Gravity Research Foundation

PO BOX 81389
WELLESLEY HILLS MA 02481-0004
USA

Roger W. Babson
FOUNDER

George M. Rideout, Jr.
President

Abstracts of Award Winning and Honorable Mention Essays for 2025

Award Essays

First Award – **Probing Quantum Structure in Gravitational Radiation** by Sreenath K. Manikandan, Nordita, Stockholm University and KTH Royal Institute of Technology, Stockholm, Sweden; email: sreenath.k.manikandan@su.se and Frank Wilczek, Center for Theoretical Physics, Massachusetts Institute of Technology, Cambridge, MA 02139, USA; T. D. Lee Institute and Wilczek Quantum Center, Shanghai 200240, China; Arizona State University, Tempe, AZ 85287, USA; Stockholm University, Stockholm, Sweden; email: wilczek@mit.edu.

Abstract – Gravitational radiation from known astrophysical sources is conventionally treated classically. This treatment corresponds, implicitly, to the hypothesis that a particular class of quantum-mechanical states - the so-called coherent states - adequately describe the gravitational radiation field. We propose practicable, quantitative tests of that hypothesis using resonant bar detectors monitored in coincidence with LIGO-style interferometers. Our tests readily distinguish fields that contain significant thermal components or squeezing. We identify concrete circumstances in which the classical (i.e., coherent state) hypothesis is likely to fail. Such failures are of fundamental interest, in that addressing them requires us to treat the gravitational field quantum- mechanically, and they open a new window into the dynamics of gravitational wave sources.

Second Award – **It Costs Nothing to Teleport Information into a Black Hole** by Jonah Kudler-Flam, School of Natural Sciences, Institute for Advanced Study, Princeton, NJ 08540; Princeton Center for Theoretical Science, Princeton University, Princeton, NJ 08544; email: jkudlerflam@ias.edu and Geoff Pennington, Center for Theoretical Physics and Department of Physics, University of California, Berkeley, CA 94720; email: geoffp@berkeley.edu.

Abstract – It is often claimed that adding a qubit to a black hole requires energy $\Delta E \geq T_H \log 2$ so that the extra Bekenstein-Hawking entropy can accommodate the qubit. In this essay, we explain how the recently discovered phenomenon of black hole decoherence allows quantum information to be teleported into a black hole, with arbitrarily small energy cost. The generalized second law is not violated and there is no conflict with unitarity because the teleportation creates new entanglement, analogous to Hawking radiation, between the black hole interior and exterior. In accordance with Landauer's principle, a nonzero minimum energy cost only appears when there is a net erasure of information and noise from the exterior or, equivalently, when "zerobits" are sent into the black hole.

Third Award – **The Persistence of Non-Linear Gravitational Wave Memory** by Robert R. Caldwell, Department of Physics and Astronomy, Dartmouth College, Hanover, NH 03755; email: robert.r.caldwell@dartmouth.edu.

Abstract – Nonlinear gravitational wave memory is a surprise of theoretical physics. Whereas it is understood that a gravitational wave induces oscillatory squeezing and stretching motion in a collection of freely-falling test masses, it is unexpected that the wave leaves a residual displacement of the test masses. This displacement is the tribute *in memoriam* to the passing wave. The memory originates in a nonlinear feature of gravitation. Whilst merging black holes are a significant source of gravitational waves, the gravitational wave energy itself is a further source of gravitational waves. The memory is often described as a permanent displacement of the test masses caused by a burst of primary gravitational waves. But as we show, memory vanishes at late times in a sea of echoes.

Fourth Award – **Quantum Optics in Curved Spacetime: Surprises and Insights** by Marlan O. Scully[1,2,3]; email: scully@tamu.edu, Anatoly A. Svidzinsky[1]: email: asvid@physics.tamu.edu, and William Unruh[1,4]; email: unruh@physics.ubc.ca, [1]Texas A&M University, College Station, TX 77843; [2]Princeton University, Princeton, NJ 08544; [3]Baylor University, Waco, TX 76798; [4]University of British Columbia, Vancouver, BC, Canada V6T 1Z1

Abstract – The marriage of quantum optics and general relativity has produced interesting and even surprising results in recent times.

Fifth Award – **Space Cannot Stretch Too *Fast*** by Samir D. Mathur, Department of Physics, The Ohio State University, Columbus, OH 43210, USA; email: Mathur.16@osu.edu.

Abstract – We argue that black holes microstates leave an imprint on the gravitational vacuum through their virtual fluctuations. This imprint yields a power law fall off – rather than an exponential fall off – for the entanglement of Planck scale fluctuations at different points. These entanglements generate an extra energy when space stretches too *fast*, since causality prevents a relaxation of these entanglements to their vacuum values. We obtain semiclassical dynamics for slow processes like star formation, but a radical departure from semi classicality when a black hole horizon forms even though curvatures remain low everywhere. This resolution of the information puzzle also implies an extra energy source at the scale of the cosmological horizon, which may explain the mysteries of dark energy and the Hubble tension.

