Gravity Research Foundation

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Abstracts of Award Winning and Honorable Mention Essays for 2009

Award Essays

First Award – Instability of Black Hole Horizon with Respect to Electromagnetic Excitations – by Alexander Burinskii; Gravity Research Group, NSI, Russian Academy of Sciences, B. Tulskaya 52 Moscow 115191 Russia; email: bur@ibrae.ac.ru

Abstract – Analyzing exact solutions of the Einstein-Maxwell equations in the Kerr-Schild formalism we show that black hole horizon is unstable with respect to electromagnetic excitations. Contrary to perturbative smooth harmonic solutions, the exact solutions for electromagnetic excitations on the Kerr background are accompanied by singular beams which have very strong back reaction to the metric and break the horizon, forming holes which allow radiation to escape from the interior of the black hole. As a result, even the weak vacuum fluctuations break the horizon topologically, covering it by a set of fluctuating microholes. We conclude with a series of nontrivial consequences, one of which is that there is no information loss inside the black hole.

Second Award – On Vacuum Density, the Initial Singularity, and Dark Energy – by Saulo Carneiro[1,2] and Reza Tavakol[1]; [1]Astronomy Unit, School of Mathematical Sciences, Queen Mary University of London, Mile End Road, London E1 4NS, UK, [2]Instituto de Física, Universidade Federal da Bahia, Salvador, BA, 40210-340, Brazil; email: saulo.carneiro@pq.cnpq.br, r.tavakol@qmul.ac.uk

Abstract – Standard cosmology poses important questions. Apart from its singular origin, early and late accelerations are required by observations. Vacuum energy is a possible way to resolve some of these questions. Its density in an early de Sitter phase was estimated to be proportional to H^4, while it was suggested that QCD induces a term proportional to H at late times. These results have been employed in models which are non-singular and inflationary at early times and accelerating at late times. Here they are modeled in terms of scalar fields. At early times the spectrum of perturbations is scale-dependent, implying that slow-roll inflation is required after the primordial one. At late times, the scalar-field presents a mass of the order of the Hubble scale.

Third Award – Gravitation, Thermodynamics, and the Bound on Viscosity – by Shahar Hod; The Hadassah Institute, Jerusalem 91010, Israel; email: shaharhod@gmail.com

Abstract – The anti-de Sitter/conformal filed theory (AdS/CFT) correspondence implies that small perturbations of a black hole correspond to small deviations from thermodynamic equilibrium in a dual field theory. For gauge theories with an Einstein gravity dual, the AdS/CFT correspondence predicts a universal value for the ratio of the shear viscosity to the entropy density, $\eta/s \geq 1/4\pi$. This *conjectured* bound has been the focus of much recent attention. However, despite the flurry of research in this field we still lack a proof for the general validity of the bound. In this essay we show that this mysterious bound is actually a direct outcome of the interplay between gravity, quantum theory, and thermodynamics.

Fourth Award – Inflation, Quantum Fields, and CMB Anisotropies – by Iván Agulló[1], José Navarro-Salas[1], Gonzalo J. Olmo[2], and Leonard Parker[3]; [1]Departamento de Física Teórica and IFIC, Universidad de Valencia-CSIC, Facultad de Física, Burjassot-46100, Valencia, Spain, [2]Instituto de Estructura de la Materia, CSIC, Serrano 121, 28006 Madrid, Spain and Perimeter Institute for Theoretical Physics, Waterloo, Ontario, N2L 2Y5 Canada, [3]Physics Department, University of Wisconsin-Milwaukee, P.O. Box 413, Milwaukee, WI 53201; email: ivan.agullo@uv.es , jnavarro@ific.uv.es , olmo@iem.cfmac.csic.es , leonard@uwm.edu

Abstract – Inflationary cosmology has proved to be the most successful at predicting the properties of the anisotropies observed in the cosmic microwave background (CMB). In this essay we show that quantum field renormalization significantly influences the generation of primordial perturbations and hence the expected measureable imprint of cosmological inflation on the CMB. However, the new predictions remain in agreement with observation and, in fact, favor the simplest forms of inflation. In the near future, observations of the influence of gravitational waves from the early universe on the CMB will test our new predictions.

