Quantum Vacuum and Gravitation: Testing General Relativity in Cosmology

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The scientific program was intended to provide a discussion of the latest advances of both observational and theoretical aspects of cosmology and astrophysics, with direct participation of the active workers in the related fields such as astrophysics, black holes, quantum gravity and quantum field theory in curved space-time. The organization of the 2017 scientific program was based on the successful topical workshop at MITP in June 2015. This time there was a less intensive, two-week scientific 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 scientific 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. From 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. Moreover, there were quite remarkable high-quality short presentations on the observational side, including the ones given by younger researchers.

The scientific program boosted new collaborations among the participants in both theory and observational parts, confronting theoretical ideas with the new data that are becoming available. All 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, who is well-known by research work in the areas of the scientific program. A few review talks of 75 minutes were presented, while most of other presentations were limited to 40-50 minutes. At the end of each daily session there was a special discussion which reviewed the talks of the day and related subjects. These discussions were very interesting and very useful for a better understanding of the points of view of different researchers and problems which focus on cosmology, high-energy and gravitational physics

The main review talks were the following: 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 cosmic microwave background (CMB**)** was also discussed.

Matthias Bartelmann from the University Heidelberg gave an overview 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 does not include 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 such conclusions, one needs to understand cosmic structure formation in detail in particular on small scales and at late times.

Glenn Starkman from Case Western Reserve University reviewed the status of CMB anomalies 25 years after COBE. 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.

Alexei Starobinsky from the Landau Institute for Theoretical Physics discussed the recent theoretical and observational progress in the study of inflationary phase of the universe. It is possible to make a reconstruction of inflationary models in classical general relativity and f(R) gravity by 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.

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 a complete gravitational collapse a singular state of matter with infinite density could finally be reached, a so-called "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 fully consistent with unitary time evolution in quantum theory. Another 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.

Ruth Durrer from the University of Geneva reviewed the recent progress in the study of the cosmic microwave background (CMB). Most numbers in cosmology have been measured by using the anisotropies and polarization of the CMB. So far other data has mainly been used for consistency checks; very few inconsistent measurements exist. The reason for this is twofold. First of all, 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 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 (LSS) observations give rise for the hope that future LSS surveys can compete with and complement CMB observations.

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 a lot of arguments suggest 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. The main lesson is that effective theories provide the natural and in many cases precise language for framing proposals. Special attention has been given to the treatment of higher derivatives, which was also the subject of discussions in several other talks.

Martin Crocce from the Space Science Institute of Barcelona gave an overview of the 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, will study the origin and evolution of the large scale structure of the universe. In his talk Crocce analyzed which are the probes that these surveys use to test GR, such as galaxy clustering and weak lensing. Crocce also discussed current constrains and their implications. Moreover, 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.

Andrei Barvinsky from the Lebedev Institute presented the last results concerning the application of effective action method to the very early quantum universe. The recent 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. Barvinsky discussed the role of local gradient expansion and conformal anomaly for the effective action and applied it to the micro-canonical state of the universe. Furthermore, Barvinsky introduced his model of a new type of “hill-top” inflation.

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, 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 one wants to take full advantage of the discovery potential of upcoming gravitational-wave observations.