Executive Summary of the MITP Topical Workshop:

"Quantum Vacuum: Renormalization Group and Anomalies in Cosmology"

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23-27 of September, 2019

Goals of the Topical Workshop

The main goal of the workshop was to analyze, on the light of new results on the quantum field theory, the latest advances in conformal anomalies, renormalization group and their applications to gravitational physics and cosmology. The interplay of conformal anomalies and renormalization group gives rise to entropic theorems known as c-theorems and a-theorems. To understand the connection of these theorems and its generalizations with holographic dualities was one of the goals of the workshop. Another main objective was to deeply analyze the quantum theory of gravity from a pure field theoretical viewpoint. In particular, to analyze new recent proposals based on conformal gravity and modified theories of gravity with higher derivatives (local or nonlocal). A final goal was to find out the role of modified gravity in inflationary theories and cosmology with special emphasis on the implications of the Starobinsky model of inflation which is becoming the most successful inflationary model, according to the latest observational data releases.

Scientific Highlights of the Topical Workshop

New interesting applications of quantum field theory to gravitational physics were displayed during the workshop: new physics on de Sitter spaces, theories of inflation and new holographic dualities. On the cosmological side most of the applications concern inflationary theories with special emphasis on the Starobinsky model. A review of these applications, including some interesting observational aspects, was carried out by Prof. Alexei Starobinsky. Two review talks given by Profs.

Kostas Skenderis and Stefan Theisen on holographic dualities and conformal anomalies opened the discussion on related subjects. Two more review talks were given by Profs. Neil Turok and Georgi Dvali who analyzed, respectively, the Lorentzian functional integral approach to quantum gravity and the relations between unitarity and entropy bounds in field theory and quantum gravity.

The review talks boosted the discussions among the participants on different subjects of cosmology, high-energy and gravitational physics, selected by the organizers. The discussions were organized around several shorter talks given by the participants. A commented summary of the talks follows below.

