Light Sgoldstino: Precision Measurements versus Collider Searches

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Abstract

We study sensitivity of low-energy experiments to the scale of supersymmetry breaking $\sqrt{F}$ in models with light sgoldstinos — superpartners of goldstino. The limits on $\sqrt{F}$ may be obtained from direct and indirect measurements of sgoldstino coupling to photons, leptons, mesons and nucleons. There are three sources of constraints: (i) astrophysics and cosmology; (ii) precision laboratory experiments at low energies; (iii) rare decays. We discuss only processes with real sgoldstinos. For sgoldstino lighter than a few MeV and superpartner masses of the order of electroweak scale, astrophysical and reactor bounds on $\sqrt{F}$ are significantly stronger than limits which may be reached at future colliders. In models with heavier sgoldstino (up to 5 GeV), constraints from flavor conserving decays of mesons are complementary to ones coming from collider experiments. The most sensitive probes of sgoldstinos are flavor violating processes, provided that flavor is violated in squark and/or slepton sector. It is shown that sgoldstino contributions into FCNC and lepton flavor violation are strong enough to probe the supersymmetry breaking scale up to $\sqrt{F} \sim 10^7$ GeV, if off-diagonal entries in squark (slepton) mass matrices are close to the current limits in MSSM.

1 Introduction

Superpartners of goldstino — longitudinal component of gravitino — may be fairly light. In a variety of models with low energy supersymmetry they are lighter than a few GeV. Such pattern emerges in a number of non-minimal supergravity models [1, 2] and also in gauge mediation models if supersymmetry is broken via non-trivial superpotential (see, e.g., Ref. [3] and references therein). To understand that superpartners of goldstino may be light, it suffices to recall that in globally supersymmetric theories with canonical Kähler potential and in the absence of anomalous abelian gauge factors, the sum of scalar squared masses is equal to the sum of fermion squared masses in each separate sector of the spectrum.

Since goldstino is massless, its spinless superpartners (scalar and pseudoscalar particles, $S$ and $P$, hereafter, sgoldstinos) are massless too; they are associated with a non-compact flat direction of the scalar potential. Higher order terms from the Kähler potential contribute to sgoldstino masses. Provided these terms are sufficiently suppressed, sgoldstinos remain light. Of course, these arguments in no way guarantee that sgoldstinos are always light, but they do indicate that small sgoldstino masses are rather generic. The theoretical discussion of sgoldstino masses is contained, e.g., in Ref. [4]; here we merely assume that sgoldstinos are light and consider their phenomenology.

Sgoldstinos couple to MSSM fields in the same way as goldstino [5]; constraints on their couplings may be translated into the limits on the supersymmetry breaking parameter $F$.

There are several papers devoted to astrophysical [6], cosmological [7] and collider [8, 9, 10] constraints on models with light sgoldstinos. However, the role of light sgoldstinos in low-energy laboratory measurements has not been studied in detail. To the best of author’s knowledge, the only paper discussing this issue, Ref. [11], concentrated on sgoldstino contribution (as well as the contribution from light gravitino) into anomalous magnetic moment of muon. Here we consider a variety of low energy experiments sensitive to light sgoldstinos.

In this paper we identify those experiments which are most sensitive to different sgoldstino vertices for various sgoldstino masses. These experiments provide constraints on the corresponding coupling constants. These constants are in fact
proportional to the ratios of soft terms (squark and gaugino masses, trilinear coupling constants) and $F$. The latter parameter is related to the gravitino mass $m_{3/2}$ in a simple way, $F = \sqrt{3/(8\pi)} m_{3/2} M_{Pl}$; small $F$ corresponds to light gravitino ($m_{3/2} < M_{SUSY}$). Hence, the constraints derived in this paper are of importance for models with light gravitino, whereas sgoldstino effectively decouple from the visible sector in models with heavy gravitino.

In principle, there are both flavor-conserving and flavor-violating sgoldstino couplings to fermions. We present our results in the form of bounds on $\sqrt{F}$ setting soft flavor-conserving terms to be of the order of electroweak scale, as motivated by the supersymmetric solution to the gauge hierarchy problem. Flavor-violating couplings are governed by soft off-diagonal entries in squark (slepton) squared mass matrices. When evaluating bounds on $\sqrt{F}$ we set these off-diagonal entries equal to their current limits derived from the absence of FCNC and lepton flavor violation in MSSM $^{12}$. In this way we estimate the sensitivity of various experiments to the supersymmetry breaking scale.

We consider only low-energy processes with sgoldstinos on mass-shell. Processes with sgoldstino exchange deserve separate discussion, though we do not expect that the results obtained in this paper will be altered significantly. Also, behind the scope of this paper are loop processes with virtual sgoldstinos running in loops (for instance, $K^0 - \bar{K}^0$-mixing, $\mu \rightarrow e\gamma$, etc.). These processes were analyzed in Ref. $^{13}$ in models with heavy sgoldstinos. Constraints on $F$ obtained in Ref. $^{13}$ are significantly weaker than ones presented in our paper, so the loop processes are less sensitive to $F$ in models with heavy sgoldstinos. However, models with light sgoldstinos have not been analyzed in detail yet, though it was pointed out in Ref. $^{13}$ that enhancement effects may appear if sgoldstinos are light. In view of the results obtained in this paper we also find it conceivable that light virtual sgoldstinos may give significant contributions into rare processes considered in Ref. $^{13}$.

Let us briefly review the current status of experimental limits on $F$. If one ignores sgoldstino, then in models with light gravitino the strongest direct current bound on $F$ is obtained from Tevatron, $\sqrt{F} > 217$ GeV $^{14}$. In models with light sgoldstinos, collider experiments become more sensitive to the scale of supersymmetry breaking. Namely, LEP and Tevatron provide constraints at the level of 1 TeV on the supersymmetry breaking scale in models with $m_{S(P)}$ of order of 20 GeV $^{15,16}$. The most stringent cosmological constraint comes from Big Bang Nucleosynthesis $^{17}$: models with light gravitino, $m_{3/2} < 1$ eV, that corresponds to $\sqrt{F} < 7 \cdot 10^4$ GeV, are disfavored if sgoldstinos decouple at temperature not less than $O(100)$ MeV ($m_{S(P)} \lesssim 1$ MeV). It has been argued in Ref. $^{18}$ that among the astrophysical constraints, the strongest one comes from SN1987A: the gravitino mass is excluded in the range $10^{-1.5}$ eV $< m_{3/2} < 30$ eV for 1 keV $< m_{S(P)} < 10$ MeV and in a wider range $3 \cdot 10^{-6}$ eV $< m_{3/2} < 50$ eV for $m_{S(P)} < 1$ keV. These excluded intervals correspond to $10^4$ GeV $< \sqrt{F} < 4 \cdot 10^5$ GeV and 120 GeV $< \sqrt{F} < 5 \cdot 10^5$ GeV, respectively.

In this paper we consider various constraints on couplings of light ($m_{S(P)} \lesssim 5$ GeV) (pseudo)scalars to SM fields coming mostly from astrophysics and direct precision measurements. So, we partially fill the gap between constraints coming from collider experiments and cosmology.

As there are flavor-conserving and flavor-violating interactions of sgoldstino fields, we have to consider both flavor-symmetric and flavor asymmetric processes. Let us outline our results referring to these two cases in turn.

We begin with constraints independent of assumptions concerning breaking of flavor symmetry. As expected, strongest bounds arise from astrophysics and cosmology, that is $\sqrt{F} \gtrsim 10^6$ GeV, or $m_{3/2} > 600$ eV, for models with $m_{S(P)} < 10$ keV and MSSM soft flavor-conserving terms being of the order of electroweak scale. For the intermediate sgoldstino masses (up to a few MeV) constraints from the study of SN explosion and reactor experiments lead to $\sqrt{F} \gtrsim 300$ TeV. We will find that for heavier sgoldstinos, low energy processes (such as rare decays of mesons) provide limits comparable to ones from colliders but valid for different sgoldstino masses.

As concerns flavor-asymmetric processes, we find that these are generally very sensitive to light sgoldstino. Namely, with flavor-changing off-diagonal entries in squark (slepton) squared mass matrix close to the current bounds, direct measurements of decays of mesons (leptons) provide very strong bounds, up to $\sqrt{F} \gtrsim 900(15000)$ TeV (valid at $m_S \lesssim 5(0.34)$ GeV), which is much higher than bounds expected from future colliders. If off-diagonal entries are small, the limits on $\sqrt{F}$ become weaker: they scale as square root of the corresponding off-diagonal elements.

We will see that the rates of processes with one sgoldstino in final state are proportional to $F^{-2}$, whereas the rates
of processes with two sgoldstinos in final state are proportional to $F^{-4}$. Hence, under similar assumptions about soft terms governing sgoldstino couplings, processes with one sgoldstino are more sensitive to the supersymmetry breaking scale. Nevertheless, the coupling constants entering one-sgoldstino and two-sgoldstino processes are generally determined by different parameters, so the study of two-sgoldstino processes is also important.

Further progress in the search for sgoldstino is expected in several directions. Among the laboratory experiments, the most sensitive to flavor-conserving sgoldstino coupling for sgoldstino lighter than a few MeV are experiments with laser photons propagating in magnetic fields and reactor experiments. For heavier sgoldstinos, measurements of $\Upsilon$ partial widths exhibit the best discovery potential. If flavor violation in MSSM is sufficiently strong (say, at the level of current limits), the most promising is the study of charged kaon decays.

