Implications of quantum gravity for dark matter in the brane-world scenario

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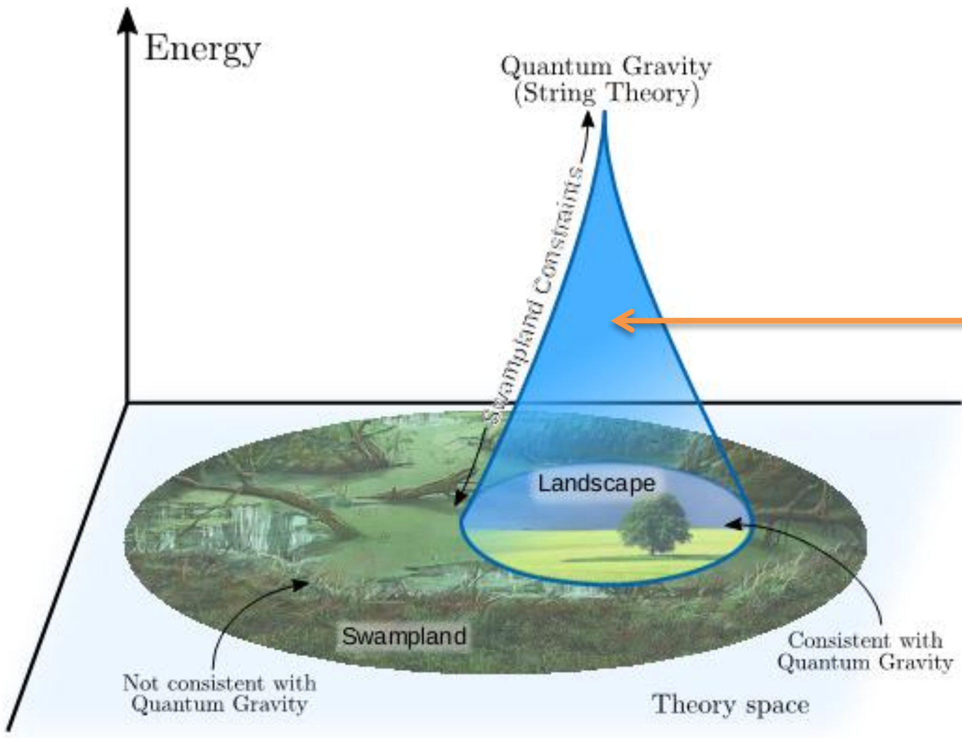
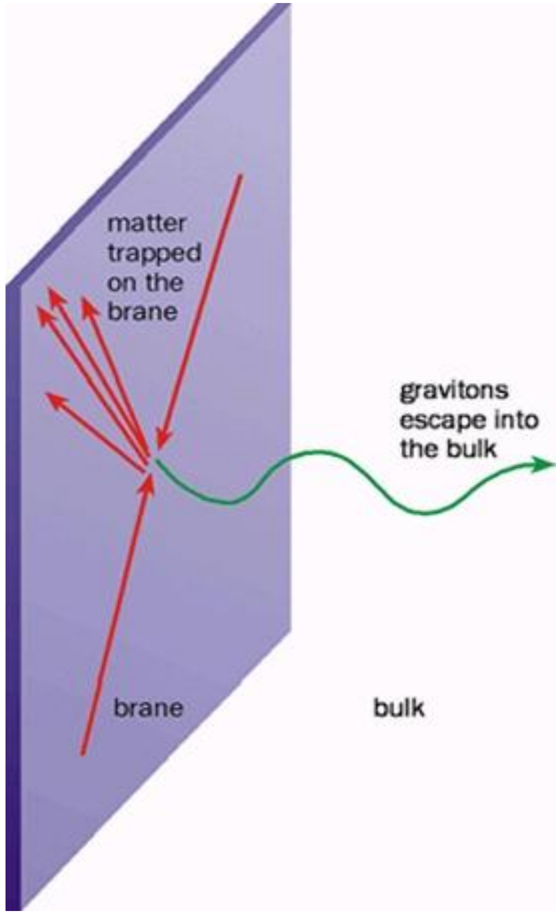
Motivation





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The swampland program establishes constraints of quantum gravity (or conditions) which effective field theories need to satisfy to be consistent with quantum gravity: Weak gravity conjecture, no global symmetries conjecture, distance conjectures,….

new guiding principles for constructing cosmological and particle physics models beyond the Standard Model

Brane-world model

- Action of bulk and brane

$$S = S_{\text{bulk}} + S_{\text{brane}},$$

$$S_{\text{bulk}} = \frac{M_5^3}{2}\int d^5X\sqrt{-G}\,(\mathcal{R}_5 - 2\Lambda_5),$$

$$S_{\text{brane}} = \int d^4x\sqrt{-\tilde{g}}\left(-f^4 + \mathcal{L}_{SM} + \cdots\right)$$

Bulk is a dimensional reduction of AdS vacuum solution of type II B on five-dimensional Sasaki-Einstein internal manifold.

