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Abstracts of Award Winning and Honorable Mention Essays for 2023

Award Essays

First Award – **Equivalence principle, de-Sitter space, and cosmological twistors** by Maciej Dunajski, Department of Applied Mathematics and Theoretical Physics, University of Cambridge, Wilberforce Road, Cambridge CB3 0WA, U.K.; email: M.Dunajski@damtp.cam.ac.uk

Abstract – I discuss the impact of the positive cosmological constant on the interplay between the equivalence principle in general relativity, and the rules of quantum mechanics. At the non-relativistic level there is an ambiguity in the definition of a phase of a wave function measured by inertial and accelerating observes. This is the cosmological analogue of the Penrose effect, which can also be seen as a non-relativistic limit of the Unruh effect. The symmetries of the associated Schrödinger equation are generated by the Newton-Hooke algebra, which arises from a non-relativistic limit of a cosmological twistor space.

Second Award – **Emergence of Quantum Field Theory in Causal Diamonds** by Tom Banks, NHETC and Department of Physics, Rutgers University, Piscataway, NJ 08854-8019; email: tibanks@ucsc.edu

Abstract – The experimental successes of quantum field theory do not justify using it to describe even a finite fraction of the entanglement entropy of a causal diamond with its exterior, in the limit of large diamonds. Susskind and Uglum and Jacobson conjectured that this divergent entropy could be thought of as a renormalization of Newton's constant in the Bekenstein-Hawking formula, *if we applied that formula to arbitrary causal diamonds*. Jacobson showed that this leads to a derivation of the null projection of Einstein's equations as the hydrodynamic equations of the area law for arbitrary diamonds, a derivation which has the added virtue of demonstrating that the cosmological constant is not an energy density. Using a gauge choice adapted to causal diamond boundaries, we revisit arguments of Carlip and Solodukhin that the proper theory of near horizon states is a (cut-off) 1+1 dimensional conformal field theory, with central charge proportional to the transverse area. This leads to a universal formula for fluctuations of the modular Hamiltonian of a diamond, which we argue is compatible with the explanation of the temperature of de Sitter space in terms of an identification between localized energy and the number of constrained q-bits of the holographic degrees of freedom.

Third Award – **The universality of black hole thermodynamics** by Samir D. Mathur and Madhur Mehta, Department of Physics, The Ohio State University, Columbus, OH 43210, USA; email: mathur.16@osu.edu, mehta.493@osu.edu

Abstract – The thermodynamic properties of black holes - temperature, entropy and radiation rates - are usually associated with the presence of a horizon. We argue that any Extremely Compact Object (ECO) must have the *same* thermodynamic properties. Quantum fields just outside the surface of an ECO have a large negative Casimir energy similar to the Boulware vacuum of black holes. If the thermal radiation emanating from the ECO does not fill the near-surface region at the local Unruh temperature, then we find that no solution of gravity equations is possible. In string theory, black holes microstates are horizonless quantum objects called fuzzballs that are expected to have a surface $\sim l_p$ outside $r = 2GM$; thus the information puzzle is resolved while preserving the semiclassical thermodynamics of black holes.

Fourth Award – **Black holes that are too cold to respect cosmic censorship** by Shahar Hod, The Ruppin Academic Center, Emeq Hefer 40250, Israel and The Hadassah Institute, Jerusalem 91010, Israel; email: shaharhod@gmail.com

Abstract – In this essay it is proved that there are black holes that are dangerously cold. In particular, by analyzing the emission spectra of highly charged black holes we reveal the fact that near-extremal black holes whose Bekenstein-Hawking temperatures lie in the regime $T_{\mathrm{BH}}\lesssim m_e^6/e^3$ may turn into horizonless naked singularities, thus violating the cosmic censorship principle, if they emit a photon with the characteristic thermal energy $\omega = O(T_{\mathrm{BH}})$ [here $\{m_e, e\}$ are respectively the proper mass and the electric charge of the electron, the lightest charged particle]. We therefore raise here the conjecture that, in the yet unknown quantum theory of gravity, the temperatures of well behaved black-hole spacetimes are fundamentally bounded from below by the relation $T_{\mathrm{BH}}\gtrsim m_e^6/e^3$.

Fifth Award – **What are neutron stars made of? Gravitational waves may reveal the answer** by Neil Lu, Susan M. Scott, and Karl Wette, Centre for Gravitational Astrophysics, The Australian National University, Canberra ACT 2601, Australia, Australian Research Council Centre of Excellence for Gravitational Wave Discovery (OzGrav); email: Neil.Lu@anu.edu.au, Susan.Scott@anu.edu.au, Karl.Wette@anu.edu.au

Abstract – Neutron stars are one of the most mysterious wonders in the Universe. Their extreme densities hint at new and exotic physics at work within. Gravitational waves could be the key to unlocking their secrets. In particular, a first detection of gravitational waves from rapidly-spinning, deformed neutron stars could yield new insights into the physics of matter at extreme densities and under strong gravity. Once a first detection is made, a critical challenge will be to robustly extract physically interesting information from the detected signals. In this essay, we describe initial research towards answering this challenge, and thereby unleashing the full power of gravitational waves as an engine for the discovery of new physics.

