Exploring extra dimensions through inflationary tensor modes

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Based on

SHI, H.P. Nilles, A. Trautner to appear (arXiv : 1707.xxxx)

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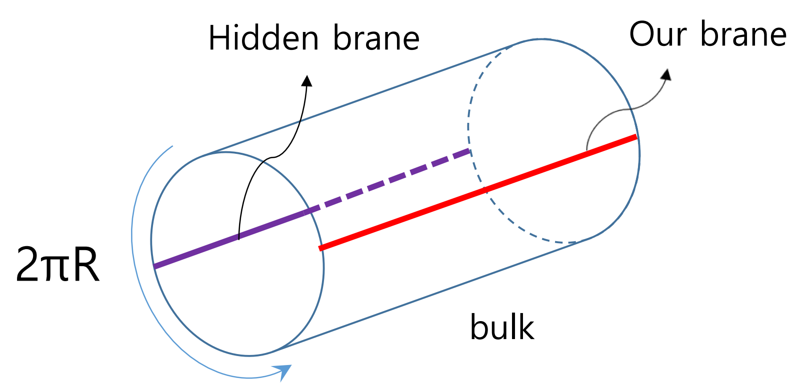
Outline

- General setup and assumptions
- Tensor mode in braneworld inflation
- LED and RS
- Linear Dilaton model
- Conclusions

General setup and assumptions

1) Stabilized compact spatial extra dimensions



R : stabilized

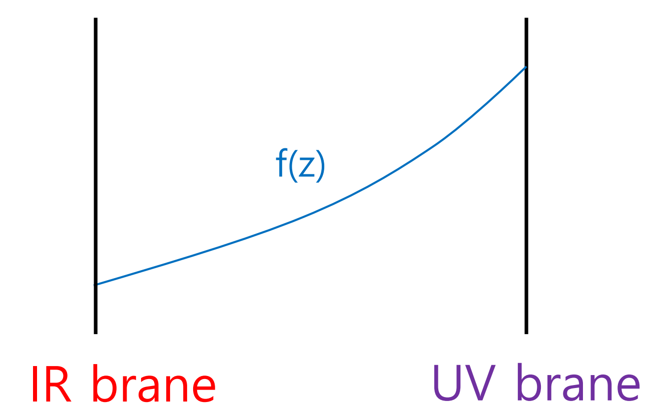
e.g. by a bulk scalar
(Goldberg, Wise '99)

(55) Einstein eq. decoupled
(Csaki, Graesser, Randall, Terning '99)

2) Weak scale hierarchy problem addressed

Our brane = IR brane

$$M_W \sim \frac{M_{\rm Pl}}{\mathcal{V}^{c_1}}\, e^{-c_2 \mathcal{V}} \qquad c_1, c_2 \geq 0$$



3) Inflationary 4D spacetime
: constant energy density (cosmological constant) dominated

$$\mathrm{d}s^2 \;=\; f(z)^2\,\left(\mathrm{d}t^2 - e^{2Ht}\,\delta_{ij}\,\mathrm{d}x^i\mathrm{d}x^j\right) - \mathrm{d}z^2$$

Metric Ansatz

Tensor mode in braneworld inflation

$$\mathcal{P}_{\rm T}(\kappa) \;=\; \frac{2}{\pi^2}\left(\frac{H(\kappa)}{M_{\rm Pl,eff}}\right)^2$$

$$M_{\rm Pl,eff}^2 \;=\; M_5^3 \int_{\rm 5D} {\rm d}z\, f(z)^2 \quad \text{with} \quad {\rm d}s^2 \;=\; f(z)^2\,\left({\rm d}t^2 - e^{2Ht}\,\delta_{ij}\,{\rm d}x^i{\rm d}x^j\right) - {\rm d}z^2$$

- The warping f(z) depends on H : Tensor mode changes compared to the 4D universe.
- Independent of a specific 5D source driving 4D inflation (e.g. bulk field, brane localized inflaton)

- Scalar (density) perturbation

  does depend on a specific source driving inflation.

