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Abstracts of Award Winning and Honorable Mention Essays for 2017

Award Essays

First Award – **Gravity and Handedness of Photons** by Ivan Agullo[1], Adrian del Rio[2], and Jose Navarro-Salas[2]; [1]Department of Physics and Astronomy, Louisiana State University, Baton Rouge, LA 70803-4001, [2]Departamento de Fisica Teorica and IFIC, Centro Mixto Universidad de Valencia-CSIC. Facultad de Fisica, Burjassot-46100, Valencia, Spain; e-mail: agullo@lsu.edu, adrian.rio@uv.es, jnavarro@ific.uv.es

Abstract – Vacuum fluctuations of quantum fields are altered in presence of a strong gravitational background, with important physical consequences. We argue that a non-trivial spacetime geometry can act as an optically active medium for quantum electromagnetic radiation, in such a way that the state of polarization of radiation changes in time, even in the absence of electromagnetic sources. This is a quantum effect, and is a consequence of an anomaly related to the classical invariance under electric-magnetic duality rotations in Maxwell theory.

Second Award – **Spacetime Has a 'Thickness'** by Samir D. Mathur; Department of Physics, The Ohio State University, Columbus, OH 43210; e-mail: mathur.16@osu.edu

Abstract – Suppose we assume that (a) information about a black hole is encoded in its Hawking radiation and (b) causality is not violated to leading order in gently curved spacetime. Then we argue that spacetime cannot just be described as a manifold with a shape; it must be given an additional attribute which we call 'thickness'. This thickness characterizes the spread of the quantum gravity wavefunctional in superspace – the space of all 3-geometries. Low energy particles travel on spacetime without noticing the thickness parameter, so they just see an effective manifold. Objects with energy large enough to create a horizon do notice the finite thickness; this modifies the semiclassical evolution in such a way that we avoid horizon formation and the consequent violation of causality.

Third Award – **Black Holes and Hurwitz Class Numbers** by Shamit Kachru[1] and Arnav Tripathy[2]; [1]Stanford Institute for Theoretical Physics, Stanford University, Palo Alto, CA 94305, [2]Department of Mathematics, Harvard University, Cambridge, MA 02138; e-mail: skachru@stanford.edu, tripathy@math.harvard.edu

Abstract – We define a natural counting function for BPS black holes in $K3\times T^2$ compactification of type II string theory, and observe that it is given by a weight 3/2 mock modular form discovered by Zagier. This hints at tantalizing relations connecting black holes, string theory, and number theory.

Fourth Award – **A Proof of the Weak Gravity Conjecture** by Shahar Hod; The Ruppin Academic Center, Emeq Hefer 40250, Israel and The Hadassah Institute, Jerusalem 91010, Israel; e-mail: shaharhod@gmail.com

Abstract – The weak gravity conjecture suggests that, in a self-consistent theory of quantum gravity, the strength of gravity is bounded from above by the strengths of the various gauge forces in the theory. In particular, this intriguing conjecture asserts that in a theory describing a U(1) gauge field coupled consistently to gravity, there must exist a particle whose proper mass is bounded (in Planck units) by its charge: $m/m_P < q$. This beautiful and remarkably compact conjecture has attracted the attention of physicists and mathematicians over the last decade. It should be emphasized, however, that despite the fact that there are numerous examples from field theory and string theory that support the conjecture, we still lack a general proof of its validity. In the present Letter we prove that the weak gravity conjecture (and, in particular, the mass-charge upper bound $m/m_P < q$) can be inferred directly from Bekenstein's generalized second law of thermodynamics, a law which is widely believed to reflect a fundamental aspect of the elusive theory of quantum gravity.

Fifth Award – **Gravitational Wave – Gauge Field Dynamics** by R. R. Caldwell[1], C. Devulder[1], and N. A. Maksimova[2]; [1]Department of Physics and Astronomy, Dartmouth College, 6127 Wilder Laboratory, Hanover, NH 03755, [2]Harvard-Smithsonian Center for Astrophysics, Cambridge, MA 02138; e-mail: robert.r.caldwell@dartmouth.edu, christopher.devulder.gr@dartmouth.edu, nina.maksimova@cfa.harvard.edu

Abstract – The dynamics of a gravitational wave propagating through a cosmic gauge field is dramatically different than in vacuum. We show that a gravitational wave acquires an effective mass, is birefringent, and its normal modes are a linear combination of gravitational waves and gauge field excitations, leading to the phenomenon of gravitational wave – gauge field oscillations. These surprising results provide insight into gravitational phenomena and may suggest new approaches to a theory of quantum gravity.

