Final Report

Funding Programme:	Helmholtz Young Investigators Groups
Project ID No.:	HZ-NG-603
Project Title:	Strings and Cosmology – an Interface for Testing Fundamental Theories
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Helmholtz Centre:	DESY Hamburg
Participating University:	
Report Period:	10/2010-09/2015

1) Summary (max. 1 DIN A4 page)

Please describe the main results and the progress achieved in comparison to the state of the art at the time of writing the application and give an outlook on possible future work and applications.

This HGF project, while stopping short of achieving a statistical prediction oft he amount of primordial gravitational waves (the tensor fraction r) for string theory models of cosmic inflation, led to considerable and significant progress in 3 main directions from which in the future the desired prediction may be obtainable.

To perform a very rough prediction of r – what we mean is a binary type of prediction whether r is large (r = O(0.1)) or whether it is small (r << 0.01) – from the string theory vacuum landscape, we need to understand several key pieces of ingredients:

1) The main mechanisms for cosmological inflation in string theory, splitting into 2 classes depending on the scalar field range traversed during the minimum 50…60 e-folds of inflationary expansion of the universe – large-field (trans-Planckian field range, r = 0.01 … 0.1), and small-field models (sub-Planckian field range, r << 0.01).

   - generic small-field models arise in string theory from large subsectors of the stabilized moduli fields, which have structure-less Gaussian random distribution of critical points. The project achieved considerable progress in determining the relative number frequency of accidental random flat small-field inflationary saddle points among all of the random critical points when compared to actual minima. The crucial result is, that while the random nature of inflationary saddles occurring this way enhances their number frequency compared to actual minima, the overall probability of such regions is double-exponentially suppressed in the dimension of the scalar field space described by the Gaussian random potential. This result will be a major part of any future prediction of the magnitude of r, and so achieves a significant partial objective of the project.

   - The immediate next open question is the combined likelihood of small-field inflation with successful evolution of the scalar fields into a minimum after inflation, that is, successful 'exit'. This analysis is under way, but will develop beyond this project.

2) The project results found the landscape of large-field models of inflation in string theory, or its 4D low-energy approximation on Calabi-Yau manifolds, no-scale supergravity, to be considerably richer than initially assumed:

   - the mechanisms of axion monodromy or axion alignment/hierarchy for large-field

inflation have shown a much larger than initially expected spectrum of primary inflation potential sources and dynamical backreaction effects of stabilized string moduli fields leading to flattening of the effective inflaton potential, or sometimes even loss of inflation; future studies of these prototypical large-field models with approximately monomial potentials will include very basic bottom-up self-consistency checks arising under the name of 'weak gravity conjectures' from the EFT of quantum gravity in its GR limit at low energies compared to the Planck scale.

- several results of the project make it rather plausible, that a class of exponentially flat plateau potential inflation models first described by Starobinsky about 40 years ago, might have decently well-controlled string theory realizations; this would complicate the question of predicting r statistically from the string landscape, because the large-field model class would decompose into 2 sub-classes with trans-Planckian field excursions, but either r = 0.01 … 0.1, or r = 0.001 … 0.01 – to estimate how often string theory realizes the 2nd large-field plateau-type class is an open question for the future.

3) String inflation cannot proceed in a controlled manner without stabilizing the moduli of the extra compact 6 dimensions of 4D string vacua. Understanding moduli stabilization hence is also required to obtain the backreaction of the moduli during inflation. The project made very significant progress here by developing 2 classes of highly explicit and expressly microscopically constructed mechanisms generating fully stabilized 4D string vacua with either dS or AdS 4D vacuum energy which can be tuned small due to a large flux discretuum:

- The project succeeded in constructing a fully string theoretically explicit class of stable 4D vacua containing dS vacua among them, from just microscopic type IIB string theory data. This enable directly a concrete study of moduli backreaction on large-field inflation, showing the range of possible implications once such explicit constructions of string vacua are in hand.

- Moreover, one of the PhD students in the project succeeded in constructing an entirely new class of perturbatively stabilized non-supersymmetric AdS vacua from higher-superspace derivative corrections which were first derived during this project in full generality. Again, having such an explicit and perturbatively controlled vacuum class in hand had direct implications, such as the successful construction of new plateau-type inflation models in string theory.

These results represent significant progress towards an r estimate from the string landscape. However, at the same time they widen the scope and richness of the landscape of inflation models in string theory so much, that the widening search for all the ingredients needed to obtain a rough expectation for r led to the successful application of the YIG leader for an ERC Consolidator Grant won in 2015.

2) Work and Results Report

a) Starting point (max. 1 DIN A4 page)

Please describe the point(s) at issue, the aims and the working hypotheses of the project.

The decade before 2010 has seen the rise of observational precision cosmology with data pointing towards a new cosmological concordance model: The universe is almost spatially flat, its energy density partitions into about 4% ordinary matter, 22% dark matter, and 74% in form of some 'dark energy' driving an accelerated expansion of the universe, and the

initial conditions of the hot big bang origin can be be explained by a very early phase of inflationary expansion.

Inflation denotes (in its most simple form) a form of quasi-exponential expansion of the very early universe driven by the potential energy density of a slowly rolling scalar field. Since inflation generically happens close to the energy scale of grand unified theories (GUTs), precision measurements of the CMB offer a unique chance to observe processes at the GUT scale where new fundamental theories can have direct influence.

String theory is an attractive candidate for a fundamental theory of all interactions, and it is a consistent theory of quantum gravity. Recent years have seen substantial progress in tackling the problem of stabilizing (that is, rendering very massive) the many moduli fields of string theory (these are scalar fields associated with the shape and size of the compact 6 spatial dimensions necessary to realize a low-energy 4-dimensional effective field theory in string theory). This allowed the construction of the first realistic and concrete models of inflation in string theory.

Research of the YIG leader during 2008 and 2009 succeeded in uncovering a simple and general mechanism (based on 'monodromy') for realizing inflation in string theory with a power law scalar potential (similar to the known 'chaotic inflation' models of effective field theory), which produces a measurable fraction of primordial gravitational waves in addition to the well-known nearly scale-invariant inflationary spectrum of density fluctuations. Then in the future – and meanwhile partially realized -- measurements (e.g. BICEP, SPIDER, QUIET or the PLANCK satellite) have already allowed for a significant tightening of the constraints on these primordial gravitational waves, and may well lead to a detection within another 5 years. Both the existing constraints and a future detection or even stronger constraints on primordial B-modes in the CMB thus may allow for the first time an experimental test of string theory. Therefore, the project targeted two sets of questions arising in connection with this recent theoretical progress and future experimental outlook:

There is a need for information about the dynamics and statistics of the different models of string inflation across the multitude of the so-called 'landscape' of string theory vacuum solutions. Understanding these topics better is necessary to obtain predictions about which inflationary string models the theory might prefer 'a priori' when comparing to future precision cosmological data.

Moreover, there is also a need to tackle moduli stabilization and use string dualities to study string inflation in less understood corners like the heterotic string. For the latter this would be appealing as heterotic string vacua came very close to resembling the actual (supersymmetrized) standard model.

b) Description of the results (max. 4 DIN A4 pages)

Please describe the scientific and/or technical success of the group as well as secondary results achieved and essential experience gained. Please classify your own work within the national and international context.

Starting phase 2010/2011

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The understanding of the number frequency prevalence of, say, large-field models of string inflation versus small-field models, using F-theory methods eventually, has very recently seen

a significant extension of the scope of monodromy based large-field models of string inflation, as as a whole new class of axion monodromy inflation models based on monodromy in the potential energy induced by higher-dimensional p-form fluxes type IIB string theory was uncovered [Dong,Horn,Silverstein,Westphal 2010]. In certain limits of moduli space these new models are related to the known 5-brane axion monodromy models [McAllister,Silverstein,Westphal 2008] by a string theoretic duality called geometric transition. This duality allows for a connection of the two axion monodromy model classes by passing through a curvature singularity of the internal Calabi-Yau space rendered calculabe by string theory (which shows its true power as a quantum theory of gravity here). At the same time, the enriched perspective on axion monodromy opened up by the flux-based models and their duality to the 5-brane constructions gave the first concrete hints why the string theoretic large-field models seem to consistently deviate compared to naive simple field-theoretic large-field models towards smaller powers of the scalar potential ('flattening') [Dong,Horn,Silverstein, Westphal 2010]. The consequences of these developments are under further study with the project's postdoc, Pascal Vaudrevange. A sufficient grasp of these consequences is essential before the F-theory based task of counting number frequencies of these large-field axion monodromy string inflation models can be addressed in earnest.

