European Research Council

ERC Starting Grant

Research proposal (Part B section 1 (B1))

Novel numerical approaches to quantum gravity, holography and extra dimensions

NumGrav

PI: Toby Wiseman

Institution: Imperial College London, UK

Duration: 60 months

Summary:

In the past three decades gravity has played an ever more prominent role in fundamental physics. My aim is to introduce novel numerical methods to tackle the key questions in *quantum* and *classical* gravity in the context of fundamental theory, where previously only analytic methods were available and failed to give answers.

Quantum gravity: The challenge of making gravity quantum mechanical has driven theoretical physics for half a century. String theory finally conjectured an answer to this most fundamental question through the `holographic correspondence'. This answer is simple in form but computing its implications is an enormous challenge. Analytic methods seem incapable of revealing the remarkable gravitational physics it describes. An analogy is the Schrodinger equation for electrons, which in principle determines all of chemistry – in practice only computers have made it possible to solve chemical problems ab initio. I recently pioneered the use of numerical methods to tackle these new theories of quantum gravity. *My first aim is to develop this numerical approach to quantum gravity* to at last solve these theories and unravel the physics of quantum black holes. As with ab initio quantum chemistry this has potential to open up an entirely new research area, in this case a highly interdisciplinary one between lattice field theory, string theory and quantum gravity.

Classical gravity: Many fundamental theories such as string theory require extra spatial dimensions. There is the amazing possibility that over the next decade LHC will actually create black holes that probe these dimensions. Solving the relevant equations that govern these classical black holes is very challenging, and analytic methods are limited curtailing our ability to make predictions for LHC and hence test these theories. I pioneered the use of numerical techniques in such contexts. *My second aim is to develop this numerical approach to classical black holes.* My key goal is to compute black holes and their properties in realistic theories of extra dimensions enabling them to be confronted by experiment. This interdisciplinary field between numerical General Relativity, string theory and particle phenomenology, is essential if we are to understand the true implications of extra dimensions.

Section 1a. **Scientific Leadership Potential**

My career has been built on pioneering the use of numerical methods to tackle physically important problems concerning gravity in the context of fundamental theory. Already during my PhD (and working alone) I founded the first numerical methods to solve classical gravity in theories with extra dimensions. In the last 5 years I have also spearheaded the numerical approach to study quantum black holes in holographic gauge theories. I not only have the first results in these fields, but have subsequently developed and crafted the methods, demonstrating the important physics accessible with these new tools. I have worked effectively with collaborators in various disciplines, including string theory, phenomenology and lattice field theory. Coming from my PhD in cosmology, I am now internationally a leader in the string theory, gravity and numerical gravity communities. My innovative interdisciplinary approach has been intrinsically risky. The fact I have been successful is the best demonstration of my scientific leadership, and I am now uniquely placed to implement the research in this proposal and to open up these fantastic research directions which potentially will allow us to unlock the secrets of quantum gravity and to subject our fundamental theories to experimental test. I received my PhD in Oct 2002, so 8.8 years ago from call date (Jul 2011). I regard the `*consolidator'* category as appropriate.

Scientific achievements and recognition:

2006; Awarded prestigious **STFC 5 year advanced fellowship**. There are ~ 10 each year in the UK across all of astrophysics, cosmology and high energy physics. Further I was awarded the `**Halliday award**', given to the top candidate for these fellowships (giving an extra £50000 of funding).

2009 & 10; **Organized 2 one week workshops** (~40 people each time) at Imperial on `novel numerical methods in quantum gravity' (2009) and `higher dimensional black holes' (2010). The participants were *top international leaders* in these areas. I was lead organizer and funded them using my Halliday award.

2011-12; Organizer (with Nishimura, Berenstein, Yaffe) for **KITP (Santa Barbara) 8 week program** "Novel numerical methods for strongly coupled QFT and quantum gravity". KITP programs **must pass a stringent refereeing** process and be deemed of sufficient international impact. Will take place Jan 2012.

Research achievements:

1) *T. Wiseman, ``Static axisymmetric vacuum solutions and nonuniform black strings,'' Class. Quant. Grav.* ***20****, 1137 (2003)* ; 135 Citations ; **Pioneered use of novel numerical methods** to find black holes in higher dimensions. Also gave first construction of new and remarkable class of exotic black holes.
2) *H. Kudoh and T. Wiseman, ``Connecting black holes and black strings," Phys. Rev. Lett. 94 (2005) 161102* ; 68 Citations; Using numerical methods I revealed the intricate structure of black holes with extra dimensions. **An important driver** for the research area of gravity in more than 4 dimensions.
3) *P. Figueras and T. Wiseman, "Gravity and large black holes in Randall-Sundrum II braneworlds," Phys. Rev. Lett.107 (2011) 081101* ; Computed black holes in the `Randall-Sundrum braneworld' model of extra dimensions. This was **very important progress** as for a decade it was widely claimed such solutions could not exist, with important phenomenological implications.
4) *Chapter 4 "General black holes in Kaluza-Klein theory" and chapter 10 "Numerical construction of static and stationary black holes " of "Higher dimensional black holes", editor G. Horowitz, to be published 2012,* ***Cambridge University Press****, ISBN-13: 9781107013452* ; I was honoured to be able to contribute 2 chapters to the recent pedagogical CUP textbook edited by the eminent gravity and string theorist G. Horowitz (UCSB). The first textbook on the subject, it is likely to become the standard text.
5) *O. Aharony, J. Marsano, S. Minwalla and T. Wiseman, `` Black hole-black string phase transitions in thermal 1+1 dimensional supersymmetric Yang-Mills theory on a circle,'' Class. Quant. Grav. 21, 5169 (2004)* ; 85 Citations; I **pioneered** simulation of quantum mechanical gauge theories (in the large N limit) which describe quantum gravity. This early work treated the quenched theory (without fermions).
6) *S. Catterall and T. Wiseman, ``Towards lattice simulation of the gauge theory duals to black holes and hot strings," JHEP 0712 (2007) 104 ; S. Catterall and T. Wiseman, ``Black hole thermodynamics from simulations of lattice Yang-Mills theory," Phys. Rev. D 78 (2008) 041502* ; 50 and 50 Citations; With leading lattice field theorist Catterall I pioneered numerical study of the full theory at finite temperature including fermions dynamically, opening up the research field of ab initio study of quantum gravity.

