Delta s)^2}{Y \left[\left(\frac{1}{2} - 2 \sin^2 \theta_w \right)^2 + 1 + \frac{3}{4} (\Delta u - \Delta d - \Delta s)^2 + \frac{3}{4} (\Delta u - \Delta d)^2 \right] + (1-Y) \left[\frac{1}{4} + \frac{3}{4} (\Delta u - \Delta d + \Delta s)^2 \right]} \right] \quad (14)
 \end{aligned}$$

and

$$\frac{\sigma(nn \rightarrow (\tilde{h}\tilde{h}) + nn)}{\sigma(nn \rightarrow (\tilde{\nu}\nu) + nn)} = \cos^2 2\alpha \quad (15)$$

(and analogously for the np and pp processes) where the angle α parametrizes the ratio of Higgs v.e.v.'s in supersymmetric models:

$$\cos 2\alpha = \frac{v_1^2 - v_2^2}{v_1^2 + v_2^2} \quad (16)$$

Our conventions are such that charge $+2/3$ quark masses are $\propto v_2$, and charge $-1/3$ quark and charge -1 lepton masses are $\propto v_1$. In most models one expects $v_2/v_1 \gtrsim 1$ [15], but the necessity of this inequality has not been proved. We assume subsequently that $v_2/v_1 > 1$, but our bounds can be extended to the opposite case simply by interchanging the suffices.

We first consider LSP emission from a photinosphere (or higgsinosphere) analogous to the neutrinosphere^{*)}. Assuming the black-body formula for both photinos and neutrinos, one has

$$\frac{Q_{\tilde{\gamma}}}{Q_{\tilde{\nu}_e}} \approx \frac{2R_{\tilde{\gamma}}^2 T_{\tilde{\gamma}}^4}{R_{\tilde{\nu}_e}^2 T_{\tilde{\nu}_e}^4} \quad (17)$$

The IMB and Kamioka experiments [20] have detected the neutrino pulse from the collapse of supernova 1987a which are interpreted as being mainly $\bar{\nu}_e$'s. The data can be used to estimate the total energy emitted via $\bar{\nu}_e$'s, which carry away about 1/6 of the total energy radiated in neutrinos, according to standard models of stellar collapse. Estimates of $\Sigma_{\nu} \int dt Q_{\nu} \approx 6 \int dt Q_{\bar{\nu}_e}$ are in the range $(2 \text{ to } 4) \times 10^{53}$ ergs [5,6,21], to be compared with the binding energy of a neutron star which is expected to be $\lesssim 4 \times 10^{53}$ ergs [13]. We therefore impose the constraint

$$\frac{Q_{\tilde{\gamma}}}{Q_{\tilde{\nu}_e}} \lesssim 6 \quad (18)$$

on the photino energy emission rate (and analogously for higgsinos), and hence

$$R_{\tilde{\gamma}}^2 T_{\tilde{\gamma}}^4 \lesssim 3 R_{\tilde{\nu}_e}^2 T_{\tilde{\nu}_e}^4 \quad (19)$$

and similarly for higgsinos.

Models of neutron stars indicate that the density ρ varies rapidly with the radius R between 15 and 20 km [22], where the neutrinosphere is located. Therefore we expect as a first approximation that $R_{\tilde{\gamma}} \approx R_{\tilde{\nu}_e}$ (corrections to this approximation are discussed later) and the constraint (19) becomes

^{*)} A different model for neutrino and photino emission was used in Ref. [17].

$$\left(T_{\tilde{\gamma}} / T_{\tilde{\nu}_e} \right)^4 \lesssim 3 \quad (20)$$

Collapse models indicate that $\rho \propto T^3$ in the range of interest, so that (20) becomes

$$\left(\rho_{\tilde{\gamma}} / \rho_{\tilde{\nu}_e} \right) \lesssim 3^{3/4} \quad (21)$$

where ρ_x denotes the density where $T = T_x$. The rapid variation of ρ with R also leads us to expect that the mean free paths $\lambda \propto 1/\rho\sigma$ are approximately the same for photinos and $\tilde{\nu}_e$'s. (Corrections to this approximation are discussed later.) Hence Eq. (21) implies

$$\frac{\sigma(\tilde{\nu}_e N \rightarrow X)}{\sigma(\tilde{\gamma} N \rightarrow \tilde{\gamma} N)} \lesssim 3^{3/4} \quad (22)$$

