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Physics Beyond the Standard Model in the Early Universe

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The Standard Model is in agreement with all confirmed experimental data, despite numerous searches for new physics. Since any extension of the Standard Model will produce observable effects in the early universe, it is possible that new physics could be found in the properties of the present Universe. The focus of this proposal is on dark matter and dark energy, which together account for approximately 96 % of the energy density of the Universe, and on theories of extra dimensions which appear to solve many other problems in particle physics and cosmology.

We intend to explore new models of dark matter and dark energy, as well as new methods of detecting dark matter. In particular we examine the possibility of detecting dark matter in rare decays of kaons and B-mesons. The result is that collider data can be used to probe for dark matter lighter than $\sim 2\ GeV$, where dedicated underground searched have very little sensitivity. We intend to further explore low mass dark matter, and other models of new physics, using measurements of the gamma ray spectrum and the abundance of nuclei in the Universe. We also propose to further develop theories of extra dimensions by exploring new models, and by constructing conditions under which these models can form, be self consistent, and remain stable.

Contents

I. INTRODUCTION

For nearly three decades the Standard Model has successfully described high energy physics and been consistent with experimental data. Experiments have confirmed the existence of several particles, and made precise measurements of the fundamental parameters, but there have been few indications of new physics.

However there are many significant problems in physics which the Standard Model cannot explain. Measurements from the WMAP satellite suggest that 73% of the Universe is an unknown form of energy with negative pressure (the dark energy problem) while a further 23 % is some new type of electrically neutral matter (the dark matter problem). The Standard Model also fails to explain why gravity is fifteen orders of magnitude weaker than the electroweak scale (the hierarchy problem), why there appear to be three generations of particles, and many other more technical problems.

There are many theories which claim to solve these problems, as well as other problems in cosmology, but as yet they have not been detected in experiments. It is possible that the next generation of collider experiments will detect some effects of new physics, but economical and technological constraints limit the energies that can be probed directly.

As an alternative, the early universe can act as a probe of new physics. In the first few seconds after the big bang, the universe was filled with ultra-high energy particles and fields. Any extension of the Standard Model should have an effect on the evolution of Universe in this era. It is possible that the new particles are unstable making the theory difficult to probe. However it is also possible that they lead to observable effects, such as peaks in the background gamma-ray spectrum or distortions of the prediction of Big Bang nucleosynthesis.

In this proposal we focus on two groups of models. In Section II we review the problem of dark matter, and outline methods of detecting particle candidates. In particular we show how rare decays of heavy particles, such as the B-meson, can produce dark matter, and propose nongravitational detection of different particle candidates. In Section II B we review the more recent confirmation of missing energy, and the related problems of explaining the extraordinarily small cosmological constant and the naturalness of such a constant. It is possible that the dark energy problem can be solved using models similar to those we intend to explore as dark matter candidates. It is also known that the dark energy problem can be resolved in some models with large extra dimensions. In Section III, we outline the restrictions on new physics arising from the luminous matter, with a focus on how such matter is altered by the existence of flat extra dimensions. In this section we also address the currently unexplained flux of 511 keV gamma rays from the galactic center, and develop constraints that could be placed on dark matter models and extra dimensional models as a result. In Section IV we review the motivation for introducing extra dimensions, and propose methods of searching for their signatures. Although no signatures have yet been detected, measurements from astrophysics and cosmology restrict the size and properties of extra dimensions. We also outline the potential problems in these models, and propose some possible solutions.

II. DARK MATTER

One of the leading problems in astrophysics and cosmology today is the missing mass of the Universe. The observable matter in the Universe, such as in stars and nebulae, accounts for less than 5 % of the energy density of the Universe [1]. The remaining matter in the Universe, which accounts for 23 % of its energy density, is believed to be a new form of matter beyond the Standard Model.

The most general method of observing dark matter is through its gravitational effects. These experiments can accurately measure the amount of dark matter, but due to the relative weakness of gravity are ineffective for measuring other properties. Therefore we cannot construct a model of dark matter based on gravitational experiments alone.