Honorable Mention Awards (Alphabetical Order)

1. **Reflections of the Observer and the Observed in Quantum Gravity** by Dharam Vir Ahluwalia; Department of Physics, Indian Institute of Technology Guwahati, Assam 781 039, India and Centre for the Studies of the Glass Bead Game, Chaugon, Bir, Himachal Pradesh 176 077; e-mail: d.v.ahluwalia@iitg.ac.in

Abstract – A broad brush impressionistic view of physics from the vantage point of she living on a nearby dark-planet Zimpok is presented so as to argue that the observed and the observer are reflected in quantum gravity through a universal mass shared by neurones and a unification scale of the high energy physics.

2. **Entanglement Entropy, Scale-Dependent Dimensions and the Origin of Gravity** by Michele Arzano[1] and Gianlua Calagni[2]; [1]Dipartimento di Fisica and INFN, "Sapienza" University of Rome, P.le A. Moro 2, 00185 Roma, Italy, [2]Instituto de Estructura de la Materia, CSIC, Serrano 121, 28006 Madrid, Spain; e-mail: michele.arzano@roma1.infn.it, calcagni@iem.cfmac.csic.es

Abstract – We argue that the requirement of a finite entanglement entropy of spacetime is closely related to the phenomenon of running spectral dimension, universal in approaches to quantum gravity. If quantum geometry hinders diffusion, for instance when its structure at some given scale is discrete or too rough, then the spectral dimension of spacetime vanishes at that scale and the entropy density blows up. A finite entanglement entropy is a key ingredient in deriving Einstein gravity in a semi-classical regime of a quantum-gravitational theory and, thus, our arguments strengthen the role of running dimensionality as an imprint of quantum geometry with potentially observable consequences.

3. **Do Event Horizons Exist?** by Valentina Baccetti[1], Robert B. Mann[2],[3], and Daniel R. Terno[1]; [1]Department of Physics and Astronomy, Macquarie University, Sydney NSW 2109, Australia, [2]Department of Physics and Astronomy, University of Waterloo, Waterloo, Ontario N2L 3G1, Canada, [3]Perimeter Institute for Theoretical Physics, Waterloo, Ontario N2L 2Y6, Canada; e-mail: valentina.baccetti@mq.edu.au, rbmann@uwaterloo.ca, daniel.terno@mq.edu.au

Abstract – Event horizons are the defining feature of classical black holes. They are the key ingredient of the information loss paradox which, as in quantum physics, is built on a combination of predictions of quantum theory and counterfactual classical features: neither horizon formation nor crossing by a test body is observable. Furthermore, they are unnecessary for the derivation of Hawking-like radiation which, when taken into account, prevents horizon crossing/formation in a large class of models as we shall demonstrate. We conjecture horizon avoidance is a general feature of collapse upon taking such radiation into account. The non-existence of event horizons dispels the paradox, but opens up important questions about thermodynamic properties of the resulting objects and correlations between different degrees of freedom.

4. **The Hilbert Space of Quantum Gravity Is Locally Finite-Dimensional** by Ning Bao, Sean M. Carroll, and Ashmeet Singh; Walter Burke Institute for Theoretical Physics, California Institute of Technology, 1200 E. California Blvd., Pasadena, CA 91125; e-mail: ningbao75@gmail.com, seancarroll@gmail.com, ashmeet@theory.caltech.edu

Abstract – We argue in a model-independent way that the Hilbert space of quantum gravity is locally finite-dimensional. In other words, the density operator describing the state corresponding to a small region of space, when such a notion makes sense, is defined on a finite-dimensional factor of a larger Hilbert space. Because quantum gravity potentially describes superpositions of different geometries, it is crucial that we associate Hilbert-space factors with spatial regions only on individual decohered branches of the universal wave function. We discuss some implications of this claim, including the fact that quantum field theory cannot be a fundamental description of Nature.

