# Particle Astrophysics Theory Group, CWRU
# 2013 Final Report on DOE grant

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## I. INTRODUCTION

The past three years has seen important changes in the group. We have now grown to four full-time faculty with the addition of Claudia de Rham in July 2011. Andrew Tolley has now been with the group since 2010 and Harsh Mathur's transition to to particle astrophysics theory continues apace. Profs. Tolley has been awarded a DOE Early Career grants, which began in May; Prof. de Rham has joined PI Starkman as Co-I on a new group grant. Prof. Mathur will continue to improve his publication record in the field in the hopes of being added to the grant in the next couple of years. Craig Copi, formerly a senior research associate, is now a lecturer, a regular (non-tenure-track) faculty member with teaching and research (but not service) expectations.

We continue to maintain close ties with members of the Astronomy group: Idit Zehavi and Chris Mihos in particular. Tom Giblin (Asst. Professor at Kenyon College) is now adjunct faculty and is a weekly visitor. Evalyn Gates, director of the Cleveland Museum of Natural History, is also adjunct faculty and attends many seminars and colloquia.

On the postdoc/research associate front, Eric Greenwood, having completed his time with us, has spent a year at Kenyon College as a Visiting Assistant Professor and will soon move to New College in Florida. Dmitry Podolsky, who moved to MIT in a postdoctoral position has been promoted to senior research associate. Matteo Fasiello has been working with Prof. Tolley as a postdoctoral fellow, funded with his startup funds; Raquel Ribeiro has joined Prof. de Rham in the same capacity. We are expecting Stefano Anselmi to join the group in September as the DOE-funded postdoc, and Daniel Muller (UNB, Brasilia) will join for a year on a Brazilian fellowship.

We now have eight students working toward the PhD in the group: David Jacobs and Amanda Yoho are expected to graduate in spring 2014 working with Dr. Starkman; Scott Beck is a year behind them (co-advisors: Starkman and Mathur), followed by James Mertens (Starkman), Lucas Keltner (Tolley), Andrew Matas (de Rham) and Nicholas Ondo (Tolley). Claudia de Rham's University of Geneva graduate student Lavinia Heisenberg is a frequent long-term visitor.

The group continues to maintain an active seminar program, and also ran an international workshop "Modifying Gravity" in spring 2012 that brought participants from around the US, Europe and Asia. This is one of a series of such workshops that the group has been running under the auspices of the Center for Education and Research in Cosmology and Astrophysics here at CWRU.

The balance of the report focuses on work produced specifically by Starkman and Mathur, the faculty supported by this grant, and by those of their students and postdocs who were supported by the grant at some point between January 2010 and April 2013 – Postdocs: D. Podolsky, E. Greenwood; Students: S. Beck, D. Jacobs, J. Mertens, R. Matsuo, Y. Ng, and A. Yoho,

## II. P.I. STARKMAN

### 1. *Strong Gravity at the LHC: BlackMax*

Starkman, D. Stojkovic (PhD, and later Visiting Asst. Prof. at CWRU, now Buffalo) and De Chang Dai (PhD Case, now Capetown) continued to work in collaboration with Isever (Oxford and CERN, until recently convenor ATLAS exotics group) and Tseng (Oxford and ATLAS) on the detection and characterization of mini-black-holes and other strong gravity phenomena at the LHC in the context of theories of large extra dimensions (i.e. TeV scale gravity). The collaboration has now grown to include: E. Rizvi (Queen Mary College, London), Nina Gausmann (Sussex U.), Ryan Buckingham (Oxford), Warren Carlson (Wits U., South Africa), Xavier Calmet (Sussex). This group wrote and now maintains the BlackMax software that can be used to generate simulated strong gravity events in proton-proton collisions, such as at the LHC. The code includes appropriate gray body factors (many of which were previously uncomputed) for Hawking emission of particles of various spin from black holes including rotation, brane tension, brane splitting, bulk curvature, and more than three spatial dimensions. BlackMax has been interfaced to Herwig and Pythia, and has been incorporated into the main ATLAS simulator, Charybdis, and is now the ATLAS standard for simulation of strong gravity events. The code is publicly available via HEPForge.net. It has also been adopted by CMS.

In the last three years work was not focused on obtaining publishable results. Rather, it was dedicated to maintaining and upgrading the BlackMax software so that it could be used by the ATLAS and CMS collaborations for modeling of the signal from strong gravity events. Starkman's role was principally to serve as a consultant on physics questions associated with potential new signals, potential new theories to include, or with resolving disagreements between BlackMax and alternate software. Version 2.02.0 of the code was released in January 2011. Version 3.0.0 is under development. The changes mostly focus on better coding standards. However improved physics input is also under development for 3.0.0.

## *2. Topology of the Universe*

Starkman and former postdoc Pascal Vaudrevange (now at DESY), with N. Cornish (Montana) and D. Spergel (Princeton) examined the CMB for non-trivial cosmic topology (Phys. Rev. D **86**, 083526 (2012)). using the circles-in-the-sky signature developed by Cornish, Spergel and Starkman (Proceedings of the National Academy of Sciences 95, 82 (1998); Physical Review **D57**, 5982 (1998); Class. Quantum Grav., **15**, 2529 (1998)). For the circles to exist, the physical dimension of the universe must be less than that of the diameter of the surface of last scattering. If this is the case, then the surfaces of last scattering will self-intersect, and pairs of circles on the sky will have the same pattern of temperature fluctuations. This work extending earlier work of Cornish, Spergel and Starkman and collaborators to circle pairs with separation angles equal to or near 180° degrees (PRL **92**:201302 (2004) with E. Komatsu;Phys. Rev **D75**:084034, 2007 with with J. Shapiro-Key) as well as using the then-latest, 7-year data release of the Wilkinson Microwave Anisotropy Probe (WMAP) satellite. This is a continuation of an ongoing decade long effort by Starkman and collaborators to determine whether the Universe is finite or infinite in spatial extent, and more generally to characterize any non-trivial topology. Cornish, Spergel, Starkman and Vaudrevange are currently repeating this analysis for the new Planck data, since the Planck team only looked at back-to-back circle pairs.

Meanwhile, Greenwood and Starkman, together with A. Jaffe (Imperial College, London) and University of Perugia computer science graduate student F. Petrogali, spent considerable time exploring the question of how to extend the search for cosmology topology beyond the last scattering surface. If the Universe is finite, how can we determine its size and its shape? The solution undoubtedly lies in the canonical question of the well known mathematician Mark Kac – "Can you hear the shape of a drum?" In other words, given the right tools, can you infer the shape of a drum from its sound alone. The mathematically precise answer is no, as there exist sets of "homophonous" drums, but modulo that degeneracy, the physics answer is yes. Our question is analogous – can we "hear" the shape of the universe – in other words, given that the eigenmodes of the gravitational potential are discrete in a compact space, and the distribution of their eigenenergies and eigen-momenta are in nearly one-to-one correspondence with the shape of the fundamental domain – can we, by measuring the spectrum, infer the fundamental domain. Unfortunately, it is probably not quite as easy as measuring the shape of a drum. We only get one chance to "listen" – one snapshot of the universe, and, given the results reported above, we probably can't detect the largest wavelength modes. Nevertheless, preliminary calculations seem to show that, using either CMB observations or future wide angle deep astronomical surveys (eg. Big BOSS, PAU), one can hope to probe the eigenspectrum well enough to detect topologies with fundamental domains significantly larger than the interior of the last scattering surface. Although Petrogali has left the field, Starkman and Jaffe, with possible assistance from Greenwood, are taking a fresh look at how best to go about using the available information to answer this question.

### *3. Astrostatistics*

In collaboration with M. March and R. Trotta, Starkman and Vaudrevange (formerly CWRU, then DESY) applied the concept of doubt – introduced in an unpublished arXiv posting (arXiv:0811.2415) by Starkman, Trotta and Vaudrevange – to examine whether a cosmological constant is a viable description of dark energy (MNRAS 410 (2011) 2488-2496). Dark energy represents about 75% of the energy density of universe. Many different models compete to accurately describe its microscopic properties, yet the cosmological constant (essentially an integration constant (CC) originally introduced by Einstein in his field equations – his most famous "biggest blunder") seems to remain a valid competitor. In order to distinguish it from e.g. dynamical models, various time-dependent parameterizations of the equation of state parameter $w$ have been proposed, and their goodness–of–fit relative to the CC has been compared. Still, there are – in principle – infinitely many different parameterizations for the equation of state, and it is impossible to perform a model comparison with the CC for all of them. Our analysis confirms that the CC is still the preferred model for the observed data and that there is no reason to doubt it.