Honorable Mention Awards **(Alphabetical Order)**

1. **An Alternative Theory of Gravity to the General Theory of Relativity on a Four-World Background** by Akindele Adekugbe-Joseph, Ondo State University of Science and Technology, Okitipupa, Nigeria, P. O. Box 2575, Akure, Ondo State 340001, Nigeria; email: cfs_ib@yahoo.com

Abstract – The general theory of relativity (GR) has been the most effective theory of gravity among a myriad of alternative theories for a century. The incompleteness of GR is nevertheless known and this has made effort to formulate a superior alternative to the theory relevant till now. An alternative more complete theory of gravity than GR based on a new coordinate geometry formulation on a four-world background is discussed in this essay. The features of the new geometry include flatness of four-dimensional spacetime and flat spacetime theory of gravity in arbitrary gravitational field, parameter transformations that yield position dependence of parameters in the gravitational field, extension to the neighborhood of several isolated bodies, completeness, internal consistency, complete agreement with experiment and absence of hypothesis.

2. **Are Entropy Bounds Epistemic?** by Emily Adlam, The Rotman Institute of Philosophy, 1151 Richmond Street, London N6A5B7; email: eadlam90@gmail.com

Abstract – In this essay we seek to gain a better understanding of the covariant entropy bound. We observe that there is a possible way of thinking about the bound which would suggest that it encodes an epistemic limitation rather than an objective count of the true number of degrees of freedom on a light-sheet; thus we distinguish between ontological and epistemic interpretations of the covariant bound. We consider the consequences that these interpretations might have for physics and we discuss what each approach has to say about gravitational phenomena. Our aim is not to advocate for either the ontological or epistemic approach in particular, but rather to articulate both possibilities clearly and explore some arguments for and against them.

3. **Measuring Gravitational shifts with Atomic Clocks** by Shraddha Agrawal, Department of Physics, University of Illinois at Urbana-Champaign Urbana, IL 61801, USA; email: sa30@illinois.edu

Abstract – Measurements of the validity of General Relativity, as well as its effects in quantum mechanics, are becoming increasingly accessible to tabletop experiments. In this essay, I will introduce atomic clocks and explain the pathway to observing state-of-the-art gravitational redshift using atomic clocks, with the help of existing experimental examples. I will conclude with possible future directions.

4. **Unraveling the Mystery of the Cosmological Constant: Does Spacetime Uncertainty Hold the Key?** by Ahmed Farag Ali and Nader Inan, Essex County College, 303 University Ave, Newark, NJ 07102, United States, Department of Physics, Faculty of Science, Benha University, Benha, 13518, Egypt, Clovis Community College, 10309 N. Willow, Fresno, CA 93730 USA, University of California, Merced, School of Natural Sciences, P.O. Box 2039, Merced, CA 95344, USA and Department of Physics, California State University Fresno, Fresno, CA 93740-8031, USA; email: aali29@essex.edu, ahmed.ali@fsc.bu.edu.eg, ninan@ucmerced.edu

Abstract – In addressing the cosmological constant problem, we propose that the discrepancy between the theoretical and observed values can be ascribed to the inherent uncertainty in the spacetime metric. Mach's principle, which posits that mass shapes spacetime, intersects with quantum mechanics' description of a particle as a quantum cloud, rendering the precise location of a particle's mass unknowable. Consequently, understanding spacetime structure at the quantum level becomes elusive. This connection between quantum and spacetime uncertainty could hold the key to resolving the cosmological constant problem. Intriguingly, the length scale of spacetime uncertainty, aligns with the macroscopic quantum weirdness observed in recent experiments. The spacetime uncertainty can be quantified by the scale factor in the Friedmann-Lemaître-Robertson-Walker (FLRW) Universe.

5. **Thermodynamics as a tool for (quantum) gravitational dynamics** by Ana Alonso-Serrano and Marek Liška, Max-Planck-Institut für Gravitationsphysik (Albert-Einstein-Institut), Am Mühlenberg 1, 14476 Potsdam, Germany, Institute of Theoretical Physics, Faculty of Mathematics and Physics, Charles University, V Holešovičkách 2, 180 00 Prague 8, Czech Republic; email: ana.alonso.serrano@aei.mpg.de, liska.mk@seznam.cz

Abstract – The thermodynamics of local causal horizons has been shown to imply gravitational dynamics. In this essay, we discuss the principles underlying this observation, and its significance in our understanding of (quantum) gravity. We also show why the local thermodynamic methods cannot by themselves recover general relativity. Instead, they lead to the so-called Weyl transverse gravity. Because of this, local thermodynamic approaches avoid huge vacuum energy contributions to the cosmological constant. They even suggest a possible source for its small observed value. We also outline a way in which thermodynamics allows us to study low energy quantum gravitational effects. We arrive at quantum corrections to the gravitational equations which are suppressed by the Planck length squared.

6. **BMS symmetry in gravity: Front form versus Instant form** by Sudarshan Ananth and Sucheta Majumdar, Indian Institute of Science Education and Research, Pune 411008, India, ENS de Lyon, CNRS, Laboratoire de physique, UMR 5672, F-69342 Lyon, France; email: ananth@iiserpune.ac.in, sucheta.majumdar@ens-lyon.fr

Abstract – In General Relativity, the allowed set of diffeomorphisms or gauge transformations at asymptotic infinity forms the BMS group, an infinite-dimensional extension of the Poincaré group. We focus on the structure of the BMS group in two distinct forms of Hamiltonian dynamics - the instant and front forms. Both similarities and differences in these two forms are examined while emphasising the role of non-covariant approaches to symmetries in gravity.