This paper is organized as follows. In section 2 the effective lagrangian for sgoldstinos is presented and sgoldstino decay modes are described. In section 3 we derive various constraints on the parameter of supersymmetry breaking $\sqrt{F}$ by considering low energy processes. There we study separately processes with one and two sgoldstinos in final states (sections 3.1 and 3.2, respectively). First, we discuss astrophysical and cosmological limits on sgoldstino interactions (section 3.1.1). Then we present laboratory bounds coming from search for light (pseudo)scalars in electromagnetic and strong processes (section 3.1.2). In sections 3.1.3 and 3.1.4. we discuss rare decays with one sgoldstino in final state due to flavor-conserving and flavor-violating sgoldstino couplings to SM fermions, respectively. Sections 3.2.1 and 3.2.2 are devoted to rare meson decays with two sgoldstinos in final state. Our conclusions and comparison of the results with ones coming from collider experiments are presented in section 4.

\section{Effective lagrangian}

Let us introduce the effective lagrangian for light goldstino supermultiplet: scalar $S$, pseudoscalar $P$ and goldstino $\tilde{G}$. The free part reads

$$\mathcal{L} = \frac{1}{2} \left( \partial_\mu S \partial^\mu S - m_S^2 S^2 \right) + \frac{1}{2} \left( \partial_\mu P \partial^\mu P - m_P^2 P^2 \right) + \frac{i}{2} \tilde{G} \gamma^\mu \partial_\mu \tilde{G} .$$

There exist two types of interactions in the low-energy effective theory involving sgoldstino fields: these are terms that govern sgoldstino couplings, processes with one sgoldstino are more sensitive to the supersymmetry breaking limits), the most promising is the study of charged kaon decays.

The direct coupling of two sgoldstinos is described by

$$\mathcal{L}_{\text{eff}} = \frac{1}{4 F^2} \left( S \partial_\mu P - P \partial_\mu S \right) \left( \tilde{m}_{L_{ij}}^{LL} + \tilde{m}_{D_{ij}}^{LR} \right) \tilde{f}_{L_i} \gamma^\mu \gamma_5 \tilde{f}_{L_j} + \left( \tilde{m}_{L_{ij}}^{LL} - \tilde{m}_{L_{ij}}^{RR} \right) \tilde{f}_{L_i} \gamma^\mu \gamma_5 \tilde{f}_{L_j} .$$

Here $M_{\gamma_5} = M_1 \cos \theta_W + M_2 \sin \theta_W$ and $M_i$ are gaugino masses; for down-quarks $i = d, s, b$, whereas for up-quarks $i = u, c, t$; $\tilde{m}_{L_{ij}}^{LR} \tilde{m}_{L_{ij}}^{LL}$ and $\tilde{m}_{D_{ij}}^{RR}$ are LR-, LL-, and RR-soft mass terms in squark squared mass matrix and for convenience we take them real. In what follows we do not discuss neutrino, so the corresponding couplings are omitted. Note that in MSSM the flavor-conserving one-sgoldstino coupling constants satisfy $\tilde{m}_{L_{ij}}^{LR} = m_{f_i} A_{f_i}$, whereas $m_{f_i}$ are fermion masses and $A_{f_i}$ are corresponding soft trilinear coupling constants. Off-diagonal soft terms $\tilde{m}_{L_{ij}}^{LR}$, $\tilde{m}_{L_{ij}}^{LL}$ and $\tilde{m}_{D_{ij}}^{RR}$ are subject to constraints from the absence of FCNC and lepton flavor violation (see, e.g., Ref. [2]).
The first part of the effective lagrangian, Eq. (1), is suppressed by $F^{-1}$, whereas the second one, Eq. (2), is proportional to $F^{-2}$, so processes with two sgoldstinos are very rare. The most stringent bounds on $F$ come from processes with one sgoldstino in final state. Nevertheless, as we will see, the absence of processes with two sgoldstinos gives rise to constraints on supersymmetry breaking parameter $F$ comparable to bounds from high-energy experiments. The latter constraints are, strictly speaking, independent of the constraints coming from one-sgoldstino processes: one-sgoldstino and direct two-sgoldstino processes are governed by $\tilde{m}_{LR}^2$ and $\tilde{m}_{LL}^2, \tilde{m}_{RR}^2$, respectively.

Let us discuss decay modes of light sgoldstino. First, sgoldstino decay into two photons is always open [9],

$$\Gamma(S(P) \to \gamma\gamma) = \frac{m_{S(P)}^3 M_{\gamma\gamma}^2}{32\pi F^2}. \quad (3)$$

Second, in models where $m_{3/2} < m_{S(P)}$ sgoldstinos may decay into gravitino pairs; however, the corresponding rates are suppressed by squared ratio of sgoldstino mass $m_{S(P)}$ and $M_{\gamma\gamma}$ in comparison with the decay into two photons, hence this mode may be disregarded. Third, relatively heavy sgoldstinos ($m_{S(P)} > M_{\gamma\gamma}$) decay into gluons (light mesons) with larger width than into photons because of color enhancement and because the corresponding coupling is proportional to gluino mass which is usually the largest among the gaugino masses, i.e. $M_3 > M_{\gamma\gamma}$. When analyzing hadronic decay modes of light sgoldstinos ($m_{S(P)} < a few\ GeV$), corresponding rates into quarks and gluons should be rewritten in terms of light mesons. This step will be presented below. Fourth, sgoldstino can decay also into light leptons if this process is allowed kinematically ($m_{S(P)} > 2m_l$). Since the corresponding coupling constants are proportional to fermion masses these rates are suppressed by a factor $m_l^2/m_{S(P)}^2$ apart from the phase space volume $[4]$. 

$$\Gamma(S \to l\bar{l}) = \frac{m_3^2 A_3^2 m_S^2}{16\pi F^2 m_S^2} \left(1 - \frac{4m_l^2}{m_S^2}\right)^{3/2}, \quad \Gamma(P \to l\bar{l}) = \frac{m_3^2 A_3^2 m_p^2}{16\pi F^2 m_p^2} \left(1 - \frac{4m_l^2}{m_p^2}\right)^{1/2}. \quad (4)$$

Consequently, depending on MSSM mass spectrum, sgoldstino masses and the value of the supersymmetry breaking parameter $F$, there are three possible situations in experiments where light (pseudo)scalar particle appears. This particle may live long enough to escape from a detector. For instance, in the theory with the superpartner scale of order 100 GeV and $\sqrt{F} = 1\ TeV$ this behavior would be exhibited by (pseudo)scalar particle with mass less than 10 MeV, at which sgoldstino width is saturated by two-photon mode. Another case is when (pseudo)scalar particle decays within detector into two photons or leptons. Apart from these cases, there is also a possibility of the decay into two gluons (quarks). For relatively light sgoldstinos (but with masses exceeding 270 MeV), the dominant hadronic decay is into two pions, while for heavier sgoldstinos $KK$ and $\eta\eta$ channels become available. Furthermore, there would be effects emerging due to $P - \pi^0(\eta, K^0)$ mixing.

Let us estimate branching ratios of hadronic and photonic decay channels neglecting threshold factor. In order to estimate sgoldstino coupling to hadrons we make use of chiral theory of light hadrons. We evaluate contributions from these two sources into meson-sgoldstino interactions separately.

First, we have to relate gluonic operators entering Eq. (1) to meson fields. We make use of the correspondence

$$-\langle(\pi\pi)_{J=0} \frac{\alpha_s}{8\pi} G^a_{\mu\nu} G^a_{\mu\nu} | 0 \rangle = \frac{1}{2} q^2 \varphi_{\pi\pi}^a \varphi_{\pi\pi}^a, \quad (5)$$

derived in Ref. [5]. Here $q^2$ is momentum of pion pair created with zero total angular momentum, $J = 0$; $\beta(\alpha_s)$ is the $\beta$-function of QCD, $\varphi_{\pi\pi}^a$ is the pion isotopic amplitude,

$$\varphi_{\pi\pi}^a = \varphi_{\pi^+}^a \varphi_{\pi^-}^a + \varphi_{\pi^0}^a \varphi_{\pi^0}^a,$$

and quarks and mesons are considered massless. At higher energies also $KK$ and $\eta\eta$ pairs may be created by gluonic operator.

There is one more relation [6],

$$\langle A \frac{N_c \alpha_s}{4\pi} G_{\mu\nu}^a \tilde{G}_{\mu\nu} G_{\mu\nu} G_{\mu\nu} | 0 \rangle = \text{const} \cdot \epsilon \cdot f_A m_A^2 \varphi_A, \quad (6)$$
where $\tilde{G}^a_{\mu\nu}$ is a tensor dual to gluonic one, $A$ is a neutral pseudoscalar meson ($\pi^0$, $\eta$) and $\text{const}$ is a normalization factor; $f_A = f_\pi = 130$ MeV and $\epsilon$ is a parameter responsible for $SU(N_f)$ flavor symmetry breaking ($\epsilon = (m_u - m_d)/(m_u + m_d)$ for $\pi^0$, $\epsilon \simeq 1$ for $\eta$).

In fact, the lagrangian (1) describes sgoldstino interactions at the superpartner scale. Sgoldstino coupling constants at low energies may be obtained by making use of renormalization group evolution. Thus for the gluonic operator one has

$$G^2_{\mu\nu}(M_3) = G^2_{\mu\nu}(\mu) \frac{\beta(\alpha_s(\mu))}{\alpha_s(\mu)} \frac{\alpha_s(M_3)}{\beta(\alpha_s(M_3))}.$$ 

Hence, we estimate the matrix element of the gluonic operator between the scalar and meson pair as

$$\langle (AA)_{J=0} | \frac{M_3}{2\sqrt{2} F} G^a_{\mu\nu} G^{a\mu\nu} S | S \rangle = \frac{\alpha_s(M_3)}{\beta(\alpha_s(M_3))} q^2 \sqrt{2} \pi \varphi A \frac{M_3}{F} \varphi S$$

and in a similar way we estimate the matrix element of another gluonic operator between the pseudoscalar and meson

$$\langle A | \frac{M_3}{2\sqrt{2} F} G^a_{\mu\nu} \tilde{G}^{a\mu\nu} P | P \rangle = \epsilon \cdot \text{const} \frac{2\sqrt{2} \pi}{\alpha_s(M_3)} \frac{f_A m_a^2 \varphi A}{N_f} \frac{M_3}{F} \varphi P.$$ 

Note, that these matrix elements are highly suppressed by squared sgoldstino or meson masses.

