Dark energy density 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, Phys. Lett. B **737** (2014) 167;

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 $m_h \simeq 125\,\text{GeV}$ 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]]

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

- 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.

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 $\rho_\Lambda\sim-<e^G>$.

- 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 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:

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

- 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 this theory, one of which is supersymmetric with $<W>=0$.
- This model should be considered as a toy example only since corrections tend to spoil the degeneracy of vacua inducing $\rho_\Lambda\neq 0$ in the vacuum where SUSY is broken.

- 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.
- Being applied to supergravity MPP implies the existence of a phase with global SUSY in flat Minkowski space.
- Such vacuum is realised only if

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

that requires an extra fine-tuning in general.

- In the SUGRA models discussed above these conditions are fulfilled without 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 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 dependence of the gauge kinetic function $f_X(z_m)$ on the hidden sector superfields z_m can result in

$$\langle F^{z_m}\rangle \sim \frac{\partial f_X(z_k)}{\partial z_m}\langle\bar{\lambda}_a\lambda_a\rangle \simeq \Lambda^3_{SQCD}/M_{Pl}\,.$$

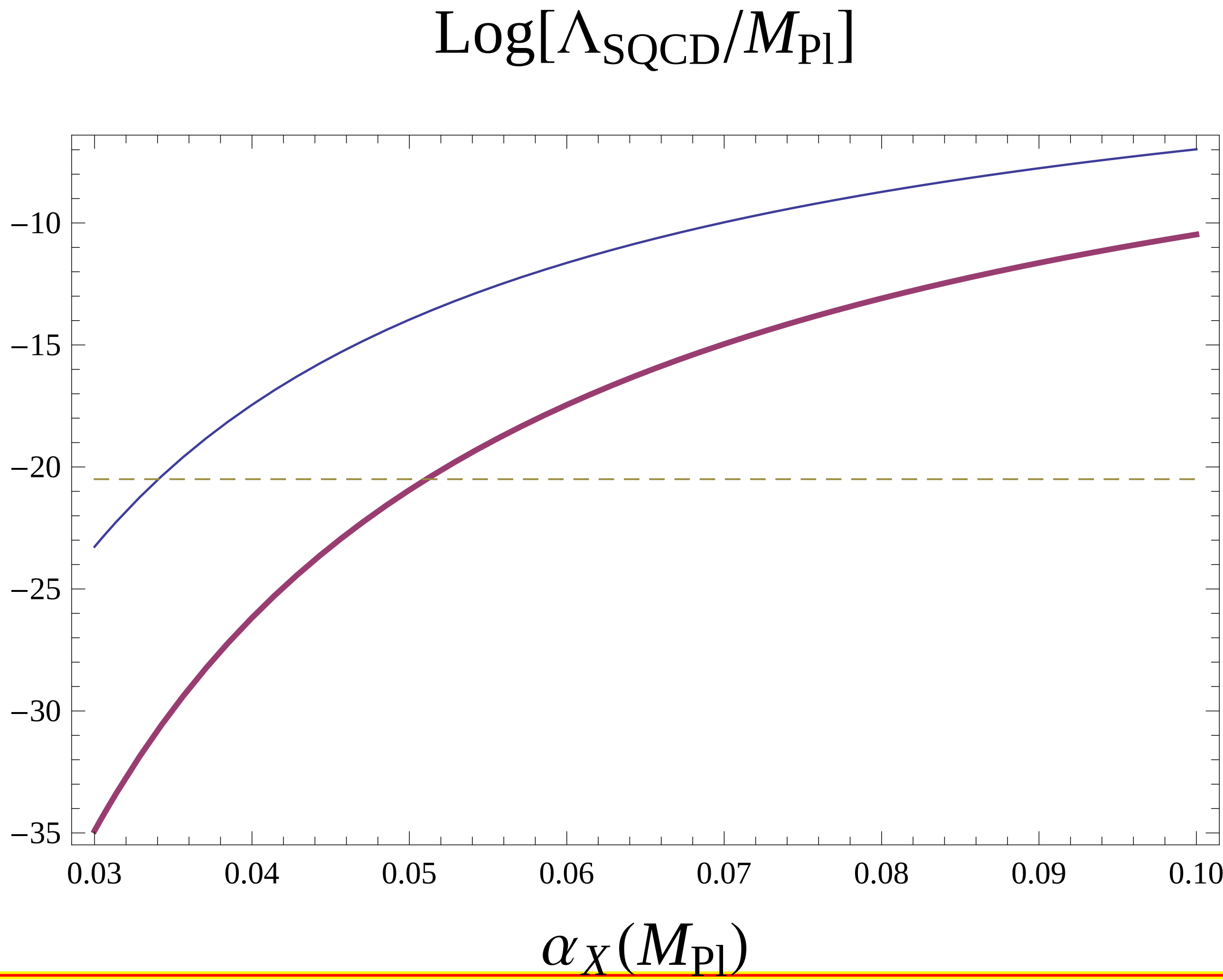
- So low SUSY breaking scale gives rise to small dark energy density

$$\rho^{(2)}_{\Lambda} \simeq \frac{\Lambda^6_{SQCD}}{M^2_{Pl}} \ll \Lambda^4_{SQCD}\,.$$

- 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

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

- In the case of $SU(2)$ and $SU(3)$ models the measured value of $\rho_{\Lambda}^{(2)}$ is reproduced for $g_X(M_{Pl}) \simeq 0.801$ and $g_X(M_{Pl}) \simeq 0.654$.



Higgs phenomenology

- In principle, there can exist the third vacuum with the same energy density where local SUSY and EW symmetry are broken somewhere near M_{Pl}.
- If the interactions between H and z_m are rather weak (say $\langle H \rangle \lesssim M_{Pl}/10$) then $z_m^{(1)} \simeq z_m^{(3)}$ so that
  - in the third vacuum $m^2 \ll \langle H^\dagger H \rangle \lesssim M_{Pl}^2$;
  - $\lambda^{(1)}(M_{Pl}) \simeq \lambda^{(3)}(M_{Pl})$ and $\beta_\lambda^{(1)}(M_{Pl}) \simeq \beta_\lambda^{(3)}(M_{Pl})$.
- Then the existence of the third vacuum with vanishingly small energy density would still imply that

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

- 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 slide

- 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.