Research in Theoretical High Energy Physics

Final Report on DOE Grant Number:DE-FG02-06ER41418 (7/1/09 - 4/30/13)

Project Title: Phenomenology, Field Theory, String Theory, and Astrophysics/Cosmology

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Project Title of Task A: Theoretical Research in String Theory at UNC
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DOE Grant Number: DE-FG02-06ER41418
Final Report
July 24, 2013

Specific Past Accomplishments 2009-2013

My work in this grant period was on several subjects. It includes a set of papers I wrote with Peter Goddard which culminated in a constructive proof that the gluon tree amplitudes of twistor string theory are equivalent to those of the four-dimensional $\mathcal{N} = 4$ Yang-Mills gauge theory. Our papers computed the link variable representation for the twistor string, which made it possible to calculate the string amplitudes more completely than elsewhere and yield explicit answers. These were precise telling calculations for any N of the gauge group $SU(N)$, and they should facilitate a direct approach to the problem of finding a worldsheet formulation of Yang-Mills loop amplitudes, which no one has yet achieved despite activity by many in the field. I also calculated the Yangian invariance of the twistor string. This supports an equivalence of this string with gauge theory, since earlier I had found the Yangian symmetry of four-dimensional $\mathcal{N} = 4$ planar superconformal gauge theory with Chiara Nappi and Edward Witten, finalizing a pursuit to uncover a new, infinite-dimensional symmetry algebra of Yang-Mills that I began in 1981. On another topic, I made a comparison of partition functions for the fivebrane and for the five-dimensional Maxwell theory, testing an abelian version of the conjectured equivalence of these two quantum theories. I showed it to be true only in the a weak coupling limit, thus suggesting an ultraviolet completion rather than an equivalence.. The fivebrane theory with 16 supercharges is conformal and finite and has no known Lagrangian, but reduces to conventional gauge theories in lower dimensions. It is believed to be responsible for the duality symmetry of $\mathcal{N} = 4$ super Yang-Mills theory, and to provide the defining structure for four-dimensional gauge theory as M-theory does for gravitational theories. Its preferred status comes from the fact that six is the maximum number of dimensions for an anomaly-free *supersymmetric conformal* field theory to exist. A representation of it is given by the dynamics of M-theory fivebranes, which have a 6d world volume. The fundamental excitations on a single fivebrane couple to a chiral two-form potential $B_{\mu\nu}$ whose three-form field strength is self-dual, and responsible for the absence of a covariant Lagrangian. Hence we computed a partition function of this field. It is believed the non-abelian quantum theory probably has no classical description and cannot be described in terms of fields. The non-abelian six-dimensional theory is hard to formulate, but compactification of it on a circle was conjectured in the literature to be equivalent to five-dimensional maximally supersymmetric Yang-Mills theory. Another paper computed conformal supergravity amplitudes from the twistor string formulation.

1. "Partition Functions for Maxwell Theory on the Five-torus and for the Fivebrane on $S^1 \times T^5$", arXiv:1208.5971 [hep-th], L. Dolan, Y. Sun.

We computed the partition function of five-dimensional abelian gauge theory on a twisted five-torus T^5 using the Dirac method of quantizing with constraints, and compared it with that of a single fivebrane compactified on S^1 times T^5, where the radius R_1 of the circle S^1 is set to the dimensionful gauge coupling constant $g_5^2 = R_1$. We proved the $SL(5, Z)$ invariance of both partition functions, and showed they were equivalent only in the limit of weak gauge coupling.

2. "Complete Equivalence Between Gluon Tree Amplitudes in Twistor String Theory and in Gauge Theory", JHEP **1206**, 030 (2012); arXiv:1111.0950 [hep-th], L. Dolan, P. Goddard.

The gluon tree amplitudes of open twistor string theory, defined rigorously as precise contour integrals over link variables, are proved to satisfy the BCFW relations, demonstrating their complete equivalence with those of gauge theory. In this approach, the integration contours are specified as encircling the zeros of certain constraint functions that force the appropriate relation between the link variables and the twistor string world-sheet variables. To do this, methods for calculating the tree amplitudes using link variables are developed further including diagrammatic methods for organizing and performing the calculations.

3. "General Split Helicity Gluon Tree Amplitudes in Open Twistor String Theory," JHEP **1005**, 044 (2010);arXiv:1002.4852 [hep-th], L. Dolan, P. Goddard.

We evaluate all split helicity gluon tree amplitudes in open twistor string theory explicitly, and show they agree with those of gauge theory. To do this we make a particular choice of the sextic constraints in the link variables that determine the poles contributing to the contour integral expression for the amplitudes. Using the residue theorem to re-express this integral in terms of contributions from poles at rational values of the link variables, which we determine, we evaluate the amplitudes explicitly. Split helicity amplitudes are those which have one set of adjacent negative helicity particles followd by a set of adjacent positive helicities. It turned out these amplitudes provided the crucial set which we could then generalize to achieve the general result in paper #2 above.

4. "Gluon Tree Amplitudes in Open Twistor String Theory," JHEP **0912**, 032 (2009); arXiv:0909.0499 [hep-th], L. Dolan, P. Goddard.

We show how the link variables of Arkani-Hamed, Cachazo, Cheung and Kaplan (ACCK), which they used in gauge field theory, can be used to compute general gluon tree amplitudes of the twistor string. They arise from instanton sectors labelled by d, with d=n-1, where n is the number of negative helicities. In particular, we show how the various forms for field theory tree amplitudes studied by ACCK can be grouped into contour integrals whose structure reveals an underlying worldsheet string theory.

5. "Current Algebra on the Torus," Commun. Math. Phys. **285**, 219 (2009), arXiv:0710.3743 [hep-th], L. Dolan and P. Goddard

We derive the N-point one-loop correlation functions for the currents of an arbitrary affine Kac-Moody algebra. The one-loop amplitudes, which are elliptic functions defined on the torus Riemann surface, are specified by group invariant tensors and certain constant tau-dependent functions. We compute the elliptic functions via a generating function, and explicitly construct the invariant tensor functions recursively in terms of Young tableaux. The lowest tensors are related to the character formula of the representation of the affine algebra. These general current algebra loop amplitudes provide a building block for open twistor string theory, among other applications.

6."Yangian in the Twistor String," JHEP **1010**, 076 (2010); arXiv:1002.4852 [hep-th], J. Corn, T. Creutzig, L. Dolan.

In addition to global PSL(4|4) symmetry, we find non-local charges forming the Yangian extension that lead to Ward identities, and show how these charges annihilate the string gluon tree amplitudes. We thus show these charges have the same form as symmetries of amplitudes in N=4 super conformal Yang Mills theory. We describe how states of the open twistor string form a realization of the PSL(4—4) Yangian superalgebra.

7. "Conformal Supergravity Tree Amplitudes", Nucl. Phys. **B819** (2009) 375; arXiv: 0811.1341 [hep-th], L Dolan, J. Ihry.

We computed three-point couplings of states in the conformal supergravity sector of the twistor string. These include 'dipole' states, which are pairs of supergravitons that do not diagonalize the translation generators.

As of April 2013, Louise Dolan has 3502 citations for publications listed at SLAC: http://inspirehep.net/search?ln=en&p=a+dolan%2C+l&action_search=Search

Individual Contributions of post-doc and graduate students:

Thomas Creutzig (postdoc)

1. T. Creutzig, "The FZZ Duality with Boundary", JHEP **1109**, 004 (2011); arXiv:1012.4731.

2. T. Creutzig, "Yangian Superalgebras in Conformal Field Theory," Nucl. Phys. **B849**, 636-653 (2011); arXiv:1011.6424 hep-th.

3. T. Creutzig and Y. Hikida, "Branes in the $OSP(1|2)$ WZNW model," Nucl. Phys. **B842**, 172-224 (2011); arXiv:1004.1977 hep-th.

4. T. Creutzig and P. B. Ronne, "From world-sheet supersymmetry to super target spaces," JHEP **1011**, 021 (2010) arXiv:1006.5874 [hep-th].

Yang Sun (current graduate student)

Yang Sun, "Partition Functions for Maxwell Theory on the Five-torus and for the Fivebrane on $S^1 \times T^5$," arXiv:1208.5971 hep-th.

