Scalar Fields in Cosmology: Inflation, Dark Matter, Dark Energy

Jan Louis[1], *Alexander Westphal*[2]

[1]II. Institut für Theoretische Physik, Universität Hamburg, Germany
[2]DESY, Hamburg, Germany

DOI: http://dx.doi.org/10.3204/PUBDB-2018-00782/C6

During the 12 years of project C6 of the SFB 676 it has achieved a set of significant contributions to our understanding of the dynamics of scalar fields in early universe cosmology and its connection to string theory. In this contribution we describe our results at this interface between theoretical cosmology and fundamental high-energy theory in their impacts on 'string inflation' consequences of multi-field inflation in string theory inspired random potentials', 'pole inflation, $f(R)$-gravity, and exponential inflationary plateaus', the 'phenomenological consequences of features before and during inflation', 'false-vacuum tunneling and its consequences for the initial conditions of inflation', connections between slow-rolling scalar fields and electroweak symmetry breaking due to couplings between the Standard Model (SM) Higgs field and inflation, 'moduli stabilization and de Sitter (dS) vacua in string theory', as well as the connection of dS vacua to 'sequestering as a solution to the cosmological constant problem', and on the connection between measurements of ΛCDM parameters from the CMB as well as local data such as the local H_0 determinations, and effects from large-scale structure such as weak gravitational lensing. We finish in section with a summary of a review by one of the PIs on the topic of 'String cosmology – Large field inflation in string theory'.

1 String inflation

Our study of models of inflation in string theory focused on two classes of inflaton candidates. Inflation in string theory can be driven by the slow-roll evolution of volume/Kähler moduli, of open-string moduli, or of axion fields. Both are generically present in 4D compactifications of string theory.

Here we first discuss models where inflation is driven by string moduli scalar fields. In our projects we analyzed the possibility of realizing inflation with a subsequent dS vacuum [1] in the Kähler uplifting scenario [2, 3] while building on [4]. The inclusion of several quantum corrections to the 4d effective action evades previous no-go theorems and allows for construction of simple and successful models of string inflation. The predictions of several benchmark models are in accord with current observations, i.e., a red spectral index, negligible non-Gaussianity, and spectral distortions similar to the simplest models of inflation. A particularly interesting subclass of models are "left-rolling" ones, where the overall volume of the compactified dimensions shrinks during inflation. We call this phenomenon "inflation by deflation" (IBD), where deflation refers to the internal manifold. This subclass has the appealing features of being insensitive to initial conditions, avoiding the overshooting problem, and allowing for observable running $\alpha \sim 0.012$ and enhanced tensor-to-scalar ratio $r \sim 10^{-5}$. The latter results differ significantly from many string inflation models.

In large-field exponential plateau models one focus were the Large Volume Scenario (LVS) [5] of IIB Calabi–Yau flux compactifications. We constructed inflationary models from higher derivative α'^3-corrections [6]. In this case inflation is driven by a Kähler modulus whose potential arises from the aforementioned corrections, while we used the inclusion of string loop effects just to ensure the existence of a graceful exit when necessary. The effective inflaton potential takes a Starobinsky-type form $V = V_0(1 - e^{-\nu\phi})^2$, where we obtained one set-up with $\nu = -1/\sqrt{3}$ and one with $\nu = 2/\sqrt{3}$ corresponding to inflation occurring for increasing or decreasing ϕ respectively. The inflationary observables are thus in perfect agreement with PLANCK, while the two scenarios remain observationally distinguishable via slightly varying predictions for the tensor-to-scalar ratio r. Both set-ups yield $r \simeq (2 \ldots 7) \times 10^{-3}$. They hence realise inflation with moderately large fields ($\Delta\phi \sim 6\, M_{Pl}$) without saturating the Lyth bound. Control over higher corrections relies in part on tuning underlying microscopic parameters, and in part on intrinsic suppressions. The intrinsic part of control arises as a leftover from an approximate effective shift symmetry at parametrically large volume.

The leading order dynamics of the type IIB Large Volume Scenario is characterised by the interplay between α' and non-perturbative effects which fix the overall volume and all local blow-up modes leaving (in general) several flat directions. We showed [7] that, in an arbitrary Calabi–Yau compactification with at least one blow-up mode resolving a point-like singularity, any remaining flat directions can be lifted at sub-leading order by the inclusions of higher derivative α' corrections. We also focused on simple fibred cases with one remaining flat direction which can behave as an inflaton if its potential is generated by both higher derivative α' and winding loop corrections. Natural values of the underlying parameters give a spectral index in agreement with observational data and a tensor-to-scalar ratio of order $r = 0.01$ which could be observed by forthcoming CMB experiments. Dangerous corrections from higher dimensional operators are suppressed due to the presence of an approximate non-compact shift symmetry [7].

These fibre inflation models [8] are built in a specific string theory construction based on the large volume scenario that produces an inflationary plateau. We outlined its relation to α-attractor models for inflation, with the cosmological sector originating from certain string theory corrections leading to $\alpha = 2$ and $\alpha = 1/2$ [9]. Above a certain field range, the steepening effect of higher-order corrections leads first to the breakdown of single-field slow-roll and after that to the onset of 2-field dynamics: the overall volume of the extra dimensions starts to participate in the effective dynamics. Finally, we proposed effective supergravity models of fibre inflation based on an $\overline{D3}$ uplift term with a nilpotent superfield. Specific moduli dependent $\overline{D3}$ induced geometries lead to cosmological fibre models but have in addition a de Sitter minimum exit. These supergravity models motivated by fibre inflation are relatively simple, stabilize the axions and disentangle the Hubble parameter from supersymmetry breaking.

We also discussed how α-attractors [10] may generalize to truly multi-field situations including the open-string moduli sector of D-branes [11]. We started the discussion from the observation, that a second order pole in the scalar kinetic term can lead to a class of inflation models with universal predictions referred to as pole inflation or α-attractors. While this kinetic structure is ubiquitous in supergravity effective field theories, realizing a consistent UV complete model in e.g. string theory is a non-trivial task. For one, one expects quantum corrections arising in the vicinity of the pole which may spoil the typical attractor dynamics.

As a conservative estimate of the range of validity of supergravity models of pole inflation we employ the weak gravity conjecture (WGC) [12]. We found that this constrains the accessible part of the inflationary plateau by limiting the decay constant of the axion partner. For the original single complex field models, the WGC does not even allow the inflaton to reach the inflationary plateau region. We proposed addressing these problems by evoking the assistance of N scalar fields from the open string moduli [11]. This improves radiative control by reducing the required range of each individual field. Furthermore, it relaxes the WGC bound allowing to inflate on the plateau, although remaining at finite distance from the pole. Finally, we outlined steps towards an embedding of pole N-flation in type IIB string theory on fibred Calabi–Yau manifolds.

Finally, we connected the structure and phenomenology of fibre inflation as string theory versions of α-attractors to the data from CMB observations. In particular, the Planck satellite may have observed a lack of power on large scales ($\ell < 40$). We argued that this putative feature can be explained by a phase of fast roll at the onset of inflation [13]. We showed that in the context of single field models what is required is an asymmetric inflection point model of which fibre inflation is a string motivated example. We studied the ability of fibre inflation to generate a suppression of the CMB 2-point function power at low l, finding that the potential derived from string loops is not steep enough for this purpose. We introduced a steeper contribution to the potential, that dominates away from the inflationary region, and show that if properly tuned it can indeed lead to a spectrum with lack of power at large scales.

We now move to the discussion of axion fields arising from the higher-dimensional p-form gauge fields of string theory as inflaton candidates. Two relevant classes of such models involve either an axion decay constant alignment mechanism for a few axions [14], or monodromy extending the field range of the single axion [15–17]. Such extensions of the axion field range are necessary, as there are no known cases of weakly coupled string theories with axions acquiring a super-Planckian axion decay constant (and hence super-Planckian field range).

We proposed a new field theory mechanism for generating an effective trans-Planckian decay constant from sub-Planckian ones [18]. Using the minimal two axions and a hierarchy between two axion decay constants is sufficient for realizing inflation through non-perturbative effects only and with minimal tuning. The inflationary motion is kept entirely within a sub-Planckian domain. We outlined possible strategies of embedding the model in a string theory setup.

Moving from axion decay constant hierarchies to alignment, we provided type IIB string embeddings of two axion variants of natural inflation [19]. We used a combination of RR 2-form axions as the inflaton field and had its potential generated by non perturbative effects in the superpotential. Besides giving rise to the inflation, the models developed took into account the stabilization of the compact space, both in the scenario by Kachru, Kallosh, Linde and Trivedi (KKLT) [20] and the LVS regime, an essential condition for any semi-realistic model of string inflation.

