# Dangerous Angular KK/Glueball Relics in String Theory Cosmology

**Reheating after String Theory Inflation**

**Dangerous Angular KK Relics**

**Observational Constraints**

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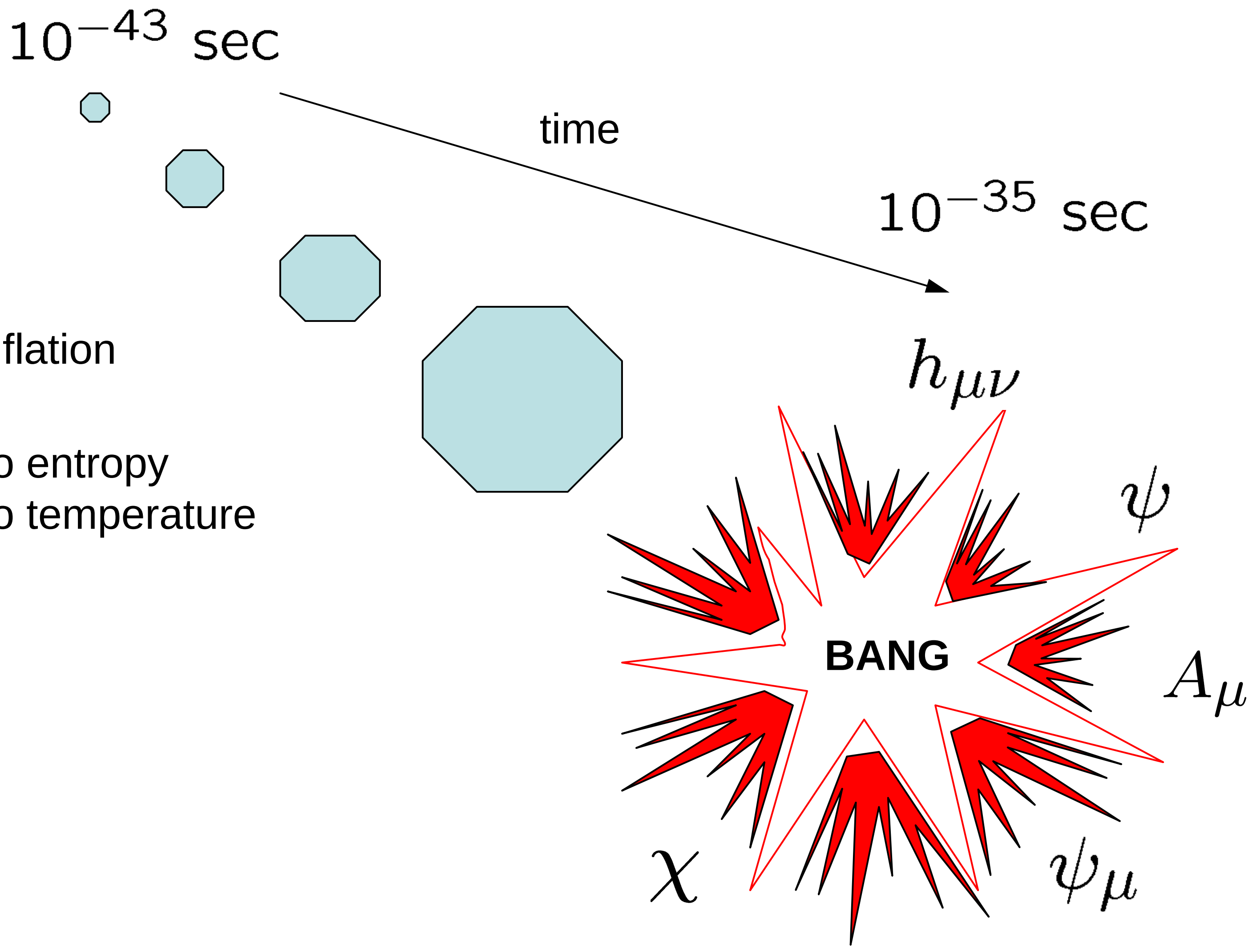
# Particlegenesis