In collaboration with M. March and R. Trotta (Imperial College, London), P. Berkes (Brandeis) and P. Vaudrevange (then CWRU), Starkman examined the current treatment of error bars in supernova (SN) Ia data sets. Supernovae of type Ia are used as standard candles in cosmology and are the (currently) most important tool in determining the properties of dark energy. As it turns out, SN of type Ia are not all exactly the same, with their light-curves differing in what is known as the stretch factor and color correction. Based on work by Gull (S. F. Gull, Bayesian data analysis: straight–line fitting, in *Maximum Entropy and Bayesian Methods, Cambridge 1988*, edited by J. Skilling, pp. 511–518, Dordrecht, 1989, Kluwer), they developed significant improvements to the statistical treatment of stretch factor and color correction. In M.N.R.A.S. **418** 2308 (2011) and in a contribution to *Astrostatistical Challenges for the New Astronomy*, (Springer Series on Astrostatistics), they presented a new method based on a Bayesian hierarchical model to extract constraints on cosmological parameters from SNIa data obtained with the SALT-II lightcurve fitter. They demonstrated with simulated data sets that their new method delivers tighter statistical constraints on the cosmological parameters over 90% of the time, that it reduces statistical bias typically by a factor  2-3 and that it has better coverage properties than the usual chi-squared approach. As a further benefit, a full posterior probability distribution for the dispersion of the intrinsic magnitude of SNe is obtained. They applied this method to recent SNIa data, alone and and in combination with CMB and BAO data,

Cosmologists will soon be in a unique position. Observational noise will gradually be replaced by cosmic variance as the dominant source of uncertainty in an increasing number of observations. In MNRAS Lett, 401, 1, L15-L18 (2010), Starkman, Trotta and Vaudrevange reflect on the ramifications for the discovery and verification of new models. If there are features in the full data set that call for a new model, there will be no subsequent observations to test that model's predictions. We give specific examples of the problem by discussing the pitfalls of model discovery by prior adjustment in the context of dark energy models and inflationary theories. We show how the gradual release of data can mitigate this difficulty, allowing anomalies to be identified, and new models to be proposed and tested. We advocate that observers plan for the frugal release of data from future cosmic variance limited observations.

## *4. Black Holes*

In an original paper by T. Vachaspati, D. Stojkovic and L. Krauss (Phys.Rev. D76 (2007) 024005), the authors considered the effect of massless radiation given off during the time of collapse. They suggested that in the absence of backreaction, the collapse of the spherically symmetric domain wall would still take an infinite amount of time to occur. However, when considering backreaction, since the collapse takes an infinite amount, the domain wall would never form a black hole since it would radiate away all of its energy and dissipate. However, if the domain wall is originally made up of say baryons, which possess a global quantum number carried only by massive particles, no massless field could radiate all this away. Hence, one must consider a massive field instead. Greenwood, Podolsky and Starkman investigated (JCAP 1111 (2011) 024) the effect of radiating away massive (scalar) fields, using the same formalism as the original authors, with the aim of determining the final state of a collapsing spherical shell when backreaction is also taken into account They found that the introduction of mass suppresses the occupation number in the infrared regime of the induced radiation during the collapse. The suppression factor is found to be given by $e^{-\beta m}$, which is in agreement with the expected Planckian distribution of induced radiation. Thus a massive collapsing domain wall will radiate mostly (if not exclusively) massless scalar fields, making it difficult for the domain wall to shed any global quantum numbers and evaporate before the horizon is formed.

During the course of this investigation, Greenwood, Podolsky and Starkman discovered an alternative formalism to describe the induced radiation given off during the collapse. As described earlier, the original and following papers utilize the so-called functional Schrödinger formalism. However, it is well known in quantum mechanics that a system can be described by both the Schrödinger picture and the Heisenberg picture. Therefore instead of working in the Schrödinger picture, one can always work in the Heisenberg picture by developing the so-called quantum kinetic equation (see for example S. M. Schmidt *et al.*, Int. J. Mod. Phys. **E7**, 709 (1998)). This new formalism reproduces the same results as the functional Schrödinger formalism; however, it has some other nice properties which allows one to examine the system more analytically, not just numerically. In a manuscript in preparation, they will introduce the quantum kinetic equation for both massless and massive scalar field induced during the time of collapse, and compare and contrast the two methods (functional Schrödinger and quantum kinetic). More importantly, studying the dynamics of in-vacuum polarization, they found that a multi-parametric family of out-vacua exists. Initial conditions for the collapse lead dynamically to different vacua from this family as the final state. Therefore, the form of the out-vacuum encodes memory about the initial quantum state of the system. While most out-vacua feature a non-thermal Hawking flux and are expected to decay quickly, there also exists a thermal vacuum state. Collectively, these observations suggest an interesting possible resolution of the information loss paradox. A manuscript (arXiv:1205.0558) has been submitted for publication to Phys. Rev. During refereeing, a flaw in the original Vachaspati *et al.*formalism was identified. Greenwood *et al.*do not believe that the flaw will qualitatively affect their result, however, they are currently reformulating their calculation avoiding an incorrect assumption underlying the Vachaspati *et al.*paper.

### *5. Modifying Gravity*

Starkman has, for several years, pursued the question of whether GR can/should be modified. On the one hand the motivation has been to examine whether modification of gravity can replace dark matter or dark energy. On the other hand, the question has at times been how generic modifications can be tested. Late in 2009, Starkman and Pedro Ferreira (Oxford) wrote an invited Science review of the promises for modified gravity theories that seek to replace either dark matter or dark energy (or both) with modified gravity. In Phil.Trans.Roy.Soc.Lond. A369 (2011) 5018-5041, Starkman provides a review of the lack of success of modified gravity theories in replacing dark matter, and the challenges they would need to overcome to do so. This included issues related to violation of Birkhoff's Law (Gauss' Law for gravity) in MOND, as discussed in Phys.Rev. D81 (2010) 024041 (Starkman with D.-C. Dai (then SUNY, Buffalo) and R. Matsuo (then CWRU)) and arXiv:0911.3658 (with R. Matsuo – submitted, but never revised after Matsuo's sudden departure from the field; not included here).

In Phys.Rev. D81 (2010) 104015, Starkman, together with J. Zuntz, (then Oxford U.) , T.G Zlosnik, (then Perimeter Inst. Theor. Phys.) , F. Bourliot, (Ecole Polytechnique, CPHT) , and P.G. Ferreira, (Oxford U.) presented a comprehensive investigation of cosmological constraints on the class of vector field formulations of modified gravity called Generalized Einstein-Aether models. Using linear perturbation theory they generated cosmic microwave background and large-scale structure spectra for general parameters of the theory, and then constrained them in various ways. They investigated two parameter regimes: a dark-matter candidate where the vector field sources structure formation, and a dark-energy candidate where it causes late-time acceleration. They found that the dark matter candidate does not fit the data, and identified five physical problems that can restrict this and other theories of dark matter. The dark energy candidate does fit the data, and they constrained its fundamental parameters; most notably finding that the theory's kinetic index parameter $n_{\rm ae}$ can differ significantly from its ΛCDM value.

Case graduate student Jacobs has been examining related systems. He has identified a conflict in certain relativistic generalizations of MOND, wherein derivatives of the metric which give the desired "MONDian" modifications to the Poisson equation also come with unexpected cosmological contributions which are of the same order. This conflict exists in GEA (and probably TeVeS), however they can be avoided in BIMOND and some F(R) theories. This work is still in progress.

## *6. Observational Probes/Observational Anomalies of the Universe*

### **Large Angle Properties of the CMB:**

Starkman and collaborators have had a long interest in the large angle properties of the universe, in particular as reflected in the CMB. The anomalies that they have uncovered have attracted considerable attention in no small measure because, if they are real, and not systematic effects, they may be revealing important new underlying physics. Recently, the Planck team confirmed the presence of these anomalies, reducing the likelihood that they reflect only systematic errors in the WMAP teams measurements or analysis.

Copi and Starkman, together with collaborators Hutterer (Michigan) and Schwarz (Bielefeld) (and occasionally others) have focused in particular on the two-point angular correlation function. On large angular scales (greater than about 60 degrees), the two-point angular correlation function of the temperature of the cosmic microwave background (CMB), as measured (outside of the plane of the Galaxy) by the Wilkinson Microwave Anisotropy Probe, shows significantly lower large-angle correlations than expected from the standard inflationary cosmological model. Furthermore, when derived from the full CMB sky, the two lowest cosmologically interesting multipoles, the quadrupole (l=2) and the octopole (l=3), are unexpectedly aligned with each other. Using randomly generated full-sky and cut-sky maps, with D. Sarkar (then Michigan) they investigated (Astropart.Phys. 34 (2011) 591-594) whether these anomalies are correlated at a statistically significant level. They conclusively demonstrated that, assuming Gaussian random and statistically isotropic CMB anisotropies, there is no statistically significant correlation between the missing power on large angular scales in the CMB and the alignment of the l=2 and l=3 multipoles. The chance to measure the sky with both such a lack of large-angle correlation and such an alignment of the low multipoles is thus quantified to be below $10^{-6}$. This work was reported as submitted last year, and is now published.

In Adv. Astron. **2010**, 847541 (2010), Copi, Huterer, Schwarz and Starkman reviewed the large-scale anomalies in the WMAP year-7 maps of temperature anisotropies in the cosmic microwave background. These include alignments of the largest modes of CMB anisotropy with each other and with geometry and direction of motion of the Solar System, and the unusually low power at these largest scales. They discussed these findings in relation to expectation from standard inflationary cosmology, their statistical significance, the tools to study them, and the various attempts to explain them. This was an invited review. A more up to date invited review was provided in Rom.J.Phys. 57 (2012) 979-991.

