1. New Sources of Tensor Modes during inflation

w/ Senatore, Zaldarriaga
Polchinski

2. Uplifting AdS/CFT to FRW cosmology

w/ Dong, Horn, Matsuura, Torroba

Tensor modes are a standard signature of inflation

$$\langle h_k \, h_{k'} \rangle = (2\pi)^3 \delta(k+k') P_h$$

$$P_h = \frac{4}{k^3} \frac{H^2}{M_p^2}$$

Lyth

$$\left(\frac{\Delta\phi}{M_p}\right) \simeq N_e \Big(\underbrace{\frac{P_h}{P_g}}_{r}\Big)^{\frac{1}{2}} \simeq \left(\frac{r}{0.01}\right)^{\frac{1}{2}}$$

(Slow Roll inflation)

Detectability $\Leftrightarrow$ $\underset{\sim H/M_p}{h} \gtrsim 10^{-6}$

→ It is often said that a detection of tensor modes (via CMB B-mode polarization)

⇒ • measurement of $H_{inflation} \gtrsim 10^{-6} M_p$

• determination that $\Delta\phi > M_p$

However, we'll see that

Quantum production of Classical GW

cf Chialva

sources can compete, producing

$$h \gtrsim 10^{-6} \text{ with } \frac{H}{M_p} \lesssim 10^{-6}$$

Motivations

- systematic understanding of inflation & CMB signatures
- New window on exotics & top-down mechanisms

New Sources of GW's

The inflaton ϕ generically couples to other degrees of freedom

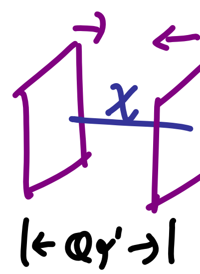
(e.g. for reheating)

For example, (Kofman + many)

(1) $$\delta\mathcal{L} = g^2\phi^2\chi^2 \rightarrow m_\chi^2 = m_0^2 + \phi^2(t,\vec{x})$$

$\Rightarrow$ particle production

(brane picture :



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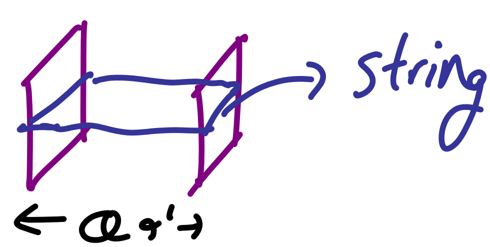
(2) $$T_{string}^2 = T_{min}^2 + \phi^2 M_0^2$$

(brane picture :



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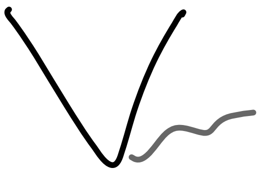
Production :

particles: $n_\chi \sim \dot{\phi}^{\frac{3}{2}} g^{\frac{3}{2}}$



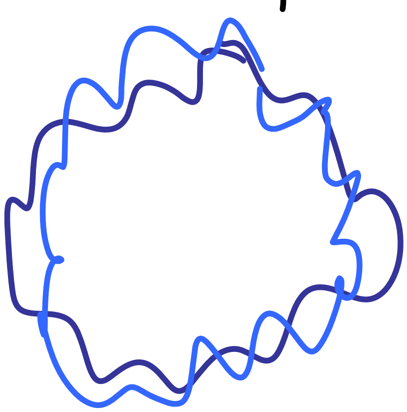
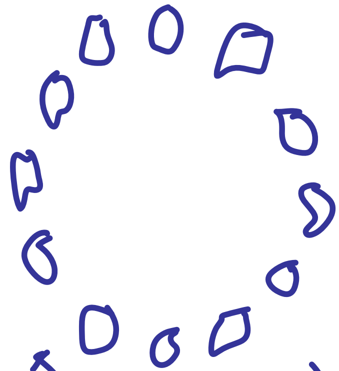
associated scalar emission

$\rightarrow \quad \rho_3 \sim \frac{H^4}{\dot{\phi}^2} g^2 N_\chi$

strings: • Tension $T(t)$ increases too fast to treat as collection of particles

w/ J. Polchinski
cf Spergel

Result:

$\dot{\phi} \rightarrow$  $\Delta t \sim \dot{T}^{-\frac{1}{3}}$ $\longrightarrow$ 

$\dot{T}^{-\frac{1}{3}}$

$\delta\omega$
δa

→ Do these produce competitive GWs?

