PARTICIPATION IN HIGH ENERGY PHYSICS AT THE UNIVERSITY OF CHICAGO

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DOE grant DE-FG02-90ER-40560 Final Report
DOE/Office of Science Program Office: Office of High Energy Physics

This report covers research at the University of Chicago in theoretical high energy physics and its connections to cosmology, over the period Nov. 1, 2009 to April 30, 2013. This research is divided broadly into two tasks: Task A, which covers a broad array of topics in high energy physics; and task C, primarily concerned with cosmology.

Contents

1 HIGH ENERGY PHYSICS (TASK A)

1.1 Introduction – Faculty on Task A

Members of Task A engage in research on a broad range of fundamental issues in particle physics, spanning all three major thrusts of DOE-sponsored research in high-energy physics – the Energy, Intensity, and Cosmic Frontiers.

On the Energy Frontier, David Kutasov and Emil Martinec have made fundamental contributions to String Theory and theoretical particle physics, most recently through investigations of the nature of branes in string theory. Kutasov's recent work has focused on dynamical aspects of quantum field theory, on the dynamics of branes in string theory, and on the interplay between the two. A particular focus of Martinec's recent research has been the application of the gauge/gravity correspondence to address issues in string cosmology and black hole physics.

The recent discovery of a Higgs-like resonance at CERN opens a window on the mechanism of electroweak symmetry breaking. Carlos E.M. Wagner has contributed to our understanding of how such experiments can probe physics beyond the Standard Model; in 2008 he was awarded an APS fellowship for these achievements. Wagner has also contributed to the understanding of the collider and flavor physics implications of low energy supersymmetry models. His current research concentrates on Higgs, flavor and beyond the Standard Model physics, through predictions and analyses of signals at present and future colliders. On the Cosmic Frontier, Wagner made significant contributions to the development of the theory of Electroweak Baryogenesis.

Recent experiments at Fermilab and CERN and some non-accelerator experiments (including measurements of parity violation in atoms) have permitted tests of the theory of electroweak interactions with unprecedented accuracy. Jonathan Rosner has investigated how these experiments shed light on new physics in the mass range of 100 GeV to several TeV. Recently, he became a member of the CLEO and CDF collaborations and has taken a leading role in several analyses and in the interpretation of experimental results in the framework of theoretical models. On the Intensity Frontier, Rosner is internationally recognized for his work on Charm- and B-Physics. Though Rosner recently joined the ranks of emeritus faculty, he maintains an active research program, and will serve as the Chair of the Division of Particles and Fields of the American Physical Society in 2013.

1.2 Graduate Students and Postdocs on Task A

HEP Theory funding by the DOE at U. Chicago has supported the mentoring of a host of successful students and postdocs over the years. Recent Research Associates who have moved on to faculty positions from our group include

- Finn Larsen (Professor, Univ. of Michigan), Per Kraus (Professor, UCLA), Ben Craps (Associate Professor, Free University, Brussels), Oleg Lunin (Assistant Professor, SUNY Albany), Nicolas Halmagyi (CNRS Staff Scientist, Univ. of Paris VI), Tao Liu (Assistant Professor, Hong Kong University of Science and Technology), Geraldine Servant (CNRS Staff Scientist, Saclay), David E. Kaplan (Professor, Johns Hopkins University), Hsin-Chia Cheng (Professor, UC Davis), and Gil Paz (Assistant Professor, Wayne State Univ.).

Successful graduate students in recent years include

- David Morrissey (Permanent Scientist, TRIUMF), Arjun Menon (Postdoc, University of Oregon), Jing Shu (Permanent Scientist, ITP, Beijing), Anibal Medina (Postdoc, University of Melbourne), Nausheen Shah (Postdoc, Fermilab), Patrick Draper (Postdoc, UC Santa Cruz), David McKeen (Pstdoc, University of Victoria (BC)), Bhubanjyoti Bhattacharya (Postdoc, University of Montreal) Arun Thalapillil (Postdoc, Rutgers) Will McElgin (Lecturer, LSU) Vasilis Niarchos (Postdoc, University of Crete) and Andrei Parnachev (Assistant Professor, University of Leiden)

Task A personnel supported under the current three-year award consist of

- **Research Associates:** Stefania Gori, Johannes Heinonen, Joseph Marsano, and Gil Paz.

- **Research Assistants:** Bhubanjyoti Bhattacharya, Patrick Draper, Szilard Farkas, Ran Huo, Aniket Joglekar. Jennifer Lin, David McKeen, Callum Quigley, Nausheen Shah, Mikhail Solon, Arun Thalapillil, and Andrew Ulvestad.

Students who earned PhD's during the most recent three-year grant period under the supervision of faculty on the grant include: B. Bhattacharya (Rosner), accepted a postdoc at Univ. of Montreal; P. Draper (Wagner), accepted a postdoc at UC Santa Cruz; D. McKeen (Rosner), accepted a postdoc at Univ. of Victoria, BC; N. Shah (Wagner), accepted a postdoc at Fermilab; A. Thalapillil (Rosner), accepted a postdoctoral appointment at Rutgers. R. Huo (Wagner) will be a postdoc at IPMU in Japan beginning Fall 2013. Two of the research associates left the group for other positions – Marsano has taken up a position in the financial industry, and Paz is now a faculty member at Wayne State University.

1.3 Synergies

A larger HEP theory faculty at U. Chicago, as well as strong ties to the theory efforts at Argonne and Fermilab, extend the reach of the group's activities. At Chicago, DOE Early Career Award winner Lian-Tao Wang is engaged in a wide variety of phenomenological pursuits, from collider physics to cosmology; Wang has collaborated with Carlos Wagner as well as Task A students and postdocs on a variety of collider phenomenology projects. Jeff Harvey and Savdeep Sethi, supported by NSF funding, have had frequent collaborations with Kutasov and Martinec on a variety of topics in string theory and gauge theory. Harvey has also had a fruitful collaboration with Richard Hill (and Fermilab's Chris Hill) on anomaly-mediated processes in strong interaction physics.

These activities of the Chicago group take place in a broader collaborative context involving the laboratories. Carlos Wagner's effort is split between his appointment on the University faculty and his role as the head of the HEP Theory Group at Argonne. Hill, Rosner and Wagner all have strong ties to and longstanding collaborations with members of the theory groups at Argonne and Fermilab. They also interact regularly with the experimental High Energy Physics group at Chicago, participating in joint weekly seminars, and discussions of Tevatron and LHC physics.

The University has sought to deepen its intellectual connection to the labs through a series part-time faculty appointments, and through its funding of collaborative projects. Fermilab Scientists Chris Quigg and Joe Lykken have recently held such part-time positions, and Marcela Carena is currently interacting with Chicago students and postdocs as Professor Part-time at Chicago. In the last few years, members of the group have been involved in the creation of several Joint Theory Institutes (JTI) with Argonne and Fermilab, funded by the University. These focussed collaborative projects have contributed to and extended the research efforts of the group, and have strengthened its ties to both of the labs. For instance, JTI support of a workshop at Argonne led to the collaboration of Harvey, Hill, and Hill mentioned above; and JTI funds have supported joint postdocs who have enriched the activities at all three institutions. Also, in conjunction with the SUSY2012 conference held at Fermilab, Chicago hosted a preSUSY Summer School for graduate students and postdocs, organized by Hill, Wagner and Wang; the University matched DOE's funding support for the event.

Members of the group also contribute actively to the intellectual atmosphere of the Kavli Institute for Cosmological Physics (KICP) and organize seminars and workshops at the KICP on such topics as Dark Matter and Baryogenesis.

Most recently, Chicago has initiated an ambitious plan to recruit outstanding theoretical physicists from around the world; Dam T. Son is the first of several appointments under this initiative. The University has also committed \$1.7M toward the establishment of a new Center for Physical Inquiry one of whose goals is to foster connections between particle/string theory and condensed matter physics. Chicago has a long history of accomplishment in this area dating back to the likes of Nambu and Kadanoff, and we are particularly excited by the opportunities afforded to explore the application of recent advances in field theory and string theory to condensed matter theory and experiment.

In the following, we review research undertaken by Task A personnel over the last three years.

1.4 Professor David Kutasov

In the last three years, Kutasov continued to work on dynamical aspects of quantum field theory, on the dynamics of branes in string theory, and on the interplay between the two. In particular, he developed new tools to study the interaction of BPS D-branes and antibranes, contributed to the understanding of metastable states in supersymmetric gauge theories in various dimensions, and clarified the relation between the analysis of metastable states in gauge theory and string theory. He showed that in brane systems in string theory that exhibit a rich landscape of metastable states, the early universe dynamics favors particular states, which interestingly are the most phenomenologically appealing. He also studied brane systems in string theory that give a holographic description of N=1 supersymmetric QCD with the number of flavors of the order of the number of colors, and the related cascading gauge theories. He made progress on understanding renormalization group flows in N=1 supersymmetric gauge theory, by generalizing some work he has done in 2003 to general theories, and studied a class of phase transitions that is expected to play a role in generalizations of QCD, models of electroweak symmetry breaking known as walking technicolor, and condensed matter systems of strongly coupled electrons confined to a plane, such as graphene.

Kutasov's collaborators in this period included O. Aharony, D. Erkal, A. Giveon, J. Lin, O. Lunin, J. McOrist, A. Parnachev, A. Royston, J. Sonnenschein, A. Wissanji and S. Yankielowicz. Erkal, Lin, McOrist and Royston were students at the University of Chicago.

1. *Brane-antibrane dynamics in string theory*

Many important problems in string theory involve the interactions of D-branes and antibranes. One example is brane inflation, where the inflationary phase corresponds to branes and antibranes moving towards each other, and the end of inflation corresponds to brane-antibrane annihilation. Another is holographic QCD (the Sakai-Sugimoto model and its generalizations, explored by Kutasov and collaborators and described in previous reports to the DOE), where the quarks are obtained by adding to the system $D8$ and $\overline{D8}$-branes.

In these and other problems, the dynamics of the open string tachyon that exists in the $D-\bar{D}$ system plays an important role. In brane inflation, the condensation of the tachyon gives rise to brane annihilation and the end of inflation, while in holographic QCD, the expectation value of the tachyon serves as an order parameter for chiral symmetry breaking and governs the mass of the quarks.

The above tachyon corresponds to an open string stretched between different branes, which are in general separated. This makes it hard to describe it in terms of a low energy effective field theory. Nevertheless, in [1], Kutasov and collaborators succeeded in making progress in this direction. The basic idea is that it was known before that in a different but closely related system, the non-BPS D-brane discovered by A. Sen, the tachyon field *can* be described in terms of an effective field theory, known as Tachyon Dirac-Born-Infeld (or TDBI) action. Moreover, the BPS branes are particular classical configurations in that theory. In [1], the authors used these observations to describe the brane-antibrane system as a configuration in the TDBI field theory, and showed that the tachyon corresponds to a particular excitation of this configuration.

The analysis of [1] shed light on real time $D - \bar{D}$ tachyon condensation, on the proposal that the tachyon field can be thought of as an extra spatial dimension whose role is similar to the radial direction in holography, proposed by Kutasov in previous work, and on A. Sen's open string completeness conjecture.

2. *Supersymmetry breaking in gauge theory and string theory*

Kutasov continued his program of studying metastable SUSY breaking vacua in field theory and string theory and exploring the relation between them. In particular in [2], Kutasov and collaborators explored the relation between the landscape of metastable SUSY breaking vacua in a certain class of brane systems in string theory, and in the gauge theories that describe the low energy dynamics of these brane systems.

It was known from previous work by Kutasov and others that there is a close relation between the two sets of vacua, however in some cases the landscape of SUSY breaking vacua in string theory is richer than that in the corresponding gauge theory. Moreover, while in gauge theory these states owe their existence to one loop contributions to the effective potential of certain light scalar fields, in string theory their existence is due to gravitational interactions between the various branes. This led to the following puzzle: how can one understand the existence of the metastable states in string theory in terms of the low energy theory. This question is important both in its own right, and for applications. Indeed, it turns out that the vacua that exist in string theory but not in the field theory are those that are most interesting for using these systems as hidden sector SUSY breaking sectors in a phenomenological model.

The answer to this question was described in [2], where it was shown that in the effective theory of the light fields, the gravitational interactions among the branes give rise to a non-canonical Kähler potential and other D-terms. String theory provides an ultraviolet completion in which these non-renormalizable terms can be computed. The field theory regime is obtained by sending the UV cutoff, by which these terms are suppressed, to infinity. In that limit, the one loop corrections to the potential for the light fields dominate. In the brane regime, the UV cutoff is finite, and the contributions to the effective potential due to the Kähler potential may be more important. These observations were used in [2] to clarify the relation between the phase structure of field theoretic models studied by Intriligator, Seiberg and Shih (ISS) [3] and their brane realizations.

In [4] the discussion of metastable vacua in supersymmetric gauge theory pioneered by ISS was extended to other spacetime dimensions. One of the motivations for this analysis is holography; one may hope that the dynamics of our universe, which is four dimensional, includes gravity and breaks supersymmetry, is related holographically to a three dimensional theory without gravity, which breaks supersymmetry spontaneously. Of course, since our universe is very large in Planck units, the dual theory is presumably strongly coupled and thus difficult to study. Nevertheless, one may hope that by studying weakly coupled three dimensional theories with broken SUSY, one can obtain insights that would be applicable to strongly coupled field theories.

The main conclusion of the analysis of [4] was that the SUSY breaking vacua found by ISS in four dimensional gauge theory, persist in lower dimensions as well. For generic values of the parameters, the superpotential used by ISS renders the theory strongly coupled, however there are regions in parameter space where these vacua can be studied reliably at weak coupling. It was also found that the relation between the gauge theory results of ISS and the corresponding brane systems in string theory studied by Kutasov and collaborators, also goes through to lower dimensions. In different regions of the parameter space of brane configurations, the dynamics is dominated either by field theory effects (the one loop effective potential) or by the gravitational effects, which again correspond to a non-trivial Kähler potential and higher D-terms for the light fields.

In [5], Kutasov and collaborators studied the question of vacuum selection due to early universe dynamics in the brane systems described above. In field theory, in the context of the ISS model of SUSY breaking, this issue was explored before. However, it was clear that it is important to reexamine it in string theory, for two reasons. One is that the dynamical origin of the metastable SUSY breaking states in string theory is different than in field theory, as explained above. The other is that, as mentioned above, in some cases the brane system has a richer landscape of metastable vacua than the corresponding gauge theory, and it is important to explore the issue of vacuum selection in the presence of these additional vacua.

To explore the early universe dynamics of the brane system described above, the authors of [5] made the assumption that the extra energy density present in that epoch goes to exciting the heavy branes in the configuration, and makes them non-extremal. Time evolution corresponds to these branes returning to extremality, in a way that was assumed to be adiabatic. The analysis showed that out of the rich landscape of vacua of supersymmeric and non-supersymmetric vacua of the brane system, the dynamics drives the system to a particular non-supersymmetric vacuum, which exists in string theory but not in the corresponding low energy gauge theory. Moreover, this vacuum is known to be the most interesting for phenomenology for reasons that are unrelated to early universe cosmology!

Recently, Kutasov returned to the study of supersymmetry breaking in field and string theory, and analyzed with A. Wissanji [6] the supersymmetry breaking vacua proposed by Kachru, Pearson and Verlinde [7] in the cascading gauge theory of Klebanov and Strassler [8]. Kutasov and Wissanji used a type IIA brane description of these vacua to establish the existence of these vacua, and showed that while they are metastable in the full string theory, the barrier for tunneling to the supersymmetric vacuum goes to infinity in the field theory limit. Thus, they are not part of the cascading gauge theory of [8].

3. *Holographic MQCD*

Kutasov maintains a long term interest in holographic approaches to QCD. In [9] he and collaborators studied a brane configuration in weakly coupled type IIA string theory, that contains $D4$-branes and $NS5$-branes and describes in a particular limit $d = 4$, $N = 1$ supersymmetric QCD with gauge group $SU(N + p)$, $2N$ flavors of fundamental hypermultiplets, and a quartic superpotential. The authors described the geometric realization of the supersymmetric vacuum structure of this gauge theory. They focused on the confining vacua of the gauge theory, whose holographic description is given by the MQCD brane configuration in the near-horizon geometry of N $D4$-branes.

They showed that this description, which gives an embedding of MQCD into a field theory decoupled from gravity, is valid for $1 << p << N$, in the limit of large five dimensional ‘t Hooft couplings for the color and flavor groups. They analyzed various properties of the theory in this limit, such as the spectrum of mesons, the finite temperature behavior, and the quark-anti-quark potential. They also discussed the same brane configuration on a circle, where it gives a geometric description of the moduli space of the Klebanov-Strassler cascading theory. Kutasov and Wissanji [6] built on these results and established a precise correspondence between the vacuum structure of the cascading gauge theory and that of the IIA brane system. They also discussed the $N = 2$ supersymmetric generalization of this theory, and clarified the origin of the duality cascade in a theory which does not have Seiberg duality.

4. *Renormalization group in four dimensional supersymmetric field theory*

Kutasov also maintains a long term interest in is the dynamics of $N = 1$ supersymmetric field theories. These theories exhibit many non-trivial dynamical phenomena, like their non-supersymmetric counterparts, but there has been enormous progress in their understanding in the last twenty years, due to the larger symmetry.

In [10] Kutasov and D. Erkal made progress on the following problem. Consider a general $N = 1$ superconformal field theory, perturbed by an arbitrary F-term (a combination of turning on a superpotential and gauging part of the global symmetry group of the theory). An interesting question is how do the RG flows affected by such perturbations look, and in particular what kind of fixed points can one reach by turning them on.

Kutasov and Erkal addressed this problem by generalizing some work by Kutasov from 2003 to this framework. The basic idea was to consider a certain generalization of the central charge a to non-conformal field theories, and use it to calculate anomalous dimensions and β-functions for the various couplings. The key idea that underlies the construction is that SUSY connects the stress tensors and supersymmetry currents to a $U(1)_R$ current, and that much can be said by following the way this current evolves along RG flows.

As by products of their analysis, Kutasov and Erkal showed that the central charge a always decreases along RG flows corresponding to F-term perturbations, and rederived and extended some recent results [11] on marginal perturbations of $N = 1$ superconformal field theories.