Study of these scales is hampered by the facts that we have only one Universe to observe, only a few independent samples of the underlying statistical distribution of these modes, and an incomplete sky to observe due to the interposing Galaxy. There has been some suggestion that the absence of large angle correlations is a result of using a sub-optimal pixel-based method to extract the two-point correlation function from the WMAP temperature map and that it would be better to reconstruct the full sky and extract the two-point correlation function from that reconstructed sky. Techniques for reconstructing a full sky from partial sky data are well known and have been applied to the large angular scales. In M.N.R.A.S. **418**, 505 (2011), Copi, Huterer, Schwarz and Starkman critically study the reconstruction process and show that, in practise, the reconstruction is biased due to leakage of information from the region obscured by foregrounds to the region used for the reconstruction. They conclude that, despite being suboptimal in a technical sense, using the unobscured region without reconstructing is the most robust measure of the true CMB sky. They also show that for noise free data reconstructing using the usual optimal, unbiased estimator may be employed without smoothing thus avoiding the leakage problem. Unfortunately, directly applying this to real data with noise and residual, unmasked foregrounds yields highly biased reconstructions requiring further care to apply this method successfully to real-world CMB.

The anomalous lack of large angle temperature correlations has been a surprising feature of the CMB since first observed by COBE-DMR and subsequently confirmed and strengthened by WMAP. This anomaly may point to the need for modifications of the standard model of cosmology or may show that our Universe is a rare statistical fluctuation within that model. Further observations of the temperature auto-correlation function will not elucidate the issue; sufficiently high precision statistical observations already exist. Instead, alternative probes are required. In arXiv posting arXiv:1303.4786, now in press at M.N.R.A.S, Copi, Huterer, Schwarz and Starkman explore the expectations for forthcoming polarisation observations and define a prescription to test the hypothesis that the large-angle CMB temperature perturbations in our Universe represent a rare statistical fluctuation within the standard cosmological model. These tests are based on the temperature-Q Stokes parameter correlation. Unfortunately these tests cannot be expected to be definitive. However, the authors do show that if this TQ-correlation is observed to be sufficiently large over an appropriately chosen angular range, then the hypothesis can be rejected at a high confidence level. They quantify these statements and optimise the statistics they have constructed to apply to the anticipated data. They find that we can construct a statistic that has a 25 per cent chance of excluding the hypothesis that we live in a rare realisation of LCDM at the 99.9 per cent confidence level.

Extensions of this work to cross-correlations between temperature and the gravitational lensing potential, and to the Newtonian potential (as probed by $21(1 + z)$-cm observations) are currently under development.

**The Effects of Being a Moving Observer of the Universe:**

The largest fluctuation in the observed CMB temperature field is the dipole, its origin being usually attributed to the Doppler Effect - the Earth's velocity with respect to the CMB rest frame. The lowest order boost correction to temperature multipolar coefficients appears only as a second order correction in the temperature power spectrum, $C_\ell$. Since $\beta \equiv v/c \simeq 10^{-3}$, this effect can be safely ignored when estimating cosmological parameters. However, a moment's thought makes clear that one should be surprised rather than reassured that the boost corrections to the full-sky angular power spectrum is second order in the observer velocity. That is because it is clear that the corrections to the underlying spherical harmonic components are large. A boost changes the cosines of angles by $O(\beta)$. A spherical harmonic $Y_{\ell m}$ has approximately $\ell$ zeros along a line of constant $\phi$, therefore if $l \geq \beta$ the boost will completely mix spherical harmonics over a relatively wide range of $\ell$. Starkman, together with graduate student Amanda Yoho, and collaborators M. Stuke (U. Bielefeld, Germany) and T. Pereira (U. Londrina, Brazil) have been investigating this issue. In arXiv:1009.4937, they argued that this effect might turn out to be important when reconstructing the power spectrum from the cut-sky data. In the meantime the potential importance of this effect has become clearer. Indeed, one finds that the appropriate expansion parameter for spherical harmonic coefficients $a_{\ell m}$ is not $\beta$ but $\beta\ell$. Thus, the fact that the angular power spectrum $C_\ell$ calculated over the full sky gets $\mathcal{O}(\beta)$ rather than $\mathcal{O}(\beta\ell)$ corrections requires careful cancellation among all the $a_{\ell m}$. Such cancellations are unlikely to be robust to sky cuts, noise, ...

The original arXiv posting evolved into M.N.R.A.S. **432** (2208-2215) 2013 by Yoho, Starkman, Copi and Pereira. In this work they describe a numerical method for removing Lorentz-boost effects from real-space temperature maps. They show that to deboost a map so that one can accurately extract the temperature power spectrum requires calculating the boost kernel at a finer pixelization than one might naively expect. In idealized cases that allow for easy comparison to analytic results, they confirm that there is mode mixing among the spherical harmonic coefficients of the temperature. They find that using a boost kernel calculated at Nside = 8192 leads to a 1 per cent bias in the binned boosted power spectrum at $\ell \simeq 2000$, while individual $C_\ell$ exhibit 5 per cent fluctuations around the binned average. However, this bias is dominated by pixelization effects and not the aberration and Doppler shift of CMB photons that causes the fluctuations. Performing analysis on maps with Galactic cuts does not induce any additional error in the boosted, binned power spectra over the full sky analysis. For multipoles that are free of resolution effects, there is no detectable deviation between the binned boosted and unboosted spectra. This result arises because the power spectrum is a slowly varying function of $\ell$ and does not show that, in general, Lorentz boosts can be neglected for other cosmological quantities such as polarization maps or higher point functions. The Planck team cited this paper in describing next steps in their analysis.

With CWRU student J. Mertens and Copi, Starkman and Yoho are extending this work to polarization maps. They are also preparing a real-space boost code for public release.

The same considerations have being applied to weak lensing studies. Boosts will induce changes in ellipticity of observed galaxies at $\mathcal{O}(\beta) \simeq 10^{-3}$, as compared to the $\sim 10^{-2}$ effect of gravitational lensing around clusters. This means that it is a (spatially) coherent noise source that must be properly accounted for if weak lensing surveys are to be useful in extracting fundamental cosmological physics. In M.N.R.A.S. **432** (1315-1318) 2013, Mertens, Yoho and Starkman demonstrate that while no ellipticity is induced in an image from the Lorentz boost to first order in $\beta = v/c$, the image is magnified. This affects the inferred convergence at a 10 per cent level, and is most notable for low multipoles in the convergence power spectrum $C^{\kappa\kappa}$ and for surveys with large sky coverage like LSST and DES. Experiments that image only small fractions of the sky and convergence power spectrum determinations at $\ell > 5$ can safely neglect the boost effect to first order in $\beta$.

**Degree-scale CMB:**

Yoho and Starkman, together with Francesc Ferrer (Wash U, formerly CWRU) investigated noticeable deviations from the prediction of the fiducial LCDM cosmology that are found in the angular power spectrum of the CMB. Besides large-angle anomalies, the WMAP 1st year data revealed a dip in the power spectrum at $\ell \sim 200$, which seemed to disappear in the 3rd year and subsequent angular power spectra. Using the WMAP 1st, 3rd, and 5th year data release, they studied the intensity and spatial distribution of this feature in order to unveil its origin and its implications for the cosmological parameters. They showed in Phys. Rev. **D83**, 083525 (2011) that in all WMAP data releases there is a substantial suppression of the first Doppler peak in a region near the north ecliptic pole. The reason for this is unknown. This work was described as submitted last year, but has now been published in the Physical Review.

**Statistical (An)isotropy from Surveys:**

A fundamental assumption in cosmology is that of statistical isotropy - that the universe, on average, looks the same in every direction in the sky. Statistical isotropy has mostly been tested using CMB data, leading to intriguing results on large angular scales (as discussed above). In Phys. Rev. **D84**, 043005 (2011), Starkman, together with former CWRU postdoc Dragan Huterer (Michigan) and C. Zunkel (then Princeton and Kwazulu-Natal, South Africa) applied some of the same techniques used in the CMB to the distribution of galaxies on the sky. Using the multipole vector approach, originally introduced to cosmology by Huterer, Copi and Starkman, where each multipole in the harmonic decomposition of galaxy density field is described by unit vectors and an amplitude, they lay out the basic formalism of how to reconstruct the multipole vectors and their statistics out of galaxy survey catalogs. They apply the algorithm to synthetic galaxy maps, and study the sensitivity of the multipole vector reconstruction accuracy to the density, depth, sky coverage, and pixelization of galaxy catalog maps.

## *7. Casimir Forces*

A great deal of work has been done in the last two decades in the context of what are called braneworld theories – theories in which the universe we observe is a (3+1)-dimensional sub-manifold of a higher-dimensional space-time. Generically that higher dimensional space-time has all but three spatial dimensions compactified at a microscopic scale, although very large, even infinite, extra dimensions have also been of interest, for example in Randall-Sundrum models, and in models that aim at infra-red modifications of gravity, such as the Dvali-Gabadadze-Porati (DGP) model. A potentially important observation that has been (to our knowledge) neglected in all of this body of work is that generic manifolds are not homogeneous. This is true even when the metric on the space **is** homogeneous. A very simple example is the two-dimensional cone, obtained by removing a wedge from two-dimensional Euclidean space. Although this space is everywhere flat (except at the apex, where the curvature is not defined), nevertheless one can definitely distinguish points that are closer to the apex of the cone from those that are farther away on the basis of which has the shortest closed non-trivial loop (one that encircles the apex at least once) through it. Thus non-local physics is non-homogeneous.

Given that the space is non-homogeneous we can expect there to be preferred locations for the brane to inhabit within the space so long as the brane is coupled to the relevant non-local physics. One obvious way in which such a coupling can emerge is via the zero-point energy of fields that inhabit the bulk and that also have boundary conditions on the brane. This should be rather generic. (If nothing else, except for co-dimension one branes, gravity should change the metric near the brane and thus affect any bulk field solutions.) We then expect the zero-point energy to be a function of the location (and orientation) of the brane within the bulk. In other words we expect there to be Casimir forces on branes in non-trivial manifolds.

