String landscape and extra dimensions

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Workshop on Quantum Gravity and Strings

Corfu, Greece, 7-14 September 2025

Landscape and Swampland

Huge number of 4D string ground states with $N \leq 1$ SUSY

with all closed string moduli stabilised in terms of discrete fluxes

all physical couplings of the EFT fixed in terms of the moduli

Validity of the framework: weak string coupling and large volume

Identify physically relevant vacua:

need an extra input of guiding principle

Swampland Program: a possible approach

searching for conditions on EFTs that can consistently coupled to gravity

Vafa '05, Ooguri-Vafa '06

Distance/duality conjecture

At large distance in field space $\phi \Rightarrow$ tower of exponentially light states

$m \sim e^{-\alpha\phi}$ with $\alpha \sim \mathcal{O}(1)$ parameter in Planck units

- provides a weakly coupled dual description up to the species scale

$$M_* = M_P/\sqrt{N}$$

Dvali '07

- tower can be either

1. a Kaluza-Klein tower (decompactification of d extra dimensions)

$$m \sim 1/R\,, \quad \phi = \ln R; \quad M_* = M_P^{(4+d)} = (m^d M_P^2)^{1/(d+2)}$$

$$N = (M_* R)^d$$

2. a tower of string excitations

$$M_* = m \sim \text{the string scale} = g_s M_P\ ; \quad \phi = -\ln g_s\,, \quad N = 1/g_s^2$$

emergent string conjecture

Lee-Lerche-Weigand '19

smallness of physical scales : large distance corner of lanscape?

Dark dimension proposal for the dark energy

$m = \lambda^{-1}\Lambda^a$ $(M_P = 1)$; $1/4 \leq a \leq 1/2$ Montero-Vafa-Valenzuela '22

- distance $\phi = -\ln\Lambda$ Lust-Palti-Vafa '19
- $a \leq 1/2$: unitarity bound $m^2_{\mathrm{spin-2}} \geq 2H^2 \sim \Lambda$ Higuchi '87
- $a \geq 1/4$: estimate of 1-loop contribution $\Lambda \gtrsim m^4$

observations: $\Lambda \sim 10^{-120}$ and $m \gtrsim 0.01$ eV (Newton's law) $\Rightarrow a = 1/4$

astro/cosmo constraints $\Rightarrow d = 1^\star$ 'dark' dimension of $\sim$ micron size

species scale (5d Planck mass): $M_* \simeq \lambda^{-1/3}\, 10^8$ GeV $10^{-4} \lesssim \lambda \lesssim 10^{-1}$

*also $d = 2$ with $M_* \sim 10$ TeV Anchordoqui-I.A.-Lust '25

Our observable universe should be localised on a '3-brane' $\perp$ to the DD

I.A.-Arkani Hamed-Dimopoulos-Dvali '98

See Review article 2405.04427 Anchordoqui-I.A.-Lust

Dark matter candidates

- 2 main new DM candidates:

  1. 5D primordial black holes in the mass range $10^{15} - 10^{21}\text{g}^{\star}$
     with Schwarzschild radius in the range $10^{-4} - 10^{-2}\ \mu$m
     Anchordoqui-I.A.-Lust '22

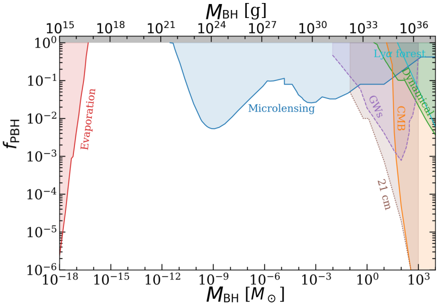
  2. KK-gravitons of decreasing mass due to internal decays (dynamical DM)
     from $\sim$ MeV at matter/radiation equality ($T \sim$ eV) to $\sim$ 50 keV today
     Gonzalo-Montero-Obied-Vafa '22

  possible equivalence between the two Anchordoqui-I.A.-Lust '22

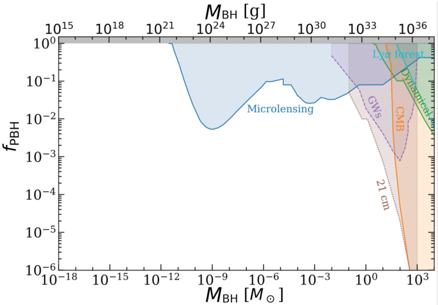
  * $10^{8} - 10^{21}$g for 6D Anchordoqui-I.A.-Lust '25

Primordial Black Holes as Dark Matter

4d PBH



5d PBH



5D BHs live longer than 4D BHs of the same mass

Dark Dimension Radion stabilization and inflation

If 4d inflation occurs with fixed DD radius $\Rightarrow$ too low inflation scale