On the the other front of the first part of the project, we have developed in collaboration with Pascal Vaudrevange and Koushik Dutta, also a DESY postdoc, an approximate analytical solution of Coleman-de Luccia tunneling of a scalar field in a meta-stable vacuum into a vacuum of lower potential energy, where the shape of the scalar potential is given as a simple combination of linear and quadratic terms [Dutta,Vaudrevange, Westphal 2011]. Such a scalar potential is suitable to give a leading-order approximation to a generic string theory landscape moduli potentials with built-in regions of slow-roll inflation. The analytical approximate tunneling solution is valid for a wide range of shape parameters of the potential (such as barrier height and width), including regions where both the known thin-wall approximation by Coleman & deLuccia [Coleman,deLuccia 1972], and the description in terms of purely linear potentials by Duncan & Jensen [Duncan,Jensen 1992] break down. As tunneling from a higher-lying metastable vacuum in the string landscape is the typical mechanism for initiating and populating the known slow-roll string inflation models, this new result comprises the first necessary step towards describing the number frequency bias between large-field and small-field inflation models which is introduced by the dynamics of populating the models and their initial condition phase space volumina, as opposed to the pure number frequency counts discussed before.

Finally, in collaboration with Andrei Linde and Mahdiyar Noorbala (Stanford U.) we analyzed [Linde,Noorbala,Westphal 2011] the effects of higher-order couplings of the inflaton to curvature (a la "Higgs inflation" by Bezrukhov & Shaposhnikov [Bezrukhov,Shaposhnikov 2006]) on the inflationary observable, as the tilt of the primordial power spectrum of density fluctuation, and the power in primordial gravitational waves generated during inflation. This may well be relevant for the discrimatory power when separating small-field from large-field models in string theory, as the higher-order couplings between the inflaton and curvature can sometimes interpolate quite efficiently between originally small-field or large-field models.

2011

(arXiv:1107.2115) Together with my student Markus Rummel we derived a sufficient condition for realizing meta-stable de Sitter vacua with small positive cosmological constant within type IIB string theory flux compactifications with spontaneously broken supersymmetry. 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 -- 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 includes 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.
This result is rather important, because metastable dS vacua are a prerequisite for any successful model of inflation in string theory. Our sufficient dS criterion moved the search for dS vacua in string theory qualitatively beyond the state of the art in 2011. This is, because the existing dS constructions (e.g. KKLT or the Large Volume Scenario) are more a kind of 'lamp post' (covering only small sets of string compactifications), and at the time only a necessary criterion for the existence of metastable dS vacua had been derived from supergravity [Covi et al. 2008].

(arXiv:1109.5182) With Koushik Dutta and Pascal Vaudrevange, we showed the absence of the usual parametrically large overshoot problem of small-field inflation if initiated by a Coleman-De Luccia (CDL) tunneling transition from an earlier vacuum in the limit of small inflationary scale compared to the tunneling scale. For low-power monomial exit potentials $V(\phi) \sim \phi^n$ with $n < 4$, the calculations yield 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. The result extends 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.

(arXiv:1110.2380, arXiv:1202.2721) In two subsequent papers we calculated, together with Koushik Dutta, Cecelie Hector, Pascal Vaudrevange, and Thomas Konstandin, the first new exact tunneling solution with exact and explicit expression for the tunneling action integral $B = S_E(\phi) - S_E(\phi_0)$ in flat space, since the piecewise-linear potential solution by Duncan & Jensen in 1992, and the influence on tunneling by kinks in the potential energy of a scalar field which can arise in leading-order treatments of string theory solutions.

Several of the these results in 2011 made it possible in 2012 to perform a first statistical analysis of the relative prevalences of large-field and small-field inflation in Calabi-Yau flux landscapes of type IIB string theory. These results have been presented in several talks in the US in 2012, and will be published very soon. They lead to a final, mathematically well posed question on the distribution of certain microscopic properties on the space of elliptically-fibered Calabi-Yau 4-fold compactifications of F-theory, which will be studied concretely using the known formal methods of toric geometry during the coming months. This brings the completion of the first major milestone within reach: Acquiring an understanding about a possible statistical prediction of the expected level of primordial gravitational waves during inflation from an accessible and large part of the landscape of string theory.

Besides there are two more publications in preparation which will use explicit constructions of elliptically-fibered Calabi-Yau 4-folds in F-theory where the method of 'Kähler uplifting' described in the effective 4d supergravity in 2011 (see above) can be explicitly realized in a full F-theoretic string construction. Simultaneously, this construction also will also show the existence of potentially extremely large-rank non-Abelian ADE singularities in F-theory even on compact Calabi-Yau 4-folds.

2012
Inflation & string theory:

(arXiv:1202.2721) In this paper and a prequel from fall 2011 we calculated, together with

Koushik Dutta, Cecelie Hector, Pascal Vaudrevange, and Thomas Konstandin, the first new exact tunneling solution with exact and explicit expression for the tunneling action integral $B = S_E(\phi) - S_E(\phi_0)$ in flat space, since the piecewise-linear potential solution by Duncan & Jensen in 1992, and the influence on tunneling by kinks in the potential energy of a scalar field which can arise in leading-order treatments of string theory solutions.

(arXiv:1205.1663) With Pascal Vaudrevange we constructed a simple purely polynomial potential for a single scalar field consistent with effective field theory requirements and arising generically in certain sectors of string compactifications, which gave a model of open slow-roll inflation following a Coleman-DeLuccia tunneling transition from high-lying false vacuum which is part of the same potential. The model demonstrated explicitly in a full example the absence of overshoot on the inflationary plateau after tunneling due to the curvature inside the nucleated bubble, thus displaying a general result about the avoidance of overshoot after tunneling published by the YIG in 2011.

(arXiv: 1206.4034) Several of the published results in 2011 have enabled us now to perform a first statistical analysis of the relative prevalences of large-field and small-field inflation in Calabi-Yau flux landscapes of type IIB string theory. These results have been presented in several talks in the US in 2012, have been published meanwhile in JHEP. They lead to two final, and complementary, mathematically well posed questions:
1) one aspect is the distribution of certain microscopic properties on the space of elliptically-fibered Calabi-Yau 4-fold compactifications of F-theory.
2) the other, complementary aspect concerns the statistics of accidentally arising saddle-point/inflection point regions of small-field inflation in the moduli potential of string compactifications.

Inflation & phenomenology:

(arXiv: 1210.6987) Here we looked at the cosmological implications of the 2012 discovery of a Higgs boson with 126 GeV mass at the LHC in the context of the stability of the electro-weak vacuum of the pure Standard Model (SM) of particle physics. If the LHC results as well as the measurements of the top quark mass tighten down at the same central values in the future, then the electro-weak symmetry breaking vacuum might get confirmed to be meta-stable under quantum-mechanical vacuum decay into anti-de-Sitter (AdS) space (the evidence for meta-stability is around 3-sigma confidence level at this time). Furthermore, in this case the electro-weak vacuum would suffer rapid vacuum instability during the phase of early cosmological inflation from inflationary quantum fluctuations. If this is case, we showed from simple effective field theory arguments that one should expect a small but potentially relevant *direct cross-coupling* between the inflaton scalar field and the Higgs field, which stabilizes the electro-weak vacuum during inflation. This Higgs-inflaton cross-coupling may be potentially measurable.

(arXiv: 1211.0070) Primordial non-Gaussianity of the quantum fluctuations generated during inflation became an important theoretical tool in the last half decade, as the momentum-space distribution of the 3-point function of the fluctuations, the 'shape', may discriminate between many different classes of inflationary models. We showed that a certain shape of non-Gaussianity (equilateral) typically associated with the presence of higher-derivative corrections during inflation can be obtained by single-field inflation models without higher-derivative terms if they have periodic corrections to their overall scalar potential. This demonstrated a degeneracy in the non-Gaussian observable which previously was assumed to discriminate between these inflation model classes. Knowledge about such degeneracies may be become even more important given the strength of the recent PLANCK satellite's constraints on non-Gaussianity.

Moduli stabilization in string theory:

(arXiv: 1208.3208) One highlight of the project consists in the successful construction of a set of explicit de Sitter vacua realizing the mechanism of 'Kähler uplifting' in both type IIB string theory and its non-perturbative F-theory limit based on a leading-order quantum correction from type IIB string theory. This is one of the few existing manifestly supersymmetric string compactifications with complete moduli stabilization where the breaking of supersymmetry in a dS state occurs entirely within the framework of spontaneously broken F-term supergravity.