Flux couplings to string theory axions yield super-Planckian field ranges along which the axion potential energy grows. At the same time, other aspects of the physics remain essentially unchanged along these large displacements, respecting a discrete shift symmetry with a sub-Planckian period. We presented new classes of specific models of monodromy inflation, with monomial potentials $\mu^{4-p}\phi^p$ [21]. A key simplification in these models is that the inflaton potential energy plays a leading role in moduli stabilization during inflation. The resulting inflaton-dependent shifts in the moduli fields lead to an effective flattening of the inflaton potential, i.e. a reduction of the exponent from a fiducial value p_0 to $p < p_0$. We focused on examples arising in compactifications of type IIB string theory on products of tori or Riemann surfaces, where the inflaton descends from the NS–NS two-form potential B_2, with monodromy induced by a coupling to the R–R field strength F_1. In this setting we exhibited models with $p = 2/3, 4/3, 2$, and 3, corresponding to predictions for the tensor-to-scalar ratio of $r \approx 0.04, 0.09, 0.13$, and 0.2, respectively. Using mirror symmetry, we also motivated a second class of examples with the role of the axions played by the real parts of complex structure moduli, with fluxes inducing monodromy.

In this scenario, we also studied the pattern of oscillations in the primordial power spectrum in axion monodromy inflation [22], accounting for drifts in the oscillation period that can be important for comparing to cosmological data [23]. In these models the potential energy has a monomial form over a super-Planckian field range, with superimposed modulations whose size is model-dependent. The amplitude and frequency of the modulations are set by the expectation values of moduli fields. We showed that during the course of inflation, the diminishing energy density can induce slow adjustments of the moduli, changing the modulations. We provided templates capturing the effects of drifting moduli, as well as drifts arising in effective field theory models based on softly broken discrete shift symmetries, and we estimated the precision required to detect a drifting period. A non-drifting template suffices over a wide range of parameters, but for the highest frequencies of interest, or for sufficiently strong drift, it is necessary to include parameters characterizing the change in frequency over the e-folds visible in the CMB. We used these templates to perform a preliminary search for drifting oscillations in a part of the parameter space in the Planck nominal mission data.

We now move to analyzing questions of backreaction from stabilized moduli fields on the mechanism of axion monodromy inflation. For this purpose, we start with analyzing the interplay between Kähler moduli stabilization and chaotic inflation in string theory based supergravity models [24]. While heavy moduli decouple from inflation in the supersymmetric limit, supersymmetry breaking generically introduces non-decoupling effects. These lead to inflation driven by a soft mass term, $m_\varphi^2 \sim m m_{3/2}$, where m is a supersymmetric mass parameter. This scenario needs no stabilizer field, but the stability of the moduli during inflation imposes a large supersymmetry breaking scale, $m_{3/2} \gg H$, and a careful choice of initial conditions. This iss illustrated in three prominent examples of moduli stabilization: KKLT stabilization, Kähler Uplifting, and the Large Volume Scenario. Remarkably, all models have a universal effective inflaton potential which is flattened compared to quadratic inflation. Hence, they share universal predictions for the CMB observables, in particular a lower bound on the tensor-to-scalar ratio, $r \gtrsim 0.05$.

Next, we address questions concerning the build-up of 3-brane and 5-brane charge in models of axion monodromy built in warped double-throat geometries. We constructed a simple explicit local geometry providing a 'bifid throat' for 5-brane axion monodromy [25]. A bifid throat is a throat that splits into two daughter throats in the IR, containing a homologous 2-cycle family reaching down into each daughter throat. Our example consists of a deformed $\mathbb{Z}_3 \times \mathbb{Z}_2$ orbifold of the conifold, which provides us with an explicit holographic dual of the bifid throat including D3-branes and fractional 5-branes at the toric singularities of our setup. Having the holographic description in terms of the dual gauge theory allowed us to address the effect of 5-brane-antibrane pair backreaction including the warping effects. This leads to the size of the backreaction being small and controllable after imposing proper normalization of the inflaton potential and hence the warping scales.

Based on these explicit double-throat geometries, we presented a particularly simple model of axion monodromy [26]: Our axion is the lowest-lying KK-mode of the RR-2-form-potential C_2 in the standard Klebanov-Strassler throat. One can think of this inflaton candidate as being defined by the integral of C_2 over the S^2 cycle of the throat. It obtains an exponentially small mass from the IR-region in which the S^2 shrinks to zero size both with respect to the Planck scale and the mass scale of local modes of the throat. Crucially, the S^2 cycle has to be shared between two throats, such that the second locus where the S^2 shrinks is also in a warped region. Well-known problems like the potentially dangerous back-reaction of brane/antibrane pairs and explicit supersymmetry breaking are not present in our scenario. However, the inflaton back-reaction starts to deform the geometry strongly once the field excursion approaches the Planck scale. We derived the system of differential equations required to treat this effect quantitatively. We find it interesting that such a simple and explicit stringy monodromy model allows an originally sub-Planckian axion to go through many periods with full quantitative control before back-reaction becomes strong. Also, the mere existence of our ultra-light throat mode (with double exponentially suppressed mass) is noteworthy.

Finally, we return the impact of general quantum gravity constraints such as the weak gravity conjecture in the context of axion monodromy inflation. Axions with broken discrete shift symmetry (axion monodromy) have played a central role both in the discussion of inflation and the 'relaxion' approach to the hierarchy problem. We suggested a very minimalist way to constrain such models by the weak gravity conjecture for domain walls [27]: While the electric side of the conjecture is always satisfied if the cosine-oscillations of the axion potential are sufficiently small, the magnetic side imposes a cutoff, $\Lambda^3 \sim mfM_{pl}$, independent of the height of these 'wiggles'. We compared our approach with the recent related proposal by Ibañez, Montero, Uranga and Valenzuela [28]. We also discussed the non-trivial question which version, if any, of the weak gravity conjecture for domain walls should hold. In particular, we showed that string compactifications with branes of different dimensions wrapped on different cycles lead to a 'geometric weak gravity conjecture' relating volumes of cycles, norms of corresponding forms and the volume of the compact space. Imposing this 'geometric conjecture', e.g. on the basis of the more widely accepted weak gravity conjecture for particles, provides at least some support for the (electric and magnetic) conjecture for domain walls.

2 Consequences of multi-field inflation in string theory inspired random potentials

We determined the frequency of regions of small-field inflation in the Wigner landscape [29, 30] as an approximation to random supergravities/type IIB flux compactifications [31]. We showed that small-field inflation occurs exponentially more often than large-field inflation. The power of primordial gravitational waves from inflation is generically tied to the scale of inflation. As for small-field models this is below observational reach, their exponential enhancement seems to indicate a tendency towards small tensor-to-scalar ratio r. However, cosmologically viable inflationary regions must provide for a successful exit from inflation into a meta-stable dS minimum. Hence there is a need to determine the 'graceful exit likelihood' before any statement about the statistically expected level of tensor modes r is possible.

In order to determine this 'graceful exit likelihood' we needed to describe the transition probability for a non-equilibrium ensemble of Wigner matrices to relax back to its equilibrium configuration via the stochastic process of Dyson Brownian Motion. We presented an analytic method for calculating the transition probability between two random Gaussian matrices with given eigenvalue spectra in the context of Dyson Brownian motion [32]. We showed that in the Coulomb gas language, in large N limit, memory of the initial state is preserved in the form of a universal linear potential acting on the eigenvalues. We computed the likelihood of any given transition as a function of time, showing that as memory of the initial state is lost, transition probabilities converge to those of the static ensemble.

We then applied this general result to small-field inflation in a Wigner random landscape. For this purpose, we developed a stochastic description of small-field inflationary histories with a graceful exit in a random potential whose Hessian is a Gaussian random matrix as a model of the unstructured part of the string landscape [33]. The dynamical evolution in such a random potential from a small-field inflation region towards a viable late-time de Sitter (dS) minimum maps to the dynamics of Dyson Brownian motion describing the relaxation of non-equilibrium eigenvalue spectra in random matrix theory. We analytically computed the relaxation probability in a saddle point approximation of the partition function of the eigenvalue distribution of the Wigner ensemble describing the mass matrices of the critical points. When applied to small-field inflation in the landscape, this leads to an exponentially strong bias against small-field ranges and an upper bound $N \ll 10$ on the number of light fields N participating during inflation from the non-observation of negative spatial curvature.

Moving beyond the inflationary dynamics, we discussed the structure of the phenomenological consequences such as the CMB observables in multifield random landscape inflation. This leads us to rather strong large-N universality governing the CMB observables. For this purpose, we constructed ensembles of random scalar potentials for N_f interacting scalar fields using non-equilibrium random matrix theory, and used these to study the generation of observables during small-field inflation [34]. For $N_f = \mathcal{O}(\text{few})$, these heavily featured scalar potentials give rise to power spectra that are highly non-linear, at odds with observations. For $N_f \gg 1$, the super-horizon evolution of the perturbations is generically substantial, yet the power spectra simplify considerably and become more predictive, with most realisations being well approximated by a linear power spectrum. This provides proof of principle that complex inflationary physics can give rise to simple emergent power spectra. We explained how these results can be understood in terms of large N_f universality of random matrix theory.