- Compactification of AdS_5 on a circle S^1

$$ds^2_{\text{brane}} = \tilde{g}_{\mu\nu}dx^\mu dx^\nu$$

$$ds^2_{\text{bulk}} = G_{MN}dX^M dX^N, \\ = g_{\mu\nu}dx^\mu dx^\nu - R_0^2\left(d\theta + X_\mu dx^\mu\right)^2$$

$$\tilde{g}_{\mu\nu} = G_{MN}\partial_\mu Y^M \partial_\nu Y^N, \\ = g_{\mu\nu} - R_0^2\left(X_\mu + \partial_\mu Y^\theta\right)\left(X_\nu + \partial_\nu Y^\theta\right)$$

KK gauge field with gauge coupling $\kappa \equiv \sqrt{2}\frac{R_0^{-1}}{M_P}$

Branon

- Isometry along the circle:

$$\theta \longrightarrow \theta + \alpha(x),$$

$$Y^\theta \longrightarrow Y^\theta + \alpha(x),$$

$$X_\mu \longrightarrow X_\mu - \partial_\mu\alpha(x).$$

Branon versus KK gauge boson

- Branon can appear in the low-energy particle spectrum in the limit that the KK gauge field decouples from the theory by sending the KK gauge coupling to zero corresponding to the limit $R_0 \to \infty$

Branon ➔ A candidate for DM

Cembranos PRL (2003)

- However, this limit belongs to the Swampland:
  - Sublattice Weak Gravity Conjecture (WGC) Heidenreich JHEP(2017)

$$\Lambda_{\rm UV} \lesssim \kappa^{1/3} M_{\rm P}$$

$\Lambda_{\rm UV}$: Cut-off of the EFT

$M_{\rm P}$: observed Planck scale

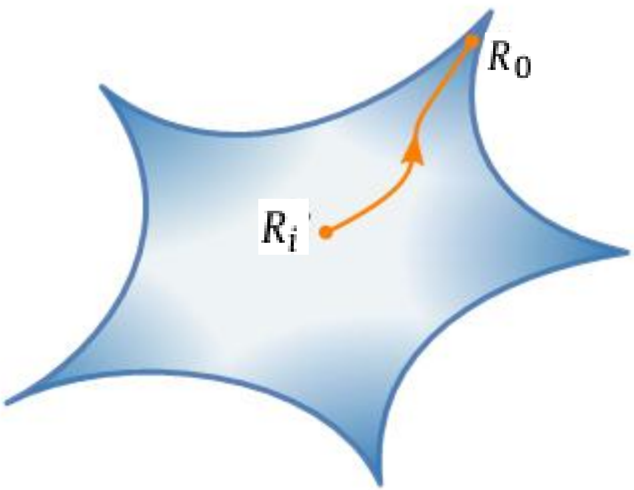
$\kappa \to 0$ ➔ $\Lambda_{\rm UV} \to 0$ ➔ The breakdown of the EFT by effects of quantum gravity

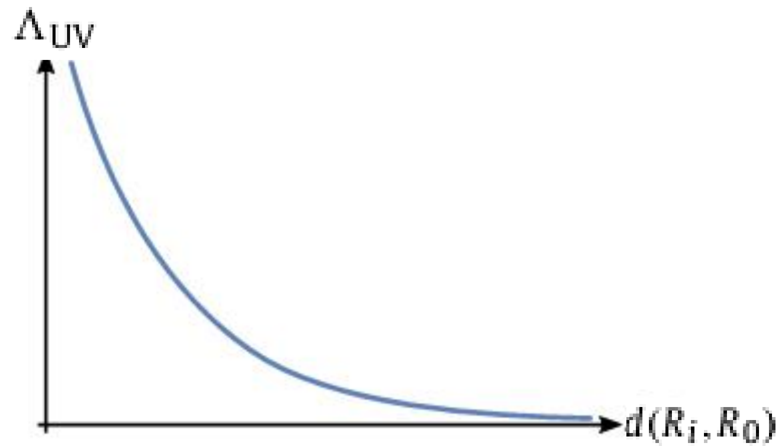
- Distance conjecture Ooguri NPB (2007)

$$m_n = \frac{n}{R_0} \sim e^{-d(R_i, R_0)}$$

Mass of KK modes

distance between two points between two point R_i and R_0 in the field space of radion





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The infinite limit of R_0 yields an infinite tower of exponentially light states which signals the breakdown of the EFT.

