GRAVITY RESEARCH FOUNDATION

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Abstracts of Award Winning and Honorable Mention Essays for 2022

Award Essays

First Award – **Proper Time Quantization of a Thin Shell** by Cenalo Vaz, University of Cincinnati, Cincinnati, OH 45221-0011; email: cenalo.vaz@uc.edu

Abstract – "Time" has different meanings in classical general relativity and in quantum theory. While all choices of a time function yield the same local classical geometries, quantum theories built on different time functions are not unitarily equivalent. This incompatibility is most vivid in model systems for which exact quantum descriptions in different time variables is available. One such system is a spherically symmetric, thin dust shell. In this essay we will compare the quantum theories of the shell built on proper time and on a particular coordinate time. We find wholly incompatible descriptions: whereas the shell quantum mechanics in coordinate time admits *no* solutions when the mass is greater than the Planck mass, its proper time quantum mechanics *only* admits solutions when the mass is greater than the Planck mass. The latter is in better agreement with what is expected from observation. We argue that proper time quantization provides a superior approach to the problem of time in canonical quantization.

Second Award – **"The More Things Change the More they Stay the Same", Minimum Lengths with Unmodified Uncertainty Principle and Dispersion Relation**
by Michael Bishop[1], Joey Contreras[2], and Douglas Singleton[2], [1]Mathematics Department, California State University Fresno, Fresno, CA 93740, [2]Physics Department, California State University Fresno, Fresno, CA 93740; email: mibishop@mail.fresnostate.edu, mkfetch@mail.fresnostate.edu, dougs@mail.fresnostate.edu

Abstract – Broad arguments indicate that quantum gravity should have a minimal length scale. In this essay we construct a minimum length model by generalizing the time-position and energy-momentum operators while keeping much of the structure of quantum mechanics and relativity intact: the standard position-momentum commutator, the special relativistic time-position, and energy-momentum relationships all remain the same. Since the time-position and energy-momentum relationships for the modified operators remain the same, we retain a form of Lorentz symmetry. This avoids the constraints on these theories coming from lack of photon dispersion while holding the potential to address the Greisen-Zatsepin-Kuzmin (GZK) puzzle of ultra high energy cosmic rays.

Third Award – **Black Holes Decohere Quantum Superpositions** by Daine L. Danielson, Gautam Satishchandran, and Robert M. Wald, Enrico Fermi Institute and Department of Physics, The University of Chicago, Chicago, IL 60637; email: daine@uchicago.edu, gautamsatish@uchicago.edu, rmwa@uchicago.edu

Abstract – We show that if a massive body is put in a quantum superposition of spatially separated states, the mere presence of a black hole in the vicinity of the body will eventually destroy the coherence of the superposition. This occurs because, in effect, the gravitational field of the body radiates soft gravitons into the black hole, allowing the black hole to acquire "which path" information about the superposition. A similar effect occurs for quantum superpositions of electrically charged bodies. We provide estimates of the decoherence time for such quantum superpositions. We believe that the fact that a black hole will eventually decohere any quantum superposition may be of fundamental significance for our understanding of the nature of black holes in a quantum theory of gravity.

Fourth Award – **Large Momentum Transfer Optics: A Means to Probe the Interplay between Gravity and Quantum Mechanics** by Shraddha Agrawal, Department of Physics, University of Illinois at Urbana-Champaign, Urbana, IL 61801; email: sa30@illinois.edu

Abstract – A consistent description of gravity in quantum mechanics and general relativity is becoming increasingly accessible to table-top experiments. In this essay, I introduce the experimental technique of large momentum transfer optics as a means to probe gravity at microscopic scales. I argue, with the help of recent experimental observations, that large momentum transfer optics is the best experimental technique to do so. I conclude with possible future directions using large momentum transfer optics.

Fifth Award – **Unitarity and Quantum Resolution of Gravitational Singularities** by Steffen Gielen[1] and Lucía Menéndez-Pidal[2], [1]School of Mathematics and Statistics, University of Sheffield, Hicks Building, Hounsfield Road, Sheffield S3 7RH, United Kingdom, [2]School of Mathematical Sciences, University of Nottingham, University Park, Nottingham NG7 2RD, United Kingdom; email: s.c.gielen@sheffield.ac.uk, lucia.menendez-pidal@nottingham.ac.uk

Abstract – We explore the consequences of requiring that quantum theories of gravity be unitary, mostly focusing on simple cosmological models to illustrate the main points. We show that unitarity for a clock that encounters a classical singularity at finite time implies quantum singularity resolution, but for a clock that encounters future infinity at finite time leads to a quantum recollapse. We then find that our starting point – assuming the general covariance of general relativity — is actually incompatible with general quantum unitarity: singularity resolution in quantum gravity can always be engineered by choosing the right clock, or avoided by using a different one.

