Inflation, universality and attractors
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We conclude this thesis by discussing the main results obtained and providing an outlook on future perspectives and possible developments.
7.1 Overview of the results

The main focus of this thesis has been inflation and its intricate connections to UV-physics scenarios. This primordial cosmological phase allows us to effectively probe energies well beyond what any particle accelerator could ever achieve. It provides a great physics arena where to investigate and eventually test our most speculative theories.

We have been particularly interested in extracting generic features of the inflationary mechanism, beyond the specific details of the model at hand. This is important as CMB data allows us to probe just a very limited region of the inflationary trajectory (we have explained this in Ch. 3 and in Ch. 4). Specifically, we have investigated some of those aspects which are of utmost relevance for a proper embedding of the inflationary paradigm into a complete framework of UV-physics. The results have turned out to be very exciting:

- On the one hand, in Ch. 4 we have shown that focusing on universality properties of inflation can yield surprisingly stringent bounds on its dynamics. First of all, a large set of inflationary models can be organized in universality classes depending on their observational predictions. This is simply a direct consequence of the small sensitivity cosmological experiments have over the whole inflationary trajectory. Secondly, we have investigated the regime where this ignorance becomes of crucial importance for a variable depending on the entire expansion period, such as the inflationary field range $\Delta\phi$. While we have provided explicit examples where a measurement of $n_s$ and $r$ correspond to a wide spectrum of values $\Delta\phi > M_{Pl}$ (see [60] and Sec. 4.4), we have also demonstrated that the inflaton range generically exhibits universal behaviour in the sub-Planckian region (see [79] and Sec. 4.5). In other words, given a point in the $(n_s, r)$ plane, there is a unique estimate for $\Delta\phi < M_{Pl}$. It is then very remarkable that knowledge about a small portion of the inflationary trajectory turns out to be enough in order to infer basic properties of a region not accessible via CMB measurements. The inflaton excursion becomes a function of both the tensor-to-scalar ratio $r$ and the spectral index $n_s$. This novel and universal dependence has allowed us to strengthen the usual Lyth bound of two order of magnitudes. One has sub-Planckian field ranges and can safely work within an EFT of inflation just for very small values $r \lesssim 2 \cdot 10^{-5}$.

- On the other hand, one would like to find a satisfying theoretical underpinning to explaining why the spectral index $n_s$ and the tensor-to-scalar ratio $r$ take the values they do. In Ch. 5, we have proven that non-trivial Kähler geometries, typically arising in string theory compactifications, un-
equivocally determine such observables. This is in a nutshell the upshot of $\alpha$-attractors: the parameter $\alpha$ controls the curvature of the moduli space and, with it, the amount of primordial gravitational waves; the value of the scalar tilt tends automatically to the “sweet spot” of Planck, no matter the details of the superpotential. The Kähler geometry basically induces an attractor for observations. We have then taken our investigation in the direction of proving the generality of this attractor mechanism, independently of the other fields involved. This definitively represents an important step towards a consistent string theory realization where many moduli appear naturally. The fundamental nature of this phenomenon appears indeed to be related to the novel $\alpha$-scale supergravity construction which we originally discovered in [94] and, then, presented in Sec. 5.4. We have thus proved that the attractor mechanism is independent of the specific direction of SUSY breaking but rather related to the Kähler structure of the inflaton sector.

- Finally, the possibility of obtaining a pure de Sitter phase in supergravity by means of a sole nilpotent superfield [221–226] and its relations to D-brane physics [230, 246, 247] acquires particular relevance in the light of constructing a unified framework for inflation and dark energy. We have indeed proved that coupling the inflaton sector with a nilpotent superfield has very striking implications. First of all, it allows to evade the restrictions imposed by the no-go theorem of [200] on the possibility of uplifting a SUSY Minkowski minimum (see [160] and Sec. 6.2 for a detailed investigation). Secondly, it greatly simplifies the inflationary dynamics and allows for remarkable phenomenological flexibility (see [203] and Sec. 6.3). However, the greatest surprise actually appears again in the context of $\alpha$-attractors: in [95] and in Sec. 6.4, we have indeed shown how such a coupling leads to an enhancement of the attractor nature of the theory.

### 7.2 Outlook

The inflationary paradigm has turned to be one of the best and most concrete physical scenarios providing a wonderful testing ground for ideas in quantum gravity. The results of this thesis have proven that there is a remarkable interplay between actual cosmological predictions and deep theoretical aspects characterizing a complete framework of UV-physics.

In particular, our investigation has focused on the generic properties of inflation when this is embedded in a supergravity setting. Then, one may wonder whether this study is enough in order to constrain the physics of
inflation in string theory, being this the ultimate goal. We have been taking
the following approach. On the one hand, it is certainly true that consistent
string theory compactifications will form just a subset of the full spectrum
of supergravity possibilities (e.g. when these are expressed in terms of $K$ and
$W$). On the other hand, not every supergravity theory will generically allow
for a consistent inflationary dynamics. In fact, we have provided compelling
evidence of the restrictions the internal Kähler geometry and SUSY breaking
directions may lead on the viability of inflation. Therefore, the subset
of supergravity models suitable for inflation will intersect the subset of the
proper string theory compactifications, thus yielding important guidance for
a consistent cosmological construction within this ultimate theory of Nature.
We have graphically condensed this discussion in Fig. 7.1.

The discovery that hyperbolic Kähler geometries make the particular de-
tails of the specific model insensitive to the final phenomenological result,
thus inducing an attractor, is rather intriguing. Yet more remarkable is the
fact that the cosmological predictions are given by

$$n_s = 1 - \frac{2}{N}, \quad r = \frac{12\alpha}{N^2},$$

in terms of the number of e-folds $N$, thus being at the center of the Planck
dome [13, 14]. This belongs to a region in the $(n_s, r)$ plane which seems

\textbf{Figure 7.1} \\
The subset of the suitable supergravity constructions for inflation (yellow slice) intersects
the subset of the effective supergravities arising from string theory compactifications
(labeled by ST). This provides a very useful guidance for the implementation of the
inflationary paradigm in string theory.
to be very appealing from the theoretical viewpoint. Higher order terms of
the Ricci scalar in a pure gravitational Lagrangian, such as the Starobinsky
model [184] and its supergravity realizations [170–172, 185–187], lead to (5.43)
with $\alpha = 1$ (by including an auxiliary vector field one can vary the value of
$\alpha$ [248]). Further, models with non-minimal couplings, such as Higgs inflation
[188] and the universal attractor model [91], yield identical observational
predictions. Interestingly, the peculiarity of such a region translates into a
common denominator being a pole of order two in the kinetic term of the
inflaton [93]. Finally, investigations on the excursion of the inflaton field
reveal a change of its behavior just around the region defined by (5.43) (as
shown [60, 79] and in Ch. 4).

A consistent realization of the attractor mechanism within string the-
ory still awaits to be discovered. Several delicate issues must be tackled in
order to have full control of the model, once embedded in this rich physi-
cal framework. These problems include the divergence of the kinetic term
inside the moduli space, the correct identification of the inflationary modu-
lus, the interactions of the latter with the other moduli (see e.g. the recent
works [249, 250]) and others. Nevertheless, certain approximate stringy incar-
nations already exist [117, 251, 252]. These definitively raise very good hopes
for successfully reaching this important goal. We look forward to facing this
exciting challenge in the very near future.