DOE Final Report:

Theoretical Research at the High Energy Frontier: Cosmology, Neutrinos, and Beyond, DE-FG02-09ER41624, Lawrence M. Krauss, PI

The growing theory group associated with this grant now includes Krauss and two postdocs, and we will be joined by three new faculty in Sept, Tanmay Vachaspati, Damien Easson, and Maurik Parikh, all of whom are expected to submit proposals for further support during the coming academic year.

During 2009-2010 the research program at ASU began to take off, with active research in a wide variety of different subjects. We describe recent and ongoing research of the PI and the two postdocs below.

Lawrence M. Krauss

Lawrence Krauss's research program since arriving at ASU has focused around four different areas: Gravitational Waves and the Early Universe, Dark Matter distribution in the galaxy, new forms of particle dark matter, and neutrino cosmology. In addition, he has been involved writing associated with the International Year of Astronomy, and his outreach activities included completing a new book on Richard Feynman, as well as carrying out a monthly column for Scientific American.

Gravitational Waves and the Early Universe: Krauss, and collaborators including Harsh Mathur, graduate student Kate Jones-Smith, as well postdoc James Dent continued to explore the possible gravitational wave signature from phase transitions in the early universe, a mechanism Krauss first suggested almost 20 years ago. Following detailed estimates performed in 2007, which demonstrated a significant enhancement for such waves from simple phase transitions without inflation, or following inflation, several questions have arisen. First, these results seemed to be in conflict with one of several general theorems proved by Steven Weinberg that suggested no local physics could alter the inflationary gravitational waves signature, which involves a constant gravitational wave amplitude outside of the horizon,. In a paper with Mathur and Jones-Smith, [**?**] Krauss demonstrated that his theorem is based on a perturbative calculation in which fields are uniform on superhorizon scales up to the effect of small perturbations. However in the case of a

phase transition, fields are completely disordered on superhorizon scales so the perturbative calculation is not appropriate.

Next, Krauss and collaborators turned their attention to distinguishing a possible gravitational wave background from cosmic phase transitions compared to that from inflation. Recently they have identified a new possible signature, obtained by comparing the gravitational wave strain amplitude on scales that might one day be measured by LISA or its successors with the magnitude of the CMB polarization signal that might be observed in the next generation of CMB polarization experiments [**?**]

Along with Scott Dodelson and Stephan Meyer, Krauss recently completed a comprehensive review of Primordial Gravitational Waves and Cosmology which has been accepted for Science, and will appear May 21st [**?**]

Dark Matter Microhalos and Direct and Indirect Detection: In collaboration with Ben Moore, and Aurel Schneider at the Institute for Theoretical Physics in Zurich, where Krauss has visited for several months for the past 2 years, Krauss recently completed a study of the possible impact of dark matter microhalos, of order 10^{-6} solar masses, thought to be the dominant small scale feature in hierarchical clustering for cold dark matter, on direct and indirect dark matter detection experiments [**?**]. Using a combination of analytical estimates and numerical modeling, Krauss and collaborators have demonstrated that tidal disruption and stellar heating disrupt these microhalos implying that the net effect in our region of the galaxy will be minimal for direct detection, with an essentially Maxwellian distribution of particles predicted, identical to that for a smooth isothermal halo. Dense central cusps of microhalos do survive and may produce a small enhancement in annihilation signals for indirect detection.

Eschatology: Krauss opened the international year of astronomy in Paris in 2009 with a lecture entitled The Big Bang, Modern Cosmology, and the Fate of the Universe: Impacts upon Culture. He recently wrote up this work for a UNESCO volume being published this year [**?**]

Ongoing work: Krauss, Dent, Mathur and Jones-Smith continue to investigate gravitational waves. Among current projects underway are: an effort to model precisely the expected CMB polarization signal from cosmic phase transitions, and an exploration of assumptions about the appropriate vacuum during inflation when deriving expected tensor mode signatures. With

Cecilia Lunardini at ASU and postdoc Christel Smith, Krauss is currently exploring possible new neutrino physics that might account for recent new estimates of the primordiial helium abundance and CMB observations suggesting perhaps an excess of energy density in relativistic species compared to what one might expect in the standard model. With James Dent and Francesc Ferrer, Krauss is investigating new supernova constraints on hidden sector dark matter models. Also with Dent, and Lunardini, Krauss is investigating new possible decay signatures from such dark matter models. Finally, with Dent and Tom Weiler, Krauss is exploring possible higher order annihiliation channels that could dramatically affect remnant dark matter abundance estimates in a number of models.