In JHEP 1303 (2013) 116 and Phys.Rev. D87 (2013) 046007, CWRU graduate student David

Jacobs, together with CWRU faculty Starkman and Tolley explore the use of both local and global effects in a braneworld scenario to naturally provide position-dependent forces that determine and stabilize the location of a single brane. For illustrative purposes, they consider the 2-dimensional hyperbolic horn and the Euclidean cone as toy models of the extra-dimensional manifold, and add a brane wrapped around one of the two spatial dimensions. They calculate the total energy due to brane tension and bending (extrinsic curvature) as well as that due to the Casimir energy of a bulk scalar satisfying a Dirchlet boundary condition on the brane. From the competition of at least two of these effects there can exist a stable minimum of the effective potential for the brane location. However, on more generic spaces (on which more symmetries are broken) any one of these effects may be sufficient to stabilize the brane. They discuss this as an example of physics that is neither local nor global, but regional.

Casimir forces on branes are likely to be of interest for brane localiztion (explaining why branes stay put in the bulk), for de-gravitation (with the cusp or horn mediating a transition from smaller to larger number of effective dimensions as fields propagate along the brane, and even possibly for an environmental explanation of the dimensionality of ordinary space.

The same group plus graduate student Andrew Matas and Rachel Bean (Cornell) are looking at the nature and consequences of what they are calling vacuum viscoity, or Casimir drag. This arises from the fact that the identifications involved in crafting a manifold of non-trivial spatial topology from its covering space define a preferred rest frame. Thus objects (particles/branes/...) coupled to any bulk fields should experience a viscous force that brings them to rest with respect to that frame. (Or perhaps, even more strangely, accelerates them relative to that rest frame.) This could again have implications for brane localization, explaining why branes come to rest in spaces, but also be important in models such as ekpyrotic universes or cyclic cosmologies.

## *8. Fine Tuning Problems*

The Higgs Fine-Tuning Problem has been a driving motivation in the development of many extensions to the Standard Model. With D. Podolsky (initially CWRU, now MIT), B. Lynn (CERN) and K. Freese (Michigan), Starkman has been investigating the most basic assertion underlying this problem – that scalar field loops in scalar field theories are quadratically divergent. They report on this research in arXiv:1112.2150 (submitted to Phys. Rev. D).

More than four decades ago, B.W. Lee and K. Symanzik proved (but did not say) that, in the

Gell Mann-Levy model (GML) with conserved vector currents (CVC) and partially conserved axial-vector currents (PCAC) (i.e. a generic set of global O(4) linear sigma models (LSM) in the $|\langle H\rangle|$ vs. $m_\pi^2/\lambda^2$ quarter-plane), tadpole renormalization (a Higgs Vacuum Stability Condition) forces all S-matrix ultra-violet quadratic divergences (UVQD) to be absorbed into the physical renormalized pseudo-scalar pion (pole) mass squared, $m_\pi^2$. The authors show that this includes "new" UVQD (widely unfamiliar to modern audiences) which they identify as corrections to the PCAC relation $\partial_\mu \vec{J}_\mu^5 = - < H > m_\pi^2 \vec{\pi}$. They also show that tadpole renormalization is an automatic consequence of Ward-Takahashi identities. They prove that all UVQD therefore vanish identically in the Goldstone-mode limit, $m_\pi^2 \to m_{\pi;NGB;LSM}^2 \equiv 0$, where pions are Nambu-Goldstone Bosons (NGB), and where Lee and Symanzik's Goldstone Symmetry Restoration Condition (a renormalization prescription) enforces spontaneous symmetry breaking and the exact massless-ness of NGB as required by Goldstone's theorem. $SU(2)_{L-R}$ chiral symmetry is restored in the spontaneously broken limit of GML. The vanishing of UVQD is therefore achieved in the Goldstone-mode by restoration of an exact symmetry, and therefore (by definition) without fine-tuning. A weak-scale Higgs mass is therefore not UVQD fine-tuned in the spontaneously broken GML. Hence Goldstone-mode O(4) LSM symmetries are sufficient to ensure that the theory does not suffer from the Higgs Fine Tuning Problem or Naturalness Problem. This is contrary to the widely accepted belief that UVQD in the Higgs mass, arising already at 1-loop, lead to such problems in the O(4) LSM, which are then presumed to be inherited by the Standard Model (SM). The key observation is to regard the spontaneously broken O(4) LSM as the Goldstone-mode limit of GML with PCAC.

The authors prove this first at 1-loop for the pure scalar GML model, then extend the proof to all-orders of loop perturbation theory. They then break the symmetry $O(4) \to SU(2)_L$ with SM Yukawa couplings, and show that the above remains true when the LSM with PCAC is extended to include SM quarks and leptons, first to 1-loop then to all-loop-orders. Lynn has argued in a companion manuscript (arXiv:1106.6354) that these results extend to the Standard Model.

As expected, the claims of this manuscript have been controversial. Referees at Phys. Rev. D were dubious, but in general without identifying concrete errors. A second round of refereeing focused the objections down to a single point – the authors' claim that the limit in which the mass of the would-be Goldstone boson of GML was taken to zero was a symmetry-restoration condition. The referee expressed doubts. The manuscript of this paper has been resubmitted to Phys. Rev. D, and it pointed out to the referee that a Ward identity insists that the NGB mass-squared is directly proportional to the coefficient of the PCAC term, so that taking the latter to zero and taking the former to zero are equivalent if the Higgs vacuum expectation value (VEV) is non-zero.

Follow up work by Lynn and Starkman has shown that the no-fine-tuning result applies: not just to the Goldstone Mode limit of GML, but to all of GML so long as the Higgs VEV and the NGB mass-squared are small; also to beyond the standard model (BSM) physics that respects the chiral $SU(2)_L \times SU(2)_R$ symmetry, such as right handed neutrinos with Majorana and Dirac masses, and massive scalar singlets. They also conjecture that it applies to quantum gravity because that is likely to respect the chiral symmetry. This follow up work resulted in the posting of a letter, submitted to PRL, shortly after the end date of this grant (arXiv:1306.5647). Significant follow up work is in progress.

Clearly, these results have important implications for cosmology, for neutrino physics and for extensions to the Standard Model if correct.

### *9. When light leaves the light cone*

Electromagnetic and gravitational radiation do not propagate solely on the null cone in a generic curved spacetime. They develop "tails," traveling at all speeds equal to and less than unity. If sizeable, this off-the-null-cone effect could mean objects at cosmological distances, such as supernovae, appear dimmer than they really are. Their light curves may be distorted relative to their flat spacetime counterparts. These in turn could affect how we infer the properties and evolution of the universe itself. Within the gravitational context, the tail effect would induce a self-force that causes a compact object orbiting a massive black hole to deviate from an otherwise geodesic path. This needs to be taken into account when modeling the gravitational waves expected from such sources. Motivated by these considerations, former CWRU PhD student (and now U.Penn postdoc) Yi-Zen Chu and Starkman, in Phys.Rev. D84 (2011) 124020, developed perturbation theory for solving the massless scalar, photon and graviton retarded Green's functions in perturbed spacetimes, assuming these Green's functions are known in the background spacetime. In particular, they elaborate on the theory in perturbed Minkowski spacetime in significant detail. This builds on and generalizes work appearing in the literature on this topic to date by DeWitt (1964) ,Kovacs (1975), and Pfenning (2000), and lays the foundation for a thorough, first principles based, investigation of how light propagates over cosmological distances, within a spatially flat inhomogeneous Friedmann-Lemaître-Robertson-Walker universe. Even if the effects are not so dramatic as to alter the inferred cosmological parameters (and they most probably are not) they may nevertheless give us new handles on probing the geometry of the universe between us and the last scattering surface.

### *10. Electroweak Stars*

In JCAP 1012 (2010) 004, D.C. Dai (then SUNY, Buffalo), A. Lue (Lincoln Labs, MIT), Starkman and D. Stojkovic (SUNY, Buffalo) study the possible existence of an electroweak star - a compact stellar-mass object whose central core temperature is higher than the electroweak symmetry restoration temperature. They identify a solution to the Tolman-Oppenheimer-Volkoff equations describing such an object. The parameters of such a star are not substantially different from a neutron star - its mass is around 1.3 Solar masses while its radius is around 8 km. What is different is the existence of a small electroweak core. The source of energy in the core that can at least temporarily balance gravity are standard-model non-perturbative baryon number (B) and lepton number (L) violating processes that allow the chemical potential of $B + L$ to relax to zero. The energy released at the core is enormous, but gravitational redshift and the enhanced neutrino interaction cross section at these energies make the energy release rate moderate at the surface of the star. The lifetime of this new quasi-equilibrium can be more than ten million years. This is long enough to represent a new stage in the evolution of a star if stellar evolution can take it there.

### *11. Coupling Gravity and Electromagnetism*

In Phys. Rev. **D82**, 064022 (2010), Starkman and then-CWRU graduate students Chu, Ng and Jacobs, construct the most general effective Lagrangian coupling gravity and electromagnetism up to mass dimension 6 by enumerating all possible non-minimal coupling terms respecting both diffeomorphism and gauge invariance. In all, there are only two unique terms after field re-definitions; one is known to arise from loop effects in QED while the other is a parity violating term which may be generated by weak interactions within the standard model of particle physics. They show that neither the cosmological propagation of light nor, contrary to earlier claims, solar system tests of General Relativity are useful probes of these terms. These non-minimal couplings of gravity and electromagnetism may remain a mystery for the foreseeable future.