(arXiv: 1212.4530) Having an explicit construction in hand furthermore was key for an explicit study of the 'discretuum' of flux vacua – the local 'landscape' – generated by scanning over the quantized values of the higher p-form fluxes of type IIB string theory. The resulting vacuum statistics for e.g. the minimal spacing of values of the cosmological constant or the gravitino mass scale of supersymmetry breaking verified for this non-trivial example general approximative analytical results in the extant literature.

2013
Inflation & string theory (reached an important step towards the *first major milestone*):

Several of the published results in 2011 have enabled us in 2012 (arXiv: 1206.4034) to perform a first statistical analysis of the relative prevalences of large-field and small-field inflation in Calabi-Yau flux landscapes of type IIB string theory. These results have been presented in several talks in the US in 2012, have been published meanwhile in JHEP. They lead to two final, and complementary, mathematically well posed questions:
1) one aspect is the distribution of certain microscopic properties on the space of elliptically-fibered Calabi-Yau 4-fold compactifications of F-theory.
2) the other, complementary aspect concerns the statistics of accidentally arising saddle-point/inflection point regions of small-field inflation in the moduli potential of string compactifications.

(arXiv: 1303.3224) We were able to determine one main part of the answer to the 2nd question. Its form implies an exponential statistical enhancement of number frequency small-field inflation over large-field inflation in the string landscape. Since it is known that the answer to question 1) can only yield a suppression of the number frequency of large-field models over small-field models of inflation in the landscape, in combination we reached a major step towards the first major milestone:

The statistical result for question 2) together with the structure of any possible answer to question 1) may lead to a statistical prediction of the expected level of primordial gravitational waves during inflation from an accessible and large part of the landscape of string theory – *provided* that we establish the joint probability of obtaining successful inflation *and* a graceful exit into a meta-stable dS vacuum of small vacuum energy.

By itself, the result in (arXiv: 1303.3224) might lead us to expect from string theory the absence of a primordial gravitational wave signal in the polarization of the cosmic microwave background (CMB) in current (such as the BICEP2 result) and the near-future observations. However, without knowing the joint probability of obtaining successful inflation *and* a graceful exit into a meta-stable dS vacuum of small vacuum energy, a prediction is invalid.

Concerning inflation model building in string theory constructions, we looked back at our explicit de Sitter construction from 2011 and 2012. There, we found that in variations of these constructions we can arrange for small model landscape of K\"ahler moduli driven small-field string inflation to occur (arXiv: 1309.0529).

In the context of flux-brane inflation, where the position of a moving D7-brane in type IIB string theory/F-theory acquires a slow-roll inflation scalar potential through turning on flux, we analyzed the resulting 2-field hybrid inflation potential. Since the axionic part of the D7-brane modulus is protected by a shift symmetry, the effective inflaton potential is of the form of hybrid inflation with a periodic cosine potential in the inflaton-axion direction – that is, we get “hybrid natural inflation” (axions with cosine potentials can drive what is called “natural inflation”). An analysis of this situation can provide for a tensor mode single r > 0.001 in mild violation of the generic Lyth bound (arXiv: 1305.1947).

Some of our most recent work focuses on the fact, that our existing observational evidence for inflation has access to just the last about 60 e-folds of inflationary expansion. We do not know, how much inflation our Universe underwent in total. However, if there was only the 55 .. 60 e-folds of 'just enough inflation' in our past, we may see this in form of deviations of the CMB temperature two-point function power spectrum for the slow-roll prediction of typical single-field inflation models. The PLANCK collaboration in 2013 has reported some evidence at the level of 2.5 -- 3 standard deviations. of exactly such an anomaly, namely that there is less CMB power on large angular scales l < 50 than predicted by a simple single-field slow-roll model. Such a power loss at low-l can occur if the slow-roll parameters start to change rapidly via steepening of the potential just at the beginning of our observable 60 e-folds of inflation, or if slow-roll breaks down there suddenly and entirely. We showed in very recent work (arXiv: 1309.3413), that there are models of inflation in string theory, such as fibre inflation in Calabi-Yau flux compactifications of type IIB string theory, where a power-loss at low-l arises rather naturally from the conditions of generating only the 60 e-folds of 'just enough inflation'.

Moduli stabilization in string theory:

As our de Sitter constructions in 2012 depend
on the presence of perturbative quantum corrections, it was natural to
enquire about the existence and consequences of possible further
string quantum corrections on these classes of dS
vacua. Recently, Anguelova et al. (2010) and Grimm et al. (2013) derived
structurally similar corrections to the K\"ahler potential of the
Calabi-Yau K\"ahler moduli at *O*(alpha'^2) in heterotic, and
type IIB string theory, respectively. On the type IIB side (arXiv: 1306.1237) analyzed the effects of a similar *O*(alpha'^2) correction to the Kahler potential, leading to potentially strong constraints on the compactification volume and gravitino mass scale in all known models of type IIB moduli stabilization in dS vacua. These constraints may impact significantly on the type IIB constructions of low-energy phenomenology and cosmological inflation.

(arXiv: 1304.1809) Here, we perform a systematic analysis of moduli stabilization for weakly coupled heterotic string theory compactified on smooth Calabi-Yau three-folds in models with (0,2) worldsheet supersymmetry. After reviewing how to stabilise all the geometric moduli in a supersymmetric way by including fractional fluxes, non-perturbative and threshold effects, we show that the inclusion of alpha'-corrections leads to new de Sitter or nearly Minkowski vacua which break supersymmetry spontaneously. The minimum lies at moderately large volumes of all the geometric moduli, at perturbative values of the string coupling and at the right phenomenological value of the grand-unified (GUT) gauge coupling. However the structure of the heterotic 3-form flux used for complex structure moduli stabilization does not contain enough freedom to tune the superpotential. This results in the generic prediction of GUT-scale supersymmetry breaking. We finally provide a dynamical derivation of anisotropic compactifications with stabilized moduli which allow for perturbative gauge coupling unification around 10^16 GeV.
This work represents a major step forward in the study of stabilized heterotic string vacua with

features which are compatible with the construction of the heterotic MSSM model classes producing particle phenomenology very close to the actually observed SM. These constructions were done at the time without addressing explicitly the questions of stabilizing the moduli and breaking supersymmetry. With our analysis we provide the first class of controlled metastable dS vacua in the weakly coupled heterotic string which are compatible with the heterotic MSSM constructions and may lead to experimentally viable non-SUSY particl phenomenology constructions in string theory.

Finally, we closed 2013 with a thorough study of moduli spaces in AdS_4 supergravity, both with N = 1 and N = 2 supergravity. The connection of such moduli spaces, which are non-generic in AdS_4 space-time, is connected to (sometimes accidental) global symmetries, most commonly a shift symmetry. As such, statements about moduli spaces in AdS_4, being the precursor to de Sitter vacua in string theory, are potentially relevant for models of inflation in string theory.

2014
Inflation & string theory:

In 2014, we saw the first detection of degree angular scale B-mode polarization in the cosmic microwave background radiation (CMB) by the BICEP2 telescope. If inflation was driven by a scalar field with a 'large' trans-Planckian field displacement, its energy scale is that of Grand Unified Theories (GUTs) at about 10^{16} GeV, and it produces a nearly scale-invariant power spectrum of primordial gravitational waves (tensor modes), which would cause a B-mode polarization signal in the CMB of roughly the same strength as the signal seen by BICEP2. Their very high energy scale renders these large-field inflation models sensitive to quantum gravity or string theory effects. Hence, the BICEP2 B-mode signal, and the question to which degree it originates from inflationary tensor modes caused a spark of theoretical interest. Since then, the reanalysis and joint analysis of the full temperature data from the Planck satellite and part of its own B-mode data has shown unexpectedly strong dust foregrounds in our galaxy together with BICEP2 and its successor, the Keck Array. *The as of fall 2015 still open possibility of a primordial B-mode gravitational wave signal producing a part of the the observed CMB B-mode signal at degree angular scales has driven a large burst of analysis and construction of large-field inflation models in string theory in 2014, many of them based on the mechanism of axion monodromy which the YIG group leader co-discovered in 2008. The members of the YIG consequently got strongly involved during 2014 in this process of analyzing the phenomenological range of string theory models of large-field inflation for B-mode production. This served the project well, as it showed that the landscape of large-field inflation models in string theory is significantly wider and varied than many anticipated earlier, and this needs now to be taken into account for the projects goal of analyzing the landscape of string inflation models. It is therefore foreseeable that, given these recent developments, a closure of the project objectives may not be reachable by the project end in September 2015.*

The joint work of the YIG on this expanded understanding of large-field inflation in string theory resulted in series of publications: 1404.7773 , 1405.0270 , 1405.3652 , 1407.2562 , 1412.1814, and an invited review article: 1409.5350 by the YIG group leader, which was also published as part of a book monograph ("Perspectives on String Phenomenology", World Scientific, 2015).