5. **Nonlinear Interaction between Electromagnetic and Gravitational Waves: an Appraisal** by W. Barreto[1],[2], H. P. de Oliveira[2], and E. L. Rodrigues[3]; [1]Centro de Física Fundamental, Universidad de Los Andes, Mérida 5101, Venezuela, [2]Departamento de Física Teórica - Instituto de Física A. D. Tavares, Universidade do Estado do Rio de Janeiro, R. São Francisco Xavier, 524. Rio de Janeiro, RJ, 20550-013, Brazil, [3]Instituto de Biociências - Departamento de Ciências Naturais, Universidade Federal do Estado do Rio de Janeiro, Av. Pasteur, 458 - Urca. Rio de Janeiro, RJ, 22290-040, Brazil; e-mail: wobarreto@gmail.com, hp.deoliveira@pq.cnpq.br, eduardo.rodrigues@unirio.br

Abstract – Wave propagation of field disturbances is ubiquitous. The electromagnetic and gravitational are cousin theories in which the corresponding waves play a relevant role to understand several related physical. It has been established that small electromagnetic waves can generate gravitational waves and vice versa when scattered by a charged black hole. In the realm of cylindrical spacetimes, we present here a simple nonlinear effect of the conversion of electromagnetic to gravitational waves reflected by the amount of mass extracted from them.

6. **The Shape of Bouncing Universes** by John D. Barrow and Chandrima Ganguly; DAMTP, Centre for Mathematical Sciences, University of Cambridge, Wilberforce Rd., Cambridge CB3 0WA United Kingdom; e-mail: J.D.Barrow@damtp.cam.ac.uk, C.Ganguly@damtp.cam.ac.uk

Abstract – What happens to the most general closed oscillating universes in general relativity? We sketch the development of interest in cyclic universes from the early work of Friedmann and Tolman to modern variations introduced by the presence of a cosmological constant. Then we show what happens in the cyclic evolution of the most general closed anisotropic universes provided by the Mixmaster universe. We show that in the presence of entropy increase its cycles grow in size and age, increasingly approaching flatness. But these cycles also grow increasingly anisotropic at their expansion maxima. If there is a positive cosmological constant, or dark energy, present then these oscillations always end and the last cycle evolves from an anisotropic inflexion point towards a de Sitter future of everlasting expansion.

7. **Measuring the Effects of Loop Quantum Cosmology in the CMB Data** by Spyros Basilakos[1], Vahid Kamali[2], Ahmad Mehrabi[2]; [1]Academy of Athens, Research Center for Astronomy and Applied Mathematics, Soranou Efesiou 4, 11527, Athens, Greece, [2]Department of Physics, Bu-Ali Sina University, Hamedan 65178, 016016, Iran; e-mail: svasil@academyofathens.gr, vkamali@basu.ac.ir, Mehrabi@basu.ac.ir

Abstract – In this Essay we investigate the observational signatures of Loop Quantum Cosmology (LQC) in the CMB data. First, we concentrate on the dynamics of LQC and we provide the basic cosmological functions. We then obtain the power spectrum of scalar and tensor perturbations in order to study the performance of LQC against the latest CMB data. We find that LQC provides a robust prediction for the main slow-roll parameters, like the scalar spectral index and the tensor-to-scalar fluctuation ratio, which are in excellent agreement within 1σ with the values recently measured by the Planck collaboration. This result indicates that LQC can be seen as an alternative scenario with respect to that of standard inflation.

8. **Unified DE/DM Scenario with Diffusive Interactions from Scalar Fields** by David Benisty and E.I. Guendelman; Department of Physics, Ben Gurion University of the Negev, Beer-Sheva 84105, Israel; e-mail: benidav@post.bgu.ac.il, guendel@post.bgu.ac.il

Abstract – Here we generalize ideas of unified Dark Matter Dark Energy in the context of Two Measure Theories and of Dynamical space time Theories. In Two Measure Theories one uses metric independent volume elements and this allows to construct unified Dark Matter Dark Energy, where the cosmological constant appears as an integration constant associated to the eq. of motion of the measure fields. The Dynamical space time Theories generalize the Two Measure Theories by introducing a vector field whose equation of motion guarantees the conservation of a certain Energy Momentum tensor, which may be related, but in general is not the same as the gravitational Energy Momentum tensor. By demanding that this vector field be the gradient of a scalar, the Dynamical space time Theory becomes a theory of Diffusive Unified Dark Energy and Dark Matter, this is because demanding that the vector field be the gradient of a scalar introduces now a mechanism that produces non conserved energy momentum tensors instead of conserved energy momentum tensors which leads at the end to a formulation of interacting DE-DM dust models in the form of a diffusive type interacting Unified Dark Energy and Dark Matter scenario.

