string data 2025

Monday 8 December 2025 - Wednesday 10 December 2025

Book of Abstracts

Contents

1

Neural Network Bootstrap for Finite Temperature CFTs

Author: Costis Papageorgakis[1]

[1] *Queen Mary University of London*

I will present a new bootstrap method for conformal field theories at finite temperature that uses neural networks to capture infinite operator contributions without positivity constraints or truncations. The approach combines the KMS condition, thermal dispersion relations, and neural networks that learn the high-spin behaviour of the thermal block expansion. I will demonstrate the method on generalised free fields and apply it to thermal corrections in holographic CFTs. This neural network approach bypasses traditional computational bottlenecks in finite temperature bootstrap calculations.

2

Searching for new Special Lagrangians with Quality-Diversity Optimization

Authors: Fabian Ruehle[1]; Hamza Ahmed[1]; Yidi Qi[1]

[1] *Northeastern University*

Special Lagrangian (sLags) submanifolds are crucial objects for string phenomenology and the SYZ conjecture, yet their explicit construction remains a significant challenge in geometry. In this talk, we introduce a novel computational framework to tackle this problem. Our approach leverages a Quality-Diversity (QD) search algorithm to navigate families of parametrized geometries. This method is engineered to simultaneously reward approximations of the sLag condition while maximizing geometric diversity. Our preliminary findings showcase the potential of this QD framework as a powerful new tool in the ongoing search for novel sLag constructions.

3

Physics-Informed Neural Networks for Holographic Minimal Surfaces: Instanton Effects and Topology Change in Gluon Scattering

Authors: Gakuto Ogiwara[1]; Koichi Kyo[2]; Koji Hashimoto[2]; Masaki Murata[1]; Norihiro Tanahashi[2]

[1] *Saitama Institute of Technology*

[2] *Kyoto University*

We describe two related developments at the intersection of string theory, holography, and scientific machine learning. First, we develop a flexible physics-informed neural network (PINN) framework to solve boundary value problems for minimal surfaces in curved spacetimes, with a particular emphasis on handling singular geometries and moving boundaries. The method encodes the governing equations and boundary conditions directly into the loss, enabling accurate solutions for challenging setups relevant to AdS/CFT. Second, we analyze instanton effects on gluon scattering amplitudes in N=4 supersymmetric Yang–Mills theory at strong coupling and large N. Using the holographic Wilson-loop minimal surface description of these amplitudes, we find that in the presence of instantons the relevant worldsheets can undergo nontrivial topology change. We outline how the PINN framework can be adapted to capture such topology-changing configurations and boundary

dynamics, providing a practical computational tool for exploring instanton-corrected holographic observables. This joint perspective demonstrates the promise of data-driven approaches for reconstructing minimal surfaces in singular spacetimes and for quantifying nonperturbative effects in gauge/string duality, with applications to precision studies of scattering amplitudes and related observables.

4

Recent Progress on Axions in String Theory

Author: David Marsh[1]

[1] *King's College London*

The past few years have seen major advances in understanding the properties of axions in string theory. This progress is thanks to new computational tools that allow for fast and automated calculations with Calabi-Yau manifolds. I will describe the predictions string theory makes for axion masses, decay constants, and axion-photon couplings, and how these depend precisely on the topology of the Calabi-Yau. I will describe explicit constructions of fuzzy dark matter, and detailed calculations relating to decaying heavy axions, both of which seem to point to a preference for low reheating temperatures in cosmology. Lastly, I will describe the correlation between QCD axion mass and topology, and how this makes it possible for axion haloscopes to experimentally test the string theory landscape.

5

Solving inverse problems of Type IIB flux vacua with conditional generative models

Author: Zhimei Liu[1]

[1] *University of Cambridge*

We address the inverse problem in Type IIB flux compactifications of identifying flux vacua with targeted phenomenological properties such as specific superpotential values or tadpole constraints using conditional generative models. These machine learning techniques overcome computational bottlenecks in traditional approaches such as rejection sampling and Markov Chain Monte Carlo (MCMC), which struggle to generate rare, finely-tuned vacua. As a proof of concept, we demonstrate that conditional generative models provide a more efficient alternative, specifically using conditional variational autoencoders (CVAEs). We introduce a CVAE framework tailored to flux compactifications, incorporating physical constraints directly into the loss function —enabling the generation of physically consistent vacua beyond the training set. Our experiments on conifold and symmetric torus background geometries show that the CVAE achieves a speedup of about O(10ˆ3) compared to Metropolis sampling, particularly in narrow target ranges for superpotential values. Additionally, the CVAE generates novel, distinct flux configurations beyond the training data, highlighting its potential for probing computationally challenging regions of the string landscape. Our results establish conditional generative models as a powerful and scalable tool for targeted flux vacua generation, opening new pathways for model building in regions of the landscape previously inaccessible by traditional model building techniques.