Fifth Award – Signatures of an Emergent Gravity from Black Hole Entropy – by Cenalo Vaz; RWC and Department of Physics, University of Cincinnati, Cincinnati, Ohio 45221-0011; email: cenalo. vaz@uc.edu

Abstract – The existence of a thermodynamic description of horizons indicates that spacetime has a microstructure. While the "fundamental" degrees of freedom remain elusive, quantizing Einstein's gravity provides some clues about their properties. A quantum AdS black hole possesses an equispaced mass spectrum, independent of Newton's constant, G, when its horizon radius is large compared to the AdS length. Moreover, the black hole's thermodynamics in this limit is inextricably connected with its thermodynamics in the opposite (Schwarzschild) limit by a duality of the Bose partition function. G, absent in the mass spectrum, reemerges in the thermodynamic description through the Schwarzschild limit, which should be viewed as a natural "ground state". It seems that the Hawking-Page phase transition separates fundamental, "particle-like" degrees of freedom from effective, "geometric" ones.

Honorable Mention Awards (Alphabetical Order)

1. Broadband Resonant Mass Gravitational Wave Detection – by Odylio D. Aguiar[1], Joaquim J. Barroso[2], Rubens M. Marinho Jr.[3], Guilherme L. Pimentel[4], and Michael E. Tobar[5]; [1]Divisão de Astrofísica, Instituto Nacional de Pesquisas Espaciais, Jd. Da Granja, São José dos Campos, SP, Brazil, 12201-970, [2]Laboratório Associado de Plasma, Instituto Nacional de Pesquisas Espaciais, Jd. da Granja, São José dos Campos, SP, Brazil, 12201-970, [3]Departamento de Física, Instituto Tecnológico de Aeronáutica, Campo Montenegro, São José dos Campos, SP, Brazil, 12228-000, [4]Joseph Henry Laboratories, Princeton University, Princeton, NJ, 08544, [5]School of Physics, The University of Western Australia, Crawley, WA, Australia, 6009; email: odylio@das.inpe.br, barroso@plasma.inpe.br, marinho@ita.br, gpimento@princeton.edu, mike@physics.uwa.edu

Abstract – By changing from a resonant multimode paradigm to a free mass paradigm for transducers in resonant mass gravitational wave detection, an array of six spheres can achieve a sensitivity response curve competitive with interferometers, being as sensitive as GEO600 and TAMA300 in the 3 – 6 kHz band and more sensitive than LIGO for 50% of the 6 – 10 kHz band. This approach has additional benefits. First, due to the relatively inexpensive nature of this technology (~US$ 1 million), it is accessible to a broader part of the world's scientific community. Additionally, spherical resonant mass detectors have the ability to discern both the direction and polarization resolutions.

2. Towards a Relativity of Dark-Matter Rods and Clocks – by D. V. Ahluwalia; Department of Physics and Astronomy, Rutherford Building, University of Canterbury, Private Bag 4800, Christchurch 8020, New Zealand; email: dharamvir.ahluwalia@canterbury.ac.nz

Abstract – In the absence of dark matter, the dynamical and kinematical interpretations of the special relativistic spacetime have been and still are the topic of philosophic debate, which whilst fertile, is by and large of little predictive power. This changes dramatically if the debate includes a dark matter candidate in a "non trivial" extension of the standard model. Here I argue that rods and clocks made out of dark matter may not reveal the same underlying algebraic structure as the rods and clocks made out of standard model particles. For the sake of concreteness I here exemplify the argument by looking at a particular dark matter candidate called Elko. Inevitably, one is led to the conclusion that gravity within the dark sector, and at the interface between dark matter and standard-model matter, may deviate from the canonical general relativistic predictions. For Elko dark matter such effects will be of second order in the sense that they will depend only on the angular momentum and spin of the gravitational environment.

3. k-Mouflage Gravity – by E. Babichev, C. Deffayet, R. Ziour; APC – UMR 7164 (CNRS, Université Paris, 7 Denis Diderot, CEA, Observatoire de Paris) and 10 rue Alice Domon et Léonie Duquet, 75205 Paris Cedex 13, France; email: babichev@apc.univ-paris7.fr, deffayet@iap.fr, ziour@apc.univ-paris7.fr

Abstract – We introduce a large class of scalar-tensor theories where gravity becomes stronger at large distances via the exchange of a scalar that mixes with the graviton. At small distances, i.e. large curvature, the scalar is screened via an analog of the Vainshtein mechanism of massive gravity. The crossover distance between the two regimes can be made cosmological by an appropriate choice of the parameters.

