Large extra dimensions from higher-dimensional inflation

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Extra dimensions

important ingredient of theories of quantum gravity such as string theory

if they are large $\Rightarrow$

gravity becomes strong at energies lower than the Planck scale

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

M_*: higher dimensional Planck scale $\sim M_{\text{string}} << M_p$

opening a new way to address physics problems and scales

Recent motivation from the Swampland Program:

searching for conditions on EFTs that can consistently coupled to gravity

based on string theory and black-hole physics Vafa '05

Dark dimension proposal for the dark energy

Swampland Distance conjecture: Ooguri-Vafa '06

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

effective description up to the species scale $M_* = M_P/\sqrt{N}$ Dvali '07

Emergent string conjecture: Lee-Lerche-Weigand '19

the tower can be made of either Kaluza-Klein or string modes

AdS distance conjecture: distance $\phi = -\ln|\Lambda|$ Lust-Palti-Vafa '19

Applied to the dark energy: $m = \lambda^{-1}\Lambda^a$ Montero-Vafa-Valenzuela '22

theoretical + experimental constraints $\Rightarrow a = 1/4$ $10^{-4} \lesssim \lambda \lesssim 10^{-1}$

$d = 1$ 'dark' dimension of $\sim$ micron size with $M_* \simeq 10^9$ GeV

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

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^{15} larger

Possible connection: through large extra dimensions

their existence is required in string theory

Horizon problem can be explained by a period of inflation

expansion rate faster than speed of light

Extra dimensions may obtain large size by higher-dim inflation

Anchordoqui-IA-Lust '22

Extra dimensions should expand from the fundamental length

to the size required for the present strength of gravity

Example: Dark Dimension and inflation

$R_0 \sim 1/M_* \simeq 10^{-22}$ cm to $R \sim \mu$m requires ~ 40 efolds!

$$ds_5^2 = -d\hat{t}^2 + \hat{a}^2(d\vec{x}^2 + R_0^2\ dy^2) \quad R_0:\ \text{initial size}\,, \quad \hat{a} = e^{H\hat{t}}$$

$$\text{4D frame} = \frac{ds_4^2}{R/R_0} + R^2 dy^2 \quad ; \quad ds_4^2 = -dt^2 + a^2 d\vec{x}^2 \quad \Rightarrow a^2 = \hat{a}^3$$

$$\Rightarrow \quad R(t) \sim t^2 \quad ; \quad a(t) \sim t^3$$

After 5d inflation of $N = 40$-efolds $\hat{a} \simeq e^{40}$

$\Rightarrow$ 60 e-folds in our 4D universe with $a = e^{3N/2} \simeq e^{60}$

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

Higuchi bound: $H_I \lesssim 1/R \sim$ eV

Large extra dimensions from higher-dim inflation

Anchordoqui-IA '23

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 expand up to the size required for the strength of gravity

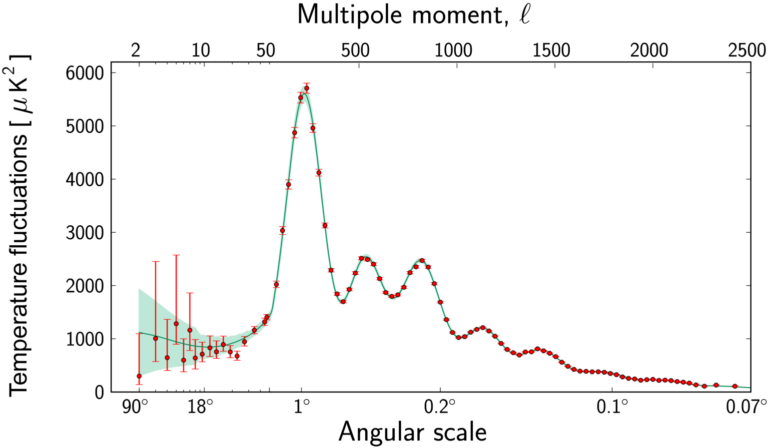
while at the same time the horizon problem is solved in our universe

- $R(t) \sim t^{2/d}$, $a(t) \sim t^{1+2/d}$
- $\hat{N}$ e-folds in $(4+d)$-dims $\Rightarrow$ $N = (1+d/2)\hat{N}$ e-folds in 4D

Impose $M_* \gtrsim 10$ TeV and $R \lesssim 30\mu$m $\Rightarrow$

the horizon problem is solved for any d $N \gtrsim 30-60$ $\left(N \gtrsim \ln \frac{M_I}{\mathrm{eV}}\right)$

Precision of CMB power spectrum measurement



CMB anomalies at large scales: preliminary evidence of scale invariance violation?