Honorable Mention Awards **(Alphabetical Order)**

1. **Information Theory of Gravity** by Jeffrey Alloy Q. Abanto, Cosmology and Astrophysics Unit, Astronomy Department, New Era University, Philippines, 1107; email: jaqabanto@neu.edu.ph

Abstract – A new model of gravity is presented here similar to the earlier work of Verlinde on Emergent Gravity but without the use of thermodynamic assumptions. The theory does not use the main assumption of Verlinde on the nature of gravity as an entropic force using the First Law of Thermodynamics. Moreover, it does not use the Equipartition Theorem such that there is no need to define a thermal bath enclosed within a holographic screen. Instead of Equipartition Theorem, the theory uses $E = NE_p$, for the total energy of a massive object where E_p is the Planck Energy while N is the number of Planck Energy to represent the maximum possible density of information that can reside in matter. The theory uses also the Holographic Principle as the basis for an information-theoretic approach to the nature of gravity. It is shown here that gravity emerges whenever there is an updating of the information within a given volume of space by the presence of matter.

2. **A Mechanism for a "Leaky" Black Hole to Catalyze Galaxy Formation** by Stephen L. Adler, Institute for Advanced Study, Einstein Drive, Princeton, NJ 08540; email: adler@ias.edu

Abstract – In the gravitational field of a Schwarzschild-like black hole, particles infalling from rest at infinity, and black hole "wind" particles with relativistic velocity leaking radially out from the nominal horizon, both have the same magnitude of velocity at any radius from the hole. Hence when equally massive infalling and wind particles collide at any radius, they yield collision products with zero center of mass radial velocity, which can then nucleate star formation at the collision radius. We suggest that this gives a mechanism by which a central black hole can catalyze galaxy formation. For disk galaxies, this mechanism explains the observed approximately exponential falloff of the surface brightness with radius, and gives an estimate of the associated scale length.

3. **Event Horizons are Tunable Factories of Quantum Entanglement** by Ivan Agullo[1], Anthony J. Brady[2], and Dimitrios Kranas[1], [1]Department of Physics and Astronomy, Louisiana State University, Baton Rouge, LA 70803, [2]Department of Electrical and Computer Engineering, University of Arizona, Tucson, AZ 85721; email: agullo@lsu.edu, ajbrady4123@email.arizona.edu, dkrana1@lsu.edu

Abstract – That event horizons generate quantum correlations via the Hawking effect is well known. We argue, however, that the creation of entanglement can be modulated as desired, by appropriately illuminating the horizon. We adapt techniques from quantum information theory to quantify the entanglement produced during the Hawking process and show that, while ambient thermal noise (e.g., CMB radiation) degrades it, the use of squeezed inputs can boost the non-separability between the interior and exterior regions in a controlled manner. We further apply our ideas to analog event horizons concocted in the laboratory and insist that the ability to tune the generation of entanglement offers a promising route towards detecting quantum signatures of the elusive Hawking effect.

4. **Generating Dark Energy from Torsion** by D. Benisty[1][2], A. van de Venn[3], D. Vasak[3], J. Struckmeier[3][4][5], and H. Stoecker[3][4][5], [1]DAMTP, Centre for Mathematical Sciences, University of Cambridge, Wilberforce Road, Cambridge CB3 0WA, United Kingdom, [2]Kavli Institute of Cosmology (KICC), University of Cambridge, Madingley Road, Cambridge, CB3 0HA, UK, [3]Frankfurt Institute for Advanced Studies (FIAS), Ruth-Moufang-Strasse 1, 60438 Frankfurt am Main, Germany, [4]Fachbereich Physik, Goethe-Universität, Max-von-Laue-Strasse 1, 60438 Frankfurt am Main, Germany, [5]GSI Helmholtzzentrum für Schwerionenforschung GmbH, Planckstrasse 1, 64291 Darmstadt, Germany; email: db888@cam.ac.uk, venn@fias.uni-frankfurt.de, vasak@fias.uni-frankfurt.de, struckmeier@fias.uni-frankfurt.de, stoecker@fias.uni-frankfurt.de

Abstract – Dark Energy from kinetic torsion is discussed. The torsion incorporated in the Einstein-Cartan (EC) Lagrangian is assumed to be totally anti-symmetric, represented by a time-like axial vector S^{μ}. The dynamics of torsion is invoked by a novel kinetic term that gives rise to dark energy, while the massive quadratic torsion term, emanating from the EC part. The massive part represents a stiff fluid that leads to a bouncing term.

