Swampland Program, Extra Dimensions, and Supersymmetry Breaking

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Abstract

By combining swampland conjectures with observational data, it was recently suggested that the cosmological hierarchy problem (i.e. the smallness of the dark energy in Planck units) could be understood as an asymptotic limit in field space, corresponding to a decompactification of one extra (dark) dimension of a size in the micron range. In these Proceedings we examine the fundamental setting of this framework and discuss general aspects of the effective low energy theory inherited from properties of the overarching string theory. We then explore some novel phenomenology encompassing the dark dimension by looking at potential dark matter candidates, decoding neutrino masses, and digging into new cosmological phenomena.

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1. INTRODUCTION

The challenge for a fundamental theory of nature is to describe both particle physics and cosmology. Accelerator experiments and cosmological observations provide complementary information to constrain the same theory. We have long known that only about 4% of the content of the universe is ordinary baryonic matter; the remainder is dark matter ($\sim 22\%$) and dark energy ($\sim 74\%$). The ΛCDM model, in which the expansion of the universe today is dominated by the cosmological constant Λ and cold dark matter (CDM), is the simplest model that provides a reasonably good account of all astronomical and cosmological observations

The cosmological evolution is described by Einstein's equation,

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R + g_{\mu\nu}\Lambda = \frac{8\pi G}{c^4} T_{\mu\nu}\,, \tag{1}$$

where $R_{\mu\nu}$ and R are respectively the Ricci tensor and scalar, $g_{\mu\nu}$ is the metric tensor, $T_{\mu\nu}$ is the energy momentum tensor, and $G = 1/(8\pi M_p^2)$ is Newton's gravitational constant. The cosmological constant encapsulates two length scales: the size of the observable Universe $[\Lambda] = L^{-2}$ and of the dark energy $[\Lambda/G \times c^3/\hbar] = L^{-4}$. The observed value of the cosmological constant $\Lambda_{\rm obs} \simeq 0.74 \times 3H_0^2/c^2 \simeq 1.4 \times (10^{26}\ {\rm m})^{-2}$ gives a characteristic length of dark energy $\simeq 85\ \mu$m, where we have adopted the recent measurement of the Hubble constant $H_0 \simeq 73$ km/s/Mpc by the HST + SH0ES team

At currently achievable collider center-of-mass energies $\sqrt{s} \sim 14$ TeV or, equivalently, at distance scales $< 10^{-21}$ m, the Standard Model (SM) of strong and electroweak interactions, amended with appropriate neutrino masses, provides a successful and predictive theoretical description of all available data

A way to connect these hierarchies between particle physics and cosmology is via the size of extra dimensions which are necessary ingredients for consistency of string theory

In these Proceedings we summarize the state-of-the-art in this subject area, and discuss future research directions.

2. FOUNDATIONS OF THE DARK DIMENSION

The Swampland program seeks to understand which are the "good" low-energy EFTs that can couple to gravity consistently (e.g. the landscape of superstring theory vacua) and distinguish them from the "bad" ones that cannot

For example, the distance conjecture (DC) forecasts the appearance of infinite towers of states that become exponentially light and trigger the collapse of the EFT at infinite distance limits in moduli space

As demonstrated in

It is of course interesting to explore whether there is a relation between the supersymmetry (SUSY) breaking scale and the measured value of the dark energy density Λ. Such a relation can be derived by combining two quantum gravity consistency swampland constraints, which tie Λ and the gravitino mass $M_{3/2}$, to the mass scale of a light KK tower and, therefore, to the UV cut-off of the EFT

Possible string theory and effective supergravity realizations of the dark dimension scenario with broken supersymmetry are discussed in

3. DARK MATTER CANDIDATES

After the big bang, the cosmological energy density scales with time t as $\rho \sim 1/(Gt^2)$ and the density needed for a region of mass $M_{\rm BH}$ to collapse within its Schwarzschild radius is $\rho \sim c^6/(G^3 M_{\rm BH}^2)$, that being so primordial black holes (PBHs) would initially have around the cosmological horizon mass

It has long been known that microscopic black holes – with Schwarzschild radii smaller than the size of the dark dimension – are quite different: they are bigger, colder, and longer-lived than a usual four-dimensional (4D) black hole of the same mass