Since direct sgoldstino coupling to quarks contributes also to meson production, we remind basic relations of chiral theory

$$\langle 0 | J_\mu^\pi(0) | \pi^0(\bar{q}) \rangle = \frac{i}{\sqrt{2}} f_\pi q_\mu,$$

$$\langle 0 | J_\mu^{\pi^+}(0) | \pi^+(\bar{q}) \rangle = i f_\pi q_\mu.$$ 

where

$$J_\mu^{\pi^0} = \frac{1}{2} (\bar{u} \gamma_\mu \gamma_5 u - d \gamma_\mu \gamma_5 d), \quad J_\mu^{\pi^+} = d \gamma_\mu \gamma_5 u.$$ 

If we parameterize sgoldstino couplings to the triplet of light quarks $q$ as

$$\mathcal{L} = -\bar{q} \left( S \hat{\Sigma}_S - i \gamma_5 P \hat{\Sigma}_P \right) q$$

with $\hat{\Sigma}_S$ and $\hat{\Sigma}_P$ being $3 \times 3$ matrices of the corresponding coupling constants (which are read off from Eq. (1)), then the standard procedure (see, e.g., Ref. [1]) gives the following low-energy effective lagrangian

$$\mathcal{L}_{meson} = B_0 \text{Tr} \left( f_\pi \hat{\Phi} \hat{\Sigma}_P P - S \hat{\Sigma}_S \hat{\Phi}^2 \right)$$

(11)

to the leading order in mesonic fields included in matrix $\hat{\Phi}$. The constant $B_0$ is related to quark condensate as $(0|\bar{q}q|0) = -\frac{1}{4} B_0 f_\pi^2$ and may be evaluated from the masses of kaon and quarks, $B_0 = M_K^2/(m_d + m_s)$. We account only for one-sgoldstino terms since others are suppressed by sgoldstino masses and additional inverse power of $F$.

The lagrangian (11) consists of two parts. The first one,

$$\mathcal{L}_{meson-1} = -B_0 f_\pi^2 \sqrt{2} \left( \frac{\pi^0}{\sqrt{2}} \left( m_{U_{11}}^{LR} - m_{D_{11}}^{LR} \right) + \frac{\eta}{\sqrt{6}} \left( m_{U_{11}}^{LR} + m_{D_{11}}^{LR} - 2 m_{D_{22}}^{LR} \right) + K^0 m_{D_{21}}^{LR} + \tilde{K}^0 m_{D_{12}}^{LR} \right) P,$$

(12)

is pseudoscalar sgoldstino mixing with $\pi^0$, $\eta$, $K^0$ and $\tilde{K}$ mesons, while the second one,

$$\mathcal{L}_{meson-2} = -B_0 f_\pi^2 \sqrt{2} \left( \frac{\pi^0}{\sqrt{2}} \left( m_{U_{11}}^{LR} + m_{D_{11}}^{LR} \right) \left( \pi^+ \pi^- + K^+ K^- + K^0 \tilde{K}^0 + \frac{1}{2} \pi^0 \pi^0 \right) \right.$$

$$\left. + \frac{1}{6} \eta \left( m_{U_{11}}^{LR} + m_{D_{11}}^{LR} + 4 m_{D_{22}}^{LR} \right) + \frac{1}{3} \pi^0 \eta \left( m_{U_{11}}^{LR} - m_{D_{11}}^{LR} \right) - \frac{1}{2} \pi^0 K^0 m_{D_{12}}^{LR} - \frac{1}{2} \pi^0 K^0 m_{D_{12}}^{LR} \right) \right.$$

$$\left. - \frac{1}{6} \tilde{K}^0 \eta m_{D_{21}}^{LR} + \frac{1}{6} \tilde{K}^0 \eta m_{D_{21}}^{LR} + K^- \pi^+ m_{D_{21}}^{LR} + K^+ \pi^- m_{D_{21}}^{LR} \right) S$$

(13)

describes scalar sgoldstino decays into mesons. Note that sgoldstino couplings with two different mesons is suppressed by off-diagonal term in squark mass matrix. In what follows we will not consider processes where real sgoldstino decays into such modes.
Now let us estimate matrix elements between sgoldstino and meson (i.e., sgoldstino-meson mixing) as a sum of two quantities, Eq. (8) and Eq. (12), while the amplitude of the scalar sgoldstino decay into pairs of light mesons is evaluated as a sum of Eq. (6) and Eq. (13). Let us compare contributions of gluon and quark operators into sgoldstino couplings to mesons. As an example, for the ratio of the corresponding contributions into coupling of the scalar to neutral pions and into pion-pseudoscalar mixing we obtain

$$\frac{\langle \pi^0,\pi^0 | S \rangle_{\text{gluon}}}{\langle \pi^0,\pi^0 | S \rangle_{\text{quark}}} = \frac{\alpha_s(M_3)}{\beta^2(\alpha_s(M_3))} \frac{m_S}{m_\pi} \frac{M_3}{M^2_{\pi\pi}} \frac{m_S}{m_\pi},$$

$$\frac{\langle \pi^0 | P \rangle_{\text{gluon}}}{\langle \pi^0 | P \rangle_{\text{quark}}} = \frac{2\pi\sqrt{2}}{\alpha_s(M_3)} \frac{M_1}{3A_Q}.$$

These ratios are larger than 10 for $M_3 = A_Q$. Hence, gluonic operators give rise to stronger coupling of light sgoldstinos to light mesons, as compared to sgoldstino-quark interactions.

Let us evaluate the rate of the scalar sgoldstino decay into light mesons, assuming that this decay is allowed kinematically. As an example, for the neutral pion mode we obtain

$$\Gamma(S \rightarrow \pi^0 \pi^0) = \frac{\alpha_s^2(M_3)}{\beta^2(\alpha_s(M_3))} \frac{\pi m_S}{324} \frac{m_\pi^2}{F^2} \left(1 - \frac{\beta^2(\alpha_s(M_3))}{4\pi} \frac{9}{4\pi} \frac{B_0}{m_\pi} \frac{m_u + m_d}{m_S} \right)^2 \sqrt{1 - \frac{4m^2_{\pi\pi}}{m^2_S}}.$$

Taking into account only the largest contribution from the gluon operator and neglecting the threshold factor we estimate the ratio of rates of sgoldstino decays into photons and mesons,

$$\frac{\Gamma(S \rightarrow \gamma\gamma)}{\Gamma(S \rightarrow \pi^0\pi^0)} = \frac{81}{8\pi^2} \frac{\alpha_s^2(M_3)}{\beta^2(\alpha_s(M_3))} \frac{M_{\pi\pi}^2}{M_1^2}.$$

We see that this ratio is smaller than 1 at $M_{\gamma\gamma} = M_3$. Since in most models gluino is several times heavier than photino, for sufficiently heavy sgoldstinos hadronic modes usually dominate over photonic one.

Let us estimate now the contribution of pion-sgoldstino mixing into pseudoscalar sgoldstino width. Recall that the pion width is almost saturated by the two-photon decay mode. Then

$$\Gamma(P \rightarrow \pi^0 \rightarrow \gamma\gamma) = \frac{1}{\alpha_s^2(M_3)} \frac{\pi^2 f^2_{\pi^0}}{4\pi} \frac{M_3^2 m_{\pi^0}^4}{F^2} \left(\frac{m_u - m_d}{m_u + m_d}\right)^2 \Gamma^*(\pi^0 \rightarrow \gamma\gamma),$$

(14)

where the two-photon width of virtual pion is taken at $p^2_{\pi^0} = m^2_P$ and may be approximated as

$$\Gamma^*(\pi^0 \rightarrow \gamma\gamma) \approx \Gamma_{\text{tot}}(\pi^0) \frac{m^3_P}{m_{\pi^0}}.$$

With account of only leading contributions from gluonic operator we obtain

$$\frac{\Gamma\text{direct}(P \rightarrow \pi^0 \rightarrow \gamma\gamma)}{\Gamma(P \rightarrow \pi^0 \rightarrow \gamma\gamma)} = \frac{\alpha_s^2(M_3)}{8\pi^3} \frac{\tau_{\pi\pi\pi} m_{\pi^0} m_{\pi^0}}{M_3^2} \frac{M_{\pi\pi}^2}{F^2} \frac{m^3_P}{m_{\pi^0}} \left(\frac{m^2_P}{m_{\pi^0}} - 1\right)^2.$$

(15)

As discussed above, $\tilde{m}_{\eta}^{HR} \approx m_A$, so at $M_{\gamma\gamma} = M_3$ and light $P$ ($m_P \ll m_{\pi^0}$) we obtain that the ratio (15) is numerically $8 \times 10^2$. In the opposite case of heavy $P$ ($m_P \gg m_{\pi^0}$) the ratio becomes even larger. Hence mixing with pions gives negligible contribution to sgoldstino decay into photons (unless $M_{\gamma\gamma} \lesssim M_3/30$; we do not consider this case). The only exception is the degenerate case, when sgoldstino and pion masses are close and this branching becomes of order 1. (In the case of strong degeneracy there is also a correction to pion life-time which may give rise to a constraint on $F$). We do not consider this unrealistic situation. The interference with $\eta$-meson gives nothing new. Indeed, Eq. (14) scales as $\tau_{\pi\pi\pi} m^3_{\pi\pi\pi}$ which is invariant under the variation of meson mass, if the meson width is (almost) saturated by anomalous decay into two photons. Decay via neutral kaon is also negligible because of large kaon life-time.