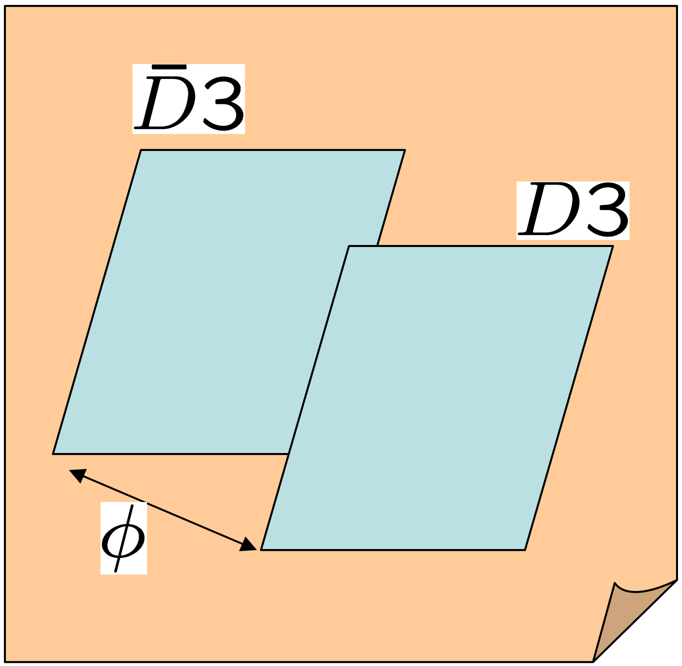

Inflation

no entropy
no temperature

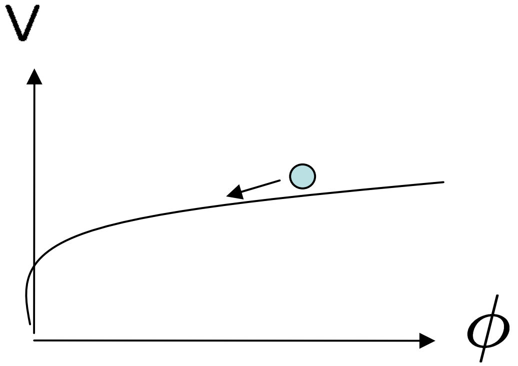
$$\mathcal{L}(\phi, \chi, \psi, A_\mu, \psi_\mu, h_{\mu\nu})$$

$$
\begin{aligned}
e^{-1}\mathcal{L} \;=\; & -\tfrac{1}{2}M_P^2\left[R+\bar{\psi}_\mu R^\mu+\mathcal{L}_{SG,torsion}\right]-g_i{}^j\left[M_P^2(\hat{\partial}_\mu z^i)(\hat{\partial}^\mu z_j)+\bar{\chi}_j\,\not{\mathcal{D}}\chi^i+\bar{\chi}^i\,\not{\mathcal{D}}\chi_j\right]\\
+\; & (\mathrm{Re}\,f_{\alpha\beta})\left[-\tfrac{1}{4}F^\alpha_{\mu\nu}F^{\mu\nu\,\beta}-\tfrac{1}{2}\bar{\lambda}^\alpha\,\hat{\not{\mathcal{D}}}\lambda^\beta\right]+\tfrac{1}{4}\mathrm{i}(\mathrm{Im}\,f_{\alpha\beta})\left[F^\alpha_{\mu\nu}\tilde{F}^{\mu\nu\,\beta}-\hat{\partial}_\mu\left(\bar{\lambda}^\alpha\gamma_5\gamma^\mu\lambda^\beta\right)\right]\\
-\; & M_P^{-2}\mathrm{e}^{\mathcal{K}}\left[-3WW^*+(\mathcal{D}^iW)g^{-1}{}_i{}^j(\mathcal{D}_jW^*)\right]-\tfrac{1}{2}(\mathrm{Re}\,f)^{-1\,\alpha\beta}\mathcal{P}_\alpha\mathcal{P}_\beta\\
& +\;\tfrac{1}{8}(\mathrm{Re}\,f_{\alpha\beta})\bar{\psi}_\mu\gamma^{\nu\rho}\left(F^\alpha_{\nu\rho}+\hat{F}^\alpha_{\nu\rho}\right)\gamma^\mu\lambda^\beta\\
& +\;\Big\{M_Pg_j{}^i\bar{\psi}_{\mu L}(\hat{\not{\partial}}z^j)\gamma^\mu\chi_i+\bar{\psi}_R\cdot\gamma\left[\tfrac{1}{2}\mathrm{i}\lambda^\alpha_L\mathcal{P}_\alpha+\chi_iY^3M_P^{-4}\mathcal{D}^iW\right]\\
& \qquad +\tfrac{1}{2}Y^3M_P^{-3}W\bar{\psi}_{\mu R}\gamma^{\mu\nu}\psi_{\nu R}-\tfrac{1}{4}M_P^{-1}f^i_{\alpha\beta}\bar{\chi}_i\gamma^{\mu\nu}\hat{F}^{-\alpha}_{\mu\nu}\lambda^\beta_L\\