It is fair to say that the results obtained by the members of the YIG on the phenomenology and string theory construction properties of large-field axion inflation had a major international impact on the whole research field during the course of 2014.

In parallel, we studied in 1408.5904 the theoretical structure and CMB observational consequences of a class of inflationary models with an asymptotically exponentially flat potential similar to the original $R+R^2$ inflation model by Starobinsky. These so-called 'strong non-minimal coupling attractor' models first introduced by Renata Kallosh, Andrei Linde, and Diederik Roest, continue to provide a very good description to the joint constraints and analysis

of the Planck CMB temperature, E-mode and B-mode polarization results and the BICEP2/Keck Array B-mode results with a tensor mode signal one order of magnitude below that of large-field models (and thus in reach of a future dedicated satellite experiment). We looked at generic perturbations of the attractor mechanism, and found in 1408.5904 that they lead exponentially rising corrections to the scalar potential, which shorten the exponentially flat inflationary plateau to finite length, create an asymmetric inflection point in the potential and drive a suppression of CMB temperature power at large angular scales due to the steepening of the potential arising from the rising exponential corrections. There are persistent hints in the CMB temperature data from both WMAP and Planck including its latest results for such a suppression of CMB temperature power a large angular scales. This renders models capable of generating inflationary power spectra of curvature perturbations with power suppression at large angular scales particularly interesting.

Driven by this interest, in 1407.1048 we undertook a general analysis of the influence on the CMB temperature power spectrum of an arbitrary pre-inflationary phase of scale-factor evolution transiting into slow-roll inflation late enough to leave just the barely enough 60 e-folds of slow-roll. We found a general expression allowing us to parametrize the effects of the pre-inflationary phase on the large-angular power spectrum in terms of just the equation-of-state parameter of the pre-inflationary regime. The suppression of CMB power at large angular scales seen in our analysis 1408.5904 of the attractor models were then seen to be a special case of our general analysis in 1407.1048.

Finally, we were able to show in 1411.6010, that certain classes of the perturbed strong-coupling attractor models analysed in 1408.5904 have dual descriptions in terms of an f(R)-theory, where we were able to obtain the function f of the Ricci scalar curvature R either exactly or asymptotically for large R in the inflationary regime. The functions f(R) we found in 1411.6010 generalize Starobinsky's original $R+R^2$ into an infinite series of R^n corrections with computable coefficients, which resum into a non-analytic fractional power functional form of f(R). The presence of this infinite series and their resummation into a nontrivial functional form is mandated by the rising exponential corrections to the potential in Einstein frame, and thus constitute a clear effect of possible ultraviolet completions of Starobinsky's model. In particular, we could show that analogous rising exponential terms limiting the width of exponentially flat inflationary plateau arise in the type IIB string theory models of fibre inflation. Hence, we were able to argue in 1411.6010 that fibre inflation, and some slight variations of its original setup we constructed there, very plausibly provide a direct UV completion in string theory of Starobinky's inflation model. Having this UV completion mandating the rising exponential corrections in turn causes the whole series of higher-derivative R^n corrections to the Starobinsky model, and allows us compute their coefficients.

2015

During the final ¾ year of the YIG we started to attack some of questions in part remaining from the earlier parts of the projects, and in a large part opened up by the results obtained in the YIG at this state, by 3 different lines of work:

i) Conditions and phase space of small-field random critical point inflation modelling the non-structured part of the string landscape:
Building on our results obtained during 2013, which told us that randomly occurring small-field inflation regions in the landscape arise with an exponentially higher number frequency compared to actual viable minima, we started to address the question of computing the probability of a given inflationary critical point to evolve along a random inflationary trajectory into an actual minimum to provide a graceful exit. Developing this question with the former YIG postdoc Francisco Pedro (meanwhile at IFT Madrid) this has led us to study the theory of Dean and Majumdar of large mass matrix eigenvalue fluctuations away from equilibrium as

the random critical point description of evolving from an inflationary region of the scalar potential into a minimum. *We hope to lead this analysis to a closure by early 2016, which may provide a first reliable answer to one of projects main questions within half a year of its closure – namely the relative likelihood of small-field inflation with undetectably small tensor modes in the string landscape.*

ii) A long-time building project of one of the YIG's 2nd-round PhD student, David Ciupke, has led in 2015 to a completely new class of perturbatively stabilized supersymmetry breaking 4D string theory vacua. David realized that the supersymmetric field theories as well as theories of supergravity had lacked a systematic understanding of the structure of their effective action at more than 2 superspace derivatives in the derivative expansion. Moreover, he realized that possible corrections arising at the order of 4 superspace derivatives may well compete in 4D with already known higher-space-time derivative curvature corrections in the 10D effective supergravity action. David began a classification of all such operators correcting 4D supergravity at 4 superspace-derivative level, and showed that they generically break the no-scale structure of the type IIB Kahler moduli scalar potential. He then performed a matching with dimensional reduction of the 10D four-curvature-power string theory correction, showing this way that string theory necessarily induces 4-superspace-derivative corrections to the scalar potential in 4D string compactifications. Together with the known 2-superspace-derivative scalar potential from such 10D corrections, these new 4-superspace-derivative corrections may lead to the stabilization of all Kahler moduli at the perturbative level for the half of all Calabi-Yau compactifications which have positive Euler number. This is major progress, potentially producing a whole new class of self-stabilizing string vacua, which significantly widens the scope of string vacua whose process of moduli stabilization needs still to be studied in its effects on models of string inflation.

In a follow-up project with both YIG PhD students David Ciupke and Benedict Broy, as well as the former YIG postdoc Francisco Pedro, we were able to construct a new class of fibre inflation models in type IIB string theory using the new class of 4-superspace derivative corrections found by David. As variants of the original fibre inflation model by Burgess, Cicoli and Quevedo (2008) this new class provides close relatives to the Starobinsky/attractor class inflation models, and it provides this with improved perturbative control properties arising from the string tree-level nature of the 4-superspace-derivative corrections.

A complementary project with the 2nd YIG PhD student Benedict Broy in collaboration with Diederik Roest and Mario Galante from Groningen, NL succeeded in describing a whole class of Starobinsky-type inflation models from a completely new perspective, where the effective plateau-type shift symmetry of these models is realized by the pole structure of the Laurent expansion of the kinetic term of an inflationary model. The universality features of this new class of mechanisms led to the name 'pole inflation', and offers a tantalizing hope of finding large classes of string theory construction of such Starobinsky-type inflation models, because the pole structure of the kinetic term needed arises quite generically for the moduli fields of string theory compactifications.

iii) In a third line of work we provided
a) a detailed study of the backreaction effects of moduli fields in string-derived 4D supergravity models of axion monodromy large-field models of inflation, which lead to flattening of the scalar potential as already first discussed in the late-2010 work, and
b) the first explicit local geometric construction of the type of bifurcated warped 2-

throat Calabi-Yau geometries necessary to realize the 2008 foundational model of 5-brane axion monodromy large-field inflation.

In both cases controlling the flattening backreaction effects of either heavy moduli fields and/or warping effects of axionic brane charge requires a certain amount of 'arrangement/tuning' of the background stabilized string setup – but represents on fundamental obstacle to obtain finite trans-Planckian field ranges.

These results acquired additional international import and visibility due to the active nature of the discussion in 2015 around basic effective quantum gravity constraints in the form of 'weak gravity conjectures' which may limit the effective field range of some classes of axionic large-field inflation models.

iv) Finally, during 2015 we developed an independent analysis of an unconventional proposal for dynamically sequestering the quantum contribution of a matter sector protected by a certain scale and shift symmetry to the overall cosmological constant proposed by work by Kaloper and Padilla in the last 2 years. Our analysis allowed us to show that matching the global non-dynamicaly aspects of the Kaloper-Padilla mechanism with a fully local QFT requires using the dynamics of spontaneously broken scale invariance in conformal field theories (CFTs). The work of Ido Ben-Dayan becoming a full part of the YIG in 2015 by extending his 2-year postdoc at DESY to a 3rd year was crucial in obtaining this rather intriguing result for a partial solution to the long-standing cosmological constant problem.

c) Outlook on future work, sustainability (max. 2 DIN A4 pages)

Did you encounter unexpected effects or questions during the funding period? Do you see the need for further research in this respect? Please describe planned activities to further develop this work, also if to be carried out elsewhere or in a different constellation.

The detailed discussion of the YIG's results above exemplifies in a clear fashion one of the most fundamental structures of research at the frontier of the unknown – for every answered question there usually arise at least several new questions, sending the quest even deeper into the unknown.

