Proposal for an ESF Research Networking Programme – Call 2009

Section I

Programme title: Holographic methods for strongly coupled systems

Programme acronym: HoloGrav

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Abstract:
The gauge/gravity duality conjecture asserts an equivalence between theories of gravity on a curved space and ordinary quantum field theories defined on the boundary of such spaces. This duality has become a powerful tool to study strongly interacting systems by use of a conjectured dual weakly coupled string/gravitational theory, allowing new computations that go beyond the standard perturbative techniques of quantum field theories. European theoretical physicists are at the international frontier of the exploration of gauge/gravity duality and its applications to physical systems. Members of this collaboration are leaders in the formal developments that attempt to prove and widen the conjecture, using string theory techniques and the integrability of certain gauge theories. Collaboration members also include world experts in the exploitation of this new computational tool to the strong nuclear force, hadronic physics, heavy ion collisions and condensed matter systems including high temperature superconductivity. This Holograv Network will orient research efforts to further the interdisciplinary aspects of the gauge/gravity duality, both in its formal aspects and in its applications to particle physics and condensed matter physics. Through the organization of workshops and schools, and through the incentive to run a common visitors programme, this network is an invaluable opportunity to promote the transfer of knowledge among participating organizations and to train graduate students who seek for a PhD in areas where strongly interacting systems are of central importance.

Previous or concurrent applications to the ESF for any of the ESF instruments:
None

Section II

Status of the relevant research field; scientific context, objectives and envisaged achievements of the proposed Programme

In 1997 Juan Maldacena triggered remarkable advance in theoretical physics. Based on some consistency checks and a lot of intuition he proposed that a gauge theory, of the type that describes the strong nuclear force, and a string theory, which includes gravity, were in fact descriptions of the same physics. This insight has led to a growing field of study both in mathematical physics and in using these ideas to provide new descriptions of many physical systems, including QCD (the strong nuclear force), heavy ion collisions, relativistic hydrodynamics, cosmology and condensed matter physics. The success of these techniques has inspired many papers and workshops round the world that bring together these diverse communities and have generated real interdisciplinary understanding. Until now though there has been no long term program to sustain this growing community, with funding coming in an adhoc manner from the different communities involved. We propose here a wide European program of this type to enable Europe to push ahead with its world leading contributions to this field.

The original "gauge/gravity duality" proposed by Maldacena considered a maximally supersymmetric gauge theory (N=4 super Yang Mills) which is conformal (it has no energy scale dependence). In string theory this gauge theory can be constructed on the surface of extended objects called D3 branes. These D3 branes induce curvature in the surrounding space-time geometry and can be thought as solitons of the dynamical gravity theory. Maldacena provided evidence that N=4 super Yang Mills gauge theory is equivalent to a string theory on the space curved by the D3 branes, namely five-dimensional Anti de-Sitter (AdS) space. The duality is a beautiful realization of old ideas introduced by 't Hooft in the 1970's, who argued that QCD, the gauge theory of strong interactions, admitted an expansion that resembled a string theory loop expansion. It also provides a beautiful description of gauge theories that are defined on the boundary of the dual AdS space where the gravitational theory is defined – this idea is called holography because the two equivalent theories differ in their space-time dimensions. The duality requires that when the gauge theory is strongly coupled (and for large number of colours N), the gravitational theory becomes weakly coupled and vice versa. Until now theoretical physics has lacked analytic tools for the study of the strongly coupled regime on either side – the duality provides such a tool.