5. *Conformal phase transitions at weak and strong coupling*

Systems of strongly coupled fermions play an important role in a number of physical systems in particle physics and condensed matter. In particular, among the possible scenarios for new physics that may be discovered at LHC is technicolor, which (in its "walking" version) is the idea that at energies of about a TeV, the dynamics that governs electroweak symmetry breaking becomes conformal. In this scenario, the weak scale is generated dynamically, via a new kind of phase transition, known as "conformal phase transition." This phase transition is believed to occur in QCD as one varies the number of flavors of quarks, but is rather poorly understood. In [12, 13] Kutasov, J. Lin and A. Parnachev proposed an approach for studying such phase transitions that uses ideas from the ϵ-expansion and gauge-gravity duality.

The particular system studied in [12] involved $2 + 1$ dimensional fermions coupled to $3 + 1$ dimensional $N = 4$ super Yang-Mills. This system has a tunable coupling, the 't Hooft coupling of $N = 4$ SYM, and thus can be studied both at weak coupling, using standard perturbative field theory techniques, and at strong coupling using holography. Kutasov et al used the gravitational description to study the transition, and in particular computed the spectrum of mesons and phase structure as a function of temperature and chemical potential. They also discussed some lessons from the analysis of this system to four dimensional QCD, which as mentioned above is also expected to undergo such a transition. In [13], Kutasov et al generalized the discussion to a larger class of systems and proposed a general bottom-up approach for studying conformal phase transitions using holography. They used it to study some important features of such models, such as the dynamical generation of a mass scale, the spectrum of bound states ("mesons") in the massive phase, and the nature of the finite temperature symmetry restoration phase transition.

6. *Other activities*

Kutasov serves as a supervisory editor of Nuclear Physics B, and was a member of the DOE site review panel at MIT in the summer of 2010. He was an invited speaker at a number of conferences, workshops and universities, and a grant reviewer for DOE, NSF, and numerous international granting agencies, and national academies of science. He designed and taught advanced graduate courses in supersymmetric field theory and string theory.

1.5 Professor Emil Martinec

Martinec's research over the past three years investigated the foundations of general relativity in the context of modified gravity; membrane dynamics in the formulation of Aharony et. al. [14]; and inflationary dynamics in string theory and quantum gravity. Collaborators in this period include Chicago graduate students Szilard Farkas, Stephen Green, Callum Quigley, and Andrew Ulvestad; as well as Peter Adshead, Jock McCorist, Savdeep Sethi, and Mark Wyman.

1. *Modified gravity*

What makes an $n+1$ dimensional (pseudo) Riemannian manifold the relevant structure in the description of the time evolution of Riemannian n-geometries? This geometrical structure is the basis of Einstein's general relativity, however Hořava has proposed a class of generalizations [15] wherein one keeps the Riemannian structure of spatial geometry but relaxes the requirement of local Lorentz symmetry, in the quest for improved ultraviolet properties.

Martinec and student Farkas investigated the structure of this class of theories. With the loss of local Lorentz symmetry, and a modification of the Hamiltonian, temporal diffeomorphisms are no longer a symmetry of the modified theory. It is the presence of this temporal diffeomorphism symmetry which eliminates negative metric conformal modes of the spatial metric from the dynamics, and allows the small fluctuation spectrum to be unitary; therefore, it is a natural question to ask whether there can be a suitable extension of the algebra of spatial diffeomorphisms that would restore the status of the conformal mode as a gauge degree of freedom, and allow preservation of unitarity. What makes the problem difficult is that a priori the form of the full algebra is not known. To restrict the possibilities, it was assumed that the Hamiltonian is a generator of constraints, and consists of a quadratic form in the momenta conjugate to the spatial metric, plus a potential of quite general (even nonlocal) form. Within this wide class of possibilities it was shown [16] that the surface deformation algebra of general relativity is the only nontrivial extension of the algebra of spatial diffeomorphisms.

2. *Higher-derivative gravity*

Conformal gravity has been suggested several times as a possible solution to the non-renormalizability of the field theory based on the Einstein-Hilbert action. However, the renormalizability of conformal gravity does not seem to be settled in the literature [17, 18, 19]. Some arguments for the renormalizability of conformal gravity are based on conformal (Weyl) and diffeomorphism symmetry of the action. It was shown by explicit calculations that in certain models one can preserve either diffeomorphism or conformal symmetry, but not both, since anomalies can be shifted between these symmetries, but cannot be eliminated altogether. Student Farkas has been investigating the restrictions on the perturbative quantization of conformal gravity imposed by the constraints of gauge invariance, unitarity, and Lorentz invariance. There are higher-derivative quantum gravity models which are known to be perturbatively renormalizable[17]. However, the starting point of the perturbative expansion is a free field theory which is not based on a positive energy unitary representation of the Poincaré group. Either the energy is unbounded from both below and above, or the invariant metric on the state space is not positive definite, so the representation is not unitary. We do not see any way to get around this conclusion about generic models [18, 20, 21]. However, uniquely in the case of conformal gravity, the analysis of the one-particle content of the free field theory needs to be done with more care, due to the gauge invariance, and the results about a generic higher-derivative theory do not extend automatically to this case.

3. *Membrane dynamics*

Work by Bagger and Lambert [22, 23], Gustavsson [24] and later by ABJM [14] represents an important step forward in our understanding of the conformal field theory describing coincident M2-branes. These constructions give explicit Lagrangian descriptions of the conformal field theory in terms of Chern-Simons gauge theory, and hence open up the possibility of explicitly computing quantities peculiar to M2-brane theories. An example is understanding the dynamics and scattering of M2-branes, much in the way [25] explored scattering of D-branes. To make progress in these directions it is important to understand the quantum corrected moduli space of the ABJM and BLG theories; in particular, the Coulomb branch of these theories has received relatively little attention, and yet it has some unexplained curious features.

One curious feature is the appearance of a special locus in the $\mathbf{C}^4$ classical moduli space. When any two M2-branes lie along this locus, certain states on the Coulomb branch of the theory become massless. In the gauge theory of D-branes, such massless states appear only when D-branes collide; they are the W-bosons (and superpartners) of an enhanced gauge symmetry of coincident branes. So a natural hypothesis would be that the massless states in the M2-brane theory are the analogues of the gauge bosons of D-branes. Indeed, these states were originally noticed by Lambert and Tong[26] in the context of the BLG theory as a type of three-pronged object; they speculated that the three-pronged object may be related to membrane-like excitations and the $N^{3/2}$ entropy scaling of M2-brane SCFTs.

However, in the M2-brane case, the locus where the light excitations appear is generically not where the branes are coincident in space, and if physical would represent new long-range (in fact nonlocal) interactions between a pair of M2-branes – the branes can be separated arbitrarily far apart without any apparent decrease in the strength of these interactions. Martinec and McOrist[27] showed that these massless states are not accidental, but rather a consequence of a particular $U(1)$ in the Chern-Simons gauge group, and are generic to this class of constructions. The resolution of the puzzle turns out to be that the same $U(1)$ has monopole instantons whose effect is to lift the flat direction in the effective action. Martinec and McOrist performed a detailed computation of the instanton effects in the ABJM theory (extending previous work of Hosomichi et.al. [28]) showing agreement with supergravity and the absence of anomalous light states in the effective theory.

4. *Closed-string tachyon condensation*

Martinec, Robbins and Sethi revisited their proposal of a matrix theory realization of string vacua with bulk closed string tachyons [29]. At issue was a claim by Banks that their estimates of the matrix string spectrum ignored strong interaction effects that would invalidate the matrix theory interpretation. Martinec and collaborators showed that in a particular example – type 0A matrix string theory in ten uncompactified spacetime – the infrared fixed point that governs the gauge theory dynamics of their proposal is the Neveu-Schwarz sector of the same symmetric orbifold that governs the supersymmetric matrix string. The resulting spectrum agrees exactly with their previous estimates, thus reinforcing the calculations in the original article. A revised version of the article has been published [29].

5. *Cosmological dynamics in string theory*

Understanding accelerating universes remains one of the primary outstanding challenges for string theory. Acceleration requires a violation of the strong energy condition. However, the supergravity theories describing low-energy string theory in ten dimensions or M-theory in eleven dimensions satisfy the strong energy condition. This property is inherited on compactification, ruling out accelerating solutions in supergravity [30]. However, string theory is not supergravity. There are ingredients such as orientifold planes in type II string theory which support higher derivative interactions that can lead to violations of the strong energy condition. These ingredients are present in every corner of the string landscape: in M-theory, they come from eight derivative modifications to eleven- dimensional supergravity. In the heterotic and type I strings, they come about from a class of four derivative interactions which are leading order in the α' expansion. Martinec, in collaboration with Green, Quigley and Sethi [31] analyzed the effects of these intrinsically stringy ingredients in the context of the heterotic string, with the aim of seeing whether they are sufficient to permit accelerating universes in string theory. The result was a no-go theorem, showing that static de Sitter space with a cosmological constant of order α' is not possible.

6. *New mechanisms for cosmological inflation*

Despite the success of inflation, it has been difficult to find models that achieve the needed $O(60)$ e-foldings of accelerated expansion without an unnatural degree of fine-tuning. A general consistency issue – the so-called 'eta problem' – is the question of why quantum corrections don't contribute order one corrections to the effective potential, spoiling whatever fine-tuning of the potential has been done to achieve sufficient inflation. In collaboration with KICP Fellow P. Adshead and postdoc M. Wyman, Martinec introduced a new mechanism of inflation [32] wherein the potential force driving the evolution of the inflaton is balanced against a Chern-Simons term. The intuition for this choice comes from the dynamics of a particle in a strong magnetic field (the simplest example of a Chern-Simons term), in which the potential force balances against the magnetic Lorentz force rather than kinetic terms, and the motion of the particle along the potential can be made arbitrarily slow as a result. Since the Chern-Simons term does not contribute to the stress-energy tensor, the cosmological expansion is dominated by the inflaton potential, however the potential can be steep because motion is damped by the Chern-Simons interaction, and the 'eta problem' is avoided. Effectively, there is a small parameter which is the ratio of the scale of the inflationary potential to the scale of the Chern-Simons interaction; so long as this ratio is radiatively stable, the duration of inflation is controlled.

The fluctuation spectrum in this class of models is quite intricate. In standard single-field inflation, only the fluctuations of the inflaton and tensor modes of the graviton are relevant. Martinec, Adshead, and Wyman analyzed the version of Chern-Simons inflation (dubbed *Chromo-Natural Inflation*) in which an axion is the inflaton, as in natural inflation, and the fields which interact with the inflaton to slow its motion through the Chern-Simons interaction are components of a non-abelian gauge field [33, 34]. In the fluctuation spectrum, the gauge field contributes two additional scalars and an additional tensor mode. The scalars substantially modify the evolution of the inflaton perturbations; an instability at small effective mass of the gauge perturbations substantially reddens the spectral tilt of the scalar curvature perturbations seen in the CMB. On the other hand, the tensor perturbations coming from the gauge field go unstable at large effective mass, and mix with the gravitational wave perturbations leading to an unobserved large value of the tensor-to-scalar ratio. These two instabilities cause the version of the model studied to be in significant tension with observational data.

7. *Pedagogical activities*

Martinec was invited to contribute an article for a retrospective volume 'Forty Years of String Theory', to be published by Elsevier. His contributed article 'Evolving Notions of Geometry in String Theory', describes how our understanding of the structure of space and time have changed since the advent of string theory.

1.6 Professor Emeritus Jonathan Rosner

Rosner joined CDF in February 2011, and has contributed to papers, run shifts, corrected nearly 200 drafts as a member of the Scientific Paper Reading Group (SPRG), served on godparent committees, and participated in meetings, especially of the b physics subgroup. In June 2010 Michael Gronau and Rosner discussed with D0 and CDF colleagues a D0 report [35, 36] of an anomalous asymmetry in the rate for production of same-sign muon pairs. They suggested checks of the D0 charge asymmetry [37], and explored the question of a second-order direct CP asymmetry in semileptonic $B_{(s)}$ decays [38].

Rosner served as Vice-Chair of the Division of Particles and Fields of the American Physical Society in 2011, Chair-Elect in 2012, Chair in 2013, and will be Past Chair in 2014. In connection with his DPF responsibilities he attended Executive Committee meetings, APS Convocations with congressional visits, a Muon Collider workshop, a DPF meeting at Brown University, Aug. 2011, meetings at APS Headquarters to organize the April 2012 and April 2013 Meetings, an Intensity Frontier Workshop near Washington, the April 2012 and 2013 APS Meetings, and numerous meetings in preparattion for a Snowmass Meeting at the University of Minnesota in July–August 2013.

In April 2011 Rosner presented joint work with Michael Gronau at a conference in Amsterdam on B_s decays and mixing [39]. At the Conference on Flavor Physics and CP Violation in Israel, May 2011, he presented a theoretical talk on quarkonium [40] and experimental results from the CLEO Collaboration [41]. After the conference he worked with Michael Gronau at the Technion on a paper dealing with triple product asymmetries in K, D, and B decays [42].

In June 2011 Rosner joined Matthew Buckley and Daniel Hooper on an interpretation of a jet-jet mass enhancement seen by CDF [43] in terms of a "leptophobic" Z' [44] and its relation to possible dark matter signals seen by DAMA and CoGeNT [45]. Rosner spent part of August and September 2011 at the Aspen Physics Center, where M. Gronau and he studied an updated claim by the D0 Collaboration for an anomalous like-sign dimuon charge asymmetry in $p\bar{p}$ collisions [46]. The sensitivity of the conclusions to estimates of backgrounds (especially charged kaon decays) was explored [47].

Rosner spent a week in February 2012 at a Heavy Flavor Workshop at the University of Washington. There he reported on theoretical and experimental topics and discussed questions of mutual interest with lattice theorists and experimentalists. Papers stemming from this interaction were a study of non-perturbative effects on $p\bar{p} \to t\bar{t} + X$ [48] and a suggestion for improving knowledge about Λ_c branching fractions [49].

Rosner attended the Aspen Center for Physics for two weeks during July-August 2012, devoting most of his time to Division of Particles and Fields organizational tasks. As a visitor at CERN during August 13 – September 7, 2012, he collaborated with Michael Gronau on a study of mixing of neutral charmed mesons [50]. He attended a meeting of the European Strategy Group in Krakow in September. The Physics Briefing Book arising from that meeting will serve as a model for a forthcoming Snowmass report.

Additional questions investigated over the past three years and plans for future work:

1. *CP violation, Cabibbo-Kobayashi-Maskawa (CKM) matrix, and B physics*

In work with M. Gronau [51], ratios of charmed meson and baryon semileptonic decay rates were found to be satisfactorily described by considering only the lowest-lying (S-wave) hadronic final states and assuming the kinematic factor describing phase space suppression is the same as that for free quarks.

Several B decays have been cited as evidence for amplitudes normally thought to be suppressed, as they involve the spectator quark in the weak interaction. However, they can also be generated by rescattering from more abundant processes. Decays such as $B^0 \to K^+K$, $B_s \to \pi^+\pi^-$, and $B^+ \to D_s\phi$ were examined, and promising states were identified from which they can be generated by rescattering. Based on observed regularities, using approximate flavor SU(3) symmetry in some cases and time-reversal invariance in others, branching fractions for a large number of as-yet-unseen B decays were predicted [52].

A difference between the direct CP asymmetries of $D^0 \to K^+K$ and $D^0 \to \pi^+\pi^-$ can affect the determination of the weak phase γ. Using an analysis of the CP asymmetries based on a $c \to u$ penguin amplitude with standard model weak phase but enhanced magnitude, typical shifts in γ of several degrees were estimated, and measurements were pinpointed which would reduce uncertainties to an acceptable level [53].

Gronau and Rosner expect to continue their long-term fruitful collaboration. Topics for study include the implications of large CP asymmetries in some three-body decays of charged B mesons reported by the LHCb Collaboration [54, 55, 56].

2. *Charmed particle decays*

Discussions were held with C. Wohl of the Particle Data Group to account for all D^0 and D^+ decays in the same manner as for D_s decays in Ref. [57]. These data exist from CLEO in unpublished form [58]. It is a high priority to get them published, as they include many modes currently not listed by the Particle Data Group [59]. Charmed meson decays to a light pseudoscalar (P) and light vector (V) meson were analyzed taking account of η–η' mixing. The frequently-used octet-singlet mixing angle of 19.5° was compared with a value of 11.7° favored by a recent analysis [60] of $D \to PP$ decays [61]. Reviews of information on meson decay constants (emphasizing f_{D^+} and f_{D_s}) were updated for the Particle Data Group's 2010 [62] and 2012 [63] editions.

In collaboration with B. Bhattacharya [64], relative phases of amplitudes for D meson decays to a light pseudoscalar meson P and a light vector meson V were compared with predictions of a flavor-symmetric treatment which extracts contributing amplitudes and their relative phases from a fit to $D \to PV$ decay rates. Good agreement was found previously for $D^0 \to K^-\pi^+\pi^0$ and $D^0 \to \pi^+\pi^-\pi^0$, but not for $D^0 \to K_S\pi^+\pi^-$ and $D^0 \to \pi^0K^+K^-$. Several suggestions were offered for this discrepancy.

The angular distributions of the D_s^* and the final-state particles in $D_s^* \to D_s\gamma$ are needed to model the decays properly, to confirm the spin-parity assignment $J^P(D_s^*) = 1^-$, and to model the acceptance for the rare process $D_s^* \to D_se^+e^-$. A brief note was prepared [65] presenting some of the necessary expressions.

In collaboration with B. Bhattacharya, Dalitz plots for $D^0 \to K^0K^-\pi^+$ and $D^0 \to \overline{K}^0K^+\pi^-$ were studied in the context of flavor SU(3) [66], utilizing a data sample from BaBar based on an integrated luminosity of 22 fb^{-1}. This note has been updated [67] in light of recent CLEO results [68], which indicate that analysis of the full BaBar sample (more than 20 times that reported) will be required for a definitive statement on phases.

Evidence for a CP asymmetry in the difference between $D^0 \to \pi^+\pi^-$ and $D^0 \to K^+K^-$ [69, 70] was analyzed [71, 72, 73] as if due to a penguin amplitude with the weak phase of the standard model $c \to b \to u$ loop diagram, but with a CP-conserving enhancement. Under this assumption CP asymmetries were predicted for several other singly-Cabibbo-suppressed decays of charmed mesons to a pair of pseudoscalar mesons.