- Festina Lente bound

Montero JHEP (2020 & 2021)

$$m_n^2 \gtrsim \sqrt{6}\kappa n M_P H_0$$

observed Hubble parameter today

This bound would be violated when taking the decoupling limit of the KK gauge field

- ✓ The presence of the KK gauge boson associated with the local isometry of S^1 is unavoidable to make the EFT to be consistently coupled to quantum gravity (and compatible with the experimental observations).
- ✓ Branon would be absorbed as the longitudinal mode of the KK gauge boson corresponding to the spontaneous breaking of the local isometry of S^1.

KK gauge boson DM

- 4D effective action

$m_X = \sqrt{2} f^2 / M_P$ $\qquad$ $\lambda = 1/M_P^2$

$$S_{4D} = \int d^4x \sqrt{-g} \left(\frac{M_P^2}{2} \mathcal{R}_4 - \frac{1}{4\kappa^2} X_{\mu\nu} X^{\mu\nu} - f^4 + \frac{m_X^2}{2\kappa^2} X_\mu X^\mu + \frac{\lambda}{\kappa^2} X^\mu X^\nu T_{\mu\nu}^{SM} + \mathcal{L}_{SM} + \cdots \right)$$

- KK gauge boson is odd under the Z_2 symmetry which guarantees its stability.
- KK gauge boson couples very weakly to the SM particles with the corresponding coupling controlled by the 4D Planck scale.

⇨ KK gauge boson behaves actually as the DM, suggesting a geometric unification of gravity and the DM.

- KK gauge boson DM could be purely gravitationally created due to the quantum fluctuations during the inflation: Graham PRD (2016)

tensor-to-scalar ratio $\qquad$ $A_s \approx 2.1 \times 10^{-9}$

Relic abundance of the KK gauge boson particles

$$\frac{\Omega_X}{\Omega_{CDM}} \simeq 1.33 \times \left(\frac{r A_s M_P^2}{10^{26}\ \mathrm{GeV}^2} \right)^{2/3} \left(\frac{m_X}{10^3\ \mathrm{GeV}} \right)^{7/6}$$

$\Omega_{CDM} h^2 \simeq 0.12$

➢ Constraint of Sublattice WGC

- First, applying the constraint of this conjecture for the previously studied models of the relevant dark vector DM: Graham PRD (2016), Ema JHEP (2019), Ahmed JHEP (2020)

$$H_i \lesssim \Lambda_{\rm UV} \lesssim g^{1/3} M_{\rm P} \lesssim \left(\frac{4\pi m_A}{H_i}\right)^{1/3} M_{\rm P} \quad \Rightarrow \quad r \lesssim 5.35 \times 10^{-6}$$

Sublattice WGC implies that the models of the dark vector DM in the literature consistently coupled to quantum gravity and compatible with the DM observations must predict a tiny tensor-to-scalar ratio that is beyond the reach of the near future experiments.

- KK gauge boson DM:

$$H_i \lesssim \Lambda_{\rm UV} \lesssim \kappa^{1/3} M_{\rm P} \quad \Rightarrow \quad A_s r \lesssim 6\sqrt{2}/\pi$$

always satisfied with the current observations of A_s and r.

The value region of the tensor-to-scalar ratio which is experimentally accessible in the present or near future is not wiped out by the constraint of Sublattice WGC.

Probing KK gauge boson DM in CMB and PGWs

- DM is coupled very weakly to the SM particles → it is hard to probe its signatures at the colliders like LHC. In other words, it is hard to confirm observationally this scenario.