Given the number of proposed candidates for dark matter, it is not possible to review all models. However there are four types of dark matter which are the subject of the majority of the literature:

- *Axions*: One of the problems with quantum chromodynamics is the prediction of CP violation in strong effects, while none are observed. The solution requires introducing a new particle, known as the axion, which has the correct properties to also explain dark matter. However limits from astrophysics and other searches restrict the mass of the axion, and result in large regions of parameter space being excluded.

- *Sterile Neutrinos*: A third candidate for dark matter is a new type of neutrino. However unlike the three known neutrinos, this neutrino can not interact through any of the usual forces, suggesting that it is a singlet state. The only allowed decay is through a weak mixing with the other neutrinos, and thus sterile neutrinos could survive from the early universe and be present in a large abundance today. The existence of sterile neutrinos is also well motivated in electroweak theories and grand unified theories. If the right handed neutrinos have a large mass, then the small masses of the left handed neutrinos can be explained.

- *WIMPs*: The most general model introduces a massive particle which has weak interactions. Such a particle would necessarily be produced in the early universe but would have a lifetime comparable or greater than the age of the Universe. As such it is expected that if they exist the Universe will have a high abundance of WIMPs, and if they also have sufficient mass could explain the missing matter.
- *Neutralinos*: Most of the current research has focused on the WIMPs which are predicted by supersymmetry. Originally motivated by problems in particle physics, supersymmetry requires that each known particle have a partner which by experimental constraints must be significantly heavier. The lightest supersymmetric particle is required to be stable, and if it is also neutral then a large abundance of such particles could account for the missing matter.

Axions, sterile neutrinos, and supersymmetric neutralinos are each predicted by other theories unrelated to the dark matter problem, and as such have been the focus of the majority of the literature. However it is also possible that dark matter is composed of some particle or mechanism which is not motivated by other theories. For this reason we believe that it is important to investigate several different models and to focus on general methods of searching for dark matter rather than searches for one specific type.

In particular we will study two classes of dark matter:

- The simplest model of dark matter consists of adding a single scalar field with a generic higgs interaction to the Standard Model. Such a model was proposed by Silveira and Zee [2], and later modified by Veltman and Yndurain [3], while complex scalars were used by McDonald [4]. Similar models can be constructed using multiple scalar fields.

- Another simple model of dark matter consists of a scalar field which has no interactions with other particles, except through gravity. A model with strongly warped extra dimensions could also generate a strong gravitational effect, and therefore produce a significant abundance of scalars. By comparison with the observed abundance of dark matter , the mass of the particle can be predicted. Similar models can be constructed using fermions and vector fields. In particular we propose to consider particles in a 5D Randall-Sundrum model [5], as the gravitational interactions of such a particle are well known [6], and in more general models.

Models of dark matter have tended to place a lower limit of $\sim 10GeV$ on the mass of the candidate to prevent an overabundance of dark matter in the Universe [7]. However this limit is very model dependent. It has been shown that models with light scalar dark matter can produce the observed abundance [8] and may explain other observations as well [9]. In particular dark matter with a mass in the range of 10 MeV - 1 GeV has not been well explored, and we therefore intend to study such models.

It is also possible to detect some forms of dark matter by measuring scattering off of nuclei. The CDMS and DAMA experiments have generated an upper bound on the WIMP-nucleon scattering cross section [10–12], however for a light particle ($M_{DM} \lesssim 10GeV$) the bounds are quite weak and therefore light WIMPs could exist. The DAMA collaboration has further claimed to have detected a dark matter signature [13] consistent with a neutralino at $m_{DM} \approx 60GeV$. Although this result has been disputed by other experiments, there are still regions of parameter space in which a WIMP can be consistent with the DAMA result while producing null results in other detectors.

We intend to develop new methods of searching for dark matter signatures. As will be shown in the following sections, we can probe for dark matter in the rare decays of heavy particles, and in astrophysical observations such as the 511 keV gamma ray flux.

A. Rare Decays as a Probe of Dark Matter

It is also possible that light dark matter could be observed in the decays of other particles. Recently we have shown that a light scalar would increase the decay width for invisible decays of kaons and B-mesons [14]. More precise measurements of these decays and the decays of heavier particles will make it possible to probe higher masses.

