Research project for an M2 stage:
The black hole evaporation puzzle and holography

Advisor: Federico Piazza, CPT, Marseille
Candidate: Alexander Taskov

1 Status of the field

Black hole evaporation seems to contradict unitary evolution [1]. During the last decade, considerable progress has been made towards the resolution of this puzzle (see [2] for a relatively up do date review). The path has been indicated by studies of holography and the AdS/CFT correspondence, but the mechanism is believed to apply also to the asymptotically flat case. A surprising and fascinating aspect of this resolution is the understanding that some of the degrees of freedom inside the black hole that in the naive calculation of Hawking are entangled with the outgoing radiation are, at a more profound level, *encoded* in it [3]. Rather than belonging to two different Hilbert spaces, they should be thought of as belonging to the same Hilbert space.

2 Aim of the internship

The amount of knowledge needed to actively research in this field is very large. Therefore the aim of this internship is first and foremost that of becoming familiar with the vast existing literature on the subject. I also envision regular journal clubs/seminars (ideally, two or three during the four months of the stage) that the candidate should make in order to share his advancements not only with me, but also with the interested other researchers in the lab. The newly discovered features of quantum gravity at low energy that this approach indicates could have implications in other neighboring fields, such as cosmology. The research will be carried out with particular attention to possible cosmological applications, along the lines e.g. of the very recent [4].

References

[1] S. W. Hawking, "Breakdown of Predictability in Gravitational Collapse," Phys. Rev. D **14** (1976), 2460-2473 doi:10.1103/PhysRevD.14.2460

[2] A. Almheiri, T. Hartman, J. Maldacena, E. Shaghoulian and A. Tajdini, "The entropy of Hawking radiation," Rev. Mod. Phys. **93** (2021) no.3, 035002 doi:10.1103/RevModPhys.93.035002 [arXiv:2006.06872 [hep-th]].

[3] D. Harlow, "TASI Lectures on the Emergence of Bulk Physics in AdS/CFT," PoS **TASI2017** (2018), 002 doi:10.22323/1.305.0002 [arXiv:1802.01040 [hep-th]].

[4] R. Bousso and E. Wildenhain, "Islands in Closed and Open Universes," [arXiv:2202.05278 [hep-th]].

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9th December 2021

Dr Tim Evans PhD (Senior Lecturer)

Dear Colleague,

This is a reference for Mr Alexander TASKOV who was a student on our MSci Physics course here at Imperial, graduating in the summer of 2021. I was his supervisor on his final year project, which is done over the whole academic year working with another student.

The project is looking at the meaning of distance in directed acyclic graphs, and starts from ideas about geometry familiar from physics, such as in special relativity, but takes this off in directions well outside the Physics course, covering more general ideas about geometry and distance along with applications in discrete systems such as graphs/networks. The focus of the project is to develop numerical implementations and experiments based on these new ideas. Alex made good progress and coped with all the new concepts.

All our interactions have been online making it harder to evaluate. Alex has shown an interest in the theoretical and algebraic side of the project and shown a lot of initiative reading outside the project in this area. Very unusual for such project students, he has been trying to push these ideas forward on his own using these ideas. Discussing such ideas in online meetings I find particularly difficult; you really need a blackboard for such discussions. In any case, this aspect is really a PhD level task that would take several months so the fact that Alex was working on the ideas in this way and making some progress was highly commendable. He also supplemented this with some good numerical work which is usually the core of my undergraduate project. Our discussions online have been very good and he will be an active participant in any course. I gave him very high marks for the project though I do not participate in the main assessment, on a formal report of the project, so I am not aware of the final grade.

Alex graduated this year with a first class degree (our top level). His distribution of marks shows a two-peaked distribution. One peak is the low-mark peak for courses where he appears not to have been motivated to perform e.g. experimental courses. The other a very high first-class peak and this includes the more theoretical courses such as Group Theory, maths courses, Quantum Field Theory, Unification, and General Relativity. General Relativity stands out as it is a course which students normally take in their fourth year as it is usually too challenging to take it in their third year as Alex has done but and Alex was very successfully in his GR course. In the more advanced theoretical courses Alex has typically had marks in the top 20% of the class. We have 150 or so students each year in our fourth-year course which is usually done by our strongest students and as one of the top Universities in the UK, that places Alex at the very top. So, I conclude from this that on the right type of postgraduate course, theoretical and mathematical, Alex is a strong candidate.

I recommend him strongly to you.

Please contact me if you need further information.

Yours faithfully,

Tim Evans

Imperial College of Science, Technology and Medicine

I am an M2 physics student from Aix-Marseille's fundamental physics program, and I am applying to the M2 internship: On aspects of black hole evaporation and holography. My interest in the field of quantum gravity (specifically black hole information and thermodynamics) began in my L2, and has led me to various research projects at the intersection of thermodynamics and relativity, as well as high grades in relevant theoretical courses.