It has become abundantly clear, that even with the impressive collection of results discussed above we only scratched a part and mostly the surface of the string landscape of inflation models, which has a by far deeper and richer structure than could have been anticipated at the project begin in 2010 (another foundational feature of science – if you already know at the beginning what you are going to find, then your project contains no truly fundamental research; science at its core faces the unknown, so it cannot predict in advance what it will find).

Hence while we obtained partial answers for some of the project goals, the final class of answer aimed for – a statistical prediction of the tensor mode level for string inflation – requires far more extensive studies, with the results of this project forming an indispensable and sizable, but necessarily (in hindsight) only first step.

For this very reason the YIG leader used the significantly widened scope of analysis necessary for reaching for answer to the original question, and the suite of results obtained with the YIG, to apply for an ERC Consolidator Grant in 2015 – and largely based on, and thanks to, the YIG's results this application was successful, leading the ERC Consolidator Grant "STRINGFLATION" won by the YIG leader, which started in 10/2015.

d) Potential for application/exploitation (max. 2 DIN A4 pages)

How do you yourself assess the potential for application or exploitation of the results? Where do you see future possibilities? Please describe realized or planned measures for applying the results. Please also include information on patents, licences, co-operations with industry, etc.

…

3) Qualification of Junior Researchers (max. 2 DIN A4 pages)

Please describe the structure of the Young Investigators Group in the course of the funding period and the main achievements regarding personal qualifications (including your own): Bachelor, Master; Diploma degrees, conferring of doctorates, "Habilitations", appointments/junior professorships, tenure track, awards, etc. Please also describe any particularities as well as your work-related plans after the end of the funding period.

Pascal Vaudrevange was a postdoc in the YIG 10/2010 – 09/2012, after which he entered a successful career in the private sector with the firm "D-fine".

Koushik Dutta, the 2nd postdoc who became an effective member of the YIG since October 2010 as his funding proceed through him being a part of the DFG Collaborative Research Center SFB 676, project C6, has left us at the end of 2011, as he went on to his new position as an assistant professor of theoretical physics at the IISER Bhopal Institute in Bhopal, India.

Markus Rummel, was a PhD student in the YIG from 10/2010 – 09/2013, and has gone on to a rather successful postdoc with Joe Conlon in Oxford since fall 2013. He also spent a 2-month invited visitor fellowship with Henry Tye and Gary Shiu at the Hongkong Institute for Advanced Study in early summer 2013.

Francisco Pedro became the YIG postdoc in 10/2012. He did his PhD in the area of string cosmology under the supervision of Joseph P. Conlon at Oxford University, UK. His postdoc in the YIG led to several significant results, and he went on successfully to a postdoc position in the group of Luis Ibanez at the IFT in Madrid, Spain, in 10/2014.

Benedict Broy (Master at Hamburg U.) and David Ciupke (Master at Goettingen U.) have joined the YIG as PhD students in October 2013, starting on projects concerning the effects of non-minimal coupling to gravity on inflation, and higher superspace-derivative correction to the effective action of inflationary models. They will finish their so far highly successful PhD projects with defenses in summer of 2016. David Ciupke will move on to a postdoctoral researcher position in the group of Michele Cicoli in Bologna, Italy, in fall 2016.

Ido Ben-Dayan has been as a postdoc in the SFB C6 project at DESY since fall 2012 for 2 years, during which he contributed significantly to the large-field axion inflation results of the YIG in 2014. Based on these successes the YIG offered him an extension for a 3rd postdoc year, this way keeping his expertise for our continued exploration during 2015. Since fall 2015 Ido moved on successfully with a postdoctoral fellowship to Hebrew University in Israel.

Finally, we were initially successful to hire Timm Wrase (at that time at Stanford U. after being at Cornell U.) for a final 2-year postdoctoral position starting fall 2014, with the 2nd year being covered by DESY. However, in summer 2014 Timm was offered a 5-year junior faculty position in Vienna, with the option for tenure-track coupled to applying for a national Austrian

research grant. Given the incommensurability of our own offer, we were not able to keep him for the postdoctoral position. As this was on such short notice and far outside the annual fall hiring cycle of high-energy theoretical physics postdocs, we used this situation to our advantage in offering Ido Ben-Dayan an extension to a 3rd year at DESY, as discussed above, as well as taking on Julian Schweizer (a local PhD student) for 9 months in 2015 as his work on de Sitter vacua in 6D supergravity is very promising in its potential to describe the 6D limit of our heterotic de Sitter vacua with Michele Cicoli and Senarath de Alwis taken on an anisotropic Calabi-Yau space.

4) Public relations
By which means did you gain publicity (e.g. reporting in media, own website)?

Winter semester 2014/2015:

- Public talk (in German) in a series of 2 physics colloquia together with Dr. Torsten Ensslin at Hamburg University about “Kosmologie nach BICEP2 und Planck” on Dec 11, 2014
  http://www3.physnet.uni-hamburg.de/VFFP/kolloquien.html

- Public evening lecture (in German) at the ‘Hamburger Planetarium’ in a series by the Hamburg Academy of Science about “Urspruenge des Kosmos - Kosmische Inflation und kosmischer Mikrowellenhintergrund” on Feb 20, 2015
  Hamburg Academy of Science link

5) Networking
What co-operation and communication structures (centre/university if applicable) have been developed during the course of the funding? How satisfied are you with the co-operation with the Helmholtz-Centre / university?

The YIG is fully integrated in the activities of the theory group at DESY, and collaborates very closely with the II. Institute for Theoretical Physics of Hamburg University. In addition, the YIG group leader remains a PI of the DFG Collaborative Research Center SFB 676, C6.

The YIG has co-organized the 2012 workshop “Implications of the Early LHC for Cosmology”:

https://indico.desy.de/conferenceDisplay.py?confId=5231

The YIG has co-organized the 2013 conference „String Phenomenology“

http://stringpheno2013.desy.de/

The YIG has co-organized the 2014 workshop “Inflation after Planck”:

https://indico.desy.de/conferenceDisplay.py?confId=9421

at DESY.

6) List of Publications

Articles in scientific journals, written contributions to scientific meetings, contributions to books, other publications.

Papers:

1) "Simple exercises to flatten your potential," X. Dong, B. Horn, E. Silverstein, A. Westphal, Phys. Rev. D **84** (2011) 026011, [arXiv:1011.4521 [hep-th]].
2) "Gravity waves from the non-renormalizable Electroweak Vacua phase transition," E. Greenwood, P. M. Vaudrevange, , [arXiv:1011.5881 [hep-th]].
3) "Observational consequences of chaotic inflation with non- minimal coupling to gravity," A. Linde, M. Noorbala, A. Westphal, JCAP **1103**, 013 (2011). [arXiv:1101.2652 [hep-th]].
4) "Improved constraints on cosmological parameters from SNIa data," M. C. March, R. Trotta, P. Berkes, G.D. Starkman, P. M. Vaudrevange, Mon. Not. Roy. Astron. Soc. **418** (2011) 2308-2329, [arXiv:1102.3237 [hep-th]].
5) "An Exact Tunneling Solution in a Simple Realistic Landscape," K. Dutta, P. M. Vaudrevange, A. Westphal, Class. Quant. Grav. **29** (2012) 065011,[arXiv:1102.4742 [hep-th]].
6) " A sufficient condition for de Sitter vacua in type IIB string theory", M. Rummel & A. Westphal, JHEP **1201** (2012) 020, arXiv:1107.2115
7) " The Overshoot Problem in Inflation after Tunneling", K. Dutta, P.M. Vaudrevange & A. Westphal, JCAP **1201** (2012) 026, arXiv:1109.5182
8) "More Exact Tunneling Solutions in Scalar Field Theory", K. Dutta, C. Hector, P.M. Vaudrevange & A. Westphal, Phys. Lett. B **708** (2012) 309-313, arXiv:1110.2380
9) "On the Existence of Tunneling Bounce Solutions in Piecewise Linear Potentials", K. Dutta, C. Hector, T. Konstandin, P.M. Vaudrevange & A. Westphal, Phys. Rev. D **86**, (2012) 123517 [arXiv:1202.2721]
10) "A Toy Model For Single Field Open Inflation", P.M. Vaudrevange & A. Westphal, arXiv:1205.1663
11) "Tensor modes on the string theory landscape," A. Westphal, JHEP **1304** (2013) 054 [arXiv:1206.4034]
12) "Building an explicit de Sitter," J. Louis, M. Rummel, R. Valandro & A. Westphal, JHEP **1210** (2012) 163 [arXiv:1208.3208]
13) "Metastable Electroweak Vacuum: Implications for Inflation," O. Lebedev & A. Westphal Phys. Lett. B **719**, 415 (2013) [arXiv:1210.6987]
14) "Resonant non-Gaussianity with equilateral properties," R. Gwyn, M. Rummel & A. Westphal, JCAP **1312** (2013) 010, [arXiv:1211.0070]
15) "Finding all flux vacua in an explicit example," D. Martinez-Pedrera, D. Mehta, M. Rummel & A. Westphal, JHEP **1306** (2013) 110 , [arXiv:1212.4530]
16) "The Scale of Inflation in the Landscape," F. G. Pedro & A. Westphal, Phys. Lett. B **739** (2014) 439-444, [arXiv:1303.3224]
17) "Heterotic Moduli Stabilization," M. Cicoli, S. de Alwis & A. Westphal, JHEP **1310** (2013) 199 [arXiv:1304.1809]
18) "Evading the Lyth Bound in Hybrid Natural Inflation," A. Hebecker, S. Kraus & A. Westphal, Phys. Rev. D **88** (2013) 123506 [arXiv:1305.1947]
19) "Extended No-Scale Structure and α'^2 Corrections to the Type IIB Action," F. G. Pedro, M. Rummel & A. Westphal, arXiv:1306.1237
20) "Moduli destabilization via gravitational collapse," D.-i. Hwang, F. G. Pedro & D.-h. Yeom, JHEP **1309** (2013) 159 [arXiv:1306.6687]
21) "Accidental inflation from Kähler uplifting," I. Ben-Dayan, S. Jing, A. Westphal & C. Wieck, JCAP **1403** (2014) 054 [arXiv:1309.0529]
22) "Low-ℓ CMB power loss in string inflation," F. G. Pedro & A. Westphal, JHEP **1404** (2014) 034 [arXiv:1309.3413]
23) "On Moduli Spaces in AdS_4 Supergravity," S. de Alwis, J. Louis, L. McAllister, H. Triendl & A. Westphal, JHEP **1405** (2014) 102, [arXiv:1312.5659]
24) "R^2 log R quantum corrections and the inflationary observables," I. Ben-Dayan, S. Jing,