see e.g. Schwarz-Copi-Huterer-Starkman '16

Density perturbations from 5D inflation

inflaton (during inflation) $\simeq$ massless scalar in de Sitter spacetime

$\Rightarrow$ scale invariant fluctuations in any d

in momentum space at late cosmic time: $\langle \Phi^2(k) \rangle \sim 1/k^3$ (4D)

$$5\text{D}: \; \langle \Phi^2(\hat{k}) \rangle \simeq \frac{4}{\pi} \frac{H^3}{\hat{k}^4} \quad ; \quad \hat{k}^2 = k^2 + n^2/R_0^2$$

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

$$\sum_n \langle \Phi^2(\hat{k}) \rangle \simeq \frac{2R_0 H^3}{k^2} \left(\frac{1}{k} \coth(\pi k R_0) + \frac{\pi R_0}{\sinh^2(\pi k R_0)} \right) \; ; \quad k = 2\pi/\lambda$$

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

- $\pi k R_0 > 1$ ('small' wave lengths) $\Rightarrow \mathcal{A} \simeq \frac{H^3}{\pi^3}$ $\quad n_s \simeq 1$

  KK sum crucial for scale invariance [11]

- $\pi k R_0 < 1$ ('large' wave lengths) $\Rightarrow \mathcal{A} \simeq \frac{2H^3}{\pi^4 k R_0}$ $\quad n_s \simeq 0$

CMB power spectrum: scale of precision [13]

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

Mpc $\rightarrow 10^{15}$m at $T_N \sim$ MeV with radiation dominated expansion

$\times$ MeV$/T_R$ at a reheating temperature T_R

$\times \left(\frac{t_I}{t_R}\right)^{2/3(1+w)}$ for a period with $p = w\rho$

$\frac{t_I}{t_R} \sim \frac{H_R}{H} = \frac{T_R^2}{M_p H}$

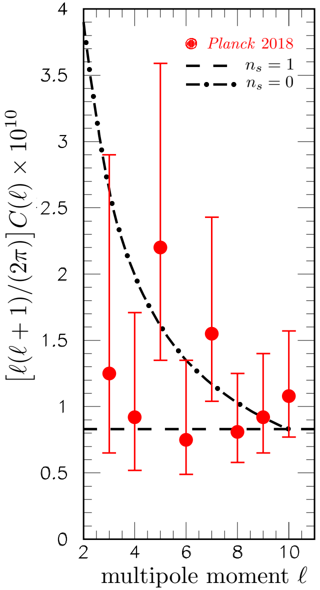
$\lesssim 10^{-3}$m (Newton's law bound) and $T_R \gtrsim$ MeV $\Rightarrow H \gtrsim$ TeV

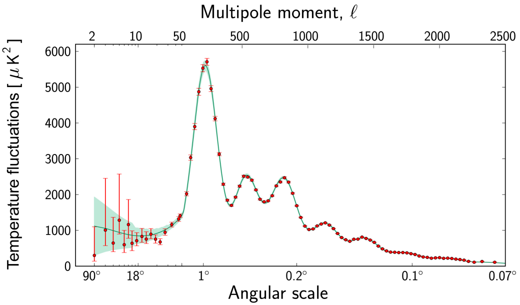
possible for a non accelerating phase from t_I to t_R with $w \geq -1/3$

Anchordoqui-I.A.-Cunat '26

$w = -1/3$: exact string solution linear dilaton in y (string metric flat) [14]

Large-angle CMB power spectrum





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

$$\mathcal{P}_\mathcal{R} \simeq \frac{1}{6\varepsilon}\mathcal{A}\left[\left(\frac{k}{\hat{a}H}\right)^{2\delta-5\varepsilon} + \varepsilon\left(\frac{k}{\hat{a}H}\right)^{-3\varepsilon} \times \begin{cases}\frac{5}{24} & R_0 k >> 1 \\ \frac{1}{3} & R_0 k << 1\end{cases}\right] \text{[8]}$$

$$\mathcal{P}_\mathcal{T} \simeq \frac{4H^3}{\pi^3 M_*^3}\left(\frac{k}{\hat{a}H}\right)^{-3\varepsilon} \times \begin{cases}1 & R_0 k >> 1 \\ \frac{2}{\pi k R_0} & R_0 k << 1\end{cases} \qquad r = 24\varepsilon < 0.032\,\text{exp}$$

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

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

slow-roll parameters: $\varepsilon = -\frac{\dot{H}}{H^2} \equiv \varepsilon_1\,; \quad \varepsilon_{n+1} = \frac{\dot{\varepsilon}_n}{H\varepsilon_n}\,; \quad \delta = \varepsilon - \varepsilon_2/2 \simeq \eta - \varepsilon$

