UNSTABLE PHOTINO MASS BOUND FROM COSMOLOGY

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ABSTRACT

If there exists an invisible axion, it is likely that its superpartner, the axino, is lighter than the photino, and consequently, the photinos can decay into axinos and photons. We derive the cosmologically allowed photino masses for this case of unstable photinos in terms of the Peccei-Quinn symmetry breaking scale.

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The most important cosmological constraint on supersymmetric theories comes from the stability of the lightest superpartner of ordinary particles. A favoured possibility is that such a particle be the photino ($\tilde{\gamma}$). If this is the case, the only way for the $\tilde{\gamma}$'s to disappear is by pair annihilation. This process must be fast enough ¹⁾ to reduce the number density of $\tilde{\gamma}$'s to a value compatible with the observed expansion rate of the Universe*. This is possible only for $\tilde{\gamma}$ heavier than 1/2 GeV ²⁾.

On the other hand, a natural way to solve the strong CP problem even in supersymmetric theories is the presence of a Peccei-Quinn symmetry** broken at a high scale ³⁾***,

$$10^8 \text{ GeV} \leq v_{PQ} \leq 10^{12} \text{ GeV} \quad (1)$$

so that we obtain an invisible axion a . The axino $\tilde{a}$ which is the fermionic superpartner of the axion is light with a mass possibly smaller than 100 eV.

* The rate of expansion of the universe requires the $\tilde{\gamma}$ density $\rho_{\tilde{\gamma}}$ to be less than $2 \times 10^{-29} (\Omega h^2) \text{ gr/cm}^3$, where Ω is the energy density in units of the closure density and h is the present Hubble parameter in units of $100 \text{ km s}^{-1} \text{ Mpc}^{-1}$. The most restrictive bound which is sometimes quoted, $\rho_{\tilde{\gamma}} \leq 2 \times 10^{-30} (\Omega h^2) \text{ gr/cm}^3$ comes from the assumption that $\tilde{\gamma}$ could take part in galaxy formation and from the limits on "dark matter" in galaxies.

** If no Peccei-Quinn symmetry is imposed, one must fine-tune θ to zero to start with, even in supersymmetric theories. It should be stressed though that spontaneously broken SUSY theories keep θ acceptably small and not infinitely renormalized [Ellis, Ferrara, Nanopoulos, Ref. ⁴⁾], whilst explicit soft breaking of SUSY may induce infinite renormalization of θ . See Ref. ⁴⁾.

***The lower bound was pointed out first by Kim (Ref. ³⁾) and calculated by Dicus et al. (Ref. ⁵⁾). The upper bound calculated by several groups (Ref. ⁶⁾) was based on the temperature dependent axion mass of Ref. ⁷⁾.

Indeed, the SUGRA invisible axino discussed in Ref. 8) gets a mass at three loop order when gauginos get Majorana masses. This is shown in Fig. 1. Its mass is estimated to be $(f^2 \alpha_c^3 / 32 \pi^4) m_{3/2} \approx (3 \text{ eV}, 300 \text{ eV})$ for $f = (10^{-2}, 10^{-1})$ and $m_{3/2} = 100 \text{ GeV}$. So, in the supersymmetric models where use is made of the Peccei-Quinn symmetry to get rid of the strong CP problem, we expect the axino to be the lightest absolutely stable superpartner. Its stability does not cause any cosmological problem. On the contrary, these light stable axinos are the additional candidates for filling the universe and moreover they can serve forming the largest inhomogeneities of the universe. The photino can decay into $\tilde{a} + \gamma$ with a vertex which comes from the "supersymmetrization" of the well-known $a + \gamma\gamma$ vertex.