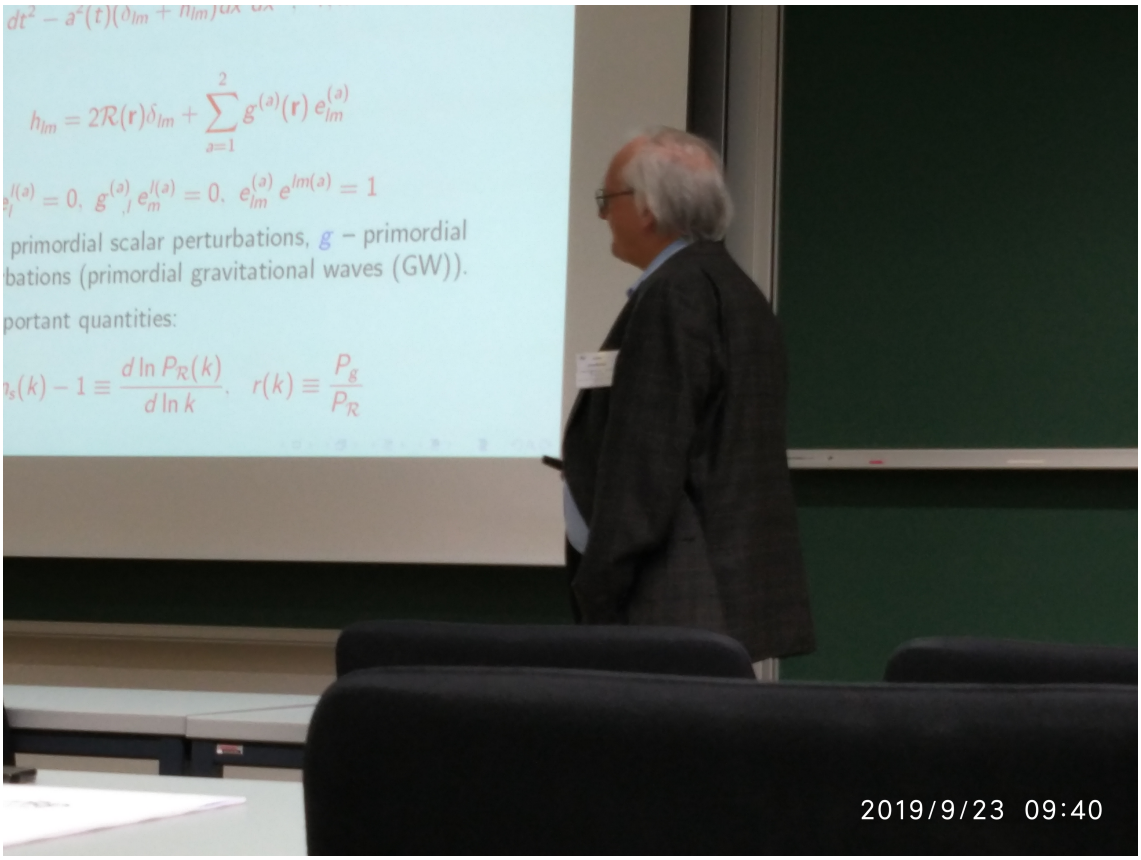

Figure 1: Prof. Alexei Starobinsky during his review talk

A. Review talks

Prof. Neil Turok (Perimeter Institute)

Title: *Quantum Universe*

Abstract: One can argue that the Lorentzian path integral is a better starting point for quantum cosmology than the Euclidean version. In particular, we revisit the mini-superspace calculation of the Feynman path integral for quantum gravity

with a positive cosmological constant. Instead of rotating to Euclidean time, we can deform the contour of integration over metrics into the complex plane, exploiting Picard-Lefschetz theory to transform the path integral from a conditionally convergent integral into an absolutely convergent one. One can show that this procedure unambiguously determines which semiclassical saddle point solutions are relevant to the quantum mechanical amplitude. Imposing "no-boundary" initial conditions, i.e., restricting attention to regular, complex metrics with no initial boundary, we find that the dominant saddle contributes a semiclassical exponential factor which is precisely the inverse of the famous Hartle-Hawking result.

Prof. Alexei Starobinsky (Landau Institute for Theoretical Physics)

Title: *Inflation and pre-inflation: present status and the simplest models*

Abstract: At the present state-of-the-art, the simplest inflationary models, based either on scalar fields in General Relativity or on modified f(R) gravity, which produce the best fit to all existing astronomical data require one, maximum two dimensionless parameters taken from observations only. The main discoveries expected for these models in future can be listed as follows. i) The most fundamental are primordial quantum gravitational waves generated during inflation. In one parametric models, including the original $R + R^2$ one, the definite prediction for the tensor-to-scalar ratio $r = 3(1 - n_s)^2 = 0.004$ follows. The role of one-loop quantum gravitational corrections to these models is considered. Inflation, as a metastable quantum state, had finite life-time, and differences in its duration in terms of the number of e-folds between various points of space can be determined with remarkable accuracy. In the models considered, the most generic predecessor of inflation is an anisotropic and inhomogeneous space-time near a generic space-like singularity. Since the transition from such space-time to the generalized quasi-de Sitter regime is generic, too, for inflation to begin inside a patch including the observable part of the Universe, causal connection inside the whole patch is not necessary. However, at the present day level observational precision it became obligatory for a graceful exit from inflation to provide practically the same number of e-folds during inflation inside this patch.

Prof. Georgi Dvali (Munich University)

Title: *Unitarity and area-law entropy bound: Black holes, solitons and instantons*

Abstract: In this talk he was describing the methods to impose qualitative entropy bounds on the black holes and other geometrical objects and on the quantum corrections in flat and curved spacetime. The results can be of an utmost importance for quantum gravity, since there may be useful to impose an upper limit on the energy density of gravitons in zero or relatively weak external gravitational field. Prof. Kostas Skenderis gave a review talk on "Holographic cosmology and the puzzles of Hot Big Bang cosmology". It was a comprehensive review of a holographic

