FINAL (3-YEAR) PROGRESS REPORT
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"Investigations in Elementary Particle Theory"

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and

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The aims of this grant were to provide fresh ideas, to interpret data, and to support experimental endeavors in the related fields of high-energy particle physics, particle astrophysics, and cosmology.

Personnel who received DOE funds under this grant were the three Co-PI's listed above, one postdoc, and two graduate students (partial funding).

BRIEF OVERVIEW of VANDERBILT GROUP

The research interests of our three Co-PI's complement each other very well. **Kephart** works mainly on models of particle unification in four or higher dimensions, on aspects of gravity such as inflation, black-holes, and the very early Universe, and on applications of knot theory and topology to various physical systems (including gluon dynamics). Recently, he has published on discrete symmetry extensions of the Standard Model, and on a mathematical categorization of entanglement, motivated by black hole considerations. **Scherrer** works mainly on aspects of the intermediate-aged Universe, including dark matter and dark energy, and particle physics in the early Universe. **Weiler** works mainly on neutrino physics, dark matter signatures, and extreme particle-astrophysics in the late Universe, including origins of the highest-energy cosmic-rays and gamma-rays, and the future potential of neutrino astrophysics. Recently he has published on causality/acausality aspects of extra-dimensional metrics. Kephart and Weiler have lately devoted some research attention to the LHC and its reach for probing physics beyond the Standard Model.

During the 3-year funding period, our grant supported one postdoc (Chiu Man Ho) and partially supported two students, Peter Denton and Lingjun Fu. Chiu Man collaborated with all three of the Co-PI's during the 3-year funding period and published 16 refereed papers. Chiu Man has gone on to a postdoc with Steve Hsu at Michigan State University and has continued his very active research program there. Denton and Fu both participated in the June, 2014, TASI. They will both receive their PhDs during the 2014-15 academic year.

Beginning in Fall 2009, we received funding from DOE to run a high-energy/cosmology seminar series at Vanderbilt. To date, our outside speakers have been:
Fall 2009: D. Marfatia, N. Afshordi, J. Dent, E. Linder, N. Okada, L. Pogosian, J. Kopp;
Spring 2010: J. Donoghue,C. Kao, P.Q. Hung, D. Boyanovsky, K. Freese, S. Koushiappas, S. Love, and D. Minic;
Fall 2010: P. Mannheim, M. Buckley, D. Feldman, R. Buniy, T. Han, L. Anchordoqui, W.-Y. Keung;
Spring 2011: C. Zachos, A. Tolley, R. Scoccimarro, H. Goldberg, P. Frampton, M. Trodden, A. Stern, S. Pakvasa, H. La, G. Medina-Tanco;
Fall 2011: S. Campbell, C. Rott, T. Curtright, K. Olive;
Spring 2012: H. Päs, D. Eby, L. Anchordoqui;
Fall 2012: none;
Spring 2013: M. Ahlers, A. Shapere, J. Khoury, S. Nandi, J. Frieman, J. Dent, M. Kaminkowski, O. Micu, A. Parry;
Fall 2013: S. Palomares-Ruiz;
Spring 2014: J. Rosa.

We occasionally supplement the speaker list with an internal researcher. Attendance at the seminar series has been quite good, 10-25 people. Besides attendees from our group, we get attendees from the astronomy group, the high-energy experimental group, and from assorted, interested postdocs and graduate students. The seminar visitor program has been very beneficial for our group with several collaborative paper between the Co-PIs and visitors resulting.

The total number of our papers published in refereed journals by the three co-PIs during the period of this grant (2011-present) is 54. The total number of talks given by the group members during this time period, including seminars, colloquia, and conference presentations, is 47. The next pages provide some details of the accomplishments of our DOE funded researchers during the grant period. Among the most outstanding achievements, Weiler was named a Simons Fellow in 2013. He presented an invited TEDx talk in 2012. His paper on closed timelike curves (2013) garnered a great deal of national publicity. Scherrer's paper on the "little rip" (2011) fostered a new area of cosmological research, and this term has now entered the lexicon of cosmology. His paper on anapole dark matter (2013) generated a great deal of interest in the community. Kephart was a Visiting Fellow at the Isaac Newton Institute in Cambridge, UK for the fall semester of 2012 where he was one of the co-organizers for a 5 month program on applications of topology to physics and biology. His research there resulted in a extended publication on topologically stabilized closed QCD flux tube states.

INDIVIDUAL CO-PI's NARRATIVE SUMMARIES, and PUBLICATIONS, TALKS, SERVICE

Thomas W. Kephart, Co-PI

During this most recent funding period my research has mostly focused on particle physics model building, especially three family flavor models, but did include several other projects. I was on academic leave at the Isaac Newton Institute, University of Cambridge in the fall semester of 2012 and had a very productive time there.

Model Building:

My work on particle physics models has centered on models that are directly testable, either at accelerators or with satellites or underground experiments, but with a focus toward the LHC. These model building projects include several recent studies of fermion masses and mixings.

[1]: In [1] James Dent, Robert Feger, S. Nandi and I studied an $SU(9)$ model of family unification with three light chiral families, and a natural hierarchy of charged fermion masses and mixings. The existence of singlet right handed neutrinos with masses about two orders of magnitude smaller than the GUT scale, as needed to understand the light neutrinos masses via the see-saw mechanism, is compelling in our model. Carl Albright, Feger and I are following up this work with a general scan of models of this type. A manuscript is in preparation.

[2, 16]: Chian-Shu Chen, Tzu-Chiang Yuan and I showed how discrete flavor symmetries can be extended to four family models [2]. We studied the lepton sector of a four generation model based on the discrete flavor group A_5. The best features of the three family A_4 model survive, including the tribimaximal pattern of three generation neutrino mixings. At leading order the three light neutrino mass relations of $m_1 = m_3$ and $m_2 = 0$ are predicted. The splitting of the neutrino masses can be naturally obtained as a result of the breaking of A_5 down to A_4 and a degenerate spectrum is preferred in our model. In our A_5 model, the electron mass is zero at tree level, but calculable through quantum corrections. To include the quark sector, the A_5 isocahedral group four generation lepton model is extended to a binary icosahedral symmetry I' flavor model [16]. We find the masses of fermions, including the heavy sectors, can be accommodated. At leading order the CKM matrix is the identity and the PMNS matrix, resulting from same set of vacua, corresponds to tribimaximal mixings. Four family I' flavor is the natural extension of three family T' flavor.

[3]: David Eby, Paul Frampton, Xiao-Gang He and I [3], we consider a model based on the group $(T' \otimes Z_2)_{global} \otimes [SU(3)^4]_{local}$ which combines the predictions of T' flavor symmetry with the features of a unified quiver gauge theory. The model accommodates the relationships between mixing angles separately for neutrinos, and for quarks, which have been previously predicted with T'. This quiver unification theory makes predictions of several additional gauge bosons and bifundamental fermions at the TeV scale.

[4]: Carl Albright, Robert Feger and I presented an SU(12) unification model with three light chiral families that avoids any external flavor symmetries [4]. The hierarchy of quark and lepton masses and mixings is explained by higher dimensional Yukawa interactions involving Higgs bosons

that contain SU(5) singlet fields with VEVs about 50 times smaller than the SU(12) unification scale. This model has been analyzed in detail and found to be in very good agreement with the observed quark and lepton masses and mixings. We are presently searching for models of this type with smaller gauge groups.

[5]: Paul H. Frampton, Chiu Man Ho and I studied a general class of minimally extended standard models (MESMs) with three generations [5]. Member of this class have gauge group $SU(3)_C \times SU(N)_L \times U(1)_X$ where for all $N \geq 3$, and anomaly cancellation requires three generations. At low energy, we recover the Standard Model (SM), while at higher energies, there must exist quarks, leptons and gauge bosons with electric charges shifted from their SM values by integer multiples of the electron charge up to $\pm[N/2]e$. Since the value $N = 5$ is the highest N consistent with QCD asymptotic freedom, we elaborated on the 3-5-1 model. The phenomenological possibilities in these MESMs are exciting. They predict fermions and gauge bosons of ever-increasing electric charge will appear as the available energy increases. At the LHC, we expect to see at least the quarks with charges $Q = -4/3$, $+5/3$ and the doubly-charged bileptons $Y^{\pm\pm}$, both corresponding to the new level $N = 3$.

[6]: HoSeong La and I have extended the chiral color model to incorporate technicolor [6], with induced dynamical breaking of the electroweak symmetry as well as chiral color to quantum chromodynamics. Gauge anomalies are canceled by introducing two generations of technifermions, and the fourth generation of quarks and leptons is required. Each technifermion generation is coupled to only two Standard Model generations by the Yukawa interaction. Various phenomenological implications are explained.

[7]: In a study of four families, Chiu Man Ho, P. Q. Hung and I investigated dynamical electroweak symmetry breaking with a fourth generation within the Z_n orbifolded $AdS_5 \otimes S^5$ framework [7]. A realistic Z_7 example was discussed. The initial theory reduces dynamically, due to the induced condensates, to a four-family trinification model near a TeV-scale conformal fixed point where the gauge hierarchy problem does not exist. We predict new gauge bosons and bifundamental fermions and scalars accessible by the LHC. While a sequential fourth family is disfavored by current LHC data (released after our paper was published), there are ways to relax the constraints by including additional Higgs fields, etc. (See e.g., X.-G. He and G. Valencia, Phys. Lett. B707, 381 (2012) for a discussion.) Our model should be reanalysed from this prospective.

