Scientific report on the Workshop
'Geometry and Physics of F-theory', Heidelberg, 24-27/02/2014

# 1 Summary

The workshop 'Geometry and Physics of F-theory' was held at the International Science Center Heidelberg (IWH) from February 24-27, 2014 and was organised by members of the faculties of Physics and Mathematics of Heidelberg University, Arthur Hebecker, Eran Palti, Daniel Roggenkamp, Timo Weigand, and Anna Wienhard. The workshop was a meeting of international experts in mathematics and physics who investigated together the geometric structure underlying string compactifications via F-theory. As such it focussed on recent progress in the description of elliptically fibered Calabi-Yau fourfolds both from a mathematical perspective and with regards to their relevance for F-theory, as well as on identifying open questions and promising avenues for future research. This lead to an inspiring exchange of ideas from pure mathematics and from theoretical physics; topics included the algebraic geometry of families of elliptic curves, aspects of intersection theory, construction of vector bundles and associated cohomology groups and applications of F-theory to particle physics in the context of Grand Unified Theories. Each of the morning sessions and in addition one of the afternoon sessions started with a 90 minute blackboard talk on the mathematical foundations of F-theory compactifications. These lectures introduced mathematical technology to describe elliptic fibrations and their physical properties to a wider audience and were essential to bridge the gap between physicists and mathematicians working in the field as represented in the workshop. The remaining twelve 60 minute talks were research presentations which highlighted some of the latest developments in F-theory both from a physics and a mathematics perspective. In a moderated discussion session open questions and future directions were actively debated on. Particularly stimulating discussions also took place in the context of a poster session in which younger researchers had an opportunity to present their research results.

# 2 Description of the scientific content

**General background**

Recent years have witnessed exciting progress in our understanding of compactifications of string theory. String theory establishes profound connections between particle physics and cosmology on the one hand and modern mathematics, most notably algebraic geometry

and topology, on the other hand. This is particularly true for the non-perturbative regime of string and M-theory, which offers a fresh look at many aspects of particle physics. A detailed understanding of non-perturbative string theory requires sophisticated mathematical technology, and this connection between mathematics and fundamental physics was the focus of the workshop.

More precisely, the workshop studied an especially efficient way to incorporate non-perturbative aspects of string and M-theory known as F-theory. F-theory is a beautiful example for the geometrisation of physics: It encodes key objects of a physical theory such as gauge fields and matter representations in the intricate geometry of an elliptically fibered Calabi-Yau 4-fold $Y_4$. As such F-theory has been studied since the seminal papers of Vafa and Morrison-Vafa in 1996. However, it has only recently been more widely appreciated that the way how F-theory combines properties of different types of string vacua - such as the appearance of exceptional gauge symmetry and the localization of matter degrees of freedom on branes - makes it an ideal corner of the string landscape to study phenomenologically relevant string solutions. This has triggered a significant amount of ongoing activity in the past six years, including a vivid interest in the mathematical structures underlying F-theory compactifications at a foundational level. Much of the geometrical data of direct physical relevance is far from well understood mathematically, but intense exchange between mathematical ideas and physics intuition is making further progress possible. This singles out F-theory as an exciting framework of direct relevance to high energy physicists and of great interest to algebraic geometers with a significant potential for new developments in the coming years. In this spirit, our workshop aimed at providing a stimulating atmosphere fostering collaborations between mathematicians and physicists by providing an opportunity to exchange key ideas across the borders of both disciplines.

**Summary of research presentations**

A principal role in making this communication between mathematicians and physicists possible at the workshop was played by five pedagogical blackboard talks of 90 minutes each, given by international experts in the mathematics underlying string and F-theory compactifications:

- Physicist Volker Braun opened the workshop by reviewing the concept of an elliptic fibration and its description as a Weierstrass model, before then working out the difference between an elliptic fbration (which necessarily has a holomorphic section) and a genus-one fibration without such a section. While so far mostly elliptic fibrations have been considered in the F-theory literature, the need to study the more general genus-one fibrations was stressed and widely appreciated by the audience.

- Mathematician Dave Morrison explained the relevance of different fiber types in codimension one and two in the description of the gauge algebra of an F-theory compactification and the various representations in which massless matter states localised in codimension-two can transform. A novel feature presented in his lecture was the importance of discrete flux data which can alter the physical interpretation of the F-theory compactification.