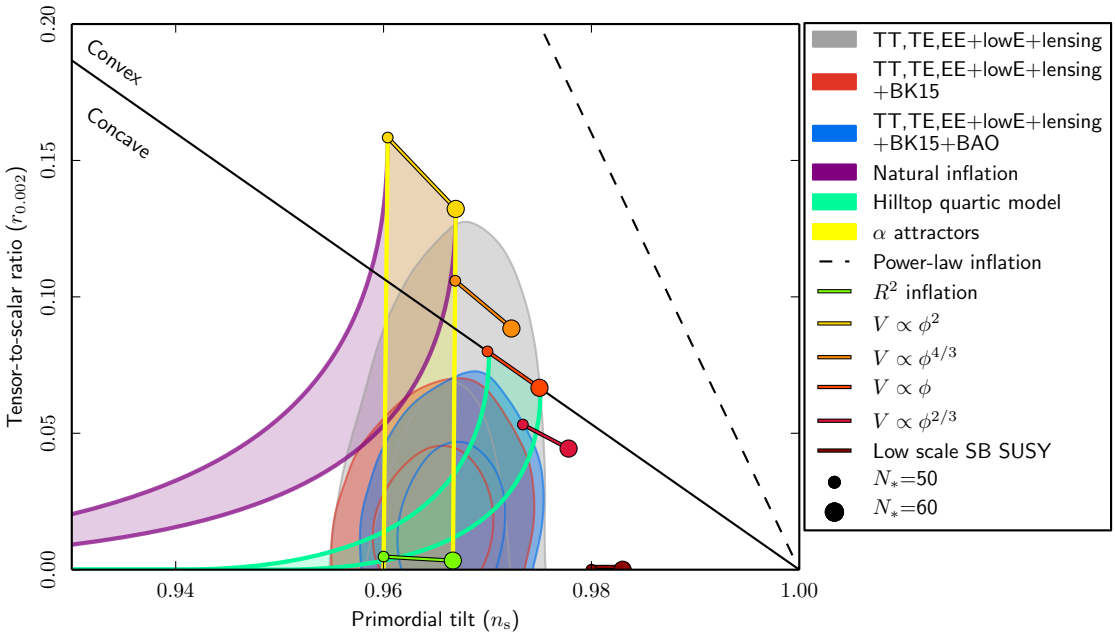

Figure 2: Constrains from Planck Collaboration on inflationary models

framework for the very easy universe, the period usually associated with inflation. In this setup cosmic evolution is mapped to inverse RG flow in the dual QFT and I will explain how standard puzzles of hot Big Bang cosmology such as the smoothness and horizon problem, the flatness problem and the relic problem are resolved in this framework.

Prof. Stefan Theisen(Max-Planck-Institut für Gravitationsphysik (Albert-Einstein-Institut))

Title:*The Weyl anomaly and some of its uses.*

Abstract: He explained the framework of conformal field theory (CFT) and how it is applied to explore the quantum field theories of massless matter fields in two, four and higher dimensions. There are known universality classes in the anomalies which change in a universal was along the running flow between high (UV) and low (IR) energy limits. The a- and c-theorems discussing these universality classes in an arbitrary even dimensions were qualitatively reviewed.

B. Regular talks.

Prof. Patrick Peter (CNRS, Paris)

Title:*A simple method for singularity avoidance and some consequences.*

Abstract: In a simple model (FLRW or Bianchi I minisuperspace and Wheeler De Witt), I discuss how the singularity can be avoided by defining quantum trajec-

tories. This permits to classify clocks and could thus be related to the issue of time. Applying similar procedures to perturbations, the primordial power spectrum can be affected, leading to possibly detectable consequences in the cosmic microwave background or large scale structure data.

Prof. Matthias Bartelmann (Heidelberg University)

Title:*Structure formation in standard and non-standard cosmology.*

Abstract: The approach which he presented is that non-linear cosmic structure formation can be described by a kinetic field theory for classical particle ensembles out of equilibrium. Building upon the path-integral formalism for classical mechanics, this theory structurally resembles a statistical quantum field theory. Its generating functional encapsulates the statistical properties of an initial state of the ensemble and the equation of motion of its particles. Interactions between the particles are described by an interaction operator, which can either be Taylor expanded into a perturbation series of Feynman diagrams, or approximated in a mean-field approach. For cosmology, the mean-field approach has proven to be quite successful, allowing to calculate non-linear power spectra for cosmic structures analytically quite deeply into the non-linear regime even at late times and small scales. The conceptual simplicity and the flexibility of this kinetic field theory allow to apply it quite easily to different models for the dark matter, and to generalisations of gravity theory. Extended model or theory spaces can now be studied with little effort for their effects on non-linear cosmic structure formation. The review talk reviewed the kinetic field theory and also summarise some results for standard cosmology. In this way one can describe extensions towards axionic or axion-like dark-matter models and some generalisations of general relativity.