[8]: Philipp Leser, Heinrich Päs and I have studied tight knots and links arising in the infrared limit of string phenomenology, and have argued that they may provide an interesting alternative to flavor symmetries for explaining the observed flavor patterns in the leptonic sector [8]. As an example we considered a type I seesaw model where the Majorana mass structure is based on the discrete length spectrum of tight knots and links. It was shown that such a model is able to provide an excellent fit to current neutrino data, and that it predicts a normal neutrino mass hierarchy as well as a small mixing angle θ_{13}.

[9]: Many discrete flavor models have potential problems with flavor changing neutral currents. In [9] Steve Barr and I have given a classification of Higgs-flavor models with several Higgs doublets in an irreducible multiplet R_Φ of a non-abelian symmetry G_Φ, under which the quarks and leptons do not transform (thus giving minimal flavor-changing for the fermions). It is found that different G_Φ and R_Φ lead to very distinctive spectra of the extra Higgs doublets, including different numbers of "sequential Higgs" and of "inert Higgs" that could play the role of dark matter, different mass relations, and different patterns of $SU(2)_L$-breaking splittings within the Higgs doublets.

[10]: Robert Feger and I have produced a group theory tool that is primarily directed toward particle physics model builders, but we believe it will find broader application and benefit others as well. Our Mathematica application LieART [10] (Lie Algebras and Representation Theory) is meant for computations frequently encountered in Lie Algebras and representation theory, such as tensor product decomposition and subalgebra branching of irreducible representations. LieART can handle all classical and exceptional Lie algebras. It computes root systems of Lie algebras, weight systems and several other properties of irreducible representations. LieART's user interface has been created with a strong focus on usability, and this allows the input of irreducible representations via their dimensional names, while the output is in the textbook style (or LaTeX if desired) used in most particle physics publications. The unique Dynkin labels of irreducible representations are used internally, and can also be used for input and output. LieART exploits the Weyl reflection group for most of the calculations, resulting in fast computations and a low memory consumption. Extensive tables of properties, tensor products and branching rules of irreducible representations are included in the appendix of the companion paper [8]. LieART is effectively the Slansky tables in dynamic form.

[17]: My work with Roman Buniy on topology and physical systems has continued during the last several year. Our focus has returned to the model of glueballs as linked/knotted chromoelectric flux tubes. Recently our mathematics collaborators, Jason Canterella and Eric Rawdon, have been releasing an extensive set of knot and link length data. The combination of these results with recent experimental data has allowed us to do a refit of our model of f_J states. A comprehensive paper has recently been published [17].

[18]: Fampton, Ho and I present an extended 331 model with T' discrete flavor symmetry[18] that simultaneously explains the need to have exactly three generations and provides acceptable quark and lepton masses and mixings. New fermionic states and gauge bosons are predicted within the reach of the LHC. We discuss the relevance to the 126 GeV scalar discovered at the LHC.

Cosmology:

[11]: Roman Buniy and I proposed a generic mechanism by which cosmological constant problem is avoided at tree level by embedding the theory into a larger theory [11]. The metric and the scalar field coupling constants in the original theory do not need to be fine-tuned, while the extra scalar field parameters and the metric associated with the extended theory are fine-tuned dynamically. Hence, no fine-tuning of parameters in the full Lagrangian is needed for the vacuum energy in the new physical system to vanish at tree level. The full cosmological constant problem can be solved if the method can be extended to quantum loops.

[12]: Chiu Man Ho and I consider a $4+N$ dimensional Einstein gravity coupled to a non-linear sigma model [12]. This theory admits a solution in which the N extra dimensions contract exponentially, while the ordinary space expands exponentially. Physically, the non-linear sigma fields induce the dynamical compactification of the extra dimensions, which in turn drives inflation. No inflatons are required.

[13]: In [13] Ho, Djordje Minic, Jack Ng, and I study spacetime emergence which 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. In this article, we propose 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.

Quantum Mechanical Entanglement:

[14,15]: In work that grew out of discussions of entanglement and black holes, Roman Buniy and I have proposed new measures that distinguish and classify entangled states [14]. The measures are algebraic invariants of linear maps associated with the states. Considering qubits as well as higher spin systems, we obtained complete entanglement classifications for cases that were either unsolved or only conjectured in the literature. Our classification [15] is based on the analysis of algebraic properties of linear maps associated with the states. The kernels of the maps define algebraic invariants, which are new discrete measures of entanglement. We prove a theorem on a correspondence between the invariants and sets of equivalent classes of entangled states. The new method works for an arbitrary finite number of finite-dimensional state subspaces. As an example of the method, we considered a large selection of cases of three subspaces of various dimensions. We also obtain an entanglement classification of four qubits, where we find 27 fundamental sets of classes. This work is now being extended in collaboration with Robert Feger, with whom we have recent preliminary results on entanglement classifications of five and six qubits. It is hoped that our work will find practical application in the development of quantum computers or elsewhere.

Classical Field Theory:

[19]: Buniy and I proposed covariant and non-abelian generalizations of the magnetic helicity and Beltrami equation [19]. The gauge invariance, variational principle, conserved current, energy-momentum tensor and choice of boundary conditions elucidate the subject. In particular, we prove that any extremal of the Yang-Mills action functional $\frac{1}{4}\int_\Omega trF_{\mu\nu}F^{\mu\nu}\,d^4x$ subject to the local constraint $\epsilon^{\mu\nu\alpha\beta}trF_{\mu\nu}F_{\alpha\beta}=0$ satisfies the covariant non-abelian Beltrami equation.

REFEREED PAPERS PUBLISHED OR SUBMITTED 1/1/2011 - 7/1/2014

1. "Natural fermion mass hierarchy and mixings in family unification," J. B. Dent, R. Feger, T. W. Kephart and S. Nandi, Phys. Lett. B **697**, 367 (2011).

2. "An A_5 Model of Four Lepton Generations," C.-S. Chen, T. W. Kephart and T.-C. Yuan, JHEP **1104**, 015 (2011).

3. "Quartification with T' Flavor," D. A. Eby, P. H. Frampton, X. -G. He and T. W. Kephart, Phys. Rev. D **84**, 037302 (2011).

4. "An explicit SU(12) family and flavor unification model with natural fermion masses and mixings," C. H. Albright, R. P. Feger and T. W. Kephart, Phys. Rev. D 86, 015012 (2012).

5. "Three Generations in Minimally Extended Standard Models," P. H. Frampton, C. M. Ho and T. W. Kephart, Phys. Lett. B **715**, 275 (2012).

6. "Techni-Chiral-Color," T. W. Kephart and H. La, Phys. Lett. B **710**, 654 (2012).

7. "Conformal Completion of the Standard Model with a Fourth Generation," C. M. Ho, P. Q. Hung and T. W. Kephart, JHEP **1206**, 045 (2012).

8. "Knotted strings and leptonic flavor structure," T. W. Kephart, P. Leser and H. Päs, Mod. Phys. Lett. A **27**, 1250224 (2012).

9. "A Classification and Analysis of Higgs-flavor Models," S. M. Barr and T. W. Kephart, Phys. Rev. D **85**, 035010 (2012).
10. "LieART – A Mathematica Application for Lie Algebras and Representation Theory," R. Feger and T. W. Kephart, [arXiv:1206.6379 [math-ph]].
11. "Toward solving the cosmological constant problem by embedding," R. V. Buniy and T. W. Kephart, Phys. Rev. D **86**, 023501 (2012).
12. "Inflatonless Inflation," C. M. Ho and T. W. Kephart, Int. J. Mod. Phys. A **27**, 1250151 (2012).
13. "Spacetime Emergence and General Covariance Transmutation," C. M. Ho, T. W. Kephart, D. Minic and Y. J. Ng, Mod. Phys. Lett. A **28**, 1350005 (2013).
14. "New Invariants for Entangled States," R. V. Buniy and T. W. Kephart, J. Phys. A: Math. Theor. **45** 182001(2012)
15. "An Algebraic Classification of Entangled States," R. V. Buniy and T. W. Kephart, J. Phys. A, 185304 (2012).
16. C. -S. Chen, T. W. Kephart and T. -C. Yuan, "Binary Icosahedral Flavor Symmetry for Four Generations of Quarks and Leptons," PTEP **2013**, no. 10, 103B01 (2013).
17. R. V. Buniy, J. Cantarella, T. W. Kephart and E. Rawdon, "The tight knot spectrum in QCD," Phys. Rev. D **89**, 054513 (2014).
18. P. H. Frampton, C. M. Ho and T. W. Kephart, ""Heterotic" Discrete Flavor Model," Phys. Rev. D **89**, 027701 (2014).
19. R. V. Buniy and T. W. Kephart, "Generalized helicity and Beltrami fields," Annals Phys. **344**, 179 (2014).