4. The Cosmological Constant Problem: a User's Guide – by Orfeu Bertolami; Instituto Superior Técnico, Departamento de Física, Av. Rovisco Pais, 1049-001 Lisboa, Portugal and Instituto de Plasmas e Fusão Nuclear, Instituto Superior Técnico, Lisbon; email: orfeu@cosmos.ist.utl.pt

Abstract – We discuss the validity of general relativity at low-energy and relate the threshold below which the theory breaks down with the observed value of the cosmological constant. This suggests the existence of a mass scale of order 10^{-3}eV and a putative violation of the equivalence principle at about 10^{-14}.

5. Surprising Simplicity of $\mathcal{N}$=8 Supergravity – by N.E.J. Bjerrum-Bohr[1] and Pierre Vanhove[2]; [1]The Niels Bohr International Academy, The Niels Bohr Institute, Blegdamsvej 17, DK-2100, Copenhagen Ø, Denmark, [2]Institut des Hautes Etudes Scientifiques, Le Bois-Marie, F-91440 Bures-sur-Yvette, France, and CEA, DSM, Institut de Physique Théoreique, IPhT, CNRS, MPPU, URA2306, Saclay, F-91191 Gif-sur-Yvette, France; email: bjbohr@nbi.dk, pierre.vanhove@cea.fr

Abstract – Gravity amplitudes are via the Kawai-Lewellen-Tye relations intimately linked to products of Yang-Mills amplitudes. Explicitly this shows up in computations of $\mathcal{N}$ = 8 supergravity where the perturbative expansion and ultraviolet behavior of this theory is akin to $\mathcal{N}$ = 4 super Yang-Mills at least through three loops. Full persistency to all loop orders would be truly remarkable and imply finiteness of $\mathcal{N}$ = 8 supergravity in four dimensions.

6. The Force of Gravity in Schwarzschild and Gullstrand-Painlevé Coordinates – by Carl Brannen; 720 Road N NE, Moses Lake, WA 98837; email: carl@brannenworks.com

Abstract – We derive the exact equations of motion (in Newtonian, $F = ma$, form) for test masses in Schwarzschild and Gullstrand-Painlevé coordinates. These equations of motion are simpler than the usual geodesic equations obtained from Christoffel tensors in that the affine parameter is eliminated. The various terms can be compared against tests of gravity. In force form, gravity can be interpreted as resulting from a flux of superluminal particles (gravitons). We show that the first order relativistic correction to Newton's gravity results from a two graviton interaction.

7. Horizons in Matter: Black Hole Hair vs. Null Big Bang – by K. A. Bronnikov[1] and Oleg B. Zaslavskii[2]; [1]Center for Gravitation and Fundamental Metrology, VNIIMS, 46 Ozyornaya Street, Moscow 119361, Russia and Institute of Gravitation and Cosmology, PFUR, 6 Miklukho-Maklaya Street, Moscow 117198, Russia; [2]Astronomical Institute of Kharkov V.N. Karazin National University, 35 Sumskaya St., Kharkov, 61022, Ukraine; email: kb20@yandex.ru ; ozaslav@kharkov.ua

Abstract – It is shown that only particular kinds of matter (in terms of the "radial" pressure to density ratio w) can coexist with Killing horizons in black-hole or cosmological space-times. Thus, for arbitrary (not necessarily spherically symmetric) static black holes, admissible are vacuum matter (w = -1, i.e., the cosmological constant or some generalization) and matter with certain values of w between 0 and -1, in particular, a gas of disordered cosmic strings (w = -1/3). If the cosmological evolution starts from a horizon (the so-called Null Big Bang scenarios), this horizon can co-exist with vacuum matter and certain kinds of phantom matter with $w \geq -3$. It is concluded that normal matter in such scenarios is entirely created from vacuum.

