Cosmological constant in SUGRA models with Planck scale SUSY breaking and degenerate vacua

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Based on:

C. D. Froggatt, R. Nevzorov, H. B. Nielsen and A. W. Thomas, arXiv:1403.1001 [hep-ph];

C. D. Froggatt, R. Nevzorov and H. B. Nielsen, Int. J. Mod. Phys. A **27** (2012) 1250063;

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

- The discovery of the BEH boson with $m_h \simeq 126\,\text{GeV}$ is an important step towards our understanding of the mechanism of the EW symmetry breaking.
- Further exploration of the TeV scale physics at the LHC may lead to the discovery of new physics.
- Despite the compelling arguments for physics beyond the SM no indication of its presence has been detected.
- Moreover there are some reasons to believe that SM is extremely fine-tuned.
- Indeed, 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 QCD condensates and EW symmetry breaking

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

- The contribution of zero–modes is expected to push total vacuum energy density even higher up to M^4_{Pl}, 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 different contributions to ρ_Λ the smallness of the cosmological constant should be regarded as a fine–tuning problem.

- Here, instead of trying to alleviate fine-tuning we postulate the exact degeneracy of different vacua (inspired by the multiple point principle (MPP)).
- MPP postulates the existence of many phases with the same energy density which are allowed by a given theory.
- The MPP applied to the SM implies that the Higgs effective potential

$$V_{eff}(H) = m^2(\phi)H^\dagger H + \lambda(\phi)(H^\dagger H)^2$$

possesses two degenerate minima taken to be at the EW and Planck scales.

- The degeneracy of these vacua can be achieved only if

$$\lambda(M_{Pl}) \simeq 0\,, \qquad \beta_\lambda(M_{Pl}) \simeq 0\,.$$

- Using these conditions one can compute M_t and M_H [C.D.Froggatt, H.B.Nielsen, Phys.Lett. **B368** (1996) 96]

$$M_t = 173 \pm 4\,\text{GeV}\,, \qquad M_H = 135 \pm 9\,\text{GeV}\,.$$

- Recently, using the extrapolation of the SM parameters up to M_{Pl} with full 3–loop RGE precision it was shown [D. Buttazzo, G. Degrassi, P. P. Giardino, G. F. Giudice, F. Sala, A. Salvio, A. Strumia, JHEP **1312** (2013) 089 [arXiv:1307.3536]]

$$\lambda(M_{Pl}) = -0.0128 - 0.0065\left(\frac{M_t}{\text{GeV}} - 173.35\right) + 0.0018\left(\frac{\alpha_3(M_Z) - 0.1184}{0.0007}\right) + 0.0029\left(\frac{M_H}{\text{GeV}} - 125.66\right)\,.$$

- Here the MPP assumption is adapted to models based on $(N=1)$ local supersymmetry, in order to provide an explanation for the small deviation of the cosmological constant from zero.

Dark energy in SUSY/SUGRA models

- An exact global SUSY ensures zero value for ρ_Λ.
- SUSY scalar potential can be written as follows

$$V = \frac{1}{2} D^a D^a + F_i^* F_i , \qquad F_i^* = -\frac{\partial W}{\partial A_i}, \qquad D^a = -g A_i^* T_{ij}^a A_j \, .$$

- However, in the exact SUSY limit, bosons and fermions from one chiral multiplet are degenerate.
- The breakdown of SUSY induces a huge and positive contribution to ρ_Λ

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

  where M_{SUSY} is a SUSY breaking scale.
- The non–observation of squarks and sleptons implies that $M_{SUSY} >> 100$ GeV.

- The full $(N=1)$ SUGRA Lagrangian is specified in terms of an analytic gauge kinetic functions $f_a(\phi_M)$ and a real gauge-invariant K$\ddot{a}$hler function $G(\phi_M, \phi^*_M)$.
- The functions $f_a(\phi_M)$ determine the kinetic terms for the fields in the vector supermultiplets and the gauge coupling constants Re$f_a(\phi_M) = 1/g_a^2$.
- The K$\ddot{a}$hler function is a combination of two functions

$$G(\phi_M, \phi^*_M) = K(\phi_M, \phi^*_M) + \ln|\mathcal{W}(\phi_M)|^2 \,.$$

where $M_{Pl}/\sqrt{8\pi} = 1$.