9. **Universally Stable Black Holes** by Pablo Bueno[1] and Pablo A. Cano[2]; [1]Instituut voor Theoretische Fysica, KU Leuven, Celestijnenlaan 200D, B-3001 Leuven, Belgium, [2]Instituto de Física Teórica, UAM/CSIC, C/ Nicolás Cabrera, 13-15, C.U. Cantoblanco, 28049 Madrid, Spain; e-mail: pablo@itf.fys.kuleuven.be, pablo.cano@uam.es

Abstract – We argue that, when certain higher-curvature corrections are added to the four-dimensional Einstein-Hilbert action, black holes become stable below certain mass. We show this to be the case for an infinite family of ghost-free theories involving terms of arbitrarily high order in curvature. The thermodynamic behavior of the new black holes is universal for arbitrary values of the couplings, with the only exception of the Schwarzschild solution itself, which is recovered when all the couplings are set to zero. For this class of theories, the issue of non-unitary evolution is inexistent, as black holes never evaporate completely.

10. **Weakness of Gravity as Illusion which Hides True Path to Unification of Gravity with Particle Physics** by Alexander Burinskii; NSI, Russian Academy of Sciences, B. Tulskaya 52 Moscow 115191 Russia; email: bur@ibrae.ac.ru

Abstract – Well known weakness of Gravity in particle physics is an illusion caused by underestimation of the role of spin in gravity. Relativistic rotation is inseparable from spin, which for elementary particles is extremely high and exceeds mass on 20-22 orders (in units $c = G = m = \hbar = 1$). Such a huge spin generates frame-dragging that distorts space much stronger than mass, and effective scale of gravitational interaction is shifted from Planck to Compton distances. We show that compatibility between gravity and quantum theory can be achieved without modifications of Einstein-Maxwell equations, by coupling to a supersymmetric Higgs model of symmetry breaking and forming a nonperturbative super-bag solution, which generates a gravity-free Compton zone necessary for consistent work of quantum theory. Super- bag is naturally upgraded to Wess-Zumino supersymmetric QED model, forming a bridge to perturbative formalism of conventional QED.

11. **Gravitational Quanta and Unification** by F. I. Cooperstock; Department of Physics and Astronomy, University of Victoria, P.O. Box 3055, Victoria, B.C. V8W 3P6 Canada; e-mail: cooperst@uvic.ca

Abstract – A major issue that has challenged physics is the goal of bringing gravity into a complete unification of the interactions and the quantization of gravity. We build upon the appreciation that electromagnetic waves are also gravitational waves because they transport local spacetime curvature. Logical steps lead us to appreciate the totality of the traditional quantized particles in nature as gravitational quanta. Thus, our present particle physics model is seen to be unified with the gravitational interaction. Whether there remains a scope for the existence of a spin-2 graviton in vacuum is brought into question by our invariant energy construct centered upon the Ricci tensor. We suggest that this construct holds the key to ultra-strong gravity's essential role in quantization.

12. **Cosmic Screening of the Gravitational Interaction** by Maxim Eingorn[1], Claus Kiefer[2], and Alexander Zhuk[3]; [1]North Carolina Central University, CREST and NASA Research Centers, Fayetteville st. 1801, Durham, North Carolina 27707, [2]Institute for Theoretical Physics, University of Cologne, Zülpicher Straβe 77, 50937 Köln, Germany, [3]Astronomical Observatory, Odessa National University, Dvoryanskaya st. 2, Odessa 65082, Ukraine; e-mail: maxim.eingorn@gmail.com, kiefer@thp.uni-koeln.de, ai.zhuk2@gmail.com

Abstract – We study a universe filled with cold dark matter in the form of discrete inhomogeneities (e.g., galaxies) and dark energy in the form of a continuous perfect fluid. We develop a first-order scalar perturbation theory in the weak gravity limit around a spatially flat Friedmann universe. Our approach works at all cosmic scales and incorporates linear and nonlinear effects with respect to energy density fluctuations. The gravitational potential can be split into individual contributions from each matter source. Each potential is characterized by a Yukawa interaction with the same range, which is of the order of 3700 Mpc at the present time. The derived equations can form the theoretical basis for numerical simulations for a wide class of modern cosmological models.

13. **Locality from Quantum Gravity: All or Nothing** by Netta Engelhardt[1] and Sebastian Fischetti[2]; [1]Department of Physics, Princeton University, Princeton, NJ 08544, [2]Theoretical Physics Group, Blackett Laboratory, Imperial College London SW7 2AZ, UK; e-mail: nengelhardt@princeton.edu, s.fischetti@imperial.ac.uk

Abstract – In a full theory of quantum gravity, local physics is expected to be approximate rather than innate. It is therefore important to understand how approximate locality in our universe emerges in the semiclassical limit. Here we show that any notion of locality emergent from a holographic theory of quantum gravity is "all or nothing": local data is not obtained gradually from subregions of the boundary, but is rather obtained all at once when enough of the boundary is accessed. Our assumptions are mild and thus this feature is quite general; for concreteness, we show how this phenomenon manifests in the special case of AdS/CFT.