M. Torabian, A. Westphal & L. Zarate, JCAP **1409** (2014) 005 [arXiv:1404.7349]

25) "Hierarchical Axion Inflation," I. Ben-Dayan, F. G. Pedro & A. Westphal, Phys. Rev. Lett. **113** (2014) 261301 [arXiv:1404.7773]
26) "Chaotic Inflation in Supergravity after Planck and BICEP2," R. Kallosh, A. Linde & A. Westphal, Phys. Rev. D **90** (2014) 2, 023534 [arXiv:1405.0270]
27) "The Powers of Monodromy," L. McAllister, E. Silverstein, A. Westphal & T. Wrase, JHEP **1409** (2014) 123 [arXiv:1405.3652]
28) "Just enough inflation: power spectrum modifications at large scales," M. Cicoli, S. Downes, B. Dutta, F. G. Pedro & A. Westphal, JCAP **1412** (2014) 12, 030 [arXiv:1407.1048]
29) "Towards Natural Inflation in String Theory," I. Ben-Dayan, F. G. Pedro & A. Westphal, Phys. Rev. D **92** (2015) 2, 023515, [arXiv:1407.2562]
30) "Power Spectrum of Inflationary Attractors," B. Broy, D. Roest & A. Westphal, Phys. Rev. D **91** (2015) 2, 023514 [arXiv:1408.5904]
31) "String cosmology — Large-field inflation in string theory," A. Westphal, Int. Jour. Mod. Phys. A **30** (2015) 09, 1530024 [arXiv:1409.5350]
32) "Disentangling the f(R) - duality," B. Broy, F. G. Pedro & A. Westphal, JCAP **1503** (2015) 03, 029 [arXiv:1411.6010]
33) "Drifting Oscillations in Axion Monodromy," R. Flauger, L. McAllister, E. Silverstein & A. Westphal, arXiv:1412.1814
34) "Challenges for Large-Field Inflation and Moduli Stabilization," W. Buchmuller, E. Dudas, L. Heurtier, A. Westphal, C. Wieck & M. W. Winkler, JHEP **1504** (2015) 058
35) "Bifid Throats for Axion Monodromy Inflation," A. Retolaza, A. M. Uranga & A. Westphal, JHEP **1507** (2015) 099
36) "Higher-Derivative Supergravity and Moduli Stabilization," D. Ciupke, J. Louis & A. Westphal, JHEP **1510** (2015) 094
37) "Pole inflation — Shift symmetry and universal corrections," B. J. Broy, M. Galante, D. Roest & A. Westphal, JHEP **1512** (2015) 149
38) "Vacuum energy sequestering and conformal symmetry,"I. Ben-Dayan, R. Richter, F. Ruehle & A. Westphal, (2015) [arXiv:1507.04158]
39) "Starobinsky-Type Inflation from α′ -Corrections," B. J. Broy, D. Ciupke, F. G. Pedro & A. Westphal, JCAP **1601** (2016) 001

Talks (given by <u>speaker</u>):

1) Invited seminar at the 2nd Bethe Center workshop "Cosmology meets Particle Physics", Bad Honnef, Germany (Oct. 2010)
   R. Flauger, T. He, S. Kachru, L. McAllister, E. Pajer, E. Silverstein, A. Westphal & G. Xu: "Large- Field Inflation & Gravity Waves in String Theory";
   http://www.bctp.uni-bonn.de/workshop2010/talks/Westphal BCTP2010.pdf .
2) Invited seminar at Technical University of Munich, Munich, Germany (Nov. 2010)
   X. Dong, B. Horn, E. Silverstein & A. Westphal:
   "Simple exercises to flatten your potential".
3) Invited seminar at Technical University of Munich, Munich, Germany (Nov. 2010)
   R. Flauger, T. He, S. Kachru, L. McAllister, E. Pajer, E. Silverstein, A. Westphal & G. Xu: "Large-Field Inflation & Gravity Waves in String Theory".
4) Invited seminar at the workshop "Theoretical Cosmology Meetings", Leiden, Netherlands (Feb. 2011)
   X. Dong, B. Horn, E. Silverstein & A. Westphal: "Simple exercises to flatten your potential";
   http://www.cosmology.nl/ .
5) Invited seminar at the workshop "Foundational Aspects of Cosmology", Hamburg, Germany (Feb 2011)
   A. Linde, M. Noorbala & A. Westphal: "Observational consequences of chaotic inflation with non- minimal coupling to gravity";

http://www.foundationalcosmology.com/talks/Friday/1_Westphal.pdf .