Honorable Mention Awards **(Alphabetical Order)**

1. **On the temperature of a rotating black hole** by Ronald J. Adler, Gravity Probe B Mission (retired), Stanford University, Stanford CA 94035; Department of Physics and Astronomy (retired), San Francisco State University, San Francisco CA 94132; email: gyroron@gmail.com

Abstract – Hawking's classic calculation of the nonzero temperature of a black hole (BH) has been of much continuing interest to both theorists and observers. The consequent expected explosive evaporations of small BHs would be of great interest, but has not yet been observed. In this work we derive the temperature of a rotating Kerr BH in agreement with previous standard analyses, but using only the ideas of classical general relativity and thermodynamics, without reference to quantum field theory or quantum gravity. Our purpose is largely pedagogical but the possibility that the cosmological dark matter may be composed of primordial BHs makes it of some research interest.

2. **Hidden Sector Dark Matter from a Z_2 Double of the Visible Universe with Positive Higgs Potential Quadratic Term** by Stephen L. Alder, Institute for Advanced Study, 1 Einstein Drive, Princeton, NJ 08540, email: adler@ias.edu

Abstract – We propose that the universe contains two sectors with identical sets of particles and gauge interactions, coupling through gravitation, which differ by a Z_2 reflection in the sign of the quadratic term in their Higgs potentials. In the visible sector the quadratic term in the Higgs potential has the negative sign of the Standard Model, giving a "Mexican hat" Higgs potential and a vacuum with spontaneous symmetry breaking and a nonvanishing Higgs vacuum expectation. In the dark sector, the quadratic term in the Higgs potential has the normal positive sign, giving a monotonic Higgs potential with a symmetric vacuum and vanishing dark Higgs vacuum expectation. Existing studies of "Higgless" theories then suggest that the least massive baryon in the dark sector will be a candidate for a self- interacting WIMP-like dark matter particle.

3. **Loopy Black-Hole Remnants** by Asier Alonso-Bardaji, Aix Marseille Univ., Univ. de Toulon, CNRS, CPT, UMR 7332, 13288 Marseille, France; email: asier.alonso@ehu.eus

Abstract – The quantized area predicted by loop quantum gravity suggests the existence of a lower bound for black-hole horizons. We prove this intuition within a covariant effective model for spherical loop quantum gravity, where nonsingular quasi- static black holes evaporate until their horizons attain the smallest positive eigenvalue of the area operator. Consistent with the third law of black-hole thermodynamics, this final state—characterized by vanishing temperature and entropy—cannot be realized in finite time. The process thus leads to the formation of stable remnants, whose estimated masses are approximately 20.94µg, lying in the Planck regime.

4. **Black Hole Thermodynamics Probes the Equivalence Principle** by Ana Alonso-Serrano, Institut für Physik, Humboldt-Universität zu Berlin, Zum Großen Windkanal 6, 12489 Berlin, Germany and Max-Planck-Institut für Gravitationsphysik (Albert-Einstein-Institut), Am Mühlenberg 1, 14476 Potsdam, Germany, email: ana.alonso.serrano@aei.mpg.de ; Luis J. Garay, Departamento de Física Teórica and IPARCOS, Universidad Complutense de Madrid, 28040 Madrid, Spain, email: luisj.garay@ucm.es; Marek Liška, School of Theoretical Physics, Dublin Institute for Advanced Studies, 10 Burlington Road, Dublin 4, Ireland; email: liskama4@stp.dias.ie

Abstract – The equivalence principle for testing gravitational physics strongly constrains dynamics of spacetime, providing a powerful criterion for selecting candidate theories of gravity. However, checking its validity for a particular theory is often a very difficult task. We devise here a simple theoretical criterion for identifying equivalence principle violations in black hole thermodynamics. Employing this criterion, we prove that Lanczos-Lovelock gravity violates the strong equivalence principle, leaving general relativity as the only local, diffeomorphism-invariant theory compatible with it. However, we also show that certain nonlocal expressions for black hole entropy appear to obey the strong equivalence principle.

5. **Do Holographic CFT States have Unique Semiclassical Bulk Duals?** by Stefano Antonini, email: santonini@berkeley.edu and Pratik Rath, email: pratik_rath@berkeley.edu, Center for Theoretical Physics and Department of Physics, University of California, Berkeley, CA 94720,

Abstract – We discuss a situation where a holographic CFT state has multiple semiclassical bulk duals. In our example, a given holographic state has two simple, semiclassical descriptions, one with a closed universe, constructed using the gravitational path integral, and one without a closed universe, constructed using the extrapolate dictionary. This highlights an ambiguity in the AdS/CFT dictionary. We propose various options for resolving this tension although none are perfectly satisfactory. We also discuss what this implies for the black hole interior and the gravitational path integral.