Prof. Sergei Ketov(Tokyo Metropolitan University)

Title:*On the equivalence between Higgs and Starobinsky inflationary models in gravity and supergravity.*

Abstract: After a brief review of the Starobinsky inflationary model, based on a modified gravity, and the Higgs inflationary model, based on a non-minimal coupling of a Higgs field to gravity, a simple proof of their equivalence for slow-roll inflation in the large field approximation is given. Both inflationary models are extended to N=1 supergravity in four spacetime dimensions with inflaton in a vector supermultiplet, while their equivalence in the large field approximation to slow-roll inflation is maintained. We provide the fundamental reasons of the equivalence and comment on further extensions in quantum field theory, string theory and higher dimensions.

Dr. Naritaka Oshita (Perimeter Institute for Theoretical Physics)

Title:*Cosmological phase transitions with cosmic impurities.*

Abstract:We discuss the effect of cosmic inhomogeneities and other impurities on the cosmological phase transition. There is a certain analogy with the phase transition in Condensed Matter Physics.

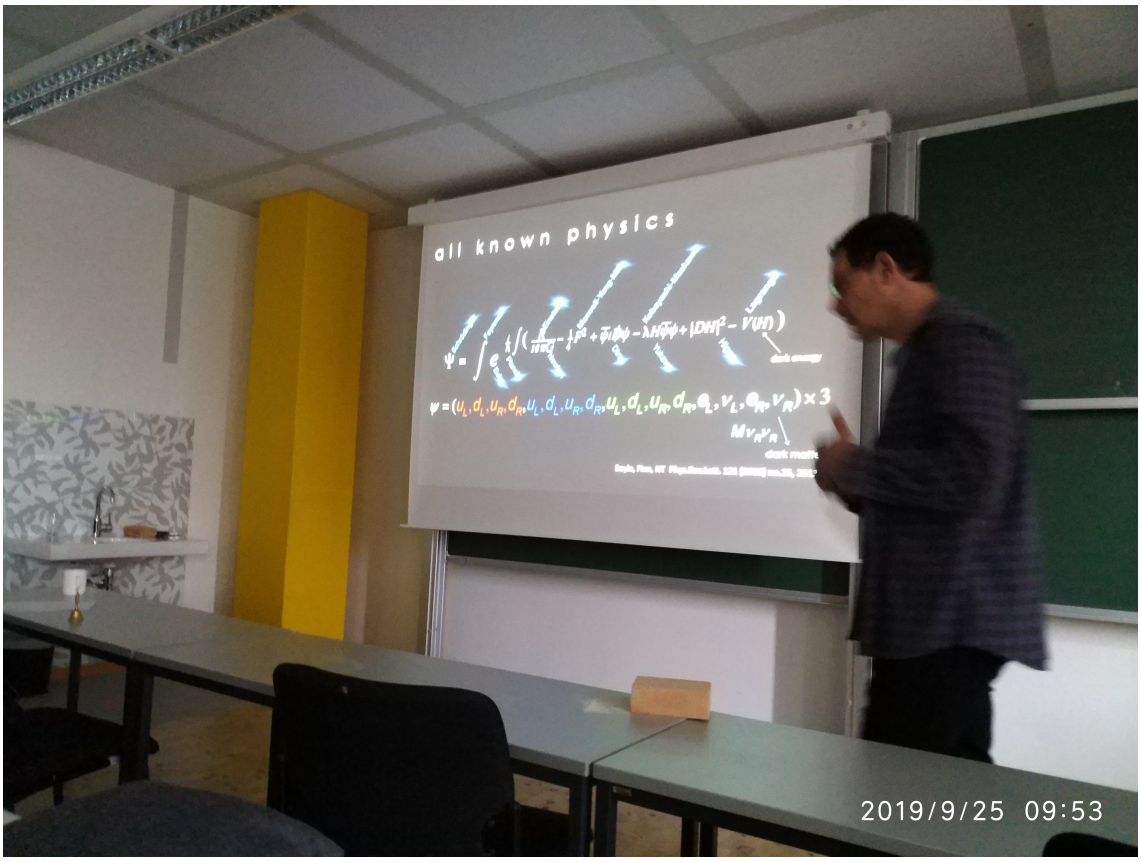

Figure 3: Prof. Neil Turok during his review talk

Prof. Tomislav Prokopec (Utrecht Univ.)