John Corn (Master's degree, UNC 2012)

J. Corn, T. Creutzig and L. Dolan, "Yangian in the Twistor String," JHEP **1010**, 076 (2010); arXiv:1002.4852 [hep-th].

Jay Ihry (Ph.D, UNC 2009)

L. Dolan, J. Ihry, "Conformal Supergravity Tree Amplitudes", Nucl. Phys. **B819** (2009) 375; arXiv: 0811.1341 [hep-th].

Talks: L. Dolan gave invited seminars on 4/2/09 at Supersymmetry, Branes and M-Theory, the Michael Duff 60th Birthday fest, at Imperial College, London, U.K., http://plato.tp.ph.ic.ac.uk/conferences/duff-fest; on 6/18/09 at the CERN theory seminar, Geneva; on 11/4/09 at the IAS, Princeton; on 6/19/09 at Brown University; on 7/7/11 at the Physics-Mathematics Summer Institute, IES, Cargese, Corsica. She was on the International Advisory Committee for Strings 2011, Uppsala, Sweden; session chair at Strings 2010 at Texas A&M; attended Strings 2009 in Rome, Italy and Strings 2012 in Munich, Germany. She was an invited participant at the workshops " Nonperturbative Effects and Dualities in QFT and Integrable Systems" Program, KITP, Santa Barbara, CA 7/28-8/17/11; and the IAS/PI Workshop on Integrability in Scattering Amplitudes, IAS, 3/11-12,2011. On NSF Math-Physics panel, February 2011. She was on leave at the IAS, Princeton 9/1/11-8/30/12. On 3/29/13, she gave an invited seminar to the High Energy Theory group at the Michigan Center for Theoretical Physics, University of Michigan, Ann Arbor.

In March 2012, L. Dolan was offered the position of Deputy Director of the Simons Center in Stony Brook, but she decided to return to UNC to maintain full time research.

Video Capture Archive of Duke/UNC String Theory Seminar:

Task A holds a joint string seminar with the group of superstring theorists including Ronen Plesser and Paul Aspinwall, in the Center for Geometry and Physics at Duke University. String theory seminar speakers at UNC in the recent project period included Maria Rodriguez (Harvard), Jan Manshot (Saclay, France), Peng Gao (Stony Brook), Jacob Bourjaily (Princeton University), Jerome Dubail (Yale), Alejandra Castro (McGill University), Miranda Cheng (Harvard), Daniel Roggenkamp (Rutgers), Ari Pakman (Brown). There were fewer talks in 2011-2012 because L. Dolan was on leave in Princeton. Seminar list: http://www.physics.unc.edu/string

This task has been a separate task or grant since shortly after L. Dolan joined UNC as a full professor in 1990, coming from Rockefeller University. It is dedicated to the construction and exploration of the fundamental forces at the deepest level. Task A currently has two graduate students, Arada Malakian and Yang Sun, with partial DOE support for one student. The postdoc Thomas Creutzig (2009-2011) was partially supported by DOE funds; he then took up a six-year position at the University of Darmstadt in Germany. Jay Ihry received his Ph.D. at UNC in 2009. He took a job at Metron, Inc. in Arlington, VA. John Corn received a UNC Master's degree in 2012 and transferred to graduate school in mathematics at the University of Pittsburg.

Here in the Southeast our task forms a coherent unit, and we have close interactions with Lev Rozansky and Ivan Cherednik in UNC mathematical physics, as well as with the string theorists Ronen Plesser and Paul Aspinwall at Duke, and with Jack Ng and Laura Mersini on this grant. The postdoc is a core part of our research effort, one of our highest priorities is providing informal discussion and encounters for the students and seminar speakers, to wit this task has had an accomplished set of fully funded string theory DOE research associates, including Ralph Bluhmenhagen now permanent faculty at Max-Planck Institute in Munich, Bjorn Andreas now at Freie University in Berlin, and Katrin Wendland now a professor at Freiburg University in Germany.

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List of papers

1. "Partition Functions for Maxwell Theory on the Five-torus and for the Fivebrane on $S^1 \times T^5$", arXiv:1208.5971 [hep-th], L. Dolan, Y. Sun.

2. "Complete Equivalence Between Gluon Tree Amplitudes in Twistor String Theory and in Gauge Theory", JHEP **1206**, 030 (2012); arXiv:1111.0950 [hep-th], L. Dolan, P. Goddard.

3. "General Split Helicity Gluon Tree Amplitudes in Open Twistor String Theory," JHEP **1005**, 044 (2010);arXiv:1002.4852 [hep-th], L. Dolan, P. Goddard.

4. "Gluon Tree Amplitudes in Open Twistor String Theory," JHEP **0912**, 032 (2009); arXiv:0909.0499 [hep-th], L. Dolan, P. Goddard.

5. "Current Algebra on the Torus," Commun. Math. Phys. **285**, 219 (2009), arXiv:0710.3743 [hep-th], L. Dolan and P. Goddard

6. "Yangian in the Twistor String," JHEP **1010**, 076 (2010); arXiv:1002.4852 [hep-th], J. Corn, T. Creutzig, L. Dolan.

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Thomas Creutzig (postdoc)

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PI of Task B: Paul H. Frampton
Project Title: Phenomenology, Field Theory and Astrophysics/Cosmology
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DOE Grant Number: DE-FG02-06ER41418, Task B, 7/1/09 - 4/30/13
Final Report (prepared by Y.J. Ng as requested by program monitor), July 24, 2013
Note that P.H. Frampton left for Argentina in January 2012.

List of papers (and abstracts)[titles of papers, authors and arXiv numbers (in brackets), followed by abstracts]

Papers not involving graduate students (D. Eby and K. Ludwick):

1. LHC Higgs Production and Decay in the T' Model, Paul H. Frampton, Chiu Man Ho, Thomas W. Kephart, and Shinya Matsuzaki (1009.0307)
At $\sqrt{s} = 7$ TeV, the standard model needs at least $10\,(fb)^{-1}$ integrated luminosity at LHC to make a definitive discovery of the Higgs boson. Using binary tetrahedral ($T^{'}$) discrete flavor symmetry, we discuss how the decay of the lightest T' Higgs into $\gamma\,\gamma$ can be effectively enhanced and dominate over its decay into $b\,\bar{b}$. Since the two-photon final state allows for a clean reconstruction, a decisive Higgs discovery may be possible at 7 TeV with the integrated luminosity only of $\sim 1\,(fb)^{-1}$.

2. Holographic Principle and the Surface of Last Scatter, Paul H. Frampton (1005.2294)
Using data, provided by WMAP7, I calculate the entropy of the visible universe, where visible refers to electromagnetic radiation, and hence the visible universe is bounded by the Surface of Last Scatter. The dimensionless entropy, S/k, is (8.85 ± 0.37) times larger than allowed by a simplified and non-covariant version of the holographic principle, that the entropy cannot exceed that of a black hole. The measurement of a shift parameter, introduced by Bond, Efstathiou and Tegmark in 1997, plays an important role in the accuracy of the calculation, which leads to the large discrepancy.

3. Probing Variant Axion Models at LHC, Chuan-Ren Chen, Paul H. Frampton, Fuminobu Takahashi, and Tsutomu T. Yanagida (1005.1185)
We study collider implications of variant axion models which naturally avoid the cosmological domain wall problem. We find that in such models the branching ratio of $h \to \gamma\gamma$ can be enhanced by a factor of 5 up to 30 as compared with the standard model prediction. The $h \to \gamma\gamma$ process is therefore a promising channel to discover a light Higgs boson at the LHC and to probe the Peccei-Quinn charge assignment of the standard model fields from Yukawa interactions.

4. Hunting for New Physics with Unitarity Boomerangs, Paul H. Frampton and Xiao-Gang He (1004.3679)
Although the unitarity triangles (UTs) carry information about the Kobayashi-Maskawa (KM) quark mixing matrix, it explicitly contains just three parameters which is one short to completely fix the KM matrix. It has been shown recently, by us, that the unitarity boomerangs (UB) formed using two UTs, with a common inner angle, can completely determine the KM matrix and, therefore, better represents, quark mixing. Here, we study detailed properties of the UBs, of which there are a total 18 possible. Among them, there is only one which does not involve very small angles and is the ideal one for practical uses. Although the UBs have different areas, there is an invariant quantity, for all UBs, which is equal to a quarter of the Jarlskog parameter J squared. Hunting new physics, with a unitarity boomerang, can reveal more information, than just using a unitarity triangle.