Extending this analysis, we studied inflation in models with many interacting fields subject to randomly generated scalar potentials. We used methods from non-equilibrium random matrix theory to construct the potentials and an adaption of the 'transport method' to evolve the two-point correlators during inflation. This construction allows for an explicit study of models with up to 100 interacting fields supporting a period of 'approximately saddle-point' inflation [35]. We determined the statistical predictions for observables by generating over 30,000 models with 2–100 fields supporting at least 60 efolds of inflation. These studies lead us to seven lessons: i) Many-field inflation is not single-field inflation, ii) The larger the number of fields, the simpler and sharper the predictions, iii) Planck compatibility is not rare, but future experiments may rule out this class of models, iv) The smoother the potentials, the sharper the predictions, v) Hyperparameters can transition from stiff to sloppy, vi) Despite tachyons, isocurvature can decay, vii) Eigenvalue repulsion drives the predictions. We conclude that many of the 'generic predictions' of single-field inflation can be emergent features of complex inflation models.

3 Pole inflation, $f(R)$-gravity, and inflationary plateaus

Our next topic deals with the study of α-attractor/pole inflation models and their connection to $f(R)$ models of inflation, mainly using the bottom-up 4D effective description.

We studied a model of inflation with terms quadratic and logarithmic in the Ricci scalar, where the gravitational action is $f(R) = R + \alpha R^2 + \beta R^2 \ln R$ [36]. These terms are expected to arise from one loop corrections involving matter fields in curved space-time. The spectral index n_s and the tensor to scalar ratio yield $10^{-4} \lesssim r \lesssim 0.03$ and $0.94 \lesssim n_s \lesssim 0.99$, i.e. r is an order of magnitude bigger or smaller than the original Starobinsky model which predicted $r \sim 10^{-3}$. Further enhancement of r gives a scale invariant $n_s \sim 1$ or higher. Other inflationary observables are $dn_s/d\ln k \gtrsim -5.2 \times 10^{-4}$, $\mu \lesssim 2.1 \times 10^{-8}$, $y \lesssim 2.6 \times 10^{-9}$.

We discussed the general structure and observational consequences of some of the simplest versions of chaotic inflation in supergravity in relation to the data by Planck 2013 and BICEP2 [37]. We showed that minimal modifications to the simplest quadratic potential are sufficient to provide a controllable tensor mode signal and a suppression of CMB power at large angular scales.

Inflationary attractors predict the spectral index and tensor-to-scalar ratio to take specific values that are consistent with Planck. An example is the universal attractor for models with a generalized non-minimal coupling, leading to Starobinsky inflation. We demonstrated that it also predicts a specific relation between the amplitude of the power spectrum and the number of e-folds [38]. The length and height of the inflationary plateau are related via the non-minimal coupling: in a wide variety of examples, the observed power normalization leads to at least 55 flat e-foldings. Prior to this phase, the inflationary predictions vary and can account for the observational indications of power loss at large angular scales.

Motivated by UV realisations of Starobinsky-like inflation models, we studied generic exponential plateau-like potentials to understand whether an exact $f(R)$-formulation may still be obtained when the asymptotic shift-symmetry of the potential is broken for larger field values [39]. Potentials which break the shift symmetry with rising exponentials at large field values only allow for corresponding $f(R)$-descriptions with a leading order term R^n with $1 < n < 2$, regardless of whether the duality is exact or approximate. The R^2-term survives as part of a series expansion of the function $f(R)$ and thus cannot maintain a plateau for all field values. We further found a lean and instructive way to obtain a function $f(R)$ describing $m^2\phi^2$-inflation which breaks the shift symmetry with a monomial, and corresponds to effectively logarithmic corrections to an $R + R^2$ model. These examples emphasise that higher order terms in $f(R)$-theory may not be neglected if they are present at all. Additionally, we related the function $f(R)$ corresponding to chaotic inflation to a more general Jordan frame set-up. In addition, we considered $f(R)$-duals of two given UV examples, both from supergravity and string theory. Finally, we outlined the CMB phenomenology of these models which show effects of power suppression at low-ℓ.

We also studied universality properties of inflationary models with a singular non-canonical kinetic term: a Laurent expansion of the kinetic function translates into a potential with a nearly shift-symmetric plateau in canonical fields. The shift symmetry can be broken at large field values by including higher-order poles, which need to be hierarchically suppressed in order not to spoil the inflationary plateau. The resulting corrections to the inflationary dynamics and predictions were shown to be universal at lowest order and possibly induce power loss at large angular scales [40]. At lowest order there are no corrections from a pole of just one order higher and we argued that this phenomenon is related to the well-known extended no-scale structure arising in string theory scenarios. We also outlined which other corrections may arise from string loop effects.

A generic non-minimal coupling can push any higher-order terms of the scalar potential sufficiently far out in field space to yield observationally viable plateau inflation. We provided analytic and numerical evidence that this generically happens for a non-minimal coupling strength

ξ of the order N_e^2 [41]. In this regime, the non-minimally coupled field is sub-Planckian during inflation and is thus protected from most higher-order terms. For larger values of ξ, the inflationary predictions converge towards the sweet spot of PLANCK. The latter includes $\xi \simeq 10^4$ obtained from CMB normalization arguments, thus providing a natural explanation for the inflationary observables measured.

4 Phenomenological consequences of features before and during inflation

In this section we analyze the impact of the features in the inflaton kinetic term or structure in the inflationary scalar potential, either right before the observable $\mathcal{O}(60)$ e-folds of slow-roll, or as periodic features along the scalar potential, on the CMB phenomenology, such as the 2-point or 3-point correlation functions ('non-Gaussianity') of the curvature perturbations. We begin with two observations, which show degeneracies in the shape function of non-Gaussianity between DBI inflation [42] and axion monodromy with a spectrum of periodic corrections, as well the curvature perturbation 2-point function of two suitably related models of canonical and non-canonical inflation.

As an example of the first kind, we discussed the effect of superimposing multiple sources of resonant non-Gaussianity, which arise for instance in models of axion inflation [43]. The resulting sum of oscillating shape contributions can be used to "Fourier synthesize" different non-oscillating shapes in the bispectrum. As an example we reproduced an approximately equilateral shape from the superposition of $\mathcal{O}(10)$ oscillatory contributions with resonant shape. This implies a possible degeneracy between the equilateral-type non-Gaussianity typical of models with non-canonical kinetic terms, such as DBI inflation, and an equilateral-type shape arising from a superposition of resonant-type contributions in theories with canonical kinetic terms. The absence of oscillations in the 2-point function together with the structure of the resonant N-point functions, imply that detection of equilateral non-Gaussianity at a level greater than the PLANCK sensitivity of $f_{NL} \sim \mathcal{O}(5)$ will rule out a resonant origin. We commented on the questions arising from possible embeddings of this idea in a string theory setting.

Next, we looked for potential observational degeneracies between canonical and non-canonical models of inflation of a single field ϕ [44]. Non-canonical inflationary models are characterized by higher than linear powers of the standard kinetic term X in the effective Lagrangian $p(X, \phi)$ and arise for instance in the context of the Dirac–Born–Infeld (DBI) action in string theory. An on-shell transformation was introduced that transforms non-canonical inflationary theories to theories with a canonical kinetic term. The 2-point function observables of the original non-canonical theory and its canonical transform were found to match in the case of DBI inflation.

We then moved towards features of the inflationary scalar potential such as 'steepening' just outside the field range corresponding to the last observable $\simeq 60$ e-folds of slow-roll. We showed that models of 'just enough' inflation, where the slow-roll evolution lasted only 50–60 e-foldings, feature modifications of the CMB power spectrum at large angular scales [45]. We performed a systematic and model-independent analysis of any possible non-slow-roll background evolution prior to the final stage of slow-roll inflation. We found a high degree of universality since most common backgrounds like fast-roll evolution, matter or radiation-dominance give rise to a power loss at large angular scales and a peak together with an oscillatory behavior at scales around the value of the Hubble parameter at the beginning of slow-roll inflation. Depending on the value of the equation of state parameter, different pre-inflationary epochs lead instead to an enhancement of power at low-ℓ, and so seem disfavored by the observational hints for a lack of CMB power at $\ell \lesssim 40$. We also commented on the importance of initial conditions and the possibility to have multiple pre-inflationary stages.

Besides features in the scalar potential itself, the presence of a spectrum of 'spectator' scalar fields during inflation can significantly modify the properties of the curvature perturbation n-point functions. We presented a complete framework for numerical calculation of the power spectrum and bispectrum in canonical inflation with an arbitrary number of light or heavy fields [46]. Our method includes all relevant effects at tree-level in the loop expansion, including (i) interference between growing and decaying modes near horizon exit; (ii) correlation and coupling between species near horizon exit and on super-horizon scales; (iii) contributions from mass terms; and (iv) all contributions from coupling to gravity. We tracked the evolution of each correlation function from the vacuum state through horizon exit and the superhorizon regime, with no need to match quantum and classical parts of the calculation; when integrated, our approach corresponds exactly with the tree-level Schwinger or 'in-in' formulation of quantum field theory. We gave the equations necessary to evolve all two- and three-point correlation functions together with suitable initial conditions. The final formalism is suitable to compute the amplitude, shape, and scale dependence of the bispectrum in models with $|f_{NL}|$ of order unity or less, which are a target for galaxy surveys such as Euclid, DESI and LSST. As an illustration we applied our framework to a number of examples, obtaining quantitatively accurate predictions for their bispectra.