- $K(\phi_M, \phi^*_M)$ is the K$\ddot{a}$hler potential whose second derivatives define the kinetic terms for the fields in the chiral supermultiplets.
- $\mathcal{W}(\phi_M)$ is the complete analytic superpotential.

- The SUGRA scalar potential can be presented as a sum of F and D–terms

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

$$G_M\equiv\frac{\partial G}{\partial\phi_M}\,,\qquad G_{\bar M}\equiv\frac{\partial G}{\partial\phi^*_M}\,,\qquad G^{M\bar N}=G^{-1}_{\bar N M}\,,\qquad D^a=g_a\sum_{i,\,j}\left(G_i T^a_{ij}\phi_j\right).$$

- In order to break supersymmetry in SUGRA models a hidden sector is introduced.
  - If hidden sector fields acquire VEVs so that at least one of their auxiliary fields

$$F^M=e^{G/2}G^{M\bar P}G_{\bar P}$$

    is non-vanishing, then local SUSY is spontaneously broken.
  - At the same time goldstino is swallowed up by the gravitino which becomes massive, i.e. $m_{3/2}\simeq\langle F^M\rangle/M_{Pl}$.
- In SUGRA models $\rho_\Lambda\sim-\langle e^G\rangle\sim-m^2_{3/2}M^2_{Pl}$.

- 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

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

- 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 models

- 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.
- The simplest Kähler potential and superpotential that satisfy these conditions can be written as

$$K(z,\, z^*) = |z|^2\,, \qquad\qquad W(z) = m_0 (z + a_0)^2\,.$$

- If $a_0 = -\sqrt{3} + 2\sqrt{2}$, SUGRA scalar potential possesses two degenerate minima with zero energy density.

- One of them is a supersymmetric Minkowski minimum that corresponds to $z^{(2)} = -a_0$.
- In the other minimum of the SUGRA scalar potential ($z^{(1)} = \sqrt{3} - \sqrt{2}$) local supersymmetry is broken, so that it can be associated with the physical vacuum.
- Varying a_0 around $-\sqrt{3} + 2\sqrt{2}$ one can obtain a positive or a negative contribution from the hidden sector to the total energy density of the physical vacuum.
- Thus a_0 can be fine-tuned so that the physical and second vacua are degenerate.
- Extra fine-tuning can be alleviated in the no–scale inspired SUGRA models with broken dilatation invariance.

- Let us consider no–scale inspired 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.
- 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.
- 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 inclusion of perturbative and non–perturbative corrections to the Lagrangian of the no–scale inspired SUGRA model is expected to spoil the degeneracy of vacua inducing a huge energy density in the vacuum where SUSY is broken.
- Therefore this model should be considered as a toy example only.
- It demonstrates that, in $(N = 1)$ supergravity, there might be a mechanism which ensures the vanishing of vacuum energy density in the physical vacuum.
- This mechanism may also lead to a set of degenerate vacua with broken and unbroken supersymmetry, resulting in the realization of the multiple point principle.

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 hidden sector may lead to the breakdown of SUSY in the supersymmetric phase.
- This may happen if vector supermultiplets, which correspond to the unbroken gauge symmetry in the hidden sector, remain massless.
- In this case the breakdown of SUSY in the second vacuum can be caused by the formation of a gaugino condensate induced at the scale $\Lambda_{SQCD} \ll M_{Pl}$.

- The gaugino condensation itself does not break global SUSY.
- Nevertheless a non-trivial dependence of the gauge kinetic function $f_X(z_m)$ on the hidden sector superfields z_m results in

$$F^{z_m} \propto \frac{\partial f_X(z_k)}{\partial z_m} \bar{\lambda}_a \lambda_a + ...$$

- Thus it is only via the effect of non-renormalisable term that gaugino condensate causes the breakdown of local SUSY in SUGRA models.
- As a consequence the SUSY breaking scale is many orders of magnitude lower than Λ_{SQCD}, i.e.

$$\langle F^{z_m} \rangle \simeq \langle \bar{\lambda}_a \lambda_a \rangle / M_{Pl} \simeq \Lambda^3_{SQCD} / M_{Pl} \, .$$