5. Possible Solution of Dark Matter, The Solution of DArk Energy and Gell-Mann as Great Theoretician, Paul H. Frampton (1004.1910)
This talk discusses the formation of primordial intermediate-mass black holes, in a double-inflationary theory, of sufficient abundance possibly to provide all of the cosmological dark matter. There follows my, hopefully convincing, explanation of the dark energy problem, based on the observation that the visible universe is well approximated by a black hole. Finally, I discuss that Gell-Mann is among the five greatest theoreticians of the twentieth century.

6. Considerations of Cosmic Acceleration, Paul H. Frampton (1004.1285)
I discuss a solution to the dark energy problem, which arises when the visible universe is approximated by a black hole, in a quasi-static asymptotically-flat approximation. Using data, provided by WMAP7, I calculate the Schwarzschild radius r_S and compare to the measured physical radius of the visible universe, bounded by the surface of last scatter. The ratio, $\epsilon(t_0) = r/r_S$ is found to be comparable to $\epsilon = 1$, as allowed by the holographic principle. The measurement of a shift parameter, σ, introduced by Bond, Efstathiou and Tegmark in 1997, plays an important role in the accuracy of the calculation. The approximation leads to a surprisingly small discrepancy, presumably explicable by the de Sitter, and expanding, nature of the actual universe.

7. Black Holes Constitute All Dark Matter, Paul H. Frampton (1003.3356)
The dimensionless entropy , $\mathcal{S} \equiv S/k$, of the visible universe, taken as a sphere of radius 50 billion light years with the Earth at its "center", is discussed. An upper limit (10^{112}), and a lower limit (10^{102}), for $\mathcal{S}$ are introduced. It is suggested that intermediate-mass black holes (IMBHs) constitute all dark matter, and that they dominate $\mathcal{S}$.

8. Entropic Inflation, Damien A. Easson, Paul H. Frampton, and George F. Smoot (1003.1528)
One of the major pillars of modern cosmology theory is a period of accelerating expansion in the early universe. This accelerating expansion, or inflation, must be sustained for at least 30 e–foldings. One mechanism used to drive the acceleration is the addition of a new energy field, called the Inflaton; often this is a scalar field. We propose an alternative mechanism which, like our approach to explain the late-time accelerating universe, uses the entropy and temperature intrinsic to information holographically stored on a surface enclosing the observed space. The acceleration is due in both cases to an emergent entropic force, naturally arising from the information storage on the horizon.

9. Unitarity Boomerang, Paul H. Frampton and Xiao-Gang He (1003.0310)
For the three family quark flavor mixing, the best parametrization is the original Kobayashi-Maskawa matrix, V_{KM}, with four real parameters: three rotation angles $\theta_{1,2,3}$ and one phase δ. A popular way of presentation is by the unitarity triangle which, however, explicitly displays only three, not four, independent parameters. Here we propose an alternative presentation which displays simultaneously all four parameters: the unitarity boomerang.

10. Entropic Accelerating Universe, Damien A. Easson, Paul H. Frampton, and George F. Smoot (1002.4278)
To accommodate the observed accelerated expansion of the universe, one popular idea is to invoke a driving term in the Friedmann-Lemaître equation of dark energy which must then comprise 70% of the present cosmological energy density. We propose an alternative interpretation which takes into account the entropy and temperature intrinsic to the horizon of the universe due to the infor-

mation holographically stored there. Dark energy is thereby obviated and the acceleration is due to an entropic force naturally arising from the information storage on the horizon surface screen. We consider an additional quantitative approach inspired by surface terms in general relativity and show that this leads to the entropic accelerating universe.

11. Primordial Black Holes as All Dark Matter, Paul H. Frampton, Masahiro Kawasaki, Fuminobu Takahashi, and Tsutomu T. Yanagida (1001.2308)
We argue that a primordial black hole is a natural and unique candidate for all dark matter. We show that, in a smooth-hybrid new double inflation model, a right amount of the primordial black holes, with a sharply-defined mass, can be produced at the end of the smooth-hybrid regime, through preheating. We first consider masses $< 10^{-7} M_\odot$ which are allowed by all the previous constraints. We next discuss much heavier mass $10^5 M_\odot$ hinted at by entropy, and galactic size evolution, arguments. Effects on the running of the scalar spectral index are computed.

12. Axigluon as Possible Explanation for $p\bar{p} \to t\bar{t}$ Forward-Backward Asymmetry, Paul H. Frampton, Jing Shu, and Kai Wang (0911.2955)
A flavor-nonuniversal chiral color model is introduced. It is used for comparison to the recent data on $\bar{p}p \to \bar{t}t$. We concluded that the data are consistent with interpretation as an axigluon exchange within 1σ and a unique rise and fall behavior is predicated with regard to the asymmetry A^t_{FB} as a function of $t\bar{t}$ invariant mass, which can distinguish our model from others before one discovers the axigluon resonance. Further aspects of the model are discussed.

13. Alternative Version of Chiral Color as Alternative to the Standard Model, Paul H. Frampton (0910.0307)
In a variant of chiral color with the electroweak gauge group generalized to $SU(3)_L \times U(1)$ anomaly cancellation occurs more readily than in the $SU(2)_L \times U(1)$ case. Three families are required by anomaly cancellation and the top family appears non-sequentially.

14. Black Holes as Dark Matter, Paul H. Frampton (0907.1704)
While the energy of the universe has been established to be about 0.04 baryons, 0.24 dark matter and 0.72 dark energy, the cosmological entropy is almost entirely, about $(1 - 10^{-15})$, from black holes and only 10^{-15} from everything else. This identification of all dark matter as black holes is natural in statistical mechanics. Cosmological history of dark matter is discussed.

15. Looking for Intermediate-Mass Black Holes, Paul H. Frampton (0907.1646)
A discussion of the entropy of the universe leads to the suggestion of very many intermediate-mass black holes between thirty and three hundred thousand solar masses in the halo. It is consistent with observations on wide binaries as well as microlensing and considerations of disk stability that such IMBHs constitute all cold dark matter.

Papers involving graduate student D. Eby (Ph.D., 2013):

1. Analysis of Quark Mixing Using Binary Tetrahedral Flavor Symmetry, David A. Eby, Paul H. Frampton, Shinya Matsuzaki (arXiv:0907.3425 [hep-ph])
Adapts and expands the theory of Binary Tetrahedral Flavor Symmetry to incorporate 3-family quark mixing and encompass the full CKM matrix. This paper also includes parameterized predictions of CKM matrix elements and newly added variables in a Next-to-Minimal Binary Tetrahedral Model.

2. Quartification with T' Flavor, David A. Eby, Paul H. Frampton, Xiao-Gang He, Thomas W. Kephart (arXiv:1103.5737 [hep-ph])
Describes a toy model adapting both Standard Model physics through a quiver theory with 4 SU(3) Lie Groups and the T' symmetry of Binary Tetrahedral Flavor Symmetry. This paper lays out a suitable scheme for the compatibility of these very different theories, successfully combining finite and continuous symmetries.

3. Dark Matter From Binary Tetrahedral Flavor Symmetry, David A. Eby, Paul H. Frampton (arXiv:1111.4938 [hep-ph])
Expands the Minimal Binary Tetrahedral Model with additional elements in order to naturally form a new weakly interacting stable massive particle that can serve as a suitable explanation of dark matter. The paper also includes preliminary calculations for this particle's mass as derived from the necessary relic density and details the full Higgs Scalar Potential of this model.

4. T2K Signals Non-Maximal Atmospheric Neutrino Mixing, David A. Eby, Paul H. Frampton (arXiv:1112.2675 [hep-ph])
Reflects on the success of a correlation equation between two neutrino mixing angles derived in an earlier paper (Phys. Lett. B 671: 386-390, 2009). Notes that experimental results have converged towards the predicted line, and presents a new visual interpretation of current data using the PMNS paramatrization angles.