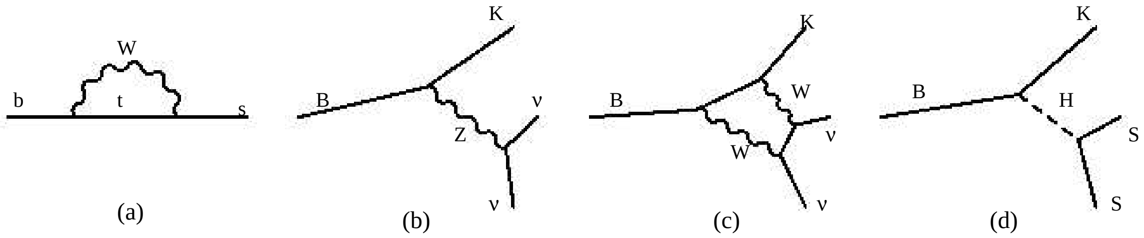

FIG. 1: Contributions to invisible decays of the B meson.

A scalar model will introduce at minimum three new parameters which must be measured experimentally, although some may be unimportant in studying dark matter. The model we considered is the minimal model [15],

$$L = L_{SM} + \frac{1}{2}\partial_\mu S \partial^\mu S - \frac{m_S^2}{2}S^2 - \frac{\lambda_S}{4}S^4 - \lambda v_{EW} S^2 H - \frac{\lambda}{2}S^2 H^2 \tag{1}$$

where H is the Higgs field, and S is a scalar field.

In the early Universe, the scalars will be produced (and annihilated) until the temperature drops below the freeze out temperature. At this point the Universe is expanding too fast for the scalars to interact. The abundance of dark matter has been measured [1]

$$\Omega_{DM} h^2 = 0.13$$

and using standard methods [16] can be used to relate the mass and thermally averaged annihilation cross section,

$$< \sigma v_{rel}/c > \approx 0.7\, pb \tag{2}$$

which can then be used to relate the mass and coupling constants.

In the minimal model [15], the partial width for the decay $B \to KSS$ is large enough to be measured at BaBar and CLEO. Using the published bounds on the decay width for $B \to K +$ *missing energy* [17, 18], the ranges