3. *Hadron spectroscopy*

An article on bottomonium spectroscopy was completed for Annual Reviews of Nuclear and Particle Science in collaboration with Claudia Patrignani and Todd Pedlar [74].

4. *Dark matter*

Rosner will follow up a suggestion of his [75] that dark matter is likely to manifest itself in many forms. He will investigate "hidden valley" models in which some particles have only standard model charges, others have only "hidden" charges, and others have both.

5. *Fragmentation models*

Fourteen exclusive decay modes of $\chi_b(1P)$ and $\chi_b'(2P)$ were identified by the CLEO group [76]. Grant Larsen, an undergraduate at Chicago, and J. Rosner constructed a fragmentation model to understand whether the observed decays are the most likely to occur in a generic model, or whether there is something exceptional about the observed modes. Results suggested that a great deal was lost by CLEO's requirement of no more than twelve charged particles + photons in the final state. David McKeen continued this work by writing a code suitable for use with PYTHIA. The predictions of such hadronization models will be studied to see if they accurately predict the branching fractions for the observed final states and provide guidance regarding modes which are *not* observed.

6. *Signatures of new physics at hadron colliders*

New physics in which Rosner has had a long interest [44], accessible in early LHC operation, is the identification of one or more extra Z bosons. Rosner will continue to pay close attention to earliest LHC results on high-mass dilepton pairs. He will study the relation between the expression of charges coupling to Z' as linear combinations of two U(1) charges [77, 78, 79] and a more recent effective field theory language championed by C. T. Hill and collaborators.

7. *Participation in CLEO*

Until the collaboration disbanded in March 2012, Rosner participated in collaboration meetings, served on paper committees, and (in collaboration with Hajime Muramatsu and Todd Pedlar) analyzed $\Upsilon(3S)$ data in a search for the lowest P-wave spin-singlet state, the $h_b(1P)$ [80, 81]. In modeling backgrounds to this search from electric dipole transitions involving the $\chi_{b1}(1P)$ states it was realized that such transitions could be specified more precisely using CLEO data [82]. Furthermore, similar background suppression techniques enabled an inclusive measurement of the branching fraction for $\psi(2S) \to \pi^0 h_c$ [81, 82].

8. *Participation in CDF*

J. Rosner serves on the Scientific Paper Reading Group (SPRG) and on godparent committees as requested. He is a co-author of more than a dozen recent CDF papers [83, 84, 85, 86, 87, 88, 89, 90, 91, 92, 93, 94, 95]. He expects to engage in analyses connected with the Λ_b baryon, including a better calibration of its branching fractions and the distribution in pseudorapidity of Λ_b and $\overline{\Lambda}_b$ production at the Tevatron. He also will join forces with Robert Harr in studying leptonic asymmetries in B decays and with Michael Albrow in analyzing centrally produced systems of light mesons in $p\bar{p}$ collisions.

9. *Division of Particles and Fields (DPF) activities*

Rosner's DPF duties have included organization of a Community Planning Meeting at Fermilab, Oct. 11-13, 2012, to prepare for a Community Summer Study in 2013 (CSS2013: "Snowmass on the Mississippi"); organization of CSS2013 to take stock of new results from the LHC and neutrino experiments and help chart a course for U.S. high energy physics; Program Co-Chair for the April 2013 APS Meeting; Chair for April 2014.

10. *Pedagogical activities*

D. McKeen received his Ph. D. and took a position at the University of Victoria with a visiting appointment at the Perimeter Institute. B. Bhattacharya graduated at the end of 2011 and has become a Research Associate at the University of Montreal. A. Thalapillil graduated in June 2012, and has joined the Theory Group at Rutgers.

1.7 Professor Carlos E.M. Wagner

In the last years, C. Wagner concentrated on phenomenology of particle physics, with emphasis on Higgs Physics, flavor physics, predictions and analyses of signals at present and future collider experiments, and the connection of particle physics with cosmology. He made progress in model-building motivated either by new theoretical ideas or by attempts to provide interpretations of experimental results, including the recently observed Standard Model Higgs-like resonance, the forward-backward asymmetry of the top quark, the reported dijet excess in the production of a W plus two jets at CDF, and anomalies in direct dark matter detection. He also concentrated on the analysis of renormalization group invariants in low energy supersymmetric theories.

C. Wagner continued his activities as the head of the HEP Theory Group at Argonne National Laboratory, and the supervision of three postdocs at the University of Chicago and Argonne, Tao Liu, Stefania Gori and Pedro Schwaller, and five students, N. Shah, P. Draper, Arun Thalapillil (jointly with J. Rosner), Ran Huo and Aniket Joglekar. Nausheen Shah graduated in July, 2009, and moved to a postdoctoral position at the Theory Group at Fermilab in October, 2009. Patrick Draper graduated in July, 2011 and moved to a postoctoral position at UC Santa Cruz. Arun Thalapillil graduated in April, 2012 and is moving with a postdoctoral position to Rutgers. Ran Huo is expected to graduate in 2013 and Aniket Joglekar in 2014.

C. Wagner supported the visit of two long term visitors to the Univ. of Chicago, Dr. Arunansu Sil and Hao Zhang. The first one obtained a permanent position in India during his visit and the second one was a one year visitor student from China, who moved to a postdoc position at the HEP Theory Group at Argonne. Wagner also acted as the head for the search committee for an Assistant Professor in high energy physics at the University of Chicago and was a member of the search committee for an Associate Physicist position at Argonne. The first search led to the hiring of LianTao Wang, who holds an Early Career Award from the DOE, and the second one led to the hiring of Frank Petriello and Radja Boughezal as Associate and Assistant Physicists at Argonne.

Wagner was a member of the Particle Physics Project Prioritization Panel, P5, and he was the Theory Convener of the Proton Decay Group of the Intensity Frontier Workshop, which was organized at the request of the DOE to guide the decisions on the future of the US program in this area. He organized a Workshop in Chicago, on November 12, 2012, to discuss the implications of the Higgs Discovery at the LHC.

1. *Higgs Physics at the Tevatron and the LHC*

About ten years ago, C. Wagner, in collaboration with M. Carena and S. Mrenna studied the possibility of testing the MSSM at the Tevatron collider. At that point, they used somewhat unrealistic projections of the Tevatron capabilities. This motivated C. Wagner, T. Liu and P. Draper, a former student at the University of Chicago, to perform such an update of the previous analyses. Their work went beyond the previous analyses in many directions. Not only did they use more realistic estimates of the Tevatron experiment reach in the search for standard and non-standard Higgs bosons, based on the most recent experimental studies, but also they used the enhanced Tevatron capabilities in the $H \to WW$ and $H \to \tau\tau$ channels, which lead to new ways of probing the MSSM.

Their result was presented for different efficiency improvements as well as for different values of the final luminosity at the Tevatron collider. They showed that, for the expected gain in efficiencies by the end of 2011, most of the Higgs MSSM parameter space may be probed at the 95 % confidence level, in different representative benchmarks which lead to very different properties of the Higgs bosons which couple in a standard and non-standard way to the weak gauge bosons. This results relies heavily on the combination of different channels, which prove to be complementary at the Tevatron collider [96]. The comparison of their results with the recently reported ones by the Tevatron collaboration shows impressive agreement in the expected reach. Let us stress that a two to three sigma excess of events has been observed by the Tevatron collaborations in the $h \to b\bar{b}$ channel.

In a subsequent work, the same authors performed an extended analysis, which include the possibility of CP-violation in the MSSM Higgs sector, making use of the recently updated version of the CPsuperH program, which has C. Wagner as one of its authors. Using the most recent studies from the Tevatron and LHC collaborations, they examined a CP-violating benchmark scenario for a range of CP-violating phases in the soft trilinear and gluino mass terms and computed the exclusion/discovery potentials for each collider on the $(M_{H^+}, \tan\beta)$ plane. Projected results from Standard Model (SM)-like, non-standard, and charged Higgs searches were combined to maximize the statistical significance. They exhibited complementarity between the SM-like Higgs searches at the LHC with low luminosity and the Tevatron, and estimate the combined reach of the two colliders in the early phase of LHC running [97].

In collaboration with Marcela Carena, Patrick Draper, Sven Heinemeyer and Georg Weiglein, Wagner studied the power of the Tevatron collider to probe the Higgs sector of minimal supersymmetric scenarios within the assumption of an early termination at the end of 2011, as well as for an extended run until the year 2014. Wagner and collaborators showed that while in both scenarios, most of the parameter space is probed, complete coverage of the parameter space at the 2 σ level, as well as possible 3 σ evidence of a Higgs could only be obtained by an extended running [98] in most of the parameter space.

Following his previous year work with Patrick Draper and Tao Liu, Wagner, in collaboration with them and with Marcela Carena, demonstrated that provided the expected sensitivity improvements are achieved, the Tevatron collider can probe the existence of the Standard Model like Higgs in all scenarios in which the resulting Higgs mass is smaller than about 120 GeV, while it falls short of this goal for scenarios, like the Maximal Mixing Scenario, in which the Higgs mass can be as large as 130 GeV, and close to the recent observation of a 126 GeV resonance. On the other hand, he showed that searches at an early LHC would become more challenging for a lighter Higgs, particularly for low values of the CP-odd Higgs mass, for which the partial width of its decay into bottom quarks tends to be enhanced. Due to their complementary strength Wagner advocated a combination of the final results of the Tevatron with those of the first LHC years [99]. Finally, Wagner and collaborators emphasized the relevance of non-standard Higgs searches to probe the MSSM parameter space in the 7 TeV LHC run.

2. *LHC Signatures of Higgs Physics*

Recently, the ATLAS and CMS LHC experiments reported the discovery of a resonance, consistent with the properties of a SM-like Higgs with mass close to 125 GeV. The significance of the Higgs signal is enhanced by the presence of an excess in the diphoton rate, which is close to two times the SM Higgs decay rate at both experiments. Although the statistical significance of the diphoton excess is only somewhat above a standard deviation at both experiments, this motivated Wagner to study the possibility of obtaining a Higgs with mass close to 125 GeV and an enhanced diphoton rate within the context of the MSSM. In collaboration with M. Carena, N. Shah and S. Gori, Wagner showed that such a Higgs would demand a large value of the stop mixing parameter. They showed that both stops could have masses below a TeV, and if the splitting between the two stop masses is large, the lightest stop mass can be as small as 100 GeV. Moreover, the enhancement of the diphoton rate may only be obtained in the presence of light staus, with large mixing between the left- and right-handed components. This can be achieved at large values of $\tan\beta$ and moderate or large values of the supersymmetric parameter μ [100].

In collaboration with Marcela Carena, Stefania Gori, Nausheen Shah, and Lian Tao Wang, Wagner studied the phenomenological consequences of the light stau scenario, recently proposed by him and the first three authors to explain the potentially enhanced rate of Higgs decay into diphotons. Precision electroweak tests as well as the questions of dark matter and the anomalous magnetic moment of the muon were analyzed and shown to be consistent with the current scenario. Moreover, consistency with flavor independence of the soft supersymmetry breaking parameters at the messenger scale, at which it is transmitted to the observable sector, lead to a prediction on this scale. Finally, he analyzed the collider signatures of this model, both in the direct stau production as in the associated production with sneutrinos. Although the first search channel does not look promising at the LHC, the latter may provide evidence for the realization of this scenario at either the 8 TeV or the 14 TeV LHC [101].

Motivated by his previous work on the light stau scenario in the MSSM, in collaboration with Marcela Carena and Ian Low, Wagner studied under which conditions can new particles induce an enhanced diphoton decay rate of the Higgs. Regular chiral fermions and scalars with positive quartic couplings to the Higgs tend to induce a suppression of this rate, but light scalars and fermions in the presence of mixing of spices of different $SU(2)$ quantum numbers can lead to an enhancement. The light staus and vector-like fermions discussed above are examples of this. The associated modification of the Z–γ Higgs decay rate was analyzed, and they showed that it has a strong dependence on the new charged particle quantum numbers [102].

In very recent works, in collaboration with Marcela Carena, Stefania Gori, Ian Low and Nausheen Shah, Wagner analyzed the question of vacuum stability in supersymmetric models with light staus. He showed that this requirement puts relevant constraints on these scenarios. While the metastability of the Universe constrains the possible enhancement in the Higgs to diphoton decay width in the light stau scenario, an increase of the order of 50 can be achieved in the region of large $\tan\beta$. Larger enhancements may be obtained, but would require values of $\tan\beta$ associated with non-perturbative values of the tau Yukawa coupling at scales below the GUT scale, thereby implying the presence of new physics beyond the MSSM [103]. Moreover, the LHC phenomenology of these scenarios in the presence of a light stop was recently analyzed by a subset of this authors and LianTao Wang. It was shown that although these scenario cannot be probed by direct sparticle searches at the 8 TeV LHC, they could be tested at the 14 TeV LHC at high luminosity [104].

In collaboration with Pedro Schwaller and Aniket Joglekar, a student at the University of Chicago, he is analyzing an extension of the Standard Model, which includes a new generation of leptons (including a right handed neutrino) and its vector partner. This model includes a possible Dark Matter candidate, and can lead to an enhanced Higgs diphoton rate for sizable values of the Yukawa couplings. The question of stability of the Higgs potential and consistency with precision electroweak precision measurements in the region of parameters that lead to an enhanced diphoton rate were analyzed, and consistency with precision electroweak data was demonstrated [105]. The large Yukawa couplings necessary to enhance the diphoton decay rate of the Higgs, however, lead to instabilities of the Higgs potential at high energies. These instabilities could be avoided in a supersymmetric extension. Wagner, in collaboration with the same authors, studied such an extension, showing that not only this leads to the possibility of enhancing the Higgs diphoton decay rate without vacuum stability problems, but also to novel Dark Matter candidates [106] .

In collaboration with the Chicago students Gabriel Lee, Arun Thalapillil and Ran Huo, Wagner studied an extension of the Minimal Supersymmetric Standard Model with a gauge group $SU(2)_1 \times SU(2)_2$ breaking to $SU(2)_L$. The extra wino has an enhanced gauge coupling to the SM-like Higgs boson and, if light, has a relevant impact on the weak scale phenomenology. The low energy Higgs quartic coupling is modified both by extra D-term corrections and by a modification of its renormalization group evolution from high energies. At low values of $\tan\beta$, the latter effect may be dominant. This leads to interesting regions of parameter space in which the model can accommodate a 125 GeV Higgs with relatively light third generation squarks and an increased $h \to \gamma\gamma$ decay branching ratio, while still satisfying the constraints from electroweak precision data and Higgs vacuum stability [107].

3. *Benchmark Scenarios for LHC Higgs Searches*

In collaboration with M. Carena, S. Heinemeyer, O. Stal, and G. Weiglein, Wagner proposed new low-energy MSSM benchmark scenarios that, over a wide parameter range, are compatible with the mass and production rates of the observed Higgs signal. These scenarios also exhibit interesting phenomenology for the MSSM Higgs sector. He proposed a slightly updated version of the well-known mhmax scenario, and a modified scenario (mhmod), where the light CP-even Higgs boson can be interpreted as the LHC signal in large parts of the M_A-$\tan\beta$ plane. Furthermore, he defined a light stop scenario that leads to a suppression of the lightest CP-even Higgs gluon fusion rate, and a light stau scenario with an enhanced decay rate of $h \to \gamma\gamma$ at large $\tan\beta$. He also suggested a Higgs scenario in which the lightest Higgs can have suppressed couplings to down-type fermions. He also discussed the sensitivity of the searches to heavy Higgs decays into light charginos and neutralinos, and to decays of the form $H \to hh$. Finally, in addition to all the other scenarios where the lightest CP-even Higgs is interpreted as the LHC signal, he proposed a low-MH scenario, where instead the heavy CP-even Higgs boson corresponds to the new state around 125.5 GeV [108].

4. *Flavor Physics*

In collaboration with T. Liu, V. Barger, P. Langacker and L. Everett, C. Wagner continued his research of extended gauge sectors, studying the flavor properties of the simplest, abelian extension of the Standard Model. In particular, he analyzed flavor-changing-neutral-current (FCNC) effects in the $b \to s$ transitions that are induced by family non-universal $U(1)'$ gauge symmetries. After systematically developing the necessary formalism, C. Wagner and collaborators presented a correlated analysis for the $\Delta B = 1, 2$ processes. They adopted a model-independent approach in which we only require family-universal charges for the first and second generations and small fermion mixing angles [109]. Within this framework, they analyzed the constraints on the resulting parameter space from $B_s - \bar{B}_s$ mixing and the time-dependent CP asymmetries of the penguin-dominated $B_d \to (\pi, \phi, \eta', \rho, \omega, f_0)K_S$ decays. Their results indicate that the currently observed discrepancies in some of these modes with respect to the Standard Model predictions can be consistently accommodated within this general class of models [110].

5. *Gauge Extensions of the Minimal Supersymmetric Standard Model*

The Minimal Supersymmetric extension of the Standard Model provides a solution to the hierarchy problem and leads to the presence of a light Higgs. A Higgs boson with mass above the present experimental bound may only be obtained for relatively heavy third generation squarks, requiring a precise, somewhat unnatural balance between different contributions to the effective Higgs mass parameter. It was recently noticed that somewhat heavier Higgs bosons, which are naturally beyond the LEP bound, may be obtained by enhanced weak SU(2) D-terms. C. Wagner's and two of his former students, Anibal Medina and Nausheen Shah, they emphasized that the enhanced SU(2) D-terms will not only raise the Higgs boson mass but also affect the spectrum of the non-standard Higgs bosons, sleptons and squarks, which therefore provide a natural contribution to the T parameter, compensating for the negative one coming from the heavy Higgs boson. This leads to very interesting phenomenological properties for these models, which include the possibility of exotic decays of the Higgs bosons, in mass regions in which they would naturally decay into heavy gauge bosons, as well as light third generation superpartners, and supersymmetric signatures dominated by the presence of tau leptons in the final state [111].