5. **Gravitizing the Quantum** by Per Berglund[1], Tristan Hübsch[2], David Mattingly[1], and Djordje Minic[3], [1]Department of Physics and Astronomy, University of New Hampshire, Durham, NH 03824, [2]Department of Physics and Astronomy, Howard University, Washington, D.C. 20059, [3]Department of Physics, Virginia Tech, Blacksburg, VA 24061; email: per.berglund@unh.edu, thubsch@howard.edu, david.mattingly@unh.edu, dminic@vt.edu

Abstract – We discuss a new approach to the problem of quantum gravity in which the quantum mechanical structures that are traditionally fixed, such as the Fubini-Study metric in the Hilbert space of states, become dynamical and so implement the idea of *gravitizing the quantum*. In particular, in this formulation of quantum gravity the quantum geometry is still consistent with the principles of unitarity and also captures fundamental aspects of (quantum) gravity, such as topology change. Furthermore, we address specific ways of testing this new approach to quantum gravity by utilizing multi-path interference and optical lattice atomic clocks.

6. **Baby Universes Born from the Void** by Panos Betzios[1], Nava Gaddam[2], and Olga Papadoulaki[3], [1]Department of Physics and Astronomy, University of British Columbia, 6224 Agricultural Road, Vancouver, B.C. V6T 1Z1, Canada, [2]Institute for Theoretical Physics and Center for Extreme Matter and Emergent Phenomena, Utrecht University, 3508 TD Utrecht, The Netherlands, [3]Perimeter Institute for Theoretical Physics, Waterloo, Ontario N2L 2Y5, Canada; email: pbetzios@phas.ubc.ca, gaddam@uu.nl, opapadoulaki@perimeterinstitute.ca

Abstract – We propose a novel construction of a third quantised baby universe Hilbert space H_{BU} for the quantum gravity path integral. In contrast to the original description of α-parameters, both the bulk and boundary microscopic parameters are fixed. Wormholes and baby universes can appear when considering more refined observables of the boundary dual quantum field theories, that crucially involve the space of representations of their gauge group. Irreducible representations, on which the path integral factorises, give rise to field theoretic superselection sectors and replace the α states.

7. **Bell's Nonlocality and Gravity** by Yuri Bonder and Johas D. Morales, Instituto de Ciencias Nucleares, Universidad Nacional Autónoma de México, Apartado Postal 70-543, Coyoacán 04510 Cd.Mx., México; email: bonder@nucleares.unam.mx

Abstract – The experimental results that test Bell's inequality have found strong evidence suggesting that there are nonlocal aspects in nature. Evidently, these nonlocal effects, which concern spacelike separated regions, create an enormous tension between general relativity and quantum mechanics. In addition, by avoiding the coincidence limit, semiclassical gravity can also accommodate nonlocal aspects. Motivated by these results, we study if it is possible to construct geometrical theories of gravitation that are nonlocal in the sense of Bell. We propose three constructions of such theories, which could constitute an important step towards our understanding of the interplay between quantum mechanics and gravitation.

8. **Way Down in the Hole... and Up Again** by Valentin Boyanov, Departamento de Física Teórica and IPARCOS, Universidad Complutense de Madrid, 28040 Madrid, Spain; email: vboyanov@ucm.es

Abstract – I argue that an approach which uses an appropriate admixture of both classical and semiclassical effects is essential for understanding the ultimate fate of gravitational collapse and the nature of black holes. I provide an example of a problem which pushes the boundaries of what is known in both the classical and semiclassical approaches: the evolution of the inner horizon of a black hole. I show that solving this problem requires considering perturbations of both classical and semiclassical origin. In fact, it has been found that classical mass inflation might be counteracted by a semiclassical tendency for the inner horizon to inflate outward.

9. **Emergent Early Universe Cosmology from BFSS Matrix Theory** by Suddhasattwa Brahma[1], Robert Brandenberger[2], and Samuel Laliberte[2], [1]Higgs Centre for Theoretical Physics, School of Physics & Astronomy, University of Edinburgh, Edinburgh EH9 3FD, UK, [2]Department of Physics, McGill University, Montreal, QC, H3A 2T8, Canada; email: sbrahma@ed.ac.uk, rhb@physics.mcgill.ca, samuel.laliberte@mail.mcgill.ca

Abstract –The BFSS matrix model is a suggested non-perturbative definition of string theory. Starting from a thermal state of this matrix model, we show how space and time can emerge dynamically. Results from the IKKT matrix model indicate that the $SO(9)$ symmetry of space is spontaneously broken to $SO(3) \times SO(6)$, with the three-dimensional subspace becoming large. Given this initial state for the universe, we show that cosmological perturbations and gravitational waves with scale-invariant spectra are generated, without the need of postulating an early phase of cosmological inflation. The Big Bang singularity is automatically resolved.