Other Projects and Outreach: Krauss continues his efforts to enhance the public understanding of science, especially in areas related to topics associated with the DOE Office of Science. He recently completed his newest book, to be entitled *Quantum Man: Richard Feynman's Life in Science* [**?**], which will appear in March 2011. In addition, besides his numerous public lectures, TV appearances, and Newspaper opinion pieces, Krauss has begun a new monthly column for Scientific American. Recent pieces are listed after the scientific bibliography

James Dent

With Tom Kephart and Satya Nandi [**?**] Dent has studied an $SU(9)$ model of family unification which has a natural hierarchy of fermion masses and mixings with three light chiral families. They showed how these families arise upon breaking of $SU(9) \to SU(5)$. They found that the hierarchy of masses and mixings of the fermions arises due to different degrees of suppression from the ratio (denoted ϵ) of an $SU(5)$ singlet Higgs VEV and the unification scale of the $SU(9)$. For example, in the up sector, the top mass comes from a dimension four Yukawa interaction, whereas the masses of the lighter quarks arise from higher order interaction terms which are suppressed by ϵ. This model is in good agreement with the experimentally known values of masses and CKM mixings for $\epsilon \sim 1/50$. They also found that singlet fermions are unavoidable which requires the existence of singlet right handed neutrinos. These neutrinos will have masses that are naturally smaller than the GUT scale, thus they can provide the usual see-saw mechanism.

With Sourish Dutta and Bob Scherrer. Dent hsa recently studied [**?**] the effects of kinetic decoupling and the Sommerfeld effect on the relic abundance of dark matter. The Sommerfeld effect produces a velocity dependent annihilation cross section (this is roughly characterized as $< \sigma v >_{ann} \sim 1/v$ for s-wave processes), and has been invoked in an attempt to explain recent anomalous excesses in cosmic ray and gamma ray data. Kinetic decoupling will alter the cross-section because, upon decoupling, a particle's temperature will no longer be equivalent to the background radiation temperature, but instead will be proportional to the square of this temperature. Since velocity is related to temperature, $v \sim T^{1/2}$, any velocity dependent cross-section with thus be altered after kinetic decoupling.

They showed that relic abundances can be an order of magnitude smaller than the known dark matter density, and when the effects of kinetic decoupling are included, the relic density can be smaller still, eventually being cut-off by saturation effects or the onset of matter domination. They derived analytic approximations which are accurate to a few percent for relic densities with and without the inclusion of kinetic decoupling. For p-wave processes we showed the effects of kinetic decoupling may increase the relic abundance by as much as 9%.

As described earlier, with K. Jones-Smith, L.M, Krauss, and H. Mathur, Dent examined a new signature by which to one could potentially discriminate between a spectrum of gravitational radiation generated by a self-ordering scalar field vs that of inflation [**?**], specifically a comparison of the magnitude of a flat spectrum at frequencies probed by future direct detection experiments to the magnitude of a possible polarization signal in the Cosmic Microwave Background (CMB) radiation. In the process we clarified several issues related to the proper calculation of such modes, focusing on the effect of post-horizon-crossing evolution.

With J.C. Bueno-Sanchez, S. Dutta, and L. Perivolaropoulos, Dent examined the growth of perturbations in scalar-tensor (ST) cosmologies [**?**]. They showed that on large subhorizon scales, in the Newtonian gauge, the usual subhorizon growth equation does not describe the growth of perturbations accurately, as a result of scale-dependent relativistic corrections to the Poisson equation. They derived a scale-dependent version of the growth equation which is in excellent agreement with exact numerical results. Based on this equation, we have proposed an accurate scale dependent parameterization for the growth of perturbations in these models. This work is currently under review at Physical Review D.

Roman Buniy

Several recent results in quantum gravity and quantum information theory indicate that there is a connection between these two fields. One example is the relation between the entropy of black holes and the degree of entanglement of quantum systems. Since black holes and entangled states are fundamental objects of study in quantum gravity and quantum information theory, respectively, there is a possibility that the two fields might be connected on the level of physics, not just mathematics.

Almost all known cases of entanglement classifications are obtained by using the standard method which relies on the classical theory of invariants and covariants. Due to combinatorially increasing difficulty of computations, the classification have been fully carried out only for the simplest cases.

Buniy and collaborators have developed a new method of restricted classification of entangled states, confirmed many known results obtained by the standard method, and obtained a large number of new classifications. Their invariants are new discrete measures of entanglement, which should be contrasted with the standard invariants which are continuous measures of entanglement. There are strong indications that our classification is the most refined restricted classification possible. [**?**] They are exploring implications of their solution for the black hole physics.