6. **Graviton Scattering on Gravitational Atoms: Relic Graviton Shot Noise** by Benjamin Avila-Lopez[1,2],email: benjamin.avila@usach.cl, Richard MacKenzie[2,3], email: richard.mackenzie@umontreal.ca, Fernando Mendez[1], email: feritox@gmail.com and M. B. Paranjape[2,3,4,5], email: paranj@lps.umontreal.ca, [1]Departamento de Física, Universidad de Santiago de Chile, Avenida Ecuador 3493, Estacion Central, Santiago, Chile 9170124, [2]Groupe de physique des particules, Département de physique, [3]Institut Courtois, [4]Centre de recherche mathématiques, Université de Montréal, C.P. 6128, succ. centreville, Montréal, Québec, Canada, H3C 3J7 and [5]Department of Physics, University of Auckland, Auckland, New Zealand

Abstract – We study the scattering of a graviton on a gravitational atom. By gravitational atom we mean a quantum mechanical system of a gravitational (bound) state of two massive particles, with possibly some boundary conditions (such as bouncing on a table or hanging as a pendulum). We demonstrate the unexpected fact that the total absorption cross section is universal, it is independent of both the mass of the gravitationally bound particle or of the mass providing the binding potential. We find that the total absorption cross-section is simply proportional to the Planck area, multiplied by a dimensionless, numerical factor. We speculate about the potential for detection of relic gravitons shot noise.

7. **Why is the Number of States in Theories of Quantum Gravity given by the Area of a Black Hole?** by Vijay Balasubramanian, Department of Physics and Astronomy, University of Pennsylvania, Philadelphia, PA 19104, Theoretische Natuurkunde, Vrije Universiteit Brussel and International Solvay Institutes, Pleinlaan 2, B-1050 Brussels, Belgium and Rudolf Peierls Centre for Theoretical Physics, University of Oxford, Oxford OX1 3PU, UK, email: vijay@physics.upenn.edu and Tom Yildirim, Department of Physics, Keble Road, University of Oxford, Oxford, OX1 3RH, UK, email: tom.yildirim@physics.ox,ac,uk

Abstract – States in a theory of quantum gravity can be defined by cutting the Euclidean gravitational path integral. We show that the thermal partition function obtained by tracing over an orthonormal basis of such states is identical to the Gibbons-Hawking prescription. The equality between these *a-priori* different gravitational path integrals is made manifest by insertions of a resolution of the identity. This result shows that the Gibbons-Hawking path integral is indeed summing over the states of the gravity theory. As this argument holds for any theory of quantum gravity with a path integral prescription, this explains the universality of the Beckenstein-Hawking entropy. While states in this basis do not need to correspond to black holes, we explain why the Beckenstein-Hawking entropy can still be thought of as counting black hole microstates.

8. **The Hydrodynamic Approach to Quantum Gravity** by Tom Banks, NHETC and Department of Physics, Rutgers University, Piscataway, NJ 08854-8019, e-mail: tibanks@ucsc.edu

Abstract – Several papers from the mid to late 1990s suggest that Einstein's equations should be thought of as the hydrodynamic equations of a special class of quantum systems. A classical solution defines subsystems by dividing space-time up into ***causal diamonds*** and Einstein's equations are the hydrodynamics of a system that assigns density matrices to each diamond with the property
$K_\Diamond = < K_\Diamond - < K_\Diamond >^2 > = A_\Diamond / 4G_N$
These define the ***empty diamond state***, the analog of the quantum field theory vacuum, in the background geometry. The assignment of density matrices to each diamond enables one to define the analog of half sided modular flow along geodesics in the background manifold, as a unitary embedding of the Hilbert space of a given diamond into the next one in a nesting with Planck scale time steps. We conjecture that this can be enhanced to a full set of compatible unitary evolutions on a Hilbert bundle over the space of time-like geodesics, using a ***Quantum Principle of Relativity*** defined in the text. The compatibility of this formalism with the experimental success of quantum field theory (QFT) is discussed, as well as the theoretical limits in which QFT emerges.

9. **Black Hole Complementarity and ER/EPR** by Ning Bao, Department of Physics, Northeastern University, Boston, MA 02115, Computational Science Initiative, Brookhaven National Laboratory, Upton, NY 11973, email: ningbao75@gmail.com, and Grant N. Remmen, Center for Cosmology and Particle Physics, Department of Physics, New York University, New York, NY 10003, email: grant.remmen@nyu.edu

Abstract – We demonstrate that wormholes must be entangled regardless of asymptotic boundary conditions. Assuming black hole complementarity, we argue that traversable wormholes instantiate entanglement-assisted quantum channels and that this entanglement must be present between the stretched horizons as an initial condition prior to traversability. This result demonstrates the forward direction of the ER/EPR conjectures.

10. **Physical Limits on Information Metrics and Quantum Gravity as Gravitized Quantum Theory** by Per Berglund[1], email: per.berglund@unh.edu, Andrew Geraci[2], email: andrew.geraci@northwestern.edu, Tristan Hübsch[3], email: thubsch@howard.edu, David Mattingly[1] , email: david.mattingly@unh.edu and Djordje Minic[4], email: dminic@vt.edu, [1]Department of Physics and Astronomy, University of New Hampshire, Durham, NH, [2]Department of Physics and Astronomy, Northwestern University, Evanston, IL, [3]Department of Physics and Astronomy, Howard University, Washington, DC, [4]Department of Physics, Virginia Tech, Blacksburg, VA

Abstract – There is a long history in both general relativity and quantum mechanics of removing fixed background structures, thereby making observed objects and measurement processes dynamical. We continue this evolution

by combining central insights from both theories to argue that physical limits on information collection resulting from quantum gravity coupled with general covariance preclude the fixed information geometry still assumed in both information theory and quantum mechanics. As a consequence there must be a gravitized, generally covariant extension of both theories. We also propose a novel experimental test involving intrinsic triple and higher order quantum interferences that would provide evidence for dynamical information metrics and a dynamical Born rule.