& \qquad -Y^3M_P^{-5}(\mathcal{D}^i\mathcal{D}^jW)\bar{\chi}_i\chi_j+\tfrac{1}{2}\mathrm{i}(\mathrm{Re}\,f)^{-1\,\alpha\beta}\mathcal{P}_\alpha M_P^{-1}f^i_{\beta\gamma}\bar{\chi}_i\lambda^\gamma-2M_P\xi_\alpha{}^ig_i{}^j\bar{\lambda}^\alpha\chi_j\\
& \qquad +\tfrac{1}{4}M_P^{-5}Y^3(\mathcal{D}^jW)g^{-1}{}_j{}^if_{\alpha\beta i}\bar{\lambda}^\alpha_R\lambda^\beta_R\\
& \qquad -\tfrac{1}{4}M_P^{-1}f^i_{\alpha\beta}\bar{\psi}_R\cdot\gamma\chi_i\bar{\lambda}^\alpha_L\lambda^\beta_L+\tfrac{1}{4}M_P^{-2}(\mathcal{D}^i\partial^jf_{\alpha\beta})\bar{\chi}_i\chi_j\bar{\lambda}^\alpha_L\lambda^\beta_L+\mathrm{h.c.}\Big\}\\
& +\;g_j{}^i\left(\tfrac{1}{8}e^{-1}\varepsilon^{\mu\nu\rho\sigma}\bar{\psi}_\mu\gamma_\nu\psi_\rho\bar{\chi}^j\gamma_\sigma\chi_i-\bar{\psi}_\mu\chi^j\,\bar{\psi}^\mu\chi_i\right)\\
& +\;M_P^{-2}\left(R^{k\ell}_{ij}-\tfrac{1}{2}g_i{}^kg_j{}^\ell\right)\bar{\chi}^i\chi^j\bar{\chi}_k\chi_\ell\\
& +\;\tfrac{3}{64}M_P^{-2}\left((\mathrm{Re}\,f_{\alpha\beta})\bar{\lambda}^\alpha\gamma_\mu\gamma_5\lambda^\beta\right)^2-\tfrac{1}{16}M_P^{-2}f^i_{\alpha\beta}\bar{\lambda}^\alpha_L\lambda^\beta_Lg^{-1}{}_i{}^jf_{\gamma\delta j}\bar{\lambda}^\gamma_R\lambda^\delta_R\\
& +\;\tfrac{1}{8}(\mathrm{Re}\,f)^{-1\,\alpha\beta}M_P^{-2}\left(f^i_{\alpha\gamma}\bar{\chi}_i\lambda^\gamma-f_{\alpha\gamma i}\bar{\chi}^i\lambda^\gamma\right)\left(f^j_{\beta\delta}\bar{\chi}_j\lambda^\delta-f_{\beta\delta j}\bar{\chi}^j\lambda^\delta\right).
\end{aligned}
$$