recalling that these cross-sections $\sigma(\tilde{\nu}_e N)$, $\sigma(\tilde{\gamma} N) \equiv \hat{\sigma}_{\tilde{\nu}_e, \tilde{\gamma}} \times E_{\tilde{\nu}_e, \tilde{\gamma}}^2 \propto \hat{\sigma}_{\tilde{\nu}_e, \tilde{\gamma}} T_{\tilde{\nu}_e, \tilde{\gamma}}^2$ and using Eq. (29), the constraint (22) finally becomes

$$\hat{\sigma}_{\tilde{\gamma}} / \hat{\sigma}_{\tilde{\nu}_e} \gtrsim 3^{-5/4} \quad (23)$$

where the left-hand side is given in Eq. (11).

The limit (23) assumed that the photinosphere and the neutrinosphere have the same radius $R_{\tilde{\gamma}} \approx R_{\tilde{\nu}}$, and that the photino and neutrino mean free paths were about equal. We believe that these are very good approximations in view of the calculated density profiles of neutron stars [22], which indicate that the density varies very rapidly near the edge of the core close to the neutrinosphere. Although the density at the photinosphere is likely to be greater than that at the neutrinosphere by a factor of two, the limit (23) is corrected only by a factor $(R_{\tilde{\gamma}}/R_{\tilde{\nu}})^{3/2}$ which is very close to unity. This correction is small compared to the uncertainty in the numerical factor of 6 on the right-hand side of Eq. (18), and is therefore neglected.

The resulting lower bound on $m_{\tilde{q}}$ depends on the assumed values of the Δq [NQM or EMC: see Eq. (7)] and on the proton number fraction Y . As can be seen in Table 1a, the bound on $m_{\tilde{q}}$ is actually rather insensitive to these inputs, and we conclude that in this thermal régime

$$m_{\tilde{q}} \lesssim 0.7 m_W \approx 60 \text{ GeV} \quad (24)$$

would be required to avoid excessive energy emission via photinos. However, the range (24) is excluded by the lower bound $m_{\tilde{q}} \gtrsim 90$ GeV recently obtained by the CDF experiment at the FNAL $\bar{p}p$ collider [14]. Squarks heavier than this experimental limit (but light enough to ensure thermal "trapping" for photinos) would imply $Q_{\tilde{\gamma}} \gtrsim 20 Q_{\tilde{\nu}_e}$, which is certainly not allowed by the supernova neutrino observations. Repeating the above analysis for higgsinos using the constraint analogous to (23) and taking $\sigma_{\tilde{h}}/\sigma_{\tilde{\nu}_e}$ from Eq. (14), we obtain the lower limits on v_2/v_1 shown in Table 2a. Again the results are relatively insensitive to the Δq and to Y , and we infer that

$$\frac{v_2}{v_1} \gtrsim 2 \quad (25)$$

which excludes some of the range $1 < v_2/v_1 \lesssim 5$ favoured by models [15].

So far we have considered photinos or higgsinos with relatively large cross-sections that are thermalized in the supernova core. There is another allowed range of cross-sections that are sufficiently small for the photinos or higgsinos to stream freely out of the core without violating the constraint (6). We estimate the energy emission rates in this free-streaming régime by using the standard calculations [23] of the URCA process $NN + NN + (\bar{\nu}\nu)$ rescaled by the ratios (13) and (15) for $\tilde{\gamma}\tilde{\gamma}$ and $\tilde{h}\tilde{h}$ pair-emission^{*}). We assume a core emitting region with $R \approx 3$ km and $T \approx 70$ MeV and $\rho \approx 3.5\rho_0$: $\rho_0 = 2.1 \times 10^{14}$ gcm⁻³, as suggested by supernova model calculations [22]. The corresponding lower limits on $m_{\tilde{q}}$ for the NQM and EMC assumptions (7) on the Δq and a plausible range of Y are shown in Table 1b. On the basis of these limits we conclude that

$$m_{\tilde{q}} \gtrsim 30 m_w \approx 2\frac{1}{2} \text{TeV} \quad (26)$$

in this régime. Since supersymmetric models that address the hierarchy problem generally have $m_{\tilde{q}} \lesssim 1$ TeV [15], we conclude that such models with $m_{\tilde{\gamma}} = O(100)$ eV are probably excluded. The corresponding free-streaming limits on v_2/v_1 are shown in Table 2b, on the basis of which we conclude that

$$\frac{v_2}{v_1} - 1 \lesssim 3 \times 10^{-4} \quad (27)$$

in this régime. Existing supersymmetric models [15] do not give v_2/v_1 in this range. The result (27) combined with (25) for the trapping régime excludes much of the preferred range of v_2/v_1 in models with $m_{\tilde{h}} = O(100)$ eV.