Graduated 2 PhD students who have gone on to successful positions; *Ben Withers* (graduated 2010), currently a postdoc in Durham, UK. *Sam Kitchen* (graduated 2011), now an IT consultant with Deloitte.

Section 1b. **Curriculum Vitae:**

Toby Wiseman

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URL: http://www3.imperial.ac.uk/people/t.wiseman

Academic history

Oct 2010- present	**Senior lecturer** in theoretical physics, Imperial College.
Oct 2006-Oct 2010	**Lecturer** in theoretical physics, Imperial College.
Oct 2006-Oct 2011	**STFC advanced fellow** – a prestigious fellowship, with only ~10 per year being awarded in the UK across the fields of cosmology, astrophysics and high energy physics, both theoretical and experimental.
Sep 2003-Sep 2006	**Postdoctoral** researcher at **Harvard** in particle theory group of Prof Nima Arkani-Hamed and Prof Lisa Randall
Mar 2002-Aug 2003	**Postdoctoral** researcher in Relativity and High Energy Physics groups at DAMTP, Cambridge; funded by JRF at Pembroke College
Oct 1998-Feb 2002	**PhD** in high energy physics group at DAMTP, Cambridge Adviser: Prof Neil Turok, Title: Non-linear gravity on branes
Oct 1997-Jul 1998	Distinction in Part III Maths (1 year advanced mathematics) at Cambridge, UK (**top result** in applied Part III course, out of ~ 80 candidates)
Oct 1994-Jul 1997	First class undergraduate degree in physics (Natural Sciences) at Cambridge, UK (**top result** in my final year out of ~120 candidates)

Selected academic awards

2006	STFC Halliday award – prestigious prize for **top** STFC advanced fellow in year
2001	Best participant award at Eriche 'Subnuclear Physics' Summer School
1998	Cambridge University Mayhew Prize for **top result in applied** Part III Maths
1997	Cambridge University Hartree and Clerk-Maxwell Prizes for **top undergraduate physics** result

PhD students

Oct 2009 - present	Supervisor for **Alex Adam** (Theory group, IC) 'Black holes in string theory and AdS-CFT' – STFC funded *Expected to graduate 2013*
Oct 2007 - Jul 2011	Supervisor for **Sam Kitchen** (Theory group, IC) 'Black holes in string theory and AdS-CFT' – STFC funded *Graduated 2011- currently working in IT consulting for Deloitte, London, UK*
Oct 2006 - Oct 2010	Supervisor for **Ben Withers** (Theory group, IC) 'Aspects of modified gravity theories' – STFC funded *Graduated 2010 - currently a postdoc in Mathematical Sciences, Durham, UK*

Selected Teaching

2011 - present	26 lecture course on 'General Relativity' as part of the Imperial physics undergraduate program.
2006 - present	30 lecture course on 'Differential Geometry' as part of the Imperial Theory group QFFF MSc program.
2008 - present	Supervise MSc dissertations for 1-2 students/year as part of Theory group QFFF MSc program.
2008 - present	Personal tutor for 10 physics undergraduates at Imperial.

Conference Organization

Jan-Mar 2012	Organizer (with Nishimura, Berenstein, Yaffe) for the **KITP Santa Barbara** 2 month program "Novel numerical methods for strongly coupled quantum field theory and quantum gravity". Such programs **must pass a stringent refereeing** process and be deemed of sufficient international interest and impact to warrant funding. Our application was *strongly supported* and goes ahead in Jan 2012
Sep 2010	Main organizer for 'Higher dimensional black holes' conference at Imperial – funded by Halliday award, 5 days, ~ 40 high profile international delegates
Oct 2009	Main organizer for 'Numerical approaches to AdS/CFT, large N and gravity' conference, held at Imperial – funded by Halliday award, 5 days, ~ 30 high profile international delegates
April 2009	Joint organizer for 'Supersymmetry, Branes and M-theory' meeting at Imperial, 2 days, ~ 80 delegates
April 2008	Joint organizer for 'Gravity, Supersymmetry and Branes' meeting at Imperial, 2 days, ~ 80 delegates
July 2007	On organizing committee, PASCOS '07 conference at Imperial, 5 days, ~ 200 delegates