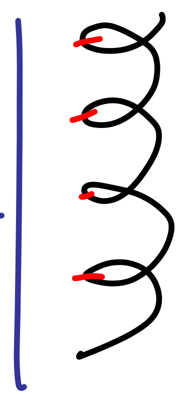
Of course inflation dilutes exotic high-scale relics; Produced particles, strings dilute in a Hubble time.

However, multiple events over $\Delta\phi_{\text{inflation}}$ are quite possible.

& in e.g. monodromy, any production events are repeated many times

McAll. ES Westph.

Axion monodromy → string production



cf Trapped Infl

Green Hor Senatore ES

Kofman, Linde

...

→ repleshinishing supply of GWs

This, plus the more general question of B-mode degeneracy, motivates analyzing this question.

First, given these classical sources of GW's, is $h_{source} \gtrsim 10^{-6}$?

$$\sim \left(\frac{\rho_{GW}}{H^2 M_p^2}\right)^{1/2}\Bigg|_{\text{freeze-out, } \omega \sim \frac{k}{a} \sim H} \sim \frac{[\partial(h M_p)]}{H M_p}\Bigg|_{\omega \sim k/a \sim H}$$

$$\rho_{GW} \sim \rho_{production} \cdot \left(\frac{H}{\omega}\right)^4 \quad \text{inflationary dilution}$$

Low-frequency sources ($\omega \approx H$) most efficient

- zeroeth-order check: $\rho_{sources} < \varepsilon H^2 M_p^2$.

  If converted $\rho_{sources} = \varepsilon H^2 M_p^2 \rightarrow \rho_{GW}\big|_{\omega = H}$

  would get $h \sim \sqrt{\varepsilon} \gg 10^{-6}$

- If all $\rightarrow$ GW of $\omega \sim \sqrt{\dot{\phi}}$,

  get $h_{source} \sim \frac{H}{M_p} \Rightarrow$ still (marginally) competitive

In general

$$\mathcal{S} = \int d^4x\sqrt{-g}\left(\frac{1}{2}M_P^2\mathcal{R} + \mathcal{L}_\phi\right) + \mathcal{S}_X + \mathcal{S}_{XY} \tag{13}$$

$$\begin{aligned}\mathcal{S}_X = & -\sum_p \int d^4x \int d\tau\, \delta^{(4)}(x^\mu - x_p^\mu(\tau))\underline{m(\phi(t,\mathbf{x}))}\sqrt{-\mathrm{g}_{\mu\nu}(\mathbf{x}_\mathrm{p}(\tau))\frac{\mathrm{d}\mathbf{x}^\mu(\tau)}{\mathrm{d}\tau}\frac{\mathrm{d}\mathbf{x}^\nu(\tau)}{\mathrm{d}\tau}}\,\theta(\mathbf{t}-\mathbf{t}_\mathrm{p}) \\ & -\sum_s \int d^4x \int d^2\sigma\, \delta^{(4)}(x^\mu - x_s^\mu(\sigma))\underline{T(\phi(t,\mathbf{x}))}\sqrt{-\mathrm{Det}\mathrm{g}_{\mu\nu}(\mathbf{x}_\mathrm{s}(\sigma))\partial_\alpha\mathbf{x}^\mu(\sigma)\partial_\beta\mathbf{x}^\nu(\tau)}\,\theta(\mathbf{t}-\mathbf{t}_\mathrm{s})\end{aligned} \tag{14}$$

Inflaton ϕ coupled to gravity, sources X (particle/string), and other sectors Y.