11. **Cosmological Mirror Symmetry and Gravitational-Wave Helicity** by Juan Calderón Bustillo, Instituto Galego de Física de Altas Enerxías, Universidade de Santiago de Compostela, 15782 Santiago de Compostela, Galicia, Spain, Department of Physics, The Chinese University of Hong Kong, Shatin, N.T., Hong Kong, email: juan.calderon.bustillo@usc.es, Adrian del Rio, Departamento de Matemáticas, Universidad Carlos III de Madrid. Avda. de la Universidad 30, 28911 Leganés, Spain , email: adrdelri@math.uc3m.es, Samson H. W. Leong, Department of Physics, The Chinese University of Hong Kong, Shatin, N.T., Hong Kong, email: samson32081@gmail.com and Nicolas Sanchis-Gua, Departamento de Astronomía y Astrofísica, Universitat de Valéncia. Dr. Moliner 50, 46100, Burjassot (València), Spain, email: nicolas.sanchis@uv.es

Abstract – Our current understanding of the Universe relies on the hypothesis that, when observed at sufficiently large scales, it looks statistically identical regardless of location or direction of observation. Consequently, the Universe should exhibit mirror-reflection symmetry. In this essay, we show that gravitational-wave astronomy provides a unique, observer-independent test of this hypothesis. In particular, we analyze the average circular polarization emitted by an ensemble of binary black hole mergers detected by LIGO-Virgo, which we compute using a novel geometric and chiral observable in general relativity. We discuss current results and future prospects with upcoming detections and technical advancements. Moreover, we show that this circular polarization and the helicity of the remnant black hole are linearly correlated, drawing a conceptual parallel with Wu experiment in particle physics.

12. **Signature Change as Phase Transition in Holography** by Marcelo Botta Cantcheff, Instituto de Física La Plata - CONICET and Departamento de Física, Universidad Nacional de La Plata C.C. 67, 1900, La Plata, Argentina, email: botta@fisica.unlp.edu.ar

Abstract – In holographic quantum gravity, Euclidean pieces of the spacetime appear in the large N limit as representing semi-classical states of the theory. In this essay, we argue that the duals of entangled states are spacetime geometries that contain Euclidean regions in order to preserve classical connectivity. Thereby, the proposal is to extend the ER-EPR conjecture to regimes whether worm- holes (Einstein-Rosen bridges) become unstable but the entangled structure of the dual state persists.

13. **Wormholes: Myth or Reality? Prospects for Future Observations** by Subenoy Chakraborty, Department of Mathematics, Brainware University, Kolkata 700125, West Bengal, India; Shinawatra University, Thailand; INTI International University, Malaysia, email: schakraborty.math@gmail.com and Madhukrishna Chakraborty, Department of Mathematics, Techno India University, Kolkata 700091, West Bengal, India, email: chakmadhu1997@gmail.com

Abstract – Traversable wormholes (TWHs) remain one of the most intriguing predictions of General Relativity (GR), offering passage through space-time. However, their existence re- quires the violation of the null energy

condition, making their detection a bit challenging. The essay aims at showing the new avenues probing the observational prospects of TWHs via quasinormal modes and grey body factors, the two fundamental aspects in wave dynamics. The role of QNMs in characterizing the ringdown phase of perturbations and the grey body factors in determining transmission probabilities through wormhole barriers has been investigated. Given their distinct spectral imprints, these features provide a potential means to distinguish wormholes from black holes in gravity wave observations. Advances in high-precision interferometry and multi-messenger astronomy may soon offer crucial insights into the existence of these exotic structures.

14. **Signatures of Asymmetry: Gravitational Wave Memory and the Parity Violation** by Indranil Chakraborty, email: indranil.phy@iitb.ac.in, Susmita Jana, email: susmitajana@iitb.ac.in and S. Shankaranarayanan, email: shanki@iitb.ac.in, Department of Physics, Indian Institute of Technology Bombay, Mumbai 00076, India

Abstract – Einstein's equivalence principle suggests a deep connection between matter and space- time, prompting the question: *if matter violates parity, must gravity?* This essay explores the detection of parity violation in gravity using gravitational wave (GW) memory. Gravitational parity violation could be observable through GW amplitude birefringence and large- scale structure correlations. With improved sensitivity, next-generation GW detectors offer unprecedented opportunities to probe these effects. We propose that the integrated cosmological memory (ICM) of GWs, amplified over cosmological distances, can enhance faint parity-violating signatures. Specifically, if GWs from astrophysical events have differing polarization amplitudes, as in Chern-Simons gravity, ICM significantly amplifies this disparity. ICM *uniquely and independently* allows us to test fundamental symmetries, constrain gravity parameters, and gain insights into the interplay of particle physics, cosmology and gravity.