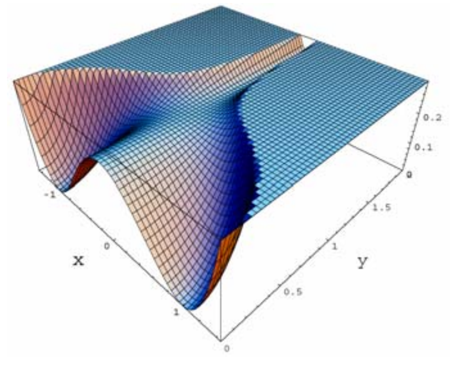
# Inflation with branes




**4-dim picture**



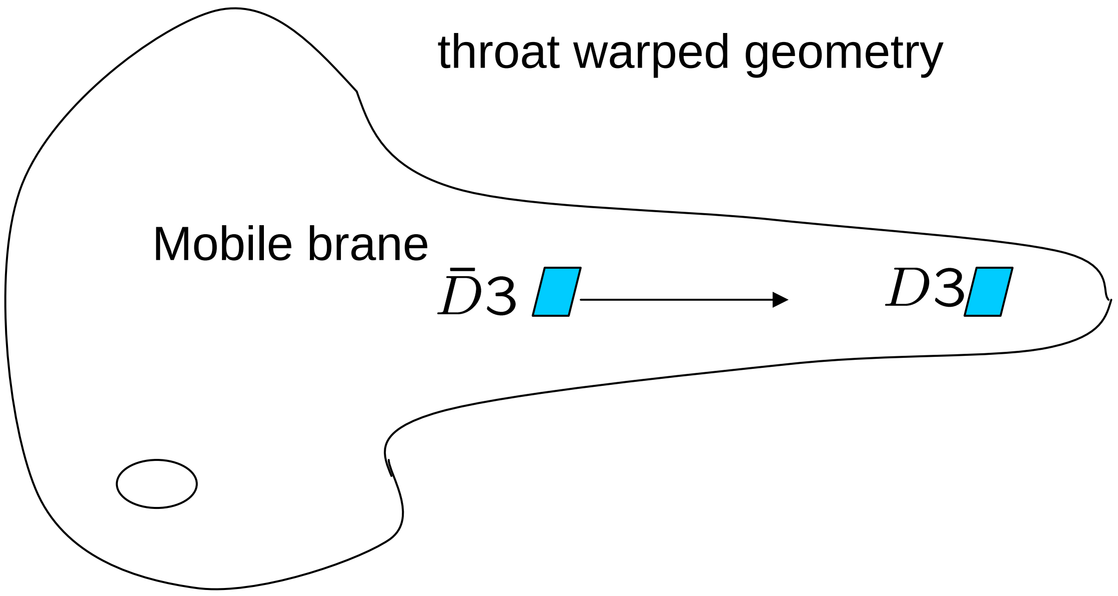

**Prototype of hybrid inflation**

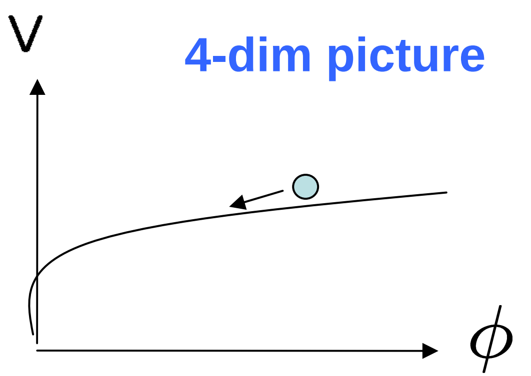


# Realization of String Theory Hybrid Inflation

Warped brane inflation

throat warped geometry



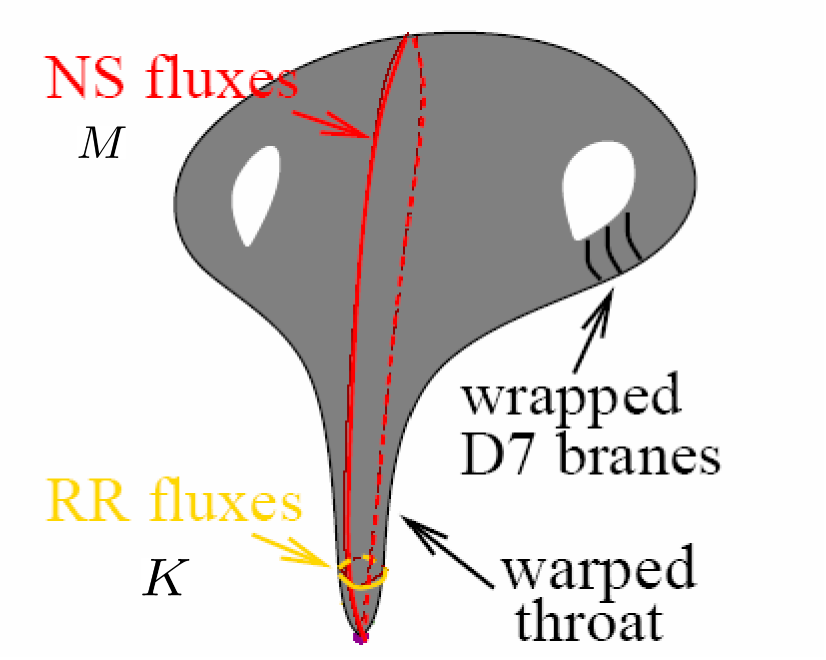

KKLMMT03

$$V = V_0 \left[ 1 - \left( \frac{\Delta}{\kappa \phi} \right)^4 \right]$$

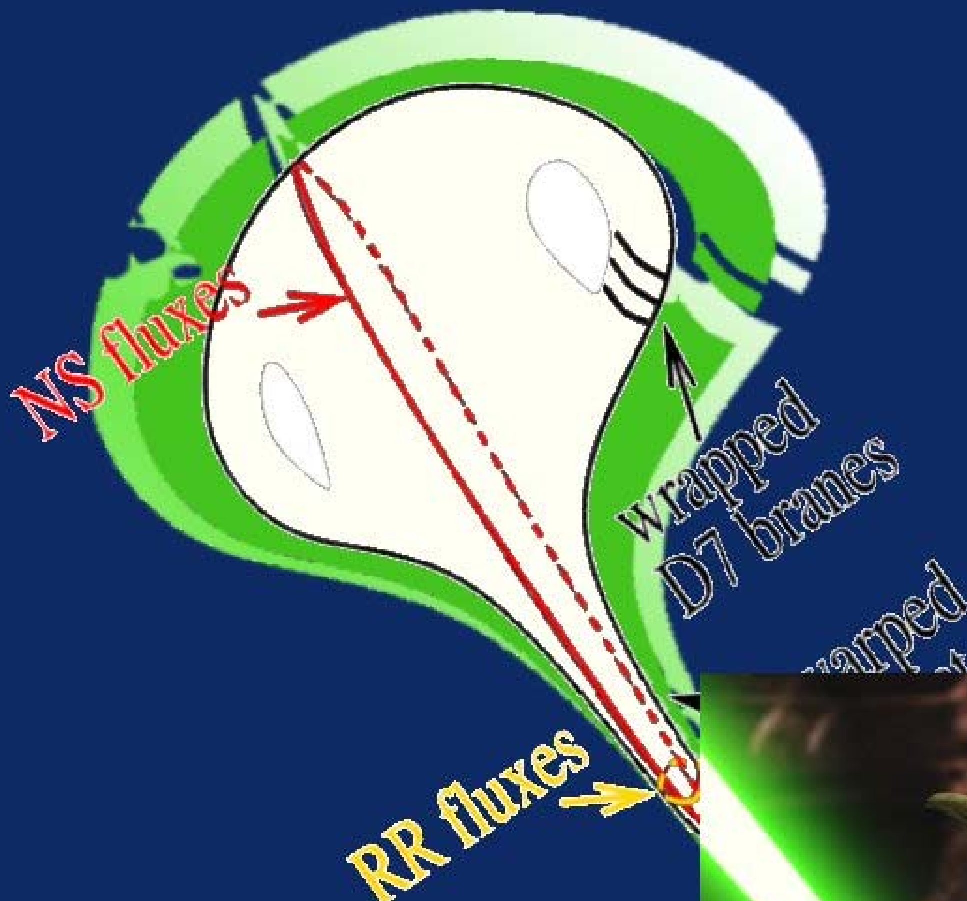
## Warped Brane Inflation in String Theory

on the ground of KKLT throat warped geometry

throat warped geometry




$$KM = \frac{\chi}{24}$$


NS fluxes
wrapped
D7 branes
warped
RR fluxes

Klebanov-Strassler geometry

$$ds^2 = h^{-1/2}(\tau)\eta_{\mu\nu}dx^\mu dx^\nu + h^{1/2}(\tau)ds_6^2$$

$$ds_6^2 = \frac{\epsilon^{4/3}}{2}K(\tau)\left[\frac{1}{3K^3(\tau)}\left(d\tau^2 + (g^5)^2\right) + \cosh^2\left(\frac{\tau}{2}\right)\left((g^3)^2 + (g^4)^2\right) + \sinh^2\left(\frac{\tau}{2}\right)\left((g^1)^2 + (g^2)^2\right)\right]$$

