I describe supersymmetric extensions of the Standard Model with light sgoldstinos and discuss the explanation of Ultra High Energy Cosmic Rays above GZK cutoff in these models. Also I briefly discuss the possibility to solve other cosmological and astrophysical puzzles, such as gamma-ray bursts and dimming of high-redshift supernovae, within the models with light sgoldstinos.

1 Introduction

In any model with supersymmetry being spontaneously broken exists goldstino supermultiplet. In a set of models (pseudo)scalar superpartners of goldstino (sgoldstinos) are light \((m < 1 \text{ GeV})\), long-living and sufficiently strongly interacting.

There are some puzzles in astrophysics and cosmology without relevant solutions in the framework of the Standard Model. In particular, Ultra High Energy Cosmic Rays (UHECRs) data require new physics and very few models of new physics are consistent with UHECRs data; a phenomenologically viable model, which is consistent, is a model with light sgoldstino. Extremely light sgoldstinos might be responsible for dimming of high-redshift supernovae. The emission of sgoldstinos from supernovae might connect gamma ray bursts and supernovae explosions.

In this talk I briefly discuss these statements.

2 Sgoldstino Couplings

In any supersymmetric extension of the Standard Model (SM) of particle physics spontaneous supersymmetry breaking occurs due to non-zero vacuum expectation value of auxiliary component of some chiral or vector superfield. For definiteness, let us consider a model where chiral
superfield
\[ \Phi = \phi + \sqrt{2} \theta \psi + \theta^2 F_\phi \]
 obtains non-zero vacuum expectation value \( F \) for the auxiliary component.

Then \( \psi \) is a Goldstone fermion and interaction between goldstino and other fields are given by Goldberger-Treiman formula
\[ L_{int} = \frac{1}{F} J^\mu_{SUSY} \partial_\mu \psi, \]
where \( J^\mu_{SUSY} \) is a supercurrent. The superpartners of goldstino,
\[ \frac{1}{\sqrt{2}} (\phi + \phi^*) \equiv S, \quad \frac{1}{i \sqrt{2}} (\phi - \phi^*) \equiv P, \]
are scalar and pseudoscalar \( sgoldstinos \), respectively. Sgoldstinos remain massless at tree level and become massive due to corrections from high order terms in Kähler potential. Provided these terms are sufficiently suppressed sgoldstinos are light. The coupling constants between gauge bosons and fermions of SM and sgoldstinos may be expressed in terms of \( F \) and the soft supersymmetry breaking parameters of the Minimal Supersymmetric extension of the Standard Model (MSSM). Carrying out of these expressions is straightforward. For instance, let us consider the vector supermultiplet containing gauge boson \( A_\mu \) and gaugino \( \lambda \). In low-energy spectrum there is a soft term for gaugino mass \( L_{soft} = M_{\lambda} \lambda + h.c. \). Since supersymmetry is broken spontaneously, this implies the interaction between gauge superfield \( W_\alpha \) and \( \Phi \)
\[ L_{SUSY} = a \Phi W_\alpha W_\alpha \bigg|_{g^2} + h.c. \]
with parameter \( a \) obeying \( aF = M_{\lambda} \). From Eq. (1) we obtain the coupling constants for “sgoldstino-gauge boson-gauge boson” vertices. In a similar way one can derive the coupling constants between sgoldstinos and SM massive fermions: quarks and charged leptons (see Ref. for details).

3 Phenomenology of Models with Light Sgoldstinos

Note, that all sgoldstino coupling constants mentioned above are completely determined by soft terms of MSSM and parameter of supersymmetry breaking \( F \) but sgoldstino masses \( (m_S, m_P) \) remain free. Depending of the values of these two unknown parameters, sgoldstinos may show up in different experiments. Phenomenologically interesting models form four classes:

1. Sgoldstino masses are of order of electroweak scale, \( \sqrt{F} \sim 1 \) TeV — sgoldstino may be produced in collisions of high energy particles at colliders.

2. Sgoldstino masses \( m_S, m_P \sim 1 \) MeV÷1 GeV, \( \sqrt{F} \sim 1 \) TeV — sgoldstinos may emerge in products of rare decays of mesons, such as \( \Upsilon \to S(P)\gamma, J/\psi \to S(P)\gamma \).

3. Light sgoldstinos in models with flavor violation in the sector of soft trilinear couplings, \( A_{ij} \neq A_{\delta ij} \) — sgoldstinos may lead to flavor violating processes. Namely, they may contribute to FCNC (mass difference in the system of neutral mesons, CP-violation in the system of neutral mesons), then, if kinematically allowed, they appear in the product of rare decays, such as \( t \to c S(P), \mu \to e S(P), K \to \pi S \), etc.