7. **Stellar equilibrium on a physical vacuum soil** by Julio Arrechea and Carlos Barceló, Instituto de Astrofísica de Andalucía (IAA-CSIC), Glorieta de la Astronomía, 18008 Granada, Spain; email: arrechea@iaa.es, carlos@iaa.es

Abstract – We show that the repulsive effects associated to the zero-point energies of quantum fields are capable of supporting ultracompact stars that overcome the compactness limits present in general relativity for any object in hydrostatic equilibrium. These objects are exact self-consistent solutions in semiclassical gravity that incorporate the backreaction of the renormalized stress-energy tensor (RSET) of quantum fields in vacuum. We arrive at stars of striking qualitative agreement through two independent modelings of the RSET, evidencing the generality and robustness of this result. The main physical properties of these novel black hole mimickers are reviewed.

8. **Punctuated Chaos and Indeterminism in Self-gravitating Many-body Systems** by Tjarda C. N. Boekholt, Simon F. Portegies Zwart, and Douglas C. Heggie, Rudolf Peierls Centre for Theoretical Physics, Clarendon Laboratory, University of Oxford, Parks Road, Oxford OX1 3PU, UK, Leiden Observatory, Leiden University, PO Box 9513, 2300 RA, Leiden, The Netherlands, School of Mathematics and Maxwell Institute for Mathematical Sciences, University of Edinburgh, 10 Kings Buildings, Edinburgh EH9 3FD, UK; email: tjarda.boekholt@physics.ox.ac.uk, spz@strw.leidenuniv.nl, d.c.heggie@ed.ac.uk

Abstract – Dynamical chaos is a fundamental manifestation of gravity in astrophysical, manybody systems. The spectrum of Lyapunov exponents quantifies the associated exponential response to small perturbations. Analytical derivations of these exponents are critical for understanding the stability and predictability of observed systems. This essay presents a new model for chaos in systems with eccentric and crossing orbits. Here, exponential divergence is not a continuous process but rather the cumulative effect of an ever-increasing linear response driven by discrete events at regular intervals, i.e., punctuated chaos. We show that long-lived systems with punctuated chaos can magnify Planck length perturbations to astronomical scales within their lifetime, rendering them fundamentally indeterministic.

9. **Black hole entropy contributions from Euclidean cores** by Jens Boos, High Energy Theory Group, Department of Physics, William & Mary, Williamsburg, VA 23187-8795, United States; email: jboos@wm.edu

Abstract – The entropy of a Schwarzschild black hole, as computed via the semiclassical Euclidean path integral in a stationary phase approximation, is determined not by the on-shell value of the action (which vanishes), but by the Gibbons-Hawking-York boundary term evaluated on a suitable hypersurface, which can be chosen arbitrarily far away from the horizon. For this reason, the black hole singularity seemingly has no influence on the Bekenstein-Hawking area law. In this Essay we estimate how a regular black hole core, deep inside a Euclidean black hole of mass M and generated via a UV regulator length scale $\ell > 0$, affects the black hole entropy. The contributions are suppressed by factors of $\ell/(2GM)$; demanding exact agreement with the area law as well as a self-consistent first law of black hole thermodynamics at all orders, however, demands that these contributions vanish identically via uniformly bounded curvature. This links the limiting curvature hypothesis to black hole thermodynamics.

10. **Gravity-induced entanglement as a probe of spacetime curvature** by Suddhasattwa Brahma and Abhinove Nagarajan Seenivasan, Higgs Centre for Theoretical Physics, School of Physics & Astronomy, University of Edinburgh, Edinburgh EH9 3FD, UK, Department of Physics, Indian Institute of Technology Guwahati, Guwahati 781039, Assam, India; email: suddhasattwa.brahma@gmail.com, abhinove523@gmail.com

Abstract – It is now widely believed that if the gravitational field is (perturbatively) quantum, it would entangle two massive objects (in spatial superpositions) which were otherwise unentangled to begin with. Recently, actual table-top experiments have been proposed to test this idea in what would be the first detection of perturbative quantum gravity. In this essay, we devise a thought experiment to prove that such gravity-induced entanglement depends on the spacetime curvature and can, in principle, act as an alternate signature of the expanding background. This will open up new and complementary directions to search for such entanglement in curved spacetime and reveal fresh perspectives on it.

11. **Implications Of The Intrinsic Dipole Components Of The Gravitational Field Of The Expanding Universe** by John Bruce Davies, Ph.D., Dept. of Physics (Retd.), University of Colorado, Boulder, CO USA, 117 Corbett Ave, Toronto, ON, M6N 1V3 Canada; email: DaviesResearch@yahoo.com

Abstract – There are numerous observations of dipole anisotropy of various Universe properties that coincide with the CRB spatial dipole direction. Einstein's Field equations reduce to a Klein-Gordon wave equation with solutions that intrinsically incorporate spatial/temporal dipole oscillations of the Gravitational Field which thereby manifest in the FLRW equations and in the Scale Factor of the Universe and its time derivatives. Such a temporal dipole explains why the time when the expanding Universe changed from Deceleration to Acceleration is essentially at half the age of the Universe. We show that the amplitude of the difference between early Universe and present-day Hubble Parameter measurements is consistent with the intrinsic temporal dipole effect. We find, as predicted, that the observed amplitudes of these spatial and temporal dipoles are essentially equal.