### *12. Quasars as Standard Sirens*

In Phys.Rev.Lett. 108 (2012) 231302, D.C. Dai, Starkman, B. Stojkovic (Benin U. & SUNY, Buffalo), D. Stojkovic (SUNY, Buffalo) and Amanda Weltman report hitherto unnoticed patterns in quasar light curves. They characterize segments of quasars' light curves with the slopes of the straight lines fit through them. These slopes appear to be directly related to the quasars' redshifts.

Alternatively, using only global shifts in time and flux, they find significant overlaps between the light curves of different pairs of quasars by fitting the ratio of their redshifts. They are then able to reliably determine the redshift of one quasar from another. This implies that one can use quasars as standard clocks, as they explicitly demonstrate by constructing two independent methods of finding the redshift of a quasar from its light curve.

### *13. Lepton Asymmetry of the Universe*

In JCAP 1203 (2012) 040, Starkman joins M. Stuke and D. Schwarz (Bielefeld U.) to investigate how large lepton asymmetries affect the evolution of the early universe at times before big bang nucleosynthesis and in particular how they influence the relic density of WIMP dark matter. In comparison to the standard calculation of the relic WIMP abundance they find a decrease, depending on the lepton flavour asymmetry. They find an effect of up to 20 per cent for lepton flavour asymmetries $l_f = \mathcal{O}(0.1)$. In J.Phys.Conf.Ser. 375 (2012) 032005, they continue to investigate the lepton asymmetry. A poorly constrained parameter in the Standard Model of Cosmology, the lepton asymmetry $l = \sum_f l_f = \sum_f (n_f + n_{\nu_f})/s$. Each flavour asymmetry $l_f$ with $f = e, \mu, \tau$ is the sum of the net particle density of the charged leptons $n_f$ and their corresponding neutrinos, normalized with the entropy density $s$. Constraints on $l_f \leq O(0.1)$ from BBN and CMB allow for lepton flavour asymmetries orders of magnitudes larger then the baryon asymmetry $b \simeq 10^{-10}$. In this conference contribution, they show how such large lepton (flavour) asymmetries influence the early universe, in particular the freeze out of WIMPs and the cosmic QCD transition.

### *14. Inflationary Models*

In JCAP 1004:031, 2010, P. M. Vaudrevange (then CWRU), D. I. Podolsky (then CWRU) and Starkman report on a new class of fast-roll inflationary models. In a huge part of its parameter space, inflationary perturbations exhibit quite unusual phenomena such as scalar and tensor modes freezing out at widely different times, as well as scalar modes reentering the horizon during inflation. In another, narrower range of parameters, this class of models agrees with observations. One specific point in parameter space is characterized by extraordinary behavior of the scalar perturbations. Freeze-out of scalar perturbations as well as particle production at horizon crossing are absent. Also the behavior of the perturbations around this quasi-de Sitter background is dual to a quantum field theory in flat space-time. Finally, the form of the primordial power spectrum is determined by the interaction between different modes of scalar perturbations.

### A. Papers Published and Posted/Submitted and Talks Delivered 2010-13

**Papers Published**

1. **"Constraints on the Topology of the Universe: Extension to General Geometries,"** P. M. Vaudrevange, G. D. Starkman, N. J. Cornish and D. N. Spergel, Phys. Rev. D **86**, 083526 (2012) [arXiv:1206.2939 [astro-ph.CO]].

2. **"Should we doubt the cosmological constant?,"** M. C. March, G. D. Starkman, R. Trotta and P. M. Vaudrevange, Mon.Not.Roy.Astron.Soc. 410 (2011) 2488-2496

3. **"Improved constraints on cosmological parameters from SNIa data"**
M. C. March, R. Trotta, P. Berkes, G. D. Starkman, P. M. Vaudrevange. M.N.R.A.S. **418** 2308 (2011).

4. **"Improved cosmological constraints from a Bayesian hierarchical model of supernova type Ia data,"** M. C. March, R. Trotta, P. Berkes, G. D. Starkman, P. M. Vaudrevange, in *Astrostatistical Challenges for the New Astronomy*, Springer Series on Astrostatistics, Editor: Joseph M Hilbe, Springer Verlag, 2012.

5. **"The Virtues of Frugality - Why cosmological observers should release their data slowly,"** G. D. Starkman, R. Trotta and P. M. Vaudrevange, MNRAS Lett, 401, 1, L15-L18 (2010)

6. **"Pre-Hawking Radiation from a Collapsing Shell"** E. Greenwood, D. I. Podolsky, G. D. Starkman. JCAP 1111 (2011) 024

7. **"Modifying Gravity: You Can't Always Get What You Want,"** G. D. Starkman, Phil. Trans. Roy. Soc. Lond. A **369**, 5018 (2011)

8. **"Limited utility of Birkhoff's theorem in modified Newtonian dynamics: Nonzero accelerations inside a shell,"** D. -C. Dai, R. Matsuo and G. Starkman, Phys. Rev. D **81** (2010) 024041

9. **"Vector field models of modified gravity and the dark sector,"** J. Zuntz, T.G Zlosnik, F. Bourliot,, P.G. Ferreira, and G.D. Starkman Phys.Rev. D81 (2010) 104015,

10. **"Missing Power vs low-l Alignments in the Cosmic Microwave Background: No Correlation in the Standard Cosmological Model,"** D. Sarkar, D. Huterer, C. J. Copi, G. D. Starkman, D. J. Schwarz. Astropart. Phys. **34**, 591-594 (2011)

11. **"Large angle anomalies in the CMB,"** C. J. Copi, D. Huterer, D. J. Schwarz, G. D. Starkman. Adv. Astron. **2010**, 847541 (2010)

12. **"The Oddly Quiet Universe: How the CMB challenges cosmology's standard model,"** G. D. Starkman, C. J. Copi, D. Huterer and D. Schwarz, Rom. J. Phys. **57**, 979 (2012)

13. **"Bias in low-multipole CMB reconstructions"** C. J. Copi, D. Huterer, D. J. Schwarz, G. D. Starkman. M.N.R.A.S. **418**, 505 (2011).

14. **"Large-Angle CMB Suppression and Polarisation Predictions,"** C. J. Copi, D. Huterer, D. J. Schwarz and G. D. Starkman, arXiv:1303.4786 [astro-ph.CO], M.N.R.A.S. in press.

15. **"Real Space Approach to CMB deboosting,"** A. Yoho, C. J. Copi, G. D. Starkman and T. S. Pereira, M.N.R.A.S. **432** (2208-2215) 2013.

16. **"Effect of Our Galaxy's Motion on Weak Lensing Measurements of Shear and Convergence,"** J. B. Mertens, A. Yoho, G. D. Starkman M.N.R.A.S. **432** (1315-1318) 2013.

17. **"Degree-scale anomalies in the CMB: localizing the first peak dip to a small patch of the north ecliptic sky,"** A. Yoho, F. Ferrer, G. D. Starkman, Phys. Rev. **D83**, 083525 (2011).

18. **"Testing the statistical isotropy of large scale structure with multipole vectors"** C. Zunckel, D. Huterer, G. D. Starkman, Phys. Rev. **D84**, 043005 (2011)

19. **"Brane Stabilization and Regionality of Extra Dimensions,"** D. M. Jacobs, G. D. Starkman and A. J. Tolley, Phys. Rev. D **87**, 046007 (2013)

20. **"Brane Localization and Stabilization via Regional Physics,"** D. M. Jacobs, G. D. Starkman and A. J. Tolley, JHEP **1303**, 116 (2013)

21. **"Retarded Green's Functions In Perturbed Spacetimes For Cosmology and Gravitational Physics"** Y. -Z. Chu, G. D. Starkman, Phys.Rev. D84 (2011) 124020.

22. **"Electroweak stars: How nature may capitalize on the standard model's ultimate fuel,"** D. -C. Dai, A. Lue, G. Starkman and D. Stojkovic, JCAP **1012**, 004 (2010)

23. **"It's Hard to Learn How Gravity and Electromagnetism Couple"** Y. -Z. Chu, D. M. Jacobs, Y. Ng, G. D. Starkman. Phys. Rev. **D82**, 064022 (2010).

24. **"Using quasars as standard clocks for measuring cosmological redshift,"** D. -C. Dai, G. D. Starkman, B. Stojkovic, D. Stojkovic and A. Weltman, Phys. Rev. Lett. **108**, 231302 (2012).

25. **"WIMP abundance and lepton (flavour) asymmetry,"** M. Stuke, D. J. Schwarz and G. Starkman, JCAP **1203**, 040 (2012)

26. **"First second of leptons,"** D. J. Schwarz, G. D. Starkman and M. Stuke, J. Phys. Conf. Ser. **375**, 032005 (2012)

27. **"Surprising phenomena in a rich new class of inflationary models,"** P. M. Vaudrevange, D. I. Podolsky and G. D. Starkman, JCAP **1004**, 031 (2010)

**Papers Posted But Not Yet Published**

1. **"Quantum kinetics and prethermalization of Hawking radiation,"** D. Podolsky, E. Greenwood and G. Starkman, arXiv:1205.0558 [hep-th].