* coupling to ϕ $\Rightarrow$ $\delta\phi$ perturbations controlled by $\partial_\phi m$ or $\partial_\phi T$ along with tensor modes

GWs

$$S_{\mu\nu} = T_{\mu\nu} - \tfrac{1}{2}\eta_{\mu\nu} T^{\lambda}{}_{\lambda}$$

$$h_{\mu\nu} = \frac{4}{8\pi M_p^2} \int \frac{d^3\tilde{x}'}{|\tilde{x}-\tilde{x}'|}\, \widetilde{S_{\mu\nu}(\tilde{x}', \omega)}\, e^{-i\omega t + i\omega|\tilde{x}-\tilde{x}'|} + c.c.$$

$$\frac{dE}{d\Omega} = \frac{2}{8\pi M_p^2} \int_0^\infty d\omega\, \omega^2 \left(T^{\lambda\nu *} T_{\lambda\nu} - \tfrac{1}{2} |T^{\lambda}{}_{\lambda}|^2 \right)$$

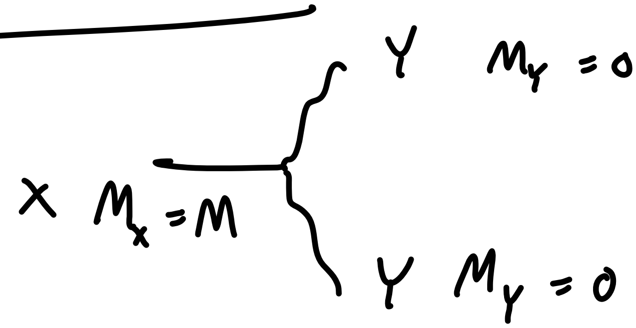
Bremsstrahlung

$$\frac{dE}{d\Omega\, d\omega} = \frac{\omega^2}{16\pi^3 M_p^2} \sum_{N,M} \frac{\eta_N \eta_M}{P_N\cdot k\; P_M\cdot k} \left[(P_N \cdot P_M)^2 - \tfrac{1}{2} m_N^2 m_M^2 \right]$$

$$\eta = \pm 1 \begin{cases} \text{incoming line} \\ \text{outgoing line} \end{cases}$$

Illustrative examples

① Decays



$$\frac{dE}{d\omega\, d\Omega} = \frac{1}{4\pi^2}\,\frac{M^2}{M_p^2} \times N_X$$

$$\to h^2 \sim \frac{E \cdot H^3}{\rho_{Tot}} \sim \frac{\rho_X}{\rho_{Tot}}\,\frac{HM}{M_p^2} \le \varepsilon \frac{H}{M_p}$$

→ tensors even for $\frac{H}{M_p}$ as low as $\frac{10^{-12}}{\varepsilon}$

(cf $\frac{H}{M_p} \sim 10^{-6}$ for usual inflationary source)

- Here taking $\partial_\alpha M$ small at decay time s.t. $\delta\alpha$ Negligible
- Scalar emission from production satisfies $P_s \le 10^{-10}$

$N_X \sim 10^8$

$\frac{H}{M_p} \sim 10^{-9}$

② Scattering Bremsstrahlung

– similar analysis

③ Decay of strings into gravitons,

in axion monodromy inflation

McAllister
ES
Westphal

- $T(\phi) = \sqrt{(\eta M_p \phi)^2 + T_0^2}$

$\simeq \eta M_p \phi$ $\Rightarrow$ coupling to ϕ along w/ h

- $\left.\frac{dE}{dt}\right|_{\delta\phi} \sim 50 \eta^2 M_p^2$

$\vee$ initially
$\vee$

$\left.\frac{dE}{dt}\right|_{GW} \sim 50 \frac{T^2}{M_p^2}$

$$\left.\frac{dE}{dt}\right|_{\delta\alpha} \sim 50\eta^2 M_p^2 \quad \underline{\text{constant}}$$