8. Interferometric Detection of Gravitational Waves: the Definitive Test for General Relativity – by Christian Corda; Associazione Scientifica Galileo Galilei, Via Pier Cironi 16 – 59100 PRATO, Italy; email: christian.corda@ego-gw.it

Abstract – Even if Einstein's General Relativity achieved a great success and overcame lots of experimental tests, it also showed some shortcomings and flaws which today advise theorists to ask if it is the definitive theory of gravity. In this essay we show that, if advanced projects on the detection of Gravitational Waves (GWs) will improve their sensitivity, allowing performing a GWs astronomy, accurate angular and frequency dependent response functions arising from various Theories of Gravity, i.e. General Relativity and Extended Theories of Gravity, will be the definitive test for General Relativity. The papers which found this essay have been the world's most cited in the official Astroparticle Publication Review of ASPERA during the 2007 with 13 citations.

9. Bjorken Expansion in the Isotropic Kasner Spacetime – by Hristu Culetu; Ovidius University, Department Of Physics, B-dul Mamaia 124, 8700 Constanta, Romania; email: hculetu@yahoo.com

Abstract – An isotropic expansion for the QGP is proposed in curved Kasner spacetime for an experimental configuration with three dimensional set of beams. The fluid of relativistic particles has no shear viscosity but the nonzero bulk viscosity ζ is time dependent and its value could explain the enormous entropy per baryon of our Universe. In addition, ζ equals the bulk viscosity of the anisotropic compressible fluid conjectured for the interior of a black hole.

10. String Gas Shells and Their Dual Radiation – by E.I. Guendelman; Department of Physics, Ben-Gurion University of the Negev, P.O. Box 653, IL-84105 Beer-Sheva, Israel; email: guendel@bgumail.bgu.ac.il

Abstract – We search for spherically symmetric, stationary solutions with a string gas shell as a source. The requirement of a uniform newtonian potential, or constancy of the 00 component of the metric, implies the existence of a "dual" radiation, which we argue can be interpreted as representing the virtual quantum fluctuations that stablize the shell. A string hedgehog can be introduced also into the solution. For zero or small hedgehog strength the string gas shell is of a regular nature, while the dual radiation is of a spacelike nature. For higher hedgehog strengths however the radiation "materializes" and becomes timelike while the string gas shell becomes space like. The significance of these solutions for the quantum theory is discussed.

11. Simple Observations concerning Black Holes and Probability – by Sándor Hegyi; KFKI Research Institute for Particle and Nuclear Physics, H-1525 Budapest, P.O. Box 49. Hungary; email: hegyi@rmki.kfki.hu

Abstract – What is common in black holes and a bell-shaped curve? The question does not seem to make much sense but it is argued that black holes and the limit distributions of probability theory share several properties when their entropy and information content are compared. In particular the no-hair theorem, the entropy maximization and holographic bound, and the quantization of entropy of black holes have their respective analogues for stable limit distributions. This observation suggests that the central limit theorem can play a fundamental role in black hole statistical mechanics and in a possibly emergent nature of gravity.

12. Angular Momentum and Gravitational Radiation – by Adam D. Helfer; Department of Mathematics, University of Missouri, Columbia, MO 65211; email: helfera@missouri.edu

Abstract – A fully general-relativistic treatment of angular momentum for radiating systems is possible by an adaptation of Penrose's approach. Instead of a model Minkowski space, the angular momentum is defined on a twistor space. The structure of this space is independent of the radiating system; this universality solves the supertranslation problem and gives good notions of flux and conservation. Breaking Poincaré to Bondi-Metzner-Sachs symmetry means that the angular momentum is not a pure j = 1 quantity $M_{ab}(x)$, but has higher-j contributions, which are shown to be the Bondi shear. Thus Bondi shear is itself a form of angular momentum, and gravitational radiation – change in shear – is emission of angular momentum. Gravitational radiation and angular momentum are, in general relativity, two facets of a single physical entity.

13. Time, Vacuum Energy, and the Cosmological Constant – by Viqar Husain; Department of Mathematics and Statistics, University of New Brunswick, Fredericton, NB E3B 5A3, Canada; email: vhusain@unb.ca

Abstract – We describe a link between the cosmological constant problem and the problem of time in quantum gravity. This arises by examining the relationship between the cosmological constant and vacuum energy in light of non-perturbative formulations of quantum gravity.