Title: Some aspects of the Weyl anomaly.

Abstract: The Standard Model of particle physics can become more "natural" if we insist that it has a local conformal invariance and derive all dimensional parameters as result of dynamical symmetry breaking, e.g. from some effective potential of a scalar field. Trying to formulate both gravitational and matter sectors as conformal invariant, one can introduce the trace of the torsion tensor, using it as a compensator field for the gauge-type Weyl symmetry. The talk described the consequent changes in the conformal (trace) anomaly.

Prof. Ilya Shapiro (UFJF, Brazil)

Title:*Anomaly-induced effective action of gravity: some new results*

Abstract: The effective action of gravity is supposed to contain the main information about quantum corrections to gravity. However, in many cases it cannot be calculated exactly. A remarkable and important exception is the effective action of vacuum for massless and conformal-invariant matter fields. In this case the

effective action can be easily derived by integrating the trace anomaly. The integration constant is an unknown conformal functional of the background metric, but for zero-order cosmology this functional is irrelevant and the solution becomes exact. Until recently the integrated anomaly was known only in dimensions d=2 and d=4, but recently we achieved the explicit result for d=6, which confirms the universal functional structure of the effective action.

Prof. Emil Mottola (Los Alamos National Laboratory)

Title:*Macroscopic Effects of the Conformal Anomaly*

Abstract: Classical General Relativity receives an infrared relevant modification from the conformal anomaly of the energy-momentum tensor of massless, or nearly massless, quantum fields. The local form of the effective action associated with the conformal anomaly is expressible in terms of a dynamical scalar field that couples to the conformal factor of the spacetime metric, allowing it to propagate over macroscopic distances. This leads to the prediction of scalar gravitational wave solutions a spin-0 breather mode in addition to the transversely polarized tensor waves of the classical Einstein theory. It also implies generically large quantum back reaction effects and conformal correlators in the vicinity of black hole horizons which are relevant to the formation of a non-singular interior, as well as an additional scalar degree of freedom in cosmology, coupling to dynamical dark energy.

Prof. Andrei Barvinsky(Lebedev Physics Institute, Theory Department)

Title:*Modified gravity models: renormalization and cosmological implications*

Abstract: We consider two classes of modified gravity models characterized by violation of Lorentz symmetry. One class of models is motivated by the search for a local renormalizable quantum gravity perturbatively consistent in UV domain. It consists of projectable Horava-Lifshitz models for which we show perturbative renormalizability in arbitrary dimension and prove their asymptotic freedom in the toy-model case of (2+1)-dimensional spacetime. Renormalization group flow is also built in (3+1)-dimensional Horava gravity for two of its coupling constants, indicating a potential domain of its asymptotic freedom for all seven couplings of this theory. Another class of models is motivated by the search for a possible mechanism of inflation and cosmological acceleration. This is the generalized unimodular gravity sharing in common with Horava models a peculiar kinematical restriction on the ADM lapse function, which manifests itself in the form of a special type of dark perfect fluid composed entirely from the metric sector of the theory and having a time dependent equation of state. Extra degree of freedom in this model – scalar graviton – has a nontrivial domain of unitarity and can drive inflationary scenario with scalar and tensor power spectra fitting observations. Quite remarkably, this model satisfies naturalness criterion – O(1) magnitude of all theory parameters. This is because a typically accepted exponentially big e-folding factor, e^N, $N \sim 60$, for this model enters a special expression for tensor to scalar ratio $r \sim e^{-N(1-n_s)} \simeq 10^{-3}$, $n_s \simeq 0.96$ being the scalar red tilt, and easily satisfies known phenomenological bounds.

