Dark Energy density in Split SUSY models inspired by degenerate vacua

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Based on:

C. D. Froggatt, R. Nevzorov and H. B. Nielsen, in preparation;

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

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

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

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

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

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

- 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 $\Lambda_{SUSY} >> 100$ GeV.

No–scale supergravity

- The scalar potential in $(N=1)$ SUGRA models is specified in terms of the K$\ddot{a}$hler function

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

- The SUGRA scalar potential is given by

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

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

$$D^a = g_a \sum_{i,\,j} \left(G_i T^a_{ij} \phi_j \right) \,.$$

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

$$m_{3/2} = < e^{G/2} >$$

- In SUGRA models $\rho_\Lambda \sim < e^{G/2} > \sim -m_{3/2}^2 M_{Pl}^2$.

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

$$T \to T + i\beta\,, \qquad\qquad \varphi_\sigma \to \varphi_\sigma$$

and dilatations

$$T \to \alpha^2 T\,, \qquad\qquad \varphi_\sigma \to \alpha\,\varphi_\sigma\,.$$

- The invariance under imaginary translations and dilatations constrain K$\ddot{a}$hler function

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

- 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

$$T \to \alpha^2 T\,, \qquad\qquad z \to \alpha\, z$$

and imaginary translations

$$T \to T + i\beta\,, \qquad\qquad z \to z\,.$$

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

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

where μ_0 and $c_n \sim 1$.

- We also assume that the dilatation invariance is broken in the K$\ddot{a}$hler potential of the observable sector

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

- 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

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

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

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

- In the vacuum where $z = -2\mu_0/3$ local supersymmetry is broken so that gravitino and all scalar particles get non–zero masses:

$$m_{3/2} = \frac{4\varkappa\mu_0^3}{27\left\langle\left(T+\overline{T}-\frac{4\mu_0^2}{9}\right)^{3/2}\right\rangle}, \qquad m_\sigma \sim \frac{m_{3/2}\xi_\sigma}{\zeta_\sigma}.$$

- 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.
- 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 $< W >= 0$.
- The presence of degenerate vacua with broken and unbroken local supersymmetry leads to the natural realisation of the multiple point principle (MPP).

- 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 $\rho_\Lambda \simeq \Lambda^4_{SQCD}$.

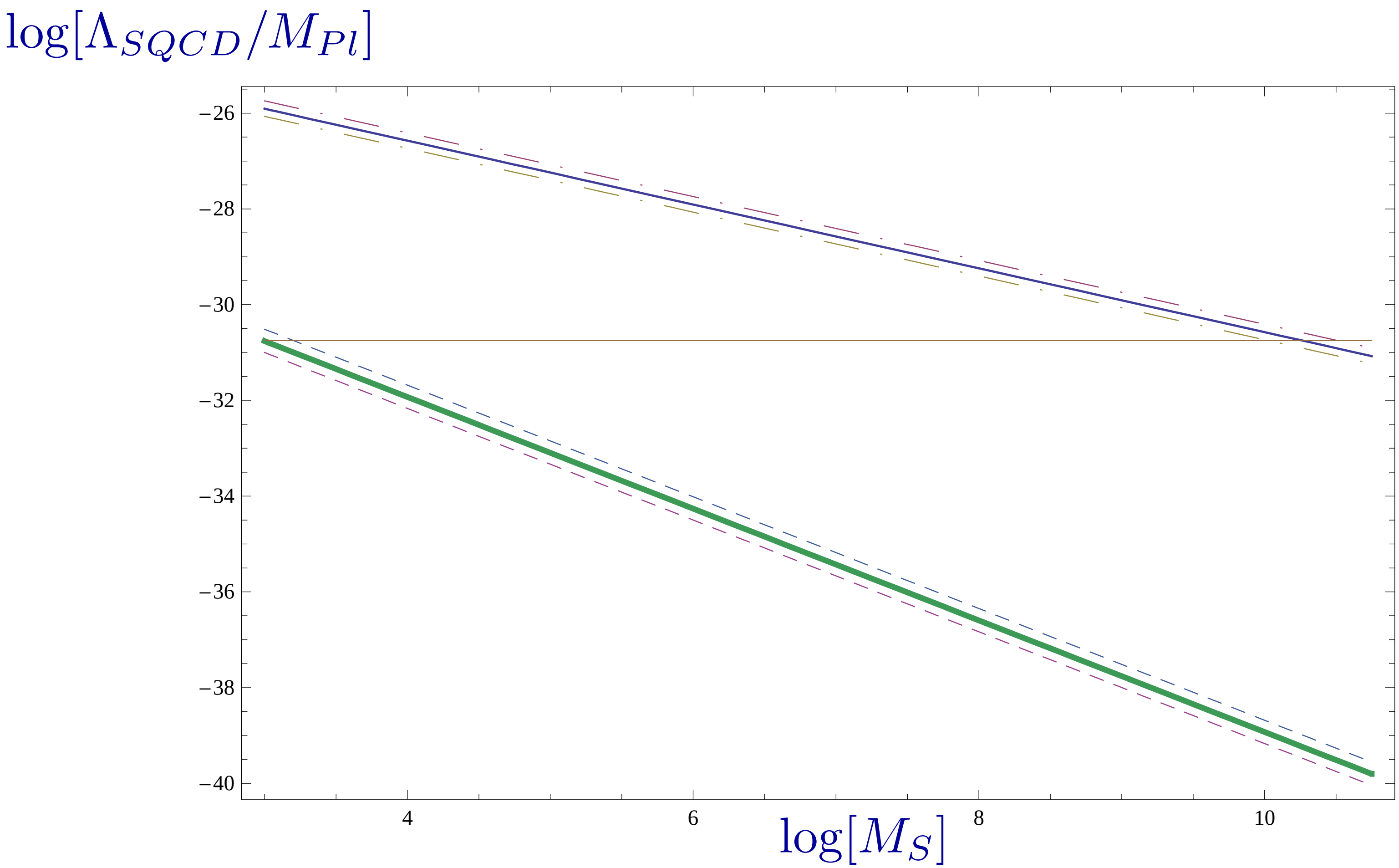
- We assume that at high energy scale the gauge and Yukawa couplings are the same in both vacua.
- Since $f_a(T, z) \simeq const$ the gauginos are substantially lighter than scalar particles, i.e. $M_a \ll m_\alpha$.
- Such a hierarchical structure of the particle spectrum appears in the models with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

- 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.



- 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

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

  - When M_S varies from $2\cdot 10^9$ GeV ($M_g = 2500$ GeV) to $3\cdot 10^{10}$ GeV ($M_g = 500$ GeV) the gluino lifetime changes from 1 sec. to $2\cdot 10^8$ 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 $M_S \simeq 1$ TeV

- In the physical vacuum extra particles gain masses $\sim M_S$ due to the presence of the bilinear terms $\left[\eta(5\cdot\bar{5}) + h.c.\right]$ in the K$\ddot{a}$hler potential.

Conclusions

- In no–scale supergravity global symmetries protect local supersymmetry and a zero value for the cosmological constant.
- The breakdown of these symmetries that ensures the vanishing of ρ_Λ near the physical vacuum leads 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.

$$\rho_\Lambda \ll 10^{-100} M_{Pl}^4 \,.$$