$$m_S < 430 MeV \qquad 510 MeV < m_S < 1.1 GeV$$

are excluded, while the range

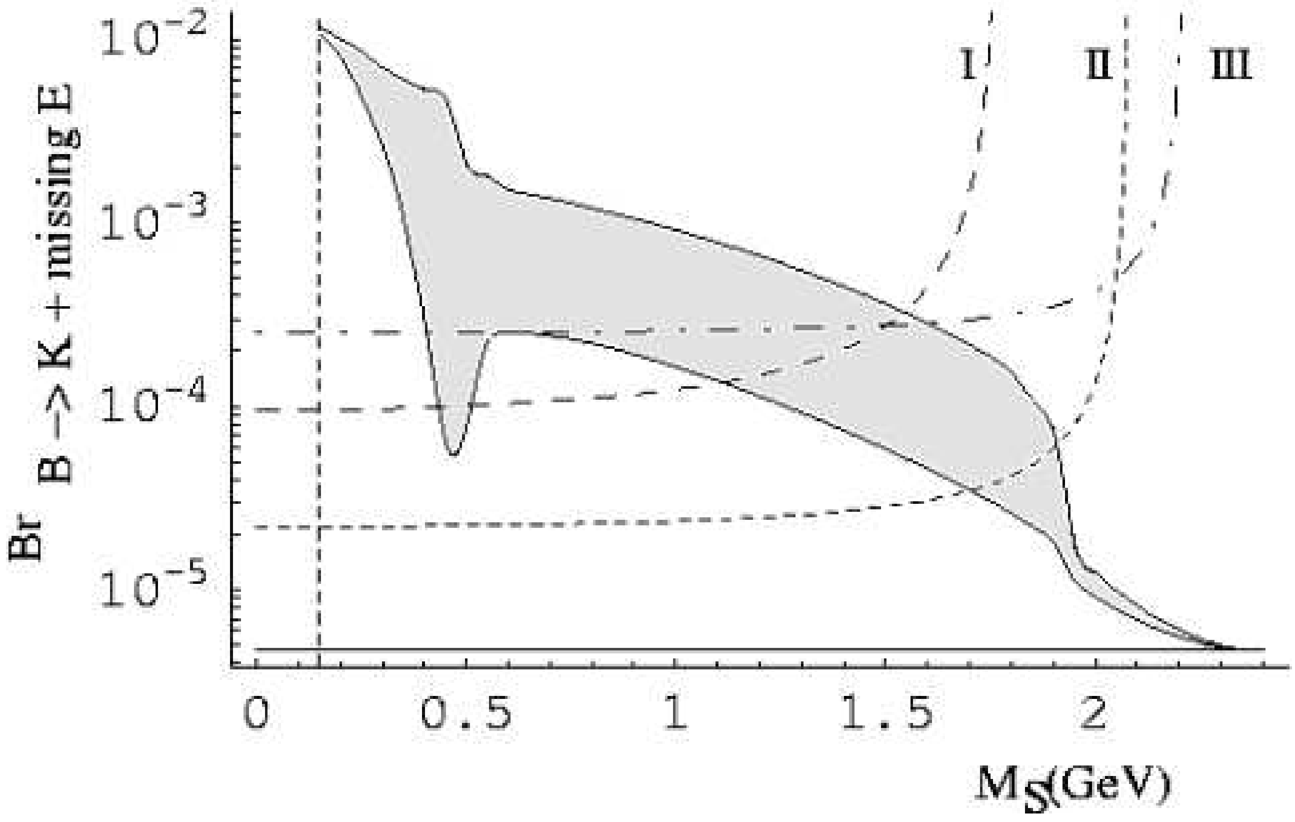

FIG. 2: Predicted branching ratios for the decay $B \to K+$ *missing energy* with dark matter (shaded region) and with only SM neutrinos (solid line). Current limits from Babar (I), CLEO (III) and predicted results from BaBar (II) are also indicated. Masses less than $\sim 150\ MeV$ are excluded by kaon decays.

$$m_S < 1.5 GeV$$

can be probed. It is expected that future results from BaBar will extend the excluded range to 1.7 GeV, with the potential to probe as high as 2 GeV.

This model can also be extended to use a complex scalar, (or N scalar fields) in which case the $m_S < 1.5GeV$ is excluded while for large N models can be probed up to $m_S \approx 2.1GeV$. The model can also be expanded to include multiple Higgs fields or other bosons.

Another model which I intend to consider is a noninteracting particles in a strongly warped background. Such particles could also be produced in the decays of heavy particles as suggested before. However the current experiments can only probe the range $m_S \lesssim 5GeV$ while limits on the radion mass from other experiments require $m_S \gtrsim 30GeV$.

B. Dark Energy

The same experiments that measured the abundance of dark matter also suggest that the remaining 73% of the energy density has negative pressure which immediately excludes all known forms of matter. In 1998 measurements of supernovae revealed that the Universe is not only expanding, but is accelerating [19–21] as a result. Of greater importance is that this new form of energy appears to permeate the Universe, with no observable clustering.

The data suggests that this dark energy is the result of a small cosmological constant, though exotic forms of matter have not been excluded [22–24]. As with the dark matter problem, new methods of searching for such exotic matter will be required.

The existence of a cosmological constant leads to other problems. This constant must be extremely small,

$$\rho_{DE} \approx 4\ keV/cm^3 \approx (2.5 \times 10^{-3} eV)^4$$

but still non-zero [25]. It is also unclear why the density of dark energy should be of the same order of magnitude as the matter density, as the former remains constant in time while the latter does not. Neither problem can be adequately resolved using current theories. However the dark energy problem and the dark matter problem are related, and as such the models of dark matter we intend to study will also be investigated for contributions to dark energy, which could lead to further constraints on such models.

It has also been shown that extra dimensions have an effect on the observed dark energy. Models with extra dimensions can lead to similiar effects without introducing a new form of energy [26], and can also introduce a low energy cutoff. It is also possible to develop higher dimensional models in which the cosmological constant is naturally small [27, 28].

III. PROBING EXOTIC PHYSICS IN THE LUMINOUS UNIVERSE

Despite representing less than 5% of the energy in the Universe, the luminous matter is still important in the search for new physics. The standard cosmology and nucleosynthesis can explain most current data, and as such any new theory must have a sufficiently small effect on the observed Universe.

