
Dark Energy density in Split SUSY models inspired by degenerate vacua

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Outline

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Based on:

C. D. Froggatt, R. Nevzorov and H. B. Nielsen, arXiv:1103.2146 [hep-ph];

C. D. Froggatt, R. Nevzorov and H. B. Nielsen, Nucl. Phys. B 743 (2006) 133;

C. D. Froggatt, L. V. Laperashvili, R. Nevzorov and H. B. Nielsen, Phys. Atom. Nucl. 67 (2004) 582 [arXiv:hep-ph/0310127].

Introduction

- Astrophysical and cosmological observations indicate that there is a **dark energy** spread all over the Universe which constitutes $70\% - 73\%$ of its energy density

$$\rho_\Lambda \sim 10^{-123} M_{Pl}^4 \sim 10^{-55} M_Z^4 \sim (10^{-3} \text{ eV})^4.$$

- In the SM much larger contributions to ρ_Λ must come from gluon condensate and EW symmetry breaking

$$\rho_{QCD} \sim \Lambda_{QCD}^4 \simeq 10^{-74} M_{Pl}^4, \quad \rho_{EW} \sim v^4 \simeq 10^{-62} M_{Pl}^4.$$

- But the contribution of zero-modes is expected to push total vacuum energy density even higher up to M_{Pl}^4 , i.e.

$$\begin{aligned} \rho_\Lambda &\simeq \sum_b \frac{\omega_b}{2} - \sum_f \frac{\omega_f}{2} = \\ &= \int_0^\Lambda \left[\sum_b \sqrt{|\vec{k}|^2 + m_b^2} - \sum_f \sqrt{|\vec{k}|^2 + m_f^2} \right] \frac{d^3 \vec{k}}{2(2\pi)^3} \simeq -\Lambda^4. \end{aligned}$$

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- Because of the enormous cancellation between the contributions of different condensates to ρ_Λ the smallness of the cosmological constant should be regarded as a **fine-tuning problem**.
 - An exact global supersymmetry ensures zero value for the vacuum energy density.
 - But supersymmetry must be broken.
 - The breakdown of SUSY induces a huge and positive contribution to ρ_Λ

$$\rho_\Lambda \sim \Lambda_{SUSY}^4,$$

where Λ_{SUSY} is a SUSY breaking scale.

- The non-observation of squarks and sleptons implies that $\Lambda_{SUSY} \gg 100 \text{ GeV}$.

No-scale supergravity

- The scalar potential in ($N = 1$) SUGRA models is specified in terms of the Kähler function

$$G(\phi_M, \phi_M^*) = K(\phi_M, \phi_M^*) + \ln |W(\phi_M)|^2 .$$

- The SUGRA scalar potential is given by

$$V(\phi_M, \phi_M^*) = \sum_{M, \bar{N}} e^G \left(G_M G^{\bar{M}\bar{N}} G_{\bar{N}} - 3 \right) + \frac{1}{2} \sum_a (D^a)^2 ,$$

$$G_M \equiv \partial G / \partial \phi_M , \quad G_{\bar{M}} \equiv \partial G / \partial \phi_M^* , \quad G^{\bar{M}\bar{N}} = G_{\bar{N}M}^{-1} ,$$

$$D^a = g_a \sum_{i,j} (G_i T_{ij}^a \phi_j) .$$

- SUGRA models include singlet fields which form hidden sector that gives rise to the breaking of local SUSY and induces non-zero gravitino mass

$$m_{3/2} = \langle e^{G/2} \rangle$$

- In SUGRA models $\rho_\Lambda \sim - \langle e^G \rangle$.

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- The Lagrangian of the simplest no-scale SUGRA model is invariant under imaginary translations

$$T \rightarrow T + i\beta, \quad \varphi_\sigma \rightarrow \varphi_\sigma$$

and dilatations

$$T \rightarrow \alpha^2 T, \quad \varphi_\sigma \rightarrow \alpha \varphi_\sigma.$$

- The invariance under imaginary translations and dilatations constrain Kähler function

$$K = -3 \ln \left[T + \bar{T} - \sum_\sigma \zeta_\sigma |\varphi_\sigma|^2 \right], \quad W = \sum_{\sigma, \lambda, \gamma} \frac{1}{6} Y_{\sigma\lambda\gamma} \varphi_\sigma \varphi_\lambda \varphi_\gamma.$$

- Global symmetries ensure the vanishing of vacuum energy density in the no-scale SUGRA models.
- These symmetries also preserve supersymmetry in all vacua.