Seminar Organization

Jul 2011- present	Imperial Physics department colloquium organizer
Sep 2006-Jan 2009	Arranged Imperial Theory group seminars
Sep 2004-Jan 2006	Arranged Joint Theory seminars between Harvard, MIT and Boston University
Sep 2004-Jan 2006	Arranged weekly Harvard phenomenology seminars
Oct 2002-Jul 2003	Arranged weekly DAMTP high energy physics/gravity seminars

Other academic responsibilties

2010- present	In charge of Imperial Theoretical physics group PhD admissions ; typically we have >100 candidates for 4 funded places. Admissions procedure entails choosing candidates to interview, coordinating interviews with other faculty members, selecting candidates.
2002- present	I referee for a variety of leading journals in my field: JHEP, Phy. Rev. Lett., Phy. Rev. D, Class. Quant. Grav., Nucl. Phys. B
2008- present	I have been a PhD examiner at Cambridge, Durham, Kings and Imperial.

Media

March 2008	My research was featured in **New Scientist** article *"Has 'dark fluid' saved Earth from oblivion?"*
Oct 2006	STFC Frontiers magazine personal interview on Halliday award; "Strings, black holes and plasma balls"

Funding ID

Oct 2011-Oct 2014	Co-investigator (1 of 12) for STFC consolidated grant "M-theory, Cosmology and Quantum Field Theory" at Imperial; total value £1,514,000

Section 1c. **Early Achievements Track-Record**

Halliday award, 2006: The STFC is the research council in the UK that funds all of theoretical and experimental high energy physics, astrophysics and cosmology. They award a number of advanced 5 year fellowships each year across all of these areas. These advances fellowships are prestigious positions, given to the **top** young researchers. However, one Halliday award is then given to the best of all these advanced fellows in the year. This is a highly prestigious awards, and also carries £50000 extra funding.

Media 2008 ; My work on modified theories of gravity (publication 13 below) was reviewed in the article "Has 'dark fluid' saved Earth from oblivion?" in the popular publication **New Scientist.**

Contributed chapters in textbooks

1) G. Horowitz and T. Wiseman, "General black holes in Kaluza-Klein theory", **Chapter 4** and T. Wiseman, "Numerical construction of static and stationary black holes", **Chapter 10** of "Higher dimensional black holes", editor G. Horowitz, to be published 2012, **Cambridge University Press**, ISBN-13: 9781107013452

Articles in major refereed journals (Citations from SPIRES database) ; SPIRES `h-index' = 20

*Note that it is conventional in high energy theory for author lists to be **alphabetical***

Colour code : Orange = citations > 100 *or* published in Phys Rev Lett. Blue = citations > 50

2) P. Figueras and T. Wiseman, "Gravity and large black holes in Randall-Sundrum II braneworlds," **Phys. Rev. Lett.**107 (2011) 081101 ; Citations: 6
3) P. Figueras, J. Lucietti and T. Wiseman, "Ricci solitons, Ricci flow, and strongly coupled CFT in the Schwarzschild Unruh or Boulware vacua," accepted for publication Class. Quant. Grav ; Citations: 3
4) T. Wiseman and B. Withers, ``Inhomogeneous post-inflationary Lambda-CDM cosmology as a moduli space expansion,'' accepted for publication Phys. Rev. D.
5) S. Catterall, Anosh Joseph and T. Wiseman, ``Thermal phases of D1-branes on a circle from lattice super Yang-Mills,'' JHEP 1012 (2010) 022 ; Citations: 10
6) T. Wiseman and B. Withers, ``Late time solutions for inhomogeneous Lambda-CDM cosmology, their characterization and observation,'' Phys. Rev. D83 (2011) 023511
7) J. P. Gauntlett, J. Sonner and T.Wiseman, ``Quantum criticality and holographic superconductors in M-theory,'' JHEP 1002 (2010) 060 ; **Citations: 72**
8) M .Headrick, S. Kitchen and T. Wiseman, ``A new approach to static numerical relativity, and its application to Kaluza-Klein black holes,'' Class.Quant.Grav. 27 (2010) 035002 ; Citations: 19
9) S. Catterall and T. Wiseman, ``Extracting black hole physics from the lattice,'' JHEP 1004 (2010) 077 ; Citations: 20
10) J. P. Gauntlett, J. Sonner and T.Wiseman, ``Holographic superconductivity in M-Theory,'' **Phys. Rev. Lett.**103 (2009) 151601 ; **Citations: 108**
11) T. Wiseman and B. Withers, ``Holographic renormalization for coincident Dp-branes,'' JHEP 0810 (2008) 037 ; Citations: 12
12) S. Catterall and T. Wiseman, ``Black hole thermodynamics from simulations of lattice Yang-Mills theory,'' Phys. Rev. D 78 (2008) 041502 ; **Citations: 50**
13) C. R. Contaldi, T. Wiseman and B. Withers, ``TeVeS gets caught on caustics,'' Phys. Rev. D 78 (2008) 044034 ; Citations: 22
14) S. Catterall and T. Wiseman, ``Towards lattice simulation of the gauge theory duals to black holes and hot strings,'' JHEP 0712 (2007) 104 ; **Citations: 50**
15) C. Doran, M. Headrick, C.P. Herzog, J. Kantor and T. Wiseman, ``Numerical Kaehler-Einstein metric on the third del Pezzo,'' Commun. Math. Phys. 282 (2008) 357 ; Citations: 16
16) A. L. Fitzpatrick, L. Randall and T. Wiseman, ``On the existence and dynamics of braneworld black holes,'' JHEP 0611 (2006) 033 ; **Citations: 41**
17) M. Headrick and T. Wiseman, ``Ricci flow and black holes,'' Class. Quant. Grav. 23 (2006) 6683 ; **Citations: 38**
18) O. Aharony, J. Marsano, S. Minwalla, K. Papadodimas, M. Van Raamsdonk and T. Wiseman, ``The phase structure of low dimensional large N gauge theories on tori,'' JHEP 0601 (2006) 140; **Cites: 42**
19) N. Arkani-Hamed, H.C. Cheng, M. A. Luty, S. Mukohyama and T. Wiseman, ``Dynamics of Gravity in a Higgs Phase,'' JHEP 0701 (2007) 036 ; **Citations: 60**