6. *Gauge Higgs Unification in Warped Extra Dimensions at the LHC*

C. Wagner contributed a section on LHC phenomenology of warped extra dimensions to a recent report on LHC phenomenology coauthored by many experts in the field. He summarized the results of his previous analyses on constraints from precision electroweak observables and on the obtention of a realistic gauge and fermion spectrum in Gauge Higgs Unification Models. The phenomenological properties include a light Higgs, as well as a relatively light Kaluza Klein mode of the top quark, which can lead to interesting phenomenological properties at the LHC. The production of this quark receives standard QCD contributions as well as form Kaluza Klein modes of the gluon, which lead to constructive interference with the standard production modes. This, in turn, leads to a reach for these quarks at the LHC which extend beyond the standard reach for these particles [112].

7. *Top quark forward-backward asymmetry*

C. Wagner worked in collaboration with Jon Rosner, two postdoctoral research associates at Argonne (Q.H. Cao and G. Shaughnessy) and a student at Chicago (D. Mckeen) on the analysis of the recently observed forward-backward asymmetry at the Tevatron collider. They adopted a Markov Chain Monte Carlo method to examine various new physics models which can generate the forward-backward asymmetry in top quark pair production observed at the Tevatron by the CDF Collaboration. They studied the following new physics models: (1) exotic gluon G', (2) extra Z' boson with flavor-conserving interaction, (3) extra Z' with flavor-violating u-t-Z' interaction, (4) extra W' with flavor-violating d-t-W' interaction, and (5) extra scalars S and $S^{\pm}$ with flavor-violating u-t-S and d-t-$S^{\pm}$ interactions. After combining the forward-backward asymmetry with the measurement of the top pair production cross section and the $t\bar{t}$ invariant mass distribution at the Tevatron, they found that an axial vector exotic gluon G' of mass about 1TeV or 2TeV or a W' of mass about 2TeV offer an improvement over the Standard Model. The other models considered do not fit the data significantly better than the Standard Model. They also emphasize a few points which have been long ignored in the literature for new physics searches: (1) heavy resonance width effects, (2) renormalization scale dependence, and (3) NLO corrections to the $t\bar{t}$ invariant mass spectrum. They argued that these three effects are crucial to test or exclude new physics effects in the top quark pair asymmetry [113].

8. *Renormalization Group Invariants in Supersymmetric Models*

In collaboration with Marcela Carena, Patrick Draper and Nausheen Shah, Wagner demonstrated the existence of fourteen Renormalization Group Invariant quantities (RGIs) involving the gauge couplings and the soft supersymmetry breaking parameters within the MSSM. The determination of the values of these invariants at colliders allows the extraction of the same quantities at high scales. Considering the most general flavor independent model at the messenger scale, there is a one to one correspondence between the free parameters of the Theory and the RGIs. In the most general gauge mediated model, this correspondence allows to extract all parameters from low energy measurements, including the messenger scale. Finally, in minimal models, the RGIs allow not only the extraction of parameters, but also sum rules that should be fulfilled at low energies [114].

Carlos Wagner continued working on Renormalization Group Invariants, putting special emphasis on the information that may be extracted by measurements of the supersymmetry spectrum at the LHC. He and his collaborators demonstrated that under the assumption of being in some minimal supersymmetry breaking scenario, the measurement of a limited number of masses is sufficient to determine most of the mass parameter of the theory, as well as the messenger scale at which supersymmetry breaking is transmitted [115]. . Since these models depend only on a limited number of parameters also several consistency relations appear between different renormalization group invariant quantities, that allow to differentiate the different supersymmetry breaking models.

In collaboration with Marcela Carena, Joe Lykken, Nausheen Shah and Sezen Senken, continued his study of Renormalization Group Invariant by (RGIs) studying what information can be obtained from current LHC data in their possible values. Wagner and collaborators started with a general phenomenological approach to the MSSM soft supersymmetry breaking parameters and study the probability distribution of the different RGIs. He applied these distributions to analyze the constraint on the realization of different, well motivated, supersymmetry breaking scenarios [116].

9. *Direct Dark Matter Direct Detection and light CP-even Scalars*

In collaboration with Patrick Draper, Tao Liu, Lian-Tao Wang and Hao Zhang, Wagner studied the next to minimal supersymmetric extension of the Standard Model close to the Peccei-Quinn symmetry limit. They demonstrated that, a light scalar and a light pseudoscalar neutral Higgs, as well as a light neutralino appear naturally in this region of parameters. These particles may lead to the proper relic density as well as to a large direct dark matter detection cross section similar to the one potentially measured at COGENT, DAMA and CRESST experiments. Wagner and collaborators provided specific realizations of these ideas and discussed constraints from collider and flavor experiments on this scenario, which was named Dark Light Higgs [117].

10. *W + 2jets at the Tevatron Collider*

In collaboration with Q.H. Cao, M. Carena, S. Gori, A. Menon, P. Schwaller and L.T. Wang, Wagner studied a model with a quasi-inert Higgs doublet as a possible explanation of the W+2 jets excess observed by the CDF experiment. The model includes a heavy charged Higgs in the range 250–300 GeV, as well as light CP-even and CP-odd Higgs bosons with masses close to 150 GeV. An excellent description of the CDF excess is provided. Agreement with precision measurements leads to a prediction of the SM-like Higgs mass, which tends to be heavier than in the Standard Model. A possible implementation of this model leads also to an explanation of the top quark forward-backward asymmetry, without being in conflict with flavor observables [118].

11. *Alternative Signatures of Higgs Physics*

In collaboration with Stefania Gori and Pedro Schwaller, Wagner studied the possibility of observing a Higgs proceeding from the decay of heavy supersymmetric particles. They concentrated on the region of parameter space that leads to a proper relic dark matter density and demonstrated that, in general, the production of Higgs is sufficiently large to ensure observation with modest luminosity at a 14 TeV LHC Collider. Moreover, for squark masses somewhat below the TeV scale, observation of Higgs production may be obtained at the 7 TeV/8 TeV run [119].

In collaboration with I. Low, P. Schwaller and G. Shaughnessy, C. Wagner worked on the study of Higgs properties at the LHC provided by detailed line-shape measurements. This method, which works well for Higgs masses above the two vector boson threshold, allows for the determination of couplings as well as the obtention of a possible invisible decay width affecting the main Higgs decay branching ratios [120].

With M. Carena, S. Gori, A. Juste, A. Menon and L.T. Wang, Wagner studied the signatures of a Higgs produced in association with bottom quarks at the LHC. In particular, they concentrated on the possibility of using boosted Higgs bosons for the measurement of the Higgs decay into bottom quark pairs. Putting appropriate cuts on the hard bottoms produced in association with the Higgs, they showed that the sensitivity for Higgs searches in this channel may be comparable with the one in the τ decay channels in broad regions of parameter space [121]

12. *Dark Matter, Baryogenesis and LHC Data*

In collaboration with Marcela Carena and Nausheen Shah, Wagner worked on the possibility of electroweak baryogenesis in the Dark Light Higgs scenario which he previously proposed to explain the large direct Dark Matter cross section potentially observed at COGENT and DAMA experiments. Their analysis shows that in this region of parameters the electroweak phase transition tends to be strongly first order, what is a condition for the realization of the baryogenesis scenario. Moreover, the phase transition strengths grows for smaller values of the lightest CP-even Higgs mass, for which the direct Dark Matter cross section also grows, establishing therefore a correlation between the value of the Direct Dark Matter cross section and the strength of the phase transition [122]

In collaboration with Marcela Carena, Germano Nardini and Mariano Quiros, Wagner studied the Higgs physics constraints on the electroweak baryogenesis scenario he proposed fifteen years ago with Carena and Quiros. Light stops, with mass of order 100 GeV, are present in this scenario. Such light stops induce an enhancement of the Higgs gluon fusion production rate as well as a small suppression of the Higgs diphoton rate. These induced signatures are in contradiction with recent Higgs search ones. Wagner and collaborators analyzed the possible modification of these conclusions induced by the decay of Higgs into light neutralinos in the region of parameters in which the stop decays into a bottom, an on-shell sneutrino and a τ^+, which is unconstrained by Tevatron and LHC searches [123].

13. *Neutrino Physics*

In collaboration with Jamie Gainer and Ran Huo, he analyzed the relation between neutrino mixing and the unification of Yukawa couplings within the MSSM. Assuming the unification of the third generation charged lepton and down- and up-quark Yukawa couplings at the Unification scale, the results of this analysis suggest that successful unification may be obtained by assuming that all relevant mixing in the lepton sector proceeds from the charged sector at high energies [124]. Making natural assumptions on the soft supersymmetry breaking parameters at high scales, they also studied the predictions for the supersymmetry particle spectrum at low energies.

In collaboration with Arun Thallapillil and Bubanjyoti Battacharya, Wagner studied the impact of sterile neutrinos, which may lead to an explanation of the short base-line neutrino experiment anomalies, on long base-line neutrino physics. In particular, they concentrated on how the MINOS and T2K experiment results may be affected by the presence of these particles, and showed that while the fit to the MINOS data slightly improved, there may be relevant effects at a higher luminosity T2K experiment. Moreover, the comparison of future T2K results on $\sin^2\theta_{13}$, with the ones of reactor experiments, which are only weakly affected by the presence of sterile neutrinos, may serve to test the light sterile neutrino hypothesis [125].

14. *Updated Fortran Code for the computation of Higgs Properties in the MSSM with CP-violation*

In collaboration with Marcela Carena, John Ellis, Jae Sik Lee and Apostolos Pilaftsis, Wagner updated their Fortran code CPsuperH for the computation of Higgs Properties in the MSSM in the persence of explicit CP-violation. The effects of stau particles, omitted before in the computation of Higgs masses and mixings, were included. Updated values of the electric dipole moment computation were presented [126].

1.8 Research Associate Stefania Gori

Particle physics entered a new era with the LHC discovery of a new boson with mass at around 125 GeV. The next direction in particle physics is understanding the fundamental properties of this new particle and the implications for beyond the Standard Model (BSM) theories. A central question is to determine which role the boson plays in electroweak symmetry breaking and if it is the Standard Model (SM) Higgs boson. Present data is not showing any striking deviations from a SM Higgs boson, however more data is needed to have a more definite answer. Detecting non SM-like properties for this boson would have very deep implications for New Physics (NP) theories. At present there are indications from both the ATLAS and the CMS experiments for an excess of the Higgs rate in the diphoton channel and for SM-like ZZ^* and WW^* rates. While this excess is not yet statistically significant, it is very interesting to study its implications for BSM theories. In the Minimal Supersymmetric Standard Model (MSSM) there are several new particles that can affect the Higgs to diphoton rate. However, as Gori and collaborators have shown [100, 101, 103], the only Susy particles that can lead to the observed pattern of deviations are light and heavily mixed staus. In these papers it was found that staus with a mass close to the LEP bound with a large left-right mixing can give an effect as large as $\sim 40\%$ in the gamma gamma rate, still being consistent with electroweak precision tests, with direct LHC searches for staus and vacuum stability. Furthermore, in [101] Gori showed that present stau LHC searches focused on promptly decaying staus produced in Susy cascade decays are not yet sensitive to test the signatures of this scenario. Gori proposed new search strategies which are optimized to enhance the LHC sensitivity to the light stau scenario. Particular attention was dedicated to the direct electroweak production of a stau and a sneutrino that gives a signature of two taus, one lepton and missing energy. An additional interesting feature of the model is that the phenomenology of stops and heavy Higgs bosons is altered by the presence of light staus, if compared to the MSSM scenarios experimentalists are testing at the LHC. In particular, in [104] Gori has shown that light right-handed stops with mass in the range (120-140) GeV can still be hidden at the LHC, thanks to their decay into a stau, a b-quark and a neutrino.

Gori and collaborators have also studied how new physics beyond the MSSM (BMSSM) can affect the phenomenology of the Higgs boson and can alleviate the naturalness problem of the MSSM [127]. If the BMSSM physics is sufficiently heavy, its effects can be studied model independently by adding to the MSSM higher dimensional operators. The higher dimensional operators can lead to CP violation in the Higgs sector already at tree level. Gori and collaborators have identified distinct Higgs collider signatures that cannot be realized, either in the BMSSM without CP violating phases or in the CP violating MSSM, and investigated the prospects to probe them at the Tevatron and at the early LHC.

Additionally, Gori and collaborators have analyzed models with exotic scalars charged under the SM gauge group interacting with the SM Higgs through the Higgs portal coupling $HH^\dagger\Phi\Phi^\dagger$ [128]. In order to obtain a good fit of the present LHC Higgs data, relatively light (100-200) GeV exotic scalars with sizable coupling to the Higgs would be preferred. Such NP particles can also be searched for directly at the LHC. Gori's analysis had a twofold aim: 1) to show that current collider constraints on the new particles allow for viable parameter space and 2) to highlight which LHC search should be improved in order to be more sensitive to our scenario. To note that this kind of theories can be in good agreement with the present data on electroweak precision observables, in spite of having very light new degrees of freedom. Along this line Gori and collaborators have analyzed the status of the fit of electroweak precision data, after the discovery of a Higgs-like particle with mass around 125 GeV [129]. In particular they proposed a modified *Beautiful Mirror* scenario with custodial protection, which contains new vector-like quarks that mix with the b quark of the SM, producing a good fit of the forward-backward asymmetry of the bottom quark. This model can naturally lead to a sizable enhancement of the Higgs to diphoton rate and will be probed soon by LHC searches of exotic quarks.

Finally Gori was involved in the study of the Higgs phenomenology of non-supersymmetric models with multi-Higgs doublets. The Two Higgs Doublet Model (2HDM) Gori has investigated is based on the Minimal Flavor Violating (MFV) idea [130]. The model is particularly attractive since, despite both the two Higgs doublets being coupled to up and down-type quarks, it is still consistent with present flavor constraints.

On a different line, motivating new experimental searches for NP particles at the LHC is a crucial task in the LHC era. Together with collaborators, both theorists and experimentalists, Gori has proposed a new search strategy for non-standard neutral Higgs bosons at the LHC in the 3b final state topology: a Higgs produced in association with a b-quark and subsequently decaying into two b-jets [121]. This investigation was motivated by an excess of events in the CDF 3b analysis at around 150 GeV. Furthermore this topology is arising naturally in very well motivated NP models like the MSSM. This channel is now studied by the CMS collaboration.

Finally, in the LHC era, it will be essential to build models that match possibly observed non standard signatures and study their distinct collider phenomenology. As an example, Gori has recently worked on the development of a NP model [118] that allows to explain the excess of events in the invariant mass distribution of jet pairs produced in association with a W-boson, presented last year by the CDF collaboration.

1.9 Research Associate Johannes Heinonen

J. Heinonen joined the theoretical HEP group at Enrico Fermi Institute (EFI) in August 2010. His research spans a variety of issues in particle physics phenomenology.

J. Heinonen joined the theoretical HEP group at Enrico Fermi Institute (EFI) in August 2010.

In collaboration with C. Wagner, J. Heinonen investigates one possibility of enhancing the $B \to \tau\nu$ branching ratio in the minimal-supersymmetric standard model (MSSM) compared to the standard model (SM) prediction [131]. For a large ratio $\tan\beta$ of Higgs VEV's, there can be large corrections to B-physics observables in the MSSM. In the particular case of $B \to \tau\nu$ this usually leads to destructive interference between the SM and MSSM diagram. However, as J. Heinonen and his collaborator point out, loop effects in the b quark Yukawa coupling can change the sign of the MSSM contribution. For this to be possible the bilinear coupling μ has to be chosen negative and in addition $|\mu|$ and the gluino mass have to be large, of the order of a few TeV, while the squarks have masses around one TeV with large splittings for the third generations squarks. The authors investigate the impact of this spectrum on other observables and show that most observables like $B \to D\tau\nu$, leptonic Kaon decays or the newly measured $B_s \to \mu\mu$ are easily accommodated with these parameters. Due to the big effect the sign of μon the decay $b \to s\gamma$ and the myonic gyromagnetic factor g_μ, one needs to additionally assume that the gaugino masses M_1 and M_2 are negative, while M_3 is positive. Also the new LHC bounds can be accommodated in this setup. The big drawback of this approach is, that is does only allow for metastable non-colorbreaking minima. Long-lived realistic metastable vacua seem to be achievable, but the life-time has to be re-calculated for each set of parameters.

In collaboration with R. Hill, J. Heinonen investigates a recent claim that a neutron might get a charge in a electromagnetic background field [132]. The authors of [132] claim that a neutron as described in the Skyrme model gets a millicharge in an electromagnetic background field due to interactions coming from the Wee-Zumino-Witten term. J. Heinonen and R. Hill point out that this claim is false and relies on an incomplete calculation and understanding of the electromagnetic current [133]. They furthermore setup the proper framework for the calculation of the charge and higher multipoles. The explicit calculation of the induced quadrupole moments by the electromagnetic background field is still in progress.

In collaboration with R. Hill and M. Solon, J. Heinonen studied the constraints of Lorentz invariance on non-relativistic theories [134]. In particular, they investigate NRQCD and HQET, where it has been proposed that so-called reparametrization invariance (RPI) imposed Lorentz invariance on the Lagrangian. J. Heinonen and his collaborators show explicitly how Lorentz invariance should be imposed at the field level on a non-relativistic theory like NRQCD/HQET using the so-called "Wigner's little group". Their construction can be easily extended to arbitrary spins and other costraints (e.g. for self-conjugate fields) can be included. Furthermore, the interpretation of the formalism does not need the knowledge of the underlying UV physics (e.g. in contrast to integrating out the antiquark to obtain a heavy quark Lagrangian). They also show explicitly how this construction is related to RPI and point out a subtlety that leads to a disagreement of some versions of RPI disagrees with Lorentz invariance at order $1/M^4$.

Continuing this work, J. Heinonen together with R. Hill, M. Solon and G. Lee have constructed the most general effective Lagrangian of arbitrary spin particles coupled to electromagnetism up to order $1/M^3$. This includes terms breaking parity (P) and/or time reversal (T). It turns out that in a Lorentz invariant effective theory one obtains constraints between coefficients of sectors with different PT transformation properties. Currently, they are using this Lagrangian to calculate scattering amplitudes in P-violating electron-proton scattering. This work is still in progress.