MPP inspired SUGRA model

- In order to achieve the appropriate breakdown of local supersymmetry dilatation invariance must be broken.
- Let us consider SUGRA model with two hidden sector fields that transform differently under the dilatations

$$T \rightarrow \alpha^2 T, \quad z \rightarrow \alpha z$$

and imaginary translations

$$T \rightarrow T + i\beta, \quad z \rightarrow z.$$

- We allow the breakdown of dilatation invariance in the superpotential of the hidden sector

$$W(z, \varphi_\alpha) = \kappa \left(z^3 + \mu_0 z^2 + \sum_{n=4}^{\infty} c_n z^n \right) + \sum_{\sigma, \lambda, \gamma} \frac{1}{6} Y_{\sigma\lambda\gamma} \varphi_\sigma \varphi_\lambda \varphi_\gamma,$$

where μ_0 and $c_n \sim 1$.

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- We also assume that the dilatation invariance is broken in the Kähler potential of the observable sector

$$K = -3 \ln \left[T + \bar{T} - |z|^2 - \sum_{\sigma} \zeta_{\sigma} |\varphi_{\sigma}|^2 \right] + \sum_{\sigma, \lambda} \left(\frac{\eta_{\sigma\lambda}}{2} \varphi_{\sigma} \varphi_{\lambda} + h.c. \right) + \sum_{\sigma} \xi_{\sigma} |\varphi_{\sigma}|^2 .$$

- Such breakdown of global symmetry preserves a zero value of the energy density in all vacua.
- The scalar potential of the hidden sector takes a form

$$V(T, z) = \frac{1}{3(T + \bar{T} - |z|^2)^2} \left| \frac{\partial W(z)}{\partial z} \right|^2 .$$

- When $c_n = 0$ this SUGRA scalar potential has two minima with zero vacuum energy density

$$z = 0, \quad z = -\frac{2\mu_0}{3} .$$

- In the vacuum where $z = -\frac{2\mu_0}{3}$ local supersymmetry is broken and gravitino gets a non-zero mass:

$$m_{3/2} = \frac{4\kappa\mu_0^3}{27 \left\langle \left(T + \bar{T} - \frac{4\mu_0^2}{9} \right)^{3/2} \right\rangle}.$$

- At low energies the interactions of observable superfields \hat{y}_α in this vacuum are described by the effective superpotential

$$\mathcal{W}_{eff} = \sum_{\alpha,\beta} \frac{\mu_{\alpha\beta}}{2} \hat{y}_\alpha \hat{y}_\beta + \sum_{\alpha,\beta,\gamma} \frac{h_{\alpha\beta\gamma}}{6} \hat{y}_\alpha \hat{y}_\beta \hat{y}_\gamma,$$

$$\mu_{\alpha\beta} = \frac{m_{3/2}\eta_{\alpha\beta}}{(C_\alpha C_\beta)^{1/2}}, \quad h_{\alpha\beta\gamma} = \frac{Y_{\alpha\beta\gamma}(C_\alpha C_\beta C_\gamma)^{-1/2}}{\langle (T + \bar{T} - |z|^2)^{3/2} \rangle},$$

$$C_\alpha = \xi_\alpha \left(1 + \frac{1}{x_\alpha} \right), \quad x_\alpha = \frac{\xi_\alpha \langle (T + \bar{T} - |z|^2) \rangle}{3\zeta_\alpha}.$$

- The effective scalar potential of the observable sector is given by

$$V_{eff} \simeq \sum_\alpha \left| \frac{\partial \mathcal{W}_{eff}(y_\beta)}{\partial y_\alpha} + m_\alpha y_\alpha^* \right|^2 + \frac{1}{2} \sum_a (D^a)^2, \quad m_\alpha = m_{3/2} \frac{x_\alpha}{(1+x_\alpha)}.$$

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- In the vacuum with $z = 0$ local SUSY remains intact and the low-energy limit of this theory is described by a pure SUSY model in flat Minkowski space.
 - If the high order terms $c_n z^n$ are present in the superpotential, $V(T, z)$ may have many degenerate vacua with broken and unbroken SUSY which energy density vanishes.
 - Then the vanishing of ρ_Λ can be considered as a result of degeneracy of all possible vacua in the considered theory, one of which is supersymmetric with $\langle \mathcal{W} \rangle = 0$.
 - Thus the breakdown of global symmetries that ensures the vanishing of ρ_Λ leads to the natural realization of the **multiple point principle (MPP)**.