  IRB (InfraRed Brane) assumption : inflaton field lives in our visible brane. Giudice, Kolb, Lesgourgues, Riotto '02

$$\Rightarrow \quad \mathcal{P}_{\rm S}(\kappa) \;=\; \frac{1}{8\,\pi^2}\,\frac{1}{\epsilon}\left(\frac{H(\kappa)}{M_{\rm Pl,exp}}\right)^2 + \mathcal{O}(\epsilon) \quad \text{with} \quad H^2 \;=\; \frac{\rho}{3\,M_{\rm Pl,exp}^2}$$

ρ : inflaton energy density

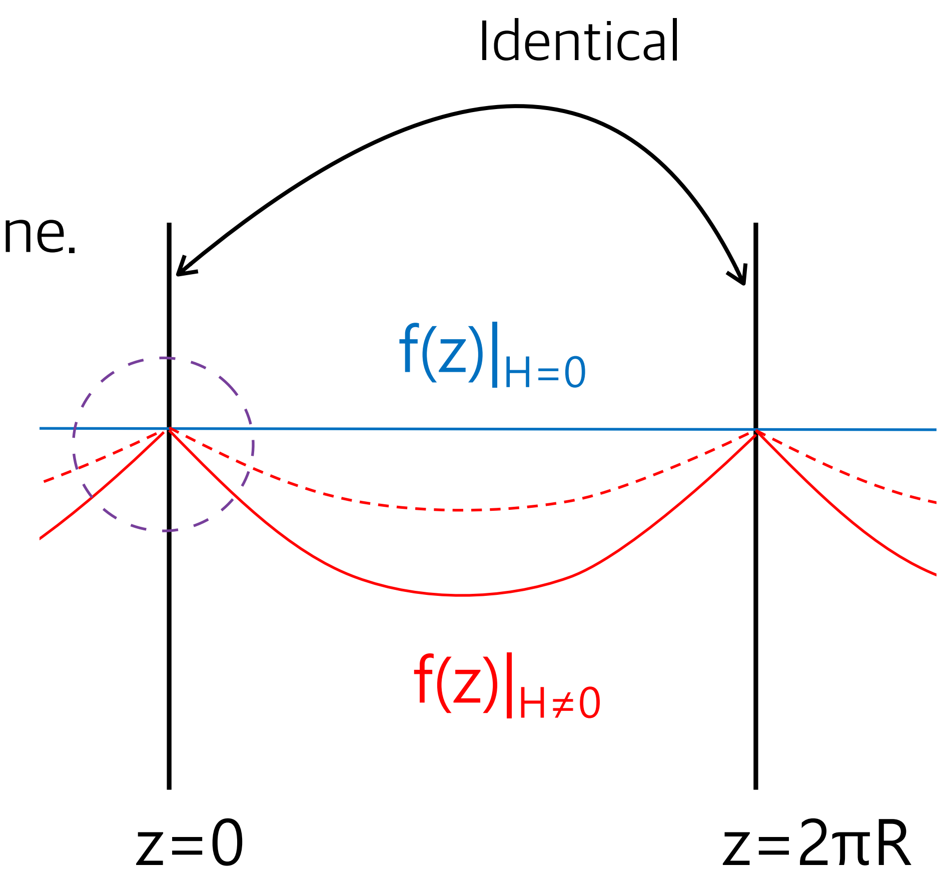
tensor-to-scalar ratio $\Rightarrow$

$$r \equiv \frac{\mathcal{P}_{\rm T}(\kappa)}{\mathcal{P}_{\rm S}(\kappa)} \;\approx\; \frac{{M_{\rm Pl,exp}}^2}{{M_{\rm Pl,eff}}^2} \times \left.\frac{\mathcal{P}_{\rm T}(\kappa)}{\mathcal{P}_{\rm S}(\kappa)}\right|_{\rm 4D}$$

- Beyond the IRB assumption, we cannot make a general statement on tensor-to-scalar ratio.
- Still, we can predict the altered behavior of the tensor mode by the effective Planck mass.