Buniy and collaborators have proposed a QCD model in which vacuum is represented by a network of interweaved loose closed flux tubes and elementary excitations are represented by tightly knotted and linked flux tubes. Dynamics is set by processes of tightening, breaking, and reconnecting of flux tubes. The model has a topological formulation and physical field configurations have well-defined topological counterparts, which enables systematic classification of various physical quantities. The model is specified by only few phenomenological parameters and makes detailed predictions for various quantities, for example, glueball masses. They are also exploring possible applications of their model to knot solitons and excitations in a quark-gluon plasma (for example, in the interior of a RHIC event, in a quark star, in the early universe). [**?**]

The typical scalar field theory has a cosmological constant problem. Buniy and collaborators have proposed a generic mechanism by which this problem is avoided by embedding the theory into a larger theory. The metric and the scalar field coupling constants in the original theory do not need to be fine-tuned, while the extra scalar field parameters and the metric associated

with the extended theory are fine-tuned dynamically. Hence, no fine-tuning of parameters in the full Lagrangian is needed for the vacuum energy in the new physical system to vanish. [**?**] They are also studying implications of their model for the dark matter particle production through the Higgs boson at LHC.

References

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Krauss: Scientific American Critical Mass Columns:

* C.P. Snow in New York Sept 2009
* Why We Really Want to Go Back to the Moon Oct 2009
* How Women Can Save the Planet Nov 2009
* War Is Peace Dec 2009
* The Doomsday Clock Still Ticks Jan 2010
* Life in a Test Tube?: The Real Promise of Synthetic Biology Feb 2010
* End of Days Danger March 2010
* Dark Matters April 2010
* Human Uniqueness and the Future May 2010

DOE Final Report:

Theoretical Research at the High Energy Frontier: Cosmology, Neutrinos, and Beyond, DE-FG02-09ER41624, Lawrence M. Krauss, PI

The growing theory group associated with this grant now includes Krauss and three postdocs (with salary support from DOE for one of these, and travel and material support for two others), and three new faculty (Tanmay Vachaspati, Damien Easson, and Maurik Parikh), each of whom is supporting a postdoc with startup funds from ASU.

During 2010-2011 the research program at ASU established itself with a cadre of postdocs, an active seminar and visitor program, and a new workshop. Research is being carried out in a broad range of subjects, from with active research in a wide variety of different subjects. We describe recent and ongoing research of the PI and the three postdocs he supports below.

Lawrence M. Krauss

Lawrence Krauss's research program since arriving at ASU has focused around four different areas: Gravitational Waves and the Early Universe; Structure Formation, Reionization, and Dark Matter; new forms of particle dark matter and their implications for detection and astrophysics; and neutrino cosmology. In addition, he has maintained his active outreach program, representing and defending science in the public form, and his new book on the science of Richard Feynman appeared in March of this year. He just completed yet another new popular book, A Universe from Nothing, which will appear in Jan 2012

Reonization, Structure Formation and Dark Matter: Krauss has recently begun a regular visiting position as Distinguished Visiting Professor in the Research School of Astronomy and Astrophysics at Australian National University in Australia. Resulting from his visits has been a new collaboration with Michael Dopita and others at ANU on one of the most important outstanding questions in astrophysics: what is the source of reonization in the early Universe? This question has long been known to be intimately tied up with structure formation, and star formation in particular. With Dopita and collaborators, Krauss has argued that direct baryonic infall into dark matter potential wells that form the seeds of galaxies can produce shock fronts which may lead to significant reionization, and could in fact be the dominant mechanism for reionization in the universe before redshifts of $z \approx 7$ [1]. In order to explore this mechanism in more detail than we have, fine scale numerical simulations of structure formation including cooling on small scales will need to be performed. While some of this work is being done at ANU, Krauss will also continue the collaboration begun earlier with Ben Moore and his colleagues at University of Zurich. Recently, they published a study of the possible impact of dark matter microhalos, of order 10^{-6} solar masses, thought to be the dominant small scale feature in hierarchical clustering for cold dark matter, on direct and indirect

dark matter detection experiments [5]. Using new simulations to be performed using algorithms developed at Zurich which take into account hydrodynamics and baryonic physics we hope to be able resolve the dynamics of early galaxy formation and baryonic infall on a scale that can hopefully determine if our shock heating mechanism is viable.