$$\begin{aligned} g^1 &= \frac{e^1 - e^3}{\sqrt{2}}, \quad g^2 = \frac{e^2 - e^4}{\sqrt{2}}, \\ g^3 &= \frac{e^1 + e^3}{\sqrt{2}}, \quad g^4 = \frac{e^2 + e^4}{\sqrt{2}}, \quad g^5 = e^5 \end{aligned}$$

$$\begin{aligned} e^1 &\equiv -\sin\theta_1 d\phi_1, \quad e^2 \equiv d\theta_1, \\ e^3 &\equiv \cos\psi\sin\theta_2 d\phi_2 - \sin\psi d\theta_2, \\ e^4 &\equiv \sin\psi\sin\theta_2 d\phi_2 + \cos\psi d\theta_2, \\ e^5 &\equiv d\psi + \cos\theta_1 d\phi_1 + \cos\theta_2 d\phi_2 \end{aligned}$$

$$h(\tau) = 2^{2/3}\cdot(g_s M\alpha')^2\epsilon^{-8/3}I(\tau),$$

$$K(\tau) = \frac{(\sinh(2\tau) - 2\tau)^{1/3}}{2^{1/3}\sinh\tau}$$

$$I(\tau) = \int_\tau^\infty dx\frac{x\coth x - 1}{\sinh^2 x}(\sinh(2x) - 2x)^{1/3}$$

$$\frac{1}{2\pi\alpha'}\int_A F_{(3)} = 2\pi M, \qquad \frac{1}{2\pi\alpha'}\int_B H_{(3)} = 2\pi K$$

$$h \simeq e^{-(2\pi K/3g_s M)}$$

$$H = \frac{1}{r^4}\left(R_+^4 + R_-^4 \log(r/R_+)^4\right)$$

$$R_+^4 \equiv \frac{27\pi}{4}\alpha'^2 g_s M K, \qquad R_-^4 \equiv \frac{3}{8\pi}\frac{27\pi}{4}\alpha'^2 g_s^2 M^2$$