- The inflation is very sensitive to the presence of the KK gauge boson DM due to

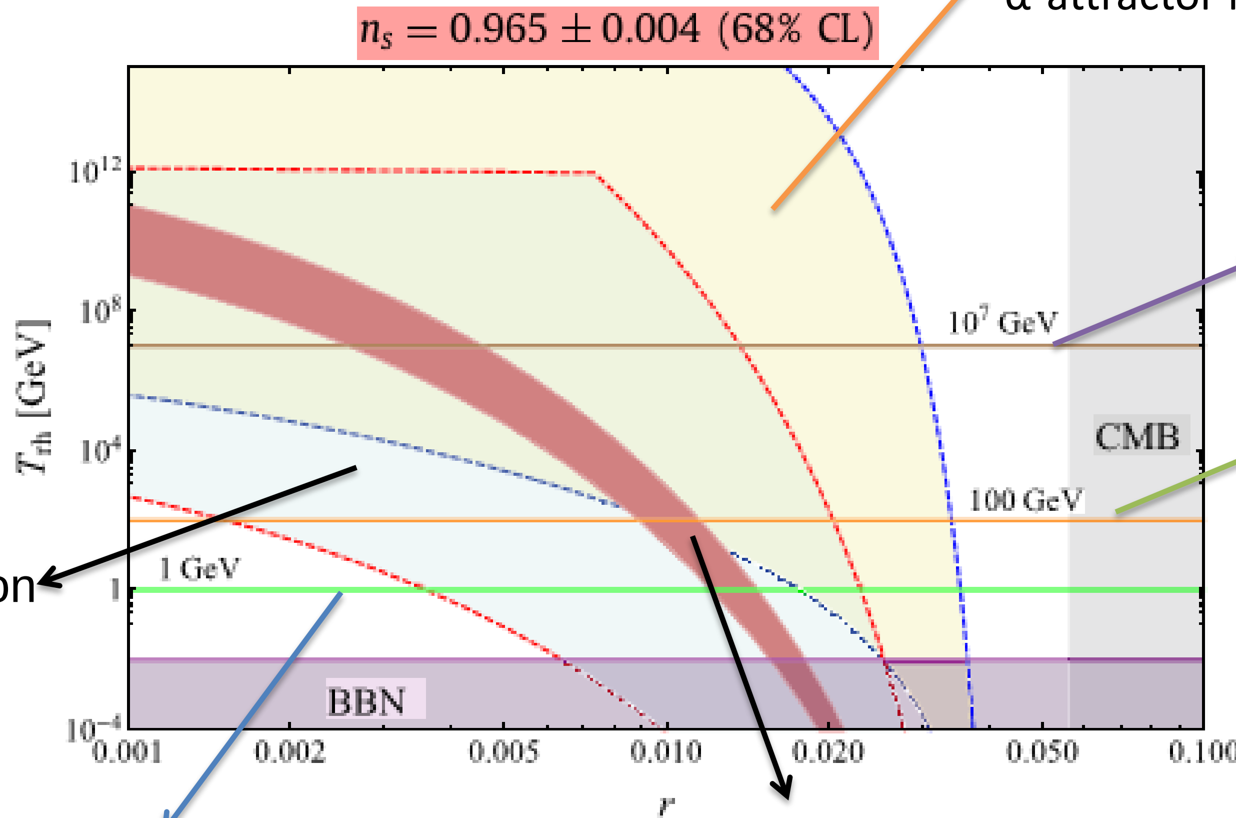
$$H^2 + \frac{k^2}{a^2} = \left(\frac{\rho_{\rm m} + M_{\rm P}^2 m_X^2/2}{6M_5^3} \right)^2 + \frac{\Lambda_5}{6}$$

⇒ KK gauge boson DM would leave its imprints in the CMB as well as the PGW spectrum produced during the inflation.

- We consider the α-attractor inflationary model which is motivated by supergravity/string theory and favors the CMB data very well.

$$V(\phi) = \Lambda^4 \left(1 - e^{-\sqrt{\frac{2}{3\alpha}}\frac{\phi}{M_{\rm P}}} \right)^2$$

The reheating temperature in terms of the tensor-to-scalar ratio in the KK gauge boson DM model