2. **"The 'Goldstone Exception' II: Absence of a Higgs Fine-Tuning Problem in the Spontaneously Broken Limit of the Gell Mann Levy Linear Sigma Model: $O(4)$ with PCAC and $SU(2)_L$ with PCAC and Standard Model Quarks and Leptons,"** B. W. Lynn, G. D. Starkman, K. Freese and D. I. Podolsky, arXiv:1112.2150 [hep-ph].

3. **"Chiral Symmetry Restoration, Naturalness and the Absence of Fine-Tuning I: Global Theories,"** B. W. Lynn and G. D. Starkman, arXiv:1306.5647 [hep-ph].

4. **"Effects of a Cut, Lorentz-Boosted sky on the Angular Power Spectrum,"** T. S. Pereira, A. Yoho, M. Stuke, G. D. Starkman, arXiv:1009.4937 [astro-ph]

**Selected Talks Delivered**

- **Plenary and Invited Conference Talks:**
  - "Cosmology and Fundamental Physics with Planck", CERN, 6/13
  - SEENET MTP Workshop Particle Physics from TeV to Planck Scale", Djerdap, Serbia 8/11
  - Royal Society Discussion Session "Gravity," London, UK 2/11
  - NYU-Penn-CWRU meeting on theoretical physics, NYU, 11/10
  - APS March meeting, Feb 2010, Washington DC

- **Selected Colloquia:**
  - Imperial College London, 10/12
  - Ohio State University, 4/12
  - Syracuse University, 11/11
  - University of North Carolina, 10/11
  - Kenyon College, 11/10
  - University of Louisiana at Lafayette, 3/10
  - University of Michigan, 2/10

- **Selected Seminars:**
  - Beyond the Standard Model Seminar Series, CERN, 7/13
  - Particle Physics Seminar, Oxford, 1/13
  - Department of Physics, California Institute of Technology, 5/12
  - Department of Physics and Astronomy, University of Pittburgh, 11/11
  - Astroparticule et Cosmologie (APC), Paris, 2/11
  - Department of Physics, McGill University, 1/11
  - Department of Physics, New York University, 12/10
  - Department of Physics, University of Pennsylvania, 12/10

**Selected Invited Public Talks**

- Academia Film Olomouc, Olomous, The Czech Republic, 4/12
- Senior Scholars, CWRU, 1-2/12
- Origins Science Scholars, CWRU, 10/10, 5/11, 11/11, 3-4/12, 10/12, 4/13
- Institute for the Science of Origins, “Life, the Universe and Hot Dogs” series, 1/12
- Honors Convocation Speaker, University of Louisiana at Lafayette, 04/11
- Ecophilia, Cleveland OH 02/11
- Rowfant Club, Cleveland, OH 04/10, title tbd

## III. CO-I. H. MATHUR

### *1. Aharonov-Bohm Radiation*

In the 1980s Alford and Wilczek showed that the predominant interaction of grand unified cosmic strings with matter would be via an Aharonov-Bohm coupling (M.G. Alford and F. Wilczek, PRL **62**, 1071 (1989)). Building on this insight we showed that a moving cosmic string would produce vacuum radiation of particles and anti-particles due to the Aharonov-Bohm coupling (a mechanism that was remarked upon by Alford and Wilczek but not computed by them). In our first paper we treated the radiation of bosonic particles (K. Jones-Smith, H. Mathur and T. Vachaspati, PRD **81**, 043503 (2010)). and in the second that of fermions (Y-Z. Chu, H. Mathur and T. Vachaspati, PRD **82**, 063515 (2010)). We developed a non-perturbative scheme that allowed us to compute particle production by slowly moving strings and a perturbative scheme that allowed us to analyze strings undergoing arbitrary motion. Cosmic string loops readily form kinks and cusps at which the string is accelerated to motion close to the speed of light. We found that it was precisely the kinks and cusps that were the predominant source of Aharonov-Bohm radiation. Because it presents an unusual twist on the Aharonov-Bohm effect our work was also of broader fundamental interest and was featured as a research highlight in Nature Physics in March 2010.

In effect Aharonov-Bohm radiation constitutes a new mechanism by which cosmic strings might reveal themselves. We are working at present on determining the spectrum of particle production by the cosmic string network and on identifying potential observational signatures (H. Mathur (in progress)).

### *2. Solar system tests of MOND theories*

Modified gravity theories of the MOND family were proposed in the 1980s as an alternative to Dark Matter. For a recent review with references to the original literature see G.D. Starkman, Phil. Trans. R. Soc. **A 369**, 5018 (2011). The original MOND model was an ad hoc non-relativistic theory. Its chief virtue is that it gives an excellent one parameter fit to a variety of galaxy rotation curves. Subsequently, MOND theories have been embedded within more fundamental relativistic co-variant theories. However, MOND models have run into problems with explaining observations on the galactic cluster (notably the bullet cluster) and on the cosmological scale. Nonetheless, due to their impressive phenomenological successes, it remains of interest to continue investigating MOND models.

With graduate student Scott Beck and Starkman, I have been exploring solar system constraints on MOND theories. It has previously been suggested that the Pioneer Anomaly might be related to MOND physics but from the outset it has been unclear whether the anomaly is a real effect or an overlooked systematic; the consensus now is that it is an overlooked systematic (S.G. Turyshev, V.T. Toth, J. Ellis, and C.B. Markwardt, Phys. Rev. Lett. **107**, 081103 (2011)).

In our work we have looked closer home to the orbit of LAGEOS II which has been measured with exquisite precision. A major goal of the LAGEOS mission was to verify the Lense-Thirring effect of classical general relativity by measurements of the orbit precession (I. Ciufolini, Nature **449**, 41 (2007)). MOND corrections to Newtonian gravity would produce an additional precession and hence the observed residual precession of LAGEOS should allow a constraint on the basic MOND parameter $a_0$, the gravitational acceleration below which departures from Newtonian physics occur. To our surprise we find that the data an put a quite stringent limit on $a_0$. A value of order $10^{-10}$ m/s$^2$ is needed to account for galaxy rotation curves; a value an order of magnitude larger than that would be detectable via the orbit of LAGEOS.

In our initial calculations we considered the precession of nearly circular orbits but in order to facilitate comparison to data we have generalized the calculation to elliptical orbits of arbitrary eccentricity. This is most easily done by calculation of the dynamics of the Runge-Lenz vector.

A second result we have obtained is a more theoretical insight into MOND gravity; namely, we showed that under suitable circumstances MOND physics cannot be mimicked by *any* distribution of dark matter. The equations of MOND gravity are highly non-linear but it is easy to calculate the MOND gravitational field of a point mass (or any spherical distribution of matter). The MOND field of a point mass is identical to the Newtonian field of a point mass surrounded by a halo of dark matter with a suitable (power law) density distribution. Non spherical configurations pose formidable problems but for a pair of point masses we were able to show that the MOND gravitational field was equivalent to the Newtonian field of a dark matter distribution with *negative* mass density in the region between the two point masses. Since negative mass density cannot occur it follows that in this case MOND gravity physics produces effects that cannot be mimicked by any distribution of dark matter.

A manuscript reporting these results entitled *Solar system test of MOND gravity* is in preparation and will be submitted for publication this summer.

### *3. Self-ordering scalar fields*

In earlier work (K. Jones-Smith, L.M. Krauss and H. Mathur, *Nearly scale invariant spectrum of gravitational radiation from global transitions*, Physical Review Letters **100**, 131302 (2008)), my collaborators and I have explored the cosmological consequences of a continuous symmetry breaking phase transition on the grand unified scale. We presume that such a transition occurs on a scale somewhat below that of inflation; a key motivation of our work was to understand to what extent such a phase transition might mask inflation. To this end in our original paper we studied the production of gravitational radiation due to the ordering of a symmetry breaking scalar field. We find a scale invariant spectrum similar to that of inflation.

Primordial gravitational radiation from inflation is expected to imprint itself on the B-mode of the cosmic microwave background polarization. Observation of such a B-mode signal is eagerly anticipated as smoking gun evidence of inflation. Our work shows that such an observation would have to be carefully disentangled from inflation in order to separate the effects of symmetry breaking from inflation. In a follow up paper we showed that if gravitational waves are observed both via B-mode and by direct detection disentanglement of the two contributions would be possible (Physical Review **D82**, 044001 (2010)).

Subsequent to our work D. Bauman and M. Zaldarriaga pointed out (JCAP 0906:013 (2009)) that by studying the real space angular correlations of a suitably defined $\tilde{B}$ mode one can disentangle inflation from symmetry breaking and other non-inflationary mechanisms. Adshead and Lim pointed out (Physical Review **D82**, 024023 (2010)) that gravitational radiation from symmetry breaking would be highly non-linear in contrast to primordial radiation from inflation. D.G. Figueroa, R.R. Caldwell and M. Kamionkowski (Physical Review **D81**, 123504 (2010)) studied non-Gaussianities in this model in the scalar sector. Giblin and Siemens (PRL **100**, 131302 (2008)) carried out numerical simulations that confirmed our analytic results, which were based on a large $N$ approximation

Last year with my former graduate student Katherine Jones-Smith and collaborators James Dent and Lawrence Krauss I revisited the problem of self-ordering scalar fields. Existing data provides constraints on the scalar to tensor ratio and to the percentage of isocurvature perturbation in the scalar sector (P. Steinhardt, private communication). All prior work on the self-ordering scalar field model has focussed on either the scalar or the tensor sector. But in order to compare to data it is important to also compute the perturbations in the vector sector. This is the calculation on which we embarked last year. We hope to complete our analysis this summer.