CONFERENCE TALKS and SEMINARS since January 2011:

- July 2011 "The tight knot spectrum in QCD," Centro di Ricerca Matematica Ennio De Giorgi, Scuola Normale Superiore, Pisa, Italy
- DEC 2011 "Flavor Symmetry for Four Generations of Quarks and Leptons," MIAMI'11, Fort Lauderdale, FL
- OCT 2012 "The Tight Knot Spectrum in QCD," University of Edinburgh, UK
- OCT 2012 "Higher Order Topological Phase: Generalizations of the Aharonov-Bohm Effect," Tangled Magnetic Fields in Astro- and Plasma Physics Isaac Newton Institute Workshop, TOD program International Centre for Mathematical Sciences, Edinburgh, UK
- NOV 2012 "Glueballs as Tight Knots," Isaac Newton Institute, Cambridge, UK
- DEC 2012 "The spectrum of tightly knotted flux tubes in QCD," Tangled Quantized Flux in Tightly Knotted and Linked Systems, Isaac Newton Institute Workshop, TOD program, Cambridge, UK
- DEC 2012 "Knotted flux tubes in QCD," MIAMI'12, Fort Lauderdale, FL

- MAY 2013 “Helicity Conservation and Beltrami Fields, Technische Universität Dortmund, Dortmund, Germany
- JULY 2013 “Minimal Family Symmetry,” FLASY13, Niigata, Japan
- JULY 2013 “Generalized Helicity Conservation and Beltrami Fields,” Academia Sinica, Nangang, Taiwan
- DEC 2013 “Generalized Helicity Conservation and Beltrami Fields,” MIAMI’13, Fort Lauderdale, FL
- MAR 2014 “Helicity Conservation and Beltrami Fields,” Simon Fraser University, Brunaby, BC, Canada

CONFERENCE CO-ORGANIZER/ADVISOR since January 2011 FOR:

- Miami 2011 December 2011, Fort Lauderdale, FL
- MIAMI 2012 December 2012, Fort Lauderdale, FL
- “Topology in Mechanics and Biology,” a five month program from 15 July–10 December, 2012 at the Isaac Newton Institute for Mathematical Sciences, Cambridge, UK
- International Advisory Board for FLASY12, Workshop on Flavor Symmetries Dortmund, 30 June–5 July 2012
- Workshop on ”Quantized Flux in Tightly Knotted and Linked Systems,” Chair International Scientific Committee for 3-7 December 2012, at the Isaac Newton Institute for Mathematical Sciences, Cambridge, UK
- International Advisory Board for FLASY13, Workshop on Flavor Symmetries Niigaga, Japan scheduled for July 2013
- MIAMI 2013 scheduled for December 2013, Fort Lauderdale, FL
- International Advisory Board for FLASY14, Workshop on Flavor Symmetries, (University of Sussex, Brighton, UK) June 2014
- MIAMI 2014 scheduled for December 2014, Fort Lauderdale, FL

Robert J. Scherrer, Co-PI

I published 12 refereed papers in the period from Jan. 1, 2011, to Jul. 1, 2014 [1-12], with two additional papers currently under review [13-14]. I supervised one graduate student (Hui-Yiing Chang), supported on an NSF graduate fellowship. Hui-Yiing has successfully defended her dissertation and will receive her Ph.D. in August. I supervised two undergraduate honors theses (Justin Menestrina and Jeff Swaney), each of which resulted in a published or submitted paper [4,14]. Justin and Jeff have both gone on to physics Ph.D. programs. I also collaborated extensively with our postdoc, Chiu Man Ho.

During this grant period I initiated a very productive collaboration with Paul Frampton and his graduate student, Kevin Ludwick. Our work was an attempt to classify the future evolution of models of the universe in which there is no future singularity, but for which the density increases monotonically with the expansion. Our original paper on these models [2] has garnered 63 citations, making it my most cited paper from the past three years, and the model we explored in that paper, which we dubbed the "little rip," has already become part of the lexicon of cosmology. In several follow-up papers, my collaborators and I explored specific models for the little rip [3,6]. With Frampton and Ludwick, I examined models in which the dark energy fluid has a density increasing with the expansion, but which are asymptotically de Sitter, a set of models we named the "pseudo-rip" [5].

A productive new research thrust during this grant period was the investigation of questions associated with cosmological limits on the number of effective neutrinos, N_{eff}. Some cosmological observations have suggested that $N_{eff} > 3$, although more recent experiments have suggested a value consistent with the standard model ($N_{eff} = 3$). Justin Menestrina and I examined a model which predicts a different value for N_{eff} determined from big bang nucleosynthesis (BBN) than the value derived from cosmic microwave background (CMB) experiments, namely a massive relic particle decaying into "dark" relativistic particles [4]. We derived the values of N_{eff} that would be predicted from both BBN and CMB experiments as a function of particle lifetime and mass. Chiu Man Ho and I used lower limits on N_{eff} to place bounds on MeV-scale dark matter [8]. Thermal dark matter annihilates significantly before it drops out of thermal equilibrium, and if this process occurs after the neutrinos decouple from the radiation background (as it does for MeV dark matter masses) then the result is a decrease in the ratio of the neutrino temperature to the photon temperature, resulting in a lower value for N_{eff}. Thus, lower bounds can be placed on the mass of the dark matter particle. In a follow-up paper, Ho and I examined a model containing both MeV-scale dark matter and additional sterile neutrinos [10]. Short baseline neutrino experiments suggest the existence of additional sterile neutrinos, but a model with two additional sterile neutrinos is ruled out by cosmological limits on N_{eff}. However, using the mechanism outlined in Ref. [8], we showed that a 3+2 neutrino model can be made consistent with these cosmological limits if MeV dark matter is also present. The annihilations of the dark matter particles decrease N_{eff} enough to compensate for the increase from the additional sterile neutrinos.

Both of these papers with Chiu Man Ho actually grew out of an earlier project on anapole dark matter [9]. There has been a great deal of recent interest in dark matter with an electric or magnetic dipole moment. However, both of those moments are forbidden for Majorana particles. Ho and I investigated the anapole moment (first proposed in the 1950s by Zel'dovich) which is the only allowed electromagnetic moment for Majorana dark matter. We showed that anapole dark matter has a number of interesting properties. Unlike electric or magnetic dipole dark matter, it annihilates only into fermion-antifermion pairs at tree level, and only via p-wave interactions. We calculated the relic abundance and direct detection signal for this model, and showed that the cross section required to give the correct relic abundance lies just below the current detection threshold in direct-detection experiments. Our work on anapole dark matter garnered a great deal of attention. With Yu Gao and Ho, I recently examined LHC limits on anapole dark matter [12]. We showed that LHC data already constrain the mass of such a particle to be larger than 100 GeV.

During the past three years I also continued my research program on the nature of the dark energy in the universe, which remains one of the most important unsolved problems in physics. My student, Hui-Yiing Chang, and I examined the coincidence problem in cyclic phantom models of the universe [7]. In such models, the universe cycles through periods of radiation domination, dark matter domination, and dark energy domination. We were able to show that such models provide a natural solution to the coincidence problem, i.e., the fact that we happen to live when the matter and dark energy densities are of the same order of magnitude. Hui-Yiing and I also completed a project on dark energy from scalar fields with an inflection point potential [11]. These scalar field potentials have been invoked as models for inflation, but we were the first to investigate them in the context of dark energy. Our results showed that such models can produce an accelerated expansion that is consistent with current observations, but this acceleration can be either transient or permanent, depending on the model parameters. I also completed two papers [1,14] as part of an ongoing effort to classify and describe scalar fields models in which the equation of state is close to that of a cosmological constant, as observations require. Ref. [14], in particular, is a generalization of most of my previous work on the subject.

REFEREED PAPERS PUBLISHED OR SUBMITTED 1/1/2011 - 7/1/2014

[1] Slow-roll freezing quintessence, S. Dutta and R. J. Scherrer, Phys. Lett. B, **704**, 265 (2011).

[2] The little rip, P. H. Frampton, K. J. Ludwick, and R. J. Scherrer, Phys. Rev. D, **84**, 063003 (2011).

[3] Models for little rip dark energy, P. H. Frampton, K. J. Ludwick, S. Nojiri, S. D. Odintsov, and R. J. Scherrer, Phys. Lett. B **708**, 204 (2012).

[4] Dark radiation from particle decays during big bang nucleosynthesis, J. L. Menestrina and R. J. Scherrer, Phys. Rev. D **85**, 047301 (2012).

[5] The pseudo-rip: Cosmological models intermediate between the cosmological constant and the little rip, P. H. Frampton, K. J. Ludwick, and R. J. Scherrer, Phys. Rev. D **85**, 083001 (2012).

[6] Scalar dark energy models mimicking ΛCDM with arbitrary future evolution, A. V. Astashenok, S. Nojiri, S. D. Odintsov, and R. J. Scherrer, Phys. Lett. B **713**, 145 (2012).

[7] Coincidence problem in cyclic phantom models of the universe, H.-Y. Chang and R. J. Scherrer, Phys. Rev. D **86**, 027303 (2012).

[8] Limits on MeV dark matter from the effective number of neutrinos, C. M. Ho and R. J. Scherrer, Phys. Rev. D **87**, 023505 (2013).

[9] Anapole dark matter, C. M. Ho and R. J. Scherrer, Phys. Lett. B, **722**, 341 (2013).

[10] Sterile neutrinos and light dark matter save each other, C. M. Ho and R. J. Scherrer Phys. Rev. D, **87**, 065016 (2013).

[11] Inflection point quintessence, H.-Y. Chang and R. J. Scherrer, Phys. Rev. D, **88**, 083003 (2013).

