Student Lectures

Finetuning and the String Landscape

Prologue

Intention of this lecture series:

- Pointing out that there might be no alternative to finetuning as an answer to several questions/problems in theoretical physics.
- String theory provides many solutions (i.e. many different effective field theories, each with different physical parameters) and hence sheds new light on how to deal with potential finetunig problems.
- In this context, String Theory is often quoted to give rise to 10^{500} different (flux) vacua. → "String Theory Landscape"
  This lecture should give you an overview, where this number comes from and how one could/should deal with this result.
- We will also argue that these effective field theories, we obtain from String Theory, are very "special" in the following sense: If you "guess" an effective field theory, you almost certainly cannot embed it into Quantum Gravity.
  In other words: The bottom-up approach fails and thus, we should use a top-down approach via String Theory.
- These notes should give an idea of the tools and concepts, String Theorists often use in the field of String Phenomenology.
  Unfortunately, due to lack of time I can often only state some results and arguments without establishing them rigorously. However, I try to make connections to contents of basic theoretical physics courses wherever possible.

Outline

Main references:

Reviews / Lecture notes / Books

[BM, 2014] Baumann, McAllister: Inflation and String Theory, arXiv: 1404.2601

[DK, 2006] Douglas, Kachru: Flux Compactification, arXiv: 0610102

[DDK, 2007] Denef, Douglas, Kachru: Physics of String Flux Compactifications, arXiv: hep-th/0701050

[Den, 2008] Denef: Les Houches Lectures on Constructing String Vacua, arXiv: 0803.1194

[BBS, 2006] Becker, Becker, Schwarz: String Theory and M-Theory: A Modern Introduction, CUP.

[IU, 2012] Ibáñez, Uranga: String Theory and Particle Physics: An Introduction to String Phenomenology, CUP.

[KQS, 2010] Krippendorf, Quevedo, Schlotterer: Cambridge Lectures on SUSY and Extra Dimensions, arXiv: 1011.1491

Main Papers

[~~GKP, 20~~ [BP, 2000] Bousso, Polchinski: arXiv: hep-th/0004134

[GKP, 2001] Giddings, Kachru, Polchinski: Hierarchies from Fluxes in String Compactifications, hep-th/0105097

[KKLT, 2003] Kachru, Kallosh, Linde, Trivedi: de Sitter vacua in String Theory, hep-th/0301240

[DD, 2004] Denef, Douglas: Distributions of flux vacua, hep-th/0404116

[Vaf, 2005] Vafa: The String Landscape and the Swampland, hep-th/0509212

[AMNV, 2006] Arkani-Hamed, Motl, Nicolis, Vafa, hep-th/0601001

1. Finetuning

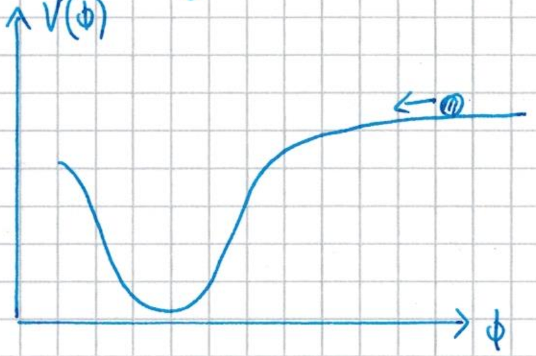
P.4 Finetuning: Precise adjustment of parameters needed.

1.1. Examples of finetuning

1.1.1. Avoiding the η-problem in inflation

Details: [BM, 2014] or Fabrizio's lecture notes

Summary:



ϕ: Inflaton field, V: potential

Slow-roll-inflation requires

$$\varepsilon \equiv \frac{1}{2} M_{PL}^2 \left(\frac{V'}{V}\right)^2 \ll 1$$

$$\|\eta\| \equiv M_{PL}^2 \left\|\frac{V''}{V}\right\| \ll 1$$

Take into account heavy fields that have been integrated out:

$$\mathcal{L}_{eff}[\phi] = \mathcal{L}[\phi] + \sum_i c_i(g) \frac{O_i[\phi]}{M^{\delta_i - 4}} \qquad (1.1)$$

local operator of dimension δ_i

Wilson coeff.

mass scale of heavier fields

couplings (of UV th.)

↳ η-Problem from (e.g.) dimension-six operator:

$$\Delta V = c\,\frac{O_6}{M^2} = c\,V(\phi)\,\frac{\phi^2}{M^2}$$

$$\Rightarrow \quad \Delta\eta \simeq 2c\left(\frac{M_{PL}}{M}\right)^2 \qquad (1.2)$$

Since we generically expect $c \sim O(1)$, $M < M_{PL}$ ruins $|\eta| \ll 1$. $\Rightarrow$ No slow-roll infl. possible unless we admit

a) a symmetry that automatically requires $c \ll 1$ (e.g. shift-symm. $\phi \to \phi + \alpha$)

b) the possibility to make c small by hand "finetuning"

Even though finetuning can be avoided at this stage by a), all inflation models I know still seem to require finetuning somewhere else.

1.1.2. The Higgs mass

- Recall that scalar fields receive ~~mass~~ radiative mass corrections

$$\Delta m^2 \sim \Lambda^2 \qquad (\Lambda: \text{ cutoff scale}) \tag{1.3}$$

Therefore, for the Higgs mass:

$$\underset{\underset{m_{obs} \simeq 125\,\text{GeV}}{\nearrow}}{m^2_{obs}} = \underset{\underset{\text{bare mass}}{\uparrow}}{m_0^2} + \Delta m_H^2$$

Lecture by Sebastian Schätzel (arXiv 1403.5176):

$$m_0^2 \approx 210\, m^2_{obs} \qquad @ \quad \Lambda = 10\,\text{TeV}$$

$\therefore$ Bare mass has to cancel corrections up to 0.2%

- Even w/ susy, one has to face this finetuning problem of the Higgs mass:
  While quadratic contributions (1.3) cancel, one gets logarithmic corrections, e.g. $\sim \log\left(\frac{M_{susy}}{M_{\tilde{t}}}\right)$.

1.1.3. The Cosmological Constant Problem

Similarly to (1.3), quantum corrections to the vacuum energy density scale as

$$\Delta\rho_{vac} \sim \Lambda^4$$

So, one would expect

$$\Delta\rho_{vac} \sim M_{PL}^4,$$

but one observes

$$\Delta\rho_{vac} \sim 10^{-120} M_{PL}^4.$$

$\Rightarrow$ Immense fine-tuning required.

1.2 The Cosmological Constant and the Anthropic Principle

- (How) can we explain a fine-tuning of the order of 10^{-120}?
- The cosmological constant Λ enters the Friedmann equations as follows:

$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho - \frac{k}{a^2} + \frac{\Lambda}{3}$$

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}\left(\rho + 3P\right) + \frac{\Lambda}{3}$$

Hence, $\Lambda > 0$ leads to accelerated expansion.

- If Λ is sufficiently large, structure formation can be prohibited.
  $\Rightarrow$ No life possible.
  "Anthropic principle": Since we exist, Λ can't be too large!
- Can we quantify "Λ can't be too large"?
  Yes! See e.g. Peebles, Weinberg, ...
  Result:
  ρ_{vac} shouldn't be larger than $200\,\rho_{today}$.
  $\Rightarrow$ Still a fine-tuning of $\mathcal{O}(100)$ needed.
  (But still much better than a fine-tuning of $\mathcal{O}(10^{120})$...)

- The smallness of Λ can be motivated even further, e.g. in the context of String Theory, where many vacua exist and where many of them have the right Λ.
  See also: [BP, 2000] & [Den, 2008].