4. Sgoldstinos are lighter than 1 MeV — these models may be tested in low energy experiments, such as reactor experiments, conversion in magnetic field, etc. Also sgoldstinos may play very important role in astrophysics and cosmology: they may distort cosmic microwave background spectrum, affect supernovae explosion and cooling rate of stars, etc.
Direct independent measurement of MSSM soft supersymmetry breaking terms and sgoldstino couplings provides the unique possibility to estimate the scale of supersymmetry breaking $\sqrt{F}$.

### 4 Sgoldstinos as UHECRs

Till now, there are no experimental evidence for sgoldstinos. The study of sgoldstino phenomenology results in obtaining bounds on its coupling constants. Meanwhile there are some problems in astroparticle physics and cosmology, which may be solved in model with sufficiently light sgoldstinos.

We will concentrate here on the problem with Ultra High Energy Cosmic Rays (UHECRs). Tens events with energy above Greisen-Zatsepin-Kuzmin (GZK) cutoff $E > 4 \cdot 10^{19}$ eV, suggest that something appears to be missing in our understanding of the sources, nature or propagation of UHECRs.

Indeed, the small-scale clustering of UHECR events suggests that the sources are point-like on cosmological scales. Recently, a statistically significant correlation, at the level of chance coincidence below $10^{-4}$, was found with the most powerful BL Lacertae (the special type of active galaxies with jets pointed in our direction). The identified sources are at high redshift $z > 0.1$, far exceeding the GZK distance of $R_{\text{GZK}} \approx 50$ Mpc, so that the primary ultra-high energy (UHE) particles can not be protons. The photon attenuation length for energies around $10^{20}$ eV is of order the GZK cutoff distance, primarily due to the extragalactic radio backgrounds, so one can conclude that UHECRs with energies around $10^{20}$ eV are very unlikely to be photons. The primaries of UHECRs should be some particles traveling for cosmological distances unattenuated (without significant energy loss). The only Standard-Model particles which can reach our Galaxy without significant loss of energy are neutrinos. In the framework of Standard Model neutrinos produce nucleons and photons via resonant $Z$-production with relic neutrinos clustered within about 50 Mpc from the Earth, giving rise to angular correlations with high-redshift sources. However, for the production rates to be sufficiently high, this scenario requires enormous neutrino fluxes and an extreme clustering of relic neutrinos with masses in the (sub-)eV range.

Thus UHECRs with energies around $10^{20}$ eV may point at the new physics beyond the Standard Model. Light sgoldstinos might be such a new physics.

Indeed, the GZK cutoff can be avoided also if the UHECRs consist of certain new particles, which can traverse the universe unimpeded at high energies. Such particles must fulfill several requirements to be candidates for UHECRs:

- they must live long enough to reach us from cosmological distances;
- they must not lose too much energy in interactions with the CMBR and other background radiations or in extragalactic magnetic fields;
- they must interact sufficiently strongly in or near our Galaxy or in the Earth’s atmosphere to produce the observed UHE events;
- their interactions must allow for the production of a significant flux at the source.

All these requirements may be fulfilled in the models with light sgoldstinos. For light scalar sgoldstinos the relevant interactions are

$$\mathcal{L} = \frac{M_{\lambda \lambda}}{2\sqrt{2}F} S G_{\mu \nu}^a G_{a}^{\mu \nu}, \quad \mathcal{L} = \frac{M_{\gamma \gamma}}{2\sqrt{2}F} S F_{\mu \nu} F^{\mu \nu},$$

*Light pseudoscalar sgoldstino may be considered in the same way.*
where

\[ M_{\gamma\gamma} = M_{\lambda_1} \cos^2 \theta_W + M_{\lambda_2} \sin^2 \theta_W \]

and \( M_{\lambda_i} \) are MSSM gaugino soft mass parameters. If \( M_S < 200 \) MeV, the dominant decay mode is into two photons:

\[ \Gamma(S \to \gamma\gamma) = \frac{M_S^2 M_S^3}{32\pi F^2} , \]

because the direct coupling to electrons is suppressed by electron mass. This light particle with the energy \( E_S \) propagates through the Universe without decay if

\[ R_{\text{Universe}} \lesssim L_{\text{decay}} = \frac{E_S}{\Gamma(S \to \gamma\gamma) M_S} . \]

Therefore, if this particle is supposed to reach us from cosmological distances one has to require

\[ \sqrt{F} \gtrsim 1.5 \times 10^6 \text{ GeV} \left( \frac{10^{20} \text{ eV}}{E_S} \right)^{1/4} \frac{M_S}{10 \text{ MeV}} \quad \text{at} \quad M_{\gamma\gamma} = 100 \text{ GeV} \, . \tag{2} \]

The tiny photon coupling required by Eq. (2) guarantees also the absence of a GZK cutoff for sgoldstino: the interactions with photon background and (extra)galactic magnetic field are negligible.