Now, integrating (**??**) and (**??**) it is easily seen that 5D black holes live longer than 4D black holes of the same mass. Armed with this result a straightforward calculation shows that for a species scale of $\mathcal{O}(10^9~{\rm GeV})$, an all-dark-matter interpretation in terms of 5D black holes must be feasible for masses in the range $10^{14} < M_{\rm BH}/{\rm g} < 10^{21}$

An astonishing coincidence is that the size of the dark dimension $R_\perp \sim$ wavelength of visible light. This means that the Schwarzschild radius of 5D black holes is well below the wavelength of light. For point-like lenses, this is the critical length where geometric optics breaks down and the effects of wave optics suppress the magnification, obstructing the sensitivity to 5D PBH microlensing signals

It was observed in

In the absence of isometries in the dark dimension, which is the common expectation, the KK momentum of the dark tower is not conserved. This means that a dark graviton of KK quantum n can decay to two other ones, with quantum numbers n_1 and n_2. If the KK quantum violation can go up to δn, the number of available channels is roughly $l\,\delta n$. In addition, because the decay is almost at threshold, the phase space factor is roughly the velocity of decay products, $v_{\rm r.m.s.} \sim \sqrt{m_{\rm KK}\,\delta n/m_l}$. Putting all this together we obtain the total decay width,

$$\begin{aligned}\Gamma^l_{\rm tot} \quad &\sim \quad \sum_{l'<l}\ \sum_{0<l''<l-l'} \Gamma^l_{l'l''} \sim \beta^2 \frac{m_l^3}{M_{\rm Pl}^2} \times \frac{m_l}{m_{\rm KK}}\,\delta n \times \sqrt{\frac{m_{\rm KK}\delta_n}{m_l}} \\ &\sim \quad \beta^2\,\delta n^{3/2}\,\frac{m_l^{7/2}}{M_{\rm Pl}^2 m_{\rm KK}^{1/2}}\,, \end{aligned} \tag{1}$$

where β parametrizes our ignorance of decays in the dark dimension

To estimate the time evolution of the dark matter mass assume that for times larger than $1/\Gamma^l_{\rm tot}$ dark matter which is heavier than the corresponding m_l has already decayed, and so it follows that

$$m_l \sim \left(\frac{M_{\rm Pl}^4\,m_{\rm KK}}{\beta^4\,\delta n^3}\right)^{1/7} t^{-2/7}\,, \tag{2}$$

where t indicates the time elapsed since the big bang

Consistency with CMB anisotropies requires $\Gamma^l_{\gamma\gamma} < 5 \times 10^{-25}~{\rm s}^{-1}$ between the last scattering surface and reionization

Now, we have seen that dark matter decay gives the daughter particles a velocity kick. Self-gravitating dark-matter halos that have a virial velocity smaller than this velocity kick may be disrupted by these particle decays. Consistency with existing data requires roughly $\delta n \sim 1$, and $\beta \sim 635$

For many purposes, a black hole can be replaced by a bound state of gravitons

The radion stabilizing the dark dimension could be yet another dark matter contender

4. NEUTRINO MASSES AND MIXING

The dark dimension scenario provides a profitable arena to realize an old idea for explaining the smallness of neutrino masses by introducing the right-handed neutrinos as 5D bulk states with Yukawa couplings to the left-handed lepton and Higgs doublets that are localized states on the SM brane stack

More indicatively, the generation of neutrino masses originates in 5D bulk-brane interactions of the form

$$\mathscr{L} \supset h_{ij} \, \overline{L}_i \, \tilde{H} \, \Psi_j(y=0) \,, \tag{1}$$

where $\tilde{H} = -i\sigma_2 H^*$, L_i denotes the lepton doublets (localized on the SM brane), Ψ_j stands for the 3 bulk (right-handed) R-neutrinos evaluated at the position of the SM brane, $y = 0$ in the fifth-dimension coordinate y, and h_{ij} are coupling constants. This gives a coupling with the L-neutrinos of the form $\langle H \rangle \, \overline{\nu}_{L_i} \, \Psi_j(y = 0)$, where $\langle H \rangle = 175$ GeV is the Higgs vacuum expectation value. Expanding Ψ_j into modes canonically normalized leads for each of them to a Yukawa 3×3 matrix suppressed by the square root of the volume of the bulk $\sqrt{\pi R_\perp M_s}$, i.e.,

$$Y_{ij} = \frac{h_{ij}}{\sqrt{\pi R_\perp M_s}} \sim h_{ij} \frac{M_s}{M_p} \,, \tag{2}$$

where $M_s \lesssim M_*$ is the string scale, and where in the second rendition we have dropped factors of π's and of the string coupling.