[12] Anapole dark matter at the LHC, Y. Gao, C. M. Ho, and R. J. Scherrer, Phys. Rev. D, **89**, 045006 (2014).

[13] Constraining primordial non-Gaussianity with moments of the large scale density field, Qingqing Mao, Andreas A. Berlind, Cameron K. McBride, Robert J. Scherrer, Roman Scoccimarro, and Marc Manera, Mon. Not. Roy. Astr. Soc., in press [arXiv:1404.3725].

[14] The quadratic approximation for quintessence with arbitrary initial conditions, J. R. Swaney and R. J. Scherrer, Phys. Rev. D, submitted [arXiv:1406.6026].

INVITED TALKS

"Anapole Dark Matter", seminar, Ohio State University, Aug. 2012.

"Anapole Dark Matter", seminar, University of Pennsylvania, Jan. 2013.

"Update/Review of Cosmological Estimates of Neutrino Number," invited presentation, Cosmic Frontier Workshop at SLAC (Snowmass March Meeting), Mar. 2013.

"Anapole Dark Matter", seminar, University of Florida, Aug. 2013.

“Could Dark Matter be Electromagnetic?” colloquium, Vanderbilt University, Oct. 2013.

“From Theorist’s Playground to Precision Science: The Evolution of Modern Cosmology”, colloquium, Lehigh University, Apr. 2014.

PUBLIC/POPULAR LECTURES

“Quantum Mechanics and Time Travel”, public lecture, Belcourt Theater, Mar. 2014.

“Science and Science Fiction”, colloquium, Nashville State Community College, Apr. 2014.

Thomas J. Weiler, Co-PI

In the time period January 1, 2011–present, I (Weiler) published sixteen papers in refereed journals, with four more submitted papers pending. In addition to myself, there are twenty-eight different co-authors on these papers, excluding the JEM-EUSO collaborators, distributed over three continents. Topics of these papers are new three-body dark matter annihilation modes and their signatures; LHC tests for dark matter, and for the effective number of spatial dimensions at $\sqrt{s} \sim$7-14 TeV; tests of Centaurus A as the dominant "local" cosmic ray source; apparent acausal travel for Higgs singlets (or sterile neutrinos) at the LHC; the role of neutrino flavors in distinguishing among cosmic neutrino acceleration mechanisms; a symmetry-motivated model for neutrino masses and mixings; extending the LHC reach in energy with dispersion relations; and aspects of the recent IceCube discovery of high-energy extraterrestrial neutrinos.

Included among the co-authors of these twenty papers are two of our formerly DOE-funded postdocs, J.B. Dent and C.M. Ho, and two partially DOE-funded graduate students, Lingjun Fu and Peter Denton. I discuss the physics content of these papers in some detail below the bibliography.

Sixteen conference talks, eleven colloquia, and two seminars were presented during this period.

In service, I am an editor for the Journal of Astroparticle Physics. On the outreach level, I presented an invited TEDx talk to about 1000 (non-scientist) paid attendees at a regional TEDx conference on 31 March 2012. The venue was the Tennessee Performing Arts Center in downtown Nashville. The title of the presentation was "Neutrinos, Einstein, Time, and Paradox". The talk is available on Youtube, at
http://www.youtube.com/playlist?list=PLD335D225669C4BAA

In 2014, I asked for and received a calendar-year research leave of absence from Vanderbilt University at half-salary. The "other" half, plus travel money for myself and my two graduate students, is provided by a Simons Fellowship.

PAPERS PUBLISHED IN, OR SUBMITTED TO, REFEREED JOURNALS SINCE 1 JAN, 2011:

1. **W/Z Bremsstrahlung as the Dominant Annihilation Channel for Dark Matter**, with N.F. Bell, J.B. Dent, and T.D. Jacques, Phys. Rev. **D83**, 013001 (2011), and arXiv:1009.2584 [hep-ph].

2. **Searching for the Layered Structure of Spacetime with the LHC**, with L. Anchordoqui, D.C. Dai, H. Goldberg, G. Landsberg, G. Shaughnessy, and D. Stojkovic, Phys. Rev. **D83**, 114046 (2011), and arXiv:1012.1870 [hep-ph].

3. **Dark Matter Annihilation Signatures from Electroweak Bremsstrahlung**, with N.F. Bell, J.B. Dent, and T.D. Jacques, Phys. Rev. **D84**, 103517 (2011), and arXiv:1101.3357 [hep-ph].

4. **Update on Tests of the Cen A Neutron-Emission Model of Highest Energy Cosmic Rays**, with L.A. Anchordoqui and H. Goldberg, Phys. Rev. **D84**, 067301 (2011), and arXiv:1103.0536 [astro-ph.HE].

5. **Causality–Violating Higgs Singlets at the LHC**, with C.M. Ho, Phys. Rev. **D87**, 045004 (2013), and arXiv:1103.1373 [hep-ph], and Erratum, Phys. Rev. **D87**, 045004 (2013).

6. **W/Z Bremsstrahlung as the Dominant Annihilation Channel for Dark Matter – Revisited**,

with N.F. Bell, J.B. Dent, A.J. Galea, T.D. Jacques, and L.M. Krauss,
Phys. Lett. **B706**, 6 (2011), and arXiv:1104.3823 [hep-ph].

7. **A Model of Superluminal Neutrinos**,
with D. Marfatia, H. Pas, and S. Pakvasa,
Phys. Lett. **B707**, 553 (2012), and arXiv:1112.0527 [hep-ph].

8. **Searching for Dark Matter at the LHC with a Mono-Z**,
with N.F. Bell, J.B. Dent, A.J. Galea, T.D. Jacques, and L.M. Krauss,
Phys. Rev. **D86**, 096011 (2012), and arXiv:1209.0231 [hep-ph].

9. **Physical and Stable Closed Timelike Curves**,
with C.M. Ho, Mod. Phys. Letters **A28**, 1250237 (2013), and arXiv:1209.3107 [gr-qc].

10. **Cosmic Neutrino Flavor Ratios with Broken ν_μ-ν_τ Symmetry**,
with Lingjun Fu and Chiu-Man Ho, Phys. Lett. **B718**, 558 (2012), and arXiv:1209.5382 [hep-ph].

11. **An Evaluation of Exposure in Nadir Observation of the JEM-EUSO Mission**, J.H. Adams et al. [JEM-EUSO Collaboration],
Astropart. Phys. **44**, 76 (2013), and arXiv:1305.2478 [astro-ph.HE].

12. **Pinning Down the Cosmic Ray Source Mechanism with New IceCube Data**,
with L.A. Anchordoqui, H. Goldberg, M.H. Lynch, A.V. Olinto, and T.C. Paul,
Phys. Rev. **D89**, 083003 (2014), and arXiv:1306.5021 [astro-ph.HE].

13. **Using Integral Dispersion Relations to Extend the LHC Reach for New Physics**,
with P.B. Denton, Phys. Rev. **D89**, 035013 (2014), and arXiv:1311.1248.

14. **Simple Mass Matrix Ansätze for Neutrino Mixing**,
with Hoseong La, submitted, and arXiv:1311.1550.

15. **Cosmic Neutrino Pevatrons: A Brand New Pathway to Astronomy, Astrophysics, and Particle Physics**,
with L. A. Anchordoqui, V. Barger, I. Cholis, H. Goldberg, D. Hooper, A. Kusenko, J. G. Learned and D. Marfatia, S. Pakvasa, and T. C. Paul,
Journal of High Energy Astrophysics **1-2**, 1 (2014), and arXiv:1312.6587 [astro-ph.HE].

16. **Weinberg's Higgs portal confronting recent LUX and LHC results together with upper limits on B^+ and K^+ decay into invisibles**,
with L. A. Anchordoqui, L. H. M. Da Silva, P. B. Denton, H. Goldberg, T. C. Paul, and B. J. Vlcek, Phys. Rev. **D89**, 083513 (2014), and arXiv:1312.2547 [hep-ph].

17. **Reply to "Comment on causality-violating Higgs singlets at the LHC"**
(by S. Gielen, Phys. Rev. **D88**, 068702 (2013)),
with C. M. Ho, Phys. Rev. **D88**, no. 6, 068702 (2013).

18. **End of the cosmic neutrino energy spectrum**,
with L. A. Anchordoqui, V. Barger, H. Goldberg, J. G. Learned, D. Marfatia, S. Pakvasa, and T. C. Paul, submitted, and arXiv:1404.0622 [hep-ph].

19. **A Relational Argument for a ~PeV Neutrino Energy Cutoff**,
with J. G. Learned, submitted, and arXiv:1407.0739 [astro-ph.HE].

20. **Glashow resonance as a window into cosmic neutrino sources**, with V. Barger, L. Fu, J. G. Learned, D. Marfatia, and S. Pakvasa, to be submitted, will appear on the arXiv on 11July, 2014.