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

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

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

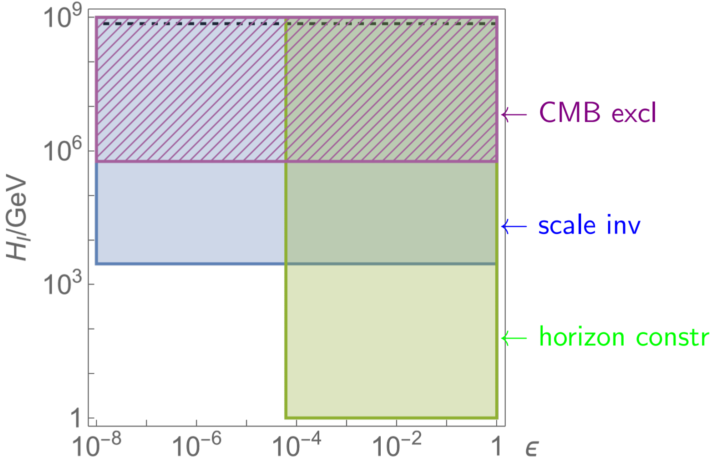
$f_{\rm NL}|_{R_0k_a\gg 1} \neq f_{\rm NL}^{\rm 4D}$: global conformal invariance is broken

requirement of conformal invariance $\Rightarrow$ different prediction [9]

IA-Mazur-Mottola '96

Cosmological history after 5D inflation

parameters: H_I, inflaton mass m, $R_0 \to \epsilon \equiv 1/(R_0 M_*)$

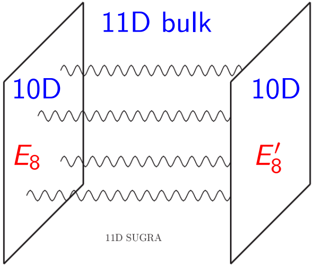


$R_\perp = 1\mu$m, $T_R = T_N = 1$ GeV, $m = 1$ eV

Why $d = 1$? Schwarz '24

dark dimension $\equiv$ 11th dimension of M-theory with two 10D boundaries

Horava-Witten '95



size of the 11th dimension $= \pi\rho$

$$M_{11} = (2\alpha V)^{-1/6} \quad ; \quad \rho = (\alpha/2)^{3/2} M_p^2 V^{1/2} \quad ; \quad \alpha = \text{gauge coupling}$$

$\rho \simeq 1$ micron, $\alpha \sim 1/25 \Rightarrow V^{-1/6} \lesssim M_{11} \sim 10^9$ GeV

also allows: linear dilaton background solution [9]

Neutrino masses

natural explanation of neutrino masses introducing ν_R in the bulk

small masses due to ν_R wave function suppression

ν-oscillation data with 3 bulk neutrinos $\Rightarrow m_{\mathrm{KK}} \gtrsim 2.5$ eV $(R \lesssim 0.4\,\mu\mathrm{m})$

Forero-Giunti-Ternes-Tyagi '22

$\Rightarrow M_* \sim 10^9$ GeV

the bound can be relaxed in the presence of bulk ν_R masses

Lukas-Ramond-Romanino-Ross '00, Carena-Li-Machado^2-Wagner '17

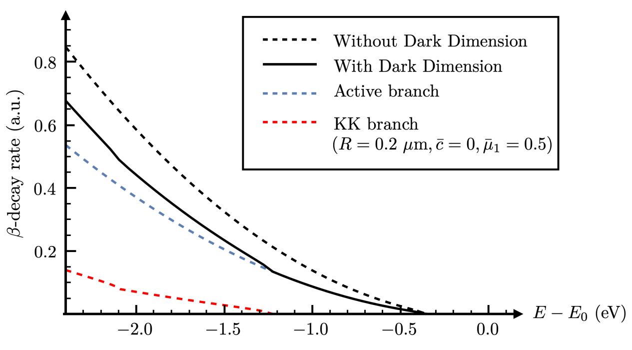
Main consequences:

- Towers of sterile KK excitations
- Dirac neutrino masses
- Bulk masses for ν_R states

Sterile KK excitations in β-decay spectrum (KATRIN, PTOLEMY)

$\mathcal{R}_\beta \sim \Delta E \sqrt{(\Delta E)^2 - m_\nu^2}\,\theta(\Delta E - m_\nu)$ $\quad \Delta E \equiv E_0 - E \quad E_0 \approx 18.57$ keV

$\Rightarrow$ kinks at the energy spectrum $E_0 - E_n \equiv \Delta E \simeq m_n$



IA-Chatrabhuti-Isono '25

Conclusions

smallness of some physical parameters might signal

a large distance corner in the string landscape of vacua

$\Rightarrow$ large extra dimensions and low scale gravity

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

mesoscopic dark dimension(s) 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/6D inflation
- radion stabilization