15. **Stochastic Origin of Primordial Fluctuations in the Sky** by Sayantan Choudhury, Institute of Theoretical Physics, Faculty of Physics, University of Warsaw, ul. Pasteura 5, 02-093 Warsaw, Poland, email: sayanphysicsisi@gmail.com

Abstract – We provide a study of the effects of the Effective Field Theory (EFT) generalization of stochastic inflation on the production of primordial black holes (PBHs) in a model- independent single-field context. We demonstrate how the scalar perturbations' Infra-Red (IR) contributions and the emerging Fokker-Planck equation driving the probability distribution characterize the Langevin equations for the "soft" modes in the quasi-de Sitter background. Both the classical-drift and quantum-diffusion- dominated regimes undergo a specific analysis of the distribution function using the stochastic-δN formalism, which helps us to evade a *no-go theorem* on the PBH mass. Using the EFT-induced alterations, we evaluate the local non-Gaussian parameters in the drift-dominated limit.

16. **Universality of Black Hole Thermodynamics Beyond the Thermal Approximation** by Christian Corda, SUNY Polytechnic Institute, Utica, NY 13502, email: cordac.galilei@gmail.com and Carlo Cafaro, University at Albany – SUNY, Albany, NY 12222, email: ccafaro@albany.edu

Abstract – Mathur and Mehta were awarded the third prize in the 2023 Gravity Research Foun- dation Essay Competition for their work demonstrating the universality of black hole (BH) thermodynamics. Their research established that any Extremely Compact Object (ECO) exhibits the same thermodynamic properties as a BH, irrespective of the presence of an event horizon. This significant finding was derived under the assumption that the BH emission spectrum behaves thermally. However, compelling arguments rooted in energy conservation and the BH back reaction indicate that the spectrum of Hawking radiation cannot be perfectly thermal. In this Essay, we explore the extension of Mathur and Mehta's findings to scenarios where the radiation spectrum deviates from exact thermal behavior, utilizing the concept of the BH dynamical state.

17. **Relativistic Virial Theorem, Limiting Compactness, and the End State of Gravitational Collapse** by Naresh Dadhich, Inter-University Centre for Astronomy & Astrophysics, Post Bag 4, Pune, 411 007, India and Astrophysics Research Centre, School of Mathematics, Statistics and Computer Science, University of KwaZulu-Natal, Private Bag X54001, Durban 4000, South Africa, email: nkd@iucaa.in

Abstract – It is noteworthy that limiting compactness of a static bounded configuration is characterized by a general principle: *one, by equipartition of mass between inside and outside, and the other by vanishing of energy inside.* The former implies gravitational energy being half of mass leading to limiting compactness $M/R = 4/9$ of Buchdahl star while for the latter, the two are equal giving $M/R = 1/2$ of black hole with horizon. *This is the relativistic Virial theorem respectively for massive and massless particles.* It is remarkable that it prescribes that there can exist only two equilibrium states which also define limiting compactness of the object. Consequently, it leads to a profound prediction that the ultimate end product of gravitational collapse could only be one of the two, Buchdahl star or black hole.

18. **Memories from the Distant Past: Non-Linear Effect due to Gravitational Waves in an Expanding Universe** by Shiladittya Debnath, Université Paris Sciences et Lettres, France, email: sd.debnath157@gmail.com

Abstract – In this essay, we investigate the gravitational wave memory effect in expanding universes, specifically in de Sitter and ΛCDM spacetime and envisage their observational implications. We employ conformal compactification to define asymptotic structures in expanding spacetimes. We apply the Bondi-Sachs formalism to derive modified mass-loss formulas. We also apply perturbative expansions within the Einstein-fluid equations for matter coupling in ΛCDM models. Importantly, we observe that cosmic expansion amplifies gravitational wave memory, with a modified Bondi mass-loss formula incorporating a redshift-dependent factor enhancing energy flux. These effects suggest detectable memory signals from high-redshift sources.

19. **Distorted Black Holes: Nonextensivity in the Gravitational Wave Emission** by H. P. de Oliveira, 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, email: henrique.oliveira@uerj.br

Abstract – We investigate the interaction between a non-rotating black hole and incoming gravitational waves using the characteristic formulation of the Einstein field equations, framed as a Bondi problem. By adopting retarded time as the null coordinate and recognizing that the final state is invariably a black hole, we show that an apparent horizon forms once sufficient mass accretes onto the black hole. We derive the evolution of the Bondi mass and compute its final value, enabling us to quantify the fraction of the incident mass absorbed by the black hole. Additionally, we establish a nonextensive relation for the absorbed mass as a function of initial parameters, such as the amplitude of the gravitational wave data.

20. **Primordial Black Hole Driven Cosmi Acceleration** by Konstantinos Dialektopoulos, Department of Mathematics and Computer Science, Transilvania University of Brasov, 500091, Brasov, Romania, email: kdialekt@gmail.com, Theodoros Papanikolaou, Scuola Superiore Meridionale, Largo San Marcellino 10, 80138 Napoli, Italy, email: t.papanikolaou@ssmeridionale.it, Vasilios Zarikas, Department of Mathematics, University of Thessaly, 35100, Lamia, Greece, email: vzarikas@uth.gr

Abstract – We propose a natural mechanism for cosmic acceleration driven by primordial black holes (PBHs) with repulsive behavior, within a "Swiss Cheese" cosmological framework. Considering regular black hole spacetimes such as Hayward, Bardeen, and Dymnikova, as well as the singular Schwarzschild–de Sitter case, we consistently find a robust PBH-driven acceleration phase. This phase ends either at an energy scale set by the PBH parameters or through evaporation. Notably, ultra-light PBHs with $m < 5 \times 10^{8}$ g, can trigger exponential inflation with graceful exit and reheating. Additionally, PBHs with $m \approx 10^{12}$ g, and abundances $0.107 < \Omega_{PBH}^{eq} < 0.5$ near matter-radiation equality can contribute early dark energy, offering a potential resolution to the Hubble tension.