Large Extra Dimension

Put a positive local energy density $\rho > 0$ at the brane.



Einstein eq. ⇒ $$\left.\frac{f'(z)}{f(z)}\right|_{0^-}^{0^+} = \frac{-\rho}{3M_5^3}$$

"Kink" of f(z) at the brane

⇒ $$f^2(z) = 1 + \underbrace{H^2\left(z^2 - 2\pi R z\right)}_{\leq 0}$$

A positive local energy density makes the graviton profile "denser" at the brane.

⇒ less spreading of graviton to the extra dimension

⇒ gravity becomes stronger during inflation (tensor mode enhanced)

$$M_{\rm Pl,eff}^2 = M_5^3 \int_0^{2\pi R} {\rm d}z\, f(z)^2 = M_{\rm Pl}^2 \left(1 - \frac{2}{3}\pi^2 R^2 H^2\right)$$ where $$M_{\rm Pl}^2 \equiv M_{\rm Pl,eff}^2\big|_{H=0} = M_5^3\, 2\pi R$$

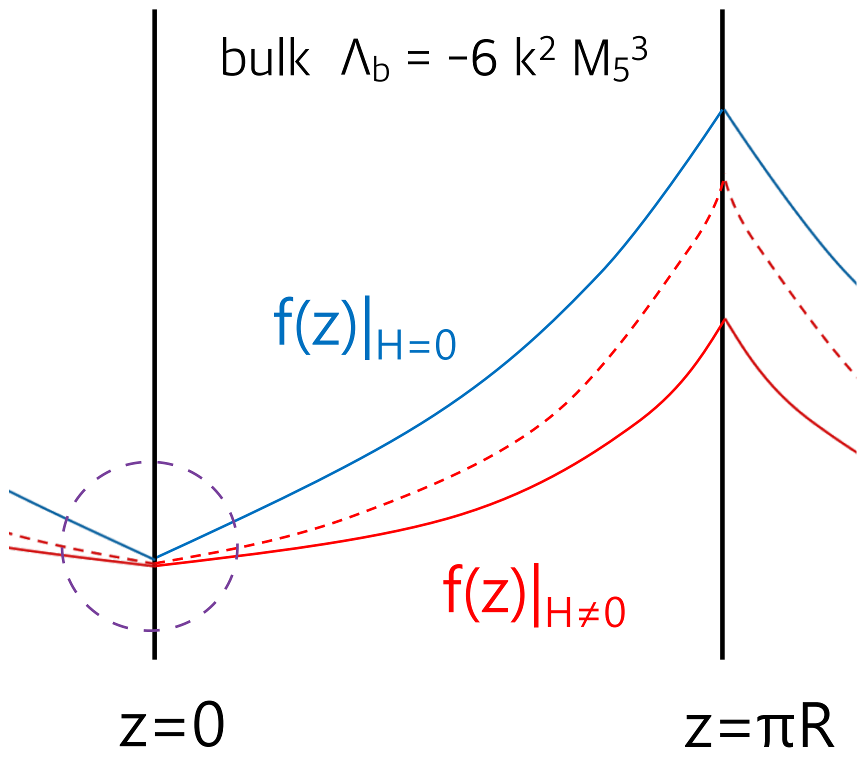
$$H^2 = \frac{\rho}{6\pi R M_5^3} = \frac{\rho}{3M_{\rm Pl}^2} \quad \left(M_{\rm Pl,exp} = M_{\rm Pl,eff}\big|_{H=0}\right)$$

⇒ $$r = r_{4D} \times \frac{1}{\left(1 - \frac{2}{3}\pi^2 R^2 H^2\right)}$$

Randall-Sundrum model

IRB assumption : Inflaton lives in the IR brane (z=0).