The Universe contains a gamma ray background which has been measured in several experiments. If there are new particles which can decay to high energy photons, then this background will be altered. For example, in models with extra dimensions Kaluza-Klein gravitons will be produced in the early Universe, with a lifetime

$$\tau \approx 10^5 \text{ sec} \left(\frac{1 \text{ TeV}}{m_{KK}}\right)^3 \tag{3}$$

which has almost no model dependence. The light modes, with $m_{KK} \lesssim 10GeV$, will decay after the gamma ray background has already formed. Since these modes can decay to gamma rays, a large abundance of KK modes would be observable as an increase in the background. Using the measurements from EGRET and COMPTEL, and upper limit on the size of extra dimensions was calculated [29], and the results are given below.

		$d = 2$	$d = 3$	$d = 4$	$d = 5$	$d = 6$
γ-rays	M_*	167 TeV	21.7 TeV	4.75 TeV	1.55 TeV	< 1 TeV†
	R	0.022 μm	2.5×10^{-5} μm	1.1×10^{-6} μm	1.7×10^{-7} μm	$> 2.9 \times 10^{-8}$ μm
neutron stars	M_*	3930 TeV	146 TeV	16.1 TeV	3.4 TeV	1 TeV
	R	4.1×10^{-5} μm	1.1×10^{-6} μm	1.7×10^{-7} μm	5.7×10^{-8} μm	2.9×10^{-8} μm

Another probe of new physics is the observed flux of $\sim$ 511 keV photons which originates in the galactic center [30, 31] . These photons appear to come from a nonlocalized source, and do not have a clear explanation in astrophysics or the Standard Model. It has been suggested that these gamma rays may be the result of dark matter annihilations, in which case the dark matter mass must between 1 MeV and 100 MeV [9]. These measurements have also been used to further constrain models of sterile neutrinos and other relics [32]. We intend to extend this work to include constraints on extra dimensions and unstable KK modes, and use both the gamma ray background and the $511keV$ flux to constrain low mass dark matter candidates.

Another probe of new physics is the abundance of light nuclei in the Universe. The observed abundance can be explained reasonably well using the Standard Model and Big Bang nucleosynthesis. However the abundances are sensitive to new physics. A heavy relic particle will lower the abundances of light elements, with the most stringent bounds on the relic abundance arising from obserations of the ^{6}Li abundance, while quasi-stable particles could dissociate nuclei leading to different relative abundances.

The effects of extra dimensions can also alter the abundance of nuclei. It is common for models of the early universe to include a period of inflation, which is generated by a massive scalar field referred to as the inflaton. The decays of the inflatons produce KK modes, and those modes with lifetimes longer than $\sim 10^8 s$ will dissociate nuclei. As the abundance of nuclei is already well explained by Big Bang nucleosynthesis, a large abundance of KK modes can be ruled out. Using this constraint on the abundance of KK modes, we were able to determine the maximum size of the dimensions [33]. The current lower bounds on the reduced Planck mass and upper bounds on the size of the dimensions, as a function of the number of dimensions and inflaton mass, are given below.

m_ϕ	$d = 2$	$d = 3$	$d = 4$	$d = 5$	$d = 6$
1 TeV	35 TeV $0.52\mu m$	13 TeV $6.0 \times 10^{-5}\mu m$	7.1 TeV $5.9 \times 10^{-7}\mu m$	4.5 TeV $3.9 \times 10^{-8}\mu m$	2.8 TeV $7.4 \times 10^{-9}\mu m$
2 TeV	47 TeV $0.29\mu m$	17 TeV $3.8 \times 10^{-5}\mu m$	9.1 TeV $4.1 \times 10^{-7}\mu m$	5.7 TeV $2.8 \times 10^{-8}\mu m$	3.4 TeV $5.7 \times 10^{-9}\mu m$
M_*	220 TeV $0.013\mu m$	42 TeV $8.5 \times 10^{-6}\mu m$	15 TeV $1.9 \times 10^{-7}\mu m$	7.9 TeV $1.8 \times 10^{-8}\mu m$	4.0 TeV $4.6 \times 10^{-9}\mu m$

In addition to fundamental particles, macroscopic objects in the Universe can also provide a probe of new physics. For example, it is expected that neutron stars will produce a flux of KK modes, which then decay to photons. This results in a flux of gamma rays from neutron stars, which could be observed by future experiments, and a flux of gamma rays towards the star, which will reheat it. Both of these effects have been used to constrain the size of the flat extra dimensions [34]. We expect to be able to use similar methods to also constrain other models with extra dimensions, and models which introduce new particles.