21. **Predictions of Stochastic Composite Gravity** by Joshua Erlich, Department of Physics, William & Mary, P. O. Box 8795, Williamsburg, VA 23187-8795

Abstract – In this essay I describe some new results of a framework for composite gravity coupled to matter. These include the Bekenstein-Hawking entropy formula, modifications to the low-£ moments of the CMB power spectrum, and new perspectives on the Hartle-Hawking no-boundary proposal and the initial conditions for inflation. We conclude with suggestions for experimental tests of the framework.

22. **Quantum Gravity Cannot be Both Consistent and Complete** by Mir Faizal[1, 2, 3, 4], email: mirfaizalmir@gmail.com, Lawrence M. Krauss[5], email: larence@originsproject.org, Arshid Shabir[2] ,email: aslone186@gmail.com, Francesco Marino[6], email: francesco.marino@ino.cnr.it, and Behnam Pourhassan[7], email: b.pourhassan@du.ac.ir, [1] Irving K. Barber School of Arts and Sciences, University of British Columbia - Okanagan, Kelowna, British Columbia V1V 1V7, Canada, [2] Canadian Quantum Research Center, 204-3002 32 Ave, Vernon, BC V1T 2L7, Canada, [3] Department of Mathematical Sciences, Durham University, Upper Mountjoy, Stockton Road, Durham DH1 3LE, UK, [4] Faculty of Sciences, Hasselt University, Agoralaan Gebouw D, Diepenbeek, 3590, Belgium, [5] Origin Project Foundation, Phoenix, AZ 85018, USA, [6] CNR-Instituto Nazionale di Ottica and INFN, Via Sansone 1, I-50019 Sesto Fiorentino (FI), Italy. [7] School of Physics, Damghan University, Damghan 3671645667, Iran.

Abstract – General relativity, despite its profound successes, fails as a complete theory due to the presence of singularities. While it is widely believed that quantum gravity has the potential to be a complete theory, in which spacetime consistently emerges from quantum degrees of freedom through computational algorithms, we demonstrate that this goal is fundamentally unattainable. Gödel's theorems establish that no theory based on computational algorithms can be both complete and consistent, while Tarski's undefinability theorem demonstrates that even within quantum gravity, or any computational framework, a fully consistent internal determination of true propositions is impossible. Chaitin's incompleteness theorem further reinforces this conclusion, revealing intrinsic limits to any computational theory. We discuss some possible consequences for descriptions of physical systems and note that a non-algorithmic approach is essential for any theory of everything.

23. **Quantum Censors: Backreaction Builds Horizons** by Antonia M. Frassino[1,2,3], email: afrassin@sissa.it, Robie A. Hennigar[4], email: robie.a.hennigar@durham.ac.uk, Juan F. Pedraza[5] , email: j.pedraza@csic.es and Andrew Svesko[6], email: andrew.svesko@kcl.ac.uk, [1]SISSA & INFN Sezione di Trieste, 34136 & 34127 Trieste, Italy, [2]Departamento de Física y Matemáticas, Universidad de Alcalá, Alcalá de Henares, 28805 Madrid, Spain, [3]Institut de Ciències del Cosmos, Universitat de Barcelona, 08028 Barcelona, Spain, [4]Centre for Particle Theory, Department of Mathematical Sciences, Durham University, Durham DH1 3LE, UK, [5]Instituto de Física Teórica UAM/CSIC, Cantoblanco, 28049 Madrid, Spain, [6]Department of Mathematics, King's College London, Strand, London, WC2R 2LS, UK

Abstract – Cosmic censorship posits spacetime singularities remain concealed behind event horizons, preserving the determinism of General Relativity. While quantum gravity is expected to resolve singularities, we argue that cosmic censorship remains necessary whenever spacetime has a reliable semi-classical description. Using holography to construct exact solutions to semi-classical gravity, we show backreaction of quantum matter generates horizons — quantum censors— to thwart potential violations of censorship. Along with a quantum Penrose inequality, this provides compelling evidence that cosmic censorship is robust, even nonperturbatively, in semi-classical gravity.