To conclude this section we summarize the situation with sgoldstino branching ratios. Let us begin with scalar sgoldstino. In Figure 1 we present scalar sgoldstino branching ratios into photons, leptons and neutral pions evaluated for four different sets of supersymmetry breaking soft terms, $A$, $M_{\gamma\gamma}$, $M_3$. To determine photonic and leptonic widths
we make use of Eqs. (3) and (4), while the width into two neutral pions is calculated according to Eq. (5) generalized to non-zero pion masses. Estimating hadronic sgoldstino partial width we account only for $\pi^+\pi^-$ and $\pi^0\pi^0$ decay modes. Other hadronic modes may be considered in the same way. Ratios between different hadronic channels are determined by chiral theory.

Scalar sgoldstino lighter than 270 MeV almost always predominantly decays into two photons. At sgoldstino mass close to $2m_e$ or $2m_\mu$, rates of the decays into pairs of corresponding leptons become comparable to the two-photon rate and even exceed the latter in models with large trilinear soft terms. Far from the lepton mass, the corresponding lepton branching ratio decreases as $m_l^2/m_S^2(P)$. At sgoldstino masses exceeding 270 MeV hadronic modes emerge. Their rates are somewhat higher than the rate of the two-photon decay except for models with large $M_{\gamma\gamma}$, in which the photonic mode always dominates.

As regards pseudoscalar sgoldstino, it does not have the decay mode into two pseudoscalar mesons to the zero order in $G_F$. Hence at $M_{\gamma\gamma} \sim M_3$ its hadronic decay modes are suppressed unless $m_P$ is quite large (well above 1 GeV). In what follows we consider photonic and leptonic decay channels of the pseudoscalar sgoldstino only.

### 3 Searches for light sgoldstino

In accordance with the discussion of sgoldstino effective lagrangian presented in the previous section, there are two types of processes we are interested in. In the processes of the first type only one sgoldstino emerges while in the processes of the second type a pair of sgoldstinos appears in the final state. These processes are governed by different coupling constants and will be considered in turn.
3.1 Processes with one sgoldstino in the final state

3.1.1 Bounds from astrophysics and cosmology

In subsections 3.1.1 and 3.1.2 we consider mainly pseudoscalar sgoldstino, though almost all constraints are valid for the scalar sgoldstino as well; a few exceptions will be pointed out.

Light pseudoscalar particles appear in particle physics models in various contexts; a well known example is an axion. There are numerous cosmological, astrophysical and laboratory bounds on interactions of light pseudoscalars which apply to sgoldstino. For completeness we collect in sections 3.1.1 and 3.1.2 the most stringent of these bounds and translate the bounds on sgoldstino coupling constants into bounds on supersymmetry breaking parameters $\sqrt{F}$ and $m_{3/2}$. Let us write the interactions of sgoldstino with photons and fermions as follows

$$
\mathcal{L}_{\gamma P} = -\sqrt{2} \frac{M_{\gamma P}}{F} P \bar{E} B \equiv g_{\gamma P} \bar{E} B , \quad \mathcal{L}_{f P} = \frac{m_{f P}}{\sqrt{2} F} P \bar{f} \gamma P f \gamma f .
$$

(16)

Then the limits on $g_{\gamma}$ and $g_{f P}$ imply limits on $\sqrt{F}$.

In what follows we set $M_{\gamma} = M_{f} = 100$ GeV in our quantitative estimates, since superpartner scale $M_{SUSY}$ is expected to be close to the electroweak scale as motivated by supersymmetric solution to the hierarchy problem in SM.

One of the sources of pseudoscalars are stars: light pseudoscalars are produced there by Primakoff process, that is $\gamma \rightarrow P$ conversion in external electromagnetic field. Another place of sgoldstino creation is galactic space where magnetic fields produce pseudoscalars from propagating photons.

| Experiment       | $m_P$ [eV] | $g_{\gamma}$, GeV$^{-1}$ | $\sqrt{F}$, GeV | $m_{3/2}$, GeV |
|------------------|------------|--------------------------|-----------------|----------------|
| "helioscope"     | $< 0.03$ eV| $< 6 \cdot 10^{-10}$     | $> 0.5 \cdot 10^{6}$ | $> 60$ eV     |
| SOLAX            | $< 1$ keV  | $< 2.7 \cdot 10^{-9}$    | $> 2.3 \cdot 10^{5}$ | $> 12$ eV     |
| SN               | $< 10^{-9}$eV| $< 10^{-11}$               | $> 4 \cdot 10^{6}$   | $> 3.5$ keV   |
| $HBS$            | $< 10$ keV | $< 6 \cdot 10^{-11}$     | $> 1.5 \cdot 10^{6}$   | $> 550$ eV   |

| Photon Background and distortion of CMBR spectrum | $1$ keV | $< 10^{-14}$ or $> 10^{-5}$ | $< 1.2 \cdot 10^{8}$ or $< 4 \cdot 10^{3}$ | $< 3.5$ MeV or $< 3.5$ meV |
|---------------------------------------------------|--------|-----------------------------|--------------------------------|----------------------------|
| $SN1987A$                                          | $< 1$ keV | $< 5.6 \cdot 10^{-10}$ or $> 10^{-2}$ | $< 5 \cdot 10^{5}$ or $< 120$ | $> 50$ eV or $< 3 \cdot 10^{-6}$ eV |
| $SN1987A$                                          | $1$ keV $< m_P < 10$ MeV | $< 9 \cdot 10^{-10}$ or $> 8 \cdot 10^{-7}$ | $> 4 \cdot 10^{5}$ or $> 1.3 \cdot 10^{4}$ | $< 10^{-1.5}$ eV |

Table 1: Constraints from astrophysics and cosmology on SUSY models with light sgoldstinos coupled to photons.

In “helioscope” method, a dipole magnet directed towards the Sun is used. Inside the volume with strong magnetic field, solar pseudoscalars can transform into X-rays by inverse Primakoff process. An alternative method, “Bragg diffraction”, was applied in SOLAX experiment to detect solar pseudoscalars. The absence of anomalous X-ray fluxes from SN1987A related to possible pseudoscalar conversion into photons in galactic magnetic field gives the strongest constraint on $g_{\gamma}$. Since this limit is valid only for unrealistically light pseudoscalar ($m_P < 10^{-9}$ eV), we consider the helium-burning life-time of Horizontal Branch Stars (HBS) in globular clusters as the most sensitive probe of $F$ at very small $m_P$.

There are two more constraints on $g_{\gamma}$ coming from cosmology and astrophysics. Light sgoldstinos are thermally produced in the early Universe via Compton process $e\gamma \rightarrow eP(S)$. Photons from sgoldstino decays contribute to the photon
extragalactic background, if sgoldstinos outlive matter-radiation decoupling. If, on the other hand, sgoldstinos decay before matter-radiation decoupling, produced photons may heat electrons leading to distortion of CMBR spectrum, which is experimentally studied well enough to exclude wide range of $F$ at corresponding sgoldstino masses. The experiments on photon background and cosmic microwave background radiation, being combined, exclude a strip in $(m_P, g_0)$ plane (see Ref. [24]). In Table 1 we present the corresponding limits for two typical values of $m_P$.

All these constraints on $g_0$ are collected in Table 1. The limits on $\sqrt{F}$ are obtained at $M_{\gamma\gamma} = 100$ GeV and scale as square root of $M_{\gamma\gamma}$. For completeness, we included in Table 1 also the limits obtained in Ref. [6] by considering SN1987A.

| Experiment | $m_P$ | $g_f$ | $\sqrt{F}$, GeV | $m_{3/2}$ |
|------------|-------|-------|-----------------|-----------|
| Red Giants | $< 10$ keV | $g_e < 2.5 \cdot 10^{-13}$ | $> 3.8 \cdot 10^5$ | $> 35$ eV |
| HBS        | $\lesssim 10$ keV | $g_{eP} < 0.5 \cdot 10^{-12}$ | $> 2.7 \cdot 10^5$ | $> 17$ eV |
| HBS        | $\lesssim 10$ keV | $g_{eS} < 1.3 \cdot 10^{-14}$ | $> 1.6 \cdot 10^6$ | $> 650$ eV |
| HBS        | $\lesssim 1$ keV | $g_N^{(0)} < 4.3 \cdot 10^{-11}$ | $\geq 1.2 \cdot 10^6$ | $> 370$ eV |
| SN1987A    | $\lesssim 10$ MeV | $g_N^{(0)} < 3 \cdot 10^{-10}$ or $g_N^{(0)} > 3 \cdot 10^{-7}$ | $\geq 5 \cdot 10^5$ or $\leq 1.5 \cdot 10^4$ | $< 0.05$ eV |

Table 2: Constraints from Astrophysics on SUSY models with light sgoldstinos coupled to fermions.

Let us proceed with sgoldstino coupling to electrons. Restrictive limits come from delay of helium ignition in low-mass red giants. There are also two limits on coupling to electrons from bremsstrahlung process $e^- + (A, Z) \rightarrow (A, Z) + e^- + P$ and Compton process $\gamma + e^- \rightarrow e^- + P$ in stars: these processes lead to energy loss of stars and are constrained by helium-burning life-time of Horizontal Branch Stars. Note that the life-time of HBS gives stronger constraints on electron coupling to scalar than to pseudoscalar.

Let us turn to (pseudo)scalar coupling to nucleons. In order to relate the corresponding constant $g_N$ to $F$ we make use of the analogy to axion. Then effective lagrangian reads

$$L_{eff} = i\bar{\psi}\gamma_5 (g_N^{(0)} + g_N^{(3)} \tau_3) \psi P,$$

where $\psi$ denotes the nucleon doublet and

$$g_N^{(0)} \sim \frac{A_Q m_N}{\sqrt{2} F}, \quad g_N^{(3)} \sim \frac{m_u - m_d}{m_u + m_d} g_N^{(0)}.$$

The energy loss of Horizontal Branch Stars via Compton process $\gamma + ^4\text{He} \rightarrow ^4\text{He} + S$ gives rise to a bound on $F$. Also, nucleon-sgoldstino coupling leads to shortening of SN1987A neutrino burst.