20) O. Aharony, S. Minwalla and T. Wiseman, ``Plasma-balls in large N gauge theories and localized black holes," Class. Quant. Grav. 23 (2006) 2171 ; **Citations: 64**
21) M. Headrick and T. Wiseman, ``Numerical Ricci-flat metrics on K3," Class. Quant. Grav. 22 (2005) 4931 ; Citations: 22
22) S. F. Ross and T. Wiseman, ``Smeared D0 charge and the Gubser-Mitra conjecture," Class. Quant. Grav. 22 (2005) 2933 ; Citations: 16
23) H. Kudoh and T. Wiseman, ``Connecting black holes and black strings," **Phys. Rev. Lett.** 94 (2005) 161102 ; **Citations: 69**
24) O. Aharony, J. Marsano, S. Minwalla and T. Wiseman, `` Black hole-black string phase transitions in thermal 1+1 dimensional supersymmetric Yang-Mills theory on a circle,'' Class. Quant. Grav. 21, 5169 (2004) ; **Citations: 85**
25) H. Kudoh and T. Wiseman, ``Properties of Kaluza-Klein black holes,'' Prog. Theor. Phys. 111, 475 (2004) ; **Citations: 61**
26) B. Kol and T. Wiseman, ``Evidence that highly nonuniform black strings have a conical waist,'' Class. Quant. Grav. 20, 3493 (2003) ; **Citations: 47**
27) T. Wiseman, ``From black strings to black holes, '' Class. Quant. Grav. 20, 1177 (2003) ; Cites: 65
28) T. Wiseman, ``Static axisymmetric vacuum solutions and nonuniform black strings,'' Class. Quant. Grav. 20, 1137 (2003) ; **Citations: 135**
29) T. Wiseman, ``Strong brane gravity and the radion at low energies'', Class. Quant. Grav. 19, 3083 (2002) ; **Citations: 70**
30) T. Wiseman, ``Relativistic stars and Randall-Sundrum gravity,'' Phys. Rev. D65, 124007 (2002) ; **Citations: 89**
31) (*) K. Kirklin, N. Turok and T. Wiseman, ``Singular cosmological instantons made regular,'' Phys. Rev. D63, 083509 (2001) ; Citations: 6

* - work with my PhD supervisor Neil Turok ; **Abbreviations**: Phys. Rev. Lett. = Physical Review Letters, Phys. Rev. D = Physical Review D, Class. Quant. Grav = Classical and Quantum Gravity, JHEP = Journal of High Energy Physics.

A selection of invited presentations to international conferences and workshops

I have only included larger international meetings involving at least 40 participants, and where I was a plenary or main speaker.

2011 Madeira *"Numerical Relativity & High Energy Physics"* ; Benasque, Spain; *"Gravity and strings"* ; Edinburgh, UK; *"Numerical relativity beyond astrophysics"*
2010 Tokyo, Japan; *"Yukawa Institute for Theoretical Physics Summer Workshop"*
2009 Benasque, Spain; *"New perspectives from strings and higher dimensions"*
2008 TIFR, Mumbai; *"Monsoon Workshop on String Theory"* ; Valencia, Spain; *"Quantum black holes, braneworlds and holography"* ; Niels Bohr, Denmark; *"Mathematical aspects of General Relativity"*
2007 Newton Institute, Cambridge; *"Strong Fields, Integrability and Strings"* ; KCL, UK, *"Fundamental Physics Conference"* ; Hebrew University, Israel; *"Higher Dimensional GR"* ; FQXi, Iceland; *"FQXi - Inaugural conference"*
2006 KITP, Santa Barbara; *"GR beyond 4 dimensions" ;* Berlin, *"11th Marcel Grossmann GR meeting"*
2004 Perimeter Institute, Canada; *"GR beyond 4d"* ; Denver, US; *"Spring APS meeting"*
2003 Ambleside, UK; *"COSMO '03"*
2002 Imperial College, UK; *"Brane world gravity"*

I have given many invited seminars to theoretical physics groups in last 10 years including; *US*: Harvard, Princeton, MIT, Fermilab, Santa Barbara, Syracuse, Brandeis, Brown, U. Mass Amherst, Chapel Hill, Lousiana, *Japan*: Yukawa Institute, Toyko Institute for Technology, *Canada:* Perimeter Institute, *UK*: Imperial, Cambridge, Oxford, Durham, Kings, York, Southampton, Sussex, Portsmouth, Queen Mary, *Holland*: Amsterdam, *Germany*: Humboldt, *Switzerland*: ETH Zurich, *Belgium*: ULB, *Italy*: ICTP Trieste

Section 1d. **Extended Synopsis of the Scientific Proposal**

In the past three decades gravity has played an ever more prominent role in fundamental physics. My aim is to introduce novel numerical methods to tackle key questions in the two topics of ***quantum*** and ***classical gravity*** in a fundamental context where previously only analytic methods existed and failed to give answers.