Gravitational Waves and the Early Universe: Krauss is continuing his long-standing collaboration with Harsh Mathur, Kate Jones-Smith, and James Dent to explore the possible gravitational wave signature from phase transitions in the early universe, a mechanism Krauss first suggested almost 20 years ago. Recently we have identified a new possible signature, obtained by comparing the gravitational wave strain amplitude on scales that might one day be measured by LISA or its successors with the magnitude of the CMB polarization signal that might be observed in the next generation of CMB polarization experiments [6]. At the same time, with Scott Dodelson and Stephan Meyer, Krauss recently published a comprehensive review of Primordial Gravitational Waves and Cosmology [4]. Two new ongoing projects are underway. With Dent, Krauss is exploring the possible extra-horizon size correlations induced by self-ordered scalar fields (SOSF) to see if they are distinguishable from inflationary tensor modes. Krauss, Dent, Mathur, in collaboration with Paul Steinhardt are also exploring the relationship between tensors and scalar modes in SOSF scenarios to see if limits can be placed on possible allowed values of the ratio of tensors to scalar modes and how this might affect interpretations of inflation should such a signal be observed in upcoming CMB experiments.

Neutrino astrophysics and cosmology: There are indirect indications, from BBN and also from CMB and large scale structure observations, that perhaps the number of light neutrino species may exceed 3. Recently in collaboration with Cecilia Lunardini and Christel Smith, Krauss has explored the implications of this for neutrino physics, including new neutrino interactions, right handed and sterile neutrinos [3]. Lunardini and Krauss are continuing their investigations, focusing on possibilities for new sterile neutrinos and new constraints one might derive on these from astrophysics and cosmology.

New Signatures for Dark Matter: In collaboration with James Dent, and also Nicole Bell and her group at U. Melbourne, and Tom Weiler, where Krauss will also be visiting in August, Krauss is exploring the impact of higher order annihilation channels, in particular W and Z bremsstrahlung, that could dramatically affect annihilation rates and indirect signatures for dark matter annihilation in the universe today [2]. With Dent and collaborators Krauss is exploring the impact of these new channels for calculations of remnant dark matter abundances in the early universe, and also possible collider signatures. These issues are discussed in more detail in the report of work by Dent, below. Also with Dent, in collaboration with Francesc Ferrar, Krauss is completing calculations of new supernova constraints on hidden sector dark matter models in which relatively light scalar particles may be emitted. With Lunardini they will extend this work to explore the impact on possible neutrino signatures from supernovae.

Modified gravity: With Dent and postdoc Soma De, Krauss is examining

possible signatures for modified gravity models that may be derived from observations of the Lyman alpha forest, which will be sensitive to the details of the growth of structure at high redshift.

Other Projects and Outreach: Krauss continues his efforts to enhance the public understanding of science, especially in areas related to topics associated with the DOE Office of Science. He recently published a new book entitled *Quantum Man: Richard Feynman's Life in Science* [7], which appeared in March 2011. His newest book, *A Universe from Nothing* is currently being completed and will appear in January 2012 [8]. In addition, besides his numerous public lectures, TV appearances, and newspaper opinion pieces, Krauss wrote a monthly column for Scientific American in 2009-2010.

James Dent

In a series of three works with collaborators Nicole Bell, Ahmad Galea, Lawrence Krauss, Thomas Jacques, and Tom Weiler, Dent has examined the effects of electroweak bremsstrahlung on dark matter annihilation. In two related works they performed a calculation of the cross-section for Majorana dark matter annihilating via t and u channel processes to leptons, and showed that inclusion of radiation of a W or Z boson, which may come from an external lepton leg, or from the internal propagator which mediates the annihilation process, can significantly enhance the cross-section [9, 2]. This enhancement is found to occur in a region of parameter space where the mass of the internally exchanged particle is roughly that of the dark matter particle (this is reminiscent of the co-annihilation region of mSUGRA). They also studied the astrophysical signals of such a process, and showed that it can severely constrain the dark matter explanation of recently observed cosmic ray anomalies in leptophilic models due most strongly from production of anti-protons [10].

In another series of three papers with various combinations of collaborators Yi-Fu Cai, Shih-Hung Chen, Sourish Dutta, and Emmanuel Saradakis, Dent has studied modified gravity in the form of $f(T)$ gravity. This is similar in spirit to $f(R)$ gravity, but now instead of using the Ricci scalar, R, functions of the torsion scalar T are employed. They first developed cosmological perturbations in $f(T)$ gravity and studied the growth of overdensities [11]. Next they showed that any given model of dynamical dark energy used to explain the late time acceleration of the universe can be exactly reproduced by a suitable $f(T)$ model [12]. Finally they showed that $f(T)$ gravity can provide a mechanism for producing bouncing cosmologies, and that there may exist features such as a background dependent sound speed for perturbations which could distinguish $f(T)$ models from Einstein gravity [13].