12. **Relativistic mechanism in prolate trochoid geometry** by L.H.A. de Lange, Bakboord 79, 1276BJ, Huizen, the Netherlands; email: laurensdelange@yahoo.com

Abstract – In Special Relativity, Albert Einstein made the connection between mass and energy. He postulated that the principle of relativity derives from the two facts that the laws of physics are the same in all inertial frames. And also, that the speed of light in a vacuum has the same constant value c in all inertial frames. Some years later Einstein developed his General Relativity, where he theorized, among important things, that the observed gravitational effect between masses results from their warping of space-time. Continuing on this path, this essay intends to shed light on the mathematical concept of prolate trochoid-geometries and how the relativistic visualisation of those geometries could result in explaining relativistic effects, mathematically at particle level.

13. **The end of spacetime** by Mir Faizal, Irving K. Barber School of Arts and Sciences, University of British Columbia - Okanagan, 3333 University Way, Kelowna, British Columbia V1V 1V7, Canada, Canadian Quantum Research Center, 204-3002, 32 Ave, Vernon, BC, V1T 2L7, Canada; email: mirfaizalmir@googlemail.com

Abstract – We will highlight that despite there being various approaches to quantum gravity, there are universal approach-independent features of quantum gravity. The geometry of spacetime becomes an emergent structure, which emerges from some purely quantum gravitational degrees of freedom. We argue that these quantum gravitational degrees of freedom can be best understood using quantum information theory. Various approaches to quantum gravity seem to suggest that quantum gravity could be a third quantized theory, and such a theory would not be defined in spacetime, but rather in an abstract configuration space of fields. This supports the view that spacetime geometry is not fundamental, thus effectively ending the spacetime description of nature.

14. **Introducing the Microverse $\mathbf{S}_{\boldsymbol{R}}^{\mathbf{3}}$ as a Model for the Big Bang and Inflation** by Arthur E. Fischer, Department of Mathematics, University of California, Santa Cruz, California 95064; email: aef@ucsc.edu

Abstract – Using the principles of general relativity, we construct the **microverse $\mathbf{S}_{\boldsymbol{R}}^{\mathbf{3}}$**, a micro-cosmological model that existed before the big bang and that is the progenitor of our current observable universe. The microverse is an *all-radiation static metastable* Friedmann micro-cosmology, about the size of a proton, with a positive cosmological constant, the geometry of a round 3-sphere, and whose photons packed together have the same total energy as our observable universe. The microverse is unstable with respect to *radiation converting to matter* and at a critical point, the microverse rapidly destabilizes into a positive feedback loop leading to the big bang, then to a change in topology, then to inflation, and finally to the spatially flat universe that we have today.

15. **Signatures of discretization in quantum black hole spectra** by Joshua Foo, Robert B. Mann, and Magdalena Zych, Centre for Quantum Computation & Communication Technology, School of Mathematics & Physics, The University of Queensland, St. Lucia, Queensland, 4072, Australia, Department of Physics and Astronomy, University of Waterloo, Waterloo, Ontario N2L 3G1, Canada, Perimeter Institute for Theoretical Physics, Waterloo, Ontario N2L 6B9, Canada, Department of Physics, Stockholm University, AlbaNova University Center, SE-106 91 Stockholm, Sweden, Centre for Engineered Quantum Systems, School of Mathematics and Physics, The University of Queensland, St. Lucia, Queensland, 4072, Australia; email: joshua.foo@uqconnect.edu.au, rbmann@uwaterloo.ca, magdalena.zych@fysik.su.se

Abstract – The quantum superposition principle states that quantum-mechanical systems such as atoms can be placed in a superposition of mass-energy eigenstates. Inspired by this idea and the seminal conjecture of Bekenstein, who proposed that black holes in quantum gravity must possess a discrete mass eigenspectrum, here we analyze the effects produced by a black hole in a superposition of masses. Analogous to using the electromagnetic field to probe atoms, we consider a quantum scalar field on the spacetime background sourced by the black hole mass superposition. From the resulting spectra, as measured by a hypothetical two-level system interacting with the field, we infer signatures of discretization of the black hole mass in support of Bekenstein's conjecture.

16. **On the Inevitable Lightness of Vacuum** by Laurent Freidel, Jerzy Kowalski-Glikman, Robert G. Leigh, and Djordje Minic, Perimeter Institute for Theoretical Physics, Caroline St. N., Waterloo ON, Canada, Institute for Theoretical Physics, University of Wroclaw, Pl. Maksa Borna 9, 50-204 Wroclaw, Poland National Centre for Nuclear Research, Pasteura 7, 02-093 Warsaw, Poland, Illinois Center for Advanced Studies of the Universe & Department of Physics, University of Illinois, 1110 West Green St., Urbana IL 61801, U.S.A., Department of Physics, Virginia Tech, Blacksburg, VA 24061, U.S.A.; email: lfreidel@perimeterinstitute.ca, jerzy.kowalski-glikman@uwr.edu.pl, rgleigh@illinois.edu, dminic@vt.edu

Abstract – In this essay, we present a new understanding of the cosmological constant problem, built upon the realization that the vacuum energy density can be expressed in terms of a phase space volume. We introduce a UV-IR regularization which implies a relationship between the vacuum energy and entropy. Combining this insight with the holographic bound on entropy then yields a bound on the cosmological constant consistent with observations. It follows that the universe is large, and the cosmological constant is naturally small, because the universe is filled with a large number of degrees of freedom.