Both the production of sgoldstino at the source and their interaction in the atmosphere require rather large cross sections, comparable to strong ones. Typical energies of UHECR interactions with nucleons in c.m. frame are \( E_{\text{cm}} \approx 100 \div 300 \) TeV. The interaction cross section with nucleons at such energies may be estimated as

\[ \sigma_S = \sigma_{\text{strong}} \frac{\alpha_S}{\alpha_s} . \]

The suppression factor

\[ \frac{\alpha_S}{\alpha_s} = \left( \frac{E_{\text{cm}} M_{\lambda_3}}{32\pi F^2} \right)^2 \tag{3} \]

should not be very small. Since our particle exhibits strong interactions one can estimate sgoldstino mean free path \( \ell_S \) in the Earth’s atmosphere by analogy with the proton mean free path \( \ell_p \) as

\[ \ell_S = \ell_p \frac{\alpha_{\text{strong}}}{\alpha_S} . \]

To initiate an atmospheric shower, \( S \) should have a relatively small mean free path. Assuming \( \ell_S < 10 \ell_p \) and using Eq. (3) and \( \alpha_s = 0.1 \) one obtains

\[ \sqrt{F} \lesssim 1.3 \times 10^4 \text{ GeV} \left( \frac{E_S}{10^{20} \text{ eV}} \right)^{1/4} \quad \text{at} \quad M_{\lambda_3} = 500 \text{ GeV} \, . \tag{4} \]

The inequalities (2) and (4) determine the region in the space of parameters \( M_S, \sqrt{F} \), which is suitable for the explanation of the UHECRs above the GZK cutoff. Strong coupling to gluons guarantees that sgoldstino will be effectively produced in the high-energy tail of the proton spectra by proton-proton collisions while their production at low energies will be negligible. Therefore, we can expect that the proton flux from the source at low energies will continue with the same slope at high energies due to sgoldstino component. Only part of the initial proton energy will be transferred to energetic sgoldstinos; most of them will be produced on the peak of the gluon distribution function with \( E \approx 0.1 E_p \). However, once produced they will escape more easily from the source compared to protons precisely because their cross section is smaller.

A variety of experimental limits on models with light sgoldstinos has been derived in Ref. This limits significantly constrain the regions of parameter space of the phenomenologically viable models with light sgoldstinos. In Fig. we present the region of parameter space where sgoldstinos may act as primaries of UHECRs and are not excluded by other limits.
Figure 1: Allowed region for the parameters \((M_S, \sqrt{F})\) at \(M_{\gamma\gamma} = 100\) GeV and gluino mass \(M_{\lambda_3} = 500\) GeV. The short-dashed line corresponds to the limit (3), the long-dashed line to (2). Sgoldstinos with masses less than 10 keV (vertical solid line) are ruled out by the helium-burning life-time of horizontal-branch stars.

5 Discussions

The allowed region in Fig. 1 suggests that the supersymmetry breaking scale should be very low, \(\sqrt{F} \sim 1 \div 10\) TeV. Hence our light sgoldstino model can be tested in searches for rare decays of \(J/\psi\) and \(\Upsilon\) and in reactor experiments (for details see Ref. 4). This low scale of supersymmetry breaking may be also tested at new generation accelerators like upgraded Tevatron and LHC. Note, that sgoldstino contributions to FCNC and lepton flavor violation are strong enough to probe the supersymmetry breaking scale up to \(\sqrt{F} \sim 10^4\) TeV if off-diagonal entries in squark (slepton) mass matrices are close to the current limits in the MSSM. Thus our light-sgoldstino scenario for UHECRs allows only small flavor violation in the scalar sector of superpartners.

Finally, let me note that sgoldstino might be responsible for other astrophysical and cosmological puzzles. For instance, light sgoldstinos emitted from supernovae might be a potential explanation for the origin of the gamma-ray bursts. Extremely light pseudoscalar sgoldstino \((M_P \sim 10^{16}\) eV) might be responsible for dimming of high-redshift supernovae: emitted photons might convert into sgoldstinos on extragalactic magnetic field. This solution does not require dark energy component, in particular, non-zero cosmological constant. In Ref. 17 the suitable region of parameter space of the model with light axion \((f_a, m_a)\) was found. The suitable region of parameter space for sgoldstino solution may be found by a simple mapping: \(f_a \to F/M_{\gamma\gamma}, m_a \to M_P\).

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