6

BART-L: Towards a Foundation Model for Theoretical High-Energy Physics

Authors: Eliel Camargo-Molina[1]; Yong Sheng Koay[None]

Co-authors: Rikard Enberg ; Stefano Moretti [2]

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Transformers excel at natural language processing, raising the question of whether they can also learn the mathematical structures underlying particle physics. We introduce BART-L, a transformer-based model trained to generate particle physics Lagrangians from field content and symmetry information. Trained on Lagrangians consistent with the Standard Model gauge group SU(3)×SU(2)×U(1), BART-L achieves over 90% accuracy for expressions involving up to six matter fields. Embedding analyses indicate that the model internalizes concepts such as group representations and conjugation operations, despite not being explicitly trained for them. We further study its out-of-distribution performance to identify architectural factors limiting generalization. This framework provides an early indication of what a foundation model for theoretical high-energy physics might look like, along with its potential capabilities and inherent limitations.

7

AInstein, atlas architecture vs embedding architecture

Author: Tancredi Schettini Gherardini[1]

[1] *University of Bonn*

A numerical scheme based on semi-supervised machine learning, "AInstein", was recently introduced (see https://iopscience.iop.org/article/10.1088/3050-287X/ae1117) to approximate generic Riemannian Einstein metrics on a given manifold. Its versatility stems from encoding the differentiable structure directly in the loss function, making the method applicable to manifolds constructed in a "bottom-up" fashion that admit no natural embedding in R^n.
After a brief review of the original AInstein model, we focus on a new architecture, adapted to the special case of real (n-1)-dimensional manifolds that can be embedded in R^n; this has the advantage that the neural-network ansatz is automatically globally defined. We present novel preliminary results obtained with the new architecture, concerning two open problems: the Kazdan–Warner (prescribed curvature) problem on S^2 and the existence of negative-curvature metrics on S^4, S^5. Finally, if time permits, we will briefly comment on a further ongoing extension of AInstein to Lorentzian metrics and black holes.

9

Structure-Induced Interpretability in Kolmogorov–Arnold Networks

Kolmogorov-Arnold Networks exhibit several properties beneficial to scientific discovery. I will outline these properties and show how they can be leveraged to build more interpretable AI models, which I will illustrate with an example from representation theory. I will also discuss how the intrinsic structure of KANs facilitates symbolic regression by employing ideas similar to Google's fun-search. Incorporating LLMs and vision transformers into the regression workflow allows for priming the NN with domain-specific symbolic regression targets. Finally, I will describe how KAN's intrinsic structure can be thought of as arising from wide, dense neural networks that have been sparsified in a specific way, and I will speculate on how this structural perspective relates to desirable empirical properties of KANs.

10

AdS-GNN: A conformally equivariant neural network

One important organizing principle for building such neural networks is that of symmetry, i.e. the idea that the symmetries of the problem should be encoded in the architecture of the network. I will provide an introduction to the resulting field of "geometric deep learning". I will then discuss our construction of a neural network that transforms nicely under the conformal group, i.e. the set of transformations that preserve angles. I will describe how our construction leverages some of the kinematics of the AdS/CFT correspondence of quantum gravity, with potential applications to problems in computer vision and critical phenomena. Based on 2505.12880 with Maksim Zhdanov, Erik Bekkers, and Patrick Forré.

11

Building a Calabi-Yau Generator

Fine, regular, and star triangulations (FRSTs) of four-dimensional reflexive polytopes give rise to toric varieties, within which generic anticanonical hypersurfaces yield smooth Calabi-Yau threefolds. We introduce CYTransformer, a deep learning model based on the transformer architecture, to automate the generation of FRSTs. We demonstrate that CYTransformer efficiently and unbiasedly samples FRSTs for polytopes across a range of sizes, and can self-improve through retraining on its own output. These results lay the foundation for AICY: a community-driven platform designed to combine self-improving machine learning models with a continuously expanding database to explore and catalog the Calabi-Yau landscape.