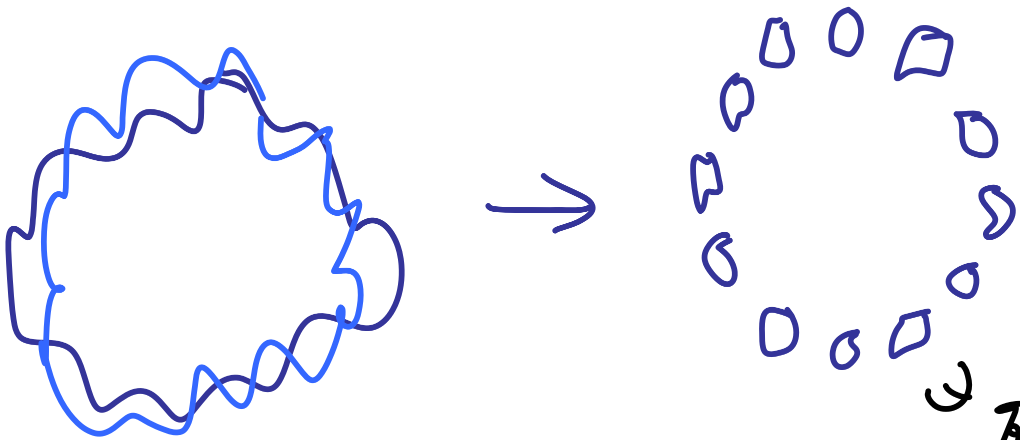
For sufficiently small η, or for a distribution including long loops (favored at high density), strings gain energy from $T(t)$ before decaying $\to \delta\alpha$

$\to$ Tension ramps up to $> \frac{1}{g'}$

$\Rightarrow$ Strings decay into closed fundamental strings Y, then to GWs.

$\to$ $h \gtrsim 10^{-6}$, depending on size distribution

④ dilute pairs



$$h^2 \sim \left(\frac{H}{M_p}\right)^2 \times \frac{\dot{\varphi}^{3/2}}{H M_p^2} \times N_{pairs}$$

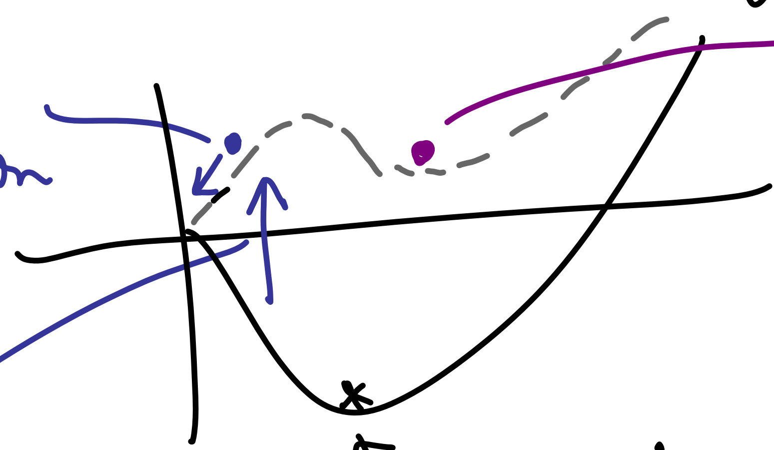
including effects of $T(t) \propto t$

Bremsstrahlung

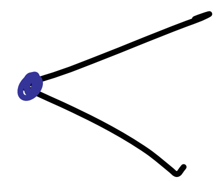
② Uplifting AdS/CFT and FRW holography

FRW expansion

metastable dS



AdS, known CFT dual



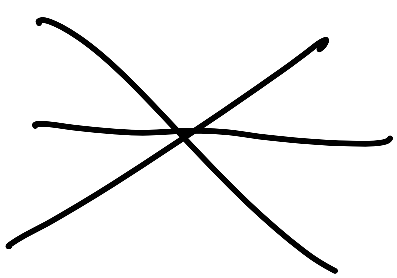
e.g.

