

MAP-fis Essay Proposal, 2020-2021

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Title

Black hole shadows, the Kerr hypothesis and fundamental physics

Area

(Materials, Optics, Condensed Theory, High Energy Theory,...);

Strong Gravity

Summary of Proposal

The Event Horizon Telescope (EHT) produced in 2019 the first image of a black hole candidate with resolved horizon scale structure. Imaging the strong gravity region around such compact objects can test the Kerr hypothesis. This hypothesis states that astrophysical black holes are well described by the paradigmatic Kerr solution. In the last few years, new black hole solutions and horizonless compact objects have been proposed considering the interaction with novel ultralight bosonic particles, which can work as a proxy for dark matter. The goal of this project is to study the strong gravitational lensing by this non-Kerr compact objects, using ray tracing codes and General Relativistic Magneto-Hydrodynamic simulations, to obtain images that can be compared

with the EHT data. This will constraint models of ultralight bosonic fields and possibly shed new light on the nature of dark matter.

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Event Horizon Telescope (EHT)

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Black hole shadows

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Black hole hair and ultralight bosonic fields

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Title

Collider, neutrino and dark relics of Grand Unification with Deep Learning

Area

(Materials, Optics, Condensed Theory, High Energy Theory,...);

High-Energy Physics

Summary of Proposal

Our current understanding of subatomic phenomena is encoded in the Standard Model (SM) of particle physics, one of the most accurate scientific models to be devised in the natural sciences, whose predictions have matched the stringiest of tests, culminating with the discovery of a fundamental and neutral scalar particle, the Higgs boson.

While its remarkable and undeniable success can not be understated, its shortcomings, however, can not be ignored. For all its perks, the SM fails to explain the experimental observation of neutrino flavor oscillation, the lack of a viable candidate (fundamental or composite) for Dark matter (DM), among others. These issues provide justification towards the augmentation of the SM, with new physics beyond the electroweak scale.

In the thesis, we will perform studies in a novel three-Higgs doublet model (3HDM) inspired by a unified framework, that simultaneously addresses the flavour problem in the SM and unifies all particles and interactions. Said model is inspired by the $E_6 \times SU(3)_F$ direct product group. New physics is emergent from the low-energy limit, including Majorana neutrinos, new scalars and new vector-like fermions. New physics models can come with the undeniable reality of more model parameters which can easily become overwhelming. A smarter approach on addressing these problems may involve the use of Deep-Learning (DL) techniques and other optimization algorithms to find the best parameter space. Not only that, but DL tools are particularly useful in collider phenomenology, where the impact of SM backgrounds can overshadow new physics signals. The techniques may involve combination of DL and Computer Vision.

With this in mind, the student is expected to perform a critical review into the current constraints and associated phenomenology of the aforementioned BSM states, as well as a look into the current state of art of the usage of DL, in particular, to the tools that have been recently employed, or that show great promising, in the high-energy physics community.

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Title

Causality in Lorentzian CFTs

Area

(Materials, Optics, Condensed Theory, High Energy Theory,...);

Conformal Field Theories, AdS/CFT Correspondence and High Energy Theory

Summary of Proposal

A Conformal Field Theory (CFT) is defined by its spectrum, more precisely by the scaling dimension and spin of its primary operators, and by the coefficients in their Operator Product Expansion (OPE). All correlation functions of local operators are determined by this CFT data, via

recursive use of the OPE. This is a non-perturbative definition of these theories leading to the bootstrap idea that aims at fixing (or constraining) CFT data by imposing consistency conditions like unitarity, OPE associativity and existence of a stress tensor.

Recently there has been an increasing interest in studying correlation functions of more than four points. While the latter can count the whole story about a given theory if they are all known, higher-point functions provide an alternative path to fix CFT data. They contain more involved conformal block decompositions but also probe more physical quantities such as OPE coefficients between exchanged operators. This suggests that if we are able to extend causality constraints to higher-point functions, this path may be fruitful in constraining, for instance, the OPE coefficient between three stress tensors, having implications in the formulation of the effective action of dual gravity theories. In this essay, we review the state of the art regarding higher-point functions and causality constraints derived for four-point functions and we draw the plan for a research that aims to extend this knowledge.

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MAP-fis Essay Proposal, 2018-2019

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Title

Investigation of quantum effects in the energy and charge transport in photosynthesis systems by means of quantum simulations

Area

(Materials, Optics, Condensed Theory, High Energy Theory,...);

Biophysics, Condensed Matter Theory, Quantum Simulation

Summary of Proposal

As quantum computation becomes increasingly powerful, both in hardware and software, the number of real-world applications also grows. The development and application of quantum simulation algorithms is an active research field. This project aims to contribute to it by studying quantum effects in biological systems and novel biomimetic materials through quantum simulation. Modelling of the dynamics of light-harvesting processes in photosynthetic systems, focusing on energy and charge transport is the main research theme, which will be addressed by means of theory and quantum simulation. This area is closely related to the physics of open quantum systems, where quantum simulations are in the initial stage yet. Many-body quantum effects require large computational resources to simulate the system of interest interacting with its environment and quantum simulations promise a computational speedup. Therefore, I aim to investigate quantum-physical effects in biosystems and biomimetic materials by means of developing and applying quantum algorithms. The essay will overview relevant theoretical backgrounds and recent advances in quantum simulations of such systems.



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Title

Towards ultrafast and ultra-compact lasers: uncovering ultrashort pulse generation mechanisms in semiconductor lasers with novel characterization approaches.

Area

(Materials, Optics, Condensed Theory, High Energy Theory,...);

Ultrafast Optics; Nonlinear Optics

Summary of Proposal

Semiconductor ultrafast lasers offer tremendous potential as compact, low-cost and efficient sources of ultrashort pulses, which would benefit applications in LASIK, biomedical imaging, spectroscopy and communications. Quantum-dot lasers have shown particularly promising features, potentially enabling the generation of pulses with 100fs or less. However, the current inability to fully understand their chirp, stability and coherence poses a strong limitation to understanding and harnessing their unique physics. A new technique, based on the dispersion-scan principle, will be developed and used to fully characterize ultrashort pulses in these lasers. Their challenging instabilities will be investigated for the

first time, leading to a better understanding of their fundamental dynamics. In conjunction with the investigation of amplification dynamics, this project aims to create the new knowledge and tools to empower the generation of high-power ultrashort pulses with 100fs or less from semiconductor lasers, which would dramatically widen access to ultrafast applications across the world.

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