17. **The infalling observer's twofold perception** by René Friedrich, 6 rue du Cygne, 67400 Illkirch/ Strasbourg, France; email: rene_friedrich@orange.fr

Abstract – Black holes, and in particular the underlying Schwarzschild metric, are associating finite and infinite time structures. In particular, the infalling observer is reaching the event horizon within finite time while according to external observers, she will never reach the event horizon. In this essay, it will be shown that up to now, the point of view of the infalling observer has been fundamentally misunderstood, because there is not taken into account the fact that every infalling observer approaching the event horizon is also an external observer, such that she disposes of two competing ways of perception.

18. **Spacetime deformations of electromagnetic nature are far from negligible** by Daniele Funaro, Dipartimento di Scienze Chimiche e Geologiche, Università di Modena e Reggio Emilia, Via Campi 103, 41125 Modena (Italy); email: daniele.funaro@unimore.it

Abstract – We would like to collect a series of considerations concerning the influence, which we believe is relevant, that phenomena of an electromagnetic nature have on the geometry of spacetime. The approach, supported by the critical observation of already well-known properties and sustained by theoretical elements, leads us to attribute a primary role to electric and magnetic interactions. In fact, a seemingly small interpretative effort can help link theories elegantly and mathematically which at the moment appear independent. Einstein's equations have a validity that goes beyond the cosmological one and, with the appropriate corrections, they can clarify what really happens inside matter, starting with the bonds that dominate at the molecular level all the way up the description of the macroscopic characteristics. This analysis allows us to leave the context hitherto reserved exclusively for quantum mechanics and to place the study of the structure of matter in a more classic framework.

19. **Non-Linear Sigma Models in Inflationary Cosmology** by Abhishek Goswami, Faculty of Mathematics and Computer Science, Adam Mickiewicz University, Poznan, Poland; email: goswami.abhishek33@gmail.com

Abstract – Non-linear Sigma Models in two dimensions ($NLSM_2$) describe the quantum field theory (QFT) of the Embedding map from a two dimensional surface to a higher dimensional target space. We assume that before the Big Bang the universe was an abstract space with a two dimensional surface embedded in it. We study QFT of the Embedding map in the universe that is $NLSM_2$. We consider the abstract target space which is a Lie Group; SU(n) manifold. Then taking a symmetry breaking potential in $NLSM_2$ QFT, we show the emergence of a geometric arrow of time via a Big Bang. This leads to an inflationary scenario driven by the Embedding map. Finally we discuss the mathematical existence of a $NLSM_2$ and some aspects of the renormalization group flow relevant to inflation.

20. **Gravity & the magical "Born Rule": Physical implications** by Johan Hansson, Division of Physics Luleå University of Technology, SE-971 87 Luleå, Sweden; email: c.johan.hansson@ltu.se

Abstract – I. The arena of quantum theory is the abstract, unobserved and unobservable, *M*-dimensional Hilbert space ≠ spacetime. II. The arena of observations, and *all* events (*i.e. everything*) in the real physical world, is the classical 4-dimensional physical spacetime of general relativity. III. The "Born Rule" is the random process "magically" transforming I. into II. Formulations of quantum theory directly in real physical spacetime constitute examples of "locally real" theories (Clauser & Horne) and are *empirically refuted* by the numerous tests of Bell's theorem. When separated and treated correctly in this way, a number of fundamental problems and "paradoxes" of gravity vs. quantum theory simply vanish, such as the black hole information paradox, the cosmological constant problem and quantization of general relativity.

21. **Analog Model for Euclidean Wormholes Effects** by Gustavo O. Heymans, Gastão Krein, and Nami F. Svaiter, Centro Brasileiro de Pesquisas Físicas, Rua Xavier Sigaud 150, Rio de Janeiro, 22290-180 Rio de Janeiro, RJ, Brazil, Instituto de Física Teórica, Universidade Estadual Paulista, Rua Dr. Bento Teobaldo Ferraz, 271, Bloco II, 01140-070, São Paulo, SP, Brazil; email: olegario@cbpf.br, nfuxsvai@cbpf.br, gastao.krein@unesp.br

Abstract – Using results of statistical field theory for systems with an anisotropic disorder, we present an analog model for Euclidean wormholes and topological fluctuation effects in a Riemannian space $\mathscr{M}^d$. The contribution of wormholes and topological fluctuations to the Euclidean gravitational functional integral is modeled by quenched randomness defined in the $\mathbb{R}^d$ manifold. We obtain a disorder-averaged free energy by taking the average over all the realizations of the random fields. In the scenario of topology fluctuation, there appears a superposition of infinite branes that contribute to the physical quantities. All topology fluctuations can be understood as two distinct kinds of Euclidean wormholes: wormholes confined to one brane, and wormholes connecting different branes.

22. **Introduction Of Dark Fields Into Einstein Field Equations Of General Relativity** by Vu B Ho, 9 Adela Court, Mulgrave, Vic 3170, Australia; email: vubho@bigpond.net.au

Abstract – We examine the possibility to introduce dark fields into Einstein field equations of general relativity, in which the cosmological constant becomes the trace of the energy-momentum tensor associated with a dark field. The introduction of dark fields is made possible by establishing field equations for the Ricci curvature tensor. We also discuss the possibility to represent a physical system consisting of a dark field and an observable field as a space of constant scalar curvature by establishing a system of field equations for the Riemann curvature tensor from the Bianchi identities. As an illustration, we show that if a dark field is a dark fluid then the pressure associated with the dark field can take negative values if the cosmological constant has positive values.