My first couple of projects had two specific motivations: 1. to investigate how simple relationships between quantum and statistical mechanics generalize in a relativistic setting, and 2. to better understand the tools necessary for probing spacetimes as thermodynamic systems.

In my last project I constructed the simplest possible random walk on Minkowski spacetime, then derived a manifestly Lorentz covariant PDE describing its continuous limit. Studying the PDE's symmetries and conservation laws revealed that it admits a thermal "arrow of time" dependent on initial conditions, explaining physically how one can have a non-hyperbolic second order PDE in a relativistic system. This arrow of time can be used to construct a "time evolved" distribution, whose PDE is similar to the KGE. Wick rotating (proper) time then returns the KGE exactly.

In another project I derived a manifestly Lorentz invariant canonical ensemble from the conservation of four-momentum, demonstrating the existence of an inverse-four temperature. This distribution not only agreed with the classical limit, but also the computationally verified Maxwell Jüttner distribution. I then used symmetry to argue that the inverse four temperature behaved like an arrow of time for the system (reminiscent of the last investigation).

My MSci (M1 equivalent) project was on the geometry of directed acyclic networks, and was supervised by Dr. Tim Evans of the Imperial College London theoretical physics group. In this project I studied how information flowed in networks with a causal structure that, in the dense limit, approximated Minkowski spacetime. In particular, I learned about how discrete propagators, diffusion metrics, and geodesic algorithms generalize to the discrete case, as well as the basics of the relationship between conformal transformations and spacetime topology.

I also have lots of training in general relativity and quantum mechanics. Not only did I achieve a 20/20 in my general relativity course last semester, but also a high grade on an introductory general relativity course in my L3, and informally took the MSc black holes course from Imperial's QFFF in my M1. I am also currently taking a doctoral course on the field theory of relativity here at Aix-Marseille.

On the quantum side, I was top of the class in quantum field theory last semester, and am currently taking the advanced quantum mechanics course on path integrals and quantum information this semester. I also achieved high grades in introductory quantum information and quantum field theory courses in my M1.

During my M1 I also learned about spacelike, timelike, and null hypersurfaces, and the Raychaudhuri equation from E. Poisson's "Tools for Relativists", and the basics of the problem of conservation in general relativity from G. Compère and A. Fiorucci's lectures on general relativity.

I have thus been training to do exactly this type of project for many years, and in that time not only achieved a firm grasp on the basic tools necessary for this purpose, but through various research projects also a unique set of perspectives on the intersection of information, thermodynamics, and general relativity.

Thank you very much for considering my application,

Alexander Taskov

Taskov, Alexander

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13005 Marseille
France
Website iff3.github.io

Education

2021-09 - 2022-05

Aix-Marseille University

M2 Fundamental Physics Program, 19.5/20 (1st semester)

M2 Modules in Progress:
Advanced Quantum FIeld Theory; Standard Model and Gauge Theory; Advanced Quantum Mechanics; Computational Modeling;

Doctoral Modules in Progress:
Field Theory of General Relativity; Renormalization and Effective Field Theory

60 ECTS

2017-10 - 2021-06

Imperial College London

MSci Physics with Theoretical Physics, First Class

246 ECTS

Scientific Writing

2021-06

A Simple Model of Brownian Motion in Spacetime

- Known constraints on the nature of Brownian processes in spacetime are used to construct the simplest possible relativistic random walk model
- Einstein's method is used to derive a PDE for the model
- The symmetries and conserved currents of the PDE are analyzed using standard methods
- The expected analogies with quantum mechanics are shown to hold in a novel way

2019-08

A Relativistically Invariant Formulation of The Canonical Ensemble

- Four-momentum conservation is used to derive a relativistically invariant canonical ensemble featuring an inverse four temperature
- Symmetry arguments are used to show that the four-temperature corresponds to a natural arrow of time
- The relationship between entropy extremisation and symmetry is discussed
- "Off-shell thermodynamics" is shown to resemble basic relativistic quantum mechanics

2021-05

An Exploration of Possibly Natural Geometries on Directed Acyclic Graphs

- Graph matrix notation is used to generalise the communicability and diffusion metrics from undirected graphs to directed acyclic graphs
- Python simulations are used to demonstrate that path algorithms must introduce a secondary length scale to reproduce Lorentzian geometry from certain directed acyclic graphs

Miscellaneous Notes

- Decoherence at Killing Horizons
- Fractal Dimension Path Integral
- An Introduction to Random Geometric Graphs for Physicists
- Matrices of Derivative Operators

All writings available at iff3.github.io

Work and Volunteering

2018-10 - 2021-06

Maths and Physics Tutor

Freelance

15 students over three years
11+, GCSE, AS/A level maths, further maths, and physics, guitar
explained complex concepts concisely and simply