In this letter, we analyse the new bounds on the photino mass in presence of the $\tilde{\gamma} \rightarrow \tilde{a} + \gamma$ decay channel. Our results are the following. For almost all values of $m_{\tilde{\gamma}}$ in the 1-100 MeV range and $m_{\tilde{e}}$ ($\tilde{e}$ = scalar electron) in the 20-150 GeV range, the rest mass density of photinos does not exceed the radiation energy density before nucleosynthesis. So, for most values of $m_{\tilde{\gamma}}$ and $m_{\tilde{e}}$, the $\tilde{\gamma}$'s decouple well before nucleosynthesis starts, but the Universe is not photino dominated during this delicate epoch. This means that the presence of the decoupled photinos does not affect the standard predictions for the primordial element abundances. The requirement of thermalization of the γ 's produced in the $\tilde{\gamma}$ decays puts severe constraints on the photino lifetime and, consequently, on $m_{\tilde{\gamma}}$ and v_{PQ} . We get a lower bound on $m_{\tilde{\gamma}}$, $m_{\tilde{\gamma}} > 1.5 \text{ MeV}$, for any value of v_{PQ} allowed by Eq. (1). For $v_{PQ} = 10^{10} \text{ GeV}$ and 10^{11} GeV , the lower bounds on $m_{\tilde{\gamma}}$ are 40 MeV and 200 MeV, respectively. Finally, for $v_{PQ} = 10^{12} \text{ GeV}$, only photinos heavier than 700 MeV are acceptable. Notice, in particular, that for this latter value of v_{PQ} the region $500 \text{ MeV} < m_{\tilde{\gamma}} < 700 \text{ MeV}$ becomes now forbidden, differently from the case of absolutely stable photinos.

We proceed now to the computation of the three fundamental quantities for our analysis: the $\tilde{\gamma}$ decoupling temperature (T_D), the temperature at which the Universe gets $\tilde{\gamma}$ dominated (T^*), and the $\tilde{\gamma}$ decay temperature (T_I).

THE PHOTINO DECOUPLING TEMPERATURE T_D

The process $\tilde{\gamma}\tilde{\gamma} \rightarrow ff$ ($f \equiv$ ordinary fermion) proceeds through Z^0 and $\tilde{f}$ ($\tilde{f} \equiv$ scalar fermion) exchanges. When the interaction time for these processes equals the age of the Universe, $t \approx (10^{20}/T^2(^{\circ}K))s.$, the photinos decouple. Following Ellis et al. ²⁾, the decoupling temperature T_D is given by:

$$T_D = m_{\tilde{\gamma}} \left[\ln \left(\tilde{a} m_{\tilde{\gamma}} M_P \sqrt{\frac{45}{\pi^5 N_F}} x_D^{1/2} + \tilde{b} m_{\tilde{\gamma}} M_P \sqrt{\frac{45}{\pi^5 N_F}} x_D^{3/2} \right) \right] \quad (2)$$

where $x_D = T_D/m_{\tilde{\gamma}}$, M_P = Planck mass, N_F counts the effective number of degrees of freedom at T_D , and $\tilde{a}$ and $\tilde{b}$ are correlated to the $\tilde{\gamma}\tilde{\gamma}$ annihilation cross-section by the relation:

$$\langle \sigma v_{rel} \rangle = \tilde{a} + \tilde{b} (T/m_{\tilde{\gamma}}) \quad (3)$$

with v_{rel} replaced by its thermal average $v_{rel}^2 \approx 6T/m_{\tilde{\gamma}}$. The Boltzmann constant is set equal to 1. If we write the low-energy effective Lagrangian for $\tilde{\gamma}\tilde{\gamma} \rightarrow ff$ as

$$\mathcal{L}_{\tilde{\gamma}\tilde{\gamma} \rightarrow ff} = \sum_f \bar{\tilde{\gamma}} \gamma^\mu \gamma_5 \tilde{\gamma} \bar{f} \gamma_\mu \left[A_f \left(\frac{1-\gamma_5}{2} \right) + B_f \left(\frac{1+\gamma_5}{2} \right) \right] f \quad (4)$$

where A_f and B_f denote the couplings of the left-handed and right-handed fermions, respectively, then $\tilde{a}$ and $\tilde{b}$ are related to A_f and B_f by:

$$\begin{aligned} \tilde{a} &= \sum_f \theta(m_{\tilde{\gamma}} - m_f) \frac{1}{2\pi} \frac{p}{m_{\tilde{\gamma}}} m_f^2 (A_f - B_f)^2 \\ \tilde{b} &= \sum_f \theta(m_{\tilde{\gamma}} - m_f) \frac{1}{2\pi} \frac{p}{m_{\tilde{\gamma}}} [(A_f^2 + B_f^2)(4m_{\tilde{\gamma}}^2 - m_f^2) + 6A_f B_f m_f^2] \end{aligned} \quad (5)$$