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- MPP postulates the existence of many phases with the same energy density which are allowed by a given theory.
 - Being applied to supergravity MPP implies the existence of a phase with global SUSY in flat Minkowski space.
 - Such vacuum is realised only if SUGRA scalar potential has a minimum where the following conditions are satisfied

$$\left\langle \mathcal{W}(z_i^0) \right\rangle = \left\langle \frac{\partial \mathcal{W}(z_i)}{\partial z_j} \right\rangle_{z_i=z_i^0} = 0,$$

that requires an extra fine-tuning in general.

- In the SUGRA models based on the weakly broken dilatation invariance the MPP conditions are fulfilled without any extra fine-tuning.

Cosmological constant

- According to MPP the physical and supersymmetric vacua have the same energy density.
- Since the vacuum energy density of supersymmetric states in flat Minkowski space is zero ρ_Λ in the physical vacuum vanishes in the leading approximation.
- However non-perturbative effects in the observable sector may lead to the breakdown of SUSY in the supersymmetric phase.
 - In SUSY phase $\alpha_3(Q)$ increases in the infrared region enhancing a role of non-perturbative effects.
 - Top quark Yukawa coupling grows with increasing of $\alpha_3(Q)$ that may induce top quark condensate at the scale Λ_{SQCD} .
 - Top quark condensate breaks SUSY resulting in positive value of the cosmological constant $\rho_\Lambda \simeq \Lambda_{SQCD}^4$.

- We assume that at high energy scale the gauge and Yukawa couplings are the same in both vacua.
- Since $f_a(T, z) \simeq \text{const}$ the gauginos are substantially lighter than scalar particles, i.e. $M_a \ll m_\alpha$.
- Such a hierarchical structure of the particle spectrum appears in the models with **Split Supersymmetry**.
- In the supersymmetric vacuum the QCD interaction becomes strong at

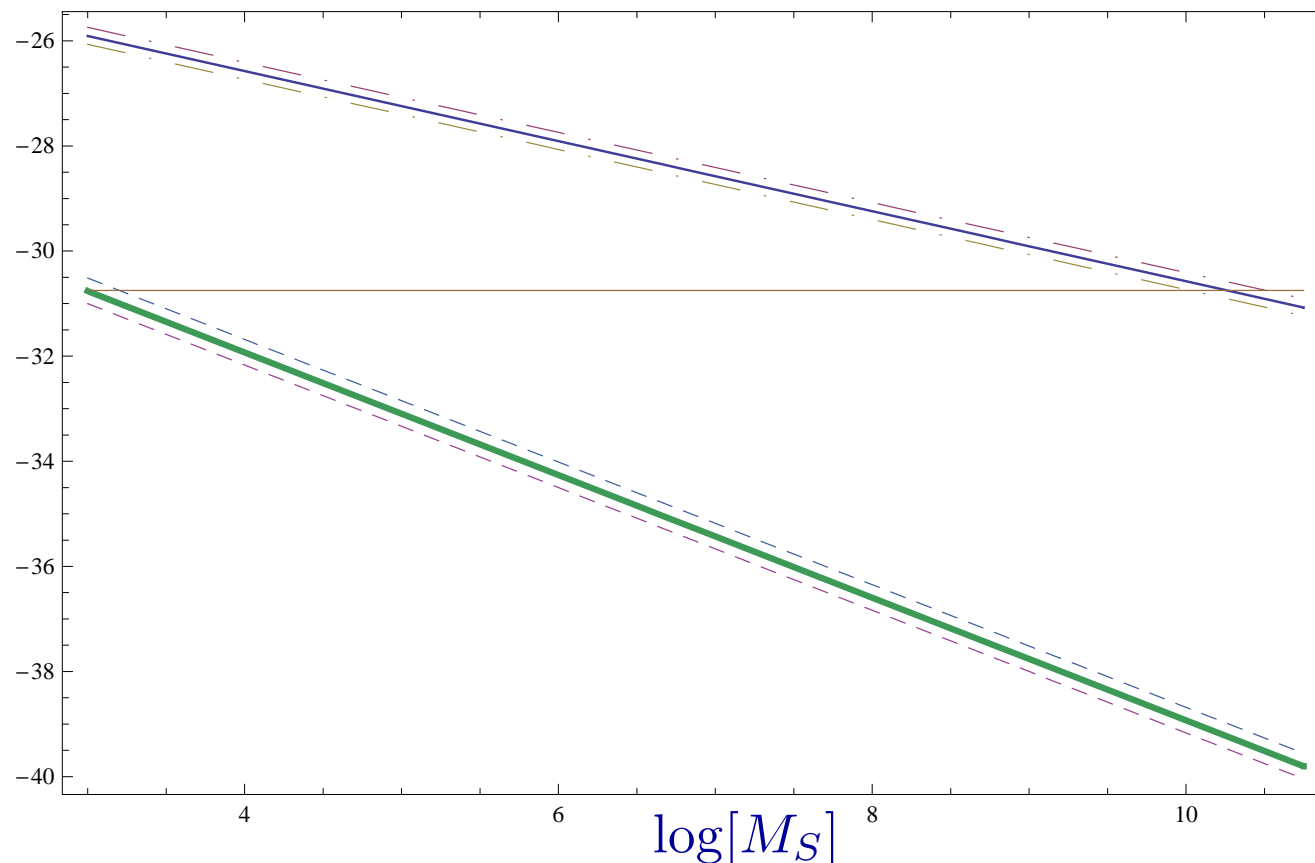
$$\Lambda_{SQCD} = M_S \exp \left[\frac{2\pi}{b_3 \alpha_3^{(2)}(M_S)} \right],$$