➜ negative IR brane tension ($\Lambda_0 < 0$) + Inflaton energy density ($\rho > 0$)



$$\frac{f'(z)}{f(z)}\Bigg|_{0^-}^{0^+} = \frac{-(\Lambda_0+\rho)}{3M_5^3}$$

$|\Lambda_0+\rho| < |\Lambda_0|$ ➜ "weaker kink" at z=0

➜ $$f^2(z) = e^{2kz} - \underbrace{\frac{H^2}{4k^2}\left[(\Omega^2-2)\,e^{2kz} - \Omega^2 e^{-2kz} + 2\right]}_{\le 0}$$

$\Omega \equiv e^{k\pi R}$

The smaller effective IR brane tension leads to weaker warping along the extra dimension.

➜ less spreading of graviton to the extra dimension

➜ gravity becomes stronger during inflation (tensor mode enhanced)

$$M_{\rm Pl,eff}^2 = M_{\rm Pl}^2\left[1-\frac{H^2}{4k^2}\left(\Omega^2-3+\frac{1}{\Omega^2-1}\,4\,k\,\pi\,R\right)\right] \quad \text{where} \quad M_{\rm Pl}^2 = \frac{M_5^3}{k}\left(e^{2k\pi R}-1\right)$$

$$H^2 = \frac{\rho}{3M_{\rm Pl}^2} \quad (M_{\rm Pl,exp} = M_{\rm Pl,eff}|_{H=0})$$

➜ $$r = r_{4D}\times\left[1-\frac{H^2}{4k^2}\left(\Omega^2-3+\frac{1}{\Omega^2-1}\,4\,k\,\pi\,R\right)\right]^{-1}$$

Randall-Sundrum : Remote Inflation

The visible (IR) brane inflation can be driven by an inflaton living in the hidden (UV) brane.

➜ positive UV brane tension ($\Lambda_\pi > 0$) + Inflaton energy density ($\rho > 0$)

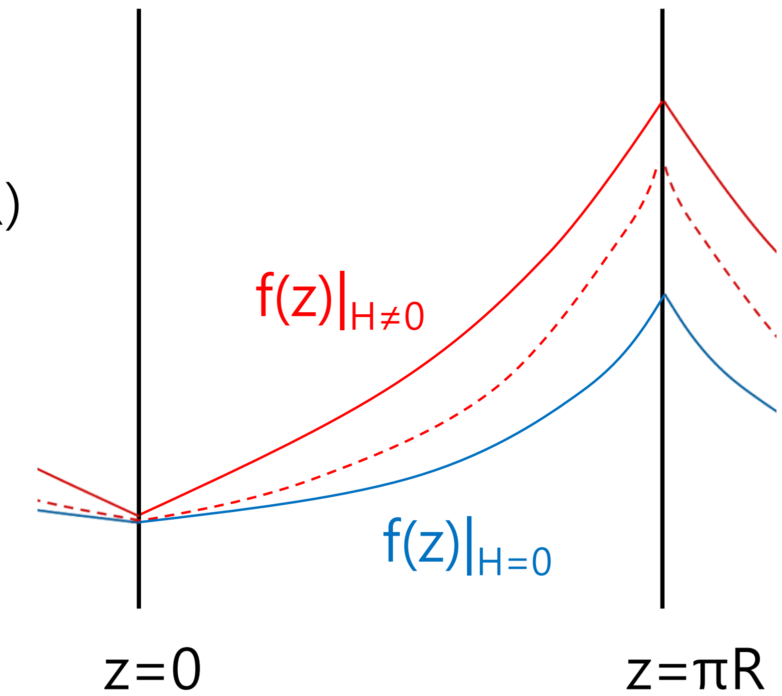
$$|\Lambda_\pi + \rho| > |\Lambda_\pi|$$

$$\left.\frac{f'(z)}{f(z)}\right|_{\pi R^-}^{\pi R^+} = \frac{(\Lambda_\pi + \rho)}{3M_5^3}$$