IV. EXTRA DIMENSIONS

Higher dimensional geometries have been studied in mathematics for centuries. The first serious applications to physics were in 1915 with the four dimensional theory of general relativity, and later in the 5D and 6D theories of Nordstrom [35],Kaluza [36] and Klein [37]. Interest in higher dimension theories waned until the 1970's when it was discovered that certain theories of quantum gravity were only consistent in 10D.

Interest in higher dimensional theories exploded in 1998 with the discovery that they may solve several problems in the Standard Model. The main result is the discovery that if all of the fields in the Standard Model are trapped on either a small region of the extra dimensions [38], or on a three dimensional membrane [39, 40], with gravity acting in all dimensions then the strength of gravity can be comparable to the strength of the other forces. Furthermore, the extra dimensions can be as large as $R \backsim 1mm$ and could be detected in modern gravity experiments. Later models also claim to predict the fermion hierarchy [41, 42], effects of dark matter and dark energy, inflation [43, 44], and nonsingular alternatives to inflation [45]. As outlined in Section II B, models with two or more extra dimensions can also generate a small cosmological constant in agreement with observation.

It is still unclear which model is correct. Many of the models are known to be unstable with respect to small perturbations. However each model produces distinct phenomena which should be observable. The most common models are given below.

- *Universal Extra Dimensions*: The original models of extra dimensions allowed all fields to exist in all dimensions. However constraints from collider experiments restrict $R \lesssim 10^{-16} cm$. Therefore the gravitational effects cannot be measured in experiments.

  There has been a renewed interest in universal extra dimensions recently to explain the three generations of the Standard Model [41, 42], dark matter [46, 47], as well as neutrino masses and possible proton decay [48].

- *Nonwarped Braneworld*: The simplest models of large extra dimensions are those which contain no warping and in which the Standard Model fields are confined to a three dimensional brane, in particular models in which the extra dimensions are compactified as a d-dimensional torus. However any function defined on a torus must satisfy periodicity constraints,and as a result the fields can be written in terms of discrete modes each of which satisfy the equations of motion for either a spin-2 particle (the graviton), a vector field (graviphotons) or a scalar (radions or graviscalars) [49]. These are known as the Kaluza-Klein modes [1], and should be observable as particles with integer masses

$$m_{\vec{n}}^2 = m_0^2 + \frac{\vec{n}^2}{R^2}$$

where $\vec{n}$ is a set of d integers. Nonwarped brane models also solve the hierarchy problem by introducing a reduced Planck mass of order 1 TeV, which is related to the 4D Planck mass by

$$M_*^{d+2} = M_{PL}^2 / R^d$$

- *Randall-Sundrum Model*: One of the most popular model of extra dimensions is the Randall Sundrum model [39], in which there exists a single extra dimension, assumed to be warped, and all traditional matter is confined to a three dimensional brane. The metric for this model is

  $$ds^2 = e^{-2k\phi(x^\mu)|y|}\eta_{\mu\nu}dx^\mu dx^\nu - \phi(x^\mu)^2 dy^2$$

  The scale of the extra dimension, denoted by $\phi(x^\mu)$, has the same properties as a traditional scalar field (called the radion) which exists only on the brane.

  The main strength of this model is as a solution of the hierarchy problem. The strength of gravity is proportional to $1/M_{PL}^2$, where $M_{PL} \approx 1.2 * 10^{19}\ GeV$ is the Planck mass. This makes gravity far weaker than any other force in nature, and leads to other problems in the Standard Model. However in the Randall-Sundrum model, the observed Planck mass is related to the actual Planck mass by [2]

  $$M_{PL} \approx M_* e^{kr_c\pi} \tag{4}$$

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[1] Such particles are expected to be observed in any model of compact extra dimensions, though the mass spectrum is model dependent.

[2] It is also common to assume that the electroweak scale is $M_{EW} \sim M_{PL}$, and that the observed scale is $M_{EW}e^{-kr_c\pi}$

where $r_c \equiv < \phi >$. The 5D Planck mass can be of order 1 TeV, and reproduce the observed Planck mass.