Another more fundamental related problem I studied with the same collaborators last year pertains to Weinberg's theorem (see S. Weinberg, *Gravitation and Cosmology*, Chapter 9 (John WIley and Sons, 1972). Weinberg assumes that the metric of the Universe is of the flat FRW form plus a small perturbation; the perturbations are assumed to be governed by linearized general relativity. He then deduces two solutions to these equations that should apply no matter what the constituents of the Universe or what laws govern them. Furthermore if there is an ancillary scalar field in the Universe, he is able to specify its evolution as well. These remarkable solutions are deduced by an ingenious argument based on gauge invariance.

Weinberg's solutions have the characteristic that modes outside the horizon undergo no evolution. If the Universe followed these solutions after inflation they would be unaffected by re-heating. Weinberg argues that the observability of inflation depends crucially on these being the solutions that describe the Universe after inflation.

In our work last year we generalized Weinberg's theorem to the vector sector. Weinberg had constructed special solutions for which the vector perturbations are exactly zero. We have shown that Weinberg's construction can be used to obtain solutions that have non-zero vector perturbations as well. Furthermore we are able to deduce the evolution of ancillary vector fields as well. Lately there has been much interest in the physics of vector gauge fields in the era of inflation particularly from the perspective of understanding primordial magnetic fields.

In earlier unpublished work we had argued that in the presence of symmetry breaking the solutions guaranteed by Weinberg's theorem are not the physically relevant ones, an argument that Weinberg accepts is valid (Weinberg, private communication). Thus under quite plausible conditions Weinberg's theorem does not assure the direct observability of inflation.

A manuscript reporting the vector generalization of Weinberg's theorem and discussing the implications of symmetry breaking is in preparation and will be submitted for publication this summer (K. Jones-Smith, J. Dent, H. Mathur and L.M. Krauss, *Superhorizon Conservation theorems and Cosmology* (in preparation)).

### *4. Doppler and Aberration effects in the Cosmic Microwave Background at large $\ell$*

Professor Starkman, his student Amanda Yoho, and their collaborators, have been investigating the effects of the Earth's proper velocity $v$ (relative to the cosmic microwave background) on the appearance of the CMB at small angles (see above). Conventional perturbation theory (eg. A. Challinor and F. van Leewen, Phys. Rev. **D65**, 103001 (2002)) in powers of $v/c$ breaks down at

$\ell > c/v$ or at angles smaller than $v/c$, precisely the regime that is now of great interest. Although conceptually simple the problem turns out to be one of formidable computational difficulty (J. Chluba, M.N. R.A.S. **415**, 3227 (2011).

In discussions of this problem, particularly with graduate student Amanda Yoho, I have been exploring an analytic approach to this problem that exploits the large $\ell$ asymptotics of the spherical harmonics. Somewhat surprisingly the relevant formulae are not available in the literature[1] though they can be derived by steepest descent evaluation of a suitable integral representation. We have been able to reproduce some of the numerical results of Chluba using our analytic formulae; see fig. The formulae are surprisingly simple and provide useful qualitative insights into the effects of boosting the CMB to the Earth's frame. Furthermore they are easy to generalize to the transformation of E and B modes.

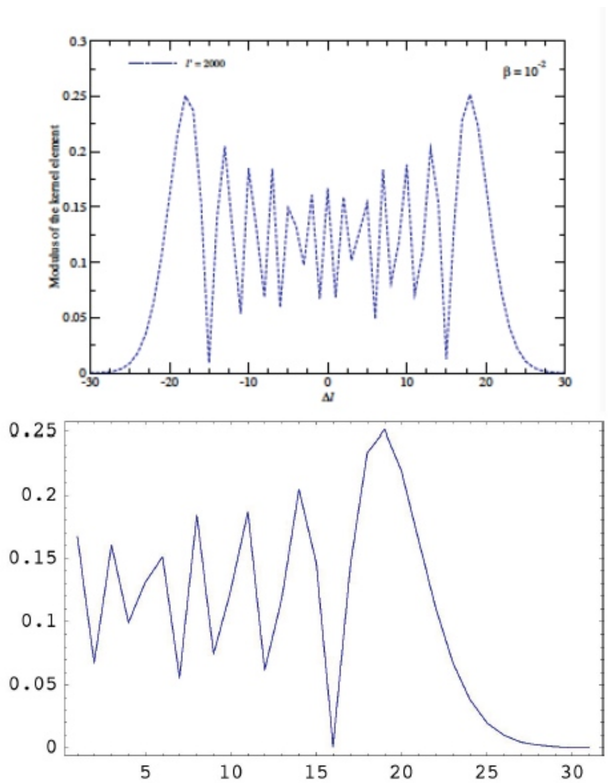


FIG. 1: Upper panel: Transformation kernel calculated by Chluba (M.N. R.A.S. **415**, 3227 (2011)); see figure 3 in that reference. Lower panel: The same quantity calculated analytically. The agreement is excellent. For more detailed information on the quantities plotted see Chluba.

I hope to complete this project in summer and write it up for publication in early fall.

## 5. *Muonic hydrogen*

Precision measurements of atomic systems are an important tool for the study of fundamental physics; see for example, J.J. Hudson, *et al.*, Nature **473**, 493 (2011) and Y. Enomoto *et al.*, Physical Review Letters **105**, 243401 (2010). The measurement and theoretical explanation of the Lamb shift in hydrogen was an important development in QED historically and it paved the way for the development of the standard model (S. Weinberg, *Quantum Theory of Fields*, vol 1(Oxford Univ Press, 1995)). A recent experiment that measured the Lamb shift in muonic hydrogen has found a significant anomaly (R. Pohl *et al.*, Nature **466**, 7303 (2010). A. Antognini, *et al.*, Science **339**, 417 (2013)). It is of great importance to determine whether the anomaly implies new physics beyond the standard model or whether it can be explained by a more careful treatment of conventional QED effects (reviewed for example by E. Borie, PRA **71**, 032508 (2005)). The latter is the object of our ongoing work.

A muon is only a factor of ten lighter than a proton and two hundred times heavier than an electron, so it seems a promising avenue to re-examine recoil effects. Recoil effects are treated within the Breit Hamiltonian in which the full bound state QED problem is reduced to a two particle wave equation for the proton and muon by integrating out the electromagnetic field oscillators, a procedure that is justified in the non-relativistic limit (a nice discussion is to be found in H. Bethe and E.E. Salpeter, *Quantum Mechanics of one and two electron atoms*, (Dover Books, 1977)). The Breit Hamiltonian incorporates leading relativistic effects such as the mass increase and spin-orbit coupling as well as tree-level QED effects such as magnetic dipole interactions between the muon and proton. Many of these effects take the form of contact interactions between the particles such as the relativistic Darwin term and the Foldy term which is a tree level QED effect. Although this is well worked terrain, there are important effects that appear to not have been calculated.

In particular the Breit Hamiltonian is usually simplified by an expansion in powers of $m/M$ where $M$ is the mass of the proton and $m$ of the secondary particle in the atom. Such an expansion is highly accurate for ordinary hydrogen but not for muonic hydrogen. We have solved the Breit Hamiltonian without making the expansion in powers of $m/M$ but so far only at the fine structure level not including hyperfine structure (tree level QED effects). Work is ongoing to include hyperfine effects. This appears to be a new effect. Another effect that does not seem to have been included is the effect of the intrinsic magnetic moment of the proton on the hyperfine terms in the Breit Hamiltonian. The conventional Breit Hamiltonian is derived from a QED model in which both electron and proton are treated as Dirac fermions minimally coupled to the electromagnetic field.

A better model is to include a Pauli coupling between the proton field and the electromagnetic field. Work on deriving the corresponding hyperfine terms in the Breit Hamiltonian is in progress.

Finally we plan to take into account the interplay between the recoil effect and the Lamb shift. In the literature relativistic effects are sometimes taken into account by working with a model in which the muon is described by the Dirac equation moving in a Uehling corrected Coulomb potential while the proton is treated as a fixed charge (E. Borie, *ibid.*). However we believe that it would be better to incorporate the Uehling perturbation in the Breit model in order to take into account corrections due to the motion of the proton.

This project was meant to be the thesis project for Scott Beck; hence it was on hold last year in anticipation of his leave of absence (see mentoring activities). It is expected that work on the project will resume this summer.

### *6. $\mathcal{PT}$ quantum mechanics*

It is a fundamental principle of quantum mechanics that the Hamiltonian must be hermitian. Bender and co-workers have explored whether one can relax this assumption and found that so long as the Hamiltonian has $\mathcal{PT}$ symmetry and this symmetry is not spontaneously broken one can still meaningfully formulate quantum mechanics based on such a non-hermitian Hamiltonian (C.M. Bender and S. Boettcher, PRL **80**, 5243 (1998); C.M. Bender, Rept. Prog. Phys. **70**, 947 (2007)). $\mathcal{PT}$ quantum mechanics promises to enlarge the set of Hamiltonians that could be used to study fundamental physics beyond the standard model. It is therefore of fundamental importance to develop the formalism of $\mathcal{PT}$ quantum mechanics and to seek realizations of it in nature. This is an exploration similar in spirit to the study of non-linear quantum mechanics (S. Weinberg, PRL **49**, 957 (1989); J.J. Bollinger *et al.* PRL **63**, 1031 (1989)).

