Science Meeting – Scientific Report

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Proposal Title: International Workshop on Condensed Matter physics and AdS/CFT
Application Reference N°: 5711

Summary (up to one page)

The “International Workshop on Condensed Matter Physics and AdS/CFT” has been held at the Kavli Institute for the Physics and Mathematics of the Universe (IPMU), Kashiwa of Japan on May 25-29, 2015. Co-sponsored by the European Science Foundation network HoloGrav, Its main theme has been the "applied AdS/CFT correspondence” - the tool to understand quantum field theories by higher dimensional theories of gravity, and its interplay with strongly interacting systems in condensed matter physics. Counting with the participation of many of the top world experts from both applied AdS/CFT and condensed matter physics, the workshop has succeeded in fostering the interaction among theoretical high energy physicists, gravitational physicists, theoretical and experimental condensed matter physicists as well, in providing an overview and assessment of recent holographic and experimental progress regarding strongly coupled phenomena in condensed matter physics. The workshop has included 20 talks by invited speakers as well as 40 gang shows supplemented by poster session by registered participants. World-renowed scientists together with very young excellent researchers have presented their recent results. The workshop is highly international as it has counted 121 participants from all over the world.

Description of the scientific content of and discussions at the event (up to four pages)

Compared to the standard model in particle physics, there are many interesting vacuum/ ground states and phases observed in the real condensed matter systems. Many of them can be understood by the traditional paradigms such as Landau-Fermi liquid or BCS theories. These traditional paradigms are generically based on sharp quasiparticles or weakly coupled degrees of freedom. While some of them completely evade such a description, for example, high temperature superconductors and strangle metals,

because the involved phenomena are supposed to be driven by strongly coupled degrees of freedom. It thus becomes extremely urgent to develop some novel theoretical frameworks such that these systems can be modeled and analyzed.

Inspired from string theory, AdS/CFT correspondence can serve as such a powerful framework in which a strongly coupled system can be mapped to a weakly coupled gravity theory with one extra dimension. This extra dimension turns out to be a highly effective way to re-organize the degrees of freedom according to the energy scale, so mimics the renormalization group flow direction.

During this workshop, various progresses towards holographic optical conductivity were reported and discussed as optical conductivity is a very window into real condensed matter systems, which include holographic calculation of DC conductivity by the data at the black hole horizon, holographic understanding of Homes law exhibited in superconductors, new metal and insulator phases as well as the transition between them by holography, holographic impurity and disorder effects as well as the possible implementation of many body localization by a nontrivial geometry of black hole horizon.

In addition, due to the very advance made in cold atom experiments, more and more non-equilibrium processes can be manipulated in a controllable way. Compared to these experimental developments, the theoretical tools are relatively limited. However, AdS/CFT correspondence is particularly suitable for one to address the boundary non-equilibrium physics by investigating time dependent bulk dynamics. In this workshop, some representative work along this lane were also reported and discussed, such as holographic thermalization by AdS instability, holographic approaches to non-equilibrium steady states, and some universal behaviors followed by instantaneous quantum quench from holography as well as its dual field theory understanding.

Another beautiful aspect about AdS/CFT correspondence is that it geometrizes the entanglement entropy of boundary field theory by the area of bulk minimal surface archored to the entangling surface. Such an implication has inspired further reflections on the deep relation between gravity and quantum information. The state of art work was presented in this workshop along this direction, which includes some new entanglement inequalities implied by holography and state/surface correspondence proposed as a generalized AdS/CFT correspondence. On top of these, a very fundament issue on the entanglement entropy for gauge fields and the application of entanglement entropy in symmetry protected topological phases were also reported and discussed.

As promised, this workshop also included some excellent review talks from purely condensed matter physicists on both experimental developments and theoretical advances such as quantum oscillations in strongly correlated electron systems, quantum many body physics modeled by cold atom experiments in optical lattices, topological semimetals, quantum criticality by Monte Carlo, and hydrodynamics from fluctuation formulas. On the other hand, we had a very impressive talk on analogue gravity by condensed matter systems, which at least offers us an orthogonal perspective into the very interplay between gravity and condensed matter physics to AdS/CFT correspondence.

Besides the invited talks mentioned above, this workshop also provided the participants with the gang show and poster session to present their works.

In all, this workshop has succeeded in bringing together world-leading experts from gravity, string theory and condensed matter physics as well as interested young

researchers, fostering the interaction among them and identifying the state of the art in the interplay between AdS/CFT, condensed matter physics and quantum information.