With Yi-Fu Cai and Damien Easson Dent has examined DBI inflation with the inclusion of dissipation, or Warm DBI inflation [14]. They introduced a dissipative term in the system phenomenologically, and solved the background equations for the inflaton and curvature perturbations. They showed that the usual constraints on DBI inflation - that upper and lower bounds on the tensor-to-scalar ratio due to geometric considerations as well as the size of non-

Gaussianities-which renders the standard models inconsistent - may be alleviated once dissipation is considered. They also found that the Lyth bound, which relates the size of the inflaton's excursion in field space during observable inflation to the tensor-to-scalar ratio, is modified. Typically one finds that if the tensor-to-scalar ratio is below $\simeq .01$, then the field range of the inflaton is sub-Planckian. However they found in the case of dissipative DBI that one may obtain a tensor-to-scalar ratio below .01 and still have a super-Planckian field range.

With Shih-Hung Chen Dent explored a new approach to the vacuum of inflationary models [15]. They proposed a model-dependent fitting function for terms in the dynamical equations for scalar and tensor modes of the metric perturbations, and then imposed boundary conditions at finite conformal time as opposed to the usual case where these are imposed at negative conformal infinity. They worked out an explicit example and outlined how the method may be generalized. It may be that some inflationary models which are ruled out could be revived due to this approach to inflationary initial conditions.

Along with Yi-Zen Chu and Tanmay Vachaspati Dent worked on developing an analytical technique to evaluate the magnetic helicity produced from sphaleron decay [16]. They found that production of baryon number leads to left-handed helicity and that the helicity is conserved at late times. This work shows the connection between sphaleron-mediated cosmic baryogenesis and cosmic magnetogenesis.

Other researchers: Roman Buniy and Holden Chen

While Buniy's and Chen's salaries supported by startup funds to Krauss from ASU, some of their supporting travel and materials costs are covered by the DOE grant. Recent work by Buniy includes studies of new measures for entanglement [17], of relevance for considerations of higher dimensional physics and black hole physics, studies of knotting and higher order linking in physical systems [18], and studies in inflation [19] and general relativity [20]. Buniy and Krauss are also exploring a possible new method for neutrino detection involving coherent scattering processes. Chen has continued his thesis work on modified gravity and 2T physics. [21, 22]

References

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Krauss: Newspaper and Magazine Columns on Science

- Rethinking the Dream, Scientific American, April 2011, issue
- Guns on Campus bill having chilling effect ,The Arizona Republic, March 25, 2011
- Religion no excuse for promoting scientific ignorance, New Scientist, Feb 8, 2011
- The Emperor's New Missile Defense, Scientific American, Guest Blog, Jan 7, 2011
- No Sacred Mantle, The New York Times, Room for Debate Jan 6, 2011
- The Lies of Science Writing, The Wall St. Journal, Dec 4, 2011
- Forgotten Dreams? A Call to investigate the mysteries of humanity, Scientific American, Guest blog Nov 18, 2010
- Our Spontaneous Universe, The Wall St..Journal, Sept. 8, 2010
- Glenn Beck and the science of crowd counts, The Los Angeles Times, Op-Ed, Sept 5, 2010
- The Gulf Spill and the Limits of Science, The Wall St. Journal, June 11, 2010

Krauss: Scientific American Critical Mass Columns:

- Why I Love Neutrinos June 2010 issue
- No Country is an Island July 2010 issue
- Faith and Foolishness August 2010 issue
- A Year of Living Dangerously Sept 2010 issue

Budget Justtification

Residual Funds

It is anticipated that there will be no residual funds at the end of the current project period.

Salaries

2.0 months of summer salary is reqeusted for PI. A three percent increase is being budgeted from budgeted salary. 12 months of salary for post doctoral research scholar is reguested with a three percent increase over current actual salary rate.

Employee-Related Expenses (ERE)

The faculty benefit rate for FY 2012 will be 31.30%. The staff benefit rate, (which include post doctoral research scholars) will be 41.6%.

Travel

One domestric trip each for PI and post doctoral research scholar for conferences and collaborations. Estimated at $1,000 for each trip. Expected domestic destinations are: Aspen, Boston, Berkeley, Princeton and Caltech. One foreign trip for PI and post doctoral research scholar for conferences and collaborations. Estimate at $1,000 for each trip. Expected foreign destinations are: Austrailia, Brazil, France, Spain, CERN, Italy and the UK.

