JOHANNES GUTENBERG UNIVERSITÄT MAINZ

MITP Program Final Report

Title: **Quantum Vacuum and Gravitation: Testing General Relativity in Cosmology**

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1. General purposes and scope of the Program

The Program was intended to provide the discussion of the latest advances of both observational and theoretical aspects of cosmology and astrophysics, with direct participation of the active workers in the neighbored fields such as astrophysics, black holes, quantum gravity and quantum field theory in curved space-time. The organization of the 2017 Program was based on the successful experience with a shorter topical workshop at MITP in June 2015. This time there was a less intensive, two week program at the MITP bringing together theorists from particle physics and General Relativity with observational cosmologists to develop new approaches to outstanding problems.

From the theoretical side, the Program was especially focused on the field-theoretical methods such as renormalization group and conformal anomalies, effective action method and the implications in Astrophysics and Cosmology. In the cosmological side there were a few review talks that included the latest experimental and observational data and their understanding in the framework of existing theoretical constructions. Also we had quite remarkable high-quality short presentations on the observational side, including the ones given by younger researchers.

1. General overview of the Program

Our evaluation that agrees with the opinion of the participants is that the Program was very successful; In particular it boosted new collaborations among the participants, in both theory and observational parts, confronting theoretical ideas with the new observational data that are becoming available. All the talks were at very high scientific level and captured the attention of participants and in some cases also that of the local group of theoretical physics, which is well known by research works in the areas of the Program. Local students also attended to some of the talks. The program of the sessions was not as intensive as that of 2015 to allow for large sessions of open discussions; although organizers tried not to deny all participants the right to present his/her works in the oral form. A few review talks lasted 75 minutes for presentation, while most of other presentations were limited to last 40-50 minutes. At the end of each daily session there was a special discussion, devoted to review the talks of the day and related subjects. These discussions were very interesting and we consider them fruitful for better understanding of the points of view of different researchers and the problems which are in the focus of attention of cosmology, high-energy and gravitational physics.

A brief summary of the main reviews:

Dr. Ivan Agullo from Louisiana State University reported on recent developments of loop quantum cosmology, which has become a robust framework to describe the highest curvature regime of the early universe. In this theory, inflation is preceded by a bounce replacing the big bang singularity. After summarizing the theoretical framework the corrections to the inflationary predictions were discussed, including the primordial spectrum of cosmological perturbations in the pre-inflationary, quantum gravity phase of the early universe evolution. The impact of the bounce on non-Gaussianity and the exciting relation to the observed large scale anomalies in the CMB was also discussed.

Prof. Matthias Bartelmann from the Universität Heidelberg gave an overview talk on the cosmological standard model and the standard approach to the formation and evolution of cosmic structures. Furthermore, he discussed a new approach to cosmic structure formation based on a non-equilibrium, statistical field theory for correlated, classical particle ensembles. This approach allows to calculate statistical properties of cosmic structures at low orders in perturbation theory even at small scales and deeply in the non-linear regime. The theory is based on first principles and is free of adjustable parameters. The evolution of cosmic structures, in particular in its late, non-linear phases, provides important clues on the evolution of the Universe as a whole. In view of possible, subtle deviations from general relativity and the cosmological standard model, non-linear cosmic structures as for example traced by the population of galaxy clusters may act as magnifiers to enhance small dynamical effects above observational thresholds. For drawing such conclusions, we need to understand cosmic structure formation in detail in particular on small scales and at late times.

Prof. Glenn Starkman from Case Western Reserve University reviewed the statust of CMB Anomalies 25 years after COBE. We learned that several unexpected features have been observed in the temperature of the microwave sky at large angular scales, from COBE to WMAP and Planck. These include lack of both variance and correlation on the largest angular scales; alignment of the lowest multipole moments with the motion and geometry of the Solar System; lack of variance in the northern hemisphere, a hemispherical power asymmetry or dipolar power modulation; a preference for odd parity modes; and an unexpectedly large cold spot in the Southern hemisphere. The individual p-values of the significance of several of these features are in the per mille to per cent level, compared to the expectations of the best-fit inflationary ΛCDM model. There are no good physical models for these anomalies, but it was explained that one can make progress by: considering how the existence of measured anomaly alters the predictions of ΛCDM for other observables; and/or making predictions from reasonable phenomenological expectations for the physics contents of measured anomalies.

Prof. Alexei Starobinsky from Landau Institute for Theoretical Physics discussed the last advances in the theoretical and observational progress in the study of inflationary phase of the universe. It is possible to make a reconstruction of inflationary models in GR and f(R) gravity using information on the power spectrum of scalar perturbations only. He also discussed the ambiguity of this procedure and how it can be fixed by aesthetic assumptions on the absence of new physical scales during and after inflation. The problem of the onset of inflation can be seen from the perspective of generic classical curvature singularity preceding it.