^{*}) If the selectron $m_{\tilde{\chi}} \approx m_{\tilde{q}}$ as is usual in models with light photinos, the emission rate [16] for the process $e^+e^- \rightarrow \tilde{\gamma}\tilde{\gamma}$ is smaller than that for the URCA process in the core, and can therefore be neglected.

Another interesting constraint may come from a study of the collapse phase. The core of the star consists largely of ^{56}Fe at this stage [24], making it nearly transparent to photinos which have only axial couplings with hadrons, and therefore only scatter off nuclei with spin. In contrast to neutrinos which have vector couplings and hence get "trapped" by coherent scattering off heavy nuclei at densities exceeding $\sim 3 \times 10^{11} \text{ g cm}^{-3}$, photinos are free to stream out until nuclear densities are reached and the nuclei merge into a degenerate Fermi gas of nucleons. The collapse phase lasts only for $\sim 1/4$ sec but the temperature rises to ~ 10 MeV, so a significant flux of photinos may be emitted at this stage. The energy carried off by photinos is less than that emitted later, during the cooling of the nascent neutron star. Hence the resulting constraints on model parameters are not as severe at this stage as the ones we derived above from free streaming during the subsequent cooling. However, the escaping photinos can introduce non-adiabaticity into the collapse since the entropy may no longer remain constant after neutrino trapping, as is conventionally assumed. The relative constancy of the entropy is an important ingredient of the "standard" collapse model [13], so it is possible that an interesting constraint on the photino flux can be derived from a detailed study, i.e., by incorporating photino processes along with neutrino processes in the standard supernova code and demanding that the dynamics not be affected observably. Detailed numerical modelling is necessary also because the photino opacity changes during collapse as the nuclear composition of the core changes due to electron capture and photodisintegration.

A photino of mass ~ 100 eV has been a serious candidate for the dark matter in the Universe ever since the original proposal in 1981 [2], and it was suggested that photino radiative decays might provide a significant source of ultra-violet radiation in cosmology and astronomy [2]. Various possibilities of this kind have been considered subsequently [3]. We now conclude that these possibilities are strongly disfavoured by the neutrino data from supernova 1987a. There remains only the possibility that $m_{\tilde{q}} \gtrsim 2\frac{1}{2} \text{ TeV}$, which if true would make it difficult to understand the stability of the gauge hierarchy [15]. A higgsino of mass ~ 100 eV may still constitute the dark matter if $v_2/v_1 \gtrsim 2$. Its radiative decay modes should therefore be investigated.

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TABLE 1 - Supernova constraints on squark masses for light photinos

a) Thermal régime: upper bounds on $m_{\tilde{q}}/m_W$

Proton fraction Y	Spin fractions from	
	NQM [18]	EMC [19]
0.2	0.66	0.69
0.3	0.71	0.67
0.4	0.75	0.66

b) Free-streaming régime: lower bounds on $m_{\tilde{q}}/m_W$

Proton fraction Y	Spin fractions from	
	NQM [18]	EMC [19]
0.2	29	34
0.3	31	34
0.4	32	33

TABLE 2 - Supernova constraints on ratio of Higgs v.e.v.'s for light photinos

a) Thermal régime: lower bounds on v_2/v_1

Proton fraction Y	Spin fractions from	
	NQM [18]	EMC [19]
0.2	2.1	2.2
0.3	2.2	2.3
0.4	2.3	2.4

b) Free-streaming régime: upper bounds on v_2/v_1-1

Proton fraction Y	Spin fractions from	
	NQM [18]	EMC [19]
0.2	2.7×10^{-4}	3.2×10^{-4}
0.3	3.0×10^{-4}	3.4×10^{-4}
0.4	3.3×10^{-4}	3.6×10^{-4}