$$\frac{1}{\alpha_3^{(2)}(M_S)} = \frac{1}{\alpha_3^{(1)}(M_Z)} - \frac{\tilde{b}_3}{4\pi} \ln \frac{M_g^2}{M_Z^2} - \frac{b'_3}{4\pi} \ln \frac{M_S^2}{M_g^2},$$

where $\tilde{b}_3 = -7$, $b_3 = -3$ and $b'_3 = -5$ are the beta functions of $\alpha_3(Q)$ in the SM, MSSM and Split SUSY, while M_g is a gluino mass.

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- For $\alpha_3(M_Z) = 0.116 - 0.121$ and $M_g = 500 - 2500$ GeV the measured value of the cosmological constant is reproduced when $M_S = 0.2 - 3 \cdot 10^{10}$ GeV.

$\log[\Lambda_{SQCD}/M_{Pl}]$



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- The obtained prediction for M_S can be tested because it leads to the extremely **long-lived gluinos** that can be produced at the LHC

$$\tau \sim 8 \left(\frac{M_S}{10^9 \text{ GeV}} \right)^4 \left(\frac{1 \text{ TeV}}{M_g} \right)^5 \text{ s.}$$

- When M_S varies from $2 \cdot 10^9 \text{ GeV}$ ($M_g = 2500 \text{ GeV}$) to $3 \cdot 10^{10} \text{ GeV}$ ($M_g = 500 \text{ GeV}$) the gluino lifetime changes from **1 sec.** to **$2 \cdot 10^8 \text{ sec.}$ (1000 years).**
- If the MSSM particle content is supplemented by a pair of $5 + \bar{5}$ multiplets ($b_3 = -2$) then the observed value of ρ_Λ can be obtained even for **$M_S \simeq 1 \text{ TeV}$**
- In the physical vacuum extra particles gain masses $\sim M_S$ due to the presence of the bilinear terms **$[\eta(5 \cdot \bar{5}) + h.c.]$** in the Kähler potential.

Conclusions

- The breakdown of global symmetries, which protect a zero value for the cosmological constant in no-scale supergravity (SUGRA) models, may lead to the natural realization of the multiple point principle (MPP).
 - MPP requires the degeneracy of all global vacua.
 - MPP also predicts the existence of a supersymmetric phase in flat Minkowski space that results in the vanishing of ρ_Λ to first approximation.
- Non-perturbative effects can give rise to the breakdown of SUSY in the supersymmetric vacuum inducing tiny and positive value of ρ_Λ , i.e. $\rho_\Lambda \ll 10^{-100} M_{Pl}^4$.
- The observed value of ρ_Λ can be reproduced in the Split-SUSY scenario if the SUSY breaking scale is of order of 10^{10} GeV.