Prof. Emil Mottola from Los Alamos reviewed and explained his well-known works on the quantum effects on black holes. Classical General Relativity (GR) together with conventional equations of state suggest that in complete gravitational collapse a singular state of matter with infinite density could be reached finally, to what is popularly called a "black hole." In addition to its interior singularities, the characteristic feature of a black hole is its apparent horizon, the surface of finite area at which outwardly directed light rays are first trapped. The loss of information to the outside world this implies gives rise to additional difficulties with well-established principles of quantum mechanics and statistical physics. An interesting alternative to the black hole formation is the gravitational vacuum condensate star proposal, which was made by Mottola et al in 2001. In this case there is no event horizon, and the Schwarzschild time of such a non-singular gravitational condensate star is a global time, which is fully consistent with unitary time evolution in quantum theory. Further observational test of gravitational condensate stars vs. black holes is the discrete surface modes of oscillation and echoes which should be detectable by their gravitational wave signatures.

Prof. Ruth Durrer from the Universite de Geneve reviewed the recent progress in the study of the Cosmic Microwave Background. Most numbers in cosmology have been measured using the anisotropies and polarization of the Cosmic Microwave Background (CMB). So far other data has mainly been used for consistency checks and very few inconsistent measurements exist. The reason for this is twofold: first the theory of the CMB is nearly linear and therefore quite simple. Secondly, the CMB spectrum peaks around frequencies which allow relatively precise observations from the ground and especially from space. Durrer explained us the relatively simple physics behind CMB anisotropies and polarization and gave some examples of how it can be used to measure cosmological parameters. Furthermore, she outlined ideas of how to go beyond present measurements which mainly constrain cosmological parameters. After all, one can use the CMB to test General Relativity on cosmological scales. The interesting new developments in the theory of Large Scale Structure observations give a hope that future LSS surveys can compete with and complement CMB observations.

Prof. Cliff P. Burgess from McMaster and Perimeter talked about "Effective Field Theories and Modifying Gravity: The View from Below". From the effective field theory perspective there are nowadays contradictory messages about how successfully we understand gravity. General Relativity seems to work very well in the Earth's immediate neighborhood, but arguments abound that it needs modification at very small and/or very large distances. The situation can be better understood in the broader context of similar situations in other areas of physics, such as QCD or Standard Model or electroweak interactions. The main lesson is that effective theories provide the natural and in many cases precise language for framing proposals. The special attention has been given to the treatment of higher derivatives, which was also the subject of discussions in several other talks.

Dr. M Crocce from the Institute for Space Science of Barcelona gave an overview of next decade program for Observational Cosmology focused on the analysis of the Large Scale Structure (LSS). The goal is to undertake large astronomical surveys that, by scanning millions of galaxies across cosmic time, we will study the origin and evolution of the Large Scale Structure of the Universe. In his talk Crocce analysed which are the probes that these surveys use to test GR, such as galaxy clustering and weak lensing, discussing current constrains and their implications. He also analyzed the main goals of LSS from the perspective of ongoing and future surveys, such as the Dark Energy Survey (DES) or the ESA/Euclid satellite.

Prof. Andrei Barvinsky from Lebedev Institute told us about the last results concerning the application of effective action method to the very early quantum Universe. The resent advances in using the effective action method in cosmology were explained with a special emphasis on its application in the theory of quantum initial conditions for the very early Universe and the models of Higgs and curvature-squared inflation. The role of local gradient expansion and conformal anomaly for the effective action has been discussed and applied to the microcanonical state of the Universe. Furthermore, Barvinsky introduced his new model of a new type of “hill-top” inflation.

Prof. Alessandra Buonanno from the Max Planck Institute for Gravitational physics presented a review on the next theoretical challenges for gravitational-wave observations. One hundred years passed after Einstein predicted the existence of gravitational waves on the basis of his theory of General Relativity. Quite recently LIGO announced the first observation of gravitational waves passing through the Earth emitted by the collision of two black holes one billion four hundred million light years away. The review included the theoretical groundwork that allowed the identification and interpretation of gravitational-wave signals, carry out tests of general relativity in the strong-field, highly dynamical regime, and also the next theoretical challenges in solving the two-body problem in General Relativity. Such a solution is very important if we want to take full advantage of the discovery potential of upcoming gravitational-wave observations.

A more complete account of the contents of the talks can be seen from the list of abstracts that can be found on the homepage of the Program, together with the slides of all presentations.

Finally, we are writing a white paper elaborated by a selected group of participants to summarize the status of the art of the main subjects discussed in the Program. This paper will be published as an output of the successful Program. The important role of MITP in the elaboration of this work will be explicitly acknowledged.