14. The Big Bang as the Ultimate Traffic Jam – by Vishnu Jejjala[1], Michael Kavic[2], Djordje Minic[2], and Chia-Hsiung Tze[2]; [1]Institut des Hautes Études Scientifiques, 35, Route de Chartes, 91440 Bures-sur-Yvette, France, [2]Institute for Particle, Nuclear, and Astronomical Science, Department of Physics, Virginia Tech, Blacksburg, VA 24061; email: vishnu@ihes.fr, kavic@vt.edu, dminic@vt.edu, kahong@vt.edu

Abstract – We present a novel solution to the nature and formation of the initial state of the Universe. It derives from the physics of a generally covariant extension of Matrix theory. We focus on the dynamical state space of this background independent quantum theory of gravity and matter, an infinite dimensional, complex non-linear Grassmannian. When this space is endowed with a Fubini-Study-like metric, the associated geodesic distance between any two of its points is zero. This striking mathematical result translates into a physical description of a hot, zero entropy Big Bang. The latter is then seen as a far from equilibrium, large fluctuation driven, metastable ordered transition, a "freezing by heating" jamming transition. Moreover, the subsequent unjamming transition could provide a mechanism for inflation while rejamming may model a Big Crunch, the final state of gravitational collapse.

15. Constraints on Emergent Gravity – by Alejandro Jenkins; Center for Theoretical Physics, Laboratory for Nuclear Science and Department of Physics, Massachusetts Institute of Technology, Cambridge, MA 02139; email: ajv@mit.edu

Abstract – In this essay we review the central difficulty in formulating a viable quantum field theory in which gravity is emergent at low energies, rather than mediated by fundamental gauge field. The Weinberg-Witten theorem forbids spin 2 massless modes from carrying Lorentz covariant stress-energy. In GR the stress-energy is not covariant because it violates a gauge symmetry, but a gravitational theory without fundamental spin 2 gauge invariance must either lack a stress-energy operator or have a non-relativistic graviton. The latter option is incompatible with the principle of equivalence, though such theories are not necessarily ruled out at low energies.

16. Dark Energy: The Absolute Electric Potential of the Universe – by Jose Beltrán Jiménez and Antonio L. Maroto; Departamento de Física Teórica, Universidad Complutense de Madrid, 28040 Madrid, Spain; email: jobeltra@fis.ucm.es; maroto@fis.ucm.es

Abstract – Is there an absolute cosmic electric potential? The recent discovery of the accelerated expansion of the universe could be indicating that this is certainly the case. In this essay we show that the consistency of the covariant and gauge invariant theory of electromagnetism is truly questionable when considered on cosmological scales. Out of the four components of the electromagnetic field, Maxwell's theory only contains two physical degrees of freedom. However, in the presence of gravity, one of the "unphysical" states cannot be consistently eliminated, thus becoming real. This third polarization state is completely decoupled from charged matter, but can be excited gravitationally thus breaking gauge invariance. On large scales the new state can be seen as a homogeneous cosmic electric potential, whose energy density behaves as a cosmological constant.

17. The Return of the Phoenix Universe – by Jean-Luc Lehners[1], Paul J. Steinhardt[2], and Neil Turok[3]; [1]Princeton Center for Theoretical Science, Princeton University, Princeton, NJ 08544, [2]Princeton Center for Theoretical Science and Joseph Henry Laboratories, Princeton University, Princeton, NJ 08544, [3]Perimeter Institute for Theoretical Physics, Waterloo, Ontario, Canada N2L 2Y5[3]; email: jlehners@princeton.edu, steinh@princeton.edu, nturok@perimeterinstitute.ca

Abstract – Georges Lemaitre introduced to the term *phoenix universe* to describe an oscillatory cosmology with alternating periods of gravitational collapse and expansion. This model is ruled out observationally because it requires a supercritical mass density and cannot accommodate dark energy. However, a new cyclic theory of the universe has been proposed that evades these problems. In a recent elaboration of this picture, almost the entire universe observed today is fated to become entrapped inside black holes, but a tiny region will emerge from these ashes like a phoenix to form an even larger smooth, flat universe filled with galaxies, stars, planets, and, presumably, life. Survival depends crucially on dark energy and suggests a reason why its density is small and positive today.