12

Deep Finite Temperature Bootstrap

We introduce a neural network-based method to bootstrap crossing equations in Conformal Field Theory at finite temperature. Traditional approaches relying on positivity constraints or truncation schemes that discard infinite towers of operators are not applicable to this problem. Instead, we use MLPs to model spin-dependent tail functions that capture the combined contribution of infinitely many operators. The method formulates the Kubo-Martin-Schwinger (KMS) condition as a non-convex optimisation problem, combining thermal dispersion relations with neural network representations of the unknown data. We demonstrate the approach on Generalized Free Fields and apply it to extract double-twist thermal data in holographic CFTs.

13

Tancredi

14

PhysLean: Digitalizing physics into Lean

This talk will discuss an open-source, community run, project called PhysLean, which aims to write physics into the interactive theorem prover Lean 4. That is, a computer programming language where

mathematical correctness is guaranteed. There are numerous benefits to this endeavor including correctness, searchability of results, and the ability to interact with AI in a way safe from (certain) hallucinations.
In this talk, I will give an overview of this project, and briefly discuss its use in String theory.

15

Ricci-flat Calabi-Yau metrics and Yukawa couplings

16

Sampling IIB Flux Vacua Using Generative Models

We discus the application of two types of generative models are applied to the construction of ISD flux vacua of type IIB string theory. The models under study are Bayesian Flow Networks (BFNs) and Transformers. We find that both models demonstrate good performance, in particular on interpolation and conditional sampling. Some extrapolation capabilities are observed, which could be leveraged in future studies to generate flux vacua in less well explored settings.

17

Deep Reinforcement Learning for Fano Hypersurfaces

In this talk, we show how deep reinforcement learning can be used to overcome the computational challenges faced by conventional search algorithms in the discovery of new Fano hypersurfaces.

By the Minimal Model Program, varieties can be reduced to three building blocks: Fano, Calabi-Yau, and general type varieties. The building blocks have singular points, which have a property known as terminality. By a result of Birkar there are only finitely many Fano varieties with terminal singularities per dimension, and so one can construct 'periodic tables'. Tables are complete in dimensions 1, 2 and partially in 3. Little is known in dimension 4.

My work aims to classify terminal Fano 4-fold hypersurfaces. There are two obstacles, however; determining terminality is difficult and computationally expensive, and the occurrence of terminal examples is sparse in a vast search space. Together, this makes the discovery of new examples difficult.

I will discuss how creating a deep reinforcement learning search architecture allowed me to find 70,000 examples in under an hour from the 10,000 I was able to produce in days using conventional methods. Interestingly, from nearly all of the examples we have discovered so far, we are able to construct associated nontoric Calabi-Yau 3-fold hypersurfaces with canonical singularities. Their ambient weighted projective spaces are nonreflexive polytopes, and thus are not necessarily in the famous Kreuzer-Skarke list of 473,800,776.

18

Learning the Landscape: Differentiable Frameworks for String Theory

String theory naturally gives rise to vast, high-dimensional datasets, yet systematic investigations of this landscape has long been impeded by the complexity of moduli spaces, quantum corrections, and the vastness of flux configurations. In this talk, I present new differentiable frameworks for string compactifications that combine automatic differentiation, and ML-based inference to construct and analyse four-dimensional effective theories. These pipelines enable controlled moduli stabilisation, incorporate strong coupling corrections, and allow efficient searches for phenomenologically relevant vacua, including regimes with small cosmological constant and rich axion sectors. By integrating analytic insights with scalable computational tools, this approach transforms the study of the string landscape into a quantitative and data-driven enterprise, opening new avenues for connecting quantum gravity to observable physics.

19

The First Large-Scale Computation of the Gukov–Manolescu Series

The Z-hat invariant defined by Gukov–Pei–Putrov–Vafa is a BPS-counting q-series built from Calabi–Yau geometry, whose values at roots of unity recover the Witten–Reshetikhin–Turaev invariants of 3-manifolds. In this talk, I will review a construction for its knot-theoretic counterpart, the Gukov–Manolescu series F_K, and present the first large-scale computation of F_K for 1,246 knots, obtained via an extensive search in the braid space and a fast C++ implementation of the F_K state-sum model.