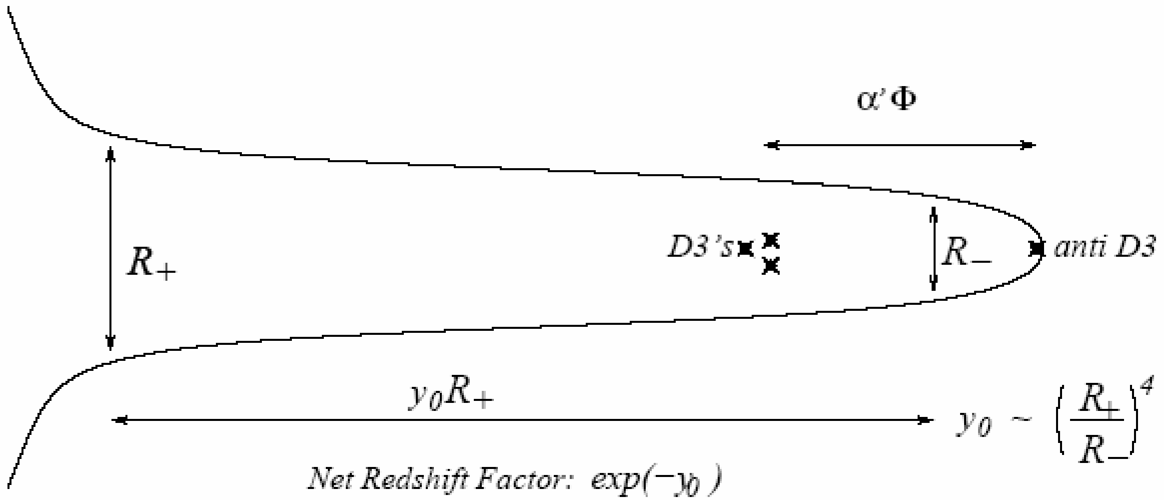
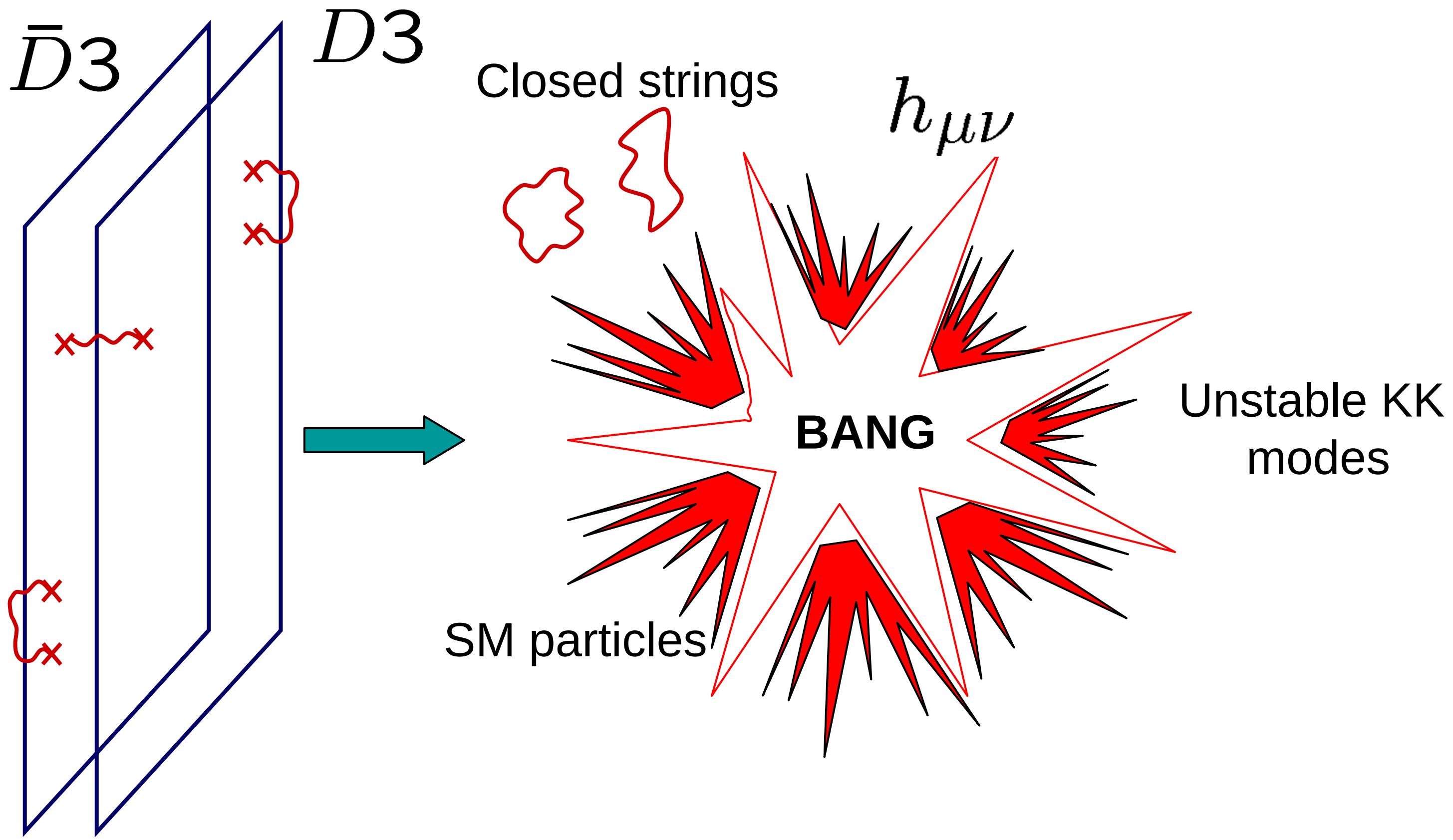