- Mathematician Antonella Grassi contrasted two ways to describe F-theory compactifications on singular elliptic fibrations: One can either consider the associated crepant resolution, which may not always exist, or analyse possible deformations of the singularity. As was pointed out, deformations are a powerful tool to analyse the matter spectrum in particular in those cases in which no such resolution exists. This approach has not been considered in great detail in the literature so far and represents an exciting new avenue for future research.

- Mathematician Lara Anderson apporached F-theory via duality with the heterotic string. After a careful review of F-theory-heterotic duality in 8 and 6 dimensions, she presented new research results on a definition of the gauge data underlying an F-theory compactification based on this duality, in terms of a generalisation of the Deligne cohomology to singular spaces. This is clearly another important direction for future investigations.

- Physicist Roberto Valandro summarised progress in the understanding of massive abelian gauge groups and their gauge fluxes in F-theory, based on duality with Type IIB string theory. Massive U(1) symmetries manifest themselves in codimension-two singularities of the elliptic fibration which do not admit a crepant resolution, but only a non-Kahler resolution. An interesting interconnection to the theory of deformations as presented in Grassi's talk arose.

The remaining eleven[1] research presentations of 60 minutes each highlighted scientific progress in both the physics and mathematics of F-theory.

- Sakura Schafer-Nameki explained recent results on codimension-two fiber types in singular elliptic fibrations and their connection to the representation theory of the gauge algebra of the F-theory fibration.

- Thomas Grimm reviewed in detail the 6- and 4-dimensional effective field theory of M-theory compactified on elliptically fibered Calabi-Yau spaces in the F-theory limit. He also pointed out the importance of Spin-7 manifolds and gave an overview of recent results on higher curvature corrections of the effective action.

[1] James Halverson had to cancel his talk due to illness.

- This point was further elaborated on by Raffaele Savelli, who contrasted different approaches to the computation of subleading effects in the effective action of F-theory on $K_3 \times K_3$ and in more general situations.

- Andreas Braun and Taizan Watari both elaborated on the landscape of F-theory compactifications on K3-surfaces.

- Andre Lukas described recent advances in the construction of Standard Model-like string compactifications of heterotic string theory, which is related to F-theory by duality as introduced by Anderson's talk. Of central importance in this work is the computation of line bundle cohomology groups on Calabi-Yau threefolds in a manner that lends itself to an algorithmic search for realistic string compactifications.

- Fernando Marchesano focussed on local aspects of F-theory compactifications in the computation of physical Yukawa couplings by evaluating the overlap of wave functions associated with massless matter states. Exploiting the localisation of these states as well as non-perturbative effects due to D-brane instantons, a hierarchical structure of Yukawa couplings consistent with the values observed in the Standard Model can be obtained.

- Denis Klevers described the connection between the Mordell-Weil group of rational sections and the physics of abelian gauge groups in F-theory. Explicit examples of such fibrations with Mordell-Weil groups of rank two and three were constructed and applications to particle physics outlined.

- Luca Martucci constructed an $SL(2, Z)$ twisted 4-dimensional field theory inspired by the physics of D3-brane instantons within F-theory.

- Inaki Garcia-Etxebarria described the implementation of Seiberg-duality via the construction of field theories by branes at singularities in Type IIB and F-theory.

- The computation of the exact massless charged spectrum of an F-theory compactification with non-trivial 3-form data was the topic of Christoph Mayrhofer's talk. The 3-form data of an F-theory model is encoded in the Deligne cohomology group $H^4_{\mathcal{D}}(Y, \mathbf{Z}(\mathbf{2}))$, elements of which can in turn be described by the Chow ring of the 4-fold in a way accessible to concrete computations.

An important and very well-received element of the workshop was in addition a special discussion session moderated by Mirjam Cvetič. Various approaches to F-theory - from very mathematical to more applied and physics-oriented - were contrasted with each other and open questions for future reearch were highlighted in a very active and vivid debate.

# 3 Assessment of the results

The talks and discussions of the workshop fully achieved the intended goal of identifying completely new directions for future research. The majority of speakers presented brand-new or even unpublished and ongoing work. The workshop was therefore truly timely and highly inspiring.