The prediction of the standard α-attractor inflationary model

Avoiding overproduction of gravitinos

very light gravitinos

Our prediction

Increasing of entropy from the production of moduli fields

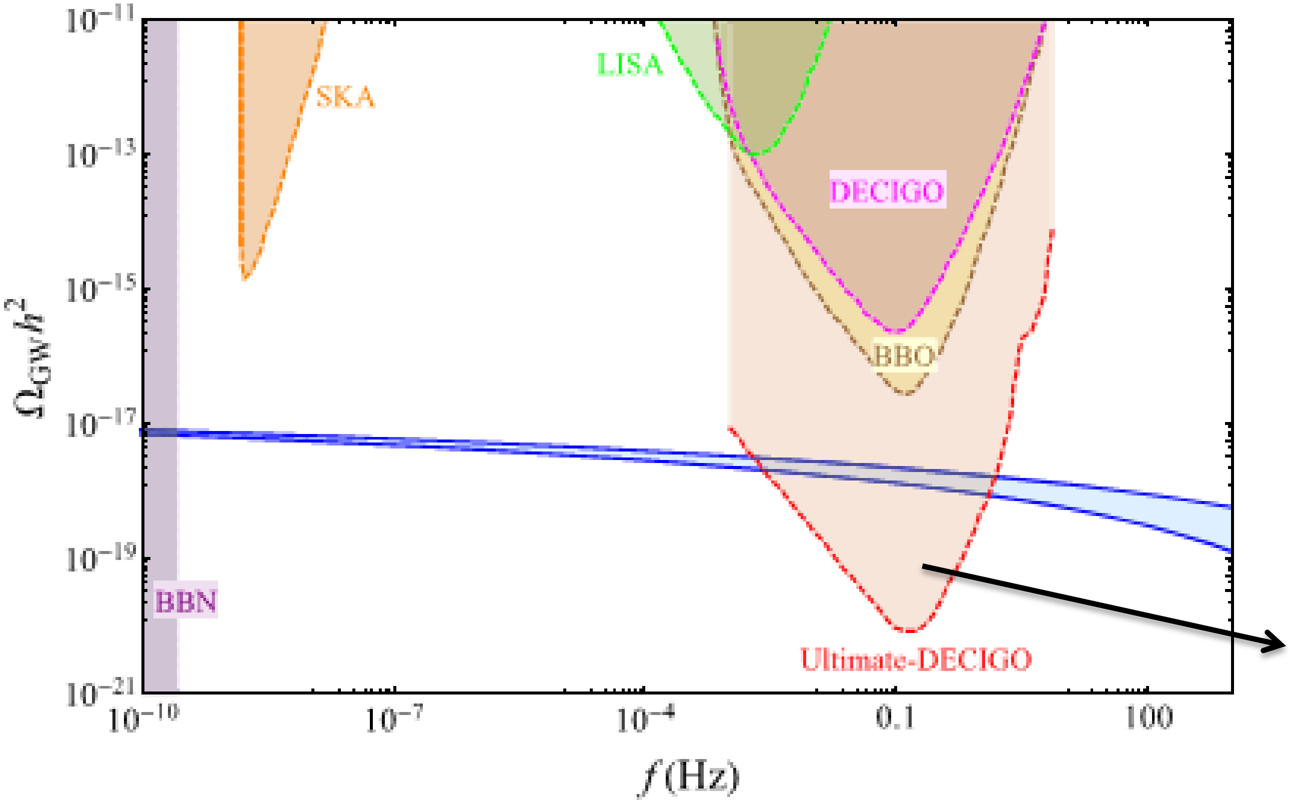
assuming an uncertainty of ~ 5x10^{-4} for n_s and its unchanged central value

- Our model predicts a low reheating temperature with the same r → would be of particular interest in constructing the cosmological models based on supergravity.

- It very predictive and testable from the accurate measurements of the spectral index n_s, r and the reheating temperature.

The reheating temperature can be determined from the spectrum of the inflationary GWs:

$$f_{\rm rh} \simeq 0.26\,{\rm Hz} \left(\frac{g_*}{106.75}\right)^{1/6} \frac{T_{\rm rh}}{10^7\ {\rm GeV}}$$



sensitivity limited by only quantum noises

Kudoh PRD (2006)

$T_{\rm rh} \sim [8.5 \times 10^4, 5.7 \times 10^7]$ GeV $\qquad r \sim [3 \times 10^{-3}, 6 \times 10^{-3}]$

Conclusion

- Compactification of string theory leads naturally to the effective low-energy theories with gravity propagating in the extra dimensions and the SM fields confined to a 3-brane, well-known as the brane-world scenario.

- In order for the brane-world scenario to be consistent with quantum gravity, the fluctuations of 3-brane along the extra dimension must be absorbed as the longitudinal mode of the KK gauge boson.

- The KK gauge boson behaves the DM → a geometric unification of gravity and the DM.

- The KK gauge boson DM provides a complementary window to detect the DM coupling very weakly to the SM in a new parameter range of the DM mass in addition to the laboratory experiments (assuming a tiny kinetic mixing between the dark vector DM and the photon of the SM).

THANK YOU FOR YOUR ATTENTION