Now, neutrino oscillation data can be well-fitted in terms of two nonzero differences $\Delta m_{ij}^2 = m_i^2 - m_j^2$ between the squares of the masses of the three mass eigenstates; namely, $\Delta m_{21}^2 = (7.53 \pm 0.18) \times 10^{-5}$ eV^2 and $\Delta m_{32}^2 = (2.453 \pm 0.033) \times 10^{-3}$ eV^2 or $\Delta m_{32}^2 = -(2.536 \pm 0.034) \times 10^{-3}$ eV^2

Note that KK modes of the 5D R-neutrino fields behave as an infinite tower of sterile neutrinos, with masses proportional to $m_{\rm KK}$. However, only the lower mass states of the tower mix with the active SM neutrinos in a pertinent fashion. The non-observation of neutrino disappearance from oscillations into sterile neutrinos at long- and short-baseline experiments places a 90% CL upper limit $R_\perp < 0.4$ μm for the normal neutrino ordering, and $R_\perp < 0.2$ μm for the inverted neutrino ordering

Before proceeding, it is important to stress that the upper bounds on $R_\perp$ discussed in the previous paragraph are sensitive to assumptions of the 5th dimension geometry. Moreover, in the presence of bulk masses

Non-minimal extensions of the dark dimension, in which $M_{3/2}$ and Λ have different KK towers, allow a high-scale SUSY breaking and can therefore host a rather heavy gravitino together with a modulino with a mass of about 50 eV

A seemingly different, but in fact closely related subject is the the *sharpened* version of the weak gravity conjecture forbidding the presence of non-SUSY AdS vacua supported by fluxes in a consistent quantum gravity theory

5. MESOSCOPIC EXTRA DIMENSION FROM 5D INFLATION

It is unnatural to entertain that the size of the dark dimension would remain fixed during the evolution of the Universe right at the species scale. One possible mechanism to accommodate this hierarchy is to inflate the size of the dark dimension. The required inflationary phase can be described by a 5D dS (or approximate) solution of Einstein equations, with cosmological constant and a 5D Planck scale $M_* \sim 10^9$ GeV

Besides solving the horizon problem, 4D slow-roll inflation predicts an approximate scale-invariant Harrison-Zel'dovich power spectrum of primordial density perturbations

Another interesting feature of 5D inflation is that the radion can be stabilized in a local (metastable) dS vacuum, using the contributions of bulk field gradients

6. TENSIONS IN COSMOLOGY

Over the last few years, low- and high-redshift observations set off tensions in the measurement of the present-day expansion rate H_0 and in the determination of the amplitude of the matter clustering in the late Universe (parameterized by S_8)

7. CONCLUDING REMARKS

We have seen that the dark dimension scenario carries with it a rich phenomenology:

- It provides a profitable arena to accommodate a very light gravitino.
- It encompasses a framework for primordial black holes, KK gravitons, and a fuzzy radion to emerge as interesting dark matter candidates.
- It also encompasses an interesting framework for studying cosmology and astroparticle physics.
- It provides a natural set up for R-neutrinos propagating in the bulk to accommodate neutrino masses in the range $10^{-4} < m_\nu/\text{eV} < 10^{-1}$, despite the lack of any fundamental scale higher than M_*. The suppressed neutrino masses are not the result of a see-saw mechanism, but rather because the bulk modes have couplings suppressed by the volume of the dark dimension (akin to the weakness of gravity at long distances).

We have also seen that uniform 5D inflation can relate the causal size of the observable universe to the present weakness of gravitational interactions by blowing up an extra compact dimension from the microscopic fundamental length of gravity to a large size in the micron range, as required by the dark dimension scenario. Moreover, uniform 5D inflation can lead to an approximate scale invariant power spectrum of primordial density perturbations consistent with observations of CMB anisotropies. The tensor-to-scalar ratio is also consistent with observations. A rough estimate of the magnitude of isocurvature perturbations based on entropy perturbations indicates that they are suppressed. A dedicated investigation along these lines is obviously important to be done.

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