Topic A - *Quantum gravity from holography*: The challenge of making gravity quantum mechanical has driven theoretical physics for half a century. String theory finally conjectured an answer to this most fundamental question through the `holographic correspondence'. This answer is simple in form but computing its implications is an enormous challenge. Analytic methods seem incapable of revealing the remarkable gravitational physics it describes. An analogy is the Schrodinger equation for electrons, which in principle determines all of chemistry – in practice only computers have made it possible to solve chemical problems ab initio. I recently pioneered the use of numerical methods to tackle these new theories of quantum gravity. *My first aim is to develop this numerical approach to quantum gravity* to at last solve these theories and unravel the physics of quantum black holes. This has potential to open up an entirely new research area, in this case a highly interdisciplinary one between lattice field theory, string theory and quantum gravity.

Topic B - *Classical gravity in fundamental theory*: Many fundamental theories such as string theory require extra spatial dimensions. There is the amazing possibility that over the next decade LHC will actually create black holes that probe these dimensions. Solving the relevant equations that govern these classical black holes is very challenging, and analytic methods are limited curtailing our ability to make predictions for LHC and hence test these theories. I pioneered the use of numerical techniques in such contexts. *My second aim is to develop this numerical approach to classical black holes.* My key goal is to compute black holes and their properties in realistic theories of extra dimensions enabling them to be confronted by experiment. This interdisciplinary field between numerical General Relativity, string theory and particle phenomenology, is essential if we are to understand the true implications of extra dimensions.

My proposal is divided into the two research topics A and B above. These are related in their application to fundamental theory as well as by the methodology of applying numerical computation. There is also specific cross over of results between the two topics. Within each topic I have two specific research objectives to pursue. I will begin by giving motivation for these topics, before describing their state of the art, my objectives within the topics, and my ability to implement this proposal.

Motivation

For many decades up until the mid 1990's the combination of quantum mechanics and classical gravity into a theory of quantum gravity had been the `holy grail' of fundamental physics. Ideally this theory would be the quantum gravity of our world, but in the absence of that any consistent theory of quantum gravity would be a tremendous breakthrough. The problem of quantum gravity is one where genuinely new physical ideas concerning the nature of space and time are required, in an analogous manner to the revolution in thinking that ushered in quantum mechanics in the 1920's. A decade or so ago modern string theory provided the first ever candidate for a fully quantum description of certain theories that contain gravity. While not phenomenologically viable for our universe, this represented a stunning breakthrough. It makes the remarkable conjecture that certain string theories, which reduce to quantum gravity in particular limits of their parameters, are completely equivalent to specific quantum field theories (theories of quantum matter) but without gravity. These are of the `*gauge theory*' type which is a class that includes QCD, the theory of the Strong nuclear force, and are perfectly well defined theories. This equivalence is called the `*holographic correspondence',* referring to the fact that the gauge theory lives in at least one dimension less than the equivalent quantum gravity theory. The fundamental object in the gravitational side of the correspondence, the black hole, is viewed as a thermal plasma in the gauge theory side. Hawking and others in the 1970's famously understood that black holes had a temperature and an associated thermodynamics. However, with no quantum description of gravity it had been unclear what microscopic degrees of freedom would underlie this thermodynamics. This culminated in Bekenstein and Hawking's 'information loss paradox', which describes the tension between our classical and quantum understanding of black holes, and specifically concerns how the information in the quantum degrees of freedom is released as a black hole in empty space evaporates by 'Hawking radiation'. To this day it remains the key unresolved question in quantum gravity. *In principle*, using this holographic correspondence we understand quantum black holes. *In practice*, despite valiant work by many theorists, like QCD these gauge theories and their thermal plasma are strongly coupled systems and appear to be analytically intractable. It is one aim of this proposal to develop the necessary numerical methods to solve them.

Of course in the end we are not just interested in *a* quantum theory of gravity, but *the* quantum gravity describing our world. Unified models of fundamental physics have involved extra spatial dimensions since the work of Kaluza and Klein in the 1920's. String theory, the most promising candidate, requires 10 or 11 such dimensions. The famous `large extra dimension' scenario which may solve the `hierarchy problem' (why the fundamental quantum scale - the Planck scale - and Standard model scale are so disparate) employs extra dimensions whose size may be shockingly large, up to ~ 0.1mm. If such large extra dimensions exist there is the tantalizing possibility of producing black holes in LHC, and actually revealing the true fundamental theory - string theory or otherwise - directly in this experiment. Once extra dimensions are introduced the geometries that describe the vacuum and black holes are usually not known as analytic methods are unable to find them. The black holes that could be formed at LHC are of at least two varieties, those of spherical and those of ring-like topology. Only the former are known explicitly, and whilst the latter are conjectured to exist (in dimensions six and above), their details and properties are completely unknown. If we are to search for black hole collisions in LHC, which will remain a major endeavor over the coming 10 years, we must understand the properties of these black holes. I aim to develop these necessary numerical techniques and systematically compute these solutions. Astrophysical black holes provide another arena to test theories of extra dimensions. For example the widely studied `Randall-Sundrum II' model (> 5000 citations) was famously conjectured to have very different behaviour for astrophysical black holes than usual Einstein gravity, and for a decade the model was assumed to be constrained by astrophysical observations. Using numerical methods I recently computed these black holes [3] showing the conjecture was wrong, and the models could not be tested this way. More generally very little is known about what black hole solutions exist in realistic phenomenological models of extra dimensions. Such models are extremely widely studied. It is essential we gain control over the physics of black holes in them in order to understand how to test them.