1.10 Research Associate Joseph Marsano

J. Marsano has been a postdoc in the theoretical HEP group at the Enrico Fermi Institute (EFI) since September 2009. During that time, he has pursued a study of string phenomenology with the aim of understanding how particle physics can emerge from string theory and characterizing extensions of the Standard Model that can be found in the string landscape. Though the landscape is vast in size, there is a simple reason to expect that particle physics may not depend on every detail of a given string vacuum: the Standard Model is only sensitive to short distance physics through a relatively small number of parameters (19). Supersymmetric extensions have more (~ 125) but even these correspond to a coarse graining of the fine details that distinguish one string vacuum from another. The objective is to get a handle on this coarse grained information and study the patterns that emerge in order to get a feel for scenarios that emerge naturally from string theory. Along the way, one encounters geometric structures that are interesting in their own right and can be studied using intuition from physics.

We are fortunate in that phenomenology points to a class of string vacua where the important data for particle physics are easily separated from other details of the compactification. In these vacua, particle physics degrees of freedom explicitly localize on a small part of the compactification and their physics is described by the 'local geometry' nearby. These local geometries are well-understood and lead to a constrained framework for building particle physics models with an additional feature: the problem of UV completion is mathematically well-defined. Given a particle physics model specified by a local geometry, we need only embed it into a global string compactification. The most important challenge then is to understand how local data (i.e. particle physics data) can be extended to global data that specifies the complete string compactification.

Most of J. Marsano's research in the past 3 years has centered on understanding the connection between local and global models and has led to consistent global constructions while uncovering obstructions to embedding large classes of models in string theory. This work has also uncovered several interesting mathematical structures of intrinsic interest whose properties are currently being explored in collaboration with algebraic geometers.

In collaboration with N. Saulina and S. Schäfer-Nameki, Marsano constructed the first global

F-theory models with (approximate) $U(1)_{PQ}$ symmetries in [135]. They observed the appearance of exotic particles whenever $U(1)_{PQ}$'s are present, discussed the problems that these particles pose, and suggested mechanisms for removing them. As one of the first papers on global F-theory compactifications, this work developed many of the fundamental model-building tools that have become standard in subsequent years.

In collaboration with N. Saulina and S. Schäfer-Nameki, Marsano initiated the program of understanding how the 'local flux data' that generates chiral spectra in local models can be extended to well-defined global flux data in [136]. This involved getting a handle on (suitably defined) $(2,2)$-forms on singular geometries and was the beginning of our current understanding of the emergence of spectral covers in F-theory models without Heterotic dual.

In collaboration with E. Kuflik, Marsano explored the possibility of building F-theoretic realizations of supersymmetric flipped $SU(5)$ models in [137]. Surprisingly, they found that supersymmetric flipped $SU(5)$ has very general problems that require specific symmetry structures to resolve. Some of these problems were previously known but Kuflik and Marsano observed a general issue with the μ parameter that can only be addressed with R symmetries. They characterized the most general discrete symmetries and continuous symmetries that can deal with both μ and the problem of rapid proton decay and discussed several problems with realizing them in F-theory compactifications. A phenomenologically problematic model was also constructed as a first step toward more realistic examples.

In [138], Marsano provided a simple explanation for the appearance of exotic particles in F-theory models with $U(1)_{PQ}$ symmetries. $U(1)_{PQ}$ was the most popular idea for addressing the μ and proton decay problems in F-theory models for several years and the necessity of exotics ruled out a number of scenarios. Their appearance is connected to the physics of anomaly cancellation and the statement that mixed anomalies of arbitrary kind cannot be canceled in F-theory compactifications without problematic consequences. In particular, mixed anomalies with insertions of Standard Model and $U(1)$ currents that do not descend from GUT anomalies cannot be canceled without breaking hypercharge and generating a massive photon. Any $U(1)$ like $U(1)_{PQ}$ that exhibits such anomalies, then, must be accompanied by exotic particles that contribute to the anomaly in any model with massless hypercharge.

With M. Dolan, N. Saulina, and S. Schäfer-Nameki, Marsano explored general implications of the anomaly constraints of [138] in F-theory models with $U(1)_{PQ}$ symmetries in [139]. They provided a technical proof of the anomaly conditions of [138] at the level of spectral cover constructions and provided a comprehensive survey of the most general particle spectra that can be obtained in $SU(5)$ F-theory models with one or two $U(1)$ symmetries. Because the $U(1)$ charges of all particles are fixed, they could make very general statements about the relation between masses of exotic particles and the suppression of μ and proton decay operators.

With N. Saulina and S. Schäfer-Nameki, Marsano extended the work of [136] to develop a deeper understanding of G-fluxes in F-theory compactifications and their relation to the bundle data of local models in [140]. These techniques borrow ideas from Heterotic/F-theory duality but extend them in a natural way to models that do not exhibit an F-theory dual. Marsano and his collaborators generalized these methods to understand $U(1)$ symmetries and $U(1)$ fluxes in a proper way in F-theory compactifications and initiated the study of how these ingredients impact the nonperturbative physics generated by M5 instantons. This physics is crucial for incorporating supersymmetry breaking and moduli stabilization in explicit F-theory vacua.

With S. Schäfer-Nameki, Marsano made the description of G-fluxes in F-theory completely explicit in a fully resolved Calabi-Yau geometry in [141]. In addition to providing examples where the techniques of [136] and [140] can be directly illustrated, they also investigated the codimension

3 singularities in F-theory compactifications responsible for generating Yukawa couplings and cleared up misconceptions in the literature about the generation of a large top quark mass in these models.

With M. Dolan and S. Schäfer-Nameki, Marsano explored phenomenological implications of F-theory models with $U(1)_{PQ}$ symmetries in [142]. The analysis focuses largely on the impact of the exotic particles required to account for the anomaly constraints of [138]. Their effect on gauge coupling renormalization and Grand Unification is studied in detail and, with an assumption of gauge mediated supersymmetry breaking, their potential implications for LHC physics are studied. The spectra of many models including exotics are studied in detail and the ability to discriminate the F-theory models from conventional scenarios without exotic particles is discussed.

1.11 Research Associate Gil Paz

Paz joined the theory group in 2009, working on a variety of problems in particle phenomenology before taking a faculty position at Wayne State University in the Fall of 2011.

In collaboration with Jorge De Blas, Paul Langacker and Lian Tao Wang, Paz worked on combining anomaly and Z-prime mediation of supersymmetry breaking. In such a scenario, the supersymmetry breaking effect mediated by an additional U(1)' is comparable with that of anomaly mediation. Combining anomaly with Z' mediation allows to solve the tachyonic slepton problem of the former and avoid significant fine tuning in the latter. Focusing on an NMSSM-like scenario where U(1)' gauge invariance is used to forbid a tree-level mu term, concrete models were presented which admit successful dynamical electroweak symmetry breaking. Gaugino masses are somewhat lighter than the scalar masses, and the third generation squarks are lighter than the first two. In the specific class of models under consideration, the gluino is light since it only receives a contribution from 2-loop anomaly mediation, and it decays dominantly into third generation quarks. Gluino production leads to distinct LHC signals and prospects of early discovery. In addition, there is a relatively light Z', with mass in the range of several TeV. Discovering and studying its properties can reveal important clues about the underlying model. The combined scenario was discussed in [143], while preliminary results were presented in [144].

In a different research project, Paz has discussed in [145] the effective field theory view of deep inelastic scattering. In such an approach, the standard factorization formula of a hard coefficient multiplied by a parton distribution function arises from matching of QCD onto an effective field theory. The DGLAP equations can then be viewed as the standard renormalization group equations that determines the cut-off dependence of the non-local operator whose forward matrix element is the parton distribution function. As an example, the non-singlet quark splitting functions was derived directly from the renormalization properties of the non-local operator itself. This approach, although discussed in the literature, does not appear to be well known to the larger high energy community.

In collaboration with Michael Benzke, Seung J. Lee, and Matthias Neubert, Paz has worked on factorization at sub-leading power and irreducible uncertainties in $\bar{B} \to X_s\gamma$ decay. In [146] a systematic factorization analysis was performed for the $\bar{B} \to X_s\gamma$ photon spectrum in the endpoint region $m_b - 2E_\gamma = \mathcal{O}(\Lambda_{\rm QCD})$, using methods from soft-collinear and heavy-quark effective theory. In that paper it was proposed that, to all orders in $1/m_b$, the spectrum obeys a novel factorization formula, which besides terms with the structure $H\,J \otimes S$ familiar from inclusive $\bar{B} \to X_u l\,\bar{\nu}$ decay distributions contains "resolved photon" contributions of the form $H\,J{\otimes}S{\otimes}\bar{J}$ and $H\,J{\otimes}S{\otimes}\bar{J}{\otimes}\bar{J}$. Here S and $\bar{J}$ are new soft and jet functions, whose form was derived. These contributions arise whenever the photon couples to light partons instead of coupling directly to the effective weak interaction. The new contributions appear first at order $1/m_b$ and are related to operators other than $Q_{7\gamma}$ in the effective weak Hamiltonian. They give rise to non-vanishing $1/m_b$ corrections to the total decay rate, which cannot be described using a local operator product expansion. A systematic analysis of these effects was performed at tree level in hard and hard-collinear interactions. The resulting uncertainty on the decay rate defined with a cut $E_\gamma > 1.6$ GeV was estimated to be approximately $\pm 5\%$. It could be reduced by an improved measurement of the isospin asymmetry Δ_{0-} to the level of $\pm 4\%$. There is no possibility to reduce this uncertainty further using reliable theoretical methods.

In collaboration with Benzke, Lee, and Neubert, Paz has worked on applying the methods of [146, 147] to the direct CP asymmetry in inclusive radiative B decays [148]. This work has shown that the asymmetry is dominated by non-perturbative effects, and can be in the range of $[-0.6\%, 2.8\%]$. This is contrary to the common belief that it is dominated by perturbative effects, which in the standard model give an asymmetry of about 0.5%. This study changes the constraints on many models of new physics, as well as one of the stated goals of the future B factories [149, 150].

The recent measurement of the charge radius of the proton from muonic hydrogen is 5 σ away from a similar measurement of regular hydrogen [151]. The same quantity can be extracted from electron-proton scattering. Together with R. Hill, Paz has studied these extractions in a model-independent way and found that previous extractions have underestimated their errors [152].

With R. Hill, Paz has studied the hadronic uncertainty in the theoretical input for the measurement of the charge radius of the proton from muonic hydrogen [153]. Using the tools of an effective field theory, namely NRQED, this study established model-independent properties of hydrogenic bound states. In particular, it pointed out that the theoretical prediction contains model-dependent pieces whose uncertainty has been ignored in the literature. This study lays the foundation for a more reliable theoretical prediction.

2 PARTICLE PHYSICS AND COSMOLOGY (TASK C)

2.1 Introduction

The interface of particle physics with cosmology and astrophysics is more active and vital than ever. Increasing numbers of particle physicists, both theorists and experimentalists, are working at this Cosmic Frontier, now recognized as one of the three frontiers of modern particle physics, along with the Energy and Intensity Frontiers. Our group helped to pioneer this interdisciplinary activity, has a 32-year record of accomplishments, and is recognized for its research, leadership, and outreach, as well as for the training and mentoring of graduate students and postdocs. In this proposal, we highlight the recent accomplishments of the group during the 2009-2013 time period of the grant.

Recent years have witnessed the establishment of an extremely successful cosmological model. In this model, the Universe is spatially flat and accelerating; composed of baryons, dark matter, and dark energy; underwent a hot, dense, early phase of expansion that produced the light elements via big bang nucleosynthesis and the cosmic microwave background (CMB) radiation; and experienced a much earlier epoch of accelerated expansion, known as inflation, which produced density perturbations from quantum fluctuations, leaving an imprint on the CMB and forming large-scale structure by gravitational instability. This cosmological model includes a number of features that point to new physics beyond the Standard Model, including the cosmic asymmetry between matter and antimatter, the large-scale isotropy and homogeneity of the Universe and the tiny primordial inhomogeneities that seed large-scale structure, the non-baryonic dark matter that holds galaxies and clusters together, and the dark energy that is causing the expansion to accelerate. Exploration of these phenomena is intimately linked to and will help enable discoveries in fundamental physics.

Current research activities of our group include most of the topics at the Cosmic Frontier: inflationary cosmology; particle dark matter and structure formation; dark energy and the accelerating Universe; primordial nucleosynthesis; astrophysical and cosmological constraints on particle physics and General Relativity; the CMB; and cosmological implications of string theory, including branes and extra dimensions. As an example, our group has pioneered and will continue to explore models for the origin of cosmic acceleration—does it arise from a new, mysterious form of stress-energy in the Universe, dark energy, or from a modification of General Relativity on large scales, or does it instead reflect large density inhomogeneities?

In addition to generating theoretical ideas for the Cosmic Frontier, members of our theoretical group play important roles in devising and refining experimental and observational tests of these ideas. Examples include the use of weak gravitational lensing, galaxy clusters, and baryon acoustic oscillations to probe the nature of dark energy. Our group has seeded and provided theoretical and analysis support for observational projects at the Cosmic Frontier, particularly the SDSS galaxy and supernovae surveys, the Dark Energy Survey (DES), and CMB anisotropy experiments; in the longer term, LSST, WFIRST and future CMB polarization experiments. Similarly, in the quest to determine the nature of dark matter we are exploring the implications of and predictions for both laboratory experiments (LHC particle production and direct detection experiments) and astrophysical probes (indirect detection in PAMELA, Fermi-GLAST, etc).

2.2 Personnel and Budget

Members of Task C over the 2009-2013 period were: PI Michael Turner (Prof. of Physics and of Astronomy & Astrophysics [A&A]); Co-I's Joshua Frieman (Prof. of A&A part time; Fermilab staff member; director Dark Energy Survey), Wayne Hu (Prof. of A&A), Edward Kolb (Prof. and Chair of A&A); postdocs Maria Beltran and Mark Wyman. Graduating students associated with the Co-I's during this period include: Felipe Marin (Frieman; postdoc U. Swinburne), Valentin Kostov (Kolb; teaching position in his native Bulgaria), Michael Mortonson (Hu; postdoc Ohio State), Fabian Schmidt (Hu; postdoc CalTech; faculty UIUC), Sasha Belikov (Hooper and Hu; postdoc IAP), Cora Dvorkin (Hu; postdoc IAS), Zosia Krusberg (Kolb; visiting Prof. Vassar College), Melanie Simit (Hooper; postdoc CMU). Current students supported by this grant are Yin Li, Vinicius Miranda, and Alan Zablocki.

2.3 Training of Graduate Students and Postdocs

Preparing the next generation of scientists to work at the Cosmic Frontier and attracting bright young students to the physical sciences in general is central to our task. Over 30 former students or postdocs associated with Task C now hold faculty positions. Those who were students include:

- Daniel Chung (Associate Professor of Physics, U. Wisconsin, Madison)
- Kimberly Coble (Associate Professor of Physics, Chicago State U.)
- Bill Collins (Climate Science Department Head, LBNL)
- Patrick Crotty (Assistant Professor of Physics, Colgate U.)
- Katherine Freese (Professor of Physics, U. Michigan)
- Joshua Frieman (Theoretical Astrophysics, Fermilab; Prof. of Astronomy, U. Chicago)
- Geza Gyuk (Chair of Astronomy Department, Adler Planetarium)
- Gil Holder (Associate Professor of Physics, McGill U.)
- Dragan Huterer (Associate Professor of Physics, U. Michigan)
- Andrew Jaffe (Professor of Astrophysics and Cosmology, Imperial College, London)
- Marc Kamionkowski (Professor of Physics, Johns Hopkins U.)
- Lloyd Knox (Professor of Physics, UC Davis)
- Arthur Kosowsky (Associate Professor of Physics and Astronomy, U. Pittsburgh)
- Marcos Lima (Assistant Professor of Physics, U. de Sao Paulo)
- Robert Scherrer (Professor and Chair of Physics, Vanderbilt U.)
- Fabian Schmidt (Assistant Professor of Physics, U. of Illinois Urbana-Champaign)
- Roman Scoccimarro (Associate Professor of Physics, NYU)
- Kendrick Smith (Assistant Professor of Physics, Perimeter Institute)
- Lawrence Widrow (Professor of Physics, Queens U.)

Those who were postdocs include:

- Christian Armendariz-Picon (Associate Professor of Physics, Syracuse U.)
- Scott Burles (formerly Assistant Professor of Physics, MIT)
- Daniel Eisenstein (Professor of Astronomy, Harvard U.)
- James Fry (Professor of Physics, U. Florida)
- Evalyn Gates (Executive Director, Cleveland Museum of Natural History)
- Kim Griest (Professor of Physics, UC San Diego)
- Manoj Kaplinghat (Associate Professor of Physics, UC Irvine)

- Yong-Seon Song (Assistant Professor, Korean Institute for Advanced Study)
- Alexander Szalay (Professor of Physics, Johns Hopkins U.)
- Jennie Traschen (Professor of Physics, U. Massachusetts)
- Rick Watkins (Professor of Physics, Willamette U.)
- Martin White (Professor of Physics, UC Berkeley)

Many have gone on to win prestigious fellowships and prizes: Polonyi Prize, NATO, SSC Fellowship, Helen B. Warner Prize, DOE Lawrence Award, Junior Fellowship at Harvard, Presidential Fellowship at the University of California, Bantrell Fellowship at Caltech, NSF AAPF. Others have also been honored with PYIs, OJIs, Sloan Fellowships, APS Fellowships, and AAAS Fellowships.

2.4 Synergy at Chicago

The wealth of cosmology-related activity in the Chicago area, and interactions between different groups create a whole greater than the sum of its parts. The KICP includes an NSF-funded Physics Frontier Center, now in its second cycle. The KICP serves as a locus of activity for research in cosmology at Chicago, as well as a national center with strong efforts in outreach and scientific symposia. Research at the KICP includes CMB observations (Carlstrom, Meyer), particle astrophysics (Collar, Olinto, Privitera), structure formation and evolution (Dodelson, Frieman, Holz, Hu, Kravstov), and early-universe theory (Kolb and Turner). Collar also leads the COUPP direct dark matter search experiment.