Figure 1: Radial geometry of a Klebanov Strassler throat. For most part of this paper, we consider KKLMMT-like inflation scenario where unstable D-brane system of D3 branes and anti-D3 branes near the bottom of the throat drives inflation, possibly with some leftover D3's.

$$ds^2 = e^{-2y/R}\,\eta_{\mu\nu}\,dx^\mu dx^\nu + dy^2 + R^2\,f_{ij}(\Omega)\,d\theta^i d\theta^j$$

## End point of inflation

LK, Yi 05




Open strings

between branes are unstable

## Reheating after String Theory Inflation

Barnaby, Burgess, Cline, hep-th/0412095

LK, Yi, hep-th/0507257

Frey, Mazumdar, Myers, hep-th/0508139

Chialva, Shiu, Underwood, hep-th/0508229

Chen, Tye, hep-th/05120000; 0602136

Berndsen, Cline, Stoica, 0710.1299

v.Harling, Hebecker, 0801.4015

Dufaux, LK, Peloso 0802.2958

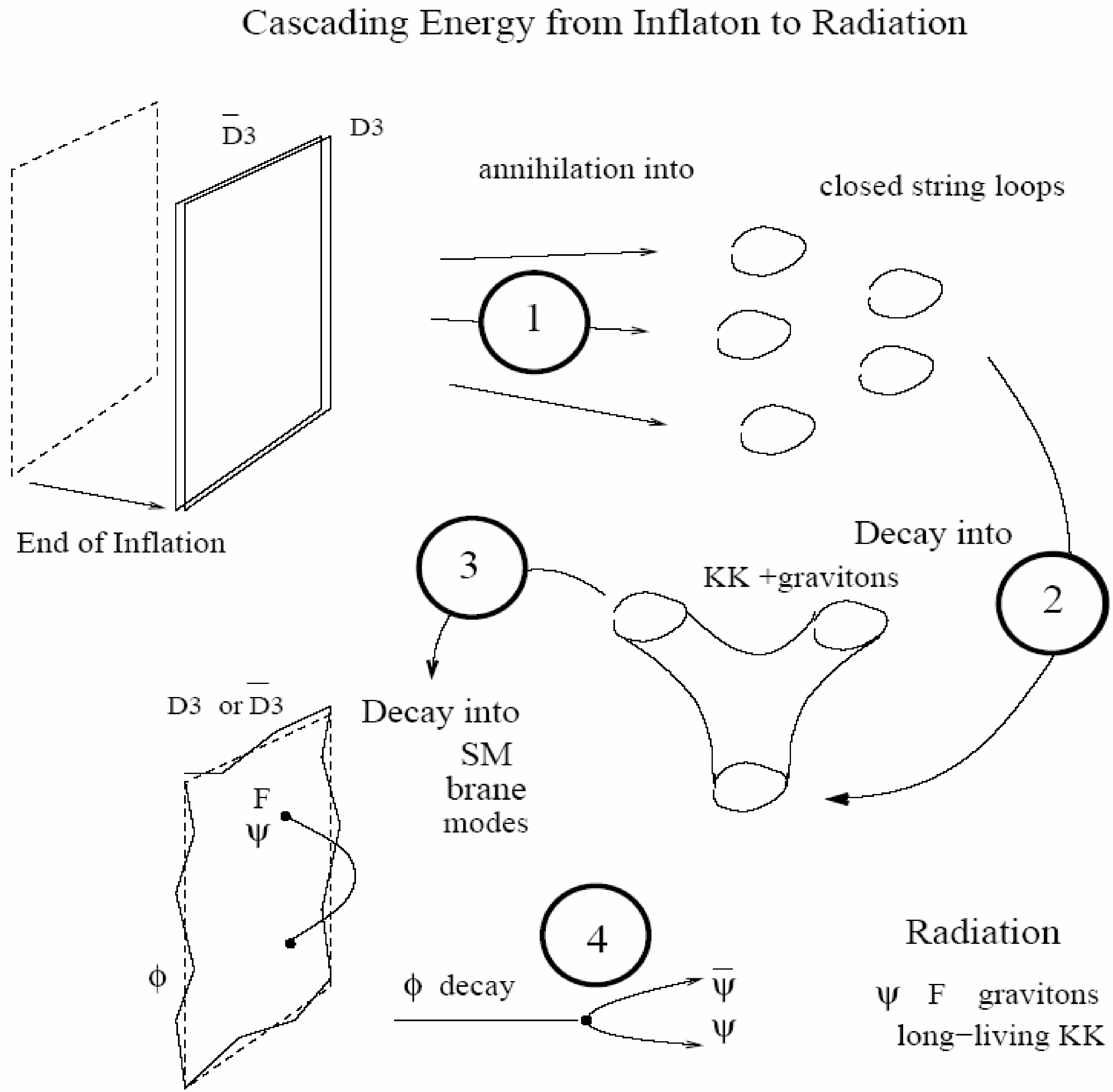



Figure 2: Identifying the channels of D-brane decay

# $D-\bar{D}$ Annihilation and Closed Strings Production

$$\omega_{n,k} = \sqrt{\vec{k}_\perp^2 + 4N}$$

$$\frac{E}{V_3} \simeq \sum_N \int d^{(d-3)}k_\perp \, D(N) \, e^{-2\pi\omega_{N,k}}$$

$$D(N) \simeq N^{-q} e^{4\pi\sqrt{N}}$$

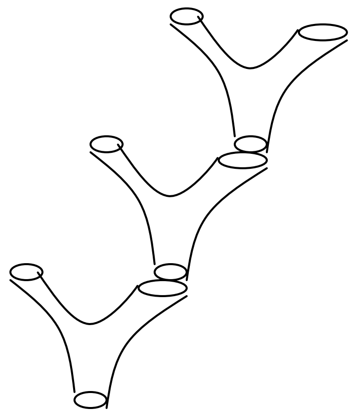