10. **Resolving Information Loss Paradox with Euclidean Path Integral** by Pisin Chen[1][2][3], Misao Sasaki[1][4][5], Dong-Han Yeom[6][7], and Junggi Yoon[8][9][10], [1]Leung Center for Cosmology and Particle Astrophysics, National Taiwan University, Taipei 10617, Taiwan, [2]Department of Physics and Graduate Institute of Astrophysics, National Taiwan University, Taipei 10617, Taiwan, [3]Kavli Institute for Particle Astrophysics and Cosmology, SLAC National Accelerator Laboratory, Stanford University, Stanford, CA 94305, [4]Kavli Institute for the Physics and Mathematics of the Universe (WPI), University of Tokyo, Chiba 277-8583, Japan, [5]Yukawa Institute for Theoretical Physics, Kyoto University, Kyoto 606-8502, Japan, [6]Department of Physics Education, Pusan National University, Busan 46241, Republic of Korea, [7]Research Center for Dielectric and Advanced Matter Physics, Pusan National University, Busan 46241, Republic of Korea, [8]Asia Pacific Center for Theoretical Physics, Pohang 37673, Republic of Korea, [9]Department of Physics, POSTECH, Pohang 37673, Republic of Korea, [10]School of Physics, Korea Institute for Advanced Study, Seoul 02455, Republic of Korea; email: pisinchen@phys.ntu.edu.tw, misao.sasaki@ipmu.jp, innocent.yeom@gmail.com, junggiyoon@gmail.com

Abstract – The information loss paradox remains unresolved ever since Hawking's seminal discovery of black hole evaporation. In this essay, we revisit the entanglement entropy via Euclidean path integral (EPI) and allow for the branching of semi-classical histories during the Lorentzian evolution. We posit that there exist two histories that contribute to EPI, where one is information-losing that dominates at early times, while the other is information-preserving that dominates at late times. By so doing we recover the Page curve and preserve the unitarity, albeit with the Page time shifted significantly towards the late time. One implication is that the entropy bound may thus be violated. We compare our approach with string-based islands and replica wormholes concepts.

11. **Dark Matter or Strong Gravity?** by Saurya Das[1] and Sourav Sur[2], [1]Theoretical Physics Group, Department of Physics and Astronomy, University of Lethbridge, 4401 University Drive, Lethbridge, Alberta T1K 3M4, Canada, [2]Department of Physics and Astrophysics, University of Delhi, New Delhi 110007, India; email: saurya.das@uleth.ca, sourav.sur@gmail.com

Abstract – We show that Newton's gravitational potential, augmented by a logarithmic term, partly or wholly mitigates the need for dark matter. As a bonus, it also explains why MOND seems to work at galactic scales. We speculate on the origin of such a potential.

12. **A Quantum Mechanical Model for the Big Bang and Inflation** by Arthur E. Fischer, Department of Mathematics, University of California, Santa Cruz, CA 95064; email: aef@ucsc.edu

Abstract – We construct a *parameterized* quantum mechanical model for the big bang and inflation which utilizes exact solutions to a quantized version of Friedmann's equation. The resulting Friedmann-Schrödinger equation is based on a non-Hermitian Hamiltonian which is quantized using a method of von Neumann. In the resulting model, the universe exhibits a semi-stable pre-big-bang epoch, followed by the big bang, an inflation interval, and a post-inflation epoch. The big bang is triggered when the parameter of the model reaches a critical value, at which point the last bound state of the pre-big-bang epoch explodes into scattering states which in turn coalesce during the inflation interval into a wave packet that emerges at the beginning of the post-inflation epoch as the *wave packet of the universe*.

13. **Schrodinger's Black Hole Cat** by Joshua Foo[1], Robert B. Mann[2][3], and Magdalena Zych[4], [1]Centre for Quantum Computation & Communication Technology, School of Mathematics & Physics, The University of Queensland, St. Lucia, Queensland, 4072, Australia, [2]Department of Physics and Astronomy, University of Waterloo, Waterloo, Ontario N2L 3G1, Canada, [3]Perimeter Institute for Theoretical Physics, Waterloo, Ontario N2L 6B9, Canada, [4]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, m.zych@uq.edu.au

Abstract –In the absence of a fully-fledged theory of quantum gravity, we propose a "bottom-up" framework for exploring quantum-gravitational physics by pairing two of the most fundamental concepts of quantum theory and general relativity, namely quantum superposition and spacetime. We show how to describe such "spacetime superpositions" and explore effects they induce upon quantum matter. Our approach capitalises on standard tools of quantum field theory in curved space, and allows us to calculate physical observables like transition probabilities for a particle detector residing in curvature-superposed de Sitter spacetime, or outside a mass-superposed black hole. Crucially, such scenarios represent genuine quantum superpositions of spacetimes, in contrast with superpositions of metrics which only differ by a coordinate transformation and thus are not different according to general relativity.