Higuchi bound: $H_I \lesssim m \sim$ eV

Interesting possibility: the extra dimension expands with time

$R_0 \sim 1/M_*$ to $R \sim \mu$m requires ~ 40 efolds! Anchordoqui-I.A.-Lust '22

$$ds_5^2 = a_5^2(-d\tau^2 + d\vec{x}^2 + R_0^2\, dy^2) \quad R_0 : \text{initial size prior to inflation}$$

$$= \frac{ds_4^2}{R} + R^2 dy^2 \quad ; \quad ds_4^2 = a^2(-d\tau^2 + d\vec{x}^2) \quad \Rightarrow a^2 = R^3$$

After 5d inflation of $N = 40$-efolds $\Rightarrow$ 60 e-folds in 4d with $a = e^{3N/2}$

Large extra dimensions from inflation in higher dimensions

Anchordoqui-IA '23

Large hierarchies in particle physics and cosmology

Particle physics: why gravity appears so weak compared to other forces?

$M_p/M_w \sim 10^{16}$

Cosmology: why the Universe is so large compared to our causal horizon?

at least 10^{26} larger

Question: can uniform $(4+d)$ inflation relate the 2 hierarchies?

size of the observable universe to the observed weakness of gravity

compared to the fundamental (gravity/string) scale M_*

Extra dimensions should expand from the fundamental length

to the size required for the present strength of gravity

while at the same time the horizon problem is solved in our universe

Answer: yes for any d

Precision of CMB power spectrum measurement

Physical distances change from higher to 4 dims

equal time distance between two points in 3-space

$$d^{\tau}_{\rm phys}(x,x') = d(x,x')\,a(\tau) = d(x,x')\,\hat{a}(\tau)\left(\frac{R}{R_0}\right)^{d/2} = \hat{d}^{\tau}_{\rm phys}(x,x')\,\frac{M_p(\tau)}{M_*}$$

co-moving distance [12]

precision of CMB data: angles $\lesssim$ 10 degrees, distances $\lesssim$ Mpc (Gpc today)

Mpc $\to$ Mkm at $M_I \sim$ TeV with radiation dominated expansion

$$\left.\begin{array}{l} \times \text{TeV}/M_I \text{ at a higher inflation scale } M_I \sim M_* \\ \times M_*/M_P \text{ conversion to higher-dim distances} \end{array}\right\} \times \text{TeV}/M_p$$

$\simeq$ micron scale!

Density perturbations from 5D inflation

inflaton (during inflation) $\simeq$ massless minimally coupled scalar in dS space

$\Rightarrow$ logarithmic growth at large distances (compared to the horizon H^{-1})

equal time 2-point function in momentum space at late cosmic time

$$\langle \Phi^2(\hat{k},\tau)\rangle_{\tau\to 0} \simeq \frac{4}{\pi}\frac{H^3}{(\hat{k}^2)^2} \quad ; \quad \hat{k}^2 = k^2 + n^2/R^2$$

2-point function on the Standard Model brane (located at $y=0$):

$$\sum_n \langle \Phi^2(\hat{k},\tau)\rangle_{\tau\to 0} \simeq \frac{2RH^3}{k^2}\left(\frac{1}{k}\coth(\pi kR) + \frac{\pi R}{\sinh^2(\pi kR)}\right) \; ; \quad k = 2\pi/\lambda$$

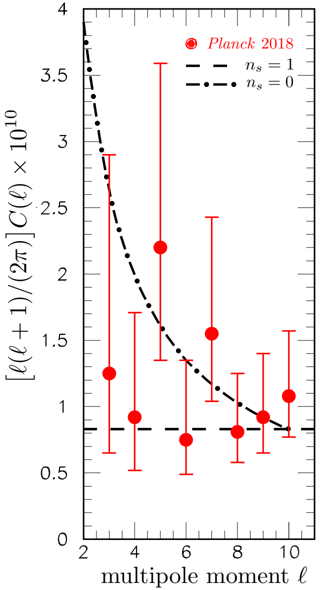
Amplitude of the power spectrum: $\mathcal{A} = \frac{k^3}{2\pi^2}\langle \Phi^2(k,\tau)\rangle_{y=0}$

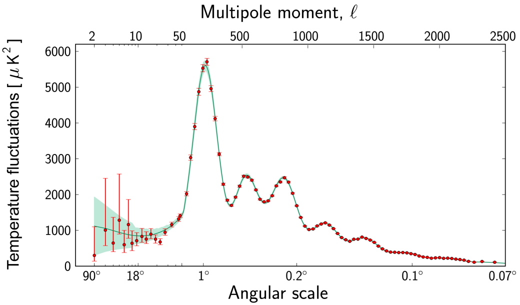
- $\pi kR > 1$ ('small' wave lengths) $\Rightarrow \mathcal{A} \sim \frac{H^2}{\pi^2}$ $\quad n_s \simeq 1$

  summation over n crucial for scale invariance: 'tower' of 4D inflatons

- $\pi kR < 1$ ('large' wave lengths) $\Rightarrow \mathcal{A} \simeq \frac{2H^3}{\pi^3 k}$ $\quad n_s \simeq 0$