Assessment of the results and impact of the event on the future directions of the field (up to two pages)

This workshop was one of the key meetings in the field of AdS/CFT and Condensed Matter Physics in this year. It was, however, unique in its own way, by bringing together condensed matter physicists and string theorists nearly in a half-half ratio.This was of course planned from the beginning, but it led to interesting and unexpected results, which may have great impact on the future directions of the field. The meeting hence revolved largely around the question "Can holography explain experiments?". For example, Suchitra Sebastian presented so-far unpublished measurements on quantum (de Haas-van Alphen) oscillations in the normal state of the cuprates, which support the interpretation that charge density wave order superstructure gaps out a large Brillouin zone into Fermi pockets in these materials. In particular, the antinodes of the Brillouin zone must be completely (hard) gapped. Incidentally, as emphasized also by Yi Ling in his talk, density wave orders seem to be present in many holographic models, and hence this mechanism may become part of a larger effort in the future to build more realistic holographic models of cuprate physics.

The goal of building more realistic holographic models of cuprate physics is tied to two related questions: Which phases of matter can AdS/CFT describe (i.e. a classificatory question), and which features of cuprate physics can be considered universal, and hence a good guiding principle for model building (i.e. a phenomenological question). Concerning the former, Koenraad Schalm pointed out in his talk that phases of matter described by holography are very non-generic from the traditional condensed matter point of view. This is an important insight whose impact still has to be fully understood. For example, AdS/CFT generically gives rise to a non-Fermi Liquid type, while Fermi-Liquid like behavior requires sufficient fine tuning of the model. Similarly, holographic superconductors are generically of non-BCS type. Right now it is not clear whether these features are more connected to strong coupling or to large N, a question which will need further investigation by trying to construct 'conventional' systems (Landau Fermi Liquids, BCS-like superconductors) in holography. On the other hand, this generic non-conventionality makes AdS/CFT a good starting point for constructing models of unconventional quantum critical materials such as the cuprates. As pointed out by Prof. Schalm in his summary talk, hyperscaling violating theories with Lifshitz scaling, quantum smectic materials and quantum critical metals with ultralocal scaling are easily constructed. Prof. Hartnoll and Prof. Kiritsis pointed out that a scaling theory of general hyperscaling violating theories will, besides the hyperscaling violating and dynamical Lifshitz exponents, contain a third exponent setting the anomalous dimension of the conserved charge current. Matching to cuprate phenomenology (see below) requires this third exponent to be nonzero, but explicit holographic models with all three exponents tunable are not known so far. Finding such a model would complete the classification of rotationally and translationally invariant charged normal states of matter in AdS/CFT. Other interesting phases of matter discussed in the workshop include supersolids (by Prof. Kiritsis), Kondo and other lattice models (by Prof. Erdmenger), quantum smectics (by Prof. Schalm), and holographic insulators with a soft gap and coherent/incoherent metals (by Prof. Gauntlett). The workshop showed that there is an inherent interest in constructing holographic insulators with a hard gap as well, and several ideas of how to achieve this were discussed. Whether this classification is complete or not remains to be seen. Other important directions discussed at the workshop revolved around non-rotationally symmetric, non-relativistic and disordered ground states, which definitely will

constitute lively future research directions in the field.

The second question posed above, namely which signs of universal physics we can use to model the cuprates in holography, was also heavily discussed in the workshop. Sean Hartnoll discussed a possible explanation for linear in temperature resistivity scaling, based on the idea that quantum critical systems saturate universal bounds for charge and energy diffusion constants, and hence do the associated electric and thermal conductivities. This idea will definitely strongly guide holographic model building in the near future. As mentioned above, Prof. Hartnoll and Prof. Kiritsis also discussed a general scaling theory for hyperscaling violating systems with a conserved current that acquires an anomalous dimension. As Prof. Hartnoll explained, it is possible to match the temperature scalings of all important DC observables (resistivity, Hall angle, Lorentz ratio) by fixing the three critical exponents (dynamical Lifshitz, hyperscaling violating and current anomalous dimension), and that in particular the last one needs to be nonzero to obtain a temperature-dependent Lorentz ratio. Mid-frequency scaling properties of the AC conductivity were discussed by Prof. Kiritsis and Prof. Phillips. Prof. Kiritsis showed two model calculations that show such nontrivial scaling, while Prof. Phillips' extensive numerical analysis of a different holographic lattice model showed that such a scaling is absent. Prof. Phillips then presented a model based on electrons coupled to scale invariant matter (unparticles), which can reproduce such scaling. In summary, the case for or against mid-frequency power laws in holographic models is far from being settled, and will surely push the field to further detailled and careful analyses. Prof. Kiritsis also discussed that the inverse Matthiesen law holds in holographic models, as it does in high temperature superconductors. Finally, Prof. Schalm discussed a holographic model in which Homes' law, a relation between the normal and superfluid phase of high temperature superconductors, is realized. This relation is believed to be universal for all cuprates, and seems tied to the incoherent metallic transport in these materials. Further analysis of this and other models to see why Homes' law holds will surely advance the field of holographic model building for the high temperature superconductors.