5. Binary Tetrahedral Flavor Symmetry, David A. Eby (arXiv:1304.4193 [hep-ph])
A doctoral thesis cataloging and updating theoretical developments and experimental tests of Binary Tetrahedral Flavor Symmetry over the past few years. This document includes a background on, and modern appraisal of, fermion mixing theory and neutrino mass. This theory also includes discussions of dark matter and unified theories in later chapters.

Papers involving graduate student K. Ludwick (Ph.D., 2013):

1. Number and Entropy of Halo Black Holes, Paul H. Frampton, Kevin Ludwick (arXiv:0910.1152 [astro-ph.GA])
Based on constraints from microlensing and disk stability, both with and without limitations from wide binary surveys, we estimate the total number and entropy of intermediate mass black holes. Given the visible universe comprises 10^{11} halos each of mass $\sim 10^{12} M_\odot$, typical core black holes of mean mass $\sim 10^7 M_\odot$ set the dimensionless entropy (S/k) of the universe at a thousand googols. Identification of all dark matter as black holes sets the dimensionless entropy of the universe at ten million googols, implying that dark matter can contribute over 99favors all dark matter as black holes in the mass regime of $\sim 10^5 M_\odot$.

2. Seeking Evolution of Dark Energy, Paul H. Frampton, Kevin J. Ludwick (arXiv:1103.2480 [hep-th])
We study how observationally to distinguish between a cosmological constant (CC) and an evolving dark energy with equation of state $\omega(Z)$. We focus on the value of redshift Z^* at which the cosmic late-time acceleration begins and $\ddot{a}(Z^*) = 0$. Four $\omega(Z)$ are studied, including the well-known CPL model and a new model that has advantages when describing the entire expansion era. If dark energy is represented by a CC model with $\omega \equiv -1$, the present ranges for $\Omega_\Lambda(t_0)$ and $\Omega_m(t_0)$ imply that $Z^* = 0.743$ with 4of a model independent measurement of Z^* with better accuracy.

3. The Little Rip, Paul H. Frampton, Kevin J. Ludwick, Robert J. Scherrer (arXiv:1106.4996 [astro-ph.CO])
We examine models in which the dark energy density increases with time (so that the equation-of-state parameter w satisfies $w < -1$), but w approaches -1 asymptotically, such that there is no future singularity. We refine previous calculations to determine the conditions necessary to produce this evolution. Such models can display arbitrarily rapid expansion in the near future, leading to the destruction of all bound structures (a "little rip"). We determine observational constraints on these models and calculate the point at which the disintegration of bound structures occurs. For the same present-day value of w, a big rip with constant w disintegrates bound structures earlier than a little rip.

4. Models for Little Rip Dark Energy, Paul H. Frampton, Kevin J. Ludwick, Shin'ichi Nojiri, Sergei D. Odintsov, Robert J. Scherrer (arXiv:1108.0067 [hep-th])
We examine in more detail specific models which yield a little rip cosmology, i.e., a universe in which the dark energy density increases without bound but the universe never reaches a finite-time singularity. We derive the conditions for the little rip in terms of the inertial force in the expanding universe and present two representative models to illustrate in more detail the difference between little rip models and those which are asymptotically de Sitter. We derive conditions on the equation of state parameter of the dark energy to distinguish between the two types of models. We show that coupling between dark matter and dark energy with a little rip equation of state can alter the evolution, changing the little rip into an asymptotic de Sitter expansion. We give conditions on minimally-coupled phantom scalar field models and on scalar-tensor models that indicate whether or not they correspond to a little rip expansion. We show that, counterintuitively, despite local instability, a little rip cosmology has an infinite lifetime.

5. Pseudo-rip: Cosmological models intermediate between the cosmological constant and the little rip, Paul H. Frampton, Kevin J. Ludwick, Robert J. Scherrer (arXiv:1112.2964 [astro-ph.CO])
If we assume that the cosmic energy density will remain constant or strictly increase in the future, then the possible fates for the universe can be divided into four categories based on the time asymptotics of the Hubble parameter $H(t)$: the cosmological constant, for which $H(t) = constant$, the big rip, for which $H(t) \to \infty$ at finite time, the little rip, for which $H(t) \to \infty$ as time goes to infinity, and the pseudo-rip, for which $H(t) \to constant$ as time goes to infinity. Here we examine the last of these possibilities in more detail. We provide models that exemplify the pseudo-rip, which is an intermediate case between the cosmological constant and the little rip. Structure disintegration in the pseudo-rip depends on the model parameters. We show that pseudo-rip models for which the density and Hubble parameter increase monotonically can produce an inertial force which does not increase monotonically, but instead peaks at a particular future time and then decreases.

6. Cyclic Cosmology from the Little Rip, Paul H. Frampton, Kevin J. Ludwick (arXiv:1304.5221 [astro-ph.CO])
We revisit a cyclic cosmology scenario proposed in 2007 to examine whether its hypotheses can be sustained if the underlying big rip evolution, which was assumed there, is replaced by the recently proposed little rip. We show that the separation into causal patches at turnaround is generally valid for a little rip, and therefore conclude that the little rip is equally as suitable a basis for cyclicity as the big rip.

PI of Task B: Paul H. Frampton
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DOE Grant Number: DE-FG02-06ER41418, Task B, 7/1/09 - 4/30/13
Final Report (prepared by Y.J. Ng as requested by program monitor), July 24, 2013
Note that P.H. Frampton left for Argentina in January 2012.

List of papers[titles of papers, authors and arXiv numbers (in brackets)]

Papers not involving graduate students (D. Eby and K. Ludwick):

1. LHC Higgs Production and Decay in the T' Model, Paul H. Frampton, Chiu Man Ho, Thomas W. Kephart, and Shinya Matsuzaki (1009.0307)

2. Holographic Principle and the Surface of Last Scatter, Paul H. Frampton (1005.2294)

3. Probing Variant Axion Models at LHC, Chuan-Ren Chen, Paul H. Frampton, Fuminobu Takahashi, and Tsutomu T. Yanagida (1005.1185)

4. Hunting for New Physics with Unitarity Boomerangs, Paul H. Frampton and Xiao-Gang He (1004.3679)

5. Possible Solution of Dark Matter, The Solution of DArk Energy and Gell-Mann as Great Theoretician, Paul H. Frampton (1004.1910)

6. Considerations of Cosmic Acceleration, Paul H. Frampton (1004.1285)

7. Black Holes Constitute All Dark Matter, Paul H. Frampton (1003.3356)

8. Entropic Inflation, Damien A. Easson, Paul H. Frampton, and George F. Smoot (1003.1528)

9. Unitarity Boomerang, Paul H. Frampton and Xiao-Gang He (1003.0310)

10. Entropic Accelerating Universe, Damien A. Easson, Paul H. Frampton, and George F. Smoot (1002.4278)

11. Primordial Black Holes as All Dark Matter, Paul H. Frampton, Masahiro Kawasaki, Fuminobu Takahashi, and Tsutomu T. Yanagida (1001.2308)

12. Axigluon as Possible Explanation for $p\bar{p} \to t\bar{t}$ Forward-Backward Asymmetry, Paul H. Frampton, Jing Shu, and Kai Wang (0911.2955)

13. Alternative Version of Chiral Color as Alternative to the Standard Model, Paul H. Frampton (0910.0307)

14. Black Holes as Dark Matter, Paul H. Frampton (0907.1704)

15. Looking for Intermediate-Mass Black Holes, Paul H. Frampton (0907.1646)

Papers involving graduate student D. Eby (Ph.D., 2013):

1. Analysis of Quark Mixing Using Binary Tetrahedral Flavor Symmetry, David A. Eby, Paul H. Frampton, Shinya Matsuzaki (arXiv:0907.3425 [hep-ph])

2. Quartification with T' Flavor, David A. Eby, Paul H. Frampton, Xiao-Gang He, Thomas W. Kephart (arXiv:1103.5737 [hep-ph])