➜ "stronger kink" at UV brane (z=πR)

$$f^2(z) = e^{2kz} + \underbrace{\frac{H^2}{2k^2}\left[\cosh(2kz) - 1\right]}_{\geq 0}$$

$$M_{\mathrm{Pl,eff}}^2 = M_{\mathrm{Pl}}^2\left[1 + \frac{H^2}{4k^2}\left(1 + \Omega^{-2} - \frac{1}{\Omega^2 - 1}\, 4\, k\, \pi\, R\right)\right] \quad \Omega \equiv e^{k\pi R}$$



The bigger effective brane tension leads to stronger warping along the extra dimension.

➜ more spreading of graviton to the extra dimension

➜ gravity becomes weaker during inflation (tensor mode suppressed)

- Reheating? e.g. gravitational particle production : K-inflation, See Artymowski's talk "Dark Inflation"
- The scalar (density) perturbation requires a dedicated study.

Linear Dilaton (LD) model

- Gravity dual of little string theory   Antoniadis, Arvanitaki, Dimopoulos, Giveon '12

$$\int d^5x\sqrt{-g}\,e^{S}\,[M_5^3 R + (\partial_M S)^2 - \Lambda]$$

➡

$$\begin{cases} S = \frac{2}{3}k\,y = 3\ln\left(1+\frac{2}{3}k\,z\right) \\ ds^2 = e^{4\,k\,y/3}\,(\eta_{\mu\nu}dx^\mu dx^\nu - dy^2) \end{cases}$$

$$= \left(1+\frac{2}{3}k\,z\right)^2\eta_{\mu\nu}dx^\mu dx^\nu - dz^2$$

Power-law warping

➡

$$\frac{1}{2}\sum_{j=0}^{N}(\partial_\mu\phi_j)^2 - \frac{m^2}{2}\sum_{j=0}^{N-1}(\phi_j - q\,\phi_{j+1})^2$$

Deconstructing 5D scalar in the LD background

"clockwork geometry"

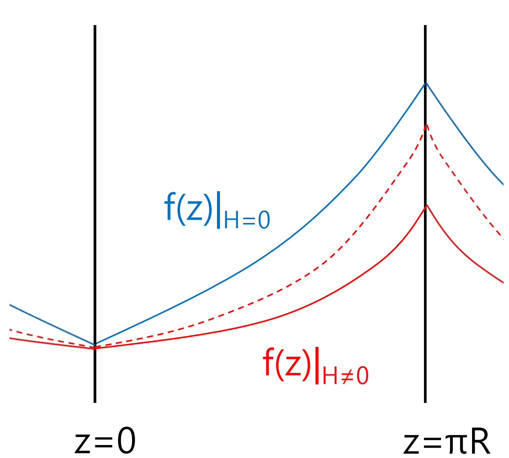
Giudice, McCullough '16
See also Changsub Shin's talk

$$M_{\rm Pl}^2 = \frac{M_5^3}{k}\left[\left(1+\frac{2\,k}{3}\pi\,R\right)^3 - 1\right]$$

$M_5 \sim k \sim$ TeV ➜ $R \sim 10$ nm

- Inflationary (dS_4) solution with the IRB assumption

Qualitatively similar to the RS



But

$$\rho_\pi \approx \frac{\rho_0}{(1+\frac{2}{3}k\,\pi\,R)^2} \neq 0$$ due to the dilaton degree of freedom

➡

$$H^2 \approx \frac{\rho_0}{3\,M_{\rm Pl}^2} + \frac{8}{27}k^3\pi^3R^3\times\frac{\rho_\pi}{3\,M_{\rm Pl}^2} \approx \frac{2}{3}k\,\pi\,R\times\frac{\rho_0}{3\,M_{\rm Pl}^2}$$