Entanglement, in particular entanglement entropy, was another important topic of the workshop. Entanglement is also important to characterize the above-discussed finite density states of matter. For example, Fermi liquids show a logarithmic violation of the area law. Prof. Ooguri showed in his talk that certain universal inequalities strongly constrain the entanglement entropy, and that these constraints AdS/CFT amount to imposing an integrated positive energy condition on the matter in the gravity theories. The impact of this condition on holographic models, in particular also with higher curvature corrections, still has to be understood. Prof. Ryu talked on symmetry protected interacting topological phases and emphasized the importance of the entanglement spectrum to characterize them, an avenue that will surely need more investigation in holographic models in the future as well. Prof. Fang talked about recent progress on topologically protected materials from the theoretical and experimental points of view, and it will be very interesting to see whether AdS/CFT can in the future be used to model materials such as SPTs and Weyl semimetals as well. Another important question is how to generalize entanglement entropy to systems whose Hilbert space does not readily factorize, such as gauge theories. Prof. Trivedi presented a new definition which works for discrete and abelian gauge groups, and can be readily extended to nonabelian cases. This is a very important development, as AdS/CFT models are usually dual to large N nonabelian gauge theories, and hence it will be very important to understand why entanglement entropy does geometrize in such a nice way in this limit. Dr. Witczak-Krempa in his talk presented new results on corner contributions to the entanglement entropy, which are also universal and reproduced in AdS/CFT. Finally, Prof. Takayanagi presented a new view on holographic duality by identifying boundary states with open and closed surfaces in the bulk through their entanglement properties. This is a very

interesting and new future direction, as it also applies to non asymptotically AdS spacetimes such as flat or de Sitter space, and hence has the potential to extend the holographic correspondence to completely new areas.

Another field where AdS/CFT models can be usefully applied to condensed matter systems is non-equilibrium situations, mostly due to the fact that traditional calculational approaches do not easily apply to dynamical situations. In AdS/CFT, on the other hand, solving a dynamical problem such as e.g. a quench at most amounts to solving time-dependent PDEs, which can easily be done by well-known methods. Prof. Takahashi talked about how such situations can be modelled in modern experiments with cold atoms, which surely will become important in the near future to test predictions from AdS/CFT. Prof. Das talked about universal scaling results in slow (Kibble-Zurek) and fast (instantaneous) quenches. The results for the latter were first obtained in AdS/CFT calculations, and are now proven to hold generally in QFTs. This universal scaling regime should also be detectable in quench experiments, such as e.g. in cold atomic experiments. Prof. Craps talked about another important non-equilibrium situation, the collapse of matter in asymptotically global AdS spacetimes. As it turns out, these spacetimes may or may not be unstable towards the formation of a black hole if matter is collapsing inside them, depending on the exact initial conditions of the collapsing matter. Answering the question whether this black hole formation instability is generic or not is very important for understanding the ground state of the dual field theories - it amounts to whether or not their ground states are stable, or whether they generically decay into a thermal state under small as well as large perturbations. Prof. Bhaseen talked about a different kind of universal results recently obtained both in AdS/CFT and in field theory, which concern the flow of momentum and energy in non-equilibrium steady states driven between different CFTs. These flows are controlled by the central charge of the dual CFT. Since AdS/CFT results are valid at strong coupling, and similar results hold for weakly coupled theories, it is tempting to believe that these results are universal properties of non-equilibrium steady states. Similar investigations into the large fluctuation relations discussed by Prof. Sasa in the AdS/CFT framework will be very interesting, as they could lead to further universality results in non-equilibrium setups in AdS/CFT. Finally, Prof. Visser talked about using condensed matter systems to model gravitational dynamics, a field of research called analogue gravity. This approach is tightly connected to cold atomic gases, which can be used to obtain analogues of black holes and their horizons, and in the future may even be used as a laboratory to test the validity of the AdS/CFT correspondence itself.

4) Annexes 4a) and 4b): Programme of the meeting and full list of speakers and participants

Annex 4a: Programme of the meeting

Program

Monday 25 May 2015:

08:30-09:25 Registration
09:30-10:30 GAUNTLETT, Jerome, Holographic Lattices
10:30-11:00 Coffee break & Poster Session
11:00-12:00 SEBASTIAN, Suchitra, Quantum oscillations in strongly correlated electron systems
12:00-12:05 Group photo
12:05-13:00 Lunch break
13:00-14:00 Poster Session
14:00-15:00 HARTNOLL, Sean, Holographically inspired thoughts on high temperature superconductors and other bad metals
15:00-15:45 Coffee break & Poster Session
15:45-16:45 OOGURI, Hirosi, Entanglement Inequalities

