New Developments in Extra-dimensional Dark Matter

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We summarize the main features of several dark matter candidates in extra-dimensional theories. In particular, we review Kaluza-Klein (KK) gravitons in universal extra dimensions and branons in brane-world models. KK gravitons are superWIMP (superweakly-interacting massive particle) dark matter, and branons are WIMP (weakly-interacting massive particle) dark matter. Both dark matter candidates are naturally produced in the correct amount to form much or all of dark matter.

1. KALUZA-KLEIN GRAVITONS

In models with universal extra dimensions (UED) [1], gravity and all Standard Model (SM) fields have access to the entire space, which is called bulk space. The first studies of such models concentrated on the Kaluza-Klein (KK) partners of SM particles, but all UED models necessarily also have KK gravitons, and these may be viable DM candidates. Given the general formalism for analyzing the dynamics of gravitons in UED theories [2], one can find the widths for decays of KK fermions and KK gauge bosons into KK gravitons. These results are of special relevance when a KK graviton is the lightest KK particle and a superWIMP candidate [3], as they determine the observable implications of KK graviton DM for Big Bang Nucleosynthesis (BBN) analyses, the cosmic microwave background, the diffuse photon flux [2] and structure formation [4]. The possibility of populating a large number of graviton states at different KK levels implies that the production of gravitons after reheating is extremely efficient and extremely sensitive to the reheat temperature T_{RH}. The constraints on T_{RH} are therefore stringent (see Figure 1).

This superWIMP scenario can be studied in colliders. Decays to KK gravitons may be observed by trapping KK lepton next lightest KK particles in water tanks placed just outside collider detectors. By draining these tanks

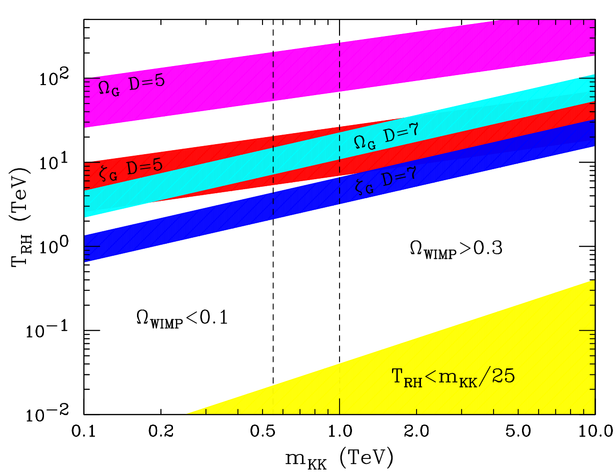

Figure 1: Overclosure and BBN constraints on the reheat temperature T_{RH}, as a function of the Kaluza Klein mass m_{KK}. The vertical bands delimit regions of B^1 thermal relic abundance Ω_{WIMP}. See [2] for details.

periodically to underground reservoirs, slepton decays may be observed in quiet environments as in the gravitino case [5–10]. Precision studies of KK lepton decays are therefore possible and can provide direct observations of gravitational effects at colliders; measurements of the extra-dimensional size and Newton's constant; precise determinations of the KK graviton's contribution to DM and laboratory studies of Big Bang nucleosynthesis and cosmic microwave background phenomena.

2. BRANONS

The brane-world (BW) scenario is defined by the fact that the SM particles are restricted to a three-dimensional hypersurface or 3-brane, whereas the gravitons can propagate along the whole bulk space. In flexible BW models (when the brane tension scale f is much smaller than the D dimensional or fundamental gravitational scale M_D, i.e. $f << M_D$), the branons are the only new relevant low-energy particles [11]. The SM-branon low-energy effective Lagrangian reads [11–13]:

$$\mathcal{L}_{Br} \;=\; \frac{1}{2}g^{\mu\nu}\partial_\mu\pi^\alpha\partial_\nu\pi^\alpha - \frac{1}{2}M^2\pi^\alpha\pi^\alpha\frac{1}{8f^4}(4\partial_\mu\pi^\alpha\partial_\nu\pi^\alpha - M^2\pi^\alpha\pi^\alpha g_{\mu\nu})T^{\mu\nu}_{SM}\,. \tag{1}$$

Branons interact by pairs with the SM energy-momentum tensor and their couplings are suppressed by the brane tension f^4. In fact, they are generically stable and weakly interacting. These features make them natural DM [14, 15] candidates. On the other hand, the branon phenomenology is very rich since they are coupled with the entire SM. The branon signals can be characterized by their number N, the brane tension scale f, and their masses M. The collider signatures for direct branon production are missing energies. In particular, the monojet and single photon signals for hadron colliders [13] and the single Z and single photon channels for e^+e^- colliders [13]. This last signature has been studied experimentally by the L3 Coll. [16] finding the most constraining bound for the brane tension scale: $f > 180$ GeV, for light branons [13, 16, 17]). On the other hand, branon radiative correction [18] modify four body interactions, electroweak precision observables, anomalous magnetic moments and Higgs boson phenomenology.