Prof. Manuel Asorey (Universidad de Zaragoza)

Title:*Soft photon theorems and infrared divergences in QED.*

Abstract: One of the striking features of QED is the appearance of infrared divergences in the presence of charged particles. We analyze the effect of infrared divergences in the derivation of soft photon theorems. The infrared pathologies may be very relevant for understanding the black hole information paradox, but also raise some questions about the consistency of the whole theory.

Mr. Latham Boyle (Perimeter Institute)

Title:*Classical/Quantum Boundary Conditions at the Beginning/End of Time*

Abstract: I will motivate and discuss certain boundary conditions at the beginning and/or end of time, and some of their theoretical and observational consequences (particularly for evaluating the effect of the conformal anomaly in cosmology).

Prof. Martin Reuter (Mainz)

Title:*Background Independent Quantum Field Theory and Gravitating Vacuum Fluctuations*

Abstract: The cosmological constant induced by quantum vacuum fluctuations is reconsidered within a manifestly Background Independent approach to quantum field theory and quantum gravity. It is shown that in absence of any distinguished rigid spacetime they do not give rise to the notorious "cosmological constant problem". The nonperturbative functional renormalization group for gravity plays a central role, but no specific UV behavior (e. g. Asymptotic Safety) is required.

Dr. Leslaw Rachwal (Czech Technical University)

Title:*Conformal Invariance and Quantization of Conformal Gravity*

Abstract: We derive the form of the partition function in conformal gravity using an extended form of the Faddeev-Popov method for two distinct families of gauges. The method uses conformal gauge fixings and special conformal ghosts. Simple covariant gauge fixing and gauge proposed by Horowitz, Perry, and Strominger are considered. In this way, at one-loop, the theory is proven to be regularized in a conformally invariant way without the need to perform an additional final conformal transformation.

Prof. Claudio Coriano (Università Del Salento, Italy)

Title:*Anomaly Actions with axions and dilatons*

Abstract: We review the structure of the local and nonlocal anomaly actions introduced in several scenarios where chiral and conformal anomalies play a key role.

Prof. Rudnei Ramos (Rio de Janeiro State University)

Title:*Dissipative dynamics of Inflation and the swampland*

Abstract: Much has been discussed recently about the swampland and inflation. An effective field theory able to describe inflation for instance, should satisfy some very restrict set of conjectures, the swampland conjectures, such to have a consistent ultraviolet completion and to be described as an effective field theory, in particular, coming from string theory. It is shown here a recent construction of such an effective field theory from fully renormalizable quantum field theory that is able to describe inflation in a strong dissipative regime, evading all the swampland conjectures. This construction naturally leads to a super-Hubble inflaton mass and sub-Planckian field excursions, which is thus technically natural and consistent with a high-energy completion within a theory of quantum gravity.

Mr. Matteo Maria Maglio (Università del Salento, INFN Lecce)

Title:*Matching CFT tensor correlators to perturbation theory*

Abstract: We review a recent analysis of the solutions of the Conformal Ward Identities in general CFTs and their matching to free field theories. We compare these results with those predicted by the Conformal Anomaly Action.

Prof. Leonardo Modesto (SUSTech, China)

Title:*Nonlocal Quantum Gravity*

Abstract: Starting from the general class of super-renormalizable theories studied by M. Asorey, J.L. Lopez, and I.L. Shapiro in 1996, we present a weakly nonlocal gravitational theory unitary and finite at quantum level in the quantum field theory framework (the theory is also compatible with causality because a Shapiro's time advance never occurs.) As a consequence of finiteness, the Weyl's anomaly is not present and the theory turns out to be conformal invariant at classical as well at quantum level. Therefore, nonlocal quantum gravity is a conformal invariant theory in the spontaneously broken phase of the Weyl symmetry. As a result, Weyl conformal symmetry solves the black hole's singularity issue and cosmological singularity problem, otherwise unavoidable in any local or nonlocal gravitational theory. At classical level, all Einstein manifolds are stable at linear and non linear level if they are stable in General relativity. The generalization of the theory in presence of matter is the topic of the current research, hence it will be discussed only briefly.