2019-10 - 2020-03

Secretary and Chief Events Officer

Imperial College London Live Music Society

Organised setup, running, and takedown of live music events in small teams (3-7 people)
Responsibile for sound checking and live mixing musical acts
Resonsible for corresponding with society members, venue administrators, Imperial College's student union, and other societies
Requires initiative, team collaboration, critical and creative problem solving, and attention to detail

Miscellaneous Skills and Hobbies

Programming

- Fluent in Python (numpy/scipy, matplotlib, pygame)
- Basic experience with C++ (standard library, boost graph library)
- Basic experience with Cython

Music

- Grade 8 Piano (2017)
- Casual guitar and vocals

Music Writing and Production

- B Minor for Piano (original piece)
- E♭ Major for Piano (original piece)
- Experienced sound mixing in Reaper and Audacity
- Experienced sound mixing with a Behringer X32 mixing desk

Languages

- French (Beginner)

Original scores available at iff3.github.io

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Academic Transcript

Student Details

Family name:	Taskov
Given name(s):	Alexander
Date of birth:	05 November 1999
Level:	Undergraduate
Imperial student ID:	01346808
HESA student ID:	
Start date:	30 September 2017
Completion date:	25 June 2021

Award

Award:	Master in Science (MSci)
Awarding institution(s)	Imperial College London
Classification:	First Class Honours
Overall mark:	71.14
Conferral date:	01 August 2021

Programme of Study

Programme title: Physics with Theoretical Physics
Department: Department of Physics

Module:	Year:	Mark:	Credit:
Electricity and Magnetism and Relativity	2017-2018	69.00	7.50
Laboratory and Computing I	2017-2018	52.00	9.00
Mathematical Analysis	2017-2018	83.00	4.00
Mathematics I	2017-2018	74.00	15.00
Mechanics, Vibrations and Waves	2017-2018	58.00	8.00
Physics Year 1 Total	2017-2018	66.70	0.00
Professional Skills & Basic Electronics	2017-2018	66.00	5.00
Project I	2017-2018	63.00	4.00
Quantum Physics and Structure of Matter	2017-2018	72.00	7.50
Atomic, Nuclear and Particle Physics	2018-2019	73.00	6.00
Electromagnetism and Optics	2018-2019	66.00	9.00
Laboratory and Computing 2	2018-2019	63.00	10.00
Mathematical Methods	2018-2019	90.00	6.00
Mathematics and Statistics of Measurement	2018-2019	62.00	9.00
Professional Skills 2	2018-2019	73.00	2.00
Quantum Mechanics	2018-2019	77.00	6.00
Solid State Physics	2018-2019	59.00	5.00
Thermodynamics and Statistical Physics	2018-2019	70.00	7.00
Advanced Classical Physics	2019-2020	74.14	6.00
Comprehensive Physics	2019-2020	64.17	16.00
Foundations of Quantum Mechanics	2019-2020	80.00	6.00
General Relativity	2019-2020	74.29	6.00

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Group Theory	2019-2020	78.57	6.00
Light and Matter	2019-2020	54.00	6.00
Physics of the Universe and Fluid Dynamics	2019-2020	60.71	6.00
Professional Skills 3	2019-2020	68.13	2.00
Statistical Mechanics	2019-2020	66.34	6.00
Cosmology	2020-2021	75.63	6.00
Dynamics, Symmetry and Integrability	2020-2021	87.46	8.00
Physics MSci Project	2020-2021	68.00	22.00
Quantum Field Theory	2020-2021	82.35	8.00
Quantum Information	2020-2021	80.24	6.00
Research Interfaces	2020-2021	68.00	8.00
Unification	2020-2021	85.00	8.00

Prizes, Distinctions and Post-nominal Awards

Post-nominal awards: Associateship of the Royal College of Science

Authorisation

David Ashton
Academic Registrar

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End of document

NOTES ET RÉSULTATS

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Dossier : 21227427
Année : 2021/2022

ÉLÉMENTS & ÉPREUVES

Code	Libellé	Rang	ECTS	Session 1	Résultat	Session 2	Résultat
SPHCSABC	Semestre 3 M2 Physique : Physique (Relevé 1partiel)						
SPHCX01C	PTP Choix S3 (18 crédits)	1/30		19.533/20			
SPHCUD2C	Statistical Physics II	1/4	6	20/20	ADM		
SPHCU07C	Quantum Field Theory	1/23	6	18.6/20	ADM		
SPHCU09C	General Relativity	1/20	6	20/20	ADM		

INFORMATIONS

Signification des codes résultats :
ADM : Admis

Fait à Aix-Marseille, le 30-01-2022, La Directrice de l'UFR Sciences Laurence MOURET