3. Dark Matter From Binary Tetrahedral Flavor Symmetry, David A. Eby, Paul H. Frampton (arXiv:1111.4938 [hep-ph])

4. T2K Signals Non-Maximal Atmospheric Neutrino Mixing, David A. Eby, Paul H. Frampton (arXiv:1112.2675 [hep-ph])

5. Binary Tetrahedral Flavor Symmetry, David A. Eby (arXiv:1304.4193 [hep-ph])

Papers involving graduate student K. Ludwick (Ph.D., 2013):

1. Number and Entropy of Halo Black Holes, Paul H. Frampton, Kevin Ludwick (arXiv:0910.1152 [astro-ph.GA])

2. Seeking Evolution of Dark Energy, Paul H. Frampton, Kevin J. Ludwick (arXiv:1103.2480 [hep-th])

3. The Little Rip, Paul H. Frampton, Kevin J. Ludwick, Robert J. Scherrer (arXiv:1106.4996 [astro-ph.CO])

4. Models for Little Rip Dark Energy, Paul H. Frampton, Kevin J. Ludwick, Shin'ichi Nojiri, Sergei D. Odintsov, Robert J. Scherrer (arXiv:1108.0067 [hep-th])

5. Pseudo-rip: Cosmological models intermediate between the cosmological constant and the little rip, Paul H. Frampton, Kevin J. Ludwick, Robert J. Scherrer (arXiv:1112.2964 [astro-ph.CO])

6. Cyclic Cosmology from the Little Rip, Paul H. Frampton, Kevin J. Ludwick (arXiv:1304.5221 [astro-ph.CO])

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Final Report, July 24, 2013

DESCRIPTION OF RESULTS FROM 7/1/09 - 4/30/13 [1 - 15]

(I) Dark matter, quantum gravity, and infinite statistics [1-6]

While dark matter has been canonized in the concordant ΛCDM model of cosmology, at the galactic scale it can explain the observed asymptotic independence of orbital velocities on the size of the orbit only by fitting data (usually with two parameters) for individual galaxies. It can do no better in explaining the observed baryonic Tully-Fisher relation, i.e., the asymptotic-velocity-mass ($v^4 \propto M$) relation. This is in stark contrast to another paradigm known as modified Newtonian dynamics (MOND) which stipulates that the usual Newtonian acceleration is modified for an acceleration less than the critical acceleration a_c which is numerically related to the speed of light c and the Hubble scale H as $a_c \approx cH/(2\pi) \sim 10^{-8} cm/s^2$. With only a single parameter (viz., a_c) MOND can explain easily and rather successfully the observed flat galactic rotation curves and the observed Tully-Fisher relation. But there are problems with MOND at the cluster and cosmological scales.

Obviously it is desirable to combine the salient successful features of both CDM and MOND into a unified scheme. We proposed such a scheme by introducing the concept of MONDian dark matter which behaves like CDM at cluster and cosmological scales but emulates MOND at the galactic scale. This work made use of the recent work of E. Verlinde in which the canonical Newton's laws are derived from the point of view of holography. Specifically, we succeeded in deriving MOND with the correct order of magnitude for the (observed) critical galactic acceleration. From our perspective, MOND (given by the Milgrom scaling) is a phenomenological consequence of quantum gravity. We also obtained a dark matter profile that relates, at the galactic scale, dark matter, dark energy (Λ) and ordinary matter to one another.

In a more recent work, we noted that the effective acceleration expression $a_{eff} = \sqrt{\vec{a}^2 + a_0^2} - a_0$ (with a_0 being the critical acceleration) we found earlier in our work on MONDian dark matter bears an uncanny resemblance to the Hamiltonian density in Born-Infeld electrodynamics which is of the form $H = \sqrt{\vec{A}^2 + A_0^2} - A_0$. When one maps A_0 to a_0 and A to a, the Born-Infeld *inspired* force law will be given by $F_{\rm BI} = m \left(\sqrt{\vec{A}^2 + A_0^2} - A_0 \right)$. Now this mapping is valid if one appeals to the equivalence principle and if one can use the energy equipartition theorem as well as the Unruh temperature formula. But the equipartition theorem, valid in classical statistics, is not true for quantum statistics (at low temperature), unless the partition function is of the Boltzmann form $Z = exp(-\beta E)$, or in other words, unless the statistics is of the type associated with infinite statistics. Thus we were led to contemplate the possibility that MONDian dark matter (introduced in our orginal work) is described in terms of the Born-Infeld theory (in some large scale and thermodynamic limit), and that the quanta of that theory obey infinite statistics (and hence MONDian dark matter obeys infinte statistics.)

Finally we [6] tested the inertial properties of MONDian dark matter and its mass profile in the context of galactic rotation curves. The MONDian dark matter profile was shown to have one less parameter than the standard cold dark matter (CDM) profiles. We showed also that the MONDian dark matter fits the galactic rotation curves as well as modified Newtonian dynamics (MOND).

(II) Spacetime foam physics [5, 7-11]

In the past few years we continued our work on spacetime foam, and found that spacetime foam manifests itself in a variety of ways. Succintly it has some attributes of a turbulent fluid. (Also see (III).) It is the source of the holographic principle. Cosmologically it may play a role in explaining why the energy density has the critical value, why dark energy/matter exists, and why the effective dynamical cosmological constant has the value as observed. Astrophysically the physics of spacetime foam, dovetailing with some results from(I), helps to elucidate why the critical acceleration in MOND has the observed value; and it provides a possible connection between global physics and local galactic dynamics involving the phenomenon of flat rotation curves of galaxies and the observed Tully-Fisher relation. Spacetime foam physics also sheds light on nonlocal gravitational dynamics.

In addition, standard statistical mechanics applied to the "particles" constituting the dark energy in the framework of holographic foam cosmology shows that the entropy becomes nonsensically negative unless the "particles" are distinguishable and nonidentical! Thus we were naturally led to speculate that the constituents of dark energy, unlike ordinary matter, obey an exotic statistics known as infinite statistics in which all representations of the particle permutation group can occur. It may appear that infinite statistics has one "defect": a theory of particles obeying infinite statistics cannot be local. However, one should recall that there is also an element of nonlocality in holographic theories. The nonlocality present in systems obeying infinite statistics could well be related to that present in holographic theories.

To connect with observation, we elaborated on the proposal to detect spacetime foam by looking for seeing disks in the images of distant quasars. We also considered the feasibility of using various existing or proposed telescopes (for wavelengths from hard X-rays down to radio waves) to test the different spacetime foam models. Then we examined recent data and the constraints they put on spacetime foam models. Thus far, images of high-redshift quasars from the Hubble Ultra-Deep Field (UDF) provide the most stringent test of spacetime foam theories. Indeed, we saw a slight wavelength-dependent blurring in the UDF images selected for this study. Using existing data in the Hubble Space Telescope archive we found it is impossible to rule out the $\alpha = 2/3$ model, but exclude all models with $\alpha < 0.65$. (Here α appears in δl, the fluctuation of a distance l, as $\delta l \gtrsim l^{1-\alpha} l_P^{\alpha}$, where l_P is the Planck length.) We noticed that the Very Large Telescope Interferometers appears to be the most promising to test the holographic model and observations with the HST in the ultraviolet region can also be very helpful.

Recently there appeared a paper in Astronomy and Astrophysics claiming that the holographic model ($\alpha = 2/3$) is essentially ruled out. The disagreement between those authors and our group was partly due to the use of different cosmological distance measures. We used the line-of-sight comoving distance whereas they used the luminosity distance, apparently oblivious of our earlier argument why the former distance measure is the correct distance to use. The use of the wrong distance measure caused those authors to overstate the constraints that can be placed on models of spacetime foam.

We noted that time lags from distant pulsed sources have also been posited as a possible test of quantum foam models. In fact, the new Fermi Gamma-ray Space Telescope results was used (wrongly) by Abdo et al. to exclude almost all the spacetime foam models. However, we demonstrated that the time-lag effect is actually much smaller than Abdo and collaborators have calculated, due to the equal probability of positive and negative fluctuations in the speed of light inherent in all such spacetime foam models. We found that the new Fermi Gamma-ray Space Telescope results only exclude models with $\alpha < 0.3$.