The interactive nature of the presentations stimulated very active discussions about key scientific questions of interest both to physicists and mathematicians. To name but a few, new research directions begging for intense future investigations include in particular the following:

- The importance of genus-one fibrations whose associated Jacobian does not allow for a crepant resolution has become evident: These geometries have very different physical properties in F-theory compared to the much better studied case of elliptic fibrations. New types of gauge groups arise and the relation to existing compactifications is to be studied further.

- The possibility of studying the matter content of an F-theory compactification by deforming, as opposed to resolving, the singularities of the fibration offers exciting directions which have mostly been unexplored to date. This point was stressed in great detail both in the talks and also during the discussion session and constitutes a new key insight of this workshop.

- A further new direction of physical relevance and mathematical interest is a better understanding of the 3-form data in F-theory compactifications in terms of the Deligne cohomology. Very recent investigations of this idea were explained in great detail in various talks, and in addition analysed further in the discussion session. It has become clear to the workshop participants that an understanding of the 3-form data at a level comparable to the geometry of the fibration is an important task for the next few years.

Apart from such direct implications for future research the workshop has also offered young scientists the possibility of presenting their recent work in the form of a beautiful poster session, which fostered highly active discussions.

The feedback from the workshop participants was overwhelmingly positive. In particular, the anouncement of workshop participants Thomas Grimm and Dave Morrison to organise similar meetings on F-theory at the interface of string mathematics and particle physics in 2015 and 2016, respectively, was enthusiastically welcomed.

# 4 List of Participants

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| Lara Anderson | Virginia Tech |
| Elena Mirela Babalic | IFIN, Bucharest |
| Rodrigo Barbosa | University of Pennsylvania |
| Florent Baume | Universität Heidelberg |
| Florian Beck | Freiburg University |
| Mikel Berasaluce-Gonzalez | IFT-UAM/CSIC |
| Marco Bertolini | Duke University |
| Martin Bies | ITP Heidelberg |
| Federico Bonetti | MPI Munich |
| Volker Braun | Oxford University |
| Andreas Braun | King's College London |
| Kang-Sin Choi | Ewha Womans University |
| Mirjam Cvetic | University of Pennsylvania |
| Keshav Dasgupta | McGill University |
| Marco Fazzi | Université Libre de Bruxelles |
| Iaki Garca Etxebarria | Max Planck Institute for Physics |
| Antonella Grassi | UPenn |
| Thomas Grimm | MPI Munich |
| James Halverson | KITP Santa Barbara |
| Alexander Haupt | University of Hannover |
| Hirotaka Hayashi | IFT UAM/CSIC |
| Arthur Hebecker | Heidelberg |
| Onirban Islam | ITP, University of Heidelberg |
| Jan Keitel | MPI Munich |
| Denis Klevers | University of Pennsylvania |
| Sebastian Kraus | ITP Heidelberg University |
| Moritz Kuentzler | King's College London |
| Craig Lawrie | King's College London |
| Seung-Joo Lee | KIAS |
| Bum-Hoon Lee | Sogang University |
| Ling Lin | ITP Heidelberg |
| Andre Lukas | Oxford University |
| Patrick Mangat | ITP Heidelberg |
| Fernando Marchesano | IFT-UAM/CSIC |
| Luca Martucci | University of Padova |
| Damian Mayorga | Bonn University |
| Christoph Mayrhofer | Heidelberg |
| Miguel Montero | IFT UAM-CSIC |
| Dave Morrison | Santa Barbara |

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| Paul Oehlmann | Bonn University |
| Eran Palti | Heidelberg |
| Christian Pehle | University of Heidelberg |
| Hernan Piragua | University of Pennsylvania |
| Tom Pugh | MPI Munich |
| Diego Regalado | IFT UAM/CSIC |
| Ander Retolaza | IFT UAM/CSIC |
| Daniel Roggenkamp | Heidelberg |
| Fabrizio Rompineve | ITP, Heidelberg |
| Fabian Rühle | DESY |
| Raffaele Savelli | CEA Saclay |
| Sakura Schaefer-Nameki | King's College London |
| Sebastian Schwieger | ITP Heidelberg |
| Carlos Shahbazi Alonso | CEA-Saclay |
| Julius Shaneson | UPenn |
| Stefan Sjors | Heidelberg University |
| Peng Song | University of Pennsylvania |
| Radu Tatar | University of Liverpool |
| Oskar Till | ITP, Heidelberg |
| Roberto Valandro | ICTP |
| Roberto Valandro | ICTP Trieste |
| Irene Valenzuela | IFT UAM-CSIC (Madrid) |
| Taizan Watari | IPMU |
| Timo Weigand | Heidelberg |
| Anna Wienhard | Heidelberg |
| Lukas Witkowski | Heidelberg |
| Gianluca Zoccarato | IFT UAM/CSIC |