14. **The Cosmic Web Crystal: Ising Model for Large Scale Structures** by Leonardo Giani and Tamara Maree Davis, School of Mathematics and Physics, The University of Queensland, Brisbane, QLD 4072, Australia; email: uqlgiani@uq.edu.au, tamarad@physics.uq.edu.au

Abstract – If Dark Matter halos possess the gravitational equivalent of an intrinsic magnetic spin, a formal analogy exists between the low redshift behaviour of the Cosmic Web in a flat FLRW background, and a crystal of spins submerged in a thermal reservoir with temperature $T \propto H(t)$. We argue that, within the use of the Bianchi type IX geometry to describe the gravitational collapse of matter inhomogeneities, the spins are nothing but the heritage of its underlying $SU(2)$ symmetry. Therefore, just like electrons in quantum mechanics, these structures may have spin independently from their orbital angular momentum. We explore the phenomenological implications on cosmological scales of a possible late time phase transition of the Cosmic Web towards (the gravitational equivalent of) a ferromagnetic state, described qualitatively using the Ising model in the mean field approximation.

15. **Gravitational Entanglement and the Mass Contribution of Internal Energy in Nonrelativistic Quantum Systems** by André Großardt, Friedrich Schiller University Jena, Institute for Theoretical Physics, Fröbelstieg 1, 07743 Jena, Germany; email: andre.grossardt@uni-jena.de

Abstract – Recently, interest has increased in the entanglement of remote quantum particles through the Newtonian gravitational interaction, both from a fundamental perspective and as a test case for the quantization of gravity. Likewise, post-Newtonian gravitational effects in composite nonrelativistic quantum systems have been discussed, where the internal energy contributes to the mass, promoting the mass to a Hilbert space operator. Employing a modified version of a previously considered thought experiment, it can be shown that both concepts, when combined, result in inconsistencies, reinforcing the arguments for the necessity of a rigorous derivation of the nonrelativistic limit of gravitating quantum matter from first principles..

16. **Relieving String Tension by Making Baby Universes in a Dynamical String Tension Braneworld Model** by Eduardo I. Guendelman[1][2][3] and Zeeya Merali[4], [1]Department of Physics, Ben-Gurion University of the Negev, Beer-Sheva, Israel, [2]Frankfurt Institute for Advanced Studies, Giersch Science Center, Campus Riedberg, Frankfurt am Main, Germany, [3]Bahamas Advanced Studies Institute and Conferences, 4A Ocean Heights, Hill View Circle, Stella Maris, Long Island, The Bahamas, [4]Foundational Questions Institute (FQXi), PO Box 3055, Decatur, GA 30031; email: guendel@bgu.ac.il, merali@fqxi.org

Abstract – String tension fundamentally determines the properties of strings; yet its value is often assigned arbitrarily, creating a fine-tuning problem. We describe a mechanism for dynamically generating string tension in a flat or almost flat spacetime, using the 'modified measures formalism,' which in turn naturally generates a new type of stringy brane-world scenario. Such a scenario allows strings to achieve near infinite tension confining the strings to two very close expanding surfaces, but the infinite tension also threatens to distort the near-flat embedding spacetime through large back reactions. We argue that this danger can be neutralised via the creation of a baby universe—a growing region of embedding spacetime that divorces from the ambient embedding spacetime, while our universe is still a brane separating two nearly flat spacetimes. The avoidance of a minimum length and a maximum Hagedorn temperature in the context of dynamical string tension generation are also discussed.

17. **Are there Echoes of Gravitational Waves?** by Bin Guo[1] and Samir D. Mathur[2], [1]Institut de Physique Théorique, Université Paris-Saclay, CNRS, CEA, Orme des Merisiers, Gif-sur-Yvette, 91191 CEDEX, France, [2]Department of Physics, The Ohio State University, Columbus, OH 43210; email: bin.guo@ipht.fr, mathur.16@osu.edu

Abstract – In several approaches to evading the information paradox, the semiclassical black hole is replaced by an Exotic Compact Object (ECO). It has been conjectured that gravitational waves emitted by the merger of ECOs can reflect off the ECOs and produce a detectable 'echo'. We argue that while a part of the wave can indeed reflect off the surface of an ECO, this reflected wave will get trapped by a *new* closed trapped surface produced by its own backreaction. Thus no detectable signal of the echo will emerge to infinity. The only assumption in this analysis is that causality is maintained to leading order in gently curved spacetime. Thus if echoes are actually detected, then we would face a profound change in our understanding of physics.