- So low SUSY breaking scale gives rise to small dark energy density

$$\rho_\Lambda^{(2)} \simeq \frac{\Lambda_{SQCD}^6}{M_{Pl}^2} \ll \Lambda_{SQCD}^4 .$$

- The postulated degeneracy of vacua implies that the physical vacuum has the same energy density.
- In order to reproduce the observed value of the cosmological constant, Λ_{SQCD} should be close to Λ_{QCD} in the physical vacuum

$$\Lambda_{SQCD} \sim \Lambda_{QCD}/10 .$$

- Although there is no compelling reason to expect that Λ_{SQCD} and Λ_{QCD} should be related, one might naively consider Λ_{QCD} and M_{Pl} as the two most natural choices for Λ_{SQCD}.

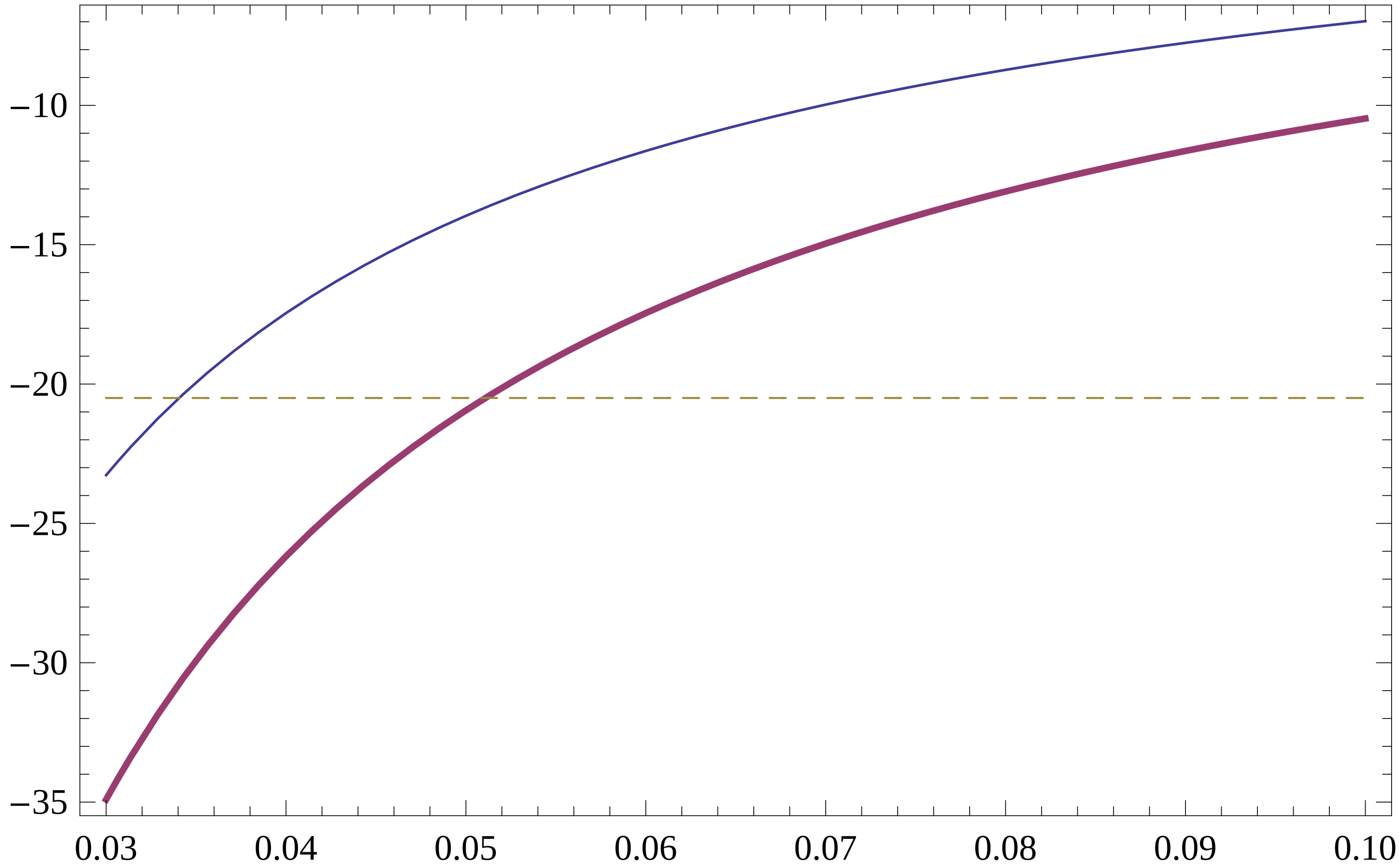
- For a given value of $\alpha_X(M_{Pl})$ one can estimate the energy scale, Λ_{SQCD}, where SUSY QCD–like interactions become strong in the second vacuum