Facilities and Administratvie Costs F&A

DHHS approved negotiated rate of 52.5% MTDC, approved June 16, 2009

DOE award number DE-SC0008016 Arizona State University

Final Report for Theoretical Research at the High Energy Frontier: Cosmology and Beyond

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Summary

The research projects described in our original proposal are continuing, with completion of several of the envisaged projects, and several new related projects underway. Research of each of the Investigators and the postdocs supported by the grant are summarized below.

Lawrence Krauss: Research, January-December 2012

In the past year Lawrence Krauss has continued his work on gravitational waves from the early universe, and completed two significant projects, one on constraints on light hidden sector gauge bosons from supernova cooling, and one on new probes of dark matter at the LHC using mono-Z decays as a probe. He is currently working on three different projects, which will be completed within weeks: New Astrophysical constraints on extra light neutrinos, constraining varying gravity models using the growth of large scale structure as a probe, and the impact of extra light neutrinos on primordial gravitational wave signatures. He and his postdocs and students have also joined the DARWIN noble gas dark matter detection consortium, and are completing a white paper exploring monte carlo expectations for the ability of the experiment to constrain dark matter models, and the astrophysics associated with them. Finally, Krauss published a new book on cosmology, and has continued to write columns on science for Slate, Scientific American, and the New York TImes and Wall St. Journal.

Journal Publications (January-December 2012)

1. Constraints on Light Hidden Sector Gauge Bosons from Supernova Cooling, with J. Dent, F. Ferrer, arXiv: 1201.2683, PRD, in press.

2. Searching for Dark Matter at the LHC with a Mono-Z, with N. Bell, J. Dent, A. Galea, and T. Weiler, Phys. Rev. D 86, 096011 (2012)

Books

1. Quantum Man paperback (Norton) 2012

2. A Universe From Nothing (Simon and Schuster) 2012

Popular articles

1. To the Moon, Newt!, Slate Magazine, January 27, 2012

2. The faithful must learn to respect those who question their beliefs, The Guardian, February 07, 2012

3. Why we need college degrees more than we need faith, The Washington Post, February 28, 2012

4. Why Are Religious Beliefs Off Limits?, The Huffington Post, March 05, 2012

5. Does Conservatism Have to Be Synonymous With Ignorance?, The Huffington Post, March 14, 2012

6. Countdown to the Man-Made Apocalypse, Slate Magazine, March 16, 2012

7. Americans Deserve a Presidential Science Debate, The Huffington Post, March 19, 2012

8. A Universe Without Purpose, The Los Angeles Times, April 1, 2012

9. Join the real world and show faith in reasoned debate, The Sydney Morning Herald, April 14, 2012

10. Its Time for the U.S. To Finally Sign the Nuclear Test-Ban Treaty, Slate Magazine, April 25, 2012

11. The Consolation of Philosophy, Scientific American, April 27, 2012

12. Did the Universe Arise from Nothing?, World Science Festival Blog, May 10, 2012

13. Does Religious Liberty Equal Freedom to Discriminate?, Richard Dawkins Foundation for Science and Reason, May 28, 2012

14. The Dark-Matter Ages, Slate Magazine, June 14, 2012

15. A Quantum Leap, Slate Magazine, July 04, 2012

16. Higgs and the holy grail of physics, CNN.com, July 06, 2012

17. How the Higgs Boson Posits a New Story of our Creation,Newsweek Magazine, July 09, 2012

18. A Blip That Speaks of Our Place in the Universe, The New York Times, July 09, 2012

19. Romney: Grounded in the Galaxy?, Richard Dawkins Foundation for Science and Reason, August 23, 2012

20. Philosophy v science: which can answer the big questions of life?, The Guardian, September 08, 2012

21. With Limited Budgets, Pursuing Science Smartl, The New York Times, October 01, 2012

22. Bombing the Test, Slate Magazine, October 03, 2012

23. Whose Space-Exploration Policy Is BetterObamas or Romneys?, Slate Magazine, October 04, 2012

24. A Quiet, Faraway Milestone for Humanity, The Wall Street Journal, October 19, 2012

25. Finding New Planets: Tracking a Stars Wobble, Newsweek Magazine, October 22, 2012

26. Mormonism in the Mainstream?, Richard Dawkins Foundation for Science and Reason, October 23, 2012

27. Italy blames the messengers, The Los Angeles Times, October 26, 2012

28. Out of the Dark, Cosmos Magazine, November 20, 2012

In progress

1. The growth of Structure in a ΛCDM Universe, with S. De and J. B. Dent

2. Damping of Primordial Gravitational Waves from Generalized Sources, with J.B. Dent, S. Sabharwal and T. Vachaspati.

3. Additional Light Sterile Neutrinos and Cosmology, with C. Lunardini, and T. Jacques

Maulik Parikh: Research, January-December 2012

In 2012, Maulik Parikh's research was on the physics of accelerating horizons in anti-de Sitter space (especially their holographically dual theories) and on the transformation of the null energy condition under conformal transformations. He is currently working on further developing the holographic description of Rindler-AdS space, as well as on investigating the necessity of the energy conditions that are used to constrain the solution space of Einstein's equations.