Large-angle CMB power spectrum [10]





Detailed computation of primordial perturbations:

IA-Cunat-Guillen '23

5D: inflaton + metric (5 gauge invariant modes) $\Rrightarrow$

4D: 2 scalar modes (inflaton + radion), 2 tensor modes, 2 vector modes

$$\mathcal{P}_{\mathcal{R}} \simeq \frac{1}{3\varepsilon}\mathcal{A}\left[\left(\frac{k}{\hat{a}H}\right)^{2\delta-5\varepsilon} + \varepsilon\left(\frac{k}{\hat{a}H}\right)^{-3\varepsilon} \times \begin{cases} \frac{5}{24} & R_0 k >> 1 \\ \frac{1}{3} & R_0 k << 1 \end{cases}\right]$$

$$\mathcal{P}_{\mathcal{T}} \simeq \frac{4H^2}{\pi^2}\left(\frac{k}{\hat{a}H}\right)^{-3\varepsilon} \times \begin{cases} R_0 H & R_0 k >> 1 \\ \frac{2H}{\pi k} & R_0 k << 1 \end{cases} \qquad r = 24\varepsilon$$

$$\mathcal{P}_{\mathcal{V}} \simeq \frac{4R_0 H^3}{\pi^2}\left(\frac{k}{\hat{a}H}\right)^{-3\varepsilon} \times \begin{cases} 1 & R_0 k >> 1 \\ \frac{\pi^3}{45}(R_0 k)^3 & R_0 k << 1 \end{cases} \quad S^1/Z_2\,(n \neq 0)$$

$$\mathcal{P}_{\mathcal{S}} \simeq \frac{9\varepsilon^2}{16}\mathcal{P}_{\mathcal{R}} \quad \text{entropy} \Rrightarrow \beta_{\rm isocurvature} = \frac{\mathcal{P}_{\mathcal{S}}}{\mathcal{P}_{\mathcal{R}} + \mathcal{P}_{\mathcal{S}}} \simeq \frac{9\varepsilon^2}{16} < 0.038\ \text{exp}$$

slow-roll parameters: $\varepsilon = -\frac{\dot{H}}{H^2}$; $\delta = \varepsilon - \frac{\dot{\varepsilon}}{2H\varepsilon} \simeq \eta - \varepsilon$

Bispectrum from 5D inflation IA-Chatrabhuti-Cunat-Isono '25

$$f_{\rm NL} \underset{\substack{R_0 k_1 \ll 1 \\ R_0 k_2 \ll 1 \\ R_0 k_3 \ll 1}}{\simeq} \frac{5}{12}\frac{8}{R_0^3 k_1 k_2 k_3}\left\{(\varepsilon_2-\varepsilon_1)\frac{k_1^4+k_2^4+k_3^4}{k_1^3+k_2^3+k_3^3}+8\varepsilon_1\frac{k_1^2k_2^2+k_1^2k_3^2+k_2^2k_3^2}{k_1^3+k_2^3+k_3^3}\right\}$$

$$f_{\rm NL} \underset{\substack{R_0 k_1 \ll 1 \\ R_0 k_2 \gg 1 \\ R_0 k_3 \gg 1}}{\simeq} \frac{5}{12}\frac{2}{R_0 k_1}\left\{(\varepsilon_2-\varepsilon_1)+16\varepsilon_1\frac{k_2^2k_3^2}{(k_2+k_3)\left(k_2^3+k_3^3\right)}\right\} \qquad k_t =: \sum_a k_a$$

$$f_{\rm NL} \underset{\substack{R_0 k_1 \gg 1 \\ R_0 k_2 \gg 1 \\ R_0 k_3 \gg 1}}{\simeq} \frac{5}{12}\left\{(\varepsilon_2-\varepsilon_1)+\frac{16\varepsilon_1}{k_1^3+k_2^3+k_3^3}\sum_{1\le a<b\le 3}\left(\frac{k_a^2k_b^2}{k_t}+k_1k_2k_3\frac{k_ak_b}{k_t^2}\right)\right\}$$

$$f_{\rm NL}^{\rm 4D} = \frac{5}{12}\left\{(\varepsilon_2-\varepsilon_1)+\frac{\varepsilon_1}{k_1^3+k_2^3+k_3^3}\sum_{1\le a<b\le 3}\left(k_ak_b^2+k_a^2k_b+\frac{8}{k_t}k_a^2k_b^2\right)\right\}$$