The vast majority of KICP expenditures are in areas other than those directly pursued by Task C, especially in experimental projects, but also in educational programs, visitors, and workshop support. However, there is some funding for postdoctoral fellows working in theoretical topics on the particle physics/cosmology interface, as well as some student support. While neither Hu nor Kolb has received KICP student support in the second cycle, the KICP has served to leverage and extend their Task C research by bringing them into closer collaboration with observers and experimenters at Chicago. Hu and Kolb do receive one-month of summer salary from the KICP.

Other groups with cosmology interests include particle theory (Harvey, Kutasov, Martinec, Rosner, Sethi and Wagner) and particle-astrophysics experiment (above and Cronin, Wakely), and the relativity group (Wald, Holz). Collider phenomenology efforts have recently been strengthened by the addition of Liantao Wang (Assistant Prof., Physics).

At Fermilab there are both theoretical and experimental astrophysics groups, now organized into the Fermilab Center for Particle Astrophysics (FCPA), which is led by Craig Hogan (jointly appointed at Chicago). The Fermilab Theoretical Astrophysics Group was founded by Kolb, Turner, and the late David Schramm in 1983; historically there have been close ties between Task C and the Fermilab group, to the benefit of both. It is currently led by Albert Stebbins, with part-time faculty members Dodelson, Frieman, Gnedin, and Hooper, who each spend approximately two days a week on campus mentoring students and postdocs. The FCPA includes experimental efforts at the Cosmic Frontier, including dark matter (CDMS - sited at the Soudan Laboratory operated by Fermilab, COUPP, DAMIC, Darkside, and DMice), dark energy (DES, DESpec, LSST, and SDSS), cosmic rays (Pierre Auger Observatory), axion searches (GammeV, CHASE, ReapR, Solid Xenon), and other initiatives (Holometer).

2.5 Professor Joshua A. Frieman

The focus of my work in the past three years and my anticipated focus for the coming years is the study of dark energy and the origin of cosmic acceleration [154]. In particular, I have focused on developing tools—from supernovae to large-scale structure—to probe dark energy as well as neutrino mass using cosmic surveys. This theoretical work, carried out with graduate and undergraduate students at U. Chicago, complements my efforts in leading, executing, and analyzing such surveys (SDSS, DES).

For the past three years, I have served as Director, Management Committee Chair, and Spokesperson for the Dark Energy Survey (DES), overseeing the integration of construction of the camera and data management systems, leading the project through annual reviews, planning for survey operations and science analysis, and overseeing optimization of the survey strategy for dark energy constraints. In the last three years, I served on the Astro2010 Decadal Survey of Astronomy Committee, on the 2012 NRC Committee for Assessment of a Plan for U.S. Participation in Euclid, on the 2012 SLAC Science & Technology Review committee, on the HEPAP Facilities Committee, and in the past on the P5 committee. I currently serve on the Astronomy and Astrophysics Advisory Committee (AAAC) and on the NRC Committee on Astronomy and Astrophysics (CAA). For the past six years, I served on the Board of Trustees of the Aspen Center for Physics.

Since 2009, I have supervised U. Chicago graduate students Felipe Marin (PhD 2010, now postdoc at U. Swinburne), Alan Zablocki (current) and Jennifer Helsby (current), and undergraduate student Rebecca Pierce. Past PhD students supervised include Andrew Jaffe (Prof., Imperial College), Roman Scoccimarro (Prof., NYU), Carlos Cunha (PhD 2008, postdoc at KIPAC), Ben Dilday (2008, postdoc at Las Cumbres Observatory), and Marcos Lima (PhD 2008, Prof., U. Sao Paulo, co-supervised with Hu). In addition, I have supervised the research of 9 postdocs at U. Chicago since the mid-1990's and have worked closely with U. Chicago SRA Rick Kessler on supernova cosmology projects. Other recent education and outreach activities include lectures at summer schools at SLAC and in Rio de Janeiro, public lectures at planetariums in Chicago and San Francisco, and video-internet lectures to high-school physics classes in rural Wyoming.

Past Accomplishments

Supernova Cosmology: Although supernovae provided the first direct evidence for cosmic acceleration and still provide the strongest limits on the dark energy equation of state parameter, further progress will require improved characterization and control of systematic errors in SN distance estimates. Toward this end, we have been using data from the SDSS Supernova Survey, a project I led from 2004 to 2009, to both derive new dark energy constraints and to learn about SN cosmology systematics for application to future surveys such as DES.

During 2005-7, the SDSS-II SN survey [155] discovered 500 spectroscopically confirmed, intermediate-redshift Type Ia supernovae and over 1000 photometric SNe Ia. We published cosmological results from the first (of three) seasons of observations in 2009 [156, 157, 158], showing that the two main methods of estimating SN distances in the literature disagreed with each other systematically and unearthing the origins of the differences. Since then, we have shown that SN distance estimates correlate with host-galaxy type [159], published a catalog of photometric SN Ia candidates from the full survey [160], measured line profiles of SNe Ia and studied their spectral properties more generally [161], studied the use of type II-P SNe for cosmology [162], explored the effects of peculiar velocities on SN cosmology results [163], correlated the spectroscopic properties of host galaxies with SN Ia Hubble diagram residuals [164], improved constraints on host-galaxy properties [165], correlated the SN Ia rate with host-galaxy properties [166], compared the precision SN Ia photometry of SDSS with the Carnegie Supernova Project [167], characterized a super-luminous supernova [168], and developed tools for classifying [169] and using photometric supernovae in cosmological analysis [170, 171]. This last item is crucial for future studies, as surveys such as DES and LSST will discover vastly more SNe Ia than the number they can obtain spectra for; for these surveys to be cosmologically valuable for SNe, the contamination rate by non-Ia supernovae must be carefully understood and controlled. We used the results of these studies to simulate in detail and thereby optimize the DES Supernova Survey and to characterize the expected impact of contamination on DES SN dark energy constraints [172].

Inflation and Dark Energy Models: Although the cosmological constant is often invoked as the most likely explanation for cosmic acceleration, we know that it was not responsible for the earlier epoch of acceleration called inflation, since that period of acceleration came to an end in our observable portion of the universe. With collaborators S. Ilic, M. Kunz, and A. Liddle [173], I explored inflationary models from the perspective of dark energy, working out constraints on the equation of state parameter during inflation.

Clusters and Cosmology: With collaborators on the Sloan Digital Sky Survey (SDSS), including U. Chicago postdoc E. Rozo, I used the abundance of galaxy clusters measured in the SDSS photometric survey to constrain cosmological parameters [174]. In this study, we used statistical weak lensing measurements to calibrate the relation between cluster optical richness (the number of red galaxies each cluster contains) and its mass. In future surveys such as the DES, this technique will serve to calibrate the cluster mass-observable relation and thus help to probe the dark energy via the cluster abundance as a function of mass and redshift. With former Task C student D. Huterer (U. Mich) and former Chicago student C. Cunha, I explored the complementarity between the cluster probe of dark energy and other probes (supernovae, baryon acoustic oscillations, and weak lensing cosmic shear), showing that clusters provide substantial dark energy constraining power even in the presence of uncertainties in the cluster mass-observable relation [175].

Photometric Redshifts for Dark Energy Surveys: Photometric surveys such as DES and LSST will rely critically on photometric redshift (photo-z) estimates derived from galaxy photometry (principally from galaxy colors) in order to achieve robust dark energy constraints. Systematic errors in photo-z estimates will likely limit the dark energy accuracy of these surveys, particularly for weak lensing and large-scale structure studies. With Fermilab collaborator H. Lin and Chicago students C. Cunha, M. Lima, and H. Oyaizu, I developed and tested new kinds of photo-z algorithms, in particular pioneering methods to robustly estimate the photo-z probability distribution function (PDF) $p(z)$ for each galaxy and thereby to estimate the redshift probability distribution $N(z)$ for a photometric galaxy sample [176]. Use of the redshift PDF in cosmological applications can reduce biases associated with single-point photo-z estimates, which implicitly assume symmetric, Gaussian errors, and these results have been applied successfully to the SDSS.

Properties of Dark Matter Halos and WIMP annihilation: With South Korean visitor K. Chae, U. Chicago colleague A. Kravtsov, and U. Penn colleague M. Bernardi, we used a variety of data sources and simulations to improve the empirical characterization of the density profiles of dark matter halos in which early-type galaxies are embedded [177]. This resulted in improved predictions for the signal from dark matter WIMP annihilation in the cores of these galaxies.

2.6 Professor Wayne Hu

Past Accomplishments

With previous DOE support from 2009-2013, I have completed 38 papers with postdocs and students [178, 179, 180, 181, 182, 183, 184, 185, 186, 187, 188, 189, 190, 191, 192, 193, 194, 195, 196, 197, 198, 199, 200, 201, 202, 203, 204, 205, 206, 207, 208, 209, 210, 211, 212, 213, 214, 215] and advised or co-advised the Ph.D. theses of 4 graduate students, one of whom has already acquired a tenure-track faculty position (see §2.2). Since DOE support began in 2001, I have (co-)advised 15 graduate students including 3 current students.

Dark Energy: Highlights of the 2009-2012 period include the first cosmological simulation of any "modified gravity" model which explains cosmic acceleration by introducing universal 5th forces while remaining compatible with local tests. Such models introduce a screening mechanism where nonlinear field interactions hide modification at solar-system and laboratory scales. This nonlinearity makes cosmological simulations both critical for defining observables and substantially more difficult than the usual Newtonian case. In a series of papers we determined how in conjunction with these simulations, galaxy clusters can be used to place the tightest current cosmological constraints on the modified Einstein-Hilbert action or $f(R)$ model [185, 190, 195, 199]. On the other hand, we showed that laboratory bounds [216] are within a factor of 2 of testing *all* classical $f(R)$ and chameleon models, regardless of the specific form of the self-interaction, due to loop corrections which signal a break down of the effective theory below the sub-mm scale [205].

We also studied models where the screening mechanism is implemented through derivative self-interactions of the so-called Vainshtein mechanism [217]. In the braneworld model, the scalar represents the position of the brane [218] and we provided the strongest constraints on the 5 dimensional crossover scale to date from a combination of distance and growth measures. We studied the formation of dark matter halos under the nonlinear Vainshtein mechanism [187] and the influence of metric perturbations in the bulk and structure in the brane [193]. The nonlinearity also causes apparent equivalence principle violation both deep within the Vainshtein radius [209] and in the transition regime [211]. The Vainshtein mechanism also appears in ghost-free massive gravity models [219] and we have shown that self-accelerating solutions exist for any isotropic distribution of matter [207]. These solutions exhibit stability to spherically symmetric perturbations [210].

Other cosmic acceleration highlights include a complete, principal components based, analysis of the impact of the dark energy equation of state on cosmological observables such as the galaxy cluster abundance and cosmic shear [188, 194, 204]. We employed an observationally complete approach on the equation of state constrained to satisfy expansion history measurements from supernovae, baryon acoustic oscillations and the Hubble constant. From these constraints, we determined the most incisive cosmological tests for current and future surveys that could not only falsify a cosmological constant but also any dark energy model, e.g. scalar field quintessence, where the dark energy remains spatially smooth compared with the dark matter within the horizon. We have also developed the non-Gaussian statistical tools to extract dark energy and neutrino mass information from CMB power spectra [206] and the means by which neutrino number and mass may be distinguished in cosmic shear surveys [212].

Inflation: Another main thrust of research has been inflation beyond the usual slow roll approximation for canonical scalar fields. In [186], we extended the so-called "generalized slow roll" approach [220]. We showed that a combination of Green function techniques and conservation laws sufficed to ensure validity of the approximation for up to order unity power spectrum features. With this approach, we constructed a complete basis expansion [192] for features in the inflaton potential that were traversed in no shorter than 1/4 of an efold [198]. Analysis of the WMAP data showed that there are no highly significant features in the potential of this type and produced falsifiable predictions of single field inflation for the polarization that are independent of the form of the inflaton potential. Low significance glitches [221, 222] will be testable with Planck polarization data even if the reionization scenario is complex [183, 179]. These results can be reinterpreted for non-canonical scalar fields, as typically appears in string-motivated inflation, by defining an exact mapping of the source for power spectrum features onto terms in the kinetic structure of the inflaton action [197].

In [196], we used these techniques to develop a fast and accurate curvature bispectrum calculations in inflationary models with features. To have an observable CMB bispectrum requires that the inflaton traverse the feature on a timescale much less than an efold. In [202], we analyzed the power spectrum for such a model, specifically by placing a sharp step in the inflaton potential or equivalently the warped brane tension [208] of string-inflationary models [223, 224]. Not only are such features allowed but they actually improve the likelihood of the WMAP, and very recently Planck, data with an effective $\Delta\chi^2 \approx 12$ for two extra parameters. The bispectra of such models have distinct and distinguishable properties. Sharpness in the potential is reflected by sharpness in the real space 3pt correlation function or by high frequency ringing in the Fourier space bispectrum. We generalized these bispectrum techniques to cover any effective field theory of single field inflation with variable expansion rate and sound speed in [214].

2.7 Professor Edward Kolb

The focus of my work in the past three years has been on three subjects at the Cosmic Frontier: Dark Matter, Dark Energy, and Inflation, and they remain the focus of current efforts. Although I plan to work in all three areas, future research will emphasize dark matter.

For the past six years I have served as Chair of the Department of Astronomy & Astrophysics at the U. Chicago. On 1 October 2012 I will step down from Chair and return full-time to research and teaching. For the past three years I also served as Chair-Elect, Vice-Chair, and Chair of the Division of Astrophysics of the American Physical Society. My rotation in that position ended on 1 April 2012. Other professional service in the last three years related to HEP included chairing the Figure of Merit Science Working Group (NASA/DOE) in 2009, serving on the Joint Dark Energy Mission Interim Science Working Group (NASA/DOE) in 2009 to 2010, and most recently, chairing the Community Dark Energy Report on the DOE Dark Energy Program, just completed in August 2012. All of these community service responsibilities have ended. The only remaining HEP service position is chairing the CERN Theory Group External Advisory Committee (from 2010-present), which only meets every other year.

Since 2009, I have supervised two Ph.D. students: Valentin Kostov, Ph.D. 2009, and Zosia Krusberg, Ph.D. 2010. After graduation, Valentin Kostov returned to Bulgaria in a teaching position. Zosia Krusberg is now at Vassar College. At present I am working with one first-year student, Jingyuan Chen, jointly with Liantao Wang. The plan is for him to be partially supported on the DOE grant. Previous students have included Terry Walker (Ohio State), Sharon Vadas (Colorado), Lloyd Knox (UC Davis), and Dan Chung (Wisconsin). In the last three years I have worked closely with Maria Beltran and Mark Wyman, postdocs supported by the DOE grant. In addition to postdocs supervised on this DOE grant, while head and member of the Theoretical Astrophysics Group at Fermilab from 1983-2006, I mentored a large number of postdocs who are now active researchers working at the Cosmic Frontier in the US and abroad.

Professional recognition since 2009 include the 2011 Jensen Prize Professorship from the University of Heidelberg; the award of a Doctorate Honoris Causa from the University of Lyon, Lyon, France, November 2010; and the Dannie Heineman Prize for Astrophysics, 2010, awarded by The American Astronomical Society and the American Institute for Physics (shared with Michael S. Turner).

Public outreach activities include many public and named lectures, most recently, a public lecture in Beijing associated with the COSMO-12 conference. Outreach to graduate students and postdocs since 2009 include many lectures and schools, most recently lectures as the DOE Summer Research Fellow Program, Brookhaven, July 2012. There have been many talks at conferences since 2009, most recently at SUSY 2012.

Past Accomplishments

A list of my research papers since 2009 is listed below [225, 226, 227, 228, 229, 230, 231, 232, 233, 234]. As mentioned above, they are all related to dark matter, inflation, or dark energy—three topics at the Cosmic Frontier.

Dark Matter: Most recently I have been working on signals of dark matter at the CERN LHC collider [228]. In this study it is assumed that dark matter interaction with standard model (SM) particles is described by an effective field theory [234].

In most WIMP models, many new particle species are expected to lie within the discovery reach of the Large Hadron Collider (LHC). More generally speaking, in the absence of heavier particles with shared quantum numbers, WIMPs will not be easily detected or studied at the LHC. Although an electroweak-scale, cold-thermal-relic particle, if it exists, would almost certainly be produced at the LHC, identifying and characterizing the nature of the WIMP simply from missing energy studies is a daunting task [235, 236].

In a series of two papers I developed an approach to discovering WIMPs at the LHC though monojet searches. In the first paper [234] with Task C student Zosia Krusberg and postdoc, Maria Beltran, and Dan Hooper, we described the basic Maverick model and studied the relic abundance, direct detection rates and limits, and the indirection detection prospects. In the second paper with Beltran, Krusberg, Hooper and Tim Tait of UC Irvine [228], we considered the possibility of production and detection of Maverick WIMPs at colliders through monojet searches.

We studied dark matter at accelerators by investigating the production and detection prospects of this WIMP candidate at the Tevatron and at the LHC. Previous studies have sought to constrain the properties of various WIMP candidates using collider data. Our effective theory for WIMP – SM interactions leads to the production of monojets at colliders through the process in which WIMPs are produced together with a hard parton: $pp\ (p\bar{p}) \to X\bar{X} + \text{jets}$.

Ours was the first serious attempt to calculate the event rates and backgrounds for WIMP detection at colliders through monojets. We simulated the signal and background events using the MadEvent package [237], for a WIMP that interacts with the SM through the maverick interaction. (The WIMP production at relativistic energies is largely independent of the exact Lorentz form of the interaction.) After MadEvent generated the hard scattering process, Pythia [238] was called to simulate parton showering and hadronization, and PGS (with the generic Tevatron and LHC detector models) provided an estimate of the detector effects [239].

We found two results: The first result was that the main background (jet plus missing energy carried off by neutrino pair production) *need not* swamp the signal from WIMPS, and colliders can place an interesting WIMP limit. The key is judicious cuts on the missing transverse energy (MET) of the event. The reason for this is simple: the WIMP signal process is described by a non-renormalizible interaction, while the main background process (neutrino-pair production) is described by a renormalizible interaction. The second result is that the shape of the number of signal and background events differ as a function of $p_{T-\mathrm{jet}}$.