Publications (January-December 2012)

1. *Rotating Rindler-AdS Space,* M. Parikh, P. Samantray, and E. Verlinde, Phys. Rev. D **86** (2012) 024005.

2. *Rindler-AdS/CFT,* M. Parikh and P. Samantray, arXiv:1211.7370.

3. *All the Stationary Vacuum States of de Sitter Space,* M. Parikh and P. Samantray, arXiv:1212.4487.

4. *Energy Conditions in Jordan Frame,* S. Chatterjee, D. Easson, and M. Parikh.

In progress:

1. *Only Scalar-Tensor f(R) Theories are Stable,* A. J. Amsel and M. K. Parikh.

2. *Is Cosmic Censorship Necessary?* S. Chatterjee, P. Davies, D. Easson, and M. Parikh.

Tanmay Vachaspati: Research, January-December 2012

In the past year, Tanmay Vachaspati has worked on the observational signatures of strings, production of cosmic magnetic fields, and the signatures of magnetic fields in the cosmic microwave background. He is currently working on projects on the production of solitons from particle scattering, propagation of gravitational waves in cosmology, electroweak strings, gravitational collapse, observation of cosmic magnetic fields, and new signatures of cosmic strings.

Publications (January-December 2012)

1. Radio Bursts from Superconducting Strings, Y.-F. Cai, E. Sabancilar and T. Vachaspati, Phys. Rev. D85, 023530 (2012).

2. CMB Distortions from Superconducting Cosmic Strings, H. Tashiro, E. Sabancilar and T. Vachaspati, Phys. Rev. D85, 103522 (2012).

3. Constraints on Superconducting Cosmic Strings from Early Reionization, H. Tashiro, E. Sabancilar and T. Vachaspati, Phys. Rev. D85, 103522 (2012).

4. Radio Broadcasts from Superconducting Strings, Y. F. Cai, E. Sabancilar, D. Steer and T. Vachaspati, Phys. Rev. D86, 043521 (2012).

5. Chiral Effects and Cosmic Magnetic Fields, H. Tashiro, T. Vachaspati and A. Vilenkin, Phys. Rev. D86, 105033 (2012).

6. Probing Primordial Magnetism with Off-Diagonal Correlators of CMB Polarization, A. Yadav, L. Pogosian and T. Vachaspati, Phys. Rev. D, in press (2012).

7. Primordial Magnetism in CMB B-modes, L. Pogosian, T. Vachaspati and A. Yadav, arXiv:1210.0308, to be published in proceedings of Theory Canada 7, Lethbridge (2012).

In progress:

1. "Numerical Exploration of Soliton Creation", H. Lamm and T. Vachaspati (2012).

2. "Damping of Primordial Gravitational Waves from Generalized Sources", J.B. Dent, L.M. Krauss, S. Sabharwal and T. Vachaspati.

3. "CMB Distortions from Damping of Acoustic Waves Produced by Cosmic Strings", H. Tashiro, E. Sabancilar and T. Vachaspati.

Thomas Jacques: Research, January-December 2012

In the past year, Thomas Jacques has worked on the search for dark matter at the Large Hadron Collider, and on the neutrino signature of DM annihilation in the sun. He is currently working on effects that can modify the apparent neutrino energy density as measured in the cosmic microwave background, and on finding model-independent ways to analyze data from dark matter direct detection experiments.

Publications (January-December 2012)

1. "Neutrino signals from electroweak bremsstrahlung in solar WIMP annihilation," N. F. Bell, A. J. Brennan and T. D. Jacques, JCAP **1210**, 045 (2012).

2. "Searching for Dark Matter at the LHC with a Mono-Z," N. F. Bell, J. B. Dent, A. J. Galea, T. D. Jacques, L. M. Krauss and T. J. Weiler, Phys. Rev. D **86**, 096011 (2012).

In progress:

1. "The Scientific Impact of Multi-tonne-scale Dark Matter Direct Detection Experiments," J. Newstead, T. Jacques, L. Krauss, J. Dent, F. Ferrer.

2. "Effect of Sterile Neutrino Thermalization Efficiency on $N_{\rm eff}$," T. Jacques, L. Krauss, C. Lunardini.