14. **Pulsar-Black Hole Binaries as a Window on Quantum Gravity** by John Estes[1], Michael Kavic[1], Matthew Lippert[1], and John H. Simonetti[2]; [1]Department of Physics, Long Island University, Brooklyn, NY 11201, [2]Department of Physics, Virginia Tech, Blacksburg, VA; e-mail: John.Estes@liu.edu, Michael.Kavic@liu.edu, Matthew.Lippert@liu.edu, jhs@vt.edu

Abstract – Pulsars are some of the most accurate clocks found in nature, while black holes offer a unique arena for the study of quantum gravity. As such, pulsar-black hole (PSR-BH) binaries provide ideal astrophysical systems for detecting effects of quantum gravity. With the success of aLIGO and the advent of instruments like the SKA and eLISA, the prospects for discovery of such PSR-BH binaries are very promising. We argue that PSR-BH binaries can serve as ready-made testing grounds for proposed resolutions to the black hole information paradox. We propose using timing signals from a pulsar beam passing through the region near a black hole event horizon as a probe of quantum gravitational effects. In particular, we demonstrate that fluctuations of the geometry outside a black hole lead to an increase in the measured root-mean-square deviation of arrival times of pulsar pulses traveling near the horizon.

15. **Is Patience a Virtue? Cosmic Censorship of Infrared Effects in de Sitter** by Ricardo Z. Ferreira[1], McCullen Sandora[2], and Martin S. Sloth[3]; [1]Departament de Física Quàntica i Astrofísica i Institut de Ciències del Cosmos, Universitat de Barcelona, Martí i Franquès , 1, 08028, Barcelona, Spain, [2]Institute of Cosmology, Department of Physics and Astronomy, Tufts University, Medford, MA 02155, [3]CP^3-Origins, Center for Cosmology and Particle Physics Phenomenology, University of Southern Denmark, Campusvej 55, 5230 Odense M, Denmark; e-mail: rferreira@icc.ub.edu, mccullen.sandora@tufts.edu, sloth@cp3.sdu.dk

Abstract – While the accumulation of long wavelength modes during inflation wreaks havoc on the large scale structure of spacetime, the question of even observability of their presence by any local observer has led to considerable confusion. Though it is commonly agreed that infrared effects are not visible to a single sub-horizon observer at late times, we argue that the question is less trivial for a patient observer who has lived long enough to have a record of the state before the soft mode was created. Though classically there is no obstruction to measuring this effect locally, we give several indications that quantum mechanical uncertainties censor the effect, rendering the observation of long modes ultimately forbidden.

16. **A Simple Model for the Birth, Big Crunch, Big Bang, and Death of the Universe** by Arthur E. Fischer; Department of Mathematics, University of California, Santa Cruz, Santa Cruz, California 95064; e-mail: aef@ucsc.edu

Abstract – We model the standard ΛCDM model of the universe by the spatially-flat FLRW line element

$$ds^2_{\Lambda\text{CDM}} = -c^2dt^2 + \left(\frac{8\pi G\rho_{m,0}}{\Lambda c^2}\right)^{2/3}\left(\sinh\left(\frac{3}{2}\sqrt{\Lambda/3}\,ct\right)\right)^{4/3} d\sigma^2_{\text{Euclid}}$$

Although there is a cosmological singularity at the big bang $t = 0$, this line element is differentiable for all $t \in (-\infty, \infty)$ and thus models the universe from its past-asymptotic initial state dS_4^- at $t = -\infty$, through the big crunch at $t = 0^-$ and the big bang at $t = 0^+$, to its future-asymptotic final state dS_4^+ at $t = \infty$. Since the universe existed *before* the big bang, we conclude that (1) the universe was *not* created *de novo* at the big bang and that (2) cosmological singularities such as black holes or the big bang itself need not be an end to spacetime. Our model shows that the universe may have been created out of nothing at $t = -\infty$ from its past-asymptotic initial state dS_4^-.