Requiring a signal significant at the 5σ level, we found the potential for dark matter discovery at the LHC at 14 TeV c.m. energy and 100 fb^{-1} integrated luminosity for WIMP masses $M_X < 275$ GeV. If no excess events are observed, then the 95% C.L. limit would be $M_X < 450$ GeV. After our paper demonstrated that WIMPs can indeed be seen at hadron colliders by MET searches, several other studies confirmed and extended our results [240, 241, 242]. It is now appreciated that MET searches at colliders can shed light on dark matter. The CDF collaboration at Fermilab recently put a limit on WIMP interaction cross sections through MET searches [243]. Most recently, ATLAS [244] and CMS[245, 246] also performed MET searches to place limits on the production cross sections of dark matter. As a result of our investigations, the search for dark matter through monojet searches is now established as part of the experimental program at hadron colliders. This is an example of the powerful connections and overlaps between the Energy Frontier and the Cosmic Frontier.

Dark Matter: With Tongyan Lin (Chicago Postdoc) and LianTao Wang (Chicago faculty), I studied a new way to extract signals of dark matter from experiments at the LHC [247].

Production and detection of dark matter is one of the most exciting new physics opportunities at the *Large Hadron Collider* (LHC). The strategy to search for dark matter (DM) depends on the physics in the yet-to-be fully explored energy range of the LHC. In the maverick scenario [228], the DM is the only new particle produced and all other new particles are beyond the scale of the LHC. Then the interaction of the DM with standard model (SM) particles at these energies can be described in terms of an effective field theory (EFT).

Monojet searches are a powerful way to place model-independent constraints on effective operators coupling dark matter to the standard model. For operators generated by the exchange of a scalar mediator, however, couplings to light quarks are suppressed and the prospect of probing such interactions through the inclusive monojet channel at the LHC is limited. We proposed dedicated searches, focusing on bottom-quark and top-quark final states, to constrain this class of operators. We showed that a search in mono b-jets can significantly improve current limits. The mono-b signal arises partly from direct production of b-quarks in association with dark matter, but the dominant component is from to pair production in the kinematic regime where one top is boosted. A search for tops plus missing energy can strengthen the bounds even more; in this case signal and background have very different missing energy distributions. We find an overall improvement by several orders of magnitude in the bound on the direct detection cross section.

With Chicago graduate student Jingyuan Chen and Chicago faculty LianTao Wang, I studied the implication of dark matter coupling to the standard model sector through coupling to electroweak gauge and Higgs bosons. If dark matter is a new species of particle produced in the early universe as a cold thermal relic (a weakly-interacting massive particle—WIMP), its present abundance, its scattering with matter in direct-detection experiments, its present-day annihilation signature in indirect-detection experiments, and its production and detection at colliders, depend crucially on the WIMP coupling to standard-model (SM) particles. It is usually assumed that the WIMP couples to the SM sector through its interactions with quarks and leptons. In this paper we explore the possibility that the WIMP coupling to the SM sector is via electroweak gauge and Higgs bosons. In the absence of an ultraviolet-complete particle-physics model, we employ effective field theory to describe the WIMP–SM coupling. We considered both scalars and Dirac fermions as possible dark-matter candidates. Starting with an exhaustive list of operators up to dimension 8, we presented detailed calculation of dark-matter annihilations to all possible final states, including $\gamma\gamma$, γZ, γh, ZZ, Zh, W^+W^-, hh, and $f\bar{f}$, and demonstrate the correlations among them. We computed the mass scale of the effective field theory necessary to obtain the correct dark-matter mass density, and well as the resulting photon line signals.

Inflation:

In a collaboration with Micol Benetti (INFN, Rome), Martina Gerbino (INFN, Rome), William H. Kinney (SUNY, Buffalo), Massimiliano Lattanzi (INFN, Ferrara), Alessandro Melchiorri (INFN, Rome), Luca Pagano (INFN, Rome), and Antonio Riotto (Geneva U), I studied the implications of CMB and other cosmological data for the existence of "new" physics [248]. Data from the Atacama Cosmology Telescope (ACT) and the South Pole Telescope (SPT), combined with the nine-year data release from the WMAP satellite, provide very precise measurements of the cosmic microwave background (CMB) angular anisotropies down to very small angular scales. Augmented with measurements from Baryonic Acoustic Oscillations surveys and determinations of the Hubble constant, we investigated whether there are indications for new physics beyond a Harrison-Zel'dovich model for primordial perturbations and the standard number of relativistic degrees of freedom at primordial recombination. All combinations of datasets pointed to physics beyond the minimal Harrison-Zel'dovich model in the form of either a scalar spectral index different from unity or additional relativistic degrees of freedom at recombination (*e.g.*, additional light neutrinos). Beyond that, the extended datasets including either ACT or SPT provided very different indications: while the extended-ACT (eACT) dataset was perfectly consistent with the predictions of standard slow-roll inflation, the extended-SPT (eSPT) dataset preferred a non-power-law scalar spectral index with a very large variation with scale of the spectral index. Both eACT and eSPT favored additional light degrees of freedom. eACT was consistent with zero neutrino masses, while eSPT favored nonzero neutrino masses at more than 95% confidence.

2.8 Professor Michael S. Turner

Past Accomplishments

Over the past few years, the focus of my research has been on dark energy and inflationary cosmology. At the end of 2008, with Frieman and Huterer I finished a major review of dark energy for *Annual Reviews of Astronomy & Astrophysics* (which now has more than 350 citations). With undergraduate Abraham Neben, who is now a graduate student at MIT, I have studied the degree to which Sandage's two numbers to describe cosmology, H_0 and q_0, can actually be measured. H_0 and q_0 have the advantage of being model-independent, and can be determined without assuming the validity of general relativity. However, it turns out, q_0 cannot be measured with both precision and accuracy, and while H_0 can be measured with precision, if q_0 is used as the second kinematic parameter for describing the Universe, the value determined is biased slightly (per cent level). With increasing accuracy in the measurements of H_0 being achieved and further accuracy being sought, this is an important practical issue facing observers. Some have turned to using the next parameter in the Sandage expansion – jerk – but doing so does little to improve matters. We have shown that using Ω_M as a second parameter is a much better alternative and avoids this difficulty. Our paper will come out shortly.

John Carlstrom and I continued to work on an invited review of the current state of cosmology for *Annual Reviews of Astronomy & Astrophysics*, which should be finished by the end of the year. I also am finishing a review article on the state of cosmology for the IOP's *Reports on Progress in Physics*. Paul Steinhardt and I continue to make progress on a paper for *Nature* entitled Inflation at the Crossroads.

Synergistic activities include lecturing on cosmology (dark matter, dark energy and inflation) at the 2009 TASI (June 2009), the University of Washington Institute for Nuclear Theory Quarks to the Cosmos Summer School (June/July 2009), the Biermann Lectures (Max Planck Institute for Astrophysics, July 2009), the Lake Louise Winter School (February 2010), the CERN Academic Lecture Series (March 2010), the 24th Spring School on Particles and Fields at National Tsing Hua University (Taiwan, April 2011), the International Summer School on Symmetry Breaking (Chiemsee, Germany, September 2011), the IDPASC Dark Matter School (Evora, Portugal, December 2011), and the UCBerkeley Cosmology on the Beach Winter School (Cancun, January 2012) and presenting colloquia at Australian National University, Brookhaven National Lab, University of Washington, Dudley Union, all Munich Physics Colloquium, Stanford University, University of South Alabama, Northern Illinois University and Colorado College. I currently serve on the Board of Directors of Fermi Research Alliance, the NRC's Board on Physics and Astronomy, and I was a member of Astro2010, the Astronomy and Astrophysics Decadal Survey, which completed its work in December 2010. In 2011, I became the Chair of the OECD Global Science Forum's AstroParicle International Forum (APIF), which both DOE and NSF participate in. I am a member of the Presidential Line of the American Physical Society (President-elect, 2012 and President, 2013). Recent honors include the Dannie Heineman Prize (shared with E.W. Kolb) for our pioneering of the field of particle astrophysics and cosmology (January 2011) and the Darwin Lecture of the Royal Astronomical Society (October 2011). I also serve as Director of the Kavli Institute for Cosmological Physics (since March 2010) and its NSF Physics Frontier Center (PFC, since September 2011). As mentioned in the opening narrative, the activities of the KICP and its PFC enhance the work of task C.

2.9 Research Associate Marilena LoVerde

Past Accomplishments

Primordial non-Gaussianity (NG), which probes the particle physics of inflation, can be sensitively measured by large-scale structure (LSS), but only if its observational effects can be accurately modeled. In collaboration with former Task C student K. Smith, I studied the halo mass function in N-body simulations with three types of NG initial conditions: $f_{\rm NL}$, $g_{\rm NL}$ and $\tau_{\rm NL}$ [249]. We verified aspects of [250] and provided a new NG halo mass function that is in excellent agreement with simulations and can be applied to any model of primordial NG. In [251] and [252] (also with grad student S. Ferraro), K. Smith and I studied large-scale halo bias and stochasticity with these NG conditions and developed new accurate models for them. Finally, K. Smith and I studied the NG dependence of the halo bispectrum [253] and continue to study other nonlinear NG statistics.

Local-type primordial non-Gaussianity couples statistics of the curvature perturbation ζ on vastly different physical scales. With Prof. S. Shandera and graduate student E. Nelson, I showed that this coupling may cause statistics (i.e. the polyspectra) of ζ in our Hubble volume to be very unrepresentative of those in the larger universe – that is, they may be biased. The bias depends on the local background value of ζ, which includes contributions from all modes with wavelength $k < H_0$ and is therefore enhanced if the entire post-inflationary patch is large compared with our Hubble volume. We studied the bias to locally-measured statistics for general local-type non-Gaussianity and presented three detailed examples of non-Gaussian initial conditions for the larger universe that generate statistics in a Hubble-size patch that are weakly Gaussian and consistent with observations despite the fact that the statistics in the larger universe look very different.

2.10 Research Associate Mark Wyman

Past Accomplishments

Over the past few years, my research has advanced on several fronts. These include finding new constraints on cosmic strings using South Pole Telescope data [201], exact solutions [207], perturbation analysis [210] and potential observational consequences [254, 255] of a recently-discovered theory of massive gravity, and introducing a new general mechanism by which inflation can proceed [256, 257, 32] and studying its observational consequences [33].

- **Cosmic Strings and the South Pole Telescope:** With former graduate student Cora Dvorkin and Professor Wayne Hu, I used the recent CMB power spectrum measurements from the South Pole Telescope together with the results from the WMAP experiment to put the tightest bounds yet reported on the possible contribution of cosmic strings to the primordial CMB anisotropy [201]. Cosmic strings are expected to be formed in certain models of inflation in string theory such as brane inflation. Our upper limits permit cosmic strings that could be detected by SPT-Pol through their generation of B-mode CMB polarization.

- **Advances in massive gravity:** A theory of gravity with a massive graviton was long thought impossible to construct, but such a theory was recently found [219]. Studying this new theory has been one of my major areas of recent research progress. With graduate student Pierre Gratia and Prof. Hu I found the most general class of exact solutions to the theory yet discovered [207], all of which intriguingly exhibits behavior identical to that of a cosmological constant. Gratia, Hu, and I have further studied isotropic perturbations around this class of solutions, demonstrating that the cosmological constant-like solution is stable to these perturbations and resolving several apparent conflicts regarding the nature of perturbations around self-accelerating solutions like these in the existing literature of this theory [210].

- **Observational consequences of modified gravity theories:** I have made two important contributions to the study of modified theories of gravity that exhibit the so-called Vainshtein screening mechanism to pass Solar System tests; the above-mentioned theory of massive gravity is included in this class. First, I found a novel gravitational lensing signature that appears in such models [254]; this signal is not degenerate with any known astrophysical systematics and could potentially be seen by upcoming weak lensing surveys. With fellow postdoc Elise Jennings and former U. Chicago graduate student and now Prof. Marcos Lima (Sao Paolo), I also conducted a large suite of N-body simulations of these models using an improved version of code that I previously wrote [258]. Using these simulations, we studied the halo properties and redshift space distortional signal, finding that the modified gravity effects on the power spectrum and halo mass function were degenerate with an enhanced power spectrum amplitude at fixed redshift, but that their long wavelength redshift space signal was observationally distinguishable from general relativity in future surveys like Euclid [255].

- **Inflation from Magnetic Drift:** In a pair of papers with postdoc Peter Adshead [256, 257], I introduced a new mechanism for inflation in a particular model we called Chromo-Natural Inflation. We then collaborated with Prof. Emil Martinec to generalize the mechanism to a host of possible string theoretic realizations [32]. In this new mechanism, a pseudo-scalar inflaton interacts with a set of gauge fields with a classical vacuum expectation value through a Chern-Simons term. This is a generalization of the phenomenon of 'magnetic drift'. Magnetic drift is what happens when a charge particle rolls down a potential in the presence of a strong magnetic field: the Lorentz force overwhelms the downward roll, slowing the particle's descent. In our case, there is no rotation, but the underlying physics is similar. That is, the interaction generically slows the evolution of the inflaton along its potential, leading to slow roll inflation for even steep potentials. Chern-Simons interactions are permitted by the symmetries of any pseudo-scalar effective field theory and are ubiquitous in string theory. In usual inflation models, slow roll is achieved through a flat potential. This flatness is not easy to preserve at the quantum level, a phenomenon known as the 'eta problem'. In our scenario, this problem is absent, because the Chern-Simons interaction slows down the roll, even on a steep potential, so we do not need to make the potential flat. Finally, we have begun to study perturbations in this class of inflationary models, studying so far the particular model of Chromo-Natural Inflation [33]. What we have found is that the gauge fields interact with the scalar field in a complex way, leading to new dynamics very different from the usual perturbative analysis of inflationary models. This permits new phenomena to arise. In particular, we found that we can evade common formulations of the so-called Lyth Bound [259] by generating observable gravitational waves even when no field traverses a Planckian distance. We also have discovered that the gravitational wave spectrum is itself chirally polarized, due to an exponential enhancement of one handedness of gravitational waves from the parity-violating physics introduced by the non-trivial gauge background. Unfortunately, this enhancement to the gravitational wave power spectrum may make it difficult, if not impossible, for the model to agree with recent limits from the Planck satellite [260]. String theoretic realizations of this general mechanism will not exhibit this exponentially enhanced gravitational wave power spectrum, however, so we expect that they will more easily be able to agree with current observational limits on perturbations from the epoch of inflation.

Appendix 1: References Cited

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Appendix 2: Publications

David Kutasov

In addition to the DOE, Kutasov's research received some support from an Isreali Binational Science Foundation (BSF) grant, which mostly goes towards travel to Israel where some of his collaborators are located.

1. **"IIA Perspective On Cascading Gauge Theory"**
   D. Kutasov and A. Wissanji.
   arXiv:1206.0747 [hep-th]
   10.1007/JHEP09(2012)080
   JHEP **1209**, 080 (2012)

2. **"Holographic Walking from Tachyon DBI"**
   D. Kutasov, J. Lin and A. Parnachev.
   arXiv:1201.4123 [hep-th]
   10.1016/j.nuclphysb.2012.05.025
   Nucl. Phys. B **863**, 361 (2012)

3. **"Conformal Phase Transitions at Weak and Strong Coupling"**
   D. Kutasov, J. Lin and A. Parnachev.
   arXiv:1107.2324 [hep-th]
   10.1016/j.nuclphysb.2012.01.004
   Nucl. Phys. B **858**, 155 (2012)

4. **"a-Maximization, Global Symmetries and RG Flows"**
   D. Erkal and D. Kutasov.
   arXiv:1007.2176 [hep-th]

5. **"Holographic MQCD"**
   O. Aharony, D. Kutasov, O. Lunin, J. Sonnenschein and S. Yankielowicz.
   arXiv:1006.5806 [hep-th]
   10.1103/PhysRevD.82.106006
   Phys. Rev. D **82**, 106006 (2010)

Emil J. Martinec

Martinec's publications were joint with collaborators having either DOE or NSF support, with the exceptions of papers 4 and 7; paper 4 was largely executed during a period when McOrist was a postdoc at DAMTP in Cambridge, while the work of paper 7 was entirely DOE supported.

1. **"Perturbations in Chromo-Natural Inflation"**
   P. Adshead, E. Martinec and M. Wyman.
   arXiv:1305.2930 [hep-th]

2. **"A Sinister Universe: Chiral gravitons lurking, and Lyth un-bound"**
   P. Adshead, E. Martinec and M. Wyman.
   arXiv:1301.2598 [hep-th]

3. **"Chern-Simons EM-flation"**
   E. Martinec, P. Adshead and M. Wyman.
   arXiv:1206.2889 [hep-th]
   10.1007/JHEP02(2013)027
   JHEP **1302**, 027 (2013)

4. **"Monopole–Instantons in M2-Brane Theories"**
   E. Martinec and J. McOrist.
   arXiv:1112.4073 [hep-th]

5. **"Constraints on String Cosmology"**
   S. R. Green, E. J. Martinec, C. Quigley and S. Sethi.
   arXiv:1110.0545 [hep-th]
   10.1088/0264-9381/29/7/075006
   Class. Quant. Grav. **29**, 075006 (2012)

6. **"Gravity from the Extension of Spatial Diffeomorphisms"**
   S. Farkas and E. J. Martinec.
   arXiv:1002.4449 [hep-th]
   10.1063/1.3596173
   J. Math. Phys. **52**, 062501 (2011)

7. **"Non-Supersymmetric String Theory"**
   E. J. Martinec, D. Robbins and S. Sethi.
   arXiv:0904.3498 [hep-th]
   10.1007/JHEP10(2011)078
   JHEP **1110**, 078 (2011)

Jonathan L. Rosner

Papers which exclusively acknowledge DOE support:

1. **"Electroweak Constraints from Atomic Parity Violation and Neutrino Scattering"**
   T. Hobbs and J. L. Rosner.
   arXiv:1005.0797 [hep-ph]
   10.1103/PhysRevD.82.013001
   Phys. Rev. D **82**, 013001 (2010)

2. **"Charmed meson decays to two pseudoscalars"**
   B. Bhattacharya and J. L. Rosner.
   arXiv:0911.2812 [hep-ph]
   10.1103/PhysRevD.81.014026
   Phys. Rev. D **81**, 014026 (2010)

3. **"The Mystery of Parity"**
   J. L. Rosner.
   arXiv:0912.1053 [hep-ph]

4. **"Dalitz Plot Structure in $D^0 \to \pi^+\pi^-\pi^0$"**
   B. Bhattacharya, C. -W. Chiang and J. L. Rosner.
   arXiv:1004.3225 [hep-ph]
   10.1103/PhysRevD.81.096008
   Phys. Rev. D **81**, 096008 (2010)

5. **"Effect of η-η' mixing on $D \to PV$ decays"**
   B. Bhattacharya and J. L. Rosner.
   arXiv:1005.2159 [hep-ph]
   10.1103/PhysRevD.82.037502
   Phys. Rev. D **82**, 037502 (2010)

6. **"Relative phases in Dalitz plot amplitudes for $D^0 \to K_S\pi^+\pi^-$ and $D^0 \to \pi^0K^+K^-$"**
   B. Bhattacharya and J. L. Rosner.
   arXiv:1008.4083 [hep-ph]
   10.1103/PhysRevD.82.074025
   Phys. Rev. D **82**, 074025 (2010)

7. **"Cross ratios between Dalitz plot amplitudes in three-body D^0 decays"**
   B. Bhattacharya and J. L. Rosner.
   arXiv:1010.1770 [hep-ph]
   10.1103/PhysRevD.82.114032
   Phys. Rev. D **82**, 114032 (2010)

8. **"Ratios of heavy hadron semileptonic decay rates"**
   M. Gronau and J. L. Rosner.
   arXiv:1012.5098 [hep-ph]
   10.1103/PhysRevD.83.034025
   Phys. Rev. D **83**, 034025 (2011)

9. B_s **decays and mixing**
   J. L. Rosner and Michael Gronau
   arXiv:1105.1923
   published by Proceedings of Science (PoS), BEAUTY2011, 045.