(III) Turbulence and quantum gravity [12-13]

We showed that there are deep similarities between quantum gravity and turbulence. The connection between these seemingly disparate fields is provided by the role of the diffeomorphism symmetry in classical gravity and the volume preserving diffeomorphisms of classical fluid dynamics. By utilizing the metrical properties of sound propagation in fluids, we argued that, in $3 + 1$ dimensions, the Kolmogorov scaling in turbulence is intimately related to the properties of spacetime fluctuations. We also proposed a very specific dictionary between string theory and turbulence. We argued that the relation between the Kolmogorov and Kraichnan scalings in two spatial dimensions is precisely the same as the one between the string and membrane theories. We also argued that the AdS/CFT correspondence finds its natural "turbulent" realization in this context.

Our proposal explained the Kolmogorov scaling in $3 + 1$ dimensions and the relationship between the Kraichnan and Kolmogorov scalings in $2 + 1$ dimensions. Our argument was crucially based on the use of Migdal's loop variables and the self-consistent solutions of Migdal's loop equations for turbulence. In particular, there is an area law for turbulence in $2 + 1$ dimensions related to the Kraichnan scaling. We speculated that the universal $2/3$ exponent we had found for scaling in turbulence is an indication that one is working in the spacetime foam regime (from a boundary point of view). This strongly suggests that not only is string theory useful in formulating a theory of turbulence but that the physics of turbulence can provide some guidance to understanding the spacetime foam phase of strong quantum gravity. There exists a curious synergy between the two seemingly disparate fields of quantum gravity and turbulence!

(IV) Spacetime emergence [14]

Spacetime emergence refers to the notion that classical spacetime "emerges" as an approximate macroscopic entity from a non-spatio-temporal structure present in a more complete theory of interacting fundamental constituents. Recently we proposed a novel mechanism involving the "soldering" of internal and external spaces for the emergence of spacetime and the twin transmutation of general covariance. In the context of string theory, this mechanism points to a critical four dimensional spacetime background. Succintly the emergence of spacetime comes about when one goes from weak to strong coupling (strings to membranes) and when one reinterprets the renormalization group flow of this membrane theory coupled to some other matter holographically as a 4d theory that involves 4d gravity. All these insights are supported by what one knows from string theory.

(V) Projective geometry and $\mathcal{PT}$-symmetric Dirac hamiltonian [15]

The (3+1)-dimensional (generalized) Dirac equation was shown to have the same form as the equation expressing the condition that a given point lies on a given line in 3-dimensional projective space. The resulting Hamiltonian with a γ_5 mass term is not Hermitian, but is invariant under the combined transformation of parity reflection $\mathcal{P}$ and time reversal $\mathcal{T}$. When the $\mathcal{PT}$ symmetry is unbroken, the energy spectrum of the free spin-$\frac{1}{2}$ theory is real, with an appropriately shifted mass.

List of Papers

1. C.M. Ho, D. Minic and Y.J. Ng, Cold Dark Matter with MOND Scaling, Phys. Lett. B693, 567 (2010).
2. C.M. Ho, D. Minic and Y.J. Ng, Quantum Gravity and Dark Matter, 5th place award in the 2011 Essay Competition of the Gravity Research Foundation; arXiv:1105.2916 [gr-qc], Gen. Rel. Grav. 43, 2567 (2011).
3. C.M. Ho, D. Minic and Y.J. Ng, Dark Matter, Infinite Statistics and Quantum Gravity, Phys. Rev. D 85, 104033 (2012), arXiv:1201.2365.
4. Y.J. Ng, MoNDian Dark Matter, Entropic Gravity, and Infinite Statistics, arXiv:1212.6433 [gr-qc], to appear in the Proceedings of the 13th Marcel Grossmann Meeting.
5. Y.J. Ng, Towards a Holographic Theory of Cosmology – Threads in a Tapestry, arXiv:1305.3918 [gr-qc].
6. D. Edmonds, D. Farrah, C.M. Ho, D. Minic, Y.J. Ng, and T. Takeuchi, Testing MONDian Dark Matter with Galactic Rotation Curves, in preparation.
7. Y.J. Ng, Spacetime Foam and Dark Energy, in the Proc. of The Dark Side of the Universe, the Fourth Int'l Workshop on the Dark Side of the Universe, ed. S. Khalil (AIP Conference Proceedings, Melville, NY, 2009), 74.
8. W. A. Christiansen, Y.J. Ng, D. Floyd and E. Perlman, Limits on Spacetime Foam, Phys. Rev. D 83, 084003 (2011).
9. Y.J. Ng, Holographic Quantum Foam, arXiv:1001.0411 [gr-qc], in Proc. of the 12th Marcel Grossmann Meeting on General Relativity, ed. by T. Damour et al. (World Scientific, Singapore, 2012), 2435.
10. Y.J Ng, Various Facets of Spacetime Foam, in the Proceedings of the 3rd International Conference on Time and Matter, ed. by M. O'Loughlin et al. (University of Nova Gorica Press, Nova Gorica, Slovenia, 2011) 103-119.
11. E.S. Perlman, Y.J. Ng, D.J.E. Floyd and W.A. Christiansen, Using Observations of Distant Quasars to Constrain Quantum Gravity, arXiv:1110.4986 [astro-ph.CO], Astronomy & Astrophysics 535, L9 (2011).
12. V. Jejjala, D. Minic, Y.J. Ng and C. H. Tze, String Theory and Turbulence, arXiv:0912.2725 [hep-th], Mod. Phys. Lett. A25, 2541 (2010).
13. V. Jejjala, D. Minic, Y.J. Ng and C. H. Tze, Quantum Gravity and Turbulence, arXiv:1005.3254 [gr-qc], Int. J. Mod. Phys. D19, 2311 (2010).
14. C.M. Ho, D. Minic and Y.J. Ng, Spacetime Emergence and General Covariance Transmutation, arXiv:1206.0085 [hep-th], Mod. Phys. Lett. A 28,1350005 (2013).
15. Y.J. Ng and H. van Dam, Projective Geometry and PT-Symmetric Dirac Hamiltonian, Phys. Lett. B 673, 237 (2009).

Talks given by Y. Jack Ng / Conferences attended

Ng attended the following conferences/workshops in 2009: PArticle, Strings, and COsmology workshop at DESY (7/6-10/09); Marcel Grossmann Meeting in Paris (7/12-18/09); Loops 09 Conference in Beijing (7/30/09-8/3/09); Overseas Chinese Physicists Association Meeting in Lanzhou, China (8/3-7/09); South-East Regional Math/Strings Meeting at Duke University (10/02/09); Workshop on Asymptotic Safety and Workshop on Lifshitz Gravity at Perimeter Institute for Theoretical Physics (11/5-10/09); Miami 09 Conference on Elementary Particles, Astrophysics and Cosmology in Fort Lauderdale, Florida (12/15-20/09). He gave invited talks at the Marcel Grossmann Meeting, Loops 09, and the OCPA Meeting. He gave a colloquium at the Goddard Space Flight Center on 10/09/09 and a seminar in the Astrophysics Journal Club at University of North Carolina on 12/04/09.

Ng attended the following conferences/workshops in 2010: Regional meeting on Strings at Duke University (4/2/2010); Miltonfest, a conference to honor Kim Milton, at University of Oklahoma (4/9 - 4/10, 2010); Conference dedicated to the memory of Julian Schwinger in Singapore (8/30 - 9/3, 2010); Crete Conference on Gauge Theories and the Structure of Spacetime at Kolymvari, Crete, Greece (9/11 - 9/18, 2010); Conference on Time and Matter in Budva, Montenegro (10/4 - 10/8, 2010); Cluster-Universe Workshop on Particle Physics, Astrophysics and Cosmology at Garching, Germany (10/11 - 10/14, 2010). He gave invited talks at the Miltonfest, the conference in Singapore, and the conference in Budva. He gave two seminars at the Headquarters of the European Southern Observatory at Garching (9/22 and 9/29, 2010) where he was on research leave during the Fall semester of 2010. He visited the University of Utrecht and gave a seminar (11/15, 2010). He also visited Universitat Autonoma de Barcelona and gave a seminar (11/26, 2010).