We also discussed a particular source of deviations from standard slow-roll inflation which arise when the asymptotic past vacuum state of quantum fields during inflation itself gets modified. When modeling inflaton fluctuations as a free quantum scalar field, the initial vacuum is conventionally imposed at the infinite past. This is called the Bunch–Davies (BD) vacuum. If however an asymptotically Minkowskian past does not exist, this requires modifications. We derived corrections to the scalar spectral index n_s and the tensor tilt n_t descending from arbitrary mixed states or from explicit non-BD initial conditions [47]. The former may stem from some pre-inflationary background and can redshift away whereas the latter are induced by a time-like hypersurface parametrizing a physical cut-off. In both cases, we found that corrections scale in parts or fully as $\mathcal{O}(\epsilon)$ where ϵ is the first slow-roll parameter. The precise observational footprint is hence dependent on the model driving inflation. Further, we showed how the inflationary consistency relation is altered. We thus provided an analytic handle on possible high scale or pre-inflationary physics.

5 False-vacuum tunneling and its consequences for the initial conditions of inflation

The string landscape relies on tunneling processes as a cosmological dynamics to physically populate its set of discrete meta-stable vacua. One such process is Coleman–De Luccia (CDL) tunneling in QFT on curved space-time [48]. As this instanton is ubiquitous (though not always the dominant tunneling instanton) in the string landscape, we analyzed its consequence for the initial conditions of a stage of slow-roll inflation taking place after tunneling inside a bubble of lowered vacuum energy formed by the CDL process.

At first, we showed the absence of the usual parametrically large overshoot problem of small-field inflation if initiated by a CDL tunneling transition from an earlier vacuum in the limit of small inflationary scale compared to the tunneling scale [49] building on prior results of [50]. For low-power monomial exit potentials $V(\phi) \sim \phi^n$, $n < 4$, we derived an expression for the amount of overshoot. This is bounded from above by the width of the steep barrier traversed after emerging from tunneling and before reaching a slow-roll region of the potential. For $n \geq 4$ we showed that overshooting is entirely absent. We extended this result through binomials to a general potential written as a series expansion, and to the case of arbitrary finite initial speed of the inflaton. This places the phase space of initial conditions for small-field and large-field inflation on the same footing in a landscape of string theory vacua populated via CDL tunneling.

Next, we presented exact bounce solutions and amplitudes for tunneling in i) a piecewise linear-quartic potential and ii) a piecewise quartic-quartic potential [51]. We cross checked their correctness by comparing with results obtained through the thin-wall approximation and with a piecewise linear-linear potential.

We close this discussion with an analysis of the effects of the kinks in using kinked scalar potential for deriving exact CDL solutions. This is due to the fact, that Coleman tunneling in a general scalar potential with two non-degenerate minima is known to have an approximation in terms of a piecewise linear triangular-shaped potential with sharp 'kinks' at the place of the local minima. This approximate potential has a regime where the existence of the bounce solution needs the scalar field to 'wait' for some amount of Euclidean time at one of the 'kinks'. We discussed under which conditions a kink approximation of locally smooth 'cap' regions provides a good estimate for the bounce action [52].

6 From slow-rolling scalar fields to the EW vacuum – implications of inflaton-Higgs portal couplings and string theory constraints

Models of axions with large field ranges in string theory based on axion monodromy may provide both for models of inflation including portal-like couplings to the Standard Model (SM) Higgs sector, and relaxation-like slow-roll dynamics which may explain the electroweak (EW) hierarchy [53]. We analyzed phenomenological consequences of such setups for the stability of the EW vacuum as well as possible UV completion of Higgs relaxation dynamics in string theory.

Within the Standard Model, the Higgs and top quark data favor metastability of the electroweak vacuum, although the uncertainties are still significant. The true vacuum is many orders of magnitude deeper than ours and the barrier separating the two is tiny compared to the depth of the well. This raises a cosmological question: how did the Higgs field get trapped in the shallow minimum and why did it stay there during inflation? The Higgs initial conditions before inflation must be fine-tuned to about one part in 10^8 in order for the Higgs field to end up in the right vacuum. We show that these problems can be resolved if there is a small positive coupling between the Higgs and the inflaton [54].

We examined the relaxion mechanism [53] in string theory. An essential feature is that an axion winds over $N \gg 1$ fundamental periods. In string theory realizations via axion monodromy, this winding number corresponds to a physical charge carried by branes or fluxes. We showed that this monodromy charge backreacts on the compact space, ruining the structure of the relaxion action. In particular, the barriers generated by strong gauge dynamics have height $\propto e^{-N}$, so the relaxion does not stop when the Higgs acquires a vev [55]. Backreaction of monodromy charge can therefore spoil the relaxion mechanism.

7 Moduli stabilization and de Sitter vacua in string theory

Here we report on a series of works, which established both a very general necessary condition for de Sitter (dS) vacua in 4D $\mathcal{N} = 1$ supergravity, and derived explicitly sufficient conditions from the leading-order quantum corrected Kähler moduli spaces in the context of a class of moduli stabilized Calabi–Yau compactifications of type IIB and heterotic string theory.

We started by performing a general analysis on the possibility of obtaining metastable vacua with spontaneously broken N=1 supersymmetry and non-negative cosmological constant in the moduli sector of string models [56]. More specifically, we studied the condition under which the scalar partners of the Goldstino are non-tachyonic, which depends only on the Kähler potential. This condition is not only necessary but also sufficient, in the sense that all of the other scalar fields can be given arbitrarily large positive square masses if the superpotential is suitably tuned. We considered both heterotic and orientifold string compactifications in the large-volume limit and showed that the no-scale property shared by these models severely restricts the allowed values for the 'sGoldstino' masses in the superpotential parameter space. We found that a positive mass term may be achieved only for certain types of compactifications and specific Goldstino directions. Additionally, we showed how sub-leading corrections to the Kähler potential which break the no-scale property may allow to lift these masses.

Next, we extended our discussion of necessary conditions for dS vacua in supergravity to the related case of slow-roll inflation. For this purpose, we performed a general algebraic analysis on the possibility of realizing slow-roll inflation in the moduli sector of string models [57]. This problem turned out to be very closely related to the characterization of models admitting metastable vacua with non-negative cosmological constant. In fact, we showed that the condition for the existence of viable inflationary trajectories is a deformation of the condition for the existence of metastable de Sitter vacua. This condition depends on the ratio between the scale of inflation and the gravitino mass and becomes stronger as this parameter grows. After performing a general study within arbitrary supergravity models, we analyzed the implications of our results in several examples. More concretely, in the case of heterotic and orientifold string compactifications on a Calabi–Yau in the large volume limit we showed that there may exist fully viable models, allowing both for inflation and stabilization. Additionally, we showed that sub-leading corrections breaking the no-scale property shared by these models always allow for slow-roll inflation but with an inflationary scale suppressed with respect to the gravitino scale. A scale of inflation larger than the gravitino scale can also be achieved under more restrictive circumstances and only for certain types of compactifications.

After studying the necessary conditions for dS vacua in 4D $\mathcal{N} = 1$ supergravity, we generalized the analysis to extended supersymmetry. Hence, we studied the stability of vacua with spontaneously broken supersymmetry in N=2 supergravity theories with only hypermultiplets [58]. Focusing on the projection of the scalar mass matrix along the sGoldstino directions, we were able to derive a universal upper bound on the lowest mass eigenvalue. This bound only depends on the gravitino mass and the cosmological constant, but not on the details of the quaternionic manifold spanned by the scalar fields. Comparing with the Breitenlohner–Freedman bound showed that metastability requires the cosmological constant to be smaller than a certain negative critical value. Therefore, only AdS vacua with a sufficiently negative cosmological constant can be stable, while Minkowski and dS vacua necessarily have a tachyonic direction.

In a first step towards handling dS vacua in string theory, we developed a method for constructing metastable de Sitter vacua in N=1 supergravity models describing the no-scale volume moduli sector of Calabi–Yau string compactifications [59]. We considered both heterotic and orientifold models. Our main guideline was the necessary condition for the existence of metastable vacua coming from the Goldstino multiplet, which constrains the allowed scalar geometries and supersymmetry-breaking directions. In the simplest non-trivial case where the volume is controlled by two moduli, this condition simplifies and turns out to be fully characterised by the intersection numbers of the Calabi–Yau manifold. We analyzed this case in detail and showed that once the metastability condition is satisfied it is possible to reconstruct in a systematic way the local form of the superpotential that is needed to stabilize all the fields. We applied this procedure to construct some examples of models where the superpotential takes a realistic form allowed by flux backgrounds and gaugino condensation effects, for which a viable vacuum arises without the need of invoking corrections to the Kähler potential breaking the no-scale property or uplifting terms. We also discussed the prospects of constructing potentially realistic models along these lines.

Based on this analysis of necessary conditions for dS vacua in supergravity, we moved on to construct two classes of explicit dS vacua based on Calabi–Yau compactifications of type IIB and of heterotic string theory. The structure of the leading quantum corrections to the Kähler moduli space of these string compactifications played a crucial role here.