The physics content of these publications is the following:

Papers [1, 3, 6]: Here it was shown for the first time that for the many dark matter models which feature a helicity suppressed annihilation rate to fermions (e.g. SUSY), radiating a massive gauge boson in addition to the final state fermions removes this helicity suppression; therefore, the branching ratios $Br(l\nu W)$, $Br(l^+l^-Z)$, and $Br(\nu\bar{\nu}Z)$ will dominate over $Br(l\bar{l})$ in some regions of parameter space. Dark matter annihilation to leptons, $\chi\chi \to l\bar{l}$, is therefore necessarily accompanied by significant electroweak radiation in parts of parameter space, necessitating accompanying protons, antiprotons, and gamma rays from W and Z production and decay. Significantly, W/Z-bremsstrahlung thus allows indirect detection of many WIMP models that would otherwise be helicity-suppressed, or v^2 suppressed. Antiprotons and even anti-deuterons become consequential final state particles. This is an important result for "leptonic" DM models which aim to fit recent cosmic ray positron and antiproton data, and for future DM searches. In this work we also develop Fierz transformation rules for the mode 2 fermions $\to$ 2 fermions + boson.

We revisited the calculation of electroweak bremsstrahlung contributions to dark matter annihilation presented in our earlier work, correcting some calculations and extending the calculation to one order higher in the ratio of the dark matter mass to the mass of the boson which mediates the annihilation process. We found that the electroweak signal is most significant when these two masses are nearly degenerate.

We calculated the spectra of stable annihilation products produced via gamma/W/Z-bremsstrahlung. After modifying the fluxes to account for the propagation through the Galaxy, we set upper bounds on the annihilation cross section via a comparison with observational data. We showed that stringent cosmic ray antiproton limits preclude a sizable dark matter contribution to observed cosmic ray positron fluxes for the common class of models in which the bremsstrahlung processes dominate.

Paper [2]: Alignment of the main energy fluxes along a straight line in a target plane has been observed in families of cosmic ray particles detected in the Pamir mountains. The fraction of events with alignment is statistically significant for families with superhigh energies and large numbers of hadrons. This can be interpreted as evidence for coplanar hard-scattering of secondary hadrons produced in the early stages of the atmospheric cascade development. This phenomenon lends some support to the recently proposed "crystal world," with latticized and anisotropic spatial dimensions. Planar events are expected to dominate particle collisions at a hard-scattering energy exceeding the scale Λ_3 at which space transitions from $3D \rightleftharpoons 2D$. We studied specific collider signatures that will test this hypothesis. At the LHC, two jet and three jet events are necessarily planar, but four or more jet events can test the hypothesis. Accordingly, we studied in a model-independent way the 5σ discovery reach of the ATLAS and CMS experiments for identifying four jets coplanarities. For the extreme scenario in which all $pp \to 4jet$ scattering processes become coplanar above Λ_3, we showed that with an integrated luminosity of $10(100)fb^{-1}$, the LHC experiments have the potential to discover correlations between jets if $\Lambda_3 \lesssim 1.25(1.6)$ TeV. We also showed in this framework that the energy-spectrum of Drell-Yan scattering is significantly modified at $\sqrt{s} \gtrsim \Lambda_3$.

Paper [4]: We proposed that neutron emission from Cen A dominates the cosmic ray sky at the high end of the spectrum. Neutrons that are able to decay generate proton diffusion fronts, whereas those that survive decay produce a spike in the direction of the source. We used recent data reported by the Pierre Auger Collaboration to normalize the injection spectrum and estimate the required luminosity in cosmic rays. We found that such a luminosity, $L_{CR} \sim 5 \times 10^{40}$ erg/s, is considerably smaller than the bolometric luminosity of Cen A, $L_{bol} \sim 10^{43}$ erg/s. We computed the incoming current flux density as viewed by an observer on Earth and showed that the anisotropy amplitude is in agreement with data at the 1σ level. Regardless of the underlying source model, our results indicated that after a decade of data taking the Pierre Auger Observatory will be able to test our proposal, as will the proposed EUSO experiment after three years aboard the ISS.

Papers [5, 9, 17]: We constructed a class of closed timelike curves (CTCs) using a compactified extra dimension u. A nonzero metric element $g_{tu}(u)$ enables particles to travel backwards in global time t. The compactified dimension guarantees that the geodesic curve closes in u. The effective 2D (t and u) nature of the metric ensures that spacetime is flat, therein satisfying all the classical stability conditions as expressed by the energy conditions. Finally, stationarity of the metric guarantees that a particle's energy is conserved. The pathologies that plague many hypothesized metrics admitting CTCs, e.g. an infinite cylinder of matter, a negative energy-distribution, particle acceleration/blue-shifting along the CTC, do not occur within our metric class. This relatively simple metric model can be used in the future to study realizations, or lack thereof, of Hawking's chronology protection conjecture, and to study the nature of possible acausality in particle physics.

We extended the model to study possible acausal signatures at Large Hadron Collider (LHC). In extra-dimensional models where gauge charges are bound to our brane, it is the KK modes of gauge-singlets that may travel through the CTCs. From our brane point of view, many of these KK modes would appear to travel backward in time. We displayed a model in which such time-traveling Higgs singlets can be produced by the LHC, either from decay of the Standard Model Higgses or through mixing with the SM Higgses. The signature of these time-traveling singlets is a secondary decay vertex pre-appearing *before* the primary vertex which produced them. The two vertices are correlated by momentum conservation. We demonstrated that pre-appearing vertices in the Higgs singlet-doublet mixing model may well be observable at the LHC.

Paper [7]: Motivated by the observation of superluminal neutrinos by the OPERA experiment, we presented a model of active-sterile neutrino oscillations in which sterile neutrinos are superluminal and active neutrinos appear superluminal by virtue of neutrino mixing. The model demonstrates some interesting possibilities but especially some serious challenges that apply to models with new particles in extra dimensions attempting to explain the OPERA result. Fortunately for conventional physics, the OPERA observation was later shown to be wrong.

Paper [8]: We investigated a mono-Z process as a potential dark matter search strategy at the LHC. In this channel a single Z boson recoils against missing transverse momentum, attributed to dark matter particles, χ, which escape the detector. This search strategy is related, and complementary to, mono-jet and mono-photon searches. For illustrative purposes we considered the process $q\bar{q} -> \chi\chi Z$ in a straightforward dark matter model, where the Z boson is emitted from either the initial state quarks, or from the internal propagator. Among the signatures of this process are a pair of muons with high p_T that reconstruct to the invariant mass of the Z, and large amounts of missing transverse energy. Being a purely electroweak signal, QCD and other Standard Model backgrounds are relatively easily removed with modest selection cuts. We compared the signal to Standard Model backgrounds and demonstrated that, even for conservative cuts, there exist regions of parameter space where the signal may be clearly visible above background in future LHC data, allowing either new discovery potential or the possibility of supplementing information about the dark sector beyond that available from other observable channels.

Papers [10 and 14]: Reactor neutrino experiments have now observed a nonzero value for θ_{13} at 5σ, and global fits to data imply a nonzero value above 10σ. Nonzero values for θ_{13} and/or $\theta_{32} - \pi/4$ break a ν_μ-ν_τ symmetry, which has qualitative as well as quantitative implications for the time-evolution of neutrino flavors. In particular, the large-distance flavor evolution matrix, non-invertible with ν_μ-ν_τ symmetry, is now invertible. This means that measurements of neutrino flavor ratios at Earth can now be inverted to directly reveal the flavor ratios injected at cosmically distant sources. With the updated values of the three neutrino mixing angles, we obtained the inverted large-distance evolution matrix and use it to derive several phenomenological relations between the injection flavor ratios and the observable ratios at Earth. Taking three popular injection models as examples, we also exhibited the shift of Earthly observed flavor ratios from the corresponding values in the case with ν_μ-ν_τ symmetry.

In thematically related work, we estimated the PMNS (Pontecorvo-Maki-Nakagawa-Sakata) matrix in terms of neutrino and charged lepton mixing given as $U_{\rm PMNS} = V^\dagger_{\rm lep}(\tilde\theta_{13})U_\nu(\tilde\theta_{23},\tilde\theta_{12})$. This form results from a new (emergent) global lepton flavor symmetry. The neutrino and charged lepton mass matrices have simple textures. The resulting $U_{\rm PMNS}$ gives excellent agreement with experimental data (including $|U_{e3}| = 0.16$).

Paper [11]: We evaluated the exposure during nadir observations with JEM-EUSO, the Extreme Universe Space Observatory, onboard the Japanese Experiment Module of the International Space Station. Designed as a mission to explore the extreme energy Universe from space, JEM-EUSO will monitor the Earth's nighttime atmosphere to record the ultraviolet light from tracks generated by extensive air showers initiated by ultra-high energy cosmic rays. In the present work, the particularities of space-based observation are discussed and the annual exposure in nadir observation is computed. The results are based on studies of the expected trigger aperture and observational duty cycle, as well as, on the investigations of the effects of clouds and different types of background light. We showed that the annual exposure is about one order of magnitude higher than those of the presently operating ground-based observatories.

Papers [12, 15, 18, 19, 20]: In 2012, the IceCube Collaboration has reported an observation of 28 neutrino candidates over 2yrs with energies between 50 TeV and 2 PeV, constituting a 4.3σ excess compared to the atmospheric background. A third year of data has now pushed the significance above 5σ. In [12] we investigated the compatibility between the data and a hypothesized unbroken power-law neutrino spectrum for various values of spectral index $\Gamma \geq 2$. We showed that $\Gamma \sim 2.3$ is consistent at the $\sim 1.5\sigma$ level with the observed events up to 2 PeV, and to the null observation of events at higher energies. We then assumed that the sources of this unbroken spectrum are Galactic, and deduced (i) an energy-transfer fraction from parent protons to pions (finding $\epsilon_{\pi^\pm}$ and ϵ_π), and (ii) a way of discriminating among models which have been put forth to explain the "knee" and "ankle" features of the cosmic ray spectrum. Future IceCube data will test the unbroken power law hypothesis and provide a multi-messenger approach to elucidating features of the cosmic ray spectrum, including the transition from Galactic to extragalactic dominance.