In 2011 Ng attended conferences and/or gave invited talks (on quantum foam, dark energy, dark matter and modified Newtonian dynamics) at University of Hawaii (July 2011), Overseas Chinese Physicists Association Meeting in Kaohsiung, Taiwan (8/1-5/11), National Dong Hwa University, Taiwan (August 2011), and Miami2011 Conference (December 2011).

In 2012 and early 2013 Ng participated in Conference on "Conformal Nature of the Universe" at Perimeter Institute of Theoretical Physics (May 2012), Workshop on "What is ν?" at Florence, Italy (June 2012), and Strong and Electroweak Matter 2012 Conference at Swansea, United Kingdom (July 2012). He gave a talk at the 13th Marcel Grossmann Meeting at Stockholm, Sweden (July 2012), at Miami2012 Conference (12/14-20/12), and he gave a colloquium at Virginia Tech (2/1/13).

Graduate Students:

Paul Carr, Concerning the Representability of Self-Reference in Arithmetic, arXiv: 1109.0949.

Miguel Perez received MA degree in physics in 2011.

Ng served as the chairman of the Ph.D. Committee for both David Eby and Kevin Ludwick. (See Report from Task B.)

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Final Report, July 24, 2013

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10. Y.J Ng, Various Facets of Spacetime Foam, in the Proceedings of the 3rd International Conference on Time and Matter, ed. by M. O'Loughlin et al. (University of Nova Gorica Press, Nova Gorica, Slovenia, 2011) 103-119.

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& Astrophysics 535, L9 (2011).

12. V. Jejjala, D. Minic, Y.J. Ng and C. H. Tze, String Theory and Turbulence, arXiv:0912.2725 [hep-th], Mod. Phys. Lett. A25, 2541 (2010).

13. V. Jejjala, D. Minic, Y.J. Ng and C. H. Tze, Quantum Gravity and Turbulence, arXiv:1005.3254 [gr-qc], Int. J. Mod. Phys. D19, 2311 (2010).

14. C.M. Ho, D. Minic and Y.J. Ng, Spacetime Emergence and General Covariance Transmutation, arXiv:1206.0085 [hep-th], Mod. Phys. Lett. A 28,1350005 (2013).

15. Y.J. Ng and H. van Dam, Projective Geometry and PT-Symmetric Dirac Hamiltonian, Phys. Lett. B 673, 237 (2009).

Final Report for Grant No. DE-FG02-06ER41418

For the period from 2009 to June 30, 2013

Theoretical Research in Cosmology
Cosmology Task -D

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1 Previous and Continuing Work

The two deepest mysteries in our understanding of nature are: what selected the initial conditions (IC) of our universe and, what is causing the accelerated expansion of the universe recently. L.M-H investigates both of these outstanding problems, within a new framework that extends the conventional approach to a multiverse framework. The work involves an inquiry into the foundational principles, as well as an observational analysis for guidance on these phenomena and for the testable predictions of the program.

The program, briefly described below, led by L.M-H on the Selection of the Initial Conditions of the Universe, uses the landscape of string theory as the working model and it has proven quite succesful so far in terms of its testable consequences. The most recent test came in March 2013 with the Planck data release and, in Nov.2009 with the new results by the NASA team, led by A.Kashlinsky (Astrophys.J.712:L81-L85,2010, e-Print: arXiv:0910.4958). Their expanded catalogoue of over $1,600$ clusters with distance close to $800Mpc$, confirmed that the dark flow is there as predicted by our work on the 'tilting' of the gravitational potential by the nonlocal entanglement of our universe with other domains beyond the horizon, (L.Mersini-Houghton and R.Holman JCAP 0902:006,2009).

1.1 Selection of the Initial Conditions from the String Theory Landscape

I briefly review the theoretical basis of this program here. Technically, the theoretical work is carried out by embedding quantum mechanics into the string theory landscape. L.M-H was the first one to propose in 2003 - 2004, soon after the discovery of the landscape of string theory, that we obtain the selection criterion for our universe from the landscape, by allowing the wavefunction of the universe to propagate on the landscape background. Thereby, the most probable wavefunction of the universe is found from the solutions of the Wheeler-De Witt equation (WDW), (Eur.Phys.J.C49:869-873. e-Print: hep-th/0410213 and Class.Quant.Grav.22:3481-3490,e-Print: hep-th/0504026). The next stage in this program was to address decoherence among the various branches by including the backreaction of superhorizon fluctuations on the wavefunction of the universe. The inclusion of backreaction on the WDW equation turns it into a Master Equation. The dynamic evolution of these wavefunctions, now given by solutions of the Master equation, (Phys.Rev.D74:123510, e-Print: hep-th/0511102) provided the selection criterion for survivor and terminal universes.

The main theoretical result is the finding that with the inclusion of decoherence, only high energy inflationary patches can survive the backreaction of massive fluctuation modes and give birth to a physical universe, (one that continues to grow). Hence, although the universe soon decoheres by the usual mechanism, some of the quantum entanglement from the earliest times among these survivor universes (wavefunction solutions including the fluctuations) is still present and left its imprints, due to the principle of a unitary evolution. R.Holman and I are currently preparing a status report in analyzing the fit between our predic tions and Planck data.

1.2 Status of Astrophysical Signatures of the Landscape on CMB and LSS Predicted

With R.Holman and T.Takahashi we used the principle of unitary evolution to derive astrophysical imprints of this theory. We conducted a thorough analysis for identifying testable predictions of this theory imprinted as low energy astrophysical signatures, in the present universe originating from the earliest times (Phys.Rev.D77:063510,e-Print: hep-th/0611223 and Phys.Rev.D77:063511,e-Print: hep-th/0612142). Then, in [4] with R.Holman, we estimated the 'tilt' in the background Newtonian potential of our universe induced by the superhorizon nonlocal entanglement of our domain with all else. The theory for the selection of the initial state of the universe from the landscape multiverse predicts superhorizon inhomogeneities induced by nonlocal entanglement of our Hubble volume with modes and domains beyond the horizon. These give rise to modifications to the background Newtonian potential by providing a second channel of contributions that are noninflationary in origin. Such a 'tilt' leads to a series of signatures: suppressions of power at low multipoles in CMB anisotropies; alignement of the quadrupole with the octupole; a dipole preferred direction; a negative contribution to the dipole; a giant Cold Spot at redshift about 1 of 10 degrees in the sky; a bulk flow with correlation length of order horizon size along the preferred direction; an excess of power at higher multipoles; a running of the spectral index from red to blue starting from low multipoles towards the large one; an overall suppression of σ_8; upper and lower bounds on SUSY breaking scale predicting it to be about 10^6 TeV. We estimated in [4] that the modification to the gravitational potential has a characteristic scale $L_1 \simeq 10^3 H^{-1}$, and it originates from the preinflationary remnants of the landscape. The parameters are tightly constrained since our results are not phenomenological but rather derived from fundamental physics and first principles. Thus the derived modifications lead to robust predictions for testing our theory.

Planck data release in March 2013 has just confirmed all the anomalies predicted above, at the scales and sizes we estimated. LHC findings in relation to SUSY breaking are in agreement with our prediction that SUSY breaking does not occur at TeV energies. The 'dark' flow discovered by the NASA team led by Kashlinsky et al. around $700 km/s$ with their results in Nov.2009, is in perfect agreement with our prediction. The Planck team seems to be in disagreement about their preliminary data analysis, however further results are expected within the next few months. The discovery of CMB anomalies at large scales by Planck and of the bulk flow (if confirmed) may provide a probe of the preinflationary physics and a window onto the landscape multiverse. As a result this work continues to receive worldwide media coverage with stories and interviews in USA, Europe, Australia etc., with the most recent coverage this spring in Sunday Times in London, BBC-4, and the world philosophy festival in Hay on Wye.

As a natural stage in this investigation of the origins of the universe, is the relation between the three main theories that predict a multiverse: the many world interpretation of quantum mechanics; origins of the universe from the landscape; eternal inflation. The first two are related through the wavefunction of the universe on the landscape, above. The last one, eternal inflation, has become one of the key areas of my investigation on the last three years.