23. **Universality in Binary Black Hole Dynamics: An Integrability Conjecture** by José Luis Jaramillo, Badri Krishnan, and Carlos F. Sopuerta, Institut de Mathématiques de Bourgogne (IMB), UMR 5584, CNRS, Université de Bourgogne, F-21000 Dijon, France, Institute for Mathematics, Astronomy and Particle Physics Radboud University, Heyendaalseweg, 135, 6525 AJ Nijmegen, The Netherland, Institute of Space Sciences (ICE-CSIC and IEEC), Campus UAB, Carrer de Can Magrans s/n, 08193 Cerdanyola del Vallès, Spain; email: Jose-Luis.Jaramillo@u-bourgogne.fr, badri.krishnan@ru.nl, carlos.f.sopuerta@csic.es

Abstract – The waveform of a binary black hole coalescence appears to be both simple and universal. In this essay we argue that the dynamics should admit a separation into 'fast and slow' degrees of freedom, such that the latter are described by an integrable system of equations, accounting for the simplicity and universality of the waveform. Given that Painlevé transcendents are a smoking gun of integrable structures, we propose the Painlevé-II transcendent as the key structural element threading a hierarchy of asymptotic models aiming at capturing different (effective) layers in the dynamics. Ward's conjecture relating integrable and (anti)self-dual solutions can provide the avenue to encode background binary black hole data in (non-local) twistor structures.

24. **Holographic Quantum Gravity and Horizon Instability** by Vaibhav Kalvakota, Turito Institute, 500081, Hyderabad, India; email: vaibhavkalvakota@icloud.com

Abstract – In this Essay, we will look at the relation between the No Transmission principle and the Strong cosmic censorship (SCC), which we will highlight in the background of quantum gravity. We show that taking quantum gravity into account, one can provide a complete picture of the instability of the inner horizon and the principle that two independent CFTs, under the gauge-gravity duality, imply that the dual bulks must also be independent in that there must not exist a way to transmit a signal between the two spacetimes. We show that this can simply be interpreted as SCC, and that the inner horizon must be unstable (at either linear or nonlinear orders) to be in accordance with holographic quantum gravity.

25. **Matter-gravity entanglement entropy and the second law for black holes** by Bernard S. Kay, Department of Mathematics, University of York, York YO10 5DD, UK; email: bernard.kay@york.ac.uk

Abstract – Hawking showed that a black hole formed by collapse will emit radiation and eventually disappear. We address the challenge to define an objective notion of physical entropy which increases throughout this process in a way consistent with unitarity. We have suggested that (instead of coarse-grained entropy) physical entropy is matter-gravity entanglement entropy and that this may offer an explanation of entropy increase both for the black hole collapse and evaporation system and also for other closed unitarily evolving systems. For this to work, the matter-gravity entanglement entropy of the late-time state of black hole evaporation would have to be larger than the entropy of the freshly formed black hole. We argue that this may possibly the case due to (usually neglected) photon-graviton interactions.

26. **A simple outline of spacetime thermodynamics** by Arno Keppens, Space Pole, Avenue Circulaire 3, 1180 Brussels, Belgium; email: arno.keppens@spacepole.be

Abstract – By equating three temperature definitions that should simultaneously hold for an equilibrium thermodynamics of spacetime's degrees of freedom, it is immediately found that the latter only applies to spacetime surfaces with constant Newtonian gravitational potential, a result that was only rigorously proven in 2018. The laws of thermodynamics can correspondingly be rephrased in terms of spacetime's state variables at these surfaces.

27. **The sound of the event horizon** by R. A. Konoplya, Research Centre for Theoretical Physics and Astrophysics, Institute of Physics, Silesian University in Opava, Bezručovo náměstí 13, CZ-74601 Opava, Czech Republic; email: roman.konoplya@gmail.com

Abstract – During the ringdown phase of a gravitational signal emitted by a black hole, the least damped quasinormal frequency dominates. If modifications to Einstein's theory induce noticeable deformations of the black-hole geometry only near the event horizon, the fundamental mode remains largely unaffected. However, even a small change near the event horizon can significantly impact the first few overtones, providing a means to probe the geometry of the event horizon. Overtones are stable against small deformations of spacetime at a distance from the black hole, allowing the event horizon to be distinguished from the surrounding environment. In contrast to echoes, overtones make a much larger energy contribution. These findings open up new avenues for future observations.

28. **Limits of a non-local quantum spacetime** by Dawood Kothawala, Department of Physics, Indian Institute of Technology Madras, Chennai 600 036, India; email: dawood@iitm.ac.in

Abstract – A generic implication of incorporating gravitational effects in the analysis of quantum measurements is the existence of a zero-point length of spacetime. This requires an inherently non-local description of spacetime, beyond the usual one based on metric $g_{ab}(x)$ etc. The quantum spacetime should instead be reconstructed from non-local bi-tensors of the form $\mathcal{G}_{ab\ldots i'j'\ldots}(x,x')$. A deeper look then reveals a subtle interplay interplay between non-locality and the limit $G\hbar/c^3 \to 0$. In particular, the so called emergent gravity paradigm - in which gravitational dynamics/action/spacetime are emergent and characterised by an *entropy functional* - arises as the *Cheshire* grin of a fundamentally non-local quantum spacetime. This essay describes the flow of metric with respect to Planck length, and proposes a novel action for the same.