17. **Astrophysical Jets from Topological Currents** by Antonino Flachi[1] and Kenji Fukushima[2]; [1]Department of Physics and Research and Education Center for Natural Sciences, Keio University, 4-1-1 Hiyoshi, Yokohama, Kanagawa 223-8521, Japan, [2]Department of Physics, The University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-0033, Japan; e-mail: flachi@phys-h.keio.ac.jp, fuku@nt.phys.s.u-tokyo.ac.jp

Abstract – In the presence of rotation, gravity induces, even at zero temperature, a chiral vortical current. This current is interpreted as emerging from the gravitational Chern-Simons current. We argue that this gravitational Chern-Simons chiral vortical current may provide a novel universal microscopic mechanism behind the generation of collimated jets from rotating astrophysical compact sources.

18. **Holography as Deep Learning** by Wen-Cong Gan and Fu-Wen Shu; Department of Physics, Nanchang University, No. 999 Xue Fu Avenue, Nanchang, 330031, China, and Center for Relativistic Astrophysics and High Energy Physics, Nanchang University, No. 999 Xue Fu Avenue, Nanchang 330031, China; e-mail: shufuwen@ncu.edu.cn

Abstract – Quantum many-body problem with exponentially large degrees of freedom can be reduced to a tractable computational form by neural network method. The power of deep neural network (DNN) based on deep learning is clarified by mapping it to renormalization group (RG), which may shed lights on holographic principle by identifying a sequence of RG transformations to the AdS geometry. In this essay, we show that any network which reflects RG process has intrinsic hyperbolic geometry, and discuss the structure of entanglement encoded in the graph of DNN. We find the entanglement structure of deep neural network is of Ryu-Takayanagi form. Based on these facts, we argue that the emergence of holographic gravitational theory is related to deep learning process of the quantum field theory.

19. **Weighing the Black Holes of GW150914** by Yuan K. Ha; Department of Physics, Temple University, Philadelphia, PA 19122; e-mail: yuanha@temple.edu

Abstract – We evaluate the mass of the black holes of GW150914 at their event horizons via quasi-local energy approach and obtain the values of 70 and 55 solar masses, compared to their asymptotic values of 36 and 29 units, respectively, as reported by LIGO. A higher mass at the event horizon is compulsory in order to overcome the huge negative gravitational potential energy surrounding the black holes and allow for the emission of gravitational waves. We estimate the initial mass of the stars which collapsed to form the black holes from the horizon mass and obtain the impressive values of 93 and 73 solar masses for these progenitor stars.

20. **Topological Interaction of Electromagnetism and Torsion** by Richard T. Hammond; Department of Physics, University of North Carolina at Chapel Hill, Chapel Hill, NC and Army Research Office, Research Triangle Park, NC; email: rhammond@email.unc.edu

Abstract – A fully gauge invariant topological coupling of torsion to the electromagnetic field is examined. It is shown, while the gravitational fields are unaltered, torsion may serve as a source for electromagnetism and electromagnetism may serve as a source for torsion. Unlike most couplings, this gives rise to conservation of charge, no magnetic monopoles, and is in agreement with the principle of equivalence.

21. **Testing Quantum Gravity** by Johan Hansson and Stephane Francois; Division of Physics, Luleå University of Technology, SE-971 87 Luleå, Sweden; e-mail: c.johan.hansson@ltu.se

Abstract – The search for a theory of quantum gravity is the most fundamental problem in all of theoretical physics, but there are as yet no experimental results at all to guide this endeavor. What seems to be needed is a pragmatic way to test if gravitation really occurs between quantum objects or not. In this essay we suggest such a potential way out of this deadlock, utilizing macroscopic quantum systems; superfluid helium, gaseous Bose-Einstein condensates and "macroscopic" molecules. It turns out that true quantum gravity effects - here defined as observable gravitational interactions between truly quantum objects - could and should be seen (if they occur in nature) using existing technology. A falsification of the low-energy limit, in the accessible weak-field regime, would also falsify the full theory of quantum gravity, making it enter the realm of testable, potentially falsifiable theories, *i.e.* becoming real physics after almost a century of pure theorizing. If weak-field gravity between quantum objects is shown to be absent (in the regime where the approximation should apply), we know that gravity then is a strictly classical phenomenon absent at the quantum level.

22. **A Quantum Window onto Early Inflation** by Robert J. Hardwick, Vincent Vennin, David Wands; Institute of Cosmology and Gravitation, University of Portsmouth, Dennis Sciama Building, Burnaby Road, Portsmouth, PO1 3FX, United Kingdom; e-mail: robert.hardwick@port.ac.uk

Abstract – Inflation in the early Universe is one of the most promising probes of gravity in the high-energy regime. However, observable scales give access to a limited window in the inflationary dynamics. In this essay, we argue that quantum corrections to the classical dynamics of cosmological fields allow us to probe much earlier epochs of the inflationary phase and extend this window by many orders of magnitude. We point out that both the statistics of cosmological fluctuations at observable scales, and the field displacements acquired by spectator fields that play an important role in many post-inflationary processes, are sensitive to a much longer phase of the inflationary epoch.