18. An Answer to the Main Black Hole Pathology: Forming Nonsingular Black Holes from Dust Collapse – by R. Maier and I. Damião Soares; Centro Brasileiro de Pesquisas Físicas, Rua Dr. Xavier Sigaud 150, Urca, Rio de Janeiro. CEP 22290-180-RJ, Brazil; email: rodmaier@cbpf.br , ivano@cbpf.br

Abstract – The dynamics of the gravitational collapse is examined in the realm of string based formalism of D-branes that encompass General Relativity as a low energy limit. A complete analytical solution is given to the spherically symmetric collapse of a pure dust star, including its matching with a corrected Schwarzschild exterior spacetime. The collapse forms a black hole (an exterior event horizon) enclosing not a singularity but perpetually bouncing matter in the infinite chain of spacetime maximal analytical extensions inside the outer event horizon. This chain of analytical extensions has a structure analogous to that of the Reissner-Nordstrom solution, except that the timelike singularities are avoided by bouncing barriers. The interior trapped bouncing matter has the possibility of being expelled by disruptive nonlinear resonance mechanisms.

19. How Fast Can a Black Hole Release its Information? – by Samir D. Mathur; Department of Physics, The Ohio State University, Columbus, OH 43210; email: mathur@mps.ohio-state.edu

Abstract – When a shell collapses through its horizon, semiclassical physics suggests that information cannot escape from this horizon. One might hope that nonperturbative quantum gravity effects will change this situation and avoid the "information paradox". We note that string theory has provided a set of states over which the wave function of the shell can spread, and that the number of these states is large enough that such a spreading would significantly modify the classically expected evolution. In this article we perform a simple estimate of the spreading time, showing that it is much shorter than the Hawking evaporation time for the hole. Thus information can emerge from the hole through the relaxation of the shell state into a linear combination of fuzzballs.

20. Quantum-Gravitational Running/Reduction of Space-Time Dimension – by Michael Maziashvili; Andronikashvili Institute of Physics, 6 Tamarashvili St., Tbilisi 0177, Georgia, Faculty of Physics and Mathematics, Chavchavadze State University, 32 Chavchavadze Ave., Tbilisi 0179, Georgia; email: maziashvili@gmail.com

Abstract – Quantum-gravity renders the space-time dimension to depend on the size of the region; it monotonically increases with the size of region and asymptotically approaches four for large distances. This effect was discovered in numerical simulations of lattice quantum gravity in the framework of casual dynamical triangulation [hep-th/0505113] as well as in renormalization group approach to quantum gravity [hep-th/0508202]. However, along these approaches the interpretation and the physical meaning of the effective change of dimension at shorter scales is not clear. Without invoking particular models in this essay we show that, box-counting dimension in face of the finite resolution of space-time (generally implied by quantum gravity) shows a simple way how both the qualitative and the quantitative features of this effect can be understood. In this way we derive a simple analytic expression of space-time dimension running, which implies the modification of Newton's inverse square law in perfect agreement with the modification coming from one-loop gravitational radiative corrections.

21. Gravity Heats the Universe – by Adam Moss and Douglas Scott; Department of Physics and Astronomy, University of British Columbia, Vancouver, BC, V6T 1Z1 Canada; email: adammoss@phas.ubc.ca, dscott@astro.ubc.ca

Abstract – Structure in the Universe grew through gravitational instability from very smooth initial conditions. Energy conservation requires that the growing negative potential energy of these structures is balanced by an increase in kinetic energy. A fraction of this is converted into heat in the collisional gas of the intergalactic medium. Using a toy model of gravitational heating we attempt to link the growth of structure in the Universe and the average temperature of this gas. We find that the gas is rapidly heated from collapsing structures at around $z{\sim}10$, reaching a temperature $>10^6$K today, depending on some assumptions of our simplified model. Before that there was a cold era from $z{\sim}100$ to ~10 in which the matter temperature is below that of the Cosmic Microwave Background.