The usefulness of the duality lies in the fact that it makes a definite proposal for how to compute in theories where we can not make first principle calculations. That though makes the duality hard to prove – it remains a conjecture. However, the large amount of supersymmetry of the theory provides many mathematical constraints and there has been heroic work providing consistency checks of the duality. Firstly all the low energy string theory (supergravity) states were mapped onto field theory operators. Progress was also made in the Penrose (pp-wave) limit of the geometry, where many additional string scale states were shown to correctly map to gauge theory operators. Most recently long single trace operators in the gauge theory have been mapped onto integrable spin chain models, similar to the Heisenberg spin chain, allowing integrability techniques to be used (for instance, the Bethe ansatz, so important to condensed matter physicists, has been extensively explored). These developments allow the computation of the anomalous dimension of these operators for any value of the coupling constant, providing a striking check of the duality. This program continues, most noticeably with the recent proposal to determine the exact spectrum of finite size operators using integrable Y-systems, bringing new hopes to prove the duality from first principles. The planar N=4 SYM theory appears to be a unique strongly interacting four-dimensional quantum field theory which is, in a certain sense, completely solvable analytically, thus providing us with a formidable opportunity to understand the general structure of strongly coupled gauge theories - the basis of the mathematical description of fundamental forces in Nature.

The duality is not only of mathematical interest though because many physical systems are believed to be described by strongly coupled gauge theories. The ideas of the duality have now been extended to cover many more theories based on more elaborate brane constructions in string theory. There are examples of dualities for theories with N=2, N=1, and even no supersymmetry. The matter content of these gauge theories has been modified to include quark like fields in the fundamental representation of the gauge group. The obvious motivation to study these theories is QCD, which in the infrared is a non-supersymmetric strongly coupled SU(3) gauge theory in which we can not compute analytically. The duality has revealed new descriptions of confinement and chiral symmetry breaking (mass generation) relevant to QCD. As yet, no one has been able to precisely formulate a dual of QCD itself, but inspiring models of duals of theories with similar behaviour to QCD do exist. Such models of QCD are providing quantitative insight into many aspects of QCD including the meson, glueball and baryon spectra, hadronic interactions and the hadronization process in colliders. There has been interest in these techniques from lattice gauge theorists who study QCD on super-computers and QCD phenomenologists interested in saturation phenomena in deep inelastic scattering and the hadronic spectrum.

Particle physicists have also long speculated about how strong dynamics might also occur beyond the standard model, for example, in a strongly coupled Higgs sector, or supersymmetry breaking sector. Duality techniques are improving understanding across all these areas and have the potential to make a big impact on understanding physics emerging from the Large Hadron Collider (LHC) at CERN. The Atlas and CMS experiments at LHC (and in the short term the Tevatron at FermiLab) will search the energy frontier for new physics at the TeV scale and above, with a very real chance that strong interaction physics from technicolour to unparticles will be found. Gauge/gravity techniques could be crucial in understanding this physics where we otherwise lack any computational tool.

Perhaps the biggest success of the duality techniques has been in heavy ion collision physics. Heavy ion collisions at Brookhaven, and upcoming at the ALICE experiment at the LHC, produce a plasma of quarks and gluons and are mapping out the behaviour of QCD at finite temperature and chemical potential. It has become clear that this plasma interacts very strongly and thermalizes very quickly in these experiments. Descriptions of the physics based on approaching this phase from a weakly coupled regime fail. Also, lattice regularized calculations, which provide the standard QCD technique for strong coupling calculations, are unable to describe many experimentally accessible dynamical quantities with the currently available computing resources. On the other hand gauge/gravity duality allows for the study of similar theories in this regime and reveals a relativistic hydrodynamic theory with computable transport coefficients – indeed the interaction between these two scientific communities has led to the identification of new terms in the hydrodynamic expansion of the QCD plasma and to deeper understandings of turbulence. The ratio of the shear viscosity to entropy density turns out to be $1/4\pi$ in a wide range of such duals providing an explanation for the observed fast thermalization rate in heavy ion collisions. Gauge gravity duality is also providing new descriptions of heavy/energetic quark propagation in the quark gluon plasma and there has been interest in identifying emission signals in the data. Finally we note that all these studies are improving our understanding of high density quark matter where the equation of state is still uncertain – this physics may therefore play a crucial role in the physics of neutron stars.

A recent development has been the attempt to bring the duality to bear on condensed matter systems, where observations in materials involving strongly correlated electrons challenge traditional condensed matter paradigms based on weakly interacting quasiparticles and the theory of symmetry breaking. Many technologically important systems, such as cold ion traps and high temperature superconducting materials, are ill understood and believed to be strongly coupled. The gauge/gravity duality provides therefore a unique approach to study these systems. Work is still underway to make a hard link to condensed matter experiment, but the prospects and present activity are very exciting.