A further direction is the exotic classical physics of black holes in the holographic correspondence. Aside from the problem of ab initio solution of the gauge theory to compute the full quantum black holes, even on the gravitational side of the correspondence which we do understand classically (although not quantum mechanically) we know little about the black holes that exist. This classical limit corresponds in the gauge theory to a large number of colours - *the 'large N limit'*. It is critical to understand these classical black holes in order to properly test the holographic conjecture, as we must ensure that the quantum objects we find from ab initio study of the gauge theory do indeed behave as these classical black holes in this limit. Furthermore such classical black holes in this correspondence can be used to understand certain properties of strongly coupled gauge theory physics that are inaccessible by thinking in terms of the gauge theory directly, such as the dynamics of plasma formation relevant for understanding heavy ion collider physics.

Topic A: *`Quantum gravity from holography'*

Background and state of the art

The gauge theories conjectured to be holographically equivalent to quantum gravitational theories (or more precisely string theories which contain quantum gravitational limits) are in various cases very explicitly known. The simplest examples are those derived from certain objects in string theory called 'D-branes'. In these holographic equivalences the gauge theories are maximally supersymmetric gauge theories. For quantum gravity to be described we should work at large N, where N is the number of 'colours' in the gauge theory (for QCD N = 3). There is a correspondence where the gauge theory is 1-dimensional, so it simply becomes a quantum mechanical model. For numerical calculation it is by far the simplest starting point.

I pioneered finite temperature numerical studies of such gauged quantum mechanics theories. Using numerical lattice field theory methods I performed the first studies of the quenched version (ie. ignoring fermions) of this theory in the large N limit [5]. In later work with lattice field theorist Simon Catterall (Syracuse), himself a world leader in supersymmetric lattice methods, I employed state of the art lattice field theory techniques using the `Rational Hybrid Monte Carlo' (RHMC) method together with supersymmetric lattice formulations to perform the first simulations of the large N theory including the necessary fermions [6]. For the first time we showed that the thermal plasma behaviour of the gauge theory from direct computation was consistent with the predictions from black hole thermodynamics. This was a crucial test of holography, and opened up the new research area of studying quantum black holes using these methods. Our studies were the first of their kind, with independent, concurrent and consistent results produced by a group at KEK in Japan lead by Jun Nishimura [7]. Having shown direct simulations of black holes are possible, and are consistent with predictions from gravity, these results attracted considerable interest from the international string theory and field theory communities. After only a few years these initial papers already have > 50 citations even though the number of people working in this numerical field is very small - essentially my work with Catterall and the Japanese group.

Evidence of international impact is that myself, Nishimura together with David Bekenstein and Lawrence Yaffe are **organizing an 8 week program at the prestigious KITP** (Kavli Institute for Theoretical Physics) in UC Santa Barbara (US) on novel numerical methods in quantum gravity and string theory. Such programs must pass a stringent refereeing process and be deemed of sufficient international interest and impact to warrant funding. Our application was *strongly supported* and is due to go ahead in Jan 2012.

Objectives and methodology

My objectives for Topic A are divided into two research directions, A.1 and A.2, which I will now detail;

Objective A.1: Solving quantum black holes by ab initio thermal simulation

By using thermal lattice field theory methods I will simulate gauge theories that in the large N regime describe black holes via holography. I will use brute force methods, and in addition refined algorithms to achieve this, tackling first the quantum mechanical case, and after the higher dimensional gauge theories. The goal is to **test the holographic conjecture**, and **for the first time** allow precision study of the thermal behaviour of quantum gravity and quantum black holes.

In order to take this field well beyond the current state of the art I will utilize the computing resources we are requesting to perform much larger scale simulations, and together with improved understanding of these large N gauge theories (in particular the addition of supersymmetric mass terms to regulate the low energy behaviour) this will allow dramatic improvement of results. The aim will be to confirm and test with precision that black hole physics is seen in these holographic gauge theories. Furthermore, I will examine how the effects of quantum gravity behave as one moves away from the large N limit. Semiclassical gravity methods to compute these corrections will be checked by comparison to the full simulation, and the change in behaviour moving to finite N, the fully quantum regime, we will studied.

I will also improve the basic approach using two key areas of physical input. Firstly the theories naturally have ‘slow’ and ‘fast’ degrees of freedom. Current simulation techniques do not account for this, and thus the simulation time is governed by the slow degrees of freedom. By identifying these different degrees of freedom and treating them separately in the path integral I expect an enormous improvement can be made. Secondly I believe new representations of the gauge theory can be used to improve the exploration of the large N limit. The so called ‘collective field’ representation of gauge theory has allowed progress to be made in analytic work as various simplifications can be explicitly seen in at large N [9]. This representation has not been used in Monte-Carlo simulation and I believe this innovative approach has tremendous potential.