22. Direct Detection of the Primordial Inflationary Gravitational Waves – by Wei-Tou Ni; Center for Gravitation and Cosmology, Purple Mountain Observatory, Chinese Academy of Sciences, No. 2, Beijing W. Rd., Nanjing, 210008 China; email: wtni@pmo.ac.cn

Abstract – Inflationary cosmology is successful in explaining a number of outstanding cosmological issues including the flatness, the horizon and the relic issues. More spectacular is the experimental confirmation of the structure as arose from the inflationary quantum fluctuations. However, the physics in the inflationary era is unclear. Polarization observations of Cosmic Microwave Background (CMB) missions may detect the tensor mode effects of inflationary gravitational waves (GWs) and give an energy scale of inflation. To probe the inflationary physics, direct observation of gravitational waves generated in the inflationary era is needed. In this essay, we advocate that the direct observation of these GWs with sensitivity down to $\Omega_{gw} \sim 10^{-23}$ is possible using present projected technology development if foreground could be separated.

23. Entropy Density of Spacetime and Gravity: A Conceptual Synthesis – by T. Padmanabhan; IUCAA, Post Bag 4, Ganeshkhind, Pune – 411 007, India; email: paddy@iucaa.ernet.in

Abstract – I show that combining the principle of equivalence and principle of general covariance with the known properties of local Rindler horizons, perceived by accelerated observers, leads to the following inescapable conclusion: *The field equations describing gravity in any diffeomorphism invariant theory must have a thermodynamic interpretation.* This synthesis of quantum theory, thermodynamics and gravity shows that the gravitational dynamics can be interpreted completely in terms of entropy balance between matter and spacetime. This idea has far reaching implications for the microstructure of spacetime and quantum gravity.

24. Modifying Gravity in the Infra-Red by Imposing an "Ultra-Strong" Equivalence Principle – by Federico Piazza; Perimeter Institute of Theoretical Physics, Waterloo, Ontario, N2L 2Y5, Canada; email: fpiazza@perimeterinstitute.ca

Abstract – The equivalence principle suggests considering gravity as an infra-red phenomenon, whose effects are visible only outside Einstein's free-falling elevator. In fact, by changing (curving) the large scale properties of spacetime, General Relativity makes the smallest systems free of classical gravitational effects. However, according to the standard semi-classical treatment, indirect effects of gravity can be experienced inside the elevator through the well-known mechanism of quantum particle production. Here we try a different path than the one historically followed: rather than imposing field quantization on top of a curved manifold, we attempt to upgrade the equivalence principle and extend it to the quantum phenomena. We consider, and try to realize in a theoretical framework, a stronger version of the equivalence principle, in which all the effects of gravity are definitely pushed outside the elevator and confined to the infra-red. We argue that this requires a major modification in the description of spacetime on the largest scales. Therefore, we introduce infra-red modified commutation relations for the global field operators in such a way to reabsorb, order by order in the high momentum expansion, the vacuum expectation value of the stress-energy tensor.

25. Does Gravity Prefer the Poincaré Dodecahedral Space? – by Boudewijn F. Roukema; Toruń Centre for Astronomy, Nicolaus Copernicus University, ul. Gagarina 11, 87-100 Toruń, Poland; email: boud@astro.uni.torun.pl

Abstract – The missing fluctuations problem in cosmic microwave background observations is naturally explained by well-proportioned small universe models. Among the well-proportioned models, the Poincaré dodecahedral space is empirically favored. Does gravity favor this space? The residual gravity effect is the residual acceleration induced by weak limit gravity from multiple topological images of a massive object on a nearby negligible mass test object. At the present epoch, the residual gravity effect is about a million times weaker in three of the well-proportioned spaces than in ill-proportioned spaces. However, in the Poincaré space, the effect is 10,000 times weaker still, i.e. the Poincaré space is about 10^{10} times "better balanced" than ill-proportioned spaces. Both observations and weak limit dynamics select the Poincaré space to be special.