For the first class of dS vacua, we derived a sufficient condition for realizing them within type IIB string theory flux compactifications with spontaneously broken supersymmetry [60]. There are a number of 'lamp post' constructions of de Sitter vacua in type IIB string theory and supergravity. We showed that one of them – the method of 'Kähler uplifting' by F-terms from an interplay between non-perturbative effects and the leading α'-correction [2,3] – allows for a more general parametric understanding of the existence of de Sitter vacua. The result is a condition on the values of the flux induced superpotential and the topological data of the Calabi–Yau compactification, which guarantees the existence of a meta-stable de Sitter vacuum if met. Our analysis explicitly included the stabilization of all moduli, i.e. the Kähler, dilaton and complex structure moduli, by the interplay of the leading perturbative and non-perturbative effects at parametrically large volume.

Next, we constructed an explicit example of a de Sitter vacuum in type IIB string theory that realizes the proposal of Kähler uplifting [61]. As the large volume limit in this method depends on the rank of the largest condensing gauge group we carried out a scan of gauge group ranks over the Kreuzer–Skarke set of toric Calabi–Yau three-folds. We found large numbers of models with the largest gauge group factor easily exceeding a rank of one hundred. We constructed a global model with Kähler uplifting on a two-parameter model on $\mathbb{CP}^4_{11169}$, by an explicit analysis from both the type IIB and F-theory point of view. The explicitness of the construction lies in the realization of a D7 brane configuration, gauge flux and RR and NS flux choices, such that all known consistency conditions are met and the geometric moduli are stabilized in a metastable de Sitter vacuum with spontaneous GUT scale supersymmetry breaking driven by an F-term of the Kähler moduli.

We then studied in detail the exhaustive construction method of all flux vacua of the Green–Plesser invariant subsector of a Calabi–Yau consistent with tadpole constraints. To do so, we explicitly constructed all supersymmetric flux vacua of a particular Calabi–Yau compactification of type IIB string theory for a small number of flux carrying cycles and a given D3-brane tadpole [62]. The analysis was performed in the large complex structure region by using the polynomial homotopy continuation method, which allows to find all stationary points of the polynomial equations that characterize the supersymmetric vacuum solutions. The number of vacua as a function of the D3 tadpole is in agreement with statistical studies in the literature. We calculated the available tuning of the cosmological constant from fluxes and extrapolate to scenarios with a larger number of flux carrying cycles. We also verified the range of scales for the moduli and gravitino masses found for a single explicit flux choice giving a Kähler uplifted de Sitter vacuum in the same construction.

We also constructed a class of dS vacua in the context of the heterotic $E_8 \times E_8'$ string compactified on Calabi–Yau manifolds or their orbifold limits. For this purpose, we performed a systematic analysis of moduli stabilization for weakly coupled heterotic string theory compactified on manifolds which are Calabi–Yau up to α'-effects [63]. We reviewed how to fix all geometric and bundle moduli in a supersymmetric way by fractional fluxes, the requirement of a holomorphic gauge bundle, and D-terms [64], using the addition of higher order perturbative contributions to W, non-perturbative and threshold effects. We then showed that α'-corrections to K lead to new stable Minkowski (or dS) vacua where the complex structure moduli Z and the dilaton are fixed supersymmetrically, while the fixing of the Kähler moduli at a lower scale leads to spontaneous SUSY breaking. The minimum lies at moderately large volumes of all geometric moduli, at a perturbative string coupling and at the right value of the GUT coupling. We also gave a dynamical derivation of anisotropic compactifications which allow for gauge coupling unification around 10^16 GeV. The gravitino mass can be anywhere between the GUT and TeV scale depending on the fixing of the Z-moduli. In general, these are fixed by turning on background fluxes, leading to a gravitino mass around the GUT scale since the heterotic 3-form flux does not contain enough freedom to tune W to small values. Moreover accommodating the observed value of the cosmological constant (CC) was a challenge. Low-energy SUSY could instead be obtained in particular situations where the gauge bundle is holomorphic only at a point-like sub-locus of Z-moduli space, or where the number of Z-moduli is small (like orbifold models), since in these cases one may fix all moduli without turning on any quantized flux. However tuning the CC is even more of a challenge in these cases.

The above heterotic de Sitter vacua utilize the presence of certain quantum corrections to the Kähler moduli sector at $\mathcal{O}(\alpha'^2)$. A similar type of corrections appears in the type IIB context as well. We analyzed this new $\mathcal{N} = 1$ string tree level correction at $\mathcal{O}(\alpha'^2)$ to the Kähler potential of the volume moduli of type IIB Calabi–Yau flux compactification and its impact on the moduli potential [65]. We found that it imposes a strong lower bound the Calabi–Yau volume in the Large Volume Scenario of moduli stabilization. For KKLT-like scenarios we found that consistency of the action imposes an upper bound on the flux superpotential $|W_0| \lesssim 10^{-3}$, while parametrically controlled survival of the KKLT minimum needs extreme tuning of W_0 close to zero. We also analyzed the Kähler uplifting mechanism showing that it can operate on Calabi–Yau manifolds where the new correction is present and dominated by the 4-cycle controlling the overall volume if the volume is stabilized at values $\mathcal{V} \gtrsim 10^3$. We discussed the phenomenological implication of these bounds on $\mathcal{V}$ in the various scenarios.

In a next step we performed a thorough analysis of the higher-derivative corrections to the Kähler moduli sector arising at $\mathcal{O}(\alpha'^3$ in string theory [66]. For this purpose, we started by reviewing the ghost-free four-derivative terms for chiral superfields in $\mathcal{N} = 1$ supersymmetry and supergravity. These terms induce cubic polynomial equations of motion for the chiral auxiliary fields and correct the scalar potential. We discussed the different solutions and argue that only one of them is consistent with the principles of effective field theory. Special attention was paid to the corrections along flat directions which can be stabilized or destabilized by the higher-derivative terms. We then computed these higher-derivative terms explicitly for the type IIB string compactified on a Calabi–Yau orientifold with fluxes via Kaluza–Klein reducing the $(\alpha')^3 R^4$ corrections in ten dimensions for the respective $\mathcal{N}=1$ Kähler moduli sector. We proved that together with flux and the known $(\alpha')^3$-corrections [67] the higher-derivative term stabilizes all Calabi–Yau manifolds with positive Euler number, provided the sign of the new correction is negative.

Based on these results, a full matching between the structure of the 10D $\mathcal{O}(\alpha'^3)$ R^4 correction and the 4D effective higher superspace derivative terms requires knowledge of the full structure of such 4D higher superspace derivative operators allowed in supergravity. The supersymmetric completion of such higher-derivative operators often requires introducing corrections to the scalar potential. Hence, we studied these corrections systematically in the context of theories with $\mathcal{N}=1$ global and local supersymmetry in $D=4$ focusing on ungauged chiral multiplets [68]. In globally supersymmetric theories the most general off-shell effective scalar potential can be captured by a dependence of the Kähler potential on additional chiral superfields. For supergravity we found a much richer structure of possible corrections. In this context we classified the leading order and next-to-leading order superspace derivative operators and determine the component forms of a subclass thereof. Moreover, we presented an algorithm that simplifies the computation of the respective on-shell action. As particular applications we studied the structure of the supersymmetric vacua for these theories and commented on the form of the corrections to shift-symmetric no-scale models. These results are relevant for the computation of effective actions for string compactifications and, in turn, for moduli stabilization and string inflation.

Models of 4D $\mathcal{N}=1$ supergravity coupled to chiral multiplets with vanishing or positive scalar potential have been denoted as no-scale. Of particular interest in the context of string theory are models which additionally possess a shift-symmetry. In this case there exists a dual description of chiral models in terms of real linear multiplets. We classified all ungauged shift-symmetric no-scale supergravities in both formulations and verified that they match upon dualization [69]. Additionally, we commented on the realizations within effective supergravities descending from string compactifications.

We return to the topic of backreaction, but now in the context of meta-stable dS vacua. The historically first class of dS vacua in string theory relies on using an anti-D3-brane in a warped region of the Calabi–Yau manifold as a tunable source of SUSY breaking and positive vacuum energy on top of supersymmetric AdS vacuum where the volume moduli are stabilized using non-perturbative quantum effects. Using a 10D lift of non-perturbative volume stabilization in type IIB string theory we study the limitations for obtaining de Sitter vacua. Based on this we found that the simplest KKLT vacua with a single Kähler modulus stabilized by a gaugino condensate cannot be uplifted to de Sitter. Rather, the uplift flattens out due to stronger backreaction on the volume modulus than has previously been anticipated, resulting in vacua which are meta-stable and SUSY breaking, but that are always AdS [70]. However, we also showed that setups such as racetrack stabilization can avoid this issue. In these models it is possible to obtain supersymmetric AdS vacua with a cosmological constant that can be tuned to zero while retaining finite moduli stabilization. In this regime, it seems that de Sitter uplifts are possible with negligible backreaction on the internal volume. We exhibited this behavior also from the 10D perspective.