16:45-17:45 Gong Show, Poster no. 1-20

Tuesday 26 May 2015:

09:25-09:30 Address by Hitoshi Murayama (Director, Kavli IPMU)
09:30-10:30 KIRITSIS, Elias, Tales in the realm of Holographic Conductivity
10:30-11:00 Coffee break & Poster Session
11:00-12:00 PHILLIPS, Philip, Optical Conductivity as a Window into Mottness in the Cuprates
12:00-13:00 Lunch break
13:00-14:00 Poster Session
14:00-15:00 ERDMENGER, Johanna, Magnetic impurities and universality in AdS/CMT
15:00-15:45 Coffee break & Poster Session
15:45-16:45 LING, Yi, Metal-insulator transition by holography
16:45-17:45 Gong Show, Poster no. 21-40

Wednesday 27 May 2015:

09:25-09:30 Address by Masashi Takigawa (Director, ISSP)
09:30-10:30 RYU, Shinsei, Symmetry-protected topological phases and quantum entanglement
10:30-11:00 Coffee break & Poster Session
11:00-12:00 TAKAYANAGI, Tadashi, Emergence of Holographic

Spacetime from Quantum Entanglement

Thursday 28 May 2015:

09:30-10:30 TRIVEDI, Sandip, Entanglement Entropy in Gauge Theories
10:30-11:00 Coffee & Poster Session
11:00-12:00 FANG, Zhong, Topological Semimetals
12:00-13:00 Lunch break
13:00-14:00 Poster Session
14:00-15:00 SASA, Shin-ichi, A fresh look at hydrodynamics from fluctuation formulas
15:00-15:45 Coffee break & Poster Session
5:45-16:45 DAS, Sumit, Smooth and instantaneous quenches in field theory and holography
16:45-17:45 CRAPS, Ben, Holographic thermalization and AdS (in)stability

Friday 29 May 2015:

09:30-10:30 TAKAHASHI, Yoshiro, Exploring quantum many-body physics using ultracold atoms in an optical lattice
10:30-11:00 Coffee break & Poster Session
11:00-12:00 VISSER, Matt, Overview of analogue spacetimes
12:00-13:00 Lunch break
13:00-14:00 Poster Session
14:00-15:00 BHASEEN, Joe, Holographic Approaches to Non-Equilibrium Steady States
15:00-15:45 Coffee break
15:45-16:45 WITCZAK-KREMPA, William, Quantum critical dynamics via CFT, Monte Carlo & holography
16:45-17: 45 SCHALM, Koenraad, Condensed matter physics and holography: seductivity and resistance

Annex 4b: Full list of speakers and participants

Speakers:

Joe Bhaseen (Kings College)
Ben Craps (VUB Brussels)
Sumit Das (U. of Kentucky)
Johanna Erdmenger (MPI Munich)
Zhong Fang (IOP, CAS, Beijing)
Jerome Gauntlett (Imperial)
Sean Hartnoll (Stanford U.)
Elias Kiritsis (U. of Crete and APC, Paris)
Yi Ling (IHEP&ITP, CAS, Beijing)
Hirosi Ooguri (Caltech & Kavli IPMU)
Philip Phillips (U. of Illinois)
Shinsei Ryu (U. of Illinois)
Shin-ichi Sasa (Kyoto U.)
Koenraad Schalm (Leiden U.)
Suchitra Sebastian (Cambridge)
Yoshiro Takahashi (Kyoto U.)
Tadashi Takayanagi (YITP, Kyoto U.)
Sandip Trivedi (Tata Institute)
Matt Visser (Victoria U. Wellington)
William Witczak-Krempa (Perimeter)

Participants:

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2	BANERJEE, Shamik	Kavli IPMU	JAPAN
3	BHASEEN, Joe	King's College London	UNITED KINGDOM
4	CRAPS, Ben	Vrije Universiteit Brussel	BELGIUM
5	DAS, Sumit	University of Kentucky	USA
6	DEMPSTER, Paul	Seoul National University	REPUBLIC OF KOREA
7	EBIHARA, Shu	The Univ. of Tokyo	JAPAN
8	EBIHARA, Takao	Univ. of Shizuoka	JAPAN
9	ERDMENGER, Johanna	Max Planck Institute for Physics	GERMANY
10	FANG, Zhong	Institute of Physics, Chinese Academy of Sciences	CHINA
11	FLORY, Mario	Max-Planck Institute for Physics	GERMANY
12	FUJITA, Mitsutoshi	YITP, Kyoto University	JAPAN
13	FUKAZAWA, Yuichi	Chuo University	JAPAN
14	FUKUSUMI, Yoshiki	ISSP	JAPAN
15	GAUNTLETT, Jerome	Imperial College	UNITED KINGDOM
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17	GOTO, Kanato	The Univ. of Tokyo	JAPAN
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