10. **"Triple product asymmetries in K, D_s and B_s decays"**
    M. Gronau and J. L. Rosner.
    arXiv:1107.1232 [hep-ph]
    10.1103/PhysRevD.84.096013
    Phys. Rev. D **84**, 096013 (2011)

11. **"Quarkonium - Theory"**
    J. L. Rosner.
    arXiv:1107.1273 [hep-ph]

12. **"Charm at Threshold"**
    J. L. Rosner.
    arXiv:1107.2023 [hep-ex]

13. **"CP asymmetries in singly-Cabibbo-suppressed D decays to two pseudoscalar mesons"**
    B. Bhattacharya, M. Gronau and J. L. Rosner.
    arXiv:1201.2351 [hep-ph]
    10.1103/PhysRevD.85.079901, 10.1103/PhysRevD.85.054014
    Phys. Rev. D **85**, 054014 (2012)

14. **"Flavor SU(3) tests from $D^0 \to K^0 K^- \pi^+$ and $D^0 \to \bar{K}^0 K^+ \pi^-$ Dalitz plots"**
    B. Bhattacharya and J. L. Rosner.
    arXiv:1203.6014 [hep-ph]
    10.1016/j.physletb.2012.07.009
    Phys. Lett. B **714**, 276 (2012)

15. **"Non-factorizable effects in top quark production"**
    J. L. Rosner.
    arXiv:1205.1529 [hep-ph]
    10.1103/PhysRevD.86.014011
    Phys. Rev. D **86**, 014011 (2012)

16. **"Prospects for improved Λ_c branching fractions"**
    J. L. Rosner.
    arXiv:1205.4964 [hep-ph]
    10.1103/PhysRevD.86.014017
    Phys. Rev. D **86**, 014017 (2012)

17. **"Rescattering Contributions to rare B-Meson Decays"**
    M. Gronau, D. London and J. L. Rosner.
    arXiv:1211.5785 [hep-ph]

Papers which acknowledge HEP and other agency support:

1. **"Forward-Backward Asymmetry of Top Quark Pair Production"**
   Q. -H. Cao, D. McKeen, J. L. Rosner, G. Shaughnessy and C. E. M. Wagner.
   arXiv:1003.3461 [hep-ph]
   10.1103/PhysRevD.81.114004
   Phys. Rev. D **81**, 114004 (2010)
   (Besides numerous DOE grants, UChicago Joint Theory Institute (JTI) Grant 03921-07-137.)

2. **"Calculating Phases Between B =¿ K* pi Amplitudes"**
   M. Gronau, D. Pirjol and J. L. Rosner.
   arXiv:1003.5090 [hep-ph]
   10.1103/PhysRevD.81.094026
   Phys. Rev. D **81**, 094026 (2010)
   (Galileo Galilei Institute for Theoretical Physics for hospitality and INFN for partial support.)

3. **"Background check for anomalous like-sign dimuon charge asymmetry"**
   M. Gronau and J. L. Rosner.
   arXiv:1007.4728 [hep-ph]
   10.1103/PhysRevD.82.077301
   Phys. Rev. D **82**, 077301 (2010)
   (Partial support from Steven and Priscilla Kersten.)

4. **"Second order direct CP asymmetry in $B_(s)->Xl\nu$"**
   S. Bar-Shalom, G. Eilam, M. Gronau and J. L. Rosner.
   arXiv:1008.4354 [hep-ph]
   10.1016/j.physletb.2010.10.025
   Phys. Lett. B **694**, 374 (2011)
   (Partial support from Steven and Priscilla Kersten.)

5. **"Measurements of branching fractions for electromagnetic transitions involving the $\chi_{bJ}(1P)$ states"**
   M. Kornicer *et al.* [CLEO Collaboration].
   arXiv:1012.0589 [hep-ex]
   10.1103/PhysRevD.83.054003
   Phys. Rev. D **83**, 054003 (2011)
   (J. Rosner was a primary author.)

6. **"Observation of the $h_c(1P)$ using e^+e^- collisions above $D\bar{D}$ threshold"**
   T. K. Pedlar *et al.* [CLEO Collaboration].
   arXiv:1104.2025 [hep-ex]
   10.1103/PhysRevLett.107.041803
   Phys. Rev. Lett. **107**, 041803 (2011)
   (J. Rosner was on paper committee.)

7. **"Search for the decay $D_s^+ \to \omega e^+\nu$"**
   L. Martin *et al.* [CLEO Collaboration].
   arXiv:1105.2720 [hep-ex]
   10.1103/PhysRevD.84.012005
   Phys. Rev. D **84**, 012005 (2011)
   (J. Rosner was on paper committee.)

8. **"Branching fractions for $\Upsilon(3S) \to \pi^0 h_b$ and $\psi(2S) \to \pi^0 h_c$"**
   J. Y. Ge *et al.* [CLEO Collaboration].
   arXiv:1106.3558 [hep-ex]
   10.1103/PhysRevD.84.032008
   Phys. Rev. D **84**, 032008 (2011)
   (J. Rosner was a primary author.)

9. **"A Leptophobic Z' And Dark Matter From Grand Unification"**
   M. R. Buckley, D. Hooper and J. L. Rosner.
   arXiv:1106.3583 [hep-ph]
   10.1016/j.physletb.2011.08.014
   Phys. Lett. B **703**, 343 (2011)
   (DH was partially supported by NASA grant NAG5-10842.)

10. **"Measurement of Polarization and Search for CP-Violation in $B_s^0 \to \phi\phi$ Decays"**
T. Aaltonen *et al.* [CDF Collaboration].
arXiv:1107.4999 [hep-ex]
10.1103/PhysRevLett.107.261802
Phys. Rev. Lett. **107**, 261802 (2011)
(J. Rosner was a contributing author.)

11. **"Background dependence of dimuon asymmetry in $\bar{p}p$ interactions at $\sqrt{s} = 1.96$ TeV"**
M. Gronau and J. L. Rosner.
arXiv:1111.2300 [hep-ph]
10.1016/j.physletb.2012.01.037
Phys. Lett. B **708**, 127 (2012)
(Work done in part at Aspen Center for Physics with NSF support.)

12. **"Fundamental Physics at the Intensity Frontier"**
J. L. Hewett, H. Weerts, R. Brock, J. N. Butler, B. C. K. Casey, J. Collar, A. de Govea and R. Essig *et al.*.
arXiv:1205.2671 [hep-ex]
(Many authors, some supported by DOE and some by NSF.)

13. **"Revisiting D0-D0bar mixing using U-spin"**
M. Gronau and J. L. Rosner.
arXiv:1209.1348 [hep-ph]
10.1103/PhysRevD.86.114029
Phys. Rev. D **86**, 114029 (2012)
(Partial support from CERN Theory Group.)

14. **"Shift in weak phase γ due to CP asymmetries in D decays to two pseudoscalar mesons"**
B. Bhattacharya, D. London, M. Gronau and J. L. Rosner.
arXiv:1301.5631 [hep-ph]
10.1103/PhysRevD.87.074002
Phys. Rev. D **87**, 074002 (2013)
(Supported in part by NSERC of Canada [DL].)

15. **CP asymmetries in three-body $B^{\pm}$ decays to charged pions and kaons**
B. Bhattacharya, M. Gronau, and J. L. Rosner
Enrico Fermi Institute report EFI 13-4, in preparation, to be submitted to Phys. Lett. B.
(Supported in part by NSERC of Canada [BB].)

Carlos E.M. Wagner

Wagner collaborates with DOE-supported staff at Argonne and Fermilab in addition to students and postdocs supported by this grant.

1. **"Light Stops, Light Staus and the 125 GeV Higgs"**
M. Carena, S. Gori, N. R. Shah, C. E. M. Wagner and L. -T. Wang.
arXiv:1303.4414 [hep-ph]

2. **"A Supersymmetric Theory of Vector-like Leptons"**
   A. Joglekar, P. Schwaller and C. E. M. Wagner.
   arXiv:1303.2969 [hep-ph]

3. **"MSSM Higgs Boson Searches at the LHC: Benchmark Scenarios after the Discovery of a Higgs-like Particle"**
   M. Carena, S. Heinemeyer, O. Stl, C. E. M. Wagner and G. Weiglein.
   arXiv:1302.7033 [hep-ph]

4. **"$SU(2) \otimes SU(2)$ Gauge Extensions of the MSSM Revisited"**
   R. Huo, G. Lee, A. M. Thalapillil and C. E. M. Wagner.
   arXiv:1212.0560 [hep-ph]
   10.1103/PhysRevD.87.055011

5. **"Vacuum Stability and Higgs Diphoton Decays in the MSSM"**
   M. Carena, S. Gori, I. Low, N. R. Shah and C. E. M. Wagner.
   arXiv:1211.6136 [hep-ph]
   10.1007/JHEP02(2013)114
   JHEP **1302**, 114 (2013)

6. **"CPsuperH2.3: an Updated Tool for Phenomenology in the MSSM with Explicit CP Violation"**
   J. S. Lee, M. Carena, J. Ellis, A. Pilaftsis and C. E. M. Wagner.
   arXiv:1208.2212 [hep-ph]
   10.1016/j.cpc.2012.11.006
   Comput. Phys. Commun. **184**, 1220 (2013)

7. **"MSSM Electroweak Baryogenesis and LHC Data"**
   M. Carena, G. Nardini, M. Quiros and C. E. M. Wagner.
   arXiv:1207.6330 [hep-ph]
   10.1007/JHEP02(2013)001
   JHEP **1302**, 001 (2013)

8. **"Dark Matter and Enhanced Higgs to Di-photon Rate from Vector-like Leptons"**
   A. Joglekar, P. Schwaller and C. E. M. Wagner.
   arXiv:1207.4235 [hep-ph]
   10.1007/JHEP12(2012)064
   JHEP **1212**, 064 (2012)

9. **"Implications of a Modified Higgs to Diphoton Decay Width"**
   M. Carena, I. Low and C. E. M. Wagner.
   arXiv:1206.1082 [hep-ph]
   10.1007/JHEP08(2012)060
   JHEP **1208**, 060 (2012)

10. **"The pMSSM Interpretation of LHC Results Using Rernormalization Group Invariants"**
    M. Carena, J. Lykken, S. Sekmen, N. R. Shah and C. E. M. Wagner.
    arXiv:1205.5903 [hep-ph]
    10.1103/PhysRevD.86.075025
    Phys. Rev. D **86**, 075025 (2012)

11. **“Light Stau Phenomenology and the Higgs→ $\gamma\gamma$ Rate”**
M. Carena, S. Gori, N. R. Shah, C. E. M. Wagner and L. -T. Wang.
arXiv:1205.5842 [hep-ph]
10.1007/JHEP07(2012)175
JHEP **1207**, 175 (2012)

12. **“Fundamental Physics at the Intensity Frontier”**
J. L. Hewett, H. Weerts, R. Brock, J. N. Butler, B. C. K. Casey, J. Collar, A. de Govea and R. Essig *et al.*.
arXiv:1205.2671 [hep-ex]

13. **“LHC Discovery Potential for Non-Standard Higgs Bosons in the 3b Channel”**
M. Carena, S. Gori, A. Juste, A. Menon, C. E. M. Wagner and L. -T. Wang.
arXiv:1203.1041 [hep-ph]
10.1007/JHEP07(2012)091
JHEP **1207**, 091 (2012)

14. **“A 125 GeV SM-like Higgs in the MSSM and the $\gamma\gamma$ rate”**
M. Carena, S. Gori, N. R. Shah and C. E. M. Wagner.
arXiv:1112.3336 [hep-ph]
10.1007/JHEP03(2012)014
JHEP **1203**, 014 (2012)

15. **“Implications of sterile neutrinos for medium/long-baseline neutrino experiments and the determination of θ_{13}”**
B. Bhattacharya, A. M. Thalapillil and C. E. M. Wagner.
arXiv:1111.4225 [hep-ph]
10.1103/PhysRevD.85.073004
Phys. Rev. D **85**, 073004 (2012)

16. **“An Alternative Yukawa Unified SUSY Scenario”**
J. S. Gainer, R. Huo and C. E. M. Wagner.
arXiv:1111.3639 [hep-ph]
10.1007/JHEP03(2012)097
JHEP **1203**, 097 (2012)

17. **“Light Dark Matter and the Electroweak Phase Transition in the NMSSM”**
M. Carena, N. R. Shah and C. E. M. Wagner.
arXiv:1110.4378 [hep-ph]
10.1103/PhysRevD.85.036003
Phys. Rev. D **85**, 036003 (2012)

18. **“The dark side of the Higgs boson”**
I. Low, P. Schwaller, G. Shaughnessy and C. E. M. Wagner.
arXiv:1110.4405 [hep-ph]
10.1103/PhysRevD.85.015009
Phys. Rev. D **85**, 015009 (2012)

19. **“The 7 TeV LHC Reach for MSSM Higgs Bosons”**
M. Carena, P. Draper, T. Liu and C. Wagner.

arXiv:1107.4354 [hep-ph]
10.1103/PhysRevD.84.095010
Phys. Rev. D **84**, 095010 (2011)

20. **"W plus two jets from a quasi-inert Higgs doublet"**
Q. -H. Cao, M. Carena, S. Gori, A. Menon, P. Schwaller, C. E. M. Wagner and L. -T. Wang.
arXiv:1104.4776 [hep-ph]
10.1007/JHEP08(2011)002
JHEP **1108**, 002 (2011)

21. **"Search for Higgs Bosons in SUSY Cascade Decays and Neutralino Dark Matter"**
S. Gori, P. Schwaller and C. E. M. Wagner.
arXiv:1103.4138 [hep-ph]
10.1103/PhysRevD.83.115022
Phys. Rev. D **83**, 115022 (2011)

22. **"SUSY-Breaking Parameters from RG Invariants at the LHC"**
M. Carena, P. Draper, N. R. Shah and C. E. M. Wagner.
arXiv:1011.4958 [hep-ph]
10.1103/PhysRevD.83.035014
Phys. Rev. D **83**, 035014 (2011)

23. **"Probing the Higgs Sector of High-Scale SUSY-Breaking Models at the Tevatron"**
M. Carena, P. Draper, S. Heinemeyer, T. Liu, C. E. M. Wagner and G. Weiglein.
arXiv:1011.5304 [hep-ph]
10.1103/PhysRevD.83.055007
Phys. Rev. D **83**, 055007 (2011)

24. **"Dark Light Higgs"**
P. Draper, T. Liu, C. E. M. Wagner, L. -T. Wang and H. Zhang.
arXiv:1009.3963 [hep-ph]
10.1103/PhysRevLett.106.121805
Phys. Rev. Lett. **106**, 121805 (2011)

25. **"Determining the Structure of Supersymmetry-Breaking with Renormalization Group Invariants"**
M. Carena, P. Draper, N. R. Shah and C. E. M. Wagner.
arXiv:1006.4363 [hep-ph]
10.1103/PhysRevD.82.075005
Phys. Rev. D **82**, 075005 (2010)

26. **"Forward-Backward Asymmetry of Top Quark Pair Production"**
Q. -H. Cao, D. McKeen, J. L. Rosner, G. Shaughnessy and C. E. M. Wagner.
arXiv:1003.3461 [hep-ph]
10.1103/PhysRevD.81.114004
Phys. Rev. D **81**, 114004 (2010)

27. **"The Hunt for New Physics at the Large Hadron Collider"**
P. Nath, B. D. Nelson, H. Davoudiasl, B. Dutta, D. Feldman, Z. Liu, T. Han and P. Langacker *et al.*.
arXiv:1001.2693 [hep-ph]
10.1016/j.nuclphysbps.2010.03.001
Nucl. Phys. Proc. Suppl. **200-202**, 185 (2010)

28. **"Prospects for Higgs Searches at the Tevatron and LHC in the MSSM with Explicit CP-violation"**
P. Draper, T. Liu and C. E. M. Wagner.
arXiv:0911.0034 [hep-ph]
10.1103/PhysRevD.81.015014
Phys. Rev. D **81**, 015014 (2010)

Wayne Hu

In addition to the DOE, Hu's research received support for 1 month summer salary from the NSF. This support was used for the more observational aspects of the projects below.

1. **"Self-accelerating Massive Gravity: How Zweibeins Walk through Determinant Singularities"**
P. Gratia, W. Hu and M. Wyman.
arXiv:1305.2916 [hep-th]

2. **"The abundance of voids and the excursion set formalism"**
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Rocky Kolb

Paper 1 was done during a period when Kolb received one month summer support from NSF grant NSF PHY-1125897.

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In addition to the DOE, Turner's research received support for 1 month summer salary from the NSF.

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