$$\Lambda_{SQCD} = M_{Pl} \exp\left[\frac{2\pi}{b_X \alpha_X(M_{Pl})}\right] ,$$

  where $b_X = -9$ and -6 for the $SU(3)$ and $SU(2)$ gauge groups.

- The scale Λ_{SQCD} diminishes with decreasing $\alpha_X(M_{Pl})$.
- The measured value of the cosmological constant is reproduced when $g_X(M_{Pl}) \simeq 0.801$ and $g_X(M_{Pl}) \simeq 0.654$ in the case of $SU(2)$ and $SU(3)$ models.
- If SUSY is broken near M_{Pl} in the physical vacuum then the QCD gauge coupling $g_3(M_{Pl}) \simeq 0.487$.

$\mathrm{Log}[\Lambda_{\mathrm{SQCD}}/M_{\mathrm{Pl}}]$



$\alpha_X(M_{\mathrm{Pl}})$

Higgs phenomenology

- The presence of two degenerate vacua does not rule out the possibility that there might be other vacua with the same energy density.
- In particular, there can exist a vacuum where local SUSY and EW symmetry are broken somewhere near the Planck scale.
- In this case the full scalar potential can be written as

$$V = V_{hid}(z_m) + V_0(H) + V_{int}(H, z_m) + \dots .$$

- The presence of the third degenerate vacuum can constrain $\lambda(M_{Pl})$ and $\beta_\lambda(M_{Pl})$ in the physical vacuum if the interactions between H and z_m are rather weak,
- This may happen if the VEV of the Higgs field is considerably smaller than M_{Pl} (say $\langle H \rangle \lesssim M_{Pl}/10$).

- In this case the Higgs VEV may not affect much the VEVs of the hidden sector fields z_m.
- As a consequence m^2 is expected to be much smaller than M_{Pl}^2 and $\langle H^\dagger H \rangle$ in the third vacuum.
- Then the existence of the third vacuum with vanishingly small energy density would still imply that

$$\lambda^{(3)}(M_{Pl}) \simeq \beta_\lambda^{(3)}(M_{Pl}) \simeq 0\,.$$

- Since $z_m^{(1)} \simeq z_m^{(3)}$ the values of $\lambda(M_{Pl})$ and $\beta_\lambda(M_{Pl})$ should be also almost identical in both vacua.
- Consequently in the physical vacuum we have

$$\lambda^{(1)}(M_{Pl}) \simeq \beta_\lambda^{(1)}(M_{Pl}) \simeq 0\,.$$

Conclusions

- We argued that the measured value of the cosmological constant, as well as the small values of $\lambda(M_{Pl})$ and $\beta_\lambda(M_{Pl})$ can originate from SUGRA models with degenerate vacua.
- This scenario is realised if there are at least three exactly degenerate vacua.
  - In the first vacuum local SUSY is broken near the Planck scale while the breakdown of the $SU(2)_W \times U(1)_Y$ symmetry takes place at the EW scale.
  - In the second vacuum local SUSY breaking is induced by gaugino condensation at the scale which is just slightly lower than Λ_{QCD} in the physical vacuum.
  - In the third vacuum local SUSY and EW symmetry are broken near the Planck scale.

Backup slides

- Our attempt to estimate the value of the cosmological constant relies on the assumption that the physical and SUSY Minkowski vacua are degenerate to very high accuracy which may look somewhat artificial.
- The identification of the mechanism, that can give rise to such vacua, is still work in progress.
- We can just remark that the vacua with very different dark energy densities should result in very different expansion rates and ultimately in very different space–time volumes of the universe.
- If underlying theory allows only vacua which lead to the similar order of magnitude of space-time 4-volumes then such vacua should be degenerate to the accuracy of the value of the cosmological constant in the physical vacuum.