Finally, we come full circle to study the structure of the supersymmetric moduli spaces of $\mathcal{N}=1$ and $\mathcal{N}=2$ supergravity theories in AdS_4 backgrounds [71]. These moduli spaces underlie all of the dS constructions discussed throughout this section. In the $\mathcal{N} = 1$ case, the moduli space cannot be a complex submanifold of the Kähler field space, but is instead real with respect to the inherited complex structure. In $\mathcal{N} = 2$ supergravity the same result holds for the vector multiplet moduli space, while the hypermultiplet moduli space is a Kähler submanifold of the quaternionic-Kähler field space. These findings are in agreement with AdS/CFT considerations.

8 Sequestering as solution to the cosmological constant problem

Stringy solutions to the cosmological constant (CC) problem rely on a variant of Weinberg's anthropic reasoning enabled by a very large landscape of discrete meta-stable dS vacua with varying vacuum energy. The landscape argument draws its strength in part from Weinberg's no-go theorem, which poses a stringent test for any form of adjustment or self-tuning solution to the CC problem. However, subtle non-local modifications of Einstein gravity coupled to shift and scale symmetry arguments similar to those which help protecting inflation models from dangerous quantum corrections may provide avenues for viable 4D models of 'sequestering' of the perturbative contributions to the vacuum energy.

In a series of papers Kaloper and Padilla proposed such a mechanism to sequester standard model vacuum contributions to the cosmological constant, see e.g. [72, 73]. We studied the consequences of embedding their proposal into a fully local quantum theory. In the original work, the bare cosmological constant Λ and a scaling parameter λ are introduced as global fields. We found that in the local case the resulting Lagrangian is that of a spontaneously broken conformal field theory where λ plays the role of the dilaton [74]. A vanishing or a small cosmological constant is thus a consequence of the underlying conformal field theory structure.

Kaloper and Padilla also proposed a mechanism of vacuum energy sequester as a means of protecting the observable cosmological constant from quantum radiative corrections. The original proposal was based on using global Lagrange multipliers, but later a local formulation was provided [73]. Subsequently other interesting claims of a different non-local approach to the cosmological constant problem were made, based again on global Lagrange multipliers. Given this situation, we examined some of these proposals and find their mutual relationship. We explained that the proposals which do not treat the cosmological constant counterterm as a dynamical variable require fine tunings to have acceptable solutions [75]. Furthermore, the counterterm often needs to be retuned at every order in the loop expansion to cancel the radiative corrections to the cosmological constant, just like in standard GR. These observations are an important reminder of just how the proposal of vacuum energy sequester avoids such problems.

9 Large-scale structure, lensing effects and the determination of H_0

In this series of works we discuss the effects which perturbation-induced stochastic luminosity-distance dispersion and gravitational weak lensing have on the precision determination of cosmological parameters such as e.g. H_0 which underlie our current test of models of dark energy or cosmological inflation.

Starting from the luminosity-redshift relation given up to second order in the Poisson gauge, we calculated the effects of the realistic stochastic background of perturbations of the so-called concordance model on the combined light-cone and ensemble average of various functions of the luminosity distance, and on their variance, as functions of redshift [76]. We applied a gauge-invariant light-cone averaging prescription which is free from infrared and ultraviolet divergences, making our results robust with respect to changes of the corresponding cutoffs. Our main conclusions were that such inhomogeneities not only cannot avoid the need for dark energy, but also cannot prevent, in principle, the determination of its parameters down to an accuracy of order $10^{-3} \dots 10^{-5}$, depending on the averaged observable and on the regime considered for the power spectrum. However, taking into account the appropriate corrections arising in the non-linear regime, we predicted an irreducible scatter of the data approaching the 10% level which, for limited statistics, will necessarily limit the attainable precision. The predicted dispersion appears to be in good agreement with current observational estimates of the distance-modulus variance due to Doppler and lensing effects (at low and high redshifts, respectively), and represents a challenge for future precision measurements.

The (absence of detecting) lensing dispersion of Supernovae type Ia (SNIa) can be used as an extremely efficient probe of cosmology. In this example we analyzed its consequences for the primordial power spectrum [77]. The main setback is the knowledge of the power spectrum in the non-linear regime, $1\text{Mpc}^{-1} < k < 10^2 \dots 10^3\text{Mpc}^{-1}$ up to redshift of about unity. By using the lensing dispersion and conservative estimates in this regime of wave numbers, we showed how the current upper bound $\sigma_\mu(z=1) < 0.12$ on existing data gives strong indirect constraints on the primordial power spectrum. The probe extends our handle on the spectrum to a total of 12–15 inflation e-folds. These constraints are so strong that they are already ruling out a large portion of the parameter space allowed by PLANCK for running $\alpha = dn_s/d\ln k$ and running $\beta = d^2 n_s/d\ln k^2$. The bounds follow a linear relation to a very good accuracy. A conservative bound disfavors any enhancement above the line $\beta(k_0) = 0.036 - 0.42\alpha(k_0)$ and a realistic estimate disfavors any enhancement above the line $\beta(k_0) = 0.022 - 0.44\alpha(k_0)$.

Local measurements of the Hubble expansion rate are affected by structures like galaxy clusters or voids. We presented a fully relativistic treatment of this effect, studying how clustering modifies the mean distance (modulus)-redshift relation and its dispersion in a standard ΛCDM universe [78]. The best estimates of the local expansion rate stem from supernova observations at small redshifts ($0.01 < z < 0.1$). It is interesting to compare these local measurements with global fits to data from cosmic microwave background anisotropies. In particular, we argued that cosmic variance (i.e. the effects of the local structure) is of the same order of magnitude as the current observational errors and must be taken into account in local measurements of the Hubble expansion rate.

Probing the primordial power spectrum at small scales is crucial for discerning inflationary models. We demonstrated this necessity by briefly reviewing single small field models that give a detectable gravitational waves signal, thus being degenerate with large field models on CMB scales [79]. A distinct prediction of these small field models is an enhancement of the power spectrum at small scales, lifting up the degeneracy. We proposed a way to detect this enhancement, and more generally, different features in the power spectrum at small scales $1 \lesssim k \lesssim 10^2 \dots 10^3\,\text{Mpc}^{-1}$ by considering the existing data of lensing dispersion in Type Ia supernovae. We showed that for various deviations from the simplest $n_s \simeq 0.96$ the lensing dispersion cuts considerably into the allowed parameter space by PLANCK and constrains the spectrum to smaller scales beyond the reach of other current data sets.

We studied soft limits of correlation functions for the density and velocity fields in the theory of structure formation [80]. First, we re-derived the (resummed) consistency conditions at unequal times using the eikonal approximation. These are solely based on symmetry arguments and are therefore universal. Then, we explore the existence of equal-time relations in the soft limit which, on the other hand, depend on the interplay between soft and hard modes. We scrutinize two approaches in the literature: The time-flow formalism, and a background method where the soft mode is absorbed into a locally curved cosmology. The latter has been used to set up (angular averaged) 'equal-time consistency relations'. We explicitly demonstrated that the time-flow relations and 'equal-time consistency conditions' are only fulfilled at the linear level, and fail at next-to-leading order for an Einstein–de Sitter universe. While applied to the velocities both proposals break down beyond leading order, we found that the 'equal-time consistency conditions' quantitatively approximates the perturbative results for the density contrast. Thus, we generalized the background method to properly incorporate the effect of curvature in the density and velocity fluctuations on short scales, and discussed the reasons behind this discrepancy.

Local measurements of the Hubble expansion rate are affected by structures like galaxy clusters or voids. We presented a fully relativistic treatment of this effect, studying how clustering modifies the dispersion of the mean distance (modulus)-redshift relation in a standard ΛCDM universe [81]. Our findings were that cosmic variance (i.e. the effects of the local structure) is, for supernova observations at small redshifts ($0.01 < z < 0.1$), of the same order of magnitude as the current observational errors. The cosmic variance has to be taken into account in local measurements of the Hubble expansion rate and it reduces the tension with the CMB measurement.

We provided predictions on small-scale cosmological density power spectrum from supernova lensing dispersion [82]. Parameterizing the primordial power spectrum with running α and running of running β of the spectral index, we exclude large positive α and β parameters which induce too large lensing dispersions over current observational upper bound. We ran cosmological N-body simulations of collisionless dark matter particles to investigate non-linear evolution of the primordial power spectrum with positive running parameters. The initial small-scale enhancement of the power spectrum is largely erased when entering into the non-linear regime. For example, even if the linear power spectrum at $k > 10h \times \mathrm{Mpc}^{-1}$ is enhanced by 1 to 2 orders of magnitude, the enhancement much decreases to a factor of 2 to 3 at late time ($z \leq 1.5$). Therefore, the lensing dispersion induced by the dark matter fluctuations weakly constrains the running parameters. When including baryon-cooling effects (which strongly enhance the small-scale clustering), the constraint is comparable or tighter than the PLANCK constraint, depending on the UV cut-off.

10 PhD-theses and review articles

This work described above was also part of a number of PhD-theses. These are [83–86].