The above limits apply if $v_2/v_1 > 1$. There are identical limits for $v_1/v_2 < 1$ in which the suffices (1,2) are simply interchanged

REFERENCES

- [1] J. Ellis, J.S. Hagelin, D.V. Nanopoulos, K.A. Olive and M. Srednicki - Nucl. Phys. B238 (1984) 453.
- [2] N. Cabibbo, G.R. Farrar and L. Maiani - Phys.Lett. 105B (1981) 155.
- [3] D.W. Sciama - Mon.Not.R.Astr.Soc. 230 (1988) 13p, and references therein.
- [4] S. Bajtlik, R.C. Duncan and J.P. Ostriker - Astrophys.J. 327 (1988) 570.
- [5] See, for example: D.N. Schramm - Comm.Nucl.Part.Phys. 17 (1987) 239.
- [6] J. Ellis and K.A. Olive - Phys.Lett. 193B (1987) 525;
D.N. Schramm - Proc. Rencontre de Moriond, ed. J. Tran Thanh Van (1987).
- [7] See, for example:
L.F. Abbott, A. De Rújula and T.P. Walker - Nucl.Phys. B299 (1988) 734;
D.N. Spergel and J.N. Bahcall - Phys.Lett. 200B (1988) 366.
- [8] J.M. Latimer and J. Cooperstein - Phys.Rev.Lett. 61 (1988) 23;
R. Barbieri and R.N. Mohapatra - Phys.Rev.Lett. 61 (1988) 27;
D. Norzold - Max-Planck-Institut Preprint MPI-PAE/Pth 15/88 (1988).
- [9] R. Mayle, J. Wilson, J. Ellis, K.A. Olive, D.N. Schramm and G. Steigman - Phys.Lett. 203B (1988) 188;
G. Raffelt and D. Seckel - Phys.Rev.Lett. 60 (1988) 1793;
M.S. Turner - Phys.Rev.Lett. 60 (1988) 1797.
- [10] A. Manohar - phys.Lett 192B (1987) 217;
J.A. Grifols, E. Massò and S. Peris - UAB-FT-190/88 (1988).
- [11] A. De Rújula - CERN Preprint TH. 5012 (1988).
- [12] D.W. Sciama - "Low Mass Photinos and SN1987a", Preprint (January 1988).
- [13] H.A. Bethe - in "Highlights of Modern Astrophysics", eds. S.L. Shapiro and S.A. Teukolsky (Wiley, 1986), p. 45;
J. Cooperstein - Physics Reports 163 (1988) 95.
- [14] CDF Collaboration - Preliminary result presented by J. Freeman at the Workshop on $\bar{p}p$ Collider Physics, FNAL (June 1988).
- [15] H.P. Nilles - Physics Reports 110 (1984) 1;
A.B. Lahanas and D.V. Nanopoulos - Physics Reports 145 (1987) 1.
- [16] M. Fukugita and N. Sakai - Phys.Lett. 114B (1982) 23;
J. Ellis and K.A. Olive - Nucl.Phys. 223 (1983) 252.
- [17] J.A. Grifols, E. Masso and S. Peris - UAB-FT-191/88 (1988).
- [18] M. Srednicki - Nucl.Phys. B260 (1985) 689.
- [19] J. Ellis, R.A. Flores and S. Ritz - Phys.Lett. 198B (1987) 393.
- [20] K. Hirata et al. - Phys.Rev.Lett. 58 (1987) 1490;
R.M. Bionta et al. - Phys.Rev.Lett. 58 (1987) 1494.
- [21] J.N. Bahcall, T. Piran, W.H. Press and D.N. Spergel - Nature 327 (1987) 682;
A. De Rújula - Phys.Lett. 193B (1987) 514;
L.M. Krauss - Nature 329 (1987) 689.

- [22] H.A. Bethe and J.R. Wilson - *Astrophys.J.* 295 (1985) 14;
J.R. Wilson et al. - *Ann. N.Y. Acad.Sci.* 470 (1986) 267;
A. Burrows and J.M. Lattimer - *Astrophys.J.* 307 (1985) 178.
- [23] B.L. Friman and O.V. Maxwell - *Astrophys.J.* 232 (1979) 451.
- [24] S.E. Woosley and T.A. Weaver - *Ann.Rev.Astr.Astrophys.* 24 (1986) 205.