$$AdS_5 \times S^5$$

+ magnetic flavor branes

(p,q) 7-branes

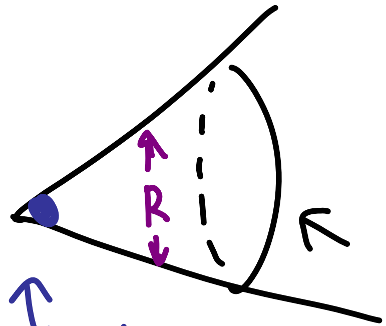
$n > 36$:



no nonsingular static solution

$\hookrightarrow$ ∞ number of d.o.f. $E_{n>8}$

AdS/CFT



$$\left(\frac{dR}{dr}\right)^2 = \frac{1}{R^2} \to R = r \quad \text{(cone)}$$

R>0 Einstein space

color branes

Gravitational Redshift $g_{00} \sim 1 - \frac{R^4}{r^4}$

= Low-energy region

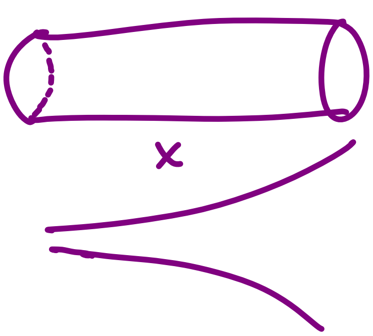
Our strategy: look for this in cosmo uplift

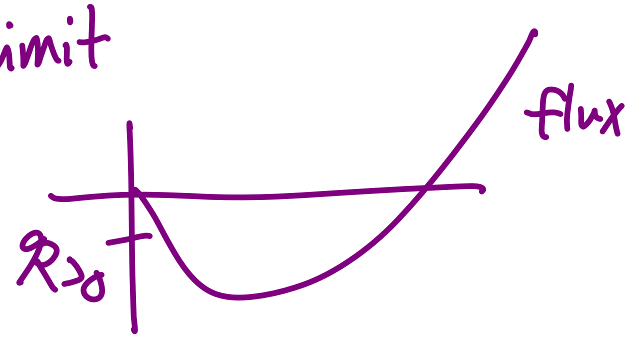
dS, FRW

cf Kerr/CFT

$$E = \sqrt{-g_{00}}\, E_{pr} \ll E_{pr}$$

→ Effective field theory dual, complete QFT in strict near-horizon limit

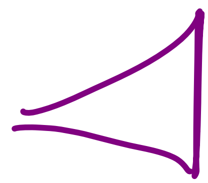




RS / warped compactifications

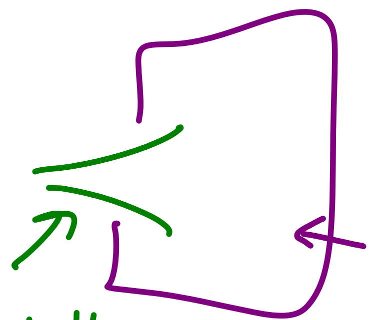
$$ds^2 \simeq \frac{r^2}{R^2}\, dx^2 + \frac{R^2}{r^2}\, dr^2 + \text{internal}$$

$r < r_{uv}$



H. Verlinde
GKP

or



$$\simeq \underbrace{CFT_{d-1}} + \underbrace{GR_{d-1}} + \cdots$$

$$E < \Lambda_c = \frac{r_{uv}}{R^2} \;\Big|\; M_p^2 \sim \frac{r_{uv}^2}{R^4} N^2 + \frac{Vol(X)}{g_s^2}$$

$\rightarrow$ complete QFT in limit

$$r_{uv} \to \infty \quad \text{with} \quad \frac{r_{uv}^2}{R^4} N^2 > \frac{Vol(X)}{g_s^2}$$

(Can happen in t-dependent way.)