23. **A New Approach to Detecting Gravitational Waves via the Coupling of Gravity to the Zero-Point Energy of the Phonon Modes of a Superconductor** by Nader A. Inan; University of California, Merced, School of Natural Sciences, P.O. Box 2039, Merced, CA 95344; e-mail: ninan@ucmerced.edu

Abstract – The response of a superconductor to a gravitational wave is shown to obey a London-like constituent equation. The Cooper pairs are described by the Ginzburg-Landau free energy density embedded in curved spacetime. The lattice ions are modeled by quantum harmonic oscillators characterized by quasi-energy eigenvalues. This formulation is shown to predict a dynamical Casimir effect since the zero-point energy of the ionic lattice phonons is modulated by the gravitational wave. It is also shown that the response to a gravitational wave is far less for the Cooper pair density than for the ionic lattice. This predicts a "charge separation effect" which can be used to detect the passage of a gravitational wave.

24. **The Time Measurement Problem in Quantum Cosmology** by Nirmalya Kajuri; Department of Physics, Indian Institute of Technology Madras, Chennai 600036, India; e-mail: nirmalya@physics.iitm.ac.in

Abstract – In the canonical approach to quantization of gravity, one often uses relational clock variables and an interpretation in terms of conditional probabilities to overcome the problem of time. In this essay we show that these suffer from serious conceptual issues.

25. **Probing the Quantum Fuzziness of Space and Time with Gravitational Waves** by Archil Kobakhidze, Cyril Lagger, and Adrian Manning; ARC Centre of Excellence for Particle Physics at the Terascale, School of Physics, The University of Sydney, NSW 2006, Australia; e-mail: archil.kobakhidze@sydney.edu.au, cyril.lagger@sydney.edu.au, adrian.manning@sydney.edu.au

Abstract – We argue that the gravitational wave signal recently observed by the LIGO detectors provides a powerful tool to probe the fundamental structure of space and time. In particular, we properly model the inspiral phase of two merging black holes in a noncommutative space-time and extract an upper bound on the scale of such quantum fuzziness at the order of the Planck scale. This improves previous constraints by ~ 15 orders of magnitude.

26. **Is the Cosmological Constant Problem Properly Posed?** by Philip D. Mannheim; Department of Physics, University of Connecticut, Storrs, CT 06269; email: philip.mannheim@uconn.edu

Abstract – In applications of Einstein gravity one replaces the quantum-mechanical energy-momentum tensor of sources such as the degenerate electrons in a white dwarf or the black-body photons in the microwave background by c-number matrix elements. And not only that, one ignores the zero-point fluctuations in these sources by only retaining the normal-ordered parts of those matrix elements. There is no apparent justification for this procedure, and we show that it is precisely this procedure that leads to the cosmological constant problem. We suggest that solving the problem requires that gravity be treated just as quantum-mechanically as the sources to which it couples, and show that one can then solve the cosmological constant problem if one replaces Einstein gravity by the fully quantum-mechanically consistent conformal gravity theory.

27. **Classical Entanglement Structure in the Wavefunction of Inflationary Fluctuations** by Elliot Nelson and C. Jess Riedel; Perimeter Institute for Theoretical Physics, 31 Caroline St. North, Waterloo, ON N2L 2Y5, Canada; e-mail: enelson@pitp.ca, jessriedel@gmail.com

Abstract – We argue that the preferred classical variables that emerge from a pure quantum state are determined by its entanglement structure in the form of redundant records: information shared between many subsystems. Focusing on the early universe, we ask how classical metric perturbations emerge from vacuum fluctuations in an inflationary background. We show that the squeezing of the quantum state for super-horizon modes, along with minimal gravitational interactions, leads to decoherence and to an exponential number of records of metric fluctuations on very large scales, $\lambda/\lambda_{\mathrm{Hubble}} > \Delta_\varsigma^{-2/3}$ where $\Delta_\varsigma \lesssim 10^{-5}$ is the amplitude of metric fluctuations. This determines a preferred decomposition of the inflationary wavefunction into orthogonal "branches" corresponding to classical metric perturbations, which defines an inflationary entropy production rate and accounts for the emergence of stochastic, inhomogeneous spacetime geometry.