Finally, on a more fundamental level, the implications of gauge/gravity duality to quantum gravity are also far reaching. For instance, many important questions in black hole physics, such as the information paradox and the membrane paradigm can be addressed within the duality framework. Moreover, in cosmology, the strong gravitational dynamics present at the big-bang singularity can also be mapped to a dual field theory language. These questions, and perhaps the larger question of whether a gauge theory dual is the best description of quantum gravity in nature, will also be explored in this Holograv Network.

The ESF Holograv Network we propose is intended to encourage and promote research across the broad range of physics applications of gauge/gravity duality discussed above. The duality has already proved to be a sufficiently powerful tool to bring condensed matter, nuclear, heavy ion, QCD, beyond the Standard Model and string theorists together. We believe this synthesis can be greatly enhanced by a network which would actively provide funding and encouragement for academic visits and PhD student exchanges. We will also hold at least two workshops for 50 participants in Europe each year on these ideas to bring together experts in their fields – in fact we intend that we would support many more smaller workshops bringing together experts in particular cross over areas. Finally we also intend to begin a larger scale international Gauge/Gravity conference program that would be held every two years. We are confident that enabling this connectivity within and between fields will generate significant and exciting new understandings, not only in the subject of gauge/gravity duality, but also in all the fields it touches.

Facilities and expertise which would be accessible by the Programme

This programme is by its nature theoretical. The most important asset is therefore its human capital. The proposed network includes the most prestigious European research institutions in theoretical physics, with scientists of the highest caliber. These institutions and scientists will actively participate in the network activities, together with their young graduate students. Moreover, this network will be extended to other world leading institutions at non-ESF partner countries, furthering the expertise available for the programme.

In the coming years, as LHC data starts to become available, we expect particle physics to go through a new golden era. This is a world effort led by European scientists. This network will also benefit greatly from these new forthcoming discoveries, for instance from the heavy ion physics programme.

A dedicated web-site will be created to manage the Holograv programme activities, such as workshops, summer schools and visitors programme. This web-site will serve as a data base for all network activities.

Expected benefit from European collaboration in this area

The study of gauge/gravity duality, as well as its applications across particle, nuclear and condensed matter physics, is an important new and rapidly expanding branch of theoretical physics. European scientists have made leading contributions to the development and success of this field to date. The research has potential implications for the understanding of physics both in the high energy discovery programme at LHC and the Tevatron, and the heavy ion physics programme at Brookhaven and the LHC. More widely these techniques can be expected to further our understanding of condensed matter physics, neutron star physics, black hole physics and cosmology. In particular, the emphasis of this programme on physical applications of the duality will push the field into developing techniques that are useful in an experimental context. This is a central aspect of the proposed research.

The Holograv programme we propose would provide unprecedented opportunity for European physicists to collaborate in this growing area of theoretical physics. We expect it to contribute to maintaining and furthering the European leadership in the field.

This Holograv Network will also initiate a strong training programme in these new techniques for Europe's graduate student community. The interdisciplinary nature of the field is of great benefit in training rounded students with a wide area of expertise in the physical sciences, therefore developing interdisciplinary competences.

European context

Collaborations between the groups in this Holograv Network builds upon long-standing research links established through past research networks at the European level, where scientists involved in this proposal have participated (*Constituents, Fundamental Forces and Symmetries of the Universe*, MRTN-CT-2004-005104; *The European Superstring Theory Network*, MRTN-CT-2004-512194). The present research proposal has a different focus, with an emphasis on the AdS/CFT duality, and on its applications to strongly interacting field theories.

With LHC at CERN, it is expected that in the forthcoming years Europe will lead the field of high energy particle physics. This proposed research programme will join European efforts to improve our understanding of strong interactions. One of the network coordinators, an expert in heavy ion physics, holds a position at the CERN theory group, therefore enabling a close coordination with activities at CERN.