24. **Can Dynamical String Tension Theories with Target Space Scale Invariance Explain Four Dimensions?** by Eduardo Guendelman, Department of Physics, Ben-Gurion University of the Negev, Beer-Sheva, Israel, Frankfurt Institute for Advanced Studies (FIAS), Ruth-Moufang-Strasse 1, 60438 Frankfurt am Main, Germany, Bahamas Advanced Study Institute and Conferences, 4A Ocean Heights, Hill View Circle, Stella Maris, Long Island, The Bahamas, email: guendel@bgu.ac.il

Abstract – The string tensions can be dynamical, as we have studied in recent publications, for example in the case when we formulate string theories in the modified measure formalism. Then string and brane tensions appears, but as an additional dynamical degree of freedom. It can be seen however that these string or brane tensions may not be universal, but rather each string and each brane generates its own tension, which can have a different value for each string or brane. The case where there are strings that can have different spontaneously generated tensions has been considered in previous publication. To have a real dynamical string tension, we consider new background fields that can couple to the strings, the tension scalar which is capable of changing locally along the world sheet the value of the tension of the extended object. When all string tensions are equal, there is now an unbroken Target space scale invariance. By considering possible effective actions of gravity and strings as matter in D dimensions, we determine D by requiring that the effective action be, as the fundamental theory, target space scale invariant, which singles out D=4.

25. **Measuring the Black Hole Interior from the Exterior** by Wu-zhong Guo, School of Physics, Huazhong University of Science and Technology, Luoyu Road 1037, Wuhan, Hubei 430074, China, email: wuzhong@hust.edu.cn

Abstract – In this essay, we argue that an observer outside the horizon can reconstruct the geometry of a black hole's interior through external measurements. This procedure builds on recent studies of the holographic duality of time like entanglement entropy and its connection to spacelike entanglement entropy. Furthermore, we propose that this phenomenon reveals a fundamental correlation between the degrees of freedom inside and outside the black hole at the level of classical spacetime.

26. **Removing Gravity from the Firewall Paradox** by Ladina Hausmann, email: hladina@ethz.ch and Renato Renner, email: renner@ethz.ch, Institute for Theoretical Physics, ETH Zürich, 8093, Switzerland

Abstract – The firewall paradox is often taken as evidence that widely accepted assumptions from quantum gravity about black holes are contradictory. We propose another possibility: the paradox may instead stem from a fundamental limitation of quantum theory — its inability to consistently handle multiple observers. Our argument hinges on the observation that the firewall paradox relies on an additional, previously overlooked, assumption about how different observers' perspectives are combined. Remarkably, as demonstrated by a non-gravitational thought experiment in quantum foundations, this assumption alone contradicts quantum theory.

27. **The Problem of Time and Its Quantum Resolution** by Marc S. Klinger, email: marck3@illinois.edu and Robert G. Leigh, email: rgleigh@illinois.edu, Illinois Center for Advanced Studies of the Universe and Department of Physics, University of Illinois, 1110 West Green St., Urbana, IL 61801

Abstract – In this essay, we argue that the problem of time should not be regarded as an issue to be resolved within the prevailing framework for studying quantum gravity, but rather as an indication that there is an issue within the framework itself. We suggest a possible resolution inspired by the observation that the quantization of gravity on null hypersurfaces leads to an anomaly, in that the constraint algebra is projectively represented in the quantum theory. We describe how accommodating these anomalies forces the theory to replace the standard interpretation of canonical time evolution with a fully quantum, diffeomorphism invariant notion of time. The full theory admits states that can be interpreted as emergent geometric spacetime regions which we refer to as quantum diamonds.

28. **Extreme Compactness, Extreme Gravity: Higher-Derivative Corrections to ECOs** by Madhur Mehta, Department of Physics, The Ohio State University, Columbus, OH 43210, email: mehta.493@osu.edu

Abstract – Higher-derivative gravity theories offer insights into the behavior of extremely compact objects (ECOs). Focusing on Gauss-Bonnet (GB) and Einstein-dilaton-Gauss-Bonnet (EdGB) gravity, we derive the compactness scale in these models and demonstrate how higher-curvature corrections lead to deviations from the standard ECO compactness scale. The corrections are of order α/r_0^2 in EGB gravity and α^2/r_0^4 in EdGB gravity, where α is the coupling constant and r_0 is the horizon radius corresponding to the mass of the ECO. Observational constraints suggest these effects could be significant in certain astrophysical systems, providing a new perspective on the nature of extremely compact objects in models of modified gravity.

29. **Echoes of Love Beyond the Horizon: A Bridge to Recovering Information from Black Holes** by Meysam Motaharfar, email: mmotah4@lsu.edu and Parampreet Singh, email: psingh@lsu.edu, Department of Physics and Astronomy, Baton Rouge, LA 70803

Abstract – We provide further evidence that information is preserved during black hole evaporation and may be recoverable, provided quantum gravitational effects resolve the singularity. We demonstrate that due to quantum gravity effects, black holes acquire quantum hair, manifested by non-zero tidal Love numbers, revealing a distinct internal structure similar to neutron stars. Interestingly, the magnitude of these Love numbers is Planck-scale suppressed, implying significant tidal deformation in the late stage of evaporation. Depending on the final state of the black hole, information may be retrieved through correlations in Hawking radiation, baby universes, or via remnants.