Astrophysical constraints on sgoldstino-fermion interactions are presented in Table 2. Bounds on $\sqrt{F}$ are obtained at $A_e = A_Q = 100$ GeV and scale as $\sqrt{A_f}$, $f = Q, e$. Note that the region $\sqrt{F} \lesssim 1.5 \cdot 10^4$ GeV allowed by SN explosion [26] is not ruled out by astrophysical arguments or direct measurements if sgoldstino is relatively heavy ($10$ keV $\lesssim m_{S(P)} \lesssim 10$ MeV) and its interactions conserve flavor (see below).

For constraints coming from Big Bang Nucleosynthesis see Ref. [7].

### 3.1.2 Laboratory bounds on very light sgoldstinos

Let us now consider direct laboratory limits on couplings of very light sgoldstinos.

The first set of bounds on $F$ comes from the study of laser beam propagation through transverse magnetic field. The production of real sgoldstinos would induce the rotation of the beam polarization, while the emission and absorption of virtual sgoldstinos would contribute to the ellipticity of the laser beam. Such effects have not been observed and their absence implies a constraint on pseudoscalar-photon coupling. There is also a constraint on the interaction of a

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1See also Ref. [24] for constraints on $g_0$ coming from Deuterium fission by scalars decaying into two photons.
pseudoscalar particle with photons coming from experiments on photon regeneration. In these experiments, light pseudoscalars produced via Primakoff effect penetrate through optic shield and then transform back into photons (“invisible light shining through walls”). Similar scheme is applied in NOMAD experiment. The results are presented in Table 3 at $M_{\gamma\gamma} = 100$ GeV; limits on $\sqrt{F}$ scale as $\sqrt{M_{\gamma\gamma}}$ whereas bounds on $m_{3/2}$ scale as $M_{\gamma\gamma}$.

| $m_P$ | Final state, $X$ | $g_{3N}^{(0)} \cdot \text{Br}_{(P\rightarrow X)}^{1/2}$, GeV | $\sqrt{F} \cdot \text{Br}_{(P\rightarrow X)}^{1/4}$, GeV | $m_{3/2} \cdot \text{Br}_{(P\rightarrow X)}^{1/2}$, meV |
|-------|-----------------|---------------------------------|---------------------------------|---------------------------------|
| $< 1.5$ MeV | $e^+e^-$ | $\lesssim 7 \cdot 10^{-10}$ [29] | $\gtrsim 3 \cdot 10^5$ | $\gtrsim 25$ eV |
| $< 1$ MeV | $\gamma\gamma$ | $\lesssim 8 \cdot 10^{-7}$ [30] | $\gtrsim 9 \cdot 10^3$ | $\gtrsim 20$ meV |

Another set of constraints is obtained from reactor experiments, where nuclear de-excitation is studied. Let us again make use of Eq. (17) and Eq. (18). Then we obtain for the isoscalar transition from excited nucleon state with the change of spin by $J$ and isospin by $T$ and with emission of photons and pseudoscalars with momenta $k_\gamma$ and $k_P$, respectively, the following ratio of rates [21]

$$\frac{\omega_j^{J=1,T=0}}{\omega_0^{M1,J=0}} \simeq \left(\frac{k_P}{k_\gamma}\right)^3 \frac{g_{3N}^{(0)} g_{NN}^2 f^2_{\pi NN}}{4\pi\alpha M_N^2} ,$$

where $M1$ refers to the type of electromagnetic transition and effective pion-nucleon coupling constant is $g_{NN}^2/4\pi = 14.6$. Products of pseudoscalar decay (two photons or $e^+e^-$) are observed in detectors. In this way two constraints on the coupling of a pseudoscalar to nucleon have been obtained: $\omega_j/\omega_0 \times \text{Br}(P \rightarrow e^+e^-) < 10^{-16}$ [28] and $\omega_j/\omega_0 \times \text{Br}(P \rightarrow \gamma\gamma) < 1.5 \cdot 10^{-10}$ [21] (we set the pseudoscalar momentum equal to photon frequency, $k_P = k_\gamma$). Corresponding bounds on $\sqrt{F}$ are presented in Table 4 at $A_Q = 100$ GeV and scale as $\sqrt{A_Q}$. The first constraint is valid for $m_P < 1.5$ MeV and becomes weaker for heavier sgoldstinos, while the second limit is relevant only for light sgoldstino, $m_P < 1$ MeV. The larger the branching ratio the stronger the corresponding bounds on $\sqrt{F}$: these bounds scale as quartic root of branching ratios. Although sgoldstino branching into $e^+e^-$ is usually very small (see Figure 3), current experimental bounds on $F$ from sgoldstino decaying into $e^+e^-$ are stronger than limits from decay into two photons. Note that reactor experiments give fairly strong bounds on $F$ but they should be considered as order-of magnitude estimates, as obtaining exact numbers requires accurate calculations involving nuclear matrix elements.

### 3.1.3 Flavor conserving rare decays

Numerous bounds arise from precise measurements of partial widths of mesons and leptons (see Tables 5, 6, 7, and 8), if corresponding processes are allowed kinematically. We begin with constraints independent of flavor violating terms in squark (slepton) mass matrix. One obtains a set of limits on supersymmetry breaking scale by considering Wilczek mechanism [32] — decay of neutral vector meson $V_{QQ}$ (1$^-$ state) into photon and (pseudo)scalar $S(P)$. There are two types of contributions into this process (see Fig. 3). The first one is emission of real photons and (pseudo)scalars by quarks, while the second is decay of virtual photons, emitted by quarks, into photons and (pseudo)scalars. The first process is governed by fermion-sgoldstino coupling, while the second one emerges due to interaction with a pair of photons. The relevant candidates on the role of $V_{QQ}$ are $J/\psi$, $Y$ and $\rho$, $\omega$, $\phi$-mesons.
Let us first consider heavy mesons, which may be described as quasistationary systems. With account of effective lagrangian \( \Theta \), we obtain

\[
\frac{\Gamma(V_{QQ} \rightarrow S(P)\gamma)}{\Gamma(V_{QQ} \rightarrow \gamma \rightarrow e^+e^-)} = \frac{M_V^2(A_Q + M_{\gamma\gamma})^2}{16\pi\alpha F^2},
\]

where \((-\,\,+)\) refers to decay into \( S(P) \). We should compare the rate \( \Gamma(V_{QQ} \rightarrow S(P)\gamma) \) with current data on the rates \( \Gamma(V_{QQ} \rightarrow \gamma + missing\,\, energy), \Gamma(V_{QQ} \rightarrow 3\gamma) \) or \( \Gamma(V_{QQ} \rightarrow \gamma + pair(s)\,\, of\,\, leptons(light\,\,mesons)) \) depending on \( m_{S(P)} \) and superpartner mass spectrum (see discussion of sgoldstino decay modes in section \( \Sigma \)). For illustration we set \( M_{\gamma\gamma} = -A_Q = 100 \,\, GeV \) in our quantitative estimates, so vector mesons would decay only into scalar sgoldstino. Eq. (19) shows that the corresponding constraints on \( \sqrt{F} \) scale as a square root of the absolute value of the difference (sum) of \( A_Q \) and \( M_{\gamma\gamma} \), if one considers decay into scalar (pseudoscalar).

| Experimental limit | \( X \) | \( m_S \) | \( \sqrt{F}Br_{(S\rightarrow X)}^{1/4} \) |
|-------------------|-------|---------|----------------|
| \( Br(J/\psi \rightarrow S\gamma(S \rightarrow X)) \) \(< 5.5 \cdot 10^{-5} \) | \( \gamma\gamma \) | \(< M_{J/\psi} \) | \( > 180 \,\, GeV \) |
| \( Br(\Upsilon(1S) \rightarrow S\gamma(S \rightarrow X)) \) \(< 3.1 \cdot 10^{-4} \) | \( \gamma\gamma \) | \(< 0.1 \,\, GeV \) | \( > 170 \,\, GeV \) |
| \( Br(\Upsilon(1S) \rightarrow S\gamma(S \rightarrow X)) \) \(< 3.1 \cdot 10^{-4} \) | \( e^+e^- \) | \(< 1.5 \,\, GeV \) | \( > 170 \,\, GeV \) |
| \( Br(\Upsilon(1S) \rightarrow S\gamma(S \rightarrow X)) \) \(< 4 \cdot 10^{-4} \) | \( \mu^+\mu^-, K^+K^- \) | \(< 1.5 \,\, GeV \) | \( > 160 \,\, GeV \) |
| \( Br(\Upsilon(1S) \rightarrow S\gamma(S \rightarrow X)) \) \(< 4 \cdot 10^{-4} \) | \( \pi^+\pi^- \) | \(< 1.5 \,\, GeV \) | \( > 160 \,\, GeV \) |
| \( Br(\Upsilon(1S) \rightarrow S\gamma(S \rightarrow X)) \) \((6.3 \pm 1.8) \cdot 10^{-5} \) | \( \pi^0\pi^0 \) | \(< 1.0 \,\, GeV \) | \( > 440 \,\, GeV \) |
| \( Br(\Upsilon(1S) \rightarrow S\gamma(S \rightarrow X)) \) \((2 \pm 2) \cdot 10^{-5} \) | \( 2K^+2K^- \) | \(< M_{J/\psi} \) | \( > 330 \,\, GeV \) |

Table 5: Constraints from decays of vector mesons on SUSY models with light sgoldstinos decaying inside detector.

| Experimental limit | \( m_S \) | \( \sqrt{F}, \, GeV \) |
|-------------------|---------|----------------|
| \( Br(J/\psi \rightarrow S\gamma) \) \(< 1.4 \cdot 10^{-5} \) | \( \ll M_{J/\psi} \) | \( > 260 \) |
| \( Br(\Upsilon(1S) \rightarrow S\gamma) \) \(< 1.3 \cdot 10^{-5} \) | \(< 5 \,\, GeV \) | \( > 370 \) |

Table 6: Constraints from decays of vector mesons on SUSY models with light sgoldstinos flying away from detector.