For several years European physicists have been organizing a number of conferences, summer schools and extended programmes on research areas that include the AdS/CFT duality. Examples for each of such activities are: *Exploring QCD: Deconfinement, Extreme Environments and Holography*, 20-24 August 2008 (Isaac Newton Institute for Mathematical Sciences, UK); *Fifth Aegean summer School: From Gravity to thermal gauge theories*, 21-26 September 2009 (Milos Conference Centre "George Iliopoulos", National Technical University of Athens, Greece); *AdS4/CFT3 and the Holographic States of Matter*, 30 August – 5 November 2010 (The Galileo Galilei Institute for Theoretical Physics, Italy). Many other examples could be given. The Holograv Network will be a key player in planning and funding a consistent programme of workshops and summer schools in the theme of gauge/gravity duality.

Proposed activities, key targets and milestones

It is our intention with this programme to provide a clear funding channel to support this diverse but interlinked scientific community within Europe and across the wider International community. We wish to enable travel within Europe, so these groups can interact more often through staff and student exchanges, workshops, conferences and summer schools. We propose the following activities:

1. Initiate a bi-annual international conference on the gauge/gravity duality of order 100 participants, with the first and second meetings taking place

respectively in 2012 and 2014. This conference will also be open to the participation of scientists from countries not participating in the network.

2. In the years of 2011, 2013 and 2015 we shall organize the network workshop with about 50-100 participants (this workshop is replaced by the above international conference in 2012 and 2014).

3. Organize a yearly summer school led by young and bright European researchers. These schools will have a strong interdisciplinary character.

4. Introduce a new type of small workshop, typically lasting for three days, with up to 10 participants. These workshops aim at strengthening existing collaborations among European scientists in the field and at creating new ones. We expect to have six of such meetings per year.

5. Enable European researchers, including graduate students, with an exchange and short term visitors' mobility programme for the benefit of active groups in the area of gauge/gravity duality.

With the above proposed activities, the Holograv Network sets a number of objectives:

1. To uncover new perspectives in strongly coupled systems over a wide range of physical applications, most notably particle physics and condensed matter physics.

2. To further our understanding of long standing problems in quantum gravity and black hole physics.

3. To create a consistent programme of conferences, workshops and summer schools in the field of gauge gravity/duality, led by the network.

4. To play a key role in the training of graduate students and young Postdocs, with a particular emphasis on the interdisciplinary applications of the duality to different branches of physics.

5. Through an active visitors programme and the creation of small *working* workhops, the network will strengthen collaborations among European researchers and also with researchers from world leading institutions that are also participating in this proposal.

Duration

60 months

Budget estimate (in €) by type of activities and per year of the Programme

The budget presented bellow is based on the activities described in the section proposed activities. A brief justification of each item is as follows:

Conference: This will be a major conference with the duration of five days and a large number invited speakers (typically 30-40 communications). The budget for such an event will clearly exceed 40 k€, so it is expected that the organization will find other funding sources.

Network Workshop: These workshops will be more specialized and centred on the European programme members than the above conference. There will be less speakers, and review lectures will also be included in the schedule. The proposed budget is 20 k€.

Summer School: This yearly activity will be led by young bright researchers that have been giving significant contributions to the field. Considerable support will be provided for students to attend the school, justifying the proposed budget of 20 k€.

Small Workshops: This set of workshops will have a very light organization. Typically they will include up to five visitors and five researchers from the organizing institutions. We plan a budget of 5 k€ per meeting and 4-5 of such meetings per year.

Exchanges and Visits: To enable a more continuous contact among researchers and students in the Holograv Network we plan a yearly budget of 20-30 k€ for exchanges and visits.

Coordination/Web site: The management of the network will be centralized on a Web site, allowing for easy remote access to the network coordinators.

Budget estimate (in k€)

Activity	2011	2012	2013	2014	2015
Conference			40		40
Network Workshop	20	20		20	
Summer School		20		20	
Small Workshops	15	30	25	25	20
Exchanges and Visits	15	30	30	20	20
Coord/Web site	5	2.5	2.5	2.5	2.5
Total	55	102.5	97.5	87.5	82.5