$f_{\rm NL}\big|_{R_0 k_a \gg 1} \neq f_{\rm NL}^{\rm 4D}$: global conformal invariance is broken

End of inflation

Inflaton: 5D field φ with a coupling to the brane to produce SM matter

e.g. via a 'Yukawa' coupling suppressed by the bulk volume $y \sim 1/(RM_*)^{1/2}$

Its decay to KK gravitons should be suppressed to ensure $\Delta N_{\rm eff} < 0.2$

Anchordoqui '20

$$\left(\Gamma^{\varphi}_{\rm SM} \sim \frac{m}{M_*} m_\varphi\right) > \left(\Gamma^{\varphi}_{\rm grav} \sim \frac{m_\varphi^4}{M_*^3}\right) \Rightarrow m_\varphi < 1\,\mathrm{TeV}$$

5D cosmological constant at the minimum of the inflaton potential

$\Rightarrow$ runaway radion potential:

$$V_0 \sim \frac{\Lambda_5^{\rm min}}{R}\,; \qquad (\Lambda_5^{\rm min})^{1/5} \lesssim 100\,\mathrm{GeV} \quad \text{(Higuchi bound)}$$

canonically normalised radion: $\phi = \sqrt{3/2}\,\ln(R/r)$ $\quad r \equiv \langle R \rangle_{\text{end of inflation}}$

$\Rightarrow$ exponential quintessence-like form $V_0 \sim e^{-\alpha\phi}$ with $\alpha \simeq 0.8$

just at the allowed upper bound: Barreiro-Copeland-Nunes '00

Radion stabilisation at the end of 5D inflation

Anchordoqui-IA '23

Potential contributions stabilising the radion:

$$V = \left(\frac{r}{R}\right)^2 \hat{V} + V_C \quad ; \quad \hat{V} = 2\pi R \Lambda_5^{\min} + T_4 + 2\pi \frac{K}{R}$$

T_4: 3-branes tension, K: kinetic gradients, V_C: Casimir energy

↑Arkani-Hamed, Hall, Tucker-Smith, Weiner '99

Radion mass m_R: $\sim$ eV (m_{KK}) to 10^{-30} eV (m_{KK}^2/M_p) depending on K

- $K \sim M_*$, all 3 terms of $\hat{V}$ of the same order, V_C negligible

  tune $\Lambda_4 \sim 0_+ \Rrightarrow m_R \lesssim m_{KK} \sim$ eV

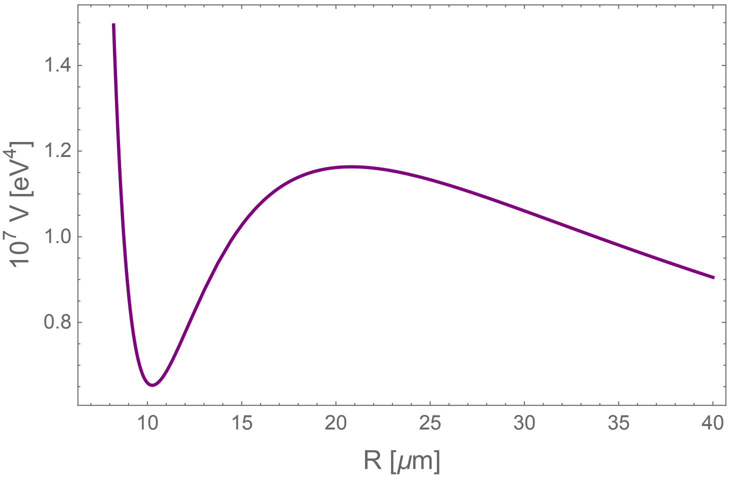
- K negligible, all 3 remaining terms of the same order

  $\Rrightarrow$ minimum is driven by a +ve $V_C = \frac{2\pi r^2}{32\pi^7 R^6}(N_F - N_B)$

  Arkani-Hamed, Dubovsky, Nicolis, Villadoro '07

  no tuning of Λ_4 but $\Lambda_5^{\min}$ should be order $(\text{subeV})^5$

Example of Radion stabilisation potential



$(\Lambda_5^{\min})^{1/5} = 25\ \mathrm{meV},\ |T_4|^{1/4} = 27\ \mathrm{meV},\ N_F - N_B = 7$

$N_F = 12$ (3 bulk R-neutrinos) $N_B = 5$ (5D graviton)

Conclusions

smallness of some physical parameters might signal

a large distance corner in the string landscape of vacua

such parameters can be the scales of dark energy and SUSY breaking

mesoscopic dark dimension proposal: interesting phenomenology

neutrino masses, dark matter, cosmology, SUSY breaking

Large extra dimensions from higher dim inflation

- connect the weakness of gravity to the size of the observable universe
- scale invariant density fluctuations from 5D inflation
- radion stabilization