Magnetic flavors & uplifting

e.g. IIB (p,q) 7Bs wrapping $\Sigma_3 \subset S^5$

Tension $\propto \Lambda \times \frac{1}{R^2}\frac{1}{g_s^2}$

Competes with curvature

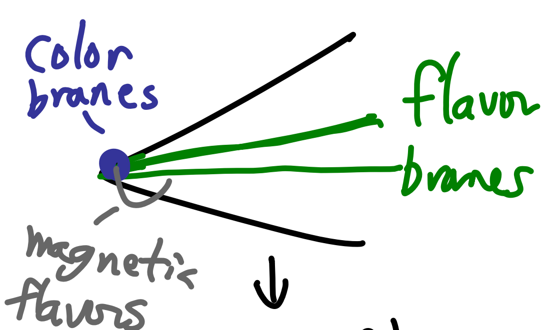
$S^1 \to S^{5 \text{ or } 3}$
$\downarrow$
$\mathbb{CP}^{2 \text{ or } 1}$

on $\mathbb{CP}^1$: 24 7Bs $\to \mathcal{R} = 0$

$\mathbb{CP}^2$: 36 7Bs $\to \mathcal{R} = 0$

$$\Delta n \equiv n - n_{\mathcal{R}=0}$$

$\Delta n < 0$	$\Delta n \gtrsim 0$	$\Delta n > 0$
AdS	Cosmo	generic



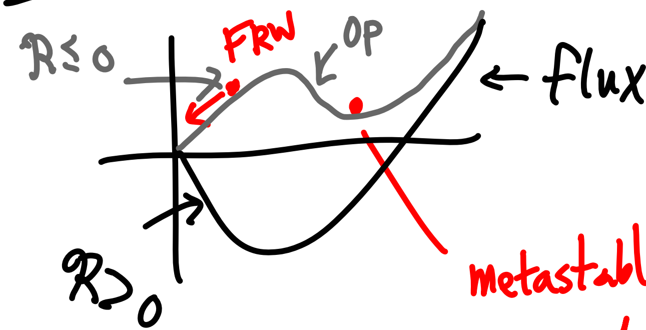
$\downarrow$

Static sol'n

no static solution, but $\exists$ simple t-dep't solutions

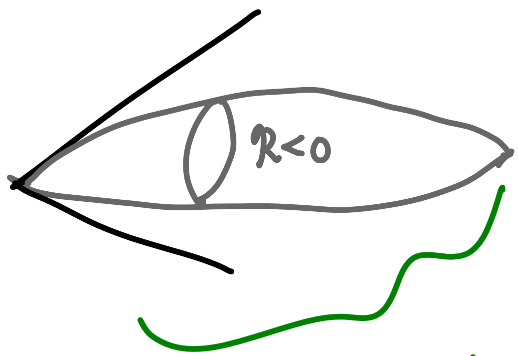
cf Kleban + Redi

dS phase



metastable dS is like Randall/Sundrum

$$ds^2 = \underbrace{\sin^2\frac{w}{L}\, ds^2_{dS_{d-1}}}_{\text{2 redshifted regions}} + dw^2$$



2 tips

Alishahiha Karch ES Tong

Dong Horn ES Torroba

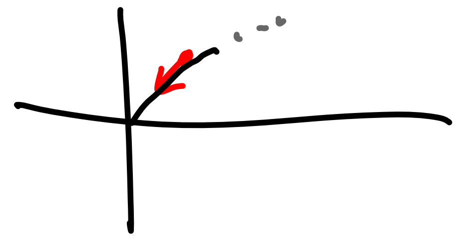
$$\left(\frac{dR}{dr}\right)^2 = \frac{-1}{R^2} + \frac{\text{const}}{R^{n>2}}$$

dS is a 2-throat warped compactification w/ $GR_{d-1} \leftrightarrow$ finite S

limited precision expected

* What about FRW?
$S \to \infty$, will see has redshifted (EFT) region with $\frac{1}{G_{N,d-1}} \to \infty$ $t \to \infty$

FRW phase $\Delta n > 0$



Vacuum Solution:

$$ds^2 = -dt_s^2 + \frac{t_s^2}{c^2}\Big(d\mathbb{H}^{(1)\,2}_{d-1} + \underbrace{d\mathbb{H}^{(2)\,2}_{d-1}\Big) + R_f^2\, d\varphi_f^2}_{(d=5)\ S^5 + 7Bs}$$