Furthermore, our work has been supplemented by a short review of string cosmology [87]. We wish to connect string-scale physics as closely as possible to observables accessible to current or near-future experiments. Our possible best hope to do so is a description of inflation in string theory. The energy scale of inflation can be as high as that of Grand Unification (GUT). If this is the case, this is the closest we can possibly get in energy scales to string-scale physics. Hence, GUT-scale inflation may be our best candidate phenomenon to preserve traces of string-scale dynamics. Our chance to look for such traces is the primordial gravitational wave, or tensor mode signal produced during inflation. For GUT-scale inflation this is strong enough to be potentially visible as a B-mode polarization of the cosmic microwave background (CMB). Moreover, a GUT-scale inflation model has a trans-Planckian excursion of the inflaton scalar field during the observable amount of inflation. Such large-field models of inflation have a clear need for symmetry protection against quantum corrections. This makes them ideal candidates for a description in a candidate fundamental theory like string theory. At the same time the need of large-field inflation models for UV completion makes them particularly susceptible to preserve imprints of their string-scale dynamics in the inflationary observables, the spectral index n_s and the fractional tensor mode power r. Hence, we focussed in this review on axion monodromy inflation as a mechanism of large-field inflation in string theory.

References

[1] I. Ben-Dayan, S. Jing, A. Westphal and C. Wieck, *Accidental inflation from Kähler uplifting*, *JCAP* **1403** (2014) 054, [1309.0529].

[2] V. Balasubramanian and P. Berglund, *Stringy corrections to Kahler potentials, SUSY breaking, and the cosmological constant problem*, *JHEP* **11** (2004) 085, [hep-th/0408054].

[3] A. Westphal, *de Sitter string vacua from Kahler uplifting*, *JHEP* **03** (2007) 102, [hep-th/0611332].

[4] A. D. Linde and A. Westphal, *Accidental Inflation in String Theory*, *JCAP* **0803** (2008) 005, [0712.1610].

[5] V. Balasubramanian, P. Berglund, J. P. Conlon and F. Quevedo, *Systematics of moduli stabilisation in Calabi-Yau flux compactifications*, *JHEP* **03** (2005) 007, [hep-th/0502058].

[6] B. J. Broy, D. Ciupke, F. G. Pedro and A. Westphal, *Starobinsky-Type Inflation from α'-Corrections*, *JCAP* **1601** (2016) 001, [1509.00024].

[7] M. Cicoli, D. Ciupke, S. de Alwis and F. Muia, *α'-Inflation: moduli stabilisation and observable tensors from higher derivatives*, *JHEP* **09** (2016) 026, [1607.01395].

[8] M. Cicoli, C. P. Burgess and F. Quevedo, *Fibre Inflation: Observable Gravity Waves from IIB String Compactifications*, *JCAP* **0903** (2009) 013, [0808.0691].

[9] R. Kallosh, A. Linde, D. Roest, A. Westphal and Y. Yamada, *Fibre Inflation and α-attractors*, *JHEP* **02** (2018) 117, [1707.05830].

[10] R. Kallosh, A. Linde and D. Roest, *Superconformal Inflationary α-Attractors*, *JHEP* **11** (2013) 198, [1311.0472].

[11] M. Dias, J. Frazer, A. Retolaza, M. Scalisi and A. Westphal, *Pole N-flation*, 1805.02659.

[12] N. Arkani-Hamed, L. Motl, A. Nicolis and C. Vafa, *The String landscape, black holes and gravity as the weakest force*, *JHEP* **06** (2007) 060, [hep-th/0601001].

[13] F. G. Pedro and A. Westphal, *Low-ℓ CMB power loss in string inflation*, *JHEP* **04** (2014) 034, [1309.3413].

[14] J. E. Kim, H. P. Nilles and M. Peloso, *Completing natural inflation*, *JCAP* **0501** (2005) 005, [hep-ph/0409138].

[15] E. Silverstein and A. Westphal, *Monodromy in the CMB: Gravity Waves and String Inflation*, *Phys. Rev.* **D78** (2008) 106003, [0803.3085].

[16] L. McAllister, E. Silverstein and A. Westphal, *Gravity Waves and Linear Inflation from Axion Monodromy*, *Phys. Rev.* **D82** (2010) 046003, [0808.0706].

[17] N. Kaloper and L. Sorbo, *A Natural Framework for Chaotic Inflation*, *Phys. Rev. Lett.* **102** (2009) 121301, [0811.1989].

[18] I. Ben-Dayan, F. G. Pedro and A. Westphal, *Hierarchical Axion Inflation*, *Phys. Rev. Lett.* **113** (2014) 261301, [1404.7773].

[19] I. Ben-Dayan, F. G. Pedro and A. Westphal, *Towards Natural Inflation in String Theory*, *Phys. Rev.* **D92** (2015) 023515, [1407.2562].

[20] S. Kachru, R. Kallosh, A. D. Linde and S. P. Trivedi, *De Sitter vacua in string theory*, *Phys. Rev.* **D68** (2003) 046005, [hep-th/0301240].

[21] L. McAllister, E. Silverstein, A. Westphal and T. Wrase, *The Powers of Monodromy*, *JHEP* **09** (2014) 123, [1405.3652].

[22] R. Flauger, L. McAllister, E. Pajer, A. Westphal and G. Xu, *Oscillations in the CMB from Axion Monodromy Inflation*, *JCAP* **1006** (2010) 009, [0907.2916].

[23] R. Flauger, L. McAllister, E. Silverstein and A. Westphal, *Drifting Oscillations in Axion Monodromy*, *JCAP* **1710** (2017) 055, [1412.1814].

[24] W. Buchmuller, E. Dudas, L. Heurtier, A. Westphal, C. Wieck and M. W. Winkler, *Challenges for Large-Field Inflation and Moduli Stabilization*, *JHEP* **04** (2015) 058, [1501.05812].

[25] A. Retolaza, A. M. Uranga and A. Westphal, *Bifid Throats for Axion Monodromy Inflation*, *JHEP* **07** (2015) 099, [1504.02103].

[26] A. Hebecker, J. Moritz, A. Westphal and L. T. Witkowski, *Towards Axion Monodromy Inflation with Warped KK-Modes*, *Phys. Lett.* **B754** (2016) 328–334, [1512.04463]. [Erratum: Phys. Lett.B767,493(2017)].

[27] A. Hebecker, F. Rompineve and A. Westphal, *Axion Monodromy and the Weak Gravity Conjecture*, *JHEP* **04** (2016) 157, [1512.03768].

[28] L. E. Ibanez, M. Montero, A. Uranga and I. Valenzuela, *Relaxion Monodromy and the Weak Gravity Conjecture*, *JHEP* **04** (2016) 020, [1512.00025].

[29] A. Aazami and R. Easther, *Cosmology from random multifield potentials*, *JCAP* **0603** (2006) 013, [hep-th/0512050].

[30] D. Marsh, L. McAllister and T. Wrase, *The Wasteland of Random Supergravities*, *JHEP* **03** (2012) 102, [1112.3034].

[31] F. G. Pedro and A. Westphal, *The Scale of Inflation in the Landscape*, *Phys. Lett.* **B739** (2014) 439–444, [1303.3224].

[32] F. G. Pedro and A. Westphal, *Nonequilibrium random matrix theory: Transition probabilities*, *Phys. Rev.* **E95** (2017) 032144, [1606.07768].

[33] F. G. Pedro and A. Westphal, *Inflation with a graceful exit in a random landscape*, *JHEP* **03** (2017) 163, [1611.07059].

[34] M. Dias, J. Frazer and M. C. D. Marsh, *Simple emergent power spectra from complex inflationary physics*, *Phys. Rev. Lett.* **117** (2016) 141303, [1604.05970].

[35] M. Dias, J. Frazer and M. c. D. Marsh, *Seven Lessons from Manyfield Inflation in Random Potentials*, *JCAP* **1801** (2018) 036, [1706.03774].

[36] I. Ben-Dayan, S. Jing, M. Torabian, A. Westphal and L. Zarate, *$R^2 \log R$ quantum corrections and the inflationary observables*, *JCAP* **1409** (2014) 005, [1404.7349].

[37] R. Kallosh, A. Linde and A. Westphal, *Chaotic Inflation in Supergravity after Planck and BICEP2*, *Phys. Rev.* **D90** (2014) 023534, [1405.0270].

[38] B. J. Broy, D. Roest and A. Westphal, *Power Spectrum of Inflationary Attractors*, *Phys. Rev.* **D91** (2015) 023514, [1408.5904].

[39] B. J. Broy, F. G. Pedro and A. Westphal, *Disentangling the $f(R)$ - Duality*, *JCAP* **1503** (2015) 029, [1411.6010].

[40] B. J. Broy, M. Galante, D. Roest and A. Westphal, *Pole inflation – Shift symmetry and universal corrections*, *JHEP* **12** (2015) 149, [1507.02277].

[41] B. J. Broy, D. Coone and D. Roest, *Plateau Inflation from Random Non-Minimal Coupling*, *JCAP* **1606** (2016) 036, [1604.05326].

[42] M. Alishahiha, E. Silverstein and D. Tong, *DBI in the sky*, *Phys. Rev.* **D70** (2004) 123505, [hep-th/0404084].