The announcement by the IceCube Collaboration of the observation of 28 cosmic neutrino candidates has been greeted with a great deal of justified excitement. The data reported so far depart by 4.3σ from the expected atmospheric neutrino background, which raises the obvious question: "Where in the Cosmos are these neutrinos coming from?" We reviewed the many possibilities which have been explored in the literature to address this question, including origins at either Galactic or extragalactic celestial objects. For completeness, we also briefly discussed new physics processes which may either explain or be constrained by IceCube data. This paper is an invited contribution to the inaugural issue of the Journal of High-Energy Astrophysics.

There may be a high-energy cutoff of neutrino events in IceCube data. In particular, IceCube does not observe the Standard Model Glashow-resonance events expected at 6.3 PeV. There are also no higher-energy neutrino signatures in the ANITA and Auger experiments. This absence of high-energy neutrino events motivates models with a fundamental restriction on neutrino energies above a few PeV. The simplest scenario to terminate the neutrino spectrum is Lorentz-invariance violating with a limiting neutrino energy, leading to a velocity that is smaller than the speed of light. If the limiting energy of the neutrino applies also to its associated charged lepton, then a significant consequence is that charged pions are stable above two times the maximum neutrino energy; such stabilized pions may serve as cosmic ray primaries. We explained these features in our paper.

In a separate paper, we presented a relationship, $E_\nu^{\max} = m_\nu M_{\mathrm{Planck}}/M_{\mathrm{weak}}$, among the highest observed neutrino energy (∼PeV) and the neutrino mass, the weak scale, and the Planck energy. We then discussed some tests of this relationship, and presented some theoretical constructs which motivate the relationship. It is possible that all massive particles are subject to maximum energies given by similar relationships, although only the neutrino seems able to offer interesting phenomenology. We discussed implications which include no neutrino detections at energies greater than ∼PeV (in the Cosmic Rest Frame ≈ Earth frame), and changes in expectations for the highest energy cosmic rays. A virtue of this hypothesis is that it is easily invalidated should neutrinos be observed with energies much great than the PeV scale. An almost inescapable implication is that Lorentz Invariance is a low energy phenomenon; yet it appears that its violation may be only observable in high-energy astrophysical neutrino data.

The Glashow resonance at $E_\nu = 6.3$ PeV is a measure of the $\bar{\nu}_e$ content of the astrophysical neutrino flux. The fractional $\bar{\nu}_e$ content depends on the neutrino production model at the cosmic neutrino source, and the environment at the source. Thus, the strength of the Glashow resonance event rate is a potential window into astrophysical sources. We quantified the ability of this "Glashow resonometer" to discriminate among six popular models of cosmic neutrino sources, and commented on the significance that no Glashow events are observed in the IceCube 3yr data.

Paper [13]: Many models of electroweak symmetry breaking predict new particles with masses at or just beyond LHC energies. Even if these particles are too massive to be produced on-shell at the LHC, it may be possible to see evidence of their existence through the use of integral dispersion relations (IDRs). Making use of Cauchy's integral formula and the analyticity of the scattering amplitude, IDRs are sensitive in principle to changes in the cross section at arbitrarily large energies. We investigated some models of new physics. We found that a sudden, order one increase in the cross section above new particle mass thresholds can be inferred well below the threshold energy. On the other hand, for two more physical models of particle production, we showed that the reach in energy and the signal strength of the IDR technique is greatly reduced. The peak sensitivity for the IDR technique is shown to occur when the new particle masses are near the machine energy, an energy where direct production of new particles is kinematically disallowed, phase-space suppressed, or in some cases, suppressed by the soft parton distribution functions. Thus, IDRs do extend the reach of the LHC, but only to a window around $M_\chi \sim \sqrt{s_{\mathrm{LHC}}}$.

Paper [16]: We discussed a number of experimental constraints on Weinberg's Higgs portal model, which extends the standard model (SM) to include one complex scalar field S and one Dirac fermion ψ. These new fields are singlets under the SM gauge group and are charged under a global U(1) symmetry. Breaking of this U(1) symmetry results in a massless Goldstone boson α and a massive CP-even scalar r, and splits the Dirac fermion into two new mass-eigenstates $\psi_\pm$, corresponding to Majorana fermions. The interest on such a minimal SM extension is twofold. On the one hand, if the Goldstone bosons are in thermal equilibrium with SM particles until the era of muon annihilation, then their contribution to the effective number of neutrino species can explain the excess suggested by cosmological observations of the surface of last scattering. On the other hand, the lightest Majorana fermion ψ_- provides a plausible dark matter candidate. We constrained the parameter space of r–Higgs doublet ϕ mixing using a variety of experimental data, including heavy meson decays with missing energy, the invisible Higgs width, and direct dark matter searches. We found that current results narrow the parameter space significantly, but still leave room for discovery. In the near future, measurements from ATLAS, CMS, LHCb, NA62, XENON1T, LUX, and CDMSlite will probe nearly the full parameter space.

SEMINARS and COLLOQUIA

1. UNC-Chapel Hill (14 February 2011) - colloquium
2. UNC-Chapel Hill (15 February 2011) - seminar
3. Vanderbilt University (20 October 2011) - colloquium
4. U. Wisconsin-Milwaukee (9 December 2011) - colloquium
5. University of Wisconsin at Milwaukee, WI (30 November, 2012) -colloquium
6. University of Western Kentucky, Bowling Green KY (19 March, 2012) - colloquium
7. University of Kansas, Lawrence, KS (April 16, 2012) - colloquium
8. University of Louisiana at Lafayette, (20 February, 2013) - colloquium
9. U. Wisconsin-Milwaukee (7 May 2013) - colloquium
10. Clemson University, Clemson, South Carolina (November 22, 2013) - colloquium
11. University of Hawaii, Honolulu, HI (February 7, 2014) - colloquium
12. University of Hawaii, Honolulu, HI (February 28, 2014) - seminar
13. Melbourne University, Australia (March 19, 2014) - colloquium

CONFERENCE/WORKSHOP TALKS/PARTICIPATION:

1. 2011 Talk at "NuSky: Looking at the Neutrino Sky", ICTP, Trieste, Italy, June 20-24.
2. 2011 Talk at "LHC Workshop", Aspen Center for Physics, CO, July 3-24.
3. 2011 Talk at "PACIFIC 2011", Moorea, French Polynesia, Sept. 8-14.
4. 2012 Talk on "Acausality in Extra Dimensions", at "LVNU (Lorentz Violating Neutrinos) 2012", Bloomington, IN, March 12-13.
5. 2012 Talk on "Acausality in Extra Dimensions", at "What's nu?", Galileo Galilei Institute (GGI), Florence, Italy, June 11-30.
6. 2012 Talk on "Acausality in Extra Dimensions", "Flavor Symmetry (FLASY) 2012", Dortmund, Germany, June 30-July 4.
7. 2012 Talk on "Dark Matter Indirect Signatures", "DUSEL Dark Matter and Neutrino Theory Workshop", Lead, South Dakota, July 14-27.
8. 2013 Talk on "Advantages of Space-Based Cosmic-Ray Observatory", "SLAC pre-Snowmass Cosmic Frontier Workshop", Stanford, CA, March 6-9.
9. 2013 Talk on "Advantages of Space-Based Cosmic-Ray Observatory", APS April Meeting (DAP parallel session), Denver, CO, April 13-16.

10. 2013 Talk on "Advantages of Space-Based Cosmic-Ray Observatory", KITP/U. Chicago Theory Workshop on "Imaging the Extreme Universe", May 7-8.

11. 2013 Talk on "Advantages of Space-Based Cosmic-Ray Observatory", 2nd annual International Particle Astrophysics (IPA) conference, U. Wisconsin, May 13-15.

12. 2013 Invited theory overview talk at annual CMS Collaboration Mtg, Vanderbilt U., May 20-22.

13. 2013 Talk on Dark Matter Signatures, "ICRC2013" at Rio de Janeiro, Brazil, July 2-9.

14. 2013 Poster on Cosmic Ray Anisotropies, "ICRC2013" at Rio de Janeiro, Brazil, July 2-9.

15. 2013 Talk on "Broken ν_μ-ν_τ Symmetry", 16th "Lomonosov" Neutrino Conference, Moscow, Russia, Aug. 22-28.

16. 2014 Nordita "News in Neutrino Physics", Stockholm, Sweden, April 7-May 2.

17. 2014 Talk on "The Glashow Resonometer, and a Possible Cosmic PeV Neutrino Cutoff", Garching, Germany, "Neutrinos in Astro- and Particle Physics", June 30-July 25.

CONFERENCE PROCEEDINGS/WHITE PAPERS/ENCYCLOPEDIA ARTICLES:

- **New, Classically Stable, Closed Timelike Curves (CTCs)**,
  with Chiu Man Ho, Proc. 2nd Workshop on Flavor Symmetries and Consequences in Acclerators and Cosmology (FLASY12), Dortmund, Germany, 30 June-4 July, 2012 arXiv:1210.6239 [hep-ph].