6) Invited seminar at Utrecht University, Utrecht, Netherlands (Mar. 2011)
A. Linde, M. Noorbala & A. Westphal: ”Observational consequences of chaotic inflation with non-minimal coupling to gravity”.
7) Seminar at the XXIII workshop ”Beyond the Standard Model”, Bad Honnef, Germany (Mar 2011)
A. Linde, M. Noorbala & A. Westphal: ”Observational consequences of chaotic inflation with non- minimal coupling to gravity”;
http://www.desy.de/uni-th/stringth/bad-honnef/2011/Alexander_Westphal.pdf
8) Seminar at the XXIII workshop ”Beyond the Standard Model”, Bad Honnef, Germany (Mar 2011)
K. Dutta, P. M. Vaudrevange, A. Westphal: ” “An Exact Tunneling Solution in a Simple Realistic Landscape”;
http://www.desy.de/uni-th/stringth/bad-honnef/2011/
9) Invited seminar at Arizona State University, Tempe, AZ, USA (Apr 2011)
K. Dutta, P. M. Vaudrevange, A. Westphal: ” “An Exact Tunneling Solution in a Simple Realistic Landscape”.
10) Invited seminar at Case Western Reserve University, Cleveland, OH, USA (Apr 2011)
K. Dutta, P. M. Vaudrevange, A. Westphal: ” “An Exact Tunneling Solution in a Simple Realistic Landscape”.
11) Invited seminar at Perimeter Institute, Waterloo, Canada (Apr 2011)
K. Dutta, P. M. Vaudrevange, A. Westphal: ” “An Exact Tunneling Solution in a Simple Realistic Landscape”.
12) Invited keynote review at PONT 2011 (Progress on Old and New Themes in cosmology), Avignon, France, (Apr. 2011)
A. Westphal: ”Inflation in String Theory”;
http://indico.cern.ch/conferenceDisplay.py?confId=114928 .
13) “A sufficient condition for IIB/F-theory dS vacua”, M. Rummel & A. Westphal, invited talk, String Theory and Precision Cosmology, Ithaca, USA, July 2011
http://www.lns.cornell.edu/Events/StringCosmo11/Program.html
14) “The overshoot problem in inflation after tunneling”, K. Dutta, P.M. Vaudrevange, A. Westphal, invited talk, String Phenomenology, Madison, USA, August 2011
http://conferencing.uwex.edu/conferences/stringpheno2011/PlenarySessions.cfm
15) “The Overshoot Problem in Inflation after Tunneling“, K. Dutta, P.M. Vaudrevange, A. Westphal, International Conference on Particle Physics and Cosmology - COSMO 11 (COSMO 2011), Porto, Portugal, August 2011
poster (pdf)
16) “A sufficient condition for IIB/F-theory dS vacua'', M. Rummel & A. Westphal, DESY Theory workshop 2011, DESY, Hamburg, Germany, September 2011
http://th-workshop2011.desy.de/e98837/e98839/
17) “The Overshoot Problem in Inflation after Tunneling'', K. Dutta, P.M. Vaudrevange & A. Westphal, DESY Theory workshop 2011, DESY, Hamburg, Germany, September 2011
http://th-workshop2011.desy.de/e98837/e98839/
18) “A sufficient condition for IIB/F-theory dS vacua'', M. Rummel & A. Westphal, IRTG PhD days 2011, DESY, Hamburg, Germany, October 2011
https://indico.desy.de/contributionDisplay.py?contribId=13&sessionId=1&confId=4734
19) “A sufficient condition for IIB/F-theory dS vacua'', M. Rummel & A. Westphal, CP3-Origins/DESY/Göttingen Autumn School on Particle Physics and Cosmology, DESY, Hamburg, Germany, October 2011
https://indico.desy.de/conferenceDisplay.py?confId=4623
20) “The Overshoot Problem in Inflation after Tunneling“, K. Dutta, P.M. Vaudrevange, A. Westphal, Seminar Talk, Aachen, Germany, October 2011
21) “The Overshoot Problem in Inflation after Tunneling”, K. Dutta, P.M. Vaudrevange, A. Westphal, Seminar Talk, Göttingen, Germany, November 2011
22) “A sufficient condition for IIB/F-theory dS vacua'', M. Rummel & A. Westphal, poster at

the “The 29th Jerusalem Winter School in Theoretical Physics”, Jerusalem, Israel, December 2011
http://www.as.huji.ac.il/schools/phys29

23) “A sufficient condition for IIB/F-theory dS vacua", M. Rummel & A. Westphal, Nordic String Theory Meeting 2012, Copenhagen, Denmark, February 2012
https://indico.nbi.ku.dk/conferenceTimeTable.py?confId=397#all
24) “Tensors in the landscape”, A. Westphal, invited seminar talk, Stanford University, USA, February 2012
http://www.stanford.edu/group/sitp/SITP%20Seminar%20Table.htm
25) “Inflation and the Landscape of String Theory”, A. Westphal, invited seminar talk, SETI institute, Mountain View, California, USA, February 2012
http://www.seti.org/weeky-lecture/inflation-and-landscape-string-theory-0
http://www.youtube.com/watch?v=t2Ov6KNZ7-Y
26) “Tensors in the landscape”, A. Westphal, invited seminar talk, UC Berkeley, USA, February 2012
http://www-theory.lbl.gov/cgi-bin/talks/plans.cgi?cal_id=0&cal_start_month=2&cal_start_year=2012
27) “The Overshoot Problem in Inflation after Tunneling", K. Dutta, P.M. Vaudrevange & A. Westphal, Beyond the Standard Model 2012, Bad Honnef, Germany, March 2012
http://www.desy.de/uni-th/stringth/bad-honnef/2012/
28) “A sufficient condition for IIB/F-theory dS vacua", M. Rummel & A. Westphal, Beyond the Standard Model 2012, Bad Honnef, Germany, March 2012
http://www.desy.de/uni-th/stringth/bad-honnef/2012
29) “Tensors in the landscape”, A. Westphal, invited talk, The Particle Physics and Cosmology of Supersymmetry and String Theory, Philadelphia, USA, March 2012
http://www.physics.upenn.edu/Int_L_program/agenda.html
30) “A sufficient condition for de Sitter vacua in type IIB string theory”, J. Louis, M. Rummel, R. Valandro & A. Westphal, invited talk, Brane backreaction, fluxes and meta-stable vacua in string theory, Uppsala, Sweden, May 2012
http://www.physics.uu.se/teorfys/en/content/brane-backreaction-fluxes-and-meta-stable-vacua-string-theory-may-2-4-2012
31) “De Sitter vacua in type IIB / F-theory by Kahler uplifting”, J. Louis, M. Rummel, R. Valandro & A. Westphal, invited talk, String Phenomenology 2012, Cambridge, United Kingdom, June 2012
http://www.newton.ac.uk/programmes/BSM/bsmw05.html
32) “Tensors models on the string theory landscape”, A. Westphal, invited talk, String Phenomenology 2012, Cambridge, United Kingdom, June 2012
http://www.newton.ac.uk/programmes/BSM/bsmw05.html
33) “Towards explicit de Sitter vacua”, J. Louis, M. Rummel, R. Valandro & A. Westphal, invited talk, The 3rd UTQuest workshop ExDiP 2012 Superstring Cosmophysics, Obihiro, Japan, August 2012
http://research.kek.jp/people/hkodama/ExDiP2012/Site/Home.html
34) “Tensors in the Landscape”, A. Westphal, invited talk, The 3rd UTQuest workshop ExDiP 2012 Superstring Cosmophysics, Obihiro, Japan, August 2012
http://research.kek.jp/people/hkodama/ExDiP2012/Site/Home.html
35) “Building an explicit de Sitter”, J. Louis, M. Rummel, R. Valandro & A. Westphal, invited talk, SISSA/ISAS Theoretical Particle Physics Group Seminar, Trieste, Italy, September 2012
http://www.sissa.it/tpp/activity/wedseminar.php
36) “Building an explicit de Sitter”, J. Louis, M. Rummel, R. Valandro & A. Westphal, invited talk, 4th Bethe Center Workshop on Unification and String Theory, Bonn/Bad Honnef, Germany, October 2012
http://www.thphys.uni-heidelberg.de/~weigand/seminar.html
37) “De Sitter vacua in type IIB string theory / F-theory by Kahler uplifting”, J. Louis, M. Rummel, R. Valandro & A. Westphal, invited talk, seminar "String Theory and Beyond

the Standard Model" at the Institute for Theoretical Physics, Heidelberg, October 2012
http://www.newton.ac.uk/programmes/BSM/bsmw05.html

38) "Building an explicit de Sitter", J. Louis, M. Rummel, R. Valandro & A. Westphal, invited talk, CERN string theory seminar, Geneva, CERN, January 2013
http://indico.cern.ch/conferenceDisplay.py?confId=208489

39) "Building an explicit de Sitter", J. Louis, M. Rummel, R. Valandro & A. Westphal, invited talk, CERN string theory seminar, Geneva, CERN, January 2013
workshop homepage

40) "Building an explicit de Sitter vacuum in string theory", J. Louis, M. Rummel, R. Valandro & A. Westphal, invited seminar talk at Padova University, Padova, Italy, February 2013
workshop homepage

41) "Tensors in the landscape", F. Pedro & A. Westphal, invited seminar talk, Rencontres Theoriciennes, Paris, France, March 2013
workshop homepage

42) "Construction of explicit de Sitter vacua in type IIB flux compactifications", J. Louis, D. Martinez-Pedrera, D. Mehta, M. Rummel, R. Valandro & A. Westphal, invited talk, XXV Workshop Beyond the Standard Model, Bad Honnef, Germany, March 2013
workshop homepage

43) "Explicit complex structure moduli stabilization in IIB flux compactifications", J. Louis, D. Martinez-Pedrera, D. Mehta, M. Rummel, R. Valandro & A. Westphal, invited talk, International Research Program "The Particle Physics and Cosmology of Supersymmetry and String Theory" workshop "New Developments in Gravity, Cosmology and Strings", Munich, Germany, March 2013
workshope homepage

44) "Inflation in the Wigner landscape", F. Pedro & A. Westphal, invited talk, International Research Program "The Particle Physics and Cosmology of Supersymmetry and String Theory" workshop "New Developments in Gravity, Cosmology and Strings", Munich, Germany, March 2013
workshope homepage

45) "Tensors in the landscape", A. Westphal, invited talk, International Research Program "The Particle Physics and Cosmology of Supersymmetry and String Theory" workshop "New Developments in Gravity, Cosmology and Strings", Munich, Germany, March 2013
workshope homepage