Dr. Drazen Glavan (CP3, Louvain)

Title:*One-loop E&M correlators of SQED in power-law inflation.*

Abstract: Vector fields are insensitive to the rapid expansion of the primordial inflating universe due to their conformal coupling. However, they may couple to other light fields that are sensitive to the expansion and experience huge gravitational particle production, such as the complex scalar. In that case the vector field can develop large electric and magnetic field fluctuations induced by the gravitationally enhanced charge fluctuations. I will present a computation of the one-loop

corrections to the electric and magnetic field correlators of SQED in power-law inflation. One-loop corrections dwarf the tree-level result, and the slow-roll corrections very soon become large.

Dr. Fedor Popov (Princeton Univ.)

Title: *Quantum Field Theory in the static patch of de Sitter.*

Abstract: It is well-known, that de Sitter space has a non-zero temperature. This effect is analogous to the famous Hawking and Unruh radiation. In my talk I will review the derivation of this temperature for the compact patch. Following this procedure it is possible to describe quantum states corresponding to the other temperatures. Also, I discuss the physical consequences of the existence of non-zero temperature.

Dr. Viacheslav Emelyanov (Karlsruhe Institute of Technology, Institute of Theoretical Physics)

Title: *The Minkowski quantum vacuum does not gravitate.*

Quantum fields give rise to an infinite vacuum energy density, which arises from quantum-field fluctuations taking place even in the absence of matter. Yet, assuming that semi-classical quantum field theory is reliable only up to the Planck-energy scale, the cut-off estimate yields zero-point energy density which is finite, though, but in a notorious tension with astrophysical observations. In this talk, we intend to show that a non-vanishing (renormalised) value of the zero-point energy in $?^4$-theory is inconsistent with the scalar-field equation at two-loop order in perturbation theory.

Dr. Diana López Nacir (University of Buenos Aires)

Title: *To the sphere and back again: de Sitter infrared correlators at NTLO in 1/N.*

Abstract: The analysis of the infrared (IR) behavior of correlation functions for interacting fields in de Sitter (dS) spacetime is of high interest in the context of semiclassical and quantum gravity. It has been shown that the loop expansion breaks down at large dS-invariant distances for light fields, due to secularly growing corrections.

Dr. Gabriel Moreau (Université Paris Diderot)

Title: *Unequal time correlator of scalar fields in de Sitter spacetime from the effective stochastic approach.*

Abstract: Applying the stochastic formalism to the test scalar field in de Sitter spacetime, we study in more details the effective theory of their infrared modes described by a Langevin equation. It corresponds to the well-known model A in statistical physics. We use the formulation in terms of a one dimensional supersymmetric field theory. We compute the unequal time field correlator at large (superhorizon)

time separations in a 1/N expansion at NLO and compare with existing quantum field theory computation. We then attempt to get a result for finite N using the non perturbative renormalization group on this one dimensional theory, going beyond the local potential approximation.

Prof. Irina Pirozhenko (Bogoliubov Lab. of Theor. Physics, Joint Inst. for Nuclear Research)

Title: *Vacuum energy in the background of lower dimensional fields or fields living in half spaces.*

Abstract: We discuss the vacuum energy of quantum fields in the background of lower dimensional fields or fields living in half spaces. We address the following examples: vacuum energy of electromagnetic field interacting with 2+1 dimensional spinor field in the Dirac model of graphene, vacuum energy of a scalar or electromagenetic field undergoing interaction with another scalar or Dirac field confined to half spaces. We also discuss domain walls with induced Chern-Simons action on a boundary with chiral bag boundary conditions.

Figure 4: Prof. Emil Mottola during his talk

Open problems and Conclusions

During one week of discussions we have covered the main topics of the program. Open problems raised during the discussions include the proof of full consistency of the quantization of UV modified theories of gravity. Some of the promising proposals include higher derivatives, non-local interactions or Lorentz symmetry violation. Some of those theories have also clear cosmological implications, specially in inflationary escenarios. Two subjects which are very interesting and were not addressed in the workshop that also remain open are the role of primordial blackholes and the B-modes imprints in the CMB spectrum.

The workshop was very useful to clarify some issues concerning conformal anomalies and their cosmological implications. In particular, an agreements was reached between the different approaches to find out the effective actions associated to the conformal anomalies.

There were also many transversal discussions on related subjects which boosted new collaborations among the participants and acknowledgement to MITP support will be recognized in the corresponding publications.