29. **Black Hole Quantum Computer** by Musfar Muhamed Kozhikkal and Shafeeq Rahman Thottoli, Institut UTINAM, Université Bourgogne Franche-Comté, France, Department of Physics, Jazan University, Saudi Arabia; email: musfarmuhamed@gmail.com, sthottoli@jazanu.edu.sa

Abstract – Quantum computers that use qubits placed in black holes to perform computations are predicted to be much faster than all other computers. A black hole quantum computer can potentially work by sending qubits into the black hole. This can be used to program the black hole to perform the desired computation using quantum gates and wormholes for entanglement. The Hawking radiation emitted by the black hole can be captured and decoded to provide the computational output.

30. **Fast Radio Bursts *signal* high-frequency gravitational waves** by Ashu Kushwaha, Sunil Malik, and S. Shankaranarayanan, Department of Physics, Indian Institute of Technology Bombay, Mumbai 400076, India, Institut für Physik und Astronomie, Universität Potsdam, Potsdam, Germany, Deutsches Elektronen-Synchrotron DESY, Zeuthen, Germany; email: ashu712@iitb.ac.in, sunil.malik@uni-potsdam.de, shanki@iitb.ac.in

Abstract – There is growing evidence for high-frequency gravitational waves (HFGWs) ranging from MHz to GHz. Several HFGW detectors have been operating for over a decade, and two GHz events have been reported recently. However, a confirmed detection might take a decade. This essay argues that unexplained observed astrophysical phenomena, like Fast Radio Bursts (FRBs), might provide indirect evidence for HFGWs. In particular, using the Gertsenshtein-Zel'dovich effect, we show that our model can explain three key features of FRBs: generate peak-flux up to 1000 Jy, naturally explain the pulse width and the coherent nature of FRBs. In short, our model offers a novel perspective on the indirection detection of HFGWs beyond current detection capabilities. Thus, transient events like FRBs are a rich source for multi-messenger astronomy.

31. **In Search of the maximum lost momentum** by Carlos O. Lousto and James Healy, Center for Computational Relativity and Gravitation (CCRG), School of Mathematical Sciences, Rochester Institute of Technology, 85 Lomb Memorial Drive, Rochester, New York 14623; email: colsma@rit.edu, jchsma@rit.edu

Abstract – We performed a series of 1381 full numerical simulations of high energy collision of black holes to search for the maximum recoil velocity after their merger. We studied equal mass binaries with opposite spins pointing along the orbital plane to maximize asymmetric gravitational radiation and performed a search of spin orientations, impact parameters, and initial linear momenta to find a maximum recoil velocity extrapolated to the extreme spinning case of 28,562±342 km/s, thus tightly bounding recoil by 10% the speed of light.

32. **Moving bodies are colder** by Morgan Henry Lynch, Center for Theoretical Physics, Seoul National University, Seoul 08826, Korea; email: morganlynch1984@gmail.com

Abstract – Since 1907, a paradox has persisted in relativistic thermodynamics; namely how a temperature transforms under Lorentz boosts. Given that cogent arguments exist for the temperature of objects getting colder, hotter, or even staying the same when moving at relavistic speeds, it seems that the resolution of this question requires an experiment to make the final judgement. The observation of the Unruh effect in ultrarelativistic channeling radiation by CERN-NA63 provides an experiment which is able to map the Fulling-Davies-Unruh (FDU) temperature, defined in the proper frame, to the data measured in the lab frame. With the data being a direct experimental measurement of the FDU temperature, *we confirm, for the case of the Unruh effect, that a moving body appears colder*.

33. **Pancakification and negative Hawking temperatures** by Tyler McMaken, JILA and Department of Physics, University of Colorado, Boulder, Colorado 80309, USA; email: tyler.mcmaken@colorado.edu

Abstract – Vacuum models of charged or spinning black holes possess two horizons, the inner of which has the oft-overlooked property that gravitational tidal forces initially spaghettifying a freely falling observer will eventually change signs and flatten the observer like a pancake. Inner horizons also induce a classical blueshift instability known as mass inflation, and a number of recent studies have found that inner horizons exhibit even stronger quantum singular behavior. In this essay we explore the quantum effect of Hawking radiation, which in the presence of compressive tidal forces seems to predict negative temperatures. By analyzing the interaction of quantum fields with black hole geometries, we can come to a closer semiclassical understanding of what really happens near a black hole's inner horizon.

34. **Nomen non est omen: why it is too soon to identify ultra-compact objects as black holes** by Sebastian Murk, Okinawa Institute of Science and Technology, 1919-1 Tancha, Onna-son, Okinawa 904-0495, Japan, School of Mathematical and Physical Sciences, Macquarie University, Sydney, New South Wales 2109, Australia, Sydney Quantum Academy, Sydney, New South Wales 2006, Australia; email: sebastian.murk@oist.jp

Abstract – Black holes play a pivotal role in the foundations of physics, but there is an alarming discrepancy between what is considered to be a black hole in observational astronomy and theoretical studies. Despite claims to the contrary, we argue that identifying the observed astrophysical black hole candidates as genuine black holes is not justified based on the currently available observational data, and elaborate on the necessary evidence required to support such a remarkable claim. In addition, we investigate whether the predictions of semiclassical gravity are equally compatible with competing theoretical models, and find that semiclassical arguments favor horizonless configurations.