It turns out that constraints on \( F \) from \( \Upsilon \) decay into photons (leptons or light mesons), summarized in Table \( \Upsilon \), are of the same order as limits from processes with single photon and missing energy (see Table \( \Upsilon \)) if corresponding branching ratios for sgoldstino decay are roughly of order one. The first type of constraints (Table \( \Upsilon \)) is relevant for sgoldstino decaying within detector (which is the case for \( m_{S(P)} \gtrsim 10 \,\, MeV \) if \( M_{\gamma\gamma} = A = 100 \,\, GeV \)); these constraints scale as quartic root of the corresponding sgoldstino branching ratios. The second type of bounds (Table \( \Upsilon \)) applies to lighter sgoldstino flying away from detector. We present in Table \( \Upsilon \) only strongest constraints on \( \sqrt{F} \). Besides these, there is a number of other \( \Upsilon \) decay modes providing somewhat weaker constraints on \( F \): \( \gamma\pi^+\pi^-K^+K^-, \gamma2\pi^+2\pi^-, \gamma3\pi^+3\pi^-, \gamma2\pi^+2\pi^-K^+K^- \).

One can show that limits on \( \sqrt{F} \) from decays of light vector mesons (\( \rho, \omega, \phi \)) are weaker at least by an order of magnitude.
Decays of $\Upsilon$ seem to have the best sensitivity to flavor-conserving goldstino couplings if $M_{\Upsilon} \gtrsim m_{S(P)} \gtrsim a \text{ few MeV}$. Since in the most part of the parameter space goldstino decays predominantly into two photons or two mesons, the most promising $\Upsilon$ decays are into three photons and into a photon and a pair of mesons. In models with large trilinear soft terms, leptonic widths of goldstinos become larger, and these modes become also interesting.

### 3.1.4 Flavor violating rare decays

There is another type of processes to be considered. These are decays of charged particles: leptons or pseudoscalar mesons. The rates of these processes are more model dependent because they are governed by flavor violating soft terms.

While the bounds on $\sqrt{F}$ coming from decays of leptons are the same irrespectively of whether scalar or pseudoscalar goldstino is created in the final state, in the flavor-violating hadronic processes the creation of scalar goldstino is more important than the creation of pseudoscalar goldstino (if they have similar masses). When we discuss hadronic processes in what follows, we consider the emission of scalar goldstino only. The simplest example is kaon decay $K^+ \to \pi^+ S$. In chiral theory kaon conversion into pion is described by matrix element

$$\langle \pi^+ | \bar{s} \gamma_\mu d | K^+ \rangle = (f_+(k_K + k_\pi)\mu + f_-(k_K - k_\pi)\mu) ,$$

where $f_+ = 1$ and $f_0 = 0$ in the case of exact $SU(3)$ flavor invariance. Then

$$-\langle \pi^+ | \bar{s} d | K^+ \rangle = f_+ \frac{m_K^2 - m_\pi^2}{m_d + m_s} + f_- \frac{m_S^2}{m_d + m_s}$$

and in what follows we neglect $f_-$ contribution.

In principle, there are two mechanisms of the decay of charged particles with goldstinos in the final state. The first one is due to flavor-conserving goldstino interactions (with fermions and intermediate $W$-boson). The second one is due to flavor-changing terms in the low-energy effective interactions of light goldstinos (see Eqs. (1), (2); for instance, decay $K^+ \to \pi^+ S$ is due to $L_{eff} = -[\frac{\tilde{m}_{Rd}^2}{\sqrt{F}}] S \bar{s} d$). Hence, the second contribution emerges because of flavor violating interactions with fermions originating from off-diagonal insertions in squark(slepton) mass matrix.

As regards the first mechanism, it gives rise to constraints on $\sqrt{F}$ at the level of 100-250 GeV. We do not present these constraints explicitly, as they are at the same level or weaker than those summarized in Tables 7, 8.

The second mechanism is more interesting. The corresponding constraints are presented in Tables 7, 8, where for definiteness we take flavor violating off-diagonal insertions in squark(slepton) mass matrix to be equal to their current experimental limits [12] at $\tilde{m}_{\text{squark}} = M_3 = 500 \text{ GeV}$, $\tilde{m}_{\text{slepton}} = 100 \text{ GeV}$. The limits on $\sqrt{F}$ scale as inverted quartic root of bounds on meson branchings and as square root of the off-diagonal elements $m_{ij}^{LR2}$ in squark squared mass matrix; they depend crucially on the strength of flavor violation in MSSM. Since hadronic and photonic modes usually dominate, limits on $\sqrt{F}$ coming from meson decays with a pair of leptons in the final state (say, $K^+ \to \pi^+ S(S \to e^+ e^-)$) are weaker, but not more than by one or two orders of magnitude, as compared to photonic and mesonic modes. Note, that similar constraints from three-body decays of neutral mesons (like $B^0 \to K^0 S(S \to \mu^+ \mu^-)$) depend on the same coupling constants and are generally weaker than limits from rare decays of charged mesons.

| Experimental limit | $m_{S(P)}$ | $(\delta_{ij})_{LR}$ | $\sqrt{F}$, GeV |
|-------------------|------------|----------------------|----------------|
| $Br(\mu \to e S(P)) < 2.6 \times 10^{-6}$ [33] | $< m_\mu$ | $\delta_{12}^l = 1.7 \times 10^{-6}$ | $> 3 \times 10^4$ |
| $Br(K^+ \to \pi^+ S) < 3 \times 10^{-10}$ [40] | $\simeq 0$ | $\delta_{12}^d = 2.7 \times 10^{-3}$ | $> 3.7 \times 10^7$ |
| $Br(K^+ \to \pi^+ S) < 5.2 \times 10^{-10}$ [11] | $< 80 \text{ MeV}$ | $\delta_{12}^d = 2.7 \times 10^{-3}$ | $> 3.3 \times 10^7$ |
| $Br(K^+ \to \pi^+ S) < 10^{-8}$ [42] | $\simeq 180 \div 240 \text{ MeV}$ | $\delta_{12}^d = 2.7 \times 10^{-3}$ | $> 1.6 \times 10^7$ |

Table 7: Constraints on SUSY models with light goldstinos flying away from detector; bounds come from flavor changing decays of charged particles, if they are allowed kinematically; we set flavor violating terms $\delta_{12}^l = \tilde{m}_{D_{ij}^L}^2/\tilde{m}_Q^2$, $\delta_{12}^d = \tilde{m}_{L_{i2}^R}/\tilde{m}_L^2$ to be equal to their current bounds [12] at equal masses of squark and gluino, $M_3 = \tilde{m}_Q = 500 \text{ GeV}$ and equal masses of slepton and photino, $\tilde{m}_l = M_5 = 100 \text{ GeV}$. 


| Experimental limit | $X$ | $m_S(p)$ | $(\delta_{ij})_{LR}$ | $\sqrt{F}Br_{S \rightarrow X}$ |
|-------------------|------|-----------|-------------------|------------------|
| $Br(\mu \rightarrow eS(P)(S(P) \rightarrow X) < 7.2^{-11}$ | $\gamma \gamma$ | $\delta_{12} = 1.7 \cdot 10^{-6}$ | 3.4 $\cdot 10^5$ GeV |
| $Br(\mu \rightarrow eS(P)(S(P) \rightarrow X) < 10^{-12}$ | $e^+e^-$ | $> 2m_e$ | $\delta_{12} = 1.7 \cdot 10^{-6}$ | 1.2 $\cdot 10^5$ GeV |
| $Br(K^+ \rightarrow \pi^+S(S \rightarrow X)) < 5 \cdot 10^{-8}$ | $\gamma \gamma$ | $< 100$ MeV | $\delta_{12} = 2.7 \cdot 10^{-3}$ | 1.0 $\cdot 10^7$ GeV |
| $Br(K^+ \rightarrow \pi^+S(S \rightarrow X)) < 1.1 \cdot 10^{-5}$ | $e^+e^-$ | $\approx 150 \pm 340$ MeV | $\delta_{12} = 2.7 \cdot 10^{-3}$ | 1.5 $\cdot 10^7$ GeV |
| $Br(K^+ \rightarrow \pi^+S(S \rightarrow X)) = (7.6 \pm 2.1) \cdot 10^{-8}$ | $\mu^+\mu^-$ | $> 2m_\mu$ | $\delta_{12} = 2.7 \cdot 10^{-3}$ | 1.3 $\cdot 10^7$ GeV |
| $Br(D^+ \rightarrow \pi^+S(S \rightarrow X)) < 5.2 \cdot 10^{-5}$ | $e^+e^-$ | $> 2m_e$ | $\delta_{12} = 3.1 \cdot 10^{-2}$ | 5.2 $\cdot 10^5$ GeV |
| $Br(D^+ \rightarrow \pi^+S(S \rightarrow X)) < 1.5 \cdot 10^{-5}$ | $\mu^+\mu^-$ | $> 2m_\mu$ | $\delta_{12} = 3.1 \cdot 10^{-2}$ | 7.0 $\cdot 10^5$ GeV |
| $Br(D^+ \rightarrow \pi^+S(S \rightarrow X)) = (2.2 \pm 0.4) \cdot 10^{-3}$ | $\pi^+\pi^-$ | $> 2m_\pi$ | $\delta_{12} = 3.1 \cdot 10^{-2}$ | 3.1 $\cdot 10^5$ GeV |
| $Br(D_s^+ \rightarrow K^+S(S \rightarrow X)) < 1.4 \cdot 10^{-4}$ | $\mu^+\mu^-$ | $> 2m_\mu$ | $\delta_{12} = 3.1 \cdot 10^{-2}$ | 3.4 $\cdot 10^5$ GeV |
| $Br(D^+_s \rightarrow K^+S(S \rightarrow X)) < 6 \cdot 10^{-4}$ | $K^+K^-$ | $> 2m_K$ | $\delta_{23} = 3.1 \cdot 10^{-2}$ | 2.4 $\cdot 10^5$ GeV |
| $Br(B^+ \rightarrow K^+S(S \rightarrow X)) < 6 \cdot 10^{-5}$ | $e^+e^-$ | $> 2m_e$ | $\delta_{23} = 1.6 \cdot 10^{-2}$ | 4.8 $\cdot 10^5$ GeV |
| $Br(B^+ \rightarrow K^+S(S \rightarrow X)) < 5.2 \cdot 10^{-6}$ | $\mu^+\mu^-$ | $> 2m_\mu$ | $\delta_{23} = 1.6 \cdot 10^{-2}$ | 9.0 $\cdot 10^5$ GeV |
| $Br(B^+ \rightarrow K^+S(S \rightarrow X)) < 2.8 \cdot 10^{-5}$ | $\pi^+\pi^-$ | $> 2m_\pi$ | $\delta_{23} = 3.3 \cdot 10^{-2}$ | 6.6 $\cdot 10^5$ GeV |
| $Br(B^+ \rightarrow K^+S(S \rightarrow X)) < 7.5 \cdot 10^{-5}$ | $K^+K^-$ | $> 2m_K$ | $\delta_{13} = 3.3 \cdot 10^{-2}$ | 7.7 $\cdot 10^5$ GeV |