26. What-If Inflation is a Spinor Condensate? – by S. Shankaranarayanan; Institute of Cosmology and Gravitation, University of Portsmouth, Mercantile House, Portsmouth P01 2EG, U.K.; email: shanki.subramaniam@port.ac.uk

Abstract – In the usual cosmological inflationary scenarios, the scalar field – inflaton – is usually assumed to be an elementary field. In this essay, we ask a question: What are the observational signatures, if the scalar field is a spinor condensate? And is there a way to distinguish between the canonical scalar field and the spinor condensate driven models? In the homogeneous and isotropic background, we show that, although the dark-spinor (Elko) condensate leads to the identical acceleration equation as that of the canonical scalar field driven inflaton, the dynamics of the two models are different. In the slow-roll limit, we show that the model, predicts a running of scalar spectral index consistent with the WMAP data. We show that the consistency relations between the spinor condensate and canonical scalar field driven model are different which can be tested using the future CMB and gravitational wave missions.

27. Curvature, Phase Space, Holography and Black Hole Entropy – by C. Sivaram and Kenath Arun; Indian Institute of Astrophysics, Bangalore; email: kenath.arun@cjc.christcollege.edu

Abstract – This paper discusses the thermodynamics of a black hole with respect to Hawking radiation and the entropy. We look at a unified picture of black hole entropy and curvature and how this can lead to the usual black hole luminosity due to Hawking radiation. It is also shown how the volume inside the horizon, apart from surface area (hologram!), can play a role in understanding the Hawking flux. In addition holography also implies a phase space associated with the interior volume and this happens to be just a quantum of phase space, filled with just one photon. Generalized uncertainty principle can be incorporated in this analysis. These results hold for all black hole masses in any dimensions.

28. Bend it Like Einstein: Gravitational Deflection of Classical, Quantum and Exotic Light – by C.S. Unnikrishnan[1] and G.T. Gillies[2]; [1]Gravitation Group, Tata Institute of Fundamental Research, Homi Bhabha Road, Mumbai – 400 005, India; [2]School of Engineering and Applied Science, University of Virginia, Charlottesville, VA 22904-4746; email: unni@tifr.res.in, gtg@virginia.edu

Abstract: Gravitational bending of light is a spectacular prediction of Einstein's general relativity, tested and observed in numerous situations. We examine the fine structure of gravitational bending in new light to reveal insights pertaining to some deep links between gravity and quantum mechanics. New results include quantum theoretical interpretation of part of the light bending, making a good case for gravity encompassing wave-particle duality, perhaps a new insight for quantum gravity itself. We reiterate the mutual compatibility of the equivalence principle and quantum dynamics in a simple proof. Finally, we address certain unresolved issues regarding the gravitational bending of ultra-slow light and tunneling photons in the context of experiments that might post fresh challenges for the interface of the two century-old theories.

29. A Toy Model of Emergent Spacetime and the UV/IR Correspondence – by Mark Van Raamsdonk; Department of Physics and Astronomy, University of British Columbia, 6224 Agricultural Road, Vancouver, B.C., V6T 1W9, Canada; email: mav@phas.ubc.ca

Abstract: In this essay, we attempt to gain insight into the emergence of spacetime from gauge theories in holographic definitions of quantum gravity. We show that even in the simplest quantum field theory, a single harmonic oscillator, there is a way to reorganize the Hilbert space that makes manifest a kind of dual spacetime. The emergent space is a discrete radial direction, the position along which is directly related to energy scale in the field theory (a universal feature known as the UV/IR correspondence in gravity/gauge theory duality).

30. The Gravitational Origin of the Distinction Between Space and Time – by Asher Yahalom; Institute of Astronomy, University of Cambridge, Madingley Road, Cambridge CB3 0HA, United Kingdom and Ariel University Center of Samaria, Ariel 40700, Israel; email: asya@ariel.ac.il

Abstract: To the ordinary human it is obvious that there is a clear distinction between the spatial dimensions in which one can go either way and the temporal dimension in which one seems only to move forward. But the uniqueness of time is also rooted in the standard presentation of general relativity in which the metric of space-time is locally Lorentzian i.e. $n_{\mu\nu}$ = diag (1, -1, -1, -1). This is presented as an independent axiom of the theory, which cannot be deduced. In this essay I will claim otherwise. I will show that the existence of time should not be enforced on the gravitational theory of general relativity but rather should be deduced from it. The method of choice is linear stability analysis of flat space-times.