20

Learning some Physics and Maths

In this talk, I present new results on (machine) learning of physics and mathematics. First, we report on advancements in training flow-based models to simulate quantum field theories (QFT). We advocate adopting physics-inspired generation paths and exploiting the physics information gained by learning such flows. The latter can be applied to simulate continuous families of theories in one go, and leads to novel and efficient methods to compute connected correlation functions. Second, in the domain of mathematical physics, we analyze datasets consisting of infinite q-series, which appear as QFT partition functions, topological invariants, or quantum modular forms. We introduce a data-analysis pipeline designed to represent, manipulate, and interpret this data. As concrete examples, we analyse how a classifier learns the homology groups of three-manifolds, and present evidence of unexpected relations between specific three-manifold topological invariants and cobordism invariants. The first part will be based on work done with Tobias Göbel and Mathis Gerdes, while the second based on work with Brandon Robinson, Shimal Harichurn, Fabian Ruehle, Sergei Gukov, and Rak-Kyeong Seong.

21

Deep Learning based discovery of Integrable Systems

Integrable systems are exactly solvable models that play a central role in QFT, string theory and statistical physics offering an ideal setting for understanding complex physical phenomena and developing novel analytical methods. However, the discovery of new integrable systems remains a major open challenge due to the nonlinearity of the Yang–Baxter equation (YBE) that defines them, and the vastness of its solution space. Here we present the first AI-based framework that enables the discovery of new quantum integrable systems in exact analytical form. Our method combines an ensemble of neural networks, trained to identify high-precision numerical solutions to the YBE, with an algebraic extraction procedure based on the Reshetikhin integrability
condition, which reconstructs the corresponding Hamiltonian families analytically. When applied

to spin chains with three- and four-dimensional site spaces, we discover hundreds of previously unknown integrable Hamiltonians. Remarkably, these Hamiltonians organize into rational algebraic varieties, and we conjecture that this rationality holds universally —revealing a deep and previously unexplored connection between quantum integrability and algebraic geometry. By unlocking integrable systems far beyond the reach of traditional methods, this AI-driven approach substantially expands the landscape of exactly solvable models and opens a scalable path to further discoveries.

22

Machine Learning Aspects of Gravity

From holography, we know that gravitational systems have codimension one degrees of freedom. Through a number of experiments, we use machine learning to study physical and mathematical aspects of black hole entropy.

23

Talk

24

Welcome

25

QM, SUSY, and Outlook in NN-FT

I'll review the essentials of a neural network approach to defining and studying field theories, listing previous results related to symmetries, conformal symmetry, locality, interactions, etc. The focus of the talk will be on two 2025 papers, one related to QM, and the other related to fermions and SUSY. The QM results include a universality theorem, a new construction of Euclidean QM theories with deep neural networks, and the recovery of cherished properties from QM, such as Heisenberg uncertainty and the spectrum of the harmonic oscillator. The fermion and SUSY results include the definition of Grassmann-valued neural networks and their use in constructing fermionic NN-FTs, including the free Dirac spinor in an infinite width limit. With fermions in hand, I will also present a new construction of interacting supersymmetric theories in 1d and 4d. I'll try to devote a significant portion at the end for outlook and also getting feedback from friends.

26

Introduction: Outward facing afternoon

27

Is AI like hadron physics?

Machine learning (ML) systems fueled by neural networks have entered our daily lives and led to scientific breakthroughs, but many open questions remain. After a nod toward the question of rigor with ML and recent progress, I'll turn to the theory of neural networks. I will argue that understanding neural networks inevitably leads to ideas from quantum field theory, the theoretical framework underlying much of modern physics. This connection was realized in the simplest case in the 1990s. I will then propose that the connection might be more general, an NN-FT correspondence of sorts, with neural networks providing a way to define a field theory. The apparent non-sequitur in the title will be used as a rhetorical device to explore where we are and where we'd like to go.

28

Panel Discussion

29

Chasing the Standard Model within heterotic line bundle constructions

In this talk, we explore the phenomenological potential of heterotic line bundle models as a promising framework for deriving the Standard Model from string theory. We present a systematic approach to constrain the low-energy effective theories derived from such compactifications using remnants of anomalous U(1) symmetries to retrieve realistic quarks and leptons masses, mixing patterns and light Higgs. We show that these features emerge in specific regions of moduli space, where vacuum expectation values of geometric moduli and bundle singlets eventually align to suppress unwanted R-parity violating couplings. This work underscores the viability of heterotic line bundle models as a pathway to connecting string theory with observable particle physics.

30

Wrap up