# Speakers and talk titles

| | |
|---|---|
| Lara Anderson (Virginia Tech) | “Geometric Constraints in Heterotic/F-theory Duality" |
| Andreas Braun (King's College, London) | “Classifying Elliptic Fibrations (on attractive K3 surfaces)” |
| Volker Braun (Oxford University) | “F-Theory With and Without Sections” |
| Inaki Garcia-Etxebarria (MPI Munich) | “Towards Seiberg duality in F-theory” |
| Antonella Grassi (University of Pennsylvania) | “Matter from geometry without resolution” |
| Thomas Grimm (MPI Munich) | “Recent progress for F-theory effective actions” |
| James Halverson (KITP Santa Barbara) | “Non-abelian Gauge Symmetry and the Higgs Mechanism in F-theory” |
| Denis Klevers (University of Pennsylvania) | “Recent Progress on F-Theory with Multiple U(1)s” |
| Andre Lukas (Oxford) | “Heterotic Line Bundle Models“ |
| Luca Martucci (University of Padova) | “Brane instantons in F-theory and the topological duality twist” |
| Fernando Marchesano (IFT-UAM/CSIC) | “Yukawas in F-theory GUTs” |
| Christoph Mayrhofer (Heidelberg University) | “U(1) Symmetries, SU(5)-Tops and Gauge Data from Chow groups” |
| Dave Morrison (UC Santa Barbara) | “Studying F-theory via M-theory” |
| Raffaele Savelli (Saclay, Paris) | “From M-theory higher curvature terms to \alpha' corrections in F-theory” |
| Sakura Schäfer-Nameki (King's College, London) | “Box Graphs and Singular Fibers” |
| Roberto Valandro (ICTP Trieste) | “Fluxes and U(1)s from stable Sen limit” |
| Taizan Watari (IPMU, Tokyo) | “Noether-Lefschetz problem and gauge-group-resolved landscape” |

| Time | Monday | Time | Tuesday | Time | Wednesday | Time | Thursday |
|---|---|---|---|---|---|---|---|
| 7:30-9:00 | Registration | 7:30-9:00 | | 7:30-9:00 | | 7:30-9:00 | Departure Organisation |
| 9:00-10:30 | V. Braun | 9:00-10:30 | Morrison | 9:00-10:30 | Anderson | 9:00-10:30 | Valandro |
| 10:30-11:00 | Coffee Break | 10:30-11:00 | Coffee Break/ Poster Session | 10:30-11:00 | Coffee Break | 10:30-11:00 | Coffee Break |
| 11:00-12:00 | Schafer-Nameki | 11:00-12:00 | Lukas | 11:00-12:00 | Watari | 11:00-12:00 | Mayrhofer |
| 12:00-13:00 | Grimm | 12:00-13:00 | Marchesano | 12:00-13:00 | Klevers | 12:00-13:00 | Garcia-Etxebarria |
| 13:00-14:30 | Lunch at IWH | 13:00-14:30 | Lunch at IWH/ Poster Session | 13:00-14:30 | Lunch at IWH | 13:00-14:30 | Lunch at IWH |
| 14:30-15:30 | Savelli | 14:30-16:00 | Grassi | 14:30-15:30 | Martucci | | |
| 15:30-15:45 | Coffee Break | 16:00-16:30 | Coffee Break/ Poster Session | 15:30-15:45 | Coffee Break | | |
| 15:45-16:45 | A. Braun | 16:30-17:30 | Halverson | | Discussion | | |
| | | | Poster Session | | | | |
| | Reception 17:00-18.30 at IWH | | | | Conference Dinner 19:00 (Restaurant Backmulde) | | |