Table 8: Constraints on SUSY models with light sgoldstinos decaying within detector, from search for flavor changing decays of charged particles; flavor violating terms $(\delta_{ij})_{LR}$ are the same as in Table 7.

From bounds presented in this section we conclude that sgoldstino interactions may give large contributions into flavor changing rare decays, including those forbidden in SM. In particular, in the case $F = 1$ TeV$^2$, the constraints from processes with final light sgoldstino significantly strengthen the bounds on off-diagonal elements in squark and slepton mass matrices in comparison with models where sgoldstinos decouple at low energies.

Our analysis suggests that contributions of intermediate (virtual) sgoldstinos into FCNC and lepton flavor violating processes may be also significant. For instance, pseudoscalar mesons may decay through light sgoldstino exchange. Also, there are potentially important contributions to loop processes like $K^0 - \bar{K}^0$, $B^0 - \bar{B}^0$ mixings, etc. These issues will be considered elsewhere.

### 3.2 Processes with two sgoldstinos

Processes with two final sgoldstinos appear due to the presence of two-sgoldstino interactions in low-energy effective lagrangian, Eq. (3), and due to the double contribution of one-sgoldstino interaction, Eq. (1). Of course, the corresponding amplitudes are highly suppressed (by additional $F^{-1}$). Nevertheless, some of these processes are sensitive enough to place constraints on $\sqrt{F}$ at the level of 1 TeV.

Recall that two-sgoldstino coupling constants (8) differ from one-sgoldstino constants (1). Indeed, they are proportional to LL and RR insertions in scalar squared mass matrix, while one-sgoldstino coupling constants are proportional to LR insertions. Note in this regard, that the current limits on flavor changing squark masses $m^{LR}_{ij}$ and $m^{RR}_{ij}$ are weaker than limits on $m^{LR}_{ij}$. Hence, it makes sense to consider processes where two-sgoldstino couplings could be observed.

Complete analysis of low-energy processes with two sgoldstinos may be carried out along the same lines as for processes with one sgoldstino. Instead of going through the limits systematically, we discuss here only some examples in order to get the feeling of sensitivity to $\sqrt{F}$. 


### 3.2.1 Light neutral mesons

We begin with pion decay into two light sgoldstinos (see Fig. 3.2.1a). The relevant part of the effective lagrangian reads

\[ \mathcal{L} = \frac{1}{4F^2} (S\partial_\mu P - P\partial_\mu S) \cdot \left( (\bar{m}_{U_{11}}^{LL} + \bar{m}_{U_{11}}^{RR}) \bar{u} \gamma^\mu \gamma^5 u + (\bar{m}_{D_{11}}^{LL} + \bar{m}_{D_{11}}^{RR}) \bar{d} \gamma^\mu \gamma^5 d \right). \]

Then by making use of Eqs. (9), (10) we obtain

\[ \Gamma(\pi^0 \rightarrow SP) = \frac{f_\pi^2}{m_\pi} \left| \left( \bar{m}_{U_{11}}^{LL} + \bar{m}_{U_{11}}^{RR} \right) - \left( \bar{m}_{D_{11}}^{LL} - \bar{m}_{D_{11}}^{RR} \right) \right|^2 \left( m_\pi^2 - \frac{m_p^2}{F^2} \right)^2 \sqrt{1 + \left( \frac{m_p^2 - m_S^2}{m_\pi^2} \right)^2} - \frac{1}{4} \frac{m_p^2}{m_\pi^2}. \]  

(20)

This rate is proportional to \((m_S^2 - m_P^2)\), so, as expected, it vanishes in the massless limit, \(m_S, m_P \rightarrow 0\). In order to examine the sensitivity of this process, let us neglect the phase volume dependence and take \(|m_S^2 - m_P^2| \sim m_\pi^2/4\). If we set the value in the square bracket equal to \(2\bar{m}_Q^2\) and choose \(\bar{m}_Q = 500 \text{ GeV}\), we obtain the limits presented in Table 9. A few remarks are in order. First, these bounds may be irrelevant in some theories because \(\sqrt{F}\) should not be significantly smaller than any of the soft terms. Second, the constraint from pion disappearance (i.e., from \(\text{Br}(\pi^0 \rightarrow SP)\)) is valid only if sgoldstinos fly away from detector. For \(m_{S(P)} \simeq m_\pi/2\) this is the case if \(M_\gamma, A_\gamma < 10 \text{ GeV}\), which is not forbidden by current experiments. Third, these limits are obtained at tuned sgoldstino masses and, in general, they are weaker (see Eq. (20)).

![Diagram](image)

**Figure 3:** a) The diagram illustrating \(\pi^0\) decay into two sgoldstinos due to two-sgoldstino interaction; b) diagram of \(\pi^0\) decay into two photons and sgoldstino due to one-sgoldstino interaction.

| Experimental limit | \(\sqrt{F}, \text{GeV}\) |
|-------------------|------------------|
| \(\text{Br}(\pi^0 \rightarrow SP) < 8.3 \times 10^{-7}\) | \(> 150\) |
| \(\text{Br}(\pi^0 \rightarrow SP(S \rightarrow 2\gamma, P \rightarrow 2\gamma) < 2 \times 10^{-8}\) | \(> 240 \cdot \text{Br}_{S \rightarrow \gamma\gamma, P \rightarrow \gamma\gamma}\) |

Table 9: Constraints on SUSY models with light sgoldstinos from neutral pion decay due to two-sgoldstino coupling to matter fields; these constraints are evaluated at \(|m_S^2 - m_P^2| = m_\pi^2/4\) and \(\bar{m}_Q = 500 \text{ GeV}\) (see text).

These results do not depend on flavor-violating couplings and are of the same order of magnitude as the limits presented in Tables 4, 5. However, the limits presented in Table 3 scale as inverted octic root of the corresponding pion partial width (see Eq. (20)).

To illustrate that two-sgoldstino processes may impose more stringent constraints than one-sgoldstino processes with the same content of final SM particles, let us estimate the one-sgoldstino contribution to pion decay into four photons. Namely let us consider emission of sgoldstinos from the photon legs of pion (see Figure 3.2.1b). If sgoldstino decays within detector into photons, this would correspond to four-photon decay of pion. Pion-photon anomalous amplitude reads

\[ A(\pi \rightarrow \gamma\gamma) = -\frac{\alpha}{\pi f_\pi} \epsilon_{\mu\nu\rho\sigma} q_1^\mu q_2^\nu q_3^\rho q_4^\sigma, \]

where \(q_1, q_2\) are the photon momenta. Then the corresponding squared matrix element of \(\pi^0 \rightarrow \gamma\gamma SP\) is

\[ |M|^2 = 4\frac{\alpha^2 M^2}{\pi^2} \frac{f_\pi^2}{F^2} \left((q_1 p)^2 + (q_1 q_3)^2\right), \]
where $p$ and $q_1$, $q_3$ are momenta of sgoldstino and outgoing photons, respectively. Neglecting sgoldstino mass we estimate the decay width as

$$\Gamma(\pi^0 \to \gamma\gamma S(P)) = \frac{1}{32} \frac{\alpha^2 m_\gamma^2 M_{\gamma\gamma}^2 m_p^2}{f_s^2 \pi^4 F^2}.$$  \hspace{1cm} (21)$$

One can check that Eq. (21) gives weaker bound on $\sqrt{F}$ than the limit presented in the second row of Table 9 if $M_{\gamma\gamma} = 100$ GeV and $\tilde{m}_Q = 500$ GeV.