where $p = \sqrt{m_{\tilde{\gamma}}^2 - m_f^2}$ is the final state 3 momentum. The light photino eigenstate corresponds to:

$$\tilde{\gamma} = \sin\theta_w \tilde{W}^3 + \cos\theta_w \tilde{B}^0$$

where θ_w is the electroweak angle. No admixture of the fermionic partners of the neutral Higgs scalars enters into the definition of $\tilde{\gamma}$. Since the Z^0 mediated $\tilde{\gamma}\tilde{\gamma} \rightarrow ff$ amplitude is proportional to the Higgsino

contributions to $\tilde{\gamma}^{(2)}$, we conclude that only the A_f and B_f coefficients referring to $\tilde{f}$ exchange have to be taken into account in Eq. (5). Furthermore, if we limit ourselves to $m_{\tilde{\gamma}} < 100$ MeV, only electrons can be produced in the $\tilde{\gamma}\tilde{\gamma}$ annihilation*. So we have only to evaluate A_e and B_e . These are approximately given by ²⁾

$$A_e \cong \frac{g^2 \sin^2 \theta_w}{2 m_{\tilde{e}_L}^2} \cong -B_e \quad (7)$$

where g is the SU(2) coupling. From Eqs. (2), (5) and (7), we can calculate T_D as a function of $m_{\tilde{\gamma}}$ and $m_{\tilde{e}_L}$. The results are given in Table 1. Notice that since T_D is in the 1-15 MeV range the photinos decouple before nucleosynthesis.

T*: TEMPERATURE AT WHICH THE UNIVERSE GETS PHOTINO DOMINATED

The Universe is matter dominated by the photinos** when their energy density, $m_{\tilde{\gamma}} n_{\tilde{\gamma}}(T)$ ($n_{\tilde{\gamma}} = \tilde{\gamma}$ number density) is equal to the energy density of relativistic particles, $1.68 a T^4$

$$m_{\tilde{\gamma}} n_{\tilde{\gamma}} |_{T = T^*} = 1.68 a T^{*4} \quad (8)$$

where $a = 4.7 \times 10^{-9} \text{ MeV } ^\circ\text{K}^{-4} \text{ cm}^{-3}$. The factor 1.68 takes into account the energy densities of γ , ν_e , $\bar{\nu}_e$, ν_μ , $\bar{\nu}_\mu$, ν_τ , $\bar{\nu}_\tau$ and the fact that the $\tilde{\gamma}$ temperature is less than the γ temperature after e^+e^- annihilation ($T_{\tilde{\gamma}} = 1.4 T_\gamma$). The $\tilde{\gamma}$ number density at T^* , $n_{\tilde{\gamma}}(T = T^*)$ can be expressed in terms of the γ number density at T_D

$$n_{\tilde{\gamma}}(T^*) = \frac{n_\gamma(T_D)}{2.75} \left(\frac{T^*}{T_D} \right)^3 \quad (9)$$

since after decoupling the number of $\tilde{\gamma}$ is conserved so that the $\tilde{\gamma}$ number density decreases as T^3 . The factor $2.75 = (1.4)^3$ in Eq. (9) is due to the increase of the temperature of the Universe by a factor 1.4 when e^+e^- annihilation takes place. Finally, taking into account the expression for $n(T_D)$

* The process $\tilde{\gamma}\tilde{\gamma} \rightarrow \nu\nu$ can occur only through Z^0 exchange. For what we said above, this process is suppressed.

** For massive unstable neutrinos, see Ref ⁹⁾.

$$n(T_D) = a m_{\tilde{\gamma}} T_D^3 \exp(-m_{\tilde{\gamma}}/T_D) \quad (10)$$

we derive T^* from Eq. (8)

$$T^* = \frac{m_{\tilde{\gamma}}}{(1.68)(2.75)} \exp(-m_{\tilde{\gamma}}/T_D) \quad (11)$$

In this way, we can add the column for T^* in Table 1 for the corresponding values of $m_{\tilde{\gamma}}$ and T_D . The remarkable point about the T^* values is that almost all of them correspond to temperatures below that of nucleosynthesis. So, the Universe is radiation dominated during nucleosynthesis and we do not have to worry about substantial modifications for the predictions of primordial element abundances. For all the cases in which $T^* < 0.1$ MeV, the only requirement we should impose on the photinos is that they decay sufficiently fast to get a thermalization of the photons in their decay products ⁹⁾.