in bosonic theory $q = 27/4$, $d = 25$; in superstring theory $d = 9$ and $q$ is not known

$$m_s^2 = e^{-2y_0}\frac{1}{\alpha'}$$

$$\omega \sim \sqrt{p^2 + m_s^2 \, N}$$

$$\omega_{max} \sim 1/g_s$$

# Closed Strings Decay to Local KK Modes



$$\Gamma \sim g_s^2 e^{-y_0}/\sqrt{\alpha'}$$

$$\Delta t_2 \sim N_{max}/\Gamma \qquad N_{max} \sim 1/g_s^2$$

$$\Delta t_2 \sim g_s^{-4} e^{y_0} \sqrt{\alpha'}$$

$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}(x^\lambda, y^c)$$

$$\mathcal{M} \times R^4$$

$$h_{\mu\nu}(x^\lambda, y^a) = \sum_m \Phi_m(y^a)\, \gamma_{\mu\nu}^{(m)}(x^\lambda)$$

$m = 0$: usual 4 dim gravitons

other $m$: modes $m_{KK} \simeq e^{-A}/R$

# KK Modes of Isometric Throat

$$\Box_{(4)}\gamma_{\mu\nu}^{(m)} = m^2\,\gamma_{\mu\nu}^{(m)} \qquad -\frac{d}{dy}\left[e^{-4y/R}\frac{d\Phi_m}{dy}\right] - \frac{e^{-4y/R}}{R^2}\Delta_f\Phi_m = m^2\,e^{-2y/R}\,\Phi_m$$

$$\Phi_m(y^c) = \psi_{nL}(y)\,Q_L^M(\Omega_5)$$

$$\Delta_f Q_L^M = -F^2(L)\,Q_L^M$$

$$\psi_{nL}(y) = N_{nL}\,e^{2y/R}\,\left[J_\nu(m_{nL}Re^{y/R})\right.$$

$$\nu = \sqrt{4+F^2(L)}$$

$$m_{nL} = \frac{\xi_{nL}}{R}\,e^{-y_t/R}$$

$m \sim (2\times10^{14} - 10^{15})\,\text{GeV}$ , short throat

$m \sim (200 - 5{,}000)\,\text{GeV}$ , long throat