Eray Sabancilar: Research, January-December 2012

In the past year, Eray Sabancilar has worked on the various observational effects of cosmic strings, such as radio transients, CMB spectral distortions, ultra high energy cosmic rays and reionization. He is currently working on propagation and observation of ultra high energy neutrinos, sterile neutrino warm dark matter detection via resonant absorption of ultra high energy neutrinos and fermion modes in the electroweak sphaleron background.

Publications (January-December 2012)

1. Radio Bursts from Superconducting Strings, Y. F. Cai, E. Sabancilar and T. Vachaspati, Phys. Rev. D85, 023530 (2012).

2. CMB Distortions from Superconducting Cosmic Strings, H. Tashiro, E. Sabancilar and T. Vachaspati, Phys. Rev. D85, 103522 (2012).

3. Constraints on Superconducting Cosmic Strings from Early Reionization, H. Tashiro, E. Sabancilar and T. Vachaspati, Phys. Rev. D85, 103522 (2012).

4. Radio Broadcasts from Superconducting Strings, Y. F. Cai, E. Sabancilar, D. Steer and T. Vachaspati, Phys. Rev. D86, 043521 (2012).

5. Cosmic Strings as Emitters of Extremely High Energy Neutrinos, C. Lunardini and E. Sabancilar, Phys. Rev. D86, 085008 (2012).

6. CMB Distortions from Damping of Acoustic Waves Produced by Cosmic Strings, H. Tashiro, E. Sabancilar and T. Vachaspati, to be submitted to Phys. Rev. Lett. [arXiv:1212.3283].

In progress:

1. Propagation and Observation of Ultra High Energy Neutrinos, C. Lunardini, E. Sabancilar and L. Yang.

2. Indirect Detection of Sterile Neutrino Warm Dark Matter with Ultra High Energy Neutrinos, C. Lunardini and E. Sabancilar.

3. Fermion Modes in the Electroweak Sphaleron Background, E. Sabancilar and T. Vachaspati.

Hiroyuki Tashiro: Research, January-December 2012

In the past year, Hiroyuki Tashiro has worked on the observational signatures of primordial non-Gaussianity, small-scale primordial density fluctuations, cosmic reionization, cosmic strings and primordial magnetic fields in the cosmic microwave background and large scale structures. He is currently working on projects on probings of primordial non-Gaussianity, cosmic magnetic fields and cosmic strings.

Publications (January-December 2012)

1. Ionized bubble number count as a probe of non-Gaussianity H. Tashiro and N. Sugiyama Month. Not. Roy. Astro. Soc., 420, 441 (2012)

2. CMB Distortions from Superconducting Cosmic Strings, H. Tashiro, E. Sabancilar and T. Vachaspati, Phys. Rev. D85, 103522 (2012).

3. Constraints on Superconducting Cosmic Strings from Early Reionization, H. Tashiro, E. Sabancilar and T. Vachaspati, Phys. Rev. D85, 103522 (2012).

4. Cosmological constraints from CMB distortion, J. B. Dent, D. A. Easson and H. Tashiro, Phys. Rev. D86, 023514 (2012).

5. Primordial magnetic fields with X-ray and Sunyaev-Zel'divich cluster surveys, H. Tashiro, K. Takahashi and I. Kiyomoto, Month. Not. Roy. Astro. Soc., 424, 927 (2012)

6. Chiral Effects and Cosmic Magnetic Fields, H. Tashiro, T. Vachaspati and A. Vilenkin, Phys. Rev. D86, 105033 (2012).

7. Background reionization history from omniscopes, S. Clesse, L. Lopez-Honorez, C. Ringeval, H. Tashiro and M. H. G. Tytgat, Phys. Rev. D86, 123506 (2012)

In progress:

1. "Constraining primordial non-Gaussianity with CMB-21cm cross-correlations?", H. Tashrio and S. Ho (2012).
2. "The effect of primordial black holes on 21 cm fluctuations", H. Tashiro and N Sugiyama (2012).
3. "CMB Distortions from Damping of Acoustic Waves Produced by Cosmic Strings", H. Tashiro, E. Sabancilar and T. Vachaspati (2012).

Other Activities

The group hosts a weekly seminar with visiting outside speakers and has hosted two research workshops with invited speakers during 2012. One on the origin of gravity, and one on neutrino astrophysics and supernovae.

Individuals currently working on this projects:

Faculty: Lawrence Krauss Damien Easson Maulik Parikh Tanmay Vachaspati

Post Doctoral Research Scholars: Thomas Jacques Andrew Long Eray Sabancillar Hiroyuki Tashiro

Graduate Students: Jayden Newstead Subir Sabharwal