35. **Buchdahl-inspired spacetimes and wormholes: Unearthing Hans Buchdahl's other 'hidden' treasure trove** by Hoang Ky Nguyen, Department of Physics, Babes–Bolyai University, 1 Kogalniceanu Street, 400084 Cluj-Napoca, Romania; email: hoang.nguyen@ubbcluj.ro

Abstract – Circa 1962 Hans A. Buchdahl pioneered a program – and made significant progress – seeking vacuo configurations in pure $\mathcal{R}^2$ gravity (*Nuovo Cimento, Vol 23, p141 (1962)* [1]). Unfortunately, he deemed the final step in his calculations impassable and prematurely suspended his pursuit. Since then, his achievements on this front have faded into dormancy. Unbeknownst to Buchdahl himself, the $\mathcal{R}^2$ vacua that he sought were within his striking distance. In our recent three-paper body of work partially published in Phys. Rev.D [2–4], we broke this six-decades-old impasse and accomplished his goal: A novel class of metrics, describing non-Schwarzschild spacetimes in quadratic gravity and carrying a hallmark of higher-derivative characteristic. Intriguing properties of Buchdahl-inspired spacetimes and their associated Morris-Thorne-Buchdahl wormholes – summarized herein – embody a new branch of phenomenology that transcends the Einstein–Hilbert paradigm.

36. **Is it time to rethink quantum gravity?** by Jonathan Oppenheim, Department of Physics and Astronomy, University College London, Gower Street, London WC1E 6BT, United Kingdom; email: j.oppenheim@ucl.ac.uk

Abstract – Although it's widely believed that gravity should have a quantum nature like every other force, the conceptual obstacles to constructing a quantum theory of gravity compel us to explore other perspectives. Gravity is not like any other force. It alone defines a universal space-time geometry, upon which quantum fields evolve. We feel gravity because matter causes space-time to bend. Time flows at unequal rates at different locations. The rate at which time flows, and the causal structure it provides, may be required to have a classical description in order for quantum theory to be well-formulated. I discuss arguments for this proposition, but ultimately conclude that we must turn to experiment to guide us.

37. **On primordial gravitational waves in Teleparallel Gravity** by Geovanny A. Rave-Franco and Celia Escamilla-Rivera, Instituto de Ciencias Nucleares, Universidad Nacional Autónoma de México, Circuito Exterior C.U., A.P. 70-543, México D.F. 04510, México; email: geovanny.rave@ciencias.unam.mx, celia.escamilla@nucleares.unam.mx

Abstract – Teleparallel Gravity is a gauge theory where gravity is a manifestation of the torsion of space-time and its success relies on being a possible solution to some problems of General Relativity. In this essay we introduce the construction of the theory by defining its geometrical setup, and how we can build it as a gauge theory of translations locally invariant under the Lorentz group. In this context, we will study the production of primordial gravitational waves and the observational implications when extended models are taken into account, particularly, we will notice how the tensor spectral index changes and produces a direct impact on the power spectrum from vacuum fluctuations and any source of tensor anisotropic stress in comparison to General Relativity.

38. **Black Holes, Equilibrium, and Cosmology** by Fil Simovic, School of Mathematical and Physical Sciences, Macquarie University, Sydney, New South Wales 2109, Australia; email: fil.simovic@mq.edu.au

Abstract – We trace the origins and development of black hole thermodynamics across the past half-century, emphasizing the framework's relation to classical thermodynamics, and the vital role played by the notions of equilibrium, stationary, and symmetry. We discuss different interpretations of the first law of black hole mechanics, and assess the validity of its mechanical, process-based interpretation for evaporating black holes. We bring these ideas to the cosmological realm, and highlight the various difficulties that arise when formulating thermodynamics for black holes in asymptotically de Sitter backgrounds. We discuss a number of proposed solutions and the open questions that arise therein.

39. **Dynamic Dark Energy from the Local Limit of Nonlocal Gravity** by Javad Tabatabaei, Abdolali Banihashemi, Shant Baghram, and Bahram Mashhoon, Department of Physics, Sharif University of Technology, Tehran 11155-9161, Iran, School of Astronomy, Institute for Research in Fundamental Sciences (IPM), Tehran 19395-5531, Iran, Department of Physics and Astronomy, University of Missouri, Columbia, Missouri 65211, USA

Abstract – Nonlocal gravity (NLG), a classical extension of Einstein's theory of gravitation, has been studied mainly in linearized form. In particular, nonlinearities have thus far prevented the treatment of cosmological models in NLG. In this essay, we discuss the local limit of NLG and apply this limit to the expanding homogenous and isotropic universe. The theory only allows spatially at cosmological models; furthermore, de Sitter spacetime is forbidden. The components of the model will have different dynamics with respect to cosmic time as compared to the standard ΛCDM model; specifically, instead of the cosmological constant, the modified flat model of cosmology involves a dynamic dark energy component in order to account for the accelerated phase of the expansion of the universe.

40. **The Virial Theorem for Retarded gravity** by Asher Yahalom, Ariel University, Ariel 40700, Israel; email: asya@ariel.ac.il

Abstract – Galaxy Clusters are huge physical systems having a generic size of tens of millions of light years. Thus any modification at the center of the cluster will affect the outskirts only tens of millions of years afterwards. Those retardation considerations seems to be neglected in present day analysis used to estimate the total mass of the galaxy cluster, including those estimates which are based on the virial theorem. The significant differences between the velocities predicted by Newtonian action at a distance theory and observations are usually dealt with by either assuming an unobservable type of matter or by modifying gravity. Here we demonstrate that considering general relativistic effects one can explain the apparent excess matter appearing in galaxy clusters virial estimates.