Objective A.2: Ab initio calculation of the spectrum of quantum gravity

I will numerically compute the spectrum and eigenstates in the large N quantum mechanics which holographically describes quantum gravity. I will study the quantum states that compose black holes. I will address the question of time dependence of fully quantum black holes, Hawking radiation and if possible, gain insight into Hawking’s `information loss paradox’.

Thermal lattice methods are ideally suited to studying equilibrium black holes physics using large N gauge theories. However to understand the real time dynamics of quantum gravity a Hamiltonian approach is most appropriate. I will examine the use of numerical methods to directly diagonalise the Hamiltonian for these gauge theories, focusing on the quantum mechanical case where such an approach is very natural. This bears much similarity to the case of quantum chemistry - a finite basis must be used to represent the wavefunction, and then the Hamitonian is diagonalized in this basis. This approach will enable the spectrum of these theories to be deduced for the first time. This allows the fascinating prospect that information on the real time dynamics will be obtained from the Hamiltonian eigenfunctions, and will shed light on Hawking’s famous long standing black hole `information loss paradox’.

Topic B: `*Classical gravity in fundamental theory’*

Background and state of the art

I pioneered the use of numerical calculation to find solutions such as black holes in higher dimensional theories of gravity where they cannot be analytically found. Over the last decade I have singlehandedly driven that field forward to the point where now we have a framework of numerical techniques designed to elegantly solve the problem. I have demonstrated that such methods yield important physical results.

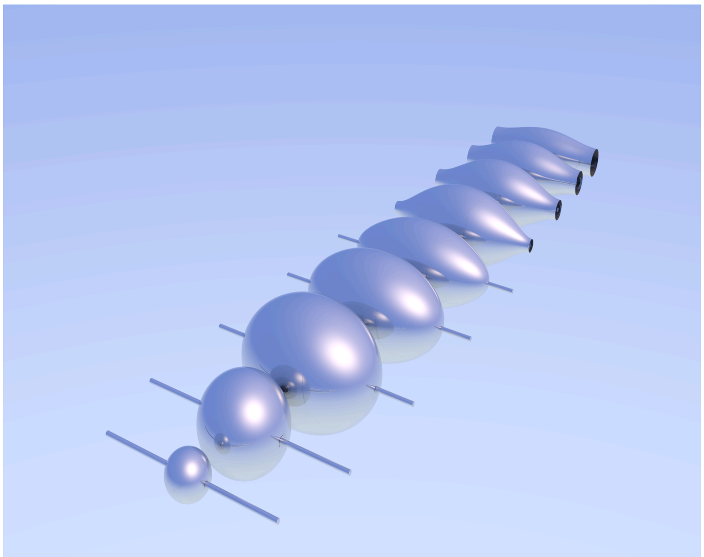

Figure depicting actual numerical solutions for black holes in the Kaluza-Klein theory

Finding equilibrium solutions in gravity, known as *stationary* solutions, as in electromagnetism should be an elliptic partial differential equation problem. The state of the art is my work, reviewed in [2], where this problem is cast as an elegant and geometric elliptic problem with algorithms to solve it - indeed the simplest one is shown to be related to the beautiful mathematical `Ricci flow', famous in contemporary geometry. This work has had considerable impact. Perhaps the cleanest application was to elucidate for the first time the behaviour of black holes in the simplest model of extra dimensions, the theory of Kaluza and Klein from the 1920's [8]. These results have been an important driver for the research field of exploration of higher dimensional gravity. Beyond black holes I also pioneered the use of numerical calculation to compute the simplest vacuum geometries (so called 'Calabi-Yau' geometries) that arise in String theory phenomenology [4].

The last decade of research has culminated in a new pedagogical textbook, "Higher dimensional black holes", which is the first in this subject and is edited by the internationally renowned string and gravity theorist Gary Horowitz (Santa Barbara, US). **One of the leading chapters is on black holes in the Kaluza-Klein model, and is written by Horowitz and myself [1]. I also have written a chapter outlining the new elliptic numerical techniques mentioned above [2].**

Another measure of impact is that recently there have been several high level international meetings (Denver, Edinburgh, Madeira all in 2010-11) specifically directed at numerical methods in gravity beyond astrophysics. I have been a key invited speaker at these and my methods have been a focus of the meetings.

Objectives and methodology

For Topic B my objectives again divide into two research directions, B.1 and |B.2, which I now detail;

Objective B.1: Black holes at LHC and in realistic extra dimensional theories

I will numerically **find the black holes that could be formed in LHC** *and* **determine their stability**, allowing detailed predictions for LHC large extra dimension scenarios to finally be made. I will also study the phenomenology of black holes in realistic extra dimensional theories (eg. Randall-Sundrum with radius stabilization). I will determine whether astrophysics can test these.

Firstly I will extend my numerical framework to include matter fields. Then I will develop on top of this the ability to test for dynamical stability of the solutions found. I will approach this in two ways. Firstly I will simulate by `brute force' the linear perturbations about the numerical solutions to test for stability. Secondly I will pursue a more subtle approach that will use analytic methods to deduce properties about stability or instability using the solution found, *without* solving the full linear perturbation problem. One direction is to use a variational approach, where using trial perturbations one shows a solution is unstable provided the trial perturbation has sufficient overlap with an instability. I do not expect to fully characterize stability or instability of solutions this way, but expect to cleanly deduce certain classes of perturbations are stable or are unstable in a much simpler manner than by solving the full linear theory.