$c > 1$

$(d=5 \quad c^2 = \frac{7}{3})$

Reduce to d-dim'l Einstein frame:

$$ds^2 = -dt^2 + c^2 t^2 \left[d\mathbb{H}^2_{d-1} = d\chi^2 + \cosh^2\frac{\chi}{\ell}\, d\mathbb{H}^2_{d-2} \right]$$

with $m_{KK} \sim \frac{1}{t}$ (from internal $\mathbb{H}_{d-1}$)

(like $AdS_5 \times S^5$, no hierarchy)

$$m_{77} \propto \frac{1}{t^{1/7}}, \quad m_{str} \propto \frac{1}{t^{4/7}}$$

This solution is sourced by the magnetic flavors alone, good for $t \to \infty$ since F_5 flux $\sim \frac{N_c}{R^4 R_f}$ dilutes away.

Can write this as a warped metric:

$$ds^2 = \frac{c^2}{\ell^{2(c-1)}}\left(\eta^2 - w^2\right)^{c-1}\left(dw^2 - d\eta^2 + \frac{\eta^2}{\ell^2} dH_{d-2}^2\right)$$

$$= \left(1 - \frac{w^2}{t^{2/c}}\right)^{c-1}\left(-dt^2 + c^2 t^2 dH_{d-2}^2\right)$$

$$+ \left(\frac{t}{\ell}\right)^{2(1-\frac{1}{c})}\left(1 - \frac{w^2}{t^{2/c}}\right)^{c-1} dw^2$$

Gravitational redshift for $c > 1$ $(\Delta n > 0)$

$$\boxed{E_t \sim \left(1 - \frac{w^2}{t^{2/c}}\right)^{\frac{c-1}{2}} E_{proper}} \Rightarrow \text{candidate EFT}$$

+ additional warping from color flux

Basic properties

1) $$\frac{1}{G_{N,d-1}} = M_{d-1}^{d-3} \sim \int dw \sqrt{g}\, g^{''} \propto t$$

GR_{d-1} at finite time; $\xrightarrow[t\to\infty]{} \infty$

☆ EFT makes large contribution to this as $t\to\infty$

$S_{Bousso} \to \infty \quad t\to\infty$

2) Particle dynamics: massive & massless particles $m \propto t^{-\gamma}$ stable in IR region (throat "long")

3) Color branes move up throat (motion sickness)

4) Power-law correlation functions for KK modes

Count of degrees of Freedom

(a) Macro :

- $\frac{1}{G_{N,d-1}} \sim t$

  $\sim N_{d.o.f.} \Lambda_c^{d-3}$

  $\Lambda_c \sim \frac{1}{t}$

  $N_{d.o.f.} \sim t^{d-2}$

- $H_{d-1}^2 \sim \frac{1}{t^2} \sim N_{d.o.f.} \Lambda_c^{d-1} \underbrace{G_{N,d-1}}_{\frac{1}{t}}$

Can also work with static metric for d-1 theory, getting

$$\Lambda_c \sim \text{const}, \quad Vol_{QFT} \sim \text{const}$$

Count of degrees of freedom

(b) <u>Micro</u>

$$\begin{array}{ccc} S^1_f & \to & S^{n+1} \\ & & \downarrow \\ & & \mathbb{CP}^{\frac{n}{2}} \end{array}$$

7Bs wrapped on fiber S^1, at real codimension 2 on $\mathbb{CP}^{\frac{n}{2}}$ base.

Counting strings stretching b/w 7Bs, & with winding + momenta on S^1, up to cutoff from backreaction & topology, in all cases we get precisely $N_{dof} \sim t^{d-2}$

· core size: $\frac{n}{r_c^5} \sim 1 \quad r_c < R \sim t^{\frac{3}{5}}$

· winding, momenta $\quad n_f, k_f < R$

$$N_{dof} \sim n n_f k_f < t^{5 \cdot \frac{3}{5} + 2 \times \frac{3}{5} = 3}$$