THE γ DECAY TEMPERATURE T_T

The axion coupling which is relevant for the $a \rightarrow \gamma\gamma$ process is given by

$$\mathcal{L}_{a\gamma\gamma} = \frac{e^2 N}{12\pi^2 V_{PQ}} \frac{1}{2} a F_{\mu\nu} F_{\rho\sigma} \epsilon^{\mu\nu\rho\sigma} \quad (12)$$

where N denotes the number of inequivalent vacua ¹⁰⁾ and e is the electromagnetic coupling constant. This coupling in a supersymmetric theory comes from

$$(\Phi W_\alpha W^\alpha)_{\theta\theta} + (\Phi^* \bar{W}^{\dot{\alpha}} \bar{W}_{\dot{\alpha}})_{\bar{\theta}\bar{\theta}} \quad (13)$$

where Φ is the scalar supermultiplet whose pseudoscalar and fermionic components are the axion and the axino, respectively, whereas the vector supermultiplet W_α has the photon and the photino as its vector boson and fermionic components, respectively. Eq. (13) yields the $\tilde{a}\tilde{\gamma}\gamma$ coupling,

$$\mathcal{L}_{\tilde{a}\tilde{\gamma}\gamma} = \frac{e^2 N}{12\pi^2 V_{PQ}} \tilde{\gamma}(\sigma^m \bar{\sigma}^n - \sigma^n \bar{\sigma}^m) \tilde{a} F_{mn} \quad (14)$$

giving rise to the photino decay rate

$$T_{\tilde{\gamma}} = \frac{\alpha_{em}^2 N^2}{9 \pi^3} \left(\frac{m_{\tilde{\gamma}}}{v_{PQ}} \right)^2 m_{\tilde{\gamma}} \quad (15)$$

where $m_{\tilde{a}}$ has been considered negligible with respect to $m_{\tilde{\gamma}}$. In Table 2, we show the decay temperatures for photino masses in the 1 MeV - 1 GeV range and v_{PQ} in the interval given in Eq. (1).

THERMALIZATION OF PHOTONS FROM $\tilde{\gamma} \rightarrow \tilde{a} + \gamma$ DECAY

Our last task here is to ascertain which of the $\tilde{\gamma}$ lifetimes in Tables 2 are compatible with an efficient thermalization of the photons produced in the $\tilde{\gamma}$ decays. The point of thermalization is that the few hard γ 's with energy $m_{\tilde{\gamma}}/2$ from the $\tilde{\gamma}$ decay must be "degraded" to many photons with average energy $\sim (T_I^A)^4$ where T_I^A denotes the temperature of the Universe after the $\tilde{\gamma}$ decay. This production of new soft γ 's proceeds through double Compton emission ($\gamma + e \rightarrow \gamma + \gamma + e$) or Thompson scattering to excite the electrons, followed by bremsstrahlung. Following the standard procedure of Ref. ⁹⁾, one gets that these two processes are efficient in producing enough new soft photons from the initial hard photons only for photino lifetimes shorter than $1.4 \times 10^6 \Omega^{2/3}$ secs. For $\Omega = 0.1$, the upper bound on $\tau_{\tilde{\gamma}}$ is

$$\tau_{\tilde{\gamma}} < 3 \times 10^5 \text{ secs.} \quad (16)$$

In Table 2, we present the photino lifetimes for $m_{\tilde{\gamma}} = 1.5 \text{ MeV} \sim 1 \text{ GeV}$ and $v_{PQ} = 10^8 - 10^{12} \text{ GeV}$, and underline the excluded lifetimes by (16). Using Eqs. (15) and (16), we can determine the forbidden region of the values of v_{PQ} and $m_{\tilde{\gamma}}$ leading to a $\tau_{\tilde{\gamma}}$ longer than $1.4 \times 10^6 \Omega^{2/3}$ secs. Fig. 1 summarizes the major conclusions of our paper. Taking $\Omega = 0.1$, the lower bound for unstable photinos decaying into axinos and photons is $m_{\tilde{\gamma}} = 1.5 \text{ MeV}^*$. For the central favourite value $v_{PQ} = 10^{10} \text{ GeV}$,