There are numerous other models, many of which are not well explored. We intend to develop several new models, with the goal of constructing a submanifold which is at least quasi-stable, and which forms naturally without requiring significant fine-tuning of the parameters.

1. Stability

The most important test of extra-dimensional models is stability. If the theory contains a scale factor (or radion field in the Kaluza-Klein formalism) which is unstable, then it will either collapse to zero and not have observable effects, or it will expand and be observable in gravity experiments.

The problem of stability is worsened by the effects of Casimir energies. When a dimension is compactified, the vacuum energy becomes dependent on its length. The result is that nature seeks to minimize this energy and the size of the dimension becomes even more unstable.

The simplest method of creating stability is to add additional fields. The most common example is the Goldberger-Wise mechanism [50, 51], in which a single scalar field is added to the bulk[3]. This field has a simple potential on each brane, which generates an additional term in the radion effective potential that creates a stable minimum.

Although numerous stable models have been proposed, and stability conditions for specific types of models have been derived, there are currently no general rules to determine which models are stable. We propose to extend the conditions derived in [52], which consider the stability of the radion field in the class of 5D models with

$$ds^2 = a(t,y)^2(\eta_{\mu\nu}dx^\mu dx^\nu) - b(t)^2 dy^2$$

to include effects from radion-scalar mixing, the effects of multiple extra dimensions, and the stability of the scale factor $a(t,y)$. It may also be possible to generalize to space and time dependent radion fields $b(x_\mu, y)$ and general 4D metrics.

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[3] Although the original proposal requires a massive scalar, it may be possible to select a potential which can stabilize the model with massless fields or bulk tachyons.

Clearly the extra dimensions in these models cannot be observed in the same way we observe the usual three dimensions. Gravitational effects have been measured at distances below 1mm, and electromagnetic effects have been measured even more precisely. Every measurement has supported a four dimensional spacetime.

Therefore if extra dimensions exist, they must have very different properties. A successful model must include either a mechanism for compactifying or warping the extra dimensions, but not significantly altering 4D spacetime.

Long before the creation of brane models and renewed interest in extra dimensions, it was known that there were (4+d)-dimensional vacuum solutions of Einstein's equations which had the property that three spatial dimensions expand while the other d-dimensions contract [43]. Slight modifications of this model (with $d \geq 2$) lead to early universe inflation [44], which is required in most consistent models of cosmology. [4] Unfortunately such models are valid for any separation of dimensions, with similar solutions containing different numbers of infinite spatial dimensions.

It is possible that new models and mechanisms may produce a natural separation and compactification. In addition to developing new models of extra dimensions, we also intend to explore the evolution of such models in the early universe, with the goal of developing conditions under which the extra dimensions compactify.

Once a mechanism has been found which creates a compact subspace, there still may be problems with the resulting 4D effective cosmology. Many of these can be solved using inflationary models. Traditionally such models have required the addition of a scalar field and potential, known as the inflaton.

Recently it has been shown that required inflaton can be replaced with the radion predicted by extra dimensional models [53, 54], or by a bulk scalar [55] such as is required by the Goldberger-Wise stabilization. However it is also possible that in some models the radion, or other bulk fields, could cause the compact dimensions to inflate to an observable size. It is also possible that the same mechanism that stabilizes the submanifold in the present could prevent compactification. By using these effects, we believe it will be possible

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[4] Several of the popular models which do not include inflation still require extra dimensions (eg. [45])

to further restrict the properties of the extra dimensions.

3. Size & Topology

The size of the extra dimensions are also important yet unknown parameters of the various theories. The main restrictions are from gravity experiments [56], which indicate the dimensions must be compactified to be smaller than ~ 0.1 mm.[5]

There are also indirect restrictions on the specific models from astrophysical observations. As shown in Section III, any high energy process should produce KK modes which would lead to observable effects. Although such calculations usually assume that the extra dimensions form a torus whose dimensions are of equal size, there is no reason to assume that this is true. It is also possible to have different sizes for each dimension, or to have different topologies.