- **The JEM-EUSO Mission: Status and Prospects in 2011**,
  The JEM-EUSO Collaboration, 33 collected contributions to the 32^{nd} International Cosmic Ray Conference, Beijing, China, Aug. 11-18, 2011 [arXiv:1204.5065].

- **Summary Report of JEM-EUSO Workshop at KICP in Chicago**,
  with J. H. Adams Jr., L. A. Anchordoqui, M. Bertaina, M. J. Christl, V. Connaughton, S. E. Csorna, T. Ebisuzaki, G. Medina-Tanco, A. V. Olinto, T. Paul, P. Picozza, A. Santangelo, K. Shinozaki, and L. Wiencke,
  KICP, U. Chicago, IL, Feb.$\tilde{2}$0-22, 2012 [arXiv:1203.3451].

- **On the Likely Dominance of WIMP Annihilation to Fermion Pair+W/Z (and Implication for Direct Detection)**,
  Proc. 2nd CETUP* Workshop, AIP Conf. Proc. 1534, 154-177 (2012), Lead, South Dakota, June-July, 2012, and arXiv:1301.0021 [hep-ph].

- **Sensitivity of Orbiting JEM-EUSO to Large Scale Cosmic-Ray Anisotropies**,
  with P.B. Denton, L.A. Anchordoqui, A. Berlind, and M. Richardson [for the JEM-EUSO Collaboration],
  in Proceedings of the 33rd International Cosmic Ray Conference (ICRC 2013), Rio de Janeiro, Brazil, 2-9 July 2013 (id 0631), arXiv:1307.7071, [astro-ph.IM], pp. 43-46.

- **JEM-EUSO Science Capabilities**,
  with G. Medina-Tanco, L.A. Anchordoqui, A.V. Olinto, and E. Parizot [for the JEM-EUSO Collaboration],
  in Proceedings of the 33rd International Cosmic Ray Conference (ICRC 2013), Rio de Janeiro, Brazil, 2-9 July 2013 (id 0937), arXiv:1307.7071, [astro-ph.IM], pp. 15-18.

- **Likely Dominance of WIMP Annihilation to Fermion Pair $+W/Z$**, in Proceedings of the 33rd International Cosmic Ray Conference (ICRC 2013), Rio de Janeiro, Brazil, 2-9 July 2013 (id 0632), arXiv:1308.1426 [astro-ph IM].

- **Roadmap for Ultra-High Energy Cosmic Ray Physics and Astronomy (whitepaper for Snowmass 2013)**, with L.A. Anchordoqui, G.R. Farrar, J.F. Krizmanic, J. Matthews, J.W. Mitchell, A.V.Olinto, T.C. Paul, P. Sokolsky, and G.B. Thomson, arXiv:1307.5312 [astro-ph.HE].

- **Snowmass Cosmic Frontiers 6 (CF6) Working Group Summary –The Bright Side of the Cosmic Frontier: Cosmic Probes of Fundamental Physics**, with J.J. Beatty et al., "Snowmass on the Mississippi' Report to APS DPF, and arXiv:1310.5662.

- **Sensitivity of orbiting JEM-EUSO to large-scale cosmic-ray anisotropies**, with P.B. Denton (speaker), L.A. Anchordoqui, A.A. Berlind, M. Richardson, for the JEM-EUSO Collaboration, Cosmic Ray Anisotropy Workshop 2013, Madison WI, 26–28 September, and arXiv:1401.5757.

- **Large Scale Anisotropy of Cosmic Rays and Directional Neutrino Signals from Galactic Sources**, with L.A. Anchordoqui, H. Goldberg, A.V. Olinto, T.C. Paul, and B.J. Vlcek, Cosmic Ray Anisotropy Workshop 2013, Madison WI, 26–28 Sept., and arXiv:1403.6628.

- **Oscillation and Mixing Among the Three Neutrino Flavors**, McGraw-Hill Physics Yearbook 2014, and arXiv:1308.1715.

SERVICE and OUTREACH:

- Invited presentation of "Neutrinos, Einstein, Time, and Paradox" at TEDx Nashville, Tennessee Performing Arts Center Theater, Nashville, TN, March 31, 2012, 1070 paid attendees (and over 11,000 hits on Youtube since presentation).

- Editorial Board member, "Astroparticle Physics Journal", Elsevier Press, September 1, 2012– present; editorial manager for about thirty papers since since joining board Sept. 1, 2012.

- Internal reviewer, Vanderbilt Research & Graduate Education, for NSF MRI Acquisition pre-proposals, 2013.

- Osher Adult Learning instructor, on "The Meaning of Time", Fall 2013.

NATIONAL SERVICE TO HIGH-ENERGY PHYSICS:

- Reviewed eight grant proposals: two DOE Career proposals, two regular DOE proposals, one DOE proposal for continued operating expenses ($4.6M/3yr), and three regular NSF proposals.

- Panel member, DOE-HEP Cosmic Frontier Experimental Operation Review, Sept. 24-28. 2012.

- Refereed seventeen journal articles.

CONFERENCE/WORKSHOP ORGANIZATION:

- Co-Organizer (with S. Sarkar, P. Lipari, and Lead-Organizer A. Smirnov) for "NuSky: Looking at the Neutrino Sky", ICTP, Trieste, Italy, June 20-24, 2011.
- Co-Convener (with G. Sinnis) for SLAC "pre-Snowmass Cosmic Frontier Workshop", Stanford, CA, March 6-8, 2013.
- Will Co-Convene (with G. Gelmini, D. Marfatia, W. Winter) for KITP/UCSB "Neutrinos Past, Present, and Future", September 29-December 19, 2014.

CHIU MAN HO, DOE–FUNDED POSTDOC, September 1, 2010 – August 31, 2013

In the time period between 1/1/2011 and 8/31/2013, I have submitted fourteen papers. During this period, fifteen of my papers were published. These papers are listed below.

PAPERS of CHIU MAN HO:

1. **D. Edmonds, D. Farrah, C. M. Ho, D. Minic, Y. J. Ng and T. Takeuchi, "Testing MONDian Dark Matter with Galactic Rotation Curves", and arXiv:1308.3252 [astro-ph.CO].**
   We fit rotation curves to a sample of 30 local spiral galaxies (z ? 0.003) using three models; MONDian dark matter (MDM), MOND, and cold dark matter (CDM). All three models fit the data well. The rotation curves predicted by MDM and MOND are virtually indistinguishable over the range of observed radii (?1 to 30 kpc). T he best-fit MDM and CDM density profiles are compared. We also compare with MDM the dark matter density profiles arising from MOND if Milgrom?s formula is interpreted as Newtonian gravity with an extra source term instead of as a modification of inertia. We find that discrepancies between MDM and MOND occur at radii smaller than typically observed. Our results show that MDM,which restricts the nature of the dark matter quantum by accounting for Milgrom?s scaling, accurately reproduces observed rotation curves.

2. **P. H. Frampton, C. M. Ho and T. W. Kephart,“ ”Heterotic” Discrete Flavor Model,” Phys. Rev. D 89, 027701 (2014), and [arXiv:1305.4402 [hep-ph]].**
   We present an extended 331 model with T' discrete flavor symmetry that simultaneously explains the need to have exactly three generations and provides acceptable quark and lepton masses and mixings. New fermionic states and gauge bosons are predicted within the reach of the LHC. We discuss the relevance to the 126 GeV scalar discovered at the LHC.

3. **C. M. Ho and R. J. Scherrer, "Sterile Neutrinos and Light Dark Matter Save Each Other", Phys. Rev. D 87, no. 6, 065016 (2013), and [arXiv:1212.1689 [hep-ph]].**
   Short baseline neutrino experiments such as LSND and MiniBooNE seem to suggest the existence of light sterile neutrinos. Meanwhile, current cosmic microwave background (CMB) and big bang nucleosynthesis (BBN) measurements place an upper bound on the effective number of light neutrinos, N_{eff} and the PLANCK satellite will measure N_{eff} to a much higher accuracy and further constrain the number of sterile neutrinos allowed. We demonstrate that if an MeV dark matter particle couples more strongly to electrons and/or photons than to neutrinos, then p-wave annihilation after neutrino decoupling can reduce the value of N_{eff} inferred from BBN and PLANCK. This mechanism can accommodate two eV sterile neutrinos even if PLANCK observes N_{eff} as low as the standard model theoretical value of 3.046, and a large neutrino asymmetry is not needed to obtain the correct primordial element abundances. The dark matter annihilation also weakens the cosmological upper bounds on the neutrino masses, and we derive a relationship between the change in these bounds and the corresponding change in N_{eff}. Dark matter with an electric dipole moment or anapole moment is a natural candidate that exhibits the desired properties for this mechanism. Coincidentally, a dark matter particle with these properties and lighter than 3 MeV is precisely one that can explain the 511 keV gamma-ray line observed by INTEGRAL. We show that the addition of two eV sterile neutrinos allows this kind of dark matter to be lighter than 3 MeV, which is otherwise ruled out by the CMB bound on N_{eff} if only active neutrinos are considered.