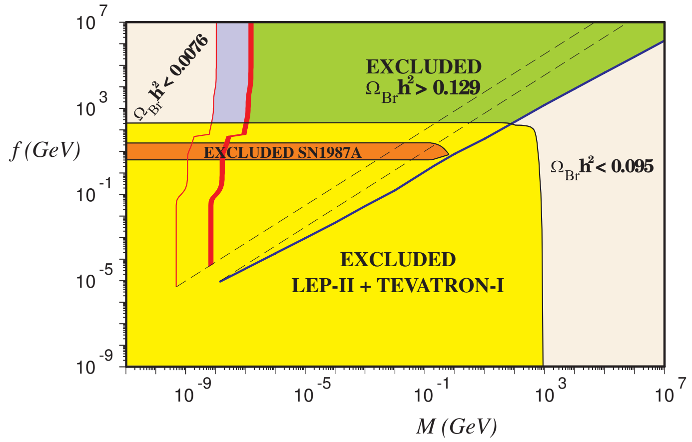

Figure 2: Relic abundance in the $f - M$ plane for a model with one branon of mass M. The two lines on the left correspond to the $\Omega_{Br}h^2 = 0.0076$ and $\Omega_{Br}h^2 = 0.129 - 0.095$ curves for hot-warm relics, whereas the right line corresponds to the latter limits for cold relics (see [14] for details). The lower area is excluded by single-photon processes at LEP-II [13, 16] together with monojet signal at Tevatron-I [13]. The astrophysical constraints are less restrictive and they mainly come from supernova cooling by branon emission [14].

3. Conclusions

In this work we have reviewed the main features of KK gravitons in UED and branons in brane-worlds. The thermal abundance of branons, and the non-thermal abundance of KK gravitons from late decays, are both naturally in the right range to form a significant component of dark matter. We have considered the main phenomenological signals and constraints of these dark matter scenarios.

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References

[1] T. Appelquist, H. C. Cheng and B. A. Dobrescu, Phys. Rev. D **64**, 035002 (2001)

[2] J. L. Feng, A. Rajaraman and F. Takayama, Phys. Rev. D **68**, 085018 (2003)

[3] L. Covi, J. E. Kim and L. Roszkowski, Phys. Rev. Lett. **82**, 4180 (1999); L. Covi, H. B. Kim, J. E. Kim and L. Roszkowski, JHEP **0105**, 033 (2001); J. L. Feng, A. Rajaraman and F. Takayama, Phys. Rev. Lett. **91**, 011302 (2003); Phys. Rev. D **68**, 063504 (2003); J. L. Feng, S. Su and F. Takayama, Phys. Rev. D **70**, 075019 (2004); Phys. Rev. D **70**, 063514 (2004); J. R. Ellis, K. A. Olive, Y. Santoso and V. C. Spanos, Phys. Lett. B **588**, 7 (2004); L. Roszkowski, R. Ruiz de Austri and K. Y. Choi, JHEP **0508**, 080 (2005)

[4] J. A. R. Cembranos, J. L. Feng, A. Rajaraman and F. Takayama, Phys. Rev. Lett **95**, 181301 (2005); M. Kaplinghat, Phys. Rev. D **72**, 063510 (2005)

[5] W. Buchmuller, K. Hamaguchi, M. Ratz and T. Yanagida, Phys. Lett. B **588**, 90 (2004)

[6] J. L. Feng, A. Rajaraman and F. Takayama, Int. J. Mod. Phys. D **13**, 2355 (2004)

[7] K. Hamaguchi, Y. Kuno, T. Nakaya and M. M. Nojiri, Phys. Rev. D **70**, 115007 (2004)

[8] J. L. Feng and B. T. Smith, Phys. Rev. D **71**, 015004 (2005)

[9] A. Brandenburg, L. Covi, K. Hamaguchi, L. Roszkowski and F. D. Steffen, Phys. Lett. B **617**, 99 (2005)

[10] J. L. Feng, S. Su and F. Takayama, hep-ph/0503117.

[11] R. Sundrum, Phys. Rev. D **59**, 085009 (1999); A. Dobado and A. L. Maroto Nucl. Phys. B **592**, 203 (2001)

[12] J. A. R. Cembranos, A. Dobado and A. L. Maroto, Phys. Rev. D **65**, 026005 (2002); hep-ph/0107155

[13] J. Alcaraz *et al.* Phys. Rev. D **67**, 075010 (2003); J. A. R. Cembranos, A. Dobado, A. L. Maroto, Phys. Rev. D **70**, 096001 (2004); hep-ph/0307015; AIP Conf. Proc. **670**, 235 (2003)

[14] J. A. R. Cembranos, A. Dobado and A. L. Maroto, Phys. Rev. Lett. **90**, 241301 (2003); T. Kugo and K. Yoshioka, Nucl. Phys. B **594**, 301 (2001); J. A. R. Cembranos, A. Dobado and A. L. Maroto hep-ph/0402142; Phys. Rev. D **68**, 103505 (2003); hep-ph/0406076; Int. J. Mod. Phys. D **13**, 2275 (2004); hep-ph/0411076; astro-ph/0411262; AMS Internal Note 2003-08-02

[15] A. L. Maroto, Phys. Rev. D **69**, 043509 (2004); Phys. Rev. D **69**, 101304 (2004)

[16] L3 Collaboration, (P. Achard *et al.*), Phys. Lett. B **597**, 145 (2004)

[17] P. Creminelli and A. Strumia, *Nucl. Phys. B* **596**, 125 (2001)

[18] G. Giudice and A. Strumia, Nucl. Phys. B **663**, 377 (2003); J. A. R. Cembranos, A. Dobado and A.L. Maroto, astro-ph/0503622; hep-ph/0507066; hep-ph/0510399; hep-ph/0511332