18. **On the Classicality of Bosonic Stars** by Carlos A. R. Herdeiro and Eugen Radu, Departamento de Matemática da Universidade de Aveiro and Center for Research and Development in Mathematics and Applications (CIDMA), Campus de Santiago, 3810-183 Aveiro, Portugal; email: herdeiro@ua.pt, eugen.radu@ua.pt

Abstract – Because the Klein-Gordon and Proca equations involve $\hbar$, they describe quantum fields. Their solutions, however, may be treated as classical if their typical action obeys $S^{\text{typical}} \gg \hbar$. This is possible due to their bosonic nature, allowing states with many particles. We show, by generic arguments, that the typical action for such bosonic stars is $S^{\text{typical}}/\hbar \gtrsim (M^{\max}/M_{\text{Pl}})^2 \sim 10^{76}\,(M^{\max}/M_{\odot})^2$, where $M^{\max}$ is the maximal bosonic star mass of the particular model and M_{Pl} is the Planck mass. Thus, for models allowing $M^{\max} \gg M_{\text{Pl}}$ and for solutions with mass $\sim M^{\max}$, the classical treatment is legitimate, which includes masses in the astrophysical interesting range $\gtrsim M_{\odot}$.

19. **Wigner Meets 't Hooft Near the Black Hole Horizon** by Clifford V. Johnson, Department of Physics, Princeton University, Princeton, NJ 08544-0708, and Department of Physics and Astronomy, University of Southern California, Los Angeles, CA 90089-0484; email: cvj@princeton.edu

Abstract – Recent work on Euclidean quantum gravity, black hole thermodynamics, and the holographic principle has seen the return of random matrix models as a powerful tool. It is explained how they allow for the study of the physics well beyond the perturbative expansion. In fact, a fully non-perturbative treatment naturally unites the familiar approach of summing over smooth geometries of all topologies with the statistical approach to characterizing the typical properties of a Hamiltonian. Remarkably, this leads to an explicit excavation of the underlying microstates of quantum gravity that has applications to the low temperature dynamics of a large class of black holes.

20. **From Maximum Force to the Field Equations of General Relativity – and Implications** by Arun Kenath[1], Christoph Schiller[2], C. Sivaram[3], [1]CHRIST (deemed to be University), Bangalore, India, [2]Motion Mountain Research, Munich, Germany, [3]Indian Institute of Astrophysics, Bangalore, India; email: kenath.arun@christuniversity.in, cs@motionmountain.net, sivaram@iiap.res.in

Abstract – There are at least two ways to deduce Einstein's field equations from the principle of maximum force $c^4/4G$ or from the equivalent principle of maximum power $c^5/4G$. Tests in gravitational wave astronomy, cosmology, and numerical gravitation confirm the two principles. Apparent paradoxes about the limits can all be resolved. Several related bounds arise. The limits illuminate the beauty, consistency and simplicity of general relativity from an unusual perspective.

21. **Gravitational Fields and Quantum Mechanics** by R. B. MacKenzie[1], Victor Massart[1], M. B. Paranjape[1][2][3], Gordon Semenoff[3], and U. A. Yajnik[4], [1]Groupe de physique des particules, Département de physique, Université de Montréal, C.P. 6128, succ. centre-ville, Montréal, Québec, Canada, H3C 3J7, [2]Centre de recherche mathématiques, Université de Montréal, C.P. 6128, succ. centre-ville, Montréal, Québec, Canada, H3C 3J7, [3]Department of Physics and Astronomy, University of British Columbia, 6224 Agricultural Road, Vancouver, BC, Canada, V6T 1Z1, [4]Department of Physics, Indian Institute of Technology Bombay, Powai, Mumbaï - 400076; email: paranj@lps.umontreal.ca, richard.mackenzie@umontreal.ca, massart.victor@live.be, gordonws@phas.ubc.ca, yajnik@iitb.ac.in

Abstract – Massive particles in spatially non-local, quantum mechanical wave functions should have interesting gravitational fields. Should their gravitational fields be classical? What aspects of their gravitational fields are observable? We study these questions using quantum field theory to gravitationally probe the wave functions of such quantum mechanical states. We find that the observable signals seem to indicate that it is very difficult to phenomenologically observe the quantum mechanical, spatially nonlocal superposition.