The predominant effects of different sizes and topologies are in the spectrum of excited KK modes. For example, a torus with different compactification radii in each dimension leads to the mass spectrum,

$$m_{\vec{n}} = \sum_{i=1}^{n} \frac{n_i^2}{R_i^2}$$

In this case the degeneracies in the spectrum are removed. Similar methods can be used to derive the KK spectrum for any submanifold. If the masses of several excited states could be measured, the size and geometry of the extra dimensions could be calculated. However this would require measurement of at least three nondegenerate excited states, which is only possible in models with universal extra dimensions and which would require colliders capable of producing at least twice the current energy. [6]

The other possible measurement would be from the gamma ray flux from neutron stars. If the energy distribution contains large peaks at regular intervals, (eg. $E_n \approx nE_0$), then these could correspond to KK decays and could be used to determine the sizes. Unfortunately the

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[5] There are more complicated theories in which the extra dimension can still be noncompact. However these require extreme warping which 'impedes' gravity.

[6] Even when several KK modes are observed, there would remain the possibility of additional dimensions whose compactification radii are smaller than the others.

next generation of gamma ray observatories are not expected to be capable of measuring ultra-high energy gamma rays and thus are unlikely to observe the KK decays.

The size and topology of the extra dimensions will also affect short range gravity experiments. However as with the search for KK modes, current experiments have been unable to measure any effects.

V. SUMMARY

It is clear that the Standard Model cannot describe all aspects of nature. Aside from the lack of a theory of quantum gravity, the Standard Model is also incapable of describing $\backsim$96 % of the energy content of the Universe. It cannot explain the large differences in the strengths of the four fundamental forces or the small cosmological constant. Terrestrial experiments have searched for new physics, but as yet have produced very few clear results.

We have shown in this proposal that it is possible to observe new physics by examining their effects in the early universe. During the first few minutes, the Universe was filled with high energy fields and processes and thus many new physical theories are expected to leave signatures. As the Universe cooled, some of these signatures may have remained and could be observed in the present.

There are many reasons and many theories that extend the Standard Model without contradicting any known experiments. The first deficiency in the Standard Model which was reviewed was the problem of dark matter. We and others have shown that in many general models of dark matter there would be detectable effects in both astrophysical and particle experiments. We also intend to further explore methods of searching for dark matter within current experiments, and to introduce several simple models which have very general properties.

The other extension reviewed was the possibility that our Universe has more than four dimensions. As with dark matter, models with extra dimensions solve many open problems in physics but remain unconfirmed. However they also have few constraints and are difficult to detect in experiments. As such our focus is on consistency requirements, such as stability of the extra dimensions and mechanisms which cause the dimensions to be compactified, and on signature left from the early Universe.

We have already published a calculation of the effects of flat extra dimensions on nucleosynthesis, with corresponding limits on the size of the extra dimensions [33]. We have also shown that models of light dark matter can be probed using B-meson and kaon decays in an article to be published in the near future [14]. In addition to these, we are currently working on the following projects:

1. *Limits on Extra Dimensions from the 511 keV γ-ray Flux*: If the center of the galaxy contains a gas of KK modes, then we would expect to observe their decays or annihilations through the resulting gamma rays. By comparing the predicted flux with observations, we can calculate the maximum size of extra dimensions.

2. *Dark Matter Models in a Warped Background*: A particle which contains only gravitational interactions could describe dark matter. The weakness of this interaction also results in a cross section for scattering off of nuclei which is smaller than the current bounds. If we assume that this particle accounts for the entire observed abundance, then we can restrict the mass of the particle. We have completed this calculation, using the Randall-Sundrum model as an example, and will be submitting a preprint soon.

3. *Stability of Extra Dimensions*: We intend to develop a set of general conditions under which a single warped extra dimension will be stable. It is our intention to then extend these conditions to include models with multiple dimensions, multiple branes, and a general set of bulk fields and interactions.

4. *Dark Matter in Meson Decays*: We plan to extend the use of B decays and kaon decays to probe other forms of light dark matter.

5. *Extra Dimensions and Inflation*: We intend to calculate the evolution of the size of extra dimensions during the inflation era. This naturally leads to conditions under which the extra dimensions can remain compact.

6. *Self-tuned Brane Models*: Brane models usually require tuning of their parameters. We are studying models in which different bulk fields and brane interactions can fix all of the parameters.

We expect to be able to complete the first two projects this year, while the other projects will be completed over the next two years.

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