28. **Quantum Gravity at Hubble Scales Determines the Cosmological Constant and the Amplitude of Primordial Perturbations** by T. Padmanabhan[1] and Hamsa Padmanabhan[2]; [1]IUCAA, Pune University Campus, Ganeshkhind, Pune - 411 007, India, [2]Institute for Astronomy, ETH Zurich, Wolfgang-Pauli-Strasse 27, CH-8093 Zurich, Switzerland; e-mail: paddy@iucaa.in, hamsa.padmanabhan@phys.ethz.ch

Abstract – Gravity controls the amount of information accessible to any specific observer. We quantify the notion of cosmic information ('CosmIn') for an eternal observer in the universe. Demanding the finiteness of CosmIn *requires* the universe to have a late-time accelerated expansion. Combined with some generic features of the quantum spacetime, this leads to the determination of (i) the numerical value of the cosmological constant, as well as (ii) the amplitude of the primordial, scale invariant perturbation spectrum in terms of a *single* free parameter, which specifies the energy scale at which the universe makes a transition from a pre-geometric phase to the classical phase. This formalism also shows that the quantum gravitational information content of spacetime can be tested using precision cosmology.

29. **A New Length Scale for Quantum Gravity - and a Resolution of the Black Hole Information Loss Paradox** by Tejinder P. Singh; Tata Institute of Fundamental Research, Homi Bhabha Road, Mumbai 400005, India; e-mail: tpsingh@tifr.res.in

Abstract – We show why and how Compton wavelength and Schwarzschild radius should be combined into one single new length scale, which we call the Compton-Schwarzschild length. Doing so offers a resolution of the black hole information loss paradox, and suggests Planck mass remnant black holes as candidates for dark matter. It also compels us to introduce torsion, and identify the Dirac field with a complex torsion field. Dirac equation and Einstein equations are shown to be mutually dual limiting cases of an underlying gravitation theory which involves the Compton-Schwarzschild length scale, and includes a complex torsion field.

30. **Dark Matter (Energy) May Be Indistinguishable from Modified Gravity (Mond)** by C. Sivaram; Indian Institute of Astrophysics, Sarjapur Road, 2nd Block, Koramangala, Bangalore, 560034, India; e-mail: profcsivaram@gmail.com

Abstract – For Newtonian dynamics to hold over galactic scales large amounts of dark matter are required which would dominate cosmic structures. Accounting for the strong observational evidence that the universe is accelerating requires the presence of an unknown dark energy component constituting about seventy percent of the matter. Several ingenious ongoing experiments to detect the dark matter particles have so far led to negative results. Moreover the comparable proportions of the dark matter and energy at the present epoch appear unnatural and not predicted by any theory. For these reasons alternative ideas like MOND and modification of gravity or general relativity over cosmic scales have been proposed. It is shown in this essay that these alternate ideas may not be easily distinguishable from the usual dark matter or dark energy hypotheses. Specific examples are given to illustrate this point that the modified theories are special cases of a generalized dark matter paradigm.

31. **Quantum Mechanix plus Newtonian Gravity Violates the Universality of Free Fall** by Matt Visser; School of Mathematics and Statistics, Victoria University of Wellington, PO Box 600, Wellington 6140, New Zealand; e-mail: matt.visser@sms.vuw.ac.nz

Abstract – Classical point particles in Newtonian gravity obey, as they do in general relativity, the universality of free fall. However classical structured particles, (for instance with a mass quadrupole moment), need not obey the universality of free fall. Quantum mechanically, an elementary "point" particle can be described by a localized wavepacket, for which we can define a probability quadrupole moment. This probability quadrupole can, under plausible hypotheses, affect the universality of free fall. This raises an important issue of principle, as possible quantum violations of the universality of free fall would fundamentally impact on our ideas of what "quantum gravity" might look like. I will present an estimate of the size of the effect, and discuss where if at all it might be measured.

32. **Gravity, Stability and Cosmological Models** by Asher Yahalom; Ariel University, Ariel 40700, Israel; e-mail: asya@ariel.ac.il

Abstract – Stability analysis plays a major role in our understanding of nature. For example it was shown that among empty flat space-times only those with a Lorentzian metric are stable. However, the universe is not empty and the energy momentum tensor is metric dependent and thus affects stability. In this essay we concentrate on simple perturbations of the standard cosmological model with and without cosmological constant which is based on a uniform mass distribution. The results suggest that while Euclidean, open or closed section models are valid solutions, the choice of **stable** solutions is limited. In particular the popular Lambda-CDM model is unstable.