22. **Computing Spacetime** by Juan F. Pedraza[1], Andrea Russo[2], Andrew Svesko[2], and Zachary Weller-Davies[3], [1]Instituto de Física Teórica UAM/CSIC, Madrid, 28049, Spain, [2]Department of Physics and Astronomy, University College London, London, WC1E 6BT, UK, [3]Perimeter Institute for Theoretical Physics, Waterloo, Ontario N2L 2Y5, Canada; email: j.pedraza@csic.es, andrea.russo.19@ucl.ac.uk, a.svesko@ucl.ac.uk, zwellerdavies@pitp.ca

Abstract – Inspired by the universality of computation, we advocate for a principle of *spacetime complexity*, where gravity arises as a consequence of spacetime optimizing the computational cost of its own quantum dynamics. This principle is explicitly realized in the context of the Anti-de Sitter/Conformal Field Theory correspondence, where complexity is naturally understood in terms of state preparation via Euclidean path integrals, and Einstein's equations emerge from the laws of quantum complexity. We visualize spacetime complexity using Lorentzian threads which, conceptually, represent the operations needed to prepare a quantum state in a tensor network discretizing spacetime. Thus, spacetime itself evolves via optimized computation.

23. **Space, Time and Heat** by Joseph Samuel, International Centre for Theoretical Sciences, Bangalore, India 560089, and Raman Research Institute, Bangalore, India 560080; email: sam@icts.res.in, sam@rri.res.in

Abstract – The local conservation law for energy in classical general relativity is subtle and has been extensively discussed. We propose a new physical interpretation for this law which naturally brings out a thermodynamic flavour of general relativity theory. Given a reference system, we are able to rewrite the local conservation law so that it separates into "work" and "heat" terms. This gives a striking geometric interpretation for "heat" in general relativity. The interpretation offered here assumes direct physical reality once quantum effects are considered. The ideas proposed here have implications at the intersection of gravity, thermodynamics and quantum theory.

24. **Why Do Elementary Particles Have Such Strange Mass Ratios? - The Importance of Quantum Gravity at Low Energies** by Tejinder P. Singh, Tata Institute of Fundamental Research, Homi Bhabha Road, Mumbai 400005, India; email: tpsingh@tifr.res.in

Abstract – When gravity is quantum, the point structure of space-time should be replaced by a non-commutative coordinate geometry. This is true even for quantum gravity in the infra-red. Using the octonions as space-time coordinates, we construct a pre-spacetime, pre-quantum Lagrangian dynamics. We show that the symmetries of this non-commutative space unify the standard model of particle physics with $SU(2)_R$ chiral gravity. The algebra of the octonionic space yields spinor states which can be identified with three generations of quarks and leptons. The geometry of the space implies quantisation of electric charge, and leads to a theoretical derivation of the mysterious mass ratios of quarks and the charged leptons. Quantum gravity is quantisation not only of the gravitational field, but also of the point structure of space-time.

25. **Holographic Reconstruction of Asymptotically Flat Spacetimes** by Erickson Tjoa[1][2] and Finnian Gray[1][3], [1]Department of Physics and Astronomy, University of Waterloo, Waterloo, Ontario, N2L 3G1, Canada, [2]Institute for Quantum Computing, University of Waterloo, Waterloo, Ontario, N2L 3G1, Canada, [3]Perimeter Institute for Theoretical Physics, Waterloo, Ontario N2L 2Y5, Canada; email: e2tjoa@uwaterloo.ca, fgray@perimeterinstitute.ca

Abstract – We present a "holographic" reconstruction of bulk spacetime geometry using correlation functions of a massless field living at the "future boundary" of the spacetime, namely future null infinity $\mathscr{I}^+$. It is holographic in the sense that there exists a one-to-one correspondence between correlation functions of a massless field in four-dimensional spacetime M and those of another massless field living in three-dimensional null boundary $\mathscr{I}^+$. The idea is to first reconstruct the bulk metric $g_{\mu\nu}$ by "inverting" the bulk correlation functions and re-express the latter in terms of boundary correlators via the correspondence. This effectively allows asymptotic observers close to $\mathscr{I}^+$ to reconstruct the deep interior of the spacetime using only correlation functions localized near $\mathscr{I}^+$.

26. **Gravity of the Cosmic Scale Conducts the Nano-Spintronics of Spiralling Electrons** by C. S. Unnikrishnan, Tata Institute of Fundamental Research, Homi Bhabha Road, Mumbai - 400 005, India; email: unni@tifr.res.in

Abstract – Starting from a simple proof of the primary relevance of the motion-induced cosmic gravitational potentials in the Hamiltonian of the microscopic quantum dynamics of particles, I tackle the long-standing enigma of spin-selective transport in chirally shaped organic molecules. I establish that the gravitational interaction of the spiralling electrons with the vast amounts of the matter-energy in the Universe, is behind a new gravitational spin-orbit phenomena, which fully explains the spin selectivity observed with molecules like DNA or Cysteine. A wide avenue of nano-spintronics is opened by this finding about relativistic gravity.