Let us now evaluate the bounds from decays of neutral kaons due to two-sgoldstino flavor violating couplings. The effective lagrangian reads

$$\mathcal{L} = \frac{1}{4F^2} (S\partial_{\mu} P - P\partial_{\mu} S) \cdot \left( (\tilde{m}_{D_{21}}^{LL} + \tilde{m}_{D_{12}}^{RR}) \hat{s}\gamma^\mu \gamma^5 d + (\tilde{m}_{D_{21}}^{LL} - \tilde{m}_{D_{12}}^{RR}) \hat{s}\gamma^\mu d \right)
+ (\tilde{m}_{D_{12}}^{LL} + \tilde{m}_{D_{12}}^{RR}) \hat{d}\gamma^\mu \gamma^5 S + (\tilde{m}_{D_{12}}^{LL} - \tilde{m}_{D_{12}}^{RR}) \hat{d}\gamma^\mu s \right).$$

One can show, that only the measurements of branching ratios of $K^0_L$ impose interesting constraints on $F$, whereas current limits on rare $K_S^0$ decays provide weak constraints on $\sqrt{F}$. We obtain by making use of chiral theory

$$\Gamma(K^0_L \to SP) = f_K^2 \frac{|\tilde{m}_{D_{21}}^{LL} + \tilde{m}_{D_{12}}^{RR} + \tilde{m}_{D_{12}}^{LL} + \tilde{m}_{D_{12}}^{RR}|^2}{612\pi F^2} \left( m_S^2 - m_p^2 \right)^2 \frac{1}{F^2} \left( 1 + \frac{m_p^2 - m_S^2}{m_K^2} - 4 \frac{m_p^2}{m_K^2} \right).$$

Note that in the limit of CP conservation, $LL$ and $RR$ squark mass matrices are real and symmetric, and the sum in the bracket equal to 2 $\tilde{m}_{D_{21}}^{LL} + \tilde{m}_{D_{12}}^{RR}$.

In analogy to the discussion of pion decays, let us neglect the phase volume dependence and set $|m_S^2 - m_p^2| \approx m_K^2/4$, $f_K = 160$ MeV. If we set the sum in the bracket equal to 4Re $\tilde{m}_{D_{21}}^{LL}$ and impose on Re $\tilde{m}_{D_{12}}^{LL}$ current constraints from the absence of FCNC [12] at squark mass $\tilde{m}_Q = 500$ GeV, we obtain the limits presented in Table 10. Note that limits

| Experimental limit | $\sqrt{F}$, GeV |
|--------------------|-----------------|
| $\text{Br}(K^0_L \to SP \to e^+e^-\gamma\gamma) = (6.9 \pm 1.0) \cdot 10^{-7}$ | $1.9 \cdot 10^{-3}$ |
| $\text{Br}(K^0_L \to SP \to e^+e^-\pi^0\pi^0) = (4.1 \pm 0.8) \cdot 10^{-8}$ | $2.7 \cdot 10^{-3}$ |
| $\text{Br}(K^0_L \to SP \to \mu^+\mu^-\gamma\gamma) = (2.9^{+6.7}_{-2.4}) \cdot 10^{-9}$ | $3 \cdot 10^{-3}$ |
| $\text{Br}(K^0_L \to SP \to e^+e^-\pi^0\pi^-) = (3.5 \pm 0.6) \cdot 10^{-7}$ | $2.1 \cdot 10^{-3}$ |

Table 10: Constraints on SUSY models with light sgoldstinos coming from decays of $K^0_L$ due to two-sgoldstino flavor-violating coupling to matter fields; we set real parts of the flavor violating term, $(\delta_{12})_{LL} = \tilde{m}_{D_{12}}^{LL} \tilde{m}_{D_{12}}^{LL}/\tilde{m}_Q$, equal to its current bound, Re $(\delta_{12})_{LL} = 4.6 \cdot 10^{-2}$ [12] at equal masses of squarks and gluino, $M_3 = \tilde{m}_Q = 500$ GeV; these constraints are evaluated at $|m_S^2 - m_p^2| = m_{K^0}^2/4$.

from kaon decays into a leptonic pair and a pair of mesons(photons) are usually more significant than limits from decays into four leptons, because of small sgoldstino decay branching ratio into leptons (see Figure 4). These bounds on $\sqrt{F}$ are obtained at tuned sgoldstino masses, $|m_S^2 - m_p^2| \approx m_K^2/4$, and generally the bounds are somewhat weaker.

We are not aware of limits on decays $K^0_L \to 4\gamma$ and $K^0_L \to \pi^+\pi^-\gamma\gamma$. If it would be possible to measure (or limit) their branching ratios at the level of $10^{-7}$, the sensitivity of experiments to two-sgoldstino couplings would increase, because the photonic decay usually dominates over leptonic decay of sgoldstinos.

### 3.2.2 Decays of heavy mesons

In analogy with light mesons we consider now heavy neutral mesons living sufficiently long, $D^0$, $B^0$ and $B^0_s$. We make use of the approach similar to the chiral theory in order to describe their interaction with sgoldstinos; in the following we set $f_{B^0_s} = f_{B^0} = f_{D^0} = 200$ MeV. The limits obtained with the same assumptions as above about sgoldstino masses and values of flavor violating couplings are listed in Table 11. All remarks concerning these assumptions given in previous
astrophysical bounds are usually stronger than laboratory ones, though they become invalid for sgoldstinos lighter than a few GeV and flavor-violating processes in MSSM are not extremely suppressed. One observes that precision measurements at low energies are promising for confirming directly such a model. The Tevatron if sgoldstinos are lighter than a few GeV and flavor-violating processes in MSSM are not extremely suppressed. In this sense our results may be considered as complementary to those derived from current bounds on sparticles mass. The Tevatron and LEP are the currently available experiments with most sensitive to the scale of supersymmetry breaking. The upgraded Tevatron may be able to cover the range of $\sqrt{F}$ up to $\sqrt{F} \approx 290$ GeV \cite{16}, while LHC will be capable to reach $\sqrt{F} < 1.6$ TeV \cite{17}. In models with light sgoldstinos, collider experiments become more sensitive to the scale of supersymmetry breaking. Most powerful among the operating machines, LEP and Tevatron, give a constraint of order 1 TeV on supersymmetry breaking scale in models with light sgoldstinos. Indeed, it was found in Ref. \cite{18} that with the LEP luminosity of 100 pb$^{-1}$, at $\sqrt{F} = 1 \div 1.5$ TeV one $e^+e^- \to ZZ$ event would occur, and ten $e^+e^- \to e^+e^-S$ events would appear at $\sqrt{F} = 1.5$ TeV. At Tevatron, about 10 events in $pp \to S\gamma(Z)$ channel, and $10^5$ events in $pp \to S\gamma(Z)$ channel would be produced at $\sqrt{F} = 1$ TeV \cite{19}. This gives rise to a possibility to detect sgoldstino, if it decays inside detector into photons and $\sqrt{F}$ is not larger than $1.5 \div 2$ TeV. However, these numbers have been obtained in a model with heavier superpartner scale, and, hence, with larger sgoldstino couplings, than we assumed in our paper. For that set of parameters bounds on $\sqrt{F}$ derived in our paper from processes originating due to flavor-conserved sgoldstino couplings should be stronger at least by a factor of 1.5.

One important remark concerns the sensitivity of collider experiments to light particles. The currently available analyses carried out by experimental collaborations are relevant only for fairly heavy sgoldstino ($M \gtrsim 20$ GeV). In this paper we have discussed lighter particles; in this sense our results may be considered as complementary to those derived up to now from LEP and Tevatron experiments.

From constraints presented in this paper we conclude that the sgoldstino signal is not likely to be observed at LEP and Tevatron if sgoldstinos are lighter than a few GeV and flavor-violating processes in MSSM are not extremely suppressed. One observes that precision measurements at low energies are promising for confirming directly such a model. The astrophysical bounds are usually stronger than laboratory ones, though they become invalid for $m_S$ and $m_P$ larger than a few MeV.

Among the laboratory processes, the most sensitive to very light sgoldstinos are propagation of laser beam in magnetic field and reactor experiments. For heavier sgoldstinos the most sensitive processes are $\Upsilon$ decays for flavor-conserving sgoldstino couplings and charged kaon decays for flavor-violating sgoldstino couplings.

| Experimental limit | $|m_S^2 - m_P^2|$ | $(\delta_{ij})_{LL}$ | $\sqrt{F}$, GeV |
|-------------------|-------------------|------------------|-----------------|
| $\text{Br}(D^0 \to SP \to 2\pi^+2\pi^-)$ | $m_{SP}^2/4$ | $\delta_{12} = 1.0 \cdot 10^{-1}$ | $360 \cdot \text{Br}_{S \to \pi^+\pi^-} \cdot \text{Br}_{P \to \pi^+\pi^-}$ |
| $\text{Br}(D^0 \to SP \to K^+K^-\pi^+\pi^-) < 8 \cdot 10^{-4}$ | $m_{SP}^2/4$ | $\delta_{12} = 1.0 \cdot 10^{-1}$ | $340 \cdot \text{Br}_{S \to \pi^+\pi^-} \cdot \text{Br}_{P \to \pi^+\pi^-}$ |
| $\text{Br}(D^0 \to SP \to 3\pi^+3\pi^-) = (4 \pm 3) \cdot 10^{-4}$ | $m_{SP}^2/4$ | $\delta_{12} = 1.0 \cdot 10^{-1}$ | $390 \cdot \text{Br}_{S \to 2\pi^+2\pi^-} \cdot \text{Br}_{P \to \pi^+\pi^-}$ |
| $\text{Br}(B^0 \to SP \to 2\pi^+2\pi^-) < 2.3 \cdot 10^{-4}$ | $m_{SP}^2/4$ | $\delta_{12} = 9.8 \cdot 10^{-2}$ | $710 \cdot \text{Br}_{S \to \pi^+\pi^-} \cdot \text{Br}_{P \to \pi^+\pi^-}$ |

Table 11: Constraints on SUSY models with light sgoldstinos from decays of heavy neutral mesons due to two-sgoldstino coupling to matter fields.
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