[43] R. Gwyn, M. Rummel and A. Westphal, *Resonant non-Gaussianity with equilateral properties*, *JCAP* **1304** (2013) 040, [1211.0070].

[44] R. Gwyn, M. Rummel and A. Westphal, *Relations between canonical and non-canonical inflation*, *JCAP* **1312** (2013) 010, [1212.4135].

[45] M. Cicoli, S. Downes, B. Dutta, F. G. Pedro and A. Westphal, *Just enough inflation: power spectrum modifications at large scales*, *JCAP* **1412** (2014) 030, [1407.1048].

[46] M. Dias, J. Frazer, D. J. Mulryne and D. Seery, *Numerical evaluation of the bispectrum in multiple field inflation?the transport approach with code*, *JCAP* **1612** (2016) 033, [1609.00379].

[47] B. J. Broy, *Corrections to n_s and n_t from high scale physics*, *Phys. Rev.* **D94** (2016) 103508, [1609.03570]. [Addendum: Phys. Rev.D94,no.10,109901(2016)].

[48] S. R. Coleman and F. De Luccia, *Gravitational Effects on and of Vacuum Decay*, *Phys. Rev.* **D21** (1980) 3305.

[49] K. Dutta, P. M. Vaudrevange and A. Westphal, *The Overshoot Problem in Inflation after Tunneling*, *JCAP* **1201** (2012) 026, [1109.5182].

[50] B. Freivogel, M. Kleban, M. Rodriguez Martinez and L. Susskind, *Observational consequences of a landscape*, *JHEP* **03** (2006) 039, [hep-th/0505232].

[51] K. Dutta, C. Hector, P. M. Vaudrevange and A. Westphal, *More Exact Tunneling Solutions in Scalar Field Theory*, *Phys.Lett.* **B708** (2012) 309–313, [1110.2380].

[52] K. Dutta, C. Hector, T. Konstandin, P. M. Vaudrevange and A. Westphal, *Validity of the kink approximation to the tunneling action*, *Phys.Rev.* **D86** (2012) 123517, [1202.2721].

[53] P. W. Graham, D. E. Kaplan and S. Rajendran, *Cosmological Relaxation of the Electroweak Scale*, *Phys. Rev. Lett.* **115** (2015) 221801, [1504.07551].

[54] O. Lebedev and A. Westphal, *Metastable Electroweak Vacuum: Implications for Inflation*, *Phys.Lett.* **B719** (2013) 415–418, [1210.6987].

[55] L. McAllister, P. Schwaller, G. Servant, J. Stout and A. Westphal, *Runaway Relaxion Monodromy*, *JHEP* **02** (2018) 124, [1610.05320].

[56] L. Covi et al., *de Sitter vacua in no-scale supergravities and Calabi-Yau string models*, *JHEP* **06** (2008) 057, [0804.1073].

[57] L. Covi et al., *Constraints on modular inflation in supergravity and string theory*, *JHEP* **08** (2008) 055, [0805.3290].

[58] M. Gomez-Reino, J. Louis and C. A. Scrucca, *No metastable de Sitter vacua in N=2 supergravity with only hypermultiplets*, *JHEP* **02** (2009) 003, [0812.0884].

[59] L. Covi, M. Gomez-Reino, C. Gross, G. A. Palma and C. A. Scrucca, *Constructing de Sitter vacua in no-scale string models without uplifting*, *JHEP* **03** (2009) 146, [0812.3864].

[60] M. Rummel and A. Westphal, *A sufficient condition for de Sitter vacua in type IIB string theory*, *JHEP* **1201** (2012) 020, [1107.2115].

[61] J. Louis, M. Rummel, R. Valandro and A. Westphal, *Building an explicit de Sitter*, *JHEP* **1210** (2012) 163, [1208.3208].

[62] D. Martinez-Pedrera, D. Mehta, M. Rummel and A. Westphal, *Finding all flux vacua in an explicit example*, *JHEP* **1306** (2013) 110, [1212.4530].

[63] M. Cicoli, S. de Alwis and A. Westphal, *Heterotic Moduli Stabilisation*, *JHEP* **10** (2013) 199, [1304.1809].

[64] L. B. Anderson, J. Gray, A. Lukas and B. Ovrut, *Stabilizing All Geometric Moduli in Heterotic Calabi-Yau Vacua*, *Phys. Rev.* **D83** (2011) 106011, [1102.0011].

[65] F. G. Pedro, M. Rummel and A. Westphal, *Extended No-Scale Structure and α'-Corrections to the Type IIB Action*, 1306.1237.

[66] D. Ciupke, J. Louis and A. Westphal, *Higher-Derivative Supergravity and Moduli Stabilization*, *JHEP* **10** (2015) 094, [1505.03092].

[67] K. Becker, M. Becker, M. Haack and J. Louis, *Supersymmetry breaking and alpha-prime corrections to flux induced potentials*, *JHEP* **06** (2002) 060, [hep-th/0204254].

[68] D. Ciupke, *Scalar Potential from Higher Derivative $\mathcal{N} = 1$ Superspace*, 1605.00651.

[69] D. Ciupke and L. Zarate, *Classification of Shift-Symmetric No-Scale Supergravities*, *JHEP* **11** (2015) 179, [1509.00855].

[70] J. Moritz, A. Retolaza and A. Westphal, *Toward de Sitter space from ten dimensions*, *Phys. Rev.* **D97** (2018) 046010, [1707.08678].

[71] S. de Alwis, J. Louis, L. McAllister, H. Triendl and A. Westphal, *Moduli spaces in AdS_4 supergravity*, *JHEP* **05** (2014) 102, [1312.5659].

[72] N. Kaloper and A. Padilla, *Sequestering the Standard Model Vacuum Energy*, *Phys. Rev. Lett.* **112** (2014) 091304, [1309.6562].

[73] N. Kaloper, A. Padilla, D. Stefanyszyn and G. Zahariade, *Manifestly Local Theory of Vacuum Energy Sequestering*, *Phys. Rev. Lett.* **116** (2016) 051302, [1505.01492].

[74] I. Ben-Dayan, R. Richter, F. Ruehle and A. Westphal, *Vacuum energy sequestering and conformal symmetry*, *JCAP* **1605** (2016) 002, [1507.04158].

[75] G. D'Amico, N. Kaloper, A. Padilla, D. Stefanyszyn, A. Westphal and G. Zahariade, *An Ètude on global vacuum energy sequester*, *JHEP* **09** (2017) 074, [1705.08950].

[76] I. Ben-Dayan, M. Gasperini, G. Marozzi, F. Nugier and G. Veneziano, *Average and dispersion of the luminosity-redshift relation in the concordance model*, *JCAP* **1306** (2013) 002, [1302.0740].

[77] I. Ben-Dayan and T. Kalaydzhyan, *Constraining the primordial power spectrum from SNIa lensing dispersion*, *Phys. Rev.* **D90** (2014) 083509, [1309.4771].

[78] I. Ben-Dayan, R. Durrer, G. Marozzi and D. J. Schwarz, *The value of H_0 in the inhomogeneous Universe*, *Phys. Rev. Lett.* **112** (2014) 221301, [1401.7973].

[79] I. Ben-Dayan, *Lensing dispersion of SNIa and small scales of the primordial power spectrum*, in *Proceedings, 49th Rencontres de Moriond on Cosmology: La Thuile, Italy, March 15-22, 2014*, pp. 95–100, 2014, 1408.3004.

[80] I. Ben-Dayan, T. Konstandin, R. A. Porto and L. Sagunski, *On Soft Limits of Large-Scale Structure Correlation Functions*, *JCAP* **1502** (2015) 026, [1411.3225].

[81] G. Marozzi, I. Ben-Dayan, R. Durrer and D. J. Schwarz, *Impact of cosmic variance on the local measurement of H_0*, *PoS* **FFP14** (2016) 087.

[82] I. Ben-Dayan and R. Takahashi, *Constraints on small-scale cosmological fluctuations from SNe lensing dispersion*, *Mon. Not. Roy. Astron. Soc.* **455** (2016) 552–562, [1504.07273].

[83] C. Gross, *De Sitter vacua and inflation in no-scale string models*, Ph.D. thesis, Universität Hamburg, 2009. http://www-library.desy.de/cgi-bin/showprep.pl?thesis09-029.

[84] M. Rummel, *Vacua and Inflation in String Theory and Supergravity*, Ph.D. thesis, Universität Hamburg, 2013. http://www-library.desy.de/cgi-bin/showprep.pl?thesis13-026.

[85] B. J. Broy, *Inflation and Effective Shift Symmetries*, Ph.D. thesis, Universität Hamburg, 2016. 10.3204/PUBDB-2016-03859 http://ediss.sub.uni-hamburg.de/volltexte/2016/7986/.

[86] D. Ciupke, *Higher-Derivative Supergravity and String Cosmology*, Ph.D. thesis, Universität Hamburg, 2016. 10.3204/PUBDB-2016-03670 http://inspirehep.net/record/1501333/files/phd_thesis_final_pub.pdf.

[87] A. Westphal, *String cosmology – Large-field inflation in string theory*, *Int. J. Mod. Phys.* **A30** (2015) 1530024, [1409.5350].