27. **Geometry of Entanglement Applied to Black Holes** by Juan Urrutia, Institut de Fisica d'Altes Energies (IFAE), The Barcelona Institute of Science and Technology, Campus UAB, 08193 Bellaterra (Barcelona), Spain; email: jurrutia@ifae.es

Abstract –We show how S^3 and S^7 Hopf fibrations correctly describe the geometrical properties of single and product state qubit measurements. Since the Schwarzschild Black Hole horizon is described by S^2 , in the same way that a Bloch Sphere is, we find a map from spacetime to vectors in Hilbert space such that the horizon of the Black Hole is a realization of the S^3 Hopf fibration. Applying the S^7 Hopf fibration to the extended Schwarzschild solution, we show that entangled states of the horizons could be interpreted as describing the shared interior of the two Black Holes. From this interpretation it follows that the throat of the wormhole is a measure of the entanglement entropy of the horizon states.

28. **Black Hole Entropy and Long Strings** by Erik Verlinde[1] and Manus Visser[2], [1]Institute for Theoretical Physics, University of Amsterdam, 1090 GL Amsterdam, The Netherlands, [2]Department of Theoretical Physics, University of Geneva, 24 quai Ernest-Ansermet, 1211 Genève 4, Switzerland; email: e.p.verlinde@uva.nl, manus.visser@unige.ch

Abstract – We discuss whether black hole entropy counts short or long range microstates in quantum gravity. In brick wall and induced gravity models the entropy arises due to short distance correlations across the event horizon cut off at the Planck length. However, the energy of these short range degrees of freedom is too high compared to the black hole energy. We argue that the long string phenomenon, which naturally appears in matrix quantum mechanics, resolves this issue by lowering the excitation energy per degree of freedom. This mechanism also reduces the total number of microscopic degrees of freedom in a given volume, leading to a correct estimate of the Bekenstein-Hawking formula for black hole entropy.

29. **Milne's Kinematic Relativity: A Late-Universe Miracle** by Ram Gopal Vishwakarma, Unidad Académica de Matemáticas, Universidad Autónoma de Zacatecas, C.P. 98068, Zacatecas, ZAC, Mexico; email: vishwa@uaz.edu.mx

Abstract – Milne's kinematic relativity is a simple and highly successful cosmological theory, which explains observations without having recourse to the dark sectors of the standard cosmology. It solves Hubble tension and also averts the lingering cosmological puzzles of the standard cosmology. The theory is generally portrayed as representing an unphysical universe, which is though not correct. The misunderstanding arises as one tries to present the Milne model as a particular case of the Friedmann models of general relativity (GR). However, Milne's theory is pointedly independent of GR. By analyzing the remarkable features of Milne's model, one gains some novel insights which help formulate a simple theory of gravity. The resulting theory, based on a Ricci-flat geometry, embraces all the successes of Einstein's theory and Milne's model.

30. **Is Space-Time Really Doomed?** by Peter Woit, Department of Mathematics, Columbia University, New York, NY 10027; email: woit@math.columbia.edu

Abstract – For many years now it has become conventional for theorists to argue that "space-time is doomed", with the difficulties in finding a quantum theory of gravity implying the necessity of basing a fundamental theory on something quite different than usual notions of space-time geometry. But what is this space-time geometry that is doomed? In this essay we'll explore how our understanding of four-dimensional geometry has evolved since Einstein, leading to new ideas about such geometry which may not be doomed at all.

31. **Lensing Effects in Galactic Retarded Gravity: Why "Dark Matter" is the Same for Both Gravitational Lensing and Rotation Curves** by Asher Yahalom, Ariel University, Ariel 40700, Israel; email: asya@ariel.ac.il

Abstract – Galaxies are huge physical systems having a generic size of tens of thousands of parsecs. Thus any modification at the center of the galaxy will affect the outskirts only tens of millennia afterwards. Those retardation considerations seem to be neglected in present day analysis used to estimated rotational velocities of matter in the rim of the galaxy and its surrounding gas. 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 usually referred to as "dark matter" or by modifying the laws of gravity (MOND as a typical example). Here we demonstrate that considering general relativistic effects one can explain the apparent excess matter leading to gravitational lensing in both galaxies and galaxy clusters. We also explain why the amount of "dark matter" must be the same for both rotational curves and gravitational lensing.