* In supersymmetric grand unified models such a low mass for $\tilde{\gamma}$ would lead to a gluino mass smaller than 2-3 GeV, which is the lower bound from the beam dump experiment at CERN for sfermion masses in the 50-100 GeV region (Ref. 11). Even in the supersymmetric standard model, radiative contributions to $m_{\tilde{\gamma}}$ lead to a photino of a few tens of MeV ¹²⁾.

this lower bound grows to $m_{\tilde{\gamma}} = 32$ MeV. If we go to the extreme situation $v_{PQ} = 10^{12}$ GeV, then the lower bound becomes $m_{\tilde{\gamma}} \approx 700$ MeV, i.e. it exceeds the lower bound of 500 MeV of the stable photino case. We stress that for almost all the cases of interest the photinos start dominating the whole energy density of the Universe only after nucleosynthesis so that no departure from the standard Big Bang predictions for nucleosynthesis is expected.

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Table 1

Temperature at which the photinos decouple (T_D) and start dominating the energy density of the Universe (T^*) for different values of the photino mass ($m_{\tilde{\gamma}}$) and the scalar electron mass ($m_{\tilde{e}_L}$). The starred values of T^* correspond to a $\tilde{\gamma}$ dominated Universe for $\Omega = 0.1$ before nucleosynthesis. For $m_{\tilde{\gamma}} = 500, 1000$ MeV, we take into account the increased degree of freedom due to muon, gluons, and the light quarks.

$m_{\tilde{\gamma}}$ (MeV)	M_{eL} (GeV)	T_D (MeV)	T^* (MeV)
10	100	---	---
	60	3.81	0.157*
	40	2.69	5.26×10^{-2}
	30	2.19	2.25×10^{-2}
20	100	7.56	0.307*
	60	4.93	7.49×10^{-2}
	40	3.79	2.21×10^{-2}
	30	3.23	8.86×10^{-2}
40	100	9.81	0.147*
	60	7.10	0.031
	40	5.76	8.35×10^{-3}
	30	5.06	3.19×10^{-3}
60	100	12.01	0.088*
	60	9.07	1.74×10^{-2}
	40	7.54	4.55×10^{-3}
	30	6.71	1.70×10^{-3}
80	100	14.11	5.95×10^{-2}
	60	10.92	1.14×10^{-2}
	40	9.21	2.93×10^{-3}
	30	8.27	1.09×10^{-3}
100	100	16.13	0.044
	60	12.69	8.19×10^{-3}
	45	11.29	3.08×10^{-3}
	25	9.17	3.98×10^{-4}
500	100	52.56	1.61×10^{-3}
	60	44.26	2.71×10^{-4}
	30	36.30	2.28×10^{-5}
1000	100	88.27	5.24×10^{-4}
	60	76.05	8.50×10^{-5}
	30	63.86	6.90×10^{-6}

Table 2

Photino lifetimes (τ_γ) in sec units for different values of the photino mass (m_γ) in MeV and of the scale of the breakdown of the Peccei-Quinn symmetry (v_{PQ}). The underlined values correspond to lifetimes exceeding the cosmological bound $\tau_\gamma < 3 \times 10^5$ secs which is obtained for $\Omega = 0.1$. For the numbers in this table we use the domain number $N_0 = 6$. For a different N , one should multiply $(N_0/N)^2$.

m_γ	v_{PQ} 10 ⁸ GeV	10 ⁹ GeV	10 ¹⁰ GeV	10 ¹¹ GeV	10 ¹² GeV
1000	9.59×10^{-4}	9.59×10^{-2}	9.59	9.59×10^2	9.59×10^4
800	1.87×10^{-3}	1.87×10^{-1}	1.87×10	1.87×10^3	1.87×10^5
500	7.67×10^{-3}	7.67×10^{-1}	7.67×10	7.67×10^3	7.67×10^5
100	0.959	9.59×10	9.59×10^3	9.59×10^5	9.59×10^7
80	1.87	1.87×10^2	1.87×10^4	1.87×10^6	1.87×10^8
60	4.44	4.44×10^2	4.44×10^4	4.44×10^6	4.44×10^8
50	7.67	7.67×10^2	7.67×10^4	7.67×10^6	7.67×10^8
40	15.0	1.50×10^3	1.50×10^5	1.50×10^7	1.50×10^9
30	35.52	3.55×10^3	3.55×10^5	3.55×10^7	3.55×10^9
20	1.20×10^2	1.20×10^4	1.20×10^6	1.20×10^8	1.20×10^{10}
10	9.59×10^2	9.59×10^4	9.59×10^6	9.59×10^8	9.59×10^{10}
8	1.87×10^3	1.87×10^5	1.87×10^7	1.87×10^9	1.89×10^{11}
6	4.44×10^3	4.44×10^5	4.44×10^7	4.44×10^9	4.44×10^{11}
4	1.50×10^4	1.50×10^6	1.50×10^8	1.50×10^{10}	1.50×10^{12}
2	1.20×10^5	1.20×10^7	1.20×10^9	1.20×10^{11}	1.20×10^{13}
1.5	2.84×10^5	2.84×10^7	2.84×10^9	2.84×10^{11}	2.84×10^{13}
1.4	3.50×10^5	3.50×10^7	3.50×10^9	3.50×10^{11}	3.50×10^{13}