1.3 The Problem of Time for Inflation

Inflation and a deeper understanding of time are relat. But, these questions: 1) Is time a dynamic or a fundamental property of spacetime? 2) Why does it have an arrow pointing from past to future? 3) Why are physical laws time-symmetric in a universe with broken time-reversal symmetry? remain a mystery. Within the relatively recent interest on the eternal nature of inflation, the enigma of time becomes more relevant than ever. In [1], I argued that the reasons behind the time-reversal symmetry of our physical laws, in a universe with broken time-reversal symmetry, can be understood by making the distinction between two types of time: a *local* emerging arrow of time in the nucleating universe and, the *fundamental time* with no arrow in the multiverse. The very event of nucleation of the universe from the multiverse breaks time-reversal symmetry for the local universe, thereby inducing a locally emergent arrow. But, the new idea here is that, the laws of physics imprinted on this bubble are not emergent or processed at birth. Instead they are inherited locally from the multiverse. Since these laws originate from the time-symmetric multiverse then they carry the property of time-reversal symmetry, [1,6].

1.4 The Book : 'Arrows of Time: A Debate in Cosmology'

As part of initiating and leading an effort in making progress with our understanding of time's enigma, I am one of the two co-editors (with Rudinger Vaas) of the book 'Time's Arrow' published in the 'Frontiers Collection' of Springer-Verlag in May 2012. I am also one of the co-authors, contributing a chapter to the book. The book fills a technical gap in literature in relation to the nature of space-time and it presents modern views of some of the most influential contemporary thinkers. The book contains contributions by world leading physicists and a philosopher, on the subject of the nature of space-time.The initial project for this book arose from a conference that I together with B.Green and J.Khoury organized on $"Time's Arrow"$, October 2007 at NYAS.

1.5 Black Hole Binaries and Dark Energy

With one of my Ph.D. students, A.Kelleher, we investigated the possibility of using localized compact object such as Black Holes, instead of large scale data, to pin down dark energy and provide complementary information to the other astrophysical data. We found in [2] that dark energy imprints on the emitted gravitational radiation and on changes of the orbital radius of the binary.

2 Eternal Inflation

2.1 A Measure for Inflation and Gravitational Entropy

Recent advances in theoretical and precision cosmology have led to a coherent picture of the standard model of Big Bang inflation. We are now in a position to ask more fundamental questions such as: 1)why did we start with such an excquisitely tuned high energy inflation; 2) considering the eternal nature of inflation, what is the measure in the multiverse and what is its relation to other multiverse models; and, 3) is there observational evidence that can test eternal inflation.The program L.M-H has led in addressing the question (1) in the framework of the string landscape multiverse, has been very succeful so far with three of its predictions already tested, as described above.

L.M-H and Malcolm Perry investigated the conceptual basis of eternal inflation in order to understand question (2), namely what the probability for eternal inflation and its relation to the landscape. We showed that pathologies related to eternal inflation such as its infinite measure stem from the fact that homogeneity of the domain that would inflate is a crucial ingredient in probability estimates. We proposed a new measure that takes both conditions for inflationary pockets into account, the diffusion of the field to large energies as well as the homogeneity of the domain where such fluctuation arises. We showed that inflation can not be eternal. We are in the process of submitting the second set of results which show that eternal inflation and the landscape are mathematically inconsistent with each other thus can not be related. The next stage in this theme of investigation needs to address the issue of gravitational entropy in the absence of event horizons.

2.2 Observational Tests of Bubble Collisions

L.M-H has been collaborating for over two years with R.Bond and J.Braden, (a Ph.D. student) at CITA in a series of papers in investigating products of bubble collisions that can observationally test eternal inflation. We are the first ones to inquire into collisions by taking quantum mechanics, specifically quantum fluctuations into account. The program is numerically horrendous, however the program includes a study of collisions of domain walls and branes besides bubble collisions and thus our results will have a wide range of applicability from ekpyrotic universe models to eternal inflation. We have discovered that fluctuations are very important in the dissolution of walls during collision as they go through broad parametric resonance and get apmplified. Ultimately that energy goes into producing localized relics such as oscillons, unlike what was previously expected of collisions in literature. We will submit our results this summer.

L.M-H and M.Bucher at Diderot University Paris are collaborating in including gravity in the study of bubble collisions.

2.3 Horizons on a Modified Gravity Background

The possibility that the observed acceleration of the universe may be attributed to a theory of modified gravity, such as scalar-tensor theories, rather than to the mysterious dark energy, remains attractive. My Ph.D. student, A.Kelleher, extended our results of dark energy accretion in a universe with modified gravity,with the purpose of discriminating between dark energy and modified theories of gravity as part of his thesis. He received his Masters in Spring 2010 and his Ph.D. in Spring 2013.

2.4 Dirac fields in Curved Space

One of my Ph.D. students, M.Astrua, was investigating the issue of unitarity for fermions on curved spacetime. M.Astrua received her Master's on these results on April 2010. She quit her Ph.D. studies in fall 2012 due to her newborn baby. A new student just joined.

2.5 Co-Authoring the Book: 'Cosmic Update: Dark Puzzles. Arrow of Time. Future History'

L.M-H is one of the three co-authors (with F.Adams and M.Buchert as the other co-authors) in the second book (F.Nekoogar ed.).

L.M-H accepted the invitation in 2009 to join the Board of Editors for the Springer's 'Frontiers Collection' series.

2.6 Bibliography

1. " Notes on Time's Enigma", L. Mersini-Houghton, in 'Time's Arrow' book, Springer Frontier Collection, arXiv:0909.2330 [gr-qc] .

2." Investigating Dark Energy with Black Hole Binaries", L. Mersini-Houghton, A. Kelleher, Nucl.Phys.Proc.Suppl.194:272-277, arXiv:0906.1563 [gr-qc].

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4." 'Tilting' the Universe with the Landscape Multiverse: The 'Dark' Flow", L. Mersini-Houghton, R. Holman, JCAP 0902:006,2009.

5. " Arrows of Time: A Debate in Cosmology' Book, (eds. L.Mersini-Houghton, R.Vaas), Frontier's Collection Springer-Verlag, ISBN-10.3642232582, May 2012.

6. "Cosmic Update: . Dark Puzzles. Arrow of Time. Future History" Book, Authors: L.Mersini-Houghton and F.Adams, (eds.F.Nekoogar), Springer, ISBN-10.1441982933, Nov.2011.

7. "Is eternal inflation eternal?", L.Mersini-Houghton, [arxiv:1106.3542 (gr-qc)].

8. "The end of eternal inflation", L.Mersini-Houghton and M.Perry, [arxiv:1211.1347 (hep-th)], submitted to PLB, with referee.

9. "Antioscillons", L.Mersini-Houghton, submitted to CQG with referee.

10. "Eternal inflation and the Landscape", L.Mersini-Houghton and M.Perry, in preparation.

11. "Amplification of Linear of Flucutuations: Dissolution of Domain Walls", R.Bond, J.Braden and L.Mersini-Houghton in preparation.

12. "Nonlinear fluctuations and Oscillons from Collisions", R.Bond, J.Braden and L.Mersini-Houghton in preparation.

13. "Oscillons from Spherical Bubble Collisions", R.Bond, J.Braden and L.Mersini-Houghton in preparation.

14. "Relics of Bubble Collisions", M.Bucher and L.Mersini-Houghton.

List of papers L. Mersini-Houghton

1. “Notes on Time’s Enigma”, L. Mersini-Houghton, in ’Time’s Arrow’ book, Springer Frontier Collection, arXiv:0909.2330 [gr-qc] .

2.” Investigating Dark Energy with Black Hole Binaries”, L. Mersini-Houghton, A. Kelleher, Nucl.Phys.Proc.Suppl.194:272-277, arXiv:0906.1563 [gr-qc].

3.” The Origin of the Universe as Revealed Through the Polarization of the Cosmic Microwave Background”, S. Dodelson et al. FERMILAB-PUB-09-052-A, Science White Paper submitted to the US Astro2010 Decadal Survey, arXiv:0902.3796 [astro-ph.CO].

4.” ’Tilting’ the Universe with the Landscape Multiverse: The ’Dark’ Flow”, L. Mersini-Houghton, R. Holman, JCAP 0902:006,2009.

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