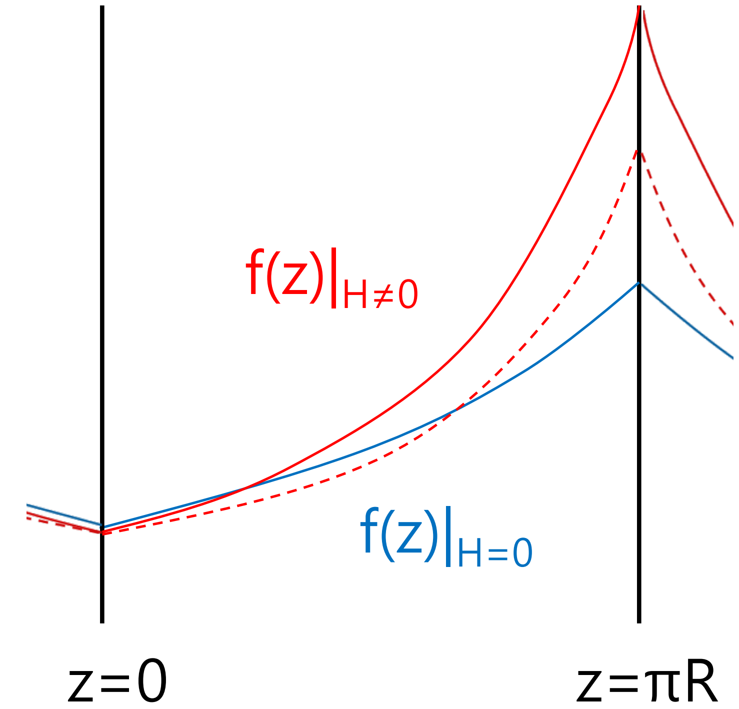
IRB assumption inconsistent : hidden brane contribution unavoidable

Linear Dilation model : IRB consistent scheme

- Radius stabilization by dilaton

brane dilaton potential

$$\left.\begin{aligned} V_0 &= \Lambda_0 + \rho + \xi_0\,(S(z) - S_0)^2 \\ V_\pi &= \Lambda_\pi + \xi_\pi\,(S(z) - S_\pi)^2 \end{aligned}\right\} \quad k\,\pi\,R = \frac{3}{2}\left[\exp\left(\frac{S_\pi - S_0}{3}\right) - 1\right]$$



At the IR brane, $\left.\frac{f'(z)}{f(z)}\right|_{0^-}^{0^+} = \frac{-(\Lambda_0 + \rho)}{3M_5^3}$ with $|\Lambda_0 + \rho| < |\Lambda_0|$: similar to RS

At the UV brane, $\left.\frac{f'(z)}{f(z)}\right|_{\pi R^-}^{\pi R^+} = e^{-S_\pi/3}\frac{\Lambda_\pi}{3\,M_5^3}\left(1 - \frac{\delta S_\pi}{3}\right)$ with $\left|\Lambda_\pi\left(1 - \frac{\delta S_\pi}{3}\right)\right| > |\Lambda_\pi|$

: dilaton backreaction strengthens the UV brane tension ($\delta S_\pi < 0$) - metric crossing over

$$M_{\rm Pl,eff}^2 = M_{\rm Pl}^2\left(1 + \frac{4}{9}\,H^2\,k\,\pi^3\,R^3 + \text{h.o.}\right)$$

tensor mode suppressed

ρ does not induce any hidden brane additional energy density
: IRB consistent, thus tensor-to-scalar ratio is also to be reduced.

- Kehagias and Riotto '16 : similar result, but in a different setup (SM & Inflaton in UV brane)

Conclusions

- Inflationary tensor perturbation is susceptible to extra dimensions.
- Remote inflation in two brane scenarios would offer a variety of possibilities including different behavior on inflationary tensor mode.
- LD with external stabilization is incompatible with the IRB assumption : Inflaton is to be non-local.
- LD with dilaton stabilization is consistent with the IRB assumption. Tensor mode is predicted to be suppressed compared to the 4D universe, in contrast to LED and RS.