In earlier work we pointed out that quantum systems fall into two classes with regard to time reversal symmetry $\mathcal{T}$: those for which $\mathcal{T}^2 = +1$ (even) and those for which $\mathcal{T}^2 = -1$ (odd). Only the even case had been previously studied in the literature. In our paper we developed the formalism for odd time reversal systems (Katherine Jones-Smith and Harsh Mathur, PRA **82**, 042101 (2010)). More recently we have constructed an exceptionally simple example of $\mathcal{PT}$ quantum mechanics, namely, a particle in a box. Prior work in $\mathcal{PT}$ quantum mechanics has considered Hamiltonians in which the potential is imaginary. Here we stayed with the usual Hermitian particle in a box Hamiltonian and instead imposed boundary conditions that were non-hermitian but $\mathcal{PT}$ symmetric (A. Dasarathy, J.P. Isaacson, K. Jones-Smith, J. Tabachnik and H. Mathur, PRA **87**, 062111

(2013)). This work was carried out in collaboration with an exceptionally talented high school student as well as two undergraduates.

In future work it would be highly desirable to identify unambiguous signatures that distinguish $\mathcal{PT}$ quantum mechanics from conventional hermitian quantum mechanics, much like the signatures of non-linear quantum mechanics identified by Weinberg (S. Weinberg,*ibid*), and in particular to explore potential applications of $\mathcal{PT}$ quantum mechanics to elementary particle physics.

### *7. Mentoring activities*

During the last calendar year I served as thesis co-advisor to Scott Beck along with Starkman. At the start of fall semester Beck determined that he wanted to take a semester's leave of absence. As a result his thesis project on muonic hydrogen went on the back burner and completion of his starter project on MOND gravity (described above) has been delayed till this summer when he has returned to our program.

My former graduate student Katherine Jones-Smith has moved from a postdoctoral position at Washington University at St Louis to visiting teaching appointments at Reed College and Oberlin college. Building on this experience she intends to look for a tenure track position at a liberal arts college with a commitment to research at which she can pursue a teaching and research career. As a result of her return to the Cleveland vicinity we have been able to move some of our joint projects forward (as described above) including a long delayed resubmission of a manuscript under review (K. Jones-Smith and H. Mathur, *Relativistic Non-Hermitan Quantum Mechanics* (resubmitted to PRL)).

I supervised summer research by an exceptionally talented high school student Anirudh Dasarathy for summer 2011 and 2012. The summer research resulted in a publication in Physical Review cited above. Dasarathy was also a National Semi-finalist in the Intel and Siemens competitions and at the International Intel Science Fair he won a grand prize that included a trip to CERN. An undergraduate I mentored, Jason Tabachnik, also a co-author on the same paper, won the prestigious Goldwater scholarship in 2012 and the Gates-Cambridge fellowship this year.

## A. Papers Published and Posted/Submitted 2010-13

1. **Probing the Gravitational Wave Signature from Cosmic Phase Transitions at Different Scales**, L.M. Krauss, K. Jones-Smith, H. Mathur and J. Dent, Phys. Rev. **D82**,

044001 (2010).

2. **Aharonov-Bohm radiation** K. Jones-Smith, H. Mathur and T. Vachaspati, Phys. Rev. **D81**, 043503 (2010).

3. **Aharonov-Bohm radiation of fermions**, Y-Z. Chu, H. Mathur and T. Vachaspati, Phys. Rev. **D82**, 063515 (2010).

4. **Non-Hermitian Quantum Hamiltonians with PT-symmetry**, Katherine Jones-Smith and Harsh Mathur, Phys. Rev. **A82**, 042101 (2010).

5. **Particle in a box in PT-symmetric quantum mechanics and an electromagnetic analog**, A. Dasarathy, J.P. Isaacson, K. Jones-Smith, J. Tabachnik and H. Mathur, Phys. Rev. **A87**, 062111 (2013).

6. **Relativistic Non-Hermitan Quantum Mechanics** K. Jones-Smith and H. Mathur, (re-submitted to Phys. Rev. Lett.)

### B. Select Talks and Conferences, 2010-13

1. March 2010, Seminar at University of Illinois, Urbana-Champaign.

2. Sept 2010, Seminar at Case Western Reserve University.

3. May 2011, Colloquium at Ohio University, Athens, Ohio.

4. Oct 2011, Colloquium at Oberlin College, Ohio.

5. Sept 2012, Colloquium at Kenyon College, Ohio.

6. Invited participant in workshop on "Unsolved Problems of Gravity", Arizona State University, Jan 18-20, 2010.

7. Participant, "Gravity Workshop at CWRU", May 10-12, 2011.

### C. Public lectures and outreach

1. Origins Science Scholars, CWRU, April 5 and 12, 2011.

2. Institute for the Science of Origins, "Life, the Universe and Hot Dogs" series, July 2012.

## IV. POSTDOC SCHOLAR: ERIC GREENWOOD

In addition to work carried out in collaboration with P.I. Starkman, Dr. Greenwood did considerable work independently, especially carrying on the line of research of his PhD thesis.

In Phys.Lett. B692 (2010) 226-231, Greenwood, together with D. C. Dai and D. Stojkovic (SUNY Buffalo) study the evolution of time-dependent fluctuations and particle production in an expanding dS and contracting AdS universe. Using the functional Schrodinger formalism they are able to probe the time dependent regime which is out of the reach of the standard approximations like the Bogolyubov method. In both cases, the evolution of fluctuations is governed by the harmonic oscillator equation with time dependent frequency. In the case of an expanding dS universe they explicitly show that the frequency of fluctuations produced at a certain moment diminish in time, while the distribution of the created particles quickly approaches the thermal radiation of the dS space. In the case of a contracting AdS universe they show that the frequency of fluctuations produced at a certain moment grow in time. Nominally, the temperature of radiation diverges as the Big Crunch is approaching, however, increasing oscillations of the spectrum make the temperature poorly defined, which is in agreement with the fact that AdS space does not have an event horizon which would cause thermal radiation. Unlimited growth of fluctuations indicates that an eventual tunneling into AdS vacuum would have catastrophic consequences for our universe.

Dr. Greenwood produced several other manuscripts which he was unsuccessful at publishing to our knowledge: arXiv:1001.1990 “Quantum Mechanical Effects in Gravitational Collapse;” arXiv:1002.2433 “Time Evolution of Entropy of a Charged Domain Wall during Gravitational Collapse;” and arXiv:1011.5881 “Gravity waves from the non-renormalizable Electroweak Vacua phase transition .”

### A. Papers Published independently 2010-13 while at CWRU

1. **“Time dependent fluctuations and particle production in cosmological de Sitter and anti-de Sitter spaces,”** E. Greenwood, D. C. Dai and D. Stojkovic, Phys. Lett. B **692**, 226 (2010)

## V. POSTDOC SCHOLAR: DMITRY PODOLSKY

In addition to work carried out in collaboration with P.I. Starkman, Dr. Podolsky invested considerable independent effort in arXiv:1003.3670, which unfortunately has yet to be accepted for publication. Interacting quantum scalar field theories in $dS_D \times M_d$ spacetime can be reduced to Euclidean field theories in $M_d$ space in the vicinity of $I_+$ infinity of $dS_D$ spacetime. Using this non-perturbative mapping, Podolsky analyzed the critical behavior of Euclidean $\lambda\phi^4_4$ theory in the symmetric phase and found the asymptotic behavior $\beta(\lambda) \sim \lambda$ of the beta function at strong coupling. Scaling violating contributions to the beta function were also estimated in this regime.

### A. Papers Published/Posted 2010-13 while at CWRU

1. **"On Triviality of $\lambda\phi^4$ Quantum Field Theory in Four Dimensions,"** D. I. Podolsky, arXiv:1003.3670 [hep-th].

## VI. PHD. STUDENT: YI-FUNG NG

In addition to work carried out in collaboration with P.I. Starkman, Yi-Fung Ng, in collaboration with L. Pogosian (Simon Fraser U.), A.P.S. Yadav (Princeton, Inst. Advanced Study), and T. Vachaspati (Arizona State U.) published Phys.Rev. D84 (2011) 043530 (and Erratum-ibid. D84 (2011) 089903 ) "Primordial Magnetism in the CMB: Exact Treatment of Faraday Rotation and WMAP7 Bounds." Faraday rotation induced B-modes can provide a distinctive signature of primordial magnetic fields because of their characteristic frequency dependence and because they are only weakly damped on small scales, allowing them to dominate B-modes from other sources. By numerically solving the full CMB radiative transport equations, the authors studied the B-mode power spectrum induced by stochastic magnetic fields that have significant power on scales smaller than the thickness of the last scattering surface. Constraints on the magnetic field energy density and inertial scale were derived from WMAP 7-year data, and are stronger than the big bang nucleosynthesis (BBN) bound for a range of parameters. Observations of the CMB polarization at smaller angular scales are crucial to provide tighter constraints or a detection.

### A. Papers Published 2010-13

1. **"Primordial Magnetism in the CMB: Exact Treatment of Faraday Rotation and WMAP7 Bounds,"** L. Pogosian, A. P. S. Yadav, Y. -F. Ng and T. Vachaspati, Phys. Rev. D **84**, 043530 (2011) [Erratum-ibid. D **84**, 089903 (2011)].

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[1] to be precise we are interested in the large $\ell$ asymptotics of $Y_{\ell,m}$ in the limit that $\ell \to \infty$ but with the ratio $m/\ell$ fixed.