Donaldson's work on the special case of Calabi-Yau geometries suggests there may be representations for the metric that are 'natural' for the geometry. In particular, embedding a geometry into a simple space where the eigenfunctions of the Laplacian are explicitly known, one can pull these back to the geometry to construct a preferred spectral basis. I will explore these ideas which have potential to dramatically improve the accuracy of the methods, allowing problems depending on many coordinates to be tackled.

Objective B.2: Classical black holes and the holographic correspondence

I will numerically find classical black holes in the gravitational side of the holographic correspondence. Firstly I will determine the classical limit that should be reproduced by the ab initio calculations on the gauge theory side in Topic A to test holography. Secondly I will use these to shed light on the dynamics of heavy ion collisions in QCD, by finding equilibrium black holes in holographic theories thought to have analogous behaviour to QCD. Thirdly I will compute black holes on the gravitational side of the correspondence suitable to describe fully out of equilibrium heat flow in large N strongly coupled gauge theories, where direct calculations are impossible.

The black holes relevant to describe the end state of heavy ion collisions from holography (so called 'plasmaball' black holes) were first found by me although only in a large energy limit. I will numerically find the finite energy solutions, and furthermore confirm their stability and determine their linear response governing return to equilibrium (ie. lowest quasinormal modes). This will have great impact, giving the first quantitative holographic information of the late stages of a heavy ion collision process.

The elliptic numerical framework I have developed is intimately tied to the notion of black hole rigidity and Killing horizons, both properties of black holes related to particular symmetries all known black holes possess. However, a fascinating class of black holes recently conjectured to describe heat flow in gauge theory apparently have horizons that are not of the Killing type. I will develop the elliptic framework to encompass these more general varieties of black holes, and explore the very interesting physical consequences associated to them. In particular one situation where these solutions are thought to exist is if the gauge theory in holography is put on a spacetime with two heat sources (black holes) with different temperatures. The physics of this solution is fascinating, giving the first way to calculate stationary but fully out of equilibrium heat transfer in a strongly coupled gauge theory.

Why me? I am the world expert in the use of numerical methods to find black hole solutions and vacuum geometries. I have also pioneered the use of numerical lattice methods to tackle the holographic gauge theories, and performed *ab initio* calculations of the thermal properties of quantum black holes for the first time. I have demonstrated scientific leadership to develop these uncharted directions and gained significant international recognition of these novel numerical approaches in scientific communities that traditionally were not familiar with numerical techniques. I have long term collaborations across discipline boundaries, for example with world leading string theorists Aharony, Headrick, Minwalla and lattice field theorist Catterall, allowing me to create work that truly is of impact to all disciplines involved. I have organized successful interdisciplinary meetings on both the topics of this proposal, bringing together top international scientists from string theory, General Relativity (GR), lattice field theory and numerical GR.

To address the objectives of this proposal I must build a group at Imperial College dedicated to these research directions. I am requesting three postdocs and one PhD student. It is critical I am able to devote the majority of my time to this research, hence I am requesting 50% of my salary. I will also purchase cluster computing hardware (200 cores) to ensure my group is resourced for large scale numerical computations.

Summary: This is an interdisciplinary proposal between string theory, lattice field theory and numerical General Relativity. It will develop novel numerical methods to address the key gravitational issues in fundamental theory, namely how to perform computations with the holographic formulations of quantum gravity, and how to understand the phenomenology of extra dimensions and test theories such as string theory using LHC and astrophysical observation. I have a proven track record in pioneering a novel numerical approach in both fields. Now is exactly the time I require the requested resources to maintain my international lead in these exciting high impact areas. My methodology is far from incremental, being focused on using new insights and ideas to push forward well beyond the current state of the art.

1. G. Horowitz and T. Wiseman, Chapter 4 of "Higher dimensional black holes", editor G. Horowitz, to be published 2012, **Cambridge University Press**, ISBN-13: 9781107013452 [arXiv:1107.5563]
2. T. Wiseman, Chapter 10 of "Higher dimensional black holes", editor G. Horowitz, to be published 2012, **Cambridge University Press**, ISBN-13: 9781107013452
3. P. Figueras and T. Wiseman, **Phys. Rev. Lett.**107 (2011) 081101
4. M. Headrick and T. Wiseman, Class. Quant. Grav. 22 (2005) 4931
5. O. Aharony, J. Marsano, S. Minwalla and T. Wiseman, Class. Quant. Grav. 21, 5169 (2004)
6. S. Catterall and T. Wiseman, JHEP 0712 (2007) 104 ; Phys. Rev. D 78 (2008) 041502
7. M. Hanada, J. Nishimura and S. Takeuchi, Phys. Rev. Lett. 99 (2007) 161602 ; K. Anagnostopoulos, M. Hanada, J. Nishimura and S. Takeuchi, Phys. Rev. Lett. 100 (2008) 021601
8. H. Kudoh and T. Wiseman, **Phys. Rev. Lett.** 94 (2005) 161102
9. A. Jevicki and B. Sakita, Nucl.Phys. B165 (1980) 511; R.Leigh, D.Minic and A.Yelnikov, Phys.Rev.Lett. 96 (2006) 222001