4. **C. M. Ho and R. J. Scherrer, "Anapole Dark Matter", Phys. Lett. B 722, 341 (2013), and [arXiv:1211.0503 [hep-ph]].**
We consider dark matter (DM) that interacts with ordinary matter exclusively through an electromagnetic anapole, which is the only allowed electromagnetic form factor for Majorana fermions. We show that unlike DM particles with an electric or magnetic dipole moment, anapole dark matter particles annihilate exclusively into fermions via purely p-wave interactions, while tree-level annihilations into photons are forbidden. We calculate the anapole moment needed to produce a thermal relic abundance in agreement with cosmological observations, and show that it is consistent with current XENON100 detection limits on the DM-nucleus cross-section for all masses, while lying just below the detection threshold for a mass $\sim$ 30-40 GeV.

5. **L. Fu, C. M. Ho and T. J. Weiler, "Cosmic Neutrino Flavor Ratios with Broken $\nu_\mu - \nu_\tau$ Symmetry", Phys. Lett. B 718, 558 (2012). arXiv: 1209.5382 [hep-ph]**
Reactor neutrino experiments have now observed a nonzero value for θ_{13} at 5σ, and global fits to data imply a nonzero value above 10σ. Nonzero values for θ_{13} and/or $\theta_{32} - \pi/4$ break a $\nu_\mu - \nu_\tau$ symmetry, which has qualitative as well as quantitative implications for the time-evolution of neutrino flavors. In particular, the large-distance flavor evolution matrix, non-invertible with $\nu_\mu - \nu_\tau$ symmetry, is now invertible. This means that measurements of neutrino flavor ratios at Earth can now be inverted to directly reveal the flavor ratios injected at cosmically distant sources. With the updated values of the three neutrino mixing angles, we obtain the inverted large-distance evolution matrix and use it to derive several phenomenological relations between the injection flavor ratios and the observable ratios at Earth. Taking the three popular injection models as examples, we also exhibit the shift of Earthly observed flavor ratios from the corresponding values in the case with $\nu_\mu - \nu_\tau$ symmetry.

6. **C. M. Ho, "On Neutrino Flavor States", JHEP 1212 (2012) 022. arXiv:1209.3453 [hep-ph]**
We review the issues associated with the construction of neutrino flavor states. We then provide a consistent proof that the flavor states are approximately well-defined only if neutrinos are ultra-relativistic or the mass differences are negligible compared to energy. However, we show that weak interactions can be consistently described by only neutrino mass eigenstates. Meanwhile, the second quantization of neutrino flavor fields generally has no physical relevance as their masses are indefinite. Therefore, the flavor states are not physical quantum states and they should simply be interpreted as definitions to denote specific linear combinations of mass eigenstates involved in weak interactions.

7. **C. M. Ho and T. J. Weiler, "Physical and Stable Closed Timelike Curves", Mod. Phys. Lett. A 28, 1250237 (2013). arXiv: 1209.3107 [gr-qc]**
We construct a class of closed timelike curves (CTCs) using a compactified extra dimension u. A nonzero metric element $g_{tu}(u)$ enables particles to travel backwards in global time t. The compactified dimension guarantees that the geodesic curve closes in u. The effective 2D (t and u) nature of the metric ensures that spacetime is flat, therein satisfying all the classical stability conditions as expressed by the energy conditions. Finally, stationarity of the metric guarantees that a particle's energy is conserved. The pathologies that plague many hypothesized metrics admitting CTCs, e.g. an infinite cylinder of matter, a negative energy-distribution, particle acceleration/blue-shifting along the CTC, do not occur within our metric class.

8. **C. M. Ho and R. J. Scherrer, "Limits on MeV Dark Matter from the Effective Number of Neutrinos", Phys. Rev. D 87, 023505, (2013). arXiv: 1208.4347 [astro-ph]**

Thermal dark matter that couples more strongly to electrons and photons than to neutrinos will heat the electron-photon plasma relative to the neutrino background if it becomes nonrelativistic after the neutrinos decouple from the thermal background. This results in a reduction in N_{eff} below the standard-model value, a result strongly disfavored by current CMB observations. Taking conservative lower bounds on N_{eff} and on the decoupling temperature of the neutrinos, we derive a bound on the dark matter particle mass of $m_\chi > 3 - 9MeV$, depending on the spin and statistics of the particle. For p-wave annihilation, our limit on the dark matter particle mass is stronger than the limit derived from distortions to the CMB fluctuation spectrum produced by annihilations near the epoch of recombination.

9. **C. M. Ho, T. W. Kephart, D. Minic and Y. J. Ng, "Spacetime Emergence and General Covariance Transmutation", Mod. Phys. Lett. A 28, 1350005 (2013). arXiv: 1206.0085 [hep-th]**
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. In this article, we propose 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.

10. **P. H. Frampton, C. M. Ho and T. W. Kephart, "Three Generations from Minimally Extended Standard Models", Phys. Lett. B 715, 275 (2012). arXiv: 1205.4483 [hep-ph]**
We present a class of minimally extended standard models with the gauge group $SU(3)_C \times SU(N)_L \times U(1)_X$ where for all $N \geq 3$, anomaly cancellation requires three generations. At low energy, we recover the Standard Model (SM), while at higher energies, there must exist quarks, leptons and gauge bosons with electric charges shifted from their SM values by integer multiples of the electron charge up to $\pm[N/2]e$. Since the value N=5 is the highest N consistent with QCD asymptotic freedom, we elaborate on the 3-5-1 model.

11. **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 [hep-th]**
We elaborate on our proposal regarding a connection between global physics and local galactic dynamics via quantum gravity. This proposal calls for the concept of MONDian dark matter which behaves like cold dark matter at cluster and cosmological scales but emulates modified Newtonian dynamics (MOND) at the galactic scale. In the present paper, we first point out a surprising connection between the MONDian dark matter and an effective gravitational Born-Infeld theory. We then argue that these unconventional quanta of MONDian dark matter must obey infinite statistics, and the theory must be fundamentally non-local. Finally, we provide a possible top-down approach to our proposal from the Matrix theory point of view.

12. **C. M. Ho, D. Minic and Y. J. Ng, "Quantum Gravity and Dark Matter," Gen. Rel. Grav. 43, 2567 (2011), and [arXiv:1105.2916 [gr-qc]].**
Note: This paper has been awarded the Fifth Prize in the 2011 Essay Competition of the Gravity Research Foundation, and re-published in Int. J. Mod. Phys. D **20**, 2887 (2011).
We propose a connection between global physics and local galactic dynamics via quantum gravity. The salient features of cold dark matter (CDM) and modified Newto- nian dynamics (MOND) are combined into a unified 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.

13. **C. M. Ho and T. J. Weiler, "Causality-Violating Higgs Singlets at the LHC", Phys. Rev. D 87, 045004 (2013). arXiv: 1103.1373 [hep-ph]**

We construct a simple class of compactified five-dimensional metrics which admits closed timelike curves (CTCs), and derive the resulting CTCs as analytic solutions to the geodesic equations of motion. The associated Einstein tensor satisfies all the null, weak, strong and dominant energy conditions. In particular, no negative-energy "tachyonic" matter is required. In extra-dimensional models where gauge charges are bound to our brane, it is the Kaluza-Klein (KK) modes of gauge-singlets that may travel through the CTCs. From our brane point of view, many of these KK modes would appear to travel backward in time. We give a simple model in which time-traveling Higgs singlets can be produced by the LHC, either from decay of the Standard Model (SM) Higgs or through mixing with the SM Higgs. The signature of these time-traveling singlets is a secondary decay vertex pre-appearing before the primary vertex which produced them. The two vertices are correlated by momentum conservation. We demonstrate that pre-appearing vertices in the Higgs singlet-doublet mixing model may well be observable at the LHC.

14. **C. M. Ho, P. Q. Hung and T. W. Kephart, "Conformal Completion of the Standard Model with a Fourth Generation", JHEP 1206 (2012) 045. arXiv: 1102.3997 [hep-ph]**
We study dynamical electroweak symmetry breaking with a fourth generation within the Z_n orbifolded $AdS_5 \otimes S^5$ framework. A realistic Z_7 example is discussed. The initial theory reduces dynamically, due to the induced condensates, to a four-family trinification near a TeV-scale conformal fixed point where the gauge hierarchy problem does not exist. We predict new gauge bosons and bifundamental fermions and scalars accessible by the LHC.

15. **C. M. Ho,"Leptogenesis and CPT Violation," Phys. Lett. B 702, 398 (2011), and [arXiv:1012.1053 [hep-ph]].**
We construct a model in which neutrinos and anti-neutrinos acquire the same mass but slightly different energy dispersion relations. Despite CPT violation, spin-statistics is preserved. We find that leptogenesis can be easily explained within this model, without upsetting the solar, atmospheric and reactor neutrino data. Leptogenesis occurs without lepton number violation and the non- equilibrium condition. We consider only three active Dirac neutrinos, and no new particles or symmetries are introduced.

16. **C. M. Ho and T. W. Kephart, "Inflatonless Inflation", Int. J. Mod. Phys. A 27, 1250151 (2012), arXiv: 1002.4044 [hep-ph]**
We consider a 4+N dimensional Einstein gravity coupled to a non-linear sigma model. This theory admits a solution in which the N extra dimensions contract exponentially while the ordinary space expand exponentially. Physically, the non-linear sigma fields induce the dynamical compactification of the extra dimensions, which in turn drives inflation. No inflatons are required.