30. **Holographic Quantum Foam: From Theory to Observations** by Y. Jack Ng, Institute of Field Physics, Department of Physics and Astronomy, University of North Carolina, Chapel Hill, NC 27599-3255, email: yjng@physics.unc.edu and Eric Steinbring, National Research Council Canada, Herzberg Astronomy & Astrophysics, 5017 West Saanich Rd., Victoria, BC, V9E 2E7, Canada, email: eric.steinbring@nrc-cnrc.gc.ca

Abstract – Spacetime is foamy: it undergoes quantum fluctuations, with distance uncertainty scaling as the cube root of distances, consistent with the holographic principle - hence the name "holographic quantum foam" (HQF). HQF, in conjunction with thermodynamics, naturally demands the existence of a dark sector, the quanta of which obey infinite statistics. Applied to the cosmos, HQF yields a cosmology with critical energy density and a dynamical cosmological constant, as well as a phenomenologically viable dark matter sector. An early cosmic acceleration can also be traced to HQF. Most importantly, it is verified by observations of gamma-ray burst GRB 221009A: the brightest ever seen in the optical/near-infrared through to X-rays; even at 251 TeV. That is possible only for HQF if accounting for how real telescopes see foam.

31. **Experimental Witness for General Relativistic Effects in Quantum Mechanics** by Luciano Petruzziello, email: luciano.petruzziello@uni-ulm.de, Trinidad B. Lantaño Pinto, email: trinidad.lantano-pinto@uni-ulm.edu, Susana F. Huelga, email: susana.huelga@uni-ulm.de, Martin B. Plenio, email: martin.plenio@uni-ulm.de, Institut für Theoretische Physik & IQST, Universität Ulm, Germany

Abstract – Over the past two decades, both experimental and theoretical research have suggested the possibility of observing non-classical gravitational effects by detecting gravitationally induced quantum correlations. Most existing proposals focus on center-of-mass interactions in mesoscopic systems within the Newtonian regime. In this essay, we explore a different approach by examining the gravitational inter- action of angular momentum eigenstates in the post-Newtonian limit. This offers a novel way to test general relativistic phenomena in a low-energy quantum mechanical setting. We also discuss the potential advantages and challenges of this approach compared to other existing schemes.

32. **Graviton Creation by the Dynamical Casimir Effect in Inspiraling Neutron Star Systems** by Fabrizio Pinto, Izmir University of Economics; Ekospace Center and Department of Aerospace Engineering, Faculty of Engineering, Teleferik Mahallesi, Sakarya Cd. No:156, 35330, Balçova, İzmir, Türkiye, email: fabrizio.pinto@ieu.edu.tr

Abstract – It is shown that the exceedingly dense interiors of neutron stars can act as moving gravitational wave-reflecting boundaries in an optical cavity. The orbital motion of the mergers causes a gravitational dynamical Casimir effect, with consequent creation of gravity quanta from the vacuum and parametric amplification of the graviton flux. The challenges and limitations of the model are discussed, along with realistic observation and detection strategies.

33. **Exotic Encounters: Buchdahl's Conditions and Physical Black Holes** by Ioannis Soranidis, email: ioannis.soranidis@mq.edu.au and Daniel R. Terno, email: daniel.terno@mq.edu.au, School of Mathematical and Physical Sciences, Macquarie University, Sydney, New South Wales, 2109, Australia

Abstract – Black holes are among the most well-known astrophysical objects, yet their physical realization remains conceptually subtle. We analyze physical black holes — light-trapping regions that form in finite time as seen by a distant observer — and investigate the proper- ties of the matter required to support them. Taking Buchdahl's theorem as a benchmark, we show that these configurations necessarily violate at least two of its four original conditions, and the post-formation state violates them all. These violations are substantial: they include the null energy condition, non-monotonic energy profiles, and strong pressure anisotropies. Thus, the requirement of truly forming a horizon places physical black holes in a class of solutions that are more exotic than exotic compact objects.

34. **General Relativity, Early Galaxy Formation and the JWST Observations** by Christos G. Tsagas, Section of Astrophysics, Astronomy and Mechanics, Department of Physics Aristotle University of Thessaloniki, Thessaloniki 54124, Greece; Clare Hall, University of Cambridge, Herschel Road, Cambridge CB3 9AL, UK, email: tsagas@astro.auth.gr

Abstract – The James Webb Space Telescope has recently detected massive, fully formed, galaxies at redshifts corresponding to few hundred million years after the Big-Bang. However, our current cosmological model cannot produce such massive systems so early in the lifetime of the universe. A number of theoretical solutions have been proposed, but they all appeal to exotic new physics and introduce rather excessive fine-tuning. In this essay, we outline a theoretical answer to the early galaxy- formation question, which operates within standard general relativity and standard cosmology, without appealing to any new physics. Instead, we account for the effect of a well-established feature of our universe. This feature, which has so far been kept in the margins of mainstream cosmology, are the peculiar velocities.

35. **Entanglement and Local Holography in Quantum Gravity** by Gabiel Wong, Oxford Math Institute, Radcliffe Observatory, Andrew Wiles Building, Woodstock Rd., Oxford OX2 5GG, UK, email: gabrielwon@gmail.com

Abstract – The It from Qubit paradigm proposes that gravitational spacetimes emerge from quantum entanglement. So far, the main evidence for this involves holographic dualities, where the entangled qubits live in a dual nongravitational theory. In this essay, we argue that string theory provides the mechanism to define these entangled qubits in the bulk gravitating theory. This involves a local form of geometric transition, which is the stringy mechanism that underlies *local* holography. We illustrate how this works in the A model topological string,