46) "Inflationary cosmology after Planck", A. Westphal, invited talk, International Research Program "The Particle Physics and Cosmology of Supersymmetry and String Theory" workshop "New Developments in Gravity, Cosmology and Strings", Munich, Germany, March 2013
workshope homepage

47) "Inflationary in the Wigner Landscape", F. G. Pedro & A. Westphal, invited talk, International Research Program "The Particle Physics and Cosmology of Supersymmetry and String Theory" workshop "New Developments in Gravity, Cosmology and Strings", Munich, Germany, March 2013
workshope homepage

48) "Heterotic moduli stabilization", S. de Alwis, M. Cicoli & A. Westphal, invited seminar talk, Stanford University, Palo Alto, USA, May 2013

49) "Extended no-scale structure and α'^2 -corrections to the type IIB action", F. G. Pedro , M. Rummel & A. Westphal, invited talk, PLANCK 2013 conference, Bonn, Germany, May 2013
workshope homepage

50) "Inflationary Ramifications of a Meta-Stable Higgs Vacuum", O. Lebedev & A. Westphal, invited talk, forum "Higgs Meta-Stability Forum", DESY, Hamburg & Berlin, Germany, June 2013
workshope homepage

51) "Tensors in the Landscape ...", A. Westphal, invited seminar talk, Goettingen University, Germany, June 2013
workshope homepage
52) "Tensors in the Landscape ...", A. Westphal, invited seminar talk, ICTP, Trieste, June 2013
workshope homepage
53) "Extended no-scale structure and α'^2 -corrections to the type IIB action", F. G. Pedro , M. Rummel & A. Westphal, invited talk, SUSY 2013 conference, ICTP, Trieste, August 2013
workshope homepage
54) "Inflation in the Wigner Landscape", F. G. Pedro & A. Westphal, invited talk, COSMO 2013 conference, Cambridge, UK, September 2013
workshope homepage
55) "Low-ℓ CMB power loss in string inflation", M. Cicoli, S. Downes, B. Dutta, F. G. Pedro & A. Westphal, invited talk, Groningen, Netherlands, Nov 2013
workshope homepage
56) Invited seminar talk at Hanover University, Hanover, Germany (January 2014) F. G. Pedro & A. Westphal: "Low-l CMB Power Loss in String Inflation"
seminar homepage
57) Invited talk at the workshop "Initial Conditions for Inflation", PCCP, Paris, France (January 2014), M. Cicoli, S. Downes, B. Dutta, F. G. Pedro & A. Westphal: "Low-l CMB Power Loss and String Inflation"
workshop homepage
58) Invited talk at the workshop "Quantum Gravity and Fundamental Cosmology", AEI, Potsdam-Golm, Germany (March 2014), M. Cicoli, S. Downes, B. Dutta, F. G. Pedro & A. Westphal: "Low-l CMB Power Loss and String Inflation"
workshop homepage
59) Invited talk at the workshop "Beyond the Standard Model", Physikzentrum Bad Honnef, Bad Honnef, Germany (March 2014), M. Cicoli, S. Downes, B. Dutta, F. G. Pedro & A. Westphal: "Pre-inflation and CMB power loss"
workshop homepage
60) Invited seminar talk at the University of New Hampshire, Durham, USA (March 2014), A. Westphal: "(String) Inflation after BICEP2"
61) Invited talk at the conference "The Particle Physics and Cosmology of Supersymmetry and String Theory", New York City, USA (March 2014), A. Westphal: "(String) Inflation after BICEP2" conference homepage
62) Invited seminar talk at the Theory Seminar of the University of Bologna, Bologna, Italy (March 2014), M. Cicoli, S. Downes, B. Dutta, F. G. Pedro & A. Westphal: "Pre-inflation and CMB power loss"
63) Invited talk at the workshop "IX Iberian cosmology meeting", Aveiro, Portugal (April 2014), M. Cicoli, S. Downes, B. Dutta, F. G. Pedro & A. Westphal: "Pre-inflation and CMB power loss"
workshop homepage
64) Invited review talk at the conference "String Phenomenology 2014", Trieste, Italy (July 2014), A. Westphal: "String Cosmology - A Short Synopsis"
conference homepage
65) Invited talk at the conference "String Phenomenology 2014", Trieste, Italy (July 2014), M. Cicoli, S. Downes, B. Dutta, F. G. Pedro & A. Westphal: "Just enough inflation: power spectrum modifications on large scales"
conference homepage
66) Invited review talk at the International Symposium Ahrenshoop "On the Theory of Elementary Particles", Berlin, Germany (August 2014), A. Westphal: "Large-Field Inflation – Naturalness and String Theory"
conference homepage
67) Invited review talk at the DESY theory workshop "Particle Cosmology after Planck",

Hamburg, Germany (September 2014), A. Westphal: “Inflation in String Theory: from small to large fields”
workshop homepage

68) Invited talk at the DESY theory workshop “Particle Cosmology after Planck”, Hamburg, Germany (September 2014), M. Cicoli, S. Downes, B. Dutta, F. G. Pedro & A. Westphal: “Just enough inflation: power spectrum modifications on large scales”
workshop homepage

69) Invited talk at the DESY theory workshop “Particle Cosmology after Planck”, Hamburg, Germany (September 2014), B. Broy, D. Roest & A. Westphal: “The Power Spectrum of Inflationary Attractors”
workshop homepage

70) Invited talk at the DESY theory workshop “Particle Cosmology after Planck”, Hamburg, Germany (September 2014), D. Ciupke, J. Louis & A. Westphal: “Higher Derivative Supergravity and Implications for Moduli Stabilization and Inflation”
workshop homepage

71) Invited talk at the workshop “Fine-Tuning, Anthropics and the String Landscape”, Madrid, Spain (October 2014), J. Louis, M. Rummel, R. Valandro & A. Westphal: “Building an explicit de Sitter”
workshop homepage

72) Invited talk at the joint ERC workshop “Superfields, Selfcompletion and Strings & Gravity”, Munich, Germany (October 2014), F.G. Pedro & A. Westphal: “The scale of inflation in the landscape”
workshop homepage

73) Invited talk at the PCTP workshop “Open Questions in String Cosmology and Inflation”, Prince- ton, USA (October 2014), A. Westphal, L. McAllister & E. Silverstein: “Axion-Monodromy Inflation I: Overview”
workshop homepage

74) Invited talk at the conference “Indian Strings Meeting 2014”, Puri, India (December 2014), A. Westphal: “Large-field inflation - strings & pheno”
workshop homepage

75) Invited talk at the workshop “Understanding the Early Universe”, CERN, Geneva (January 2015), A. Westphal: “Large-field inflation - strings & pheno”
workshop homepage

76) Invited talk at the KEK theory workshop, KEK, Tsukuba, Japan (January 2015), A. Westphal: “Large-field inflation - strings & pheno”
workshop homepage

77) Invited seminar talk at the GRAPPA institute, Amsterdam, NL (March 2015), A. Westphal: “Large-field inflation - strings & pheno”
seminar homepage

78) Invited seminar talk at ICTP & SISSA, Trieste, Italy (April 2015), A. Westphal: “Large-field inflation - strings & pheno”
seminar homepage

79) Invited seminar talk at TU Munich, Germany (April 2015), A. Westphal: “Large-field inflation - strings & pheno”
seminar homepage

80) Talk at the workshop “XXVII Workshop Beyond the Standard Model 2015”, Bad Honnef, Germany (March 2015), B. Broy: “Inflationary Attractors, f(R) - duals and the Power Spectrum”
workshop homepage

81) Talk at the DESY workshop “The Particle Physics and Cosmology of Supersymmetry and String Theory”, DESY, Hamburg, Germany (April 2015), B. Broy: “Inflationary Attractors, String inspired f(R) and the CMB”
workshop homepage

82) Talk at the DESY workshop “The Particle Physics and Cosmology of Supersymmetry and String Theory”, DESY, Hamburg, Germany (April 2015), D. Ciupke, J. Louis & A.

Westphal: “Higher-Derivative Supergravity and Moduli Stabilization”
workshop homepage

83) Talk at the conference “COSMO 2015”, Warsaw, Poland (September 2015), B. Broy: “The CMB, String Inflation, and UV inspired f(R)”
workshop homepage

84) Talk at the DESY Theory Workshop 2015, DESY, Hamburg, Germany (September 2015), B. Broy: “f(R), String Theory, and the CMB”
workshop homepage

85) Talk at the DESY Theory Workshop 2015, DESY, Hamburg, Germany (September 2015), D. Ciupke & L. Zarate: “Classification of Shift-Symmetric No-Scale Supergravities”
workshop homepage