REFERENCES

- 1) H. Goldberg, Phys. Rev. Lett. 50 (1983) 1419.
- 2) J. Ellis, J.S. Hagelin, D.V. Nanopoulos, K. Olive, and M. Srednicki, Preprint SLAC-PUB-3171 (1983).
- 3) J.E. Kim, Phys. Rev. Lett. 43 (1979) 103;
M. Dine, W. Fischler and M. Srednicki, Phys. Lett. 104B (1981) 99;
M.B. Wise, H. Georgi and S.L. Glashow, Phys. Rev. Lett. 47 (1981) 402;
H.P. Nilles and S. Raby, Nucl. Phys. B198 (1982) 102;
R. Barbieri, D.V. Nanopoulos and D. Wyler, Phys. Lett. 106B (1981) 303;
For a review, see:
J.E. Kim, talk in Asia-Pacific Physics Conference, June 12-19 (1983)
Seoul National University, Preprint SNUHE-83/03.
- 4) J. Ellis, S. Ferrara and D.V. Nanopoulos, Phys. Lett. 114B (1982) 231;
R. Akhoury, I.I. Bigi and H.E. Haber, Phys. Lett. 135B (1983) 113.
- 5) D.A. Dicus, E.W. Kolb, V.L. Teplitz, and R.V. Wagoner, Phys. Rev. D22 (1980) 839;
M. Fukugita, S. Watamura and M. Yoshimura, Phys. Rev. D26 (1982) 1840.
- 6) J. Preskill, M. Wise and F. Wilczek, Phys. Lett. 120B (1983) 127;
L. Abbott and P. Sikivie, Phys. Lett. 120B (1983) 133;
M. Dine and W. Fischler, Phys. Lett. 120B (1983) 137.
- 7) D.J. Gross, R.D. Pisarski and L.G. Yaffe, Rev. Mod. Phys. 53 (1981) 43.
- 8) J.E. Kim, CERN preprint Ref. TH-3735-CERN, to be published in Phys. Lett. B.;
J.E. Kim and H.P. Nilles, Univ. Geneva preprint UGVA-DPT-1983/10-410, to be published in Phys. Lett. B.
- 9) D.A. Dicus, E.W. Kolb and V.L. Teplitz, Astro Phys. J. 221 (1978) 327.
- 10) P. Sikivie, Phys. Rev. Lett. 48 (1982) 1156.

- 11) G.R. Farrar and P. Fayet, Phys. Lett. 76B (1978) 575;
B.A. Campbell, J. Ellis and S. Rudaz, Nucl. Phys. B198 (1982) 1;
G.L. Kane and J.P. Leveille, Phys. Lett. 112B (1982) 227;
P.R. Harrison and C.H. Llewellyn-Smith, Nucl. Phys. B213 (1983) 223;
CHARM Collaboration, F. Bergsma et al., Phys. Lett. 121B (1983) 429.

- 12) R. Barbieri, L. Girardello and A. Masiero, Phys. Lett. 127B (1983) 429.

FIGURE CAPTIONS

Fig. 1 Axino mass arising from a 3-loop Feynman diagram.

Fig. 2 Allowed domain of the photino mass versus the Peccei-Quinn symmetry breaking scale for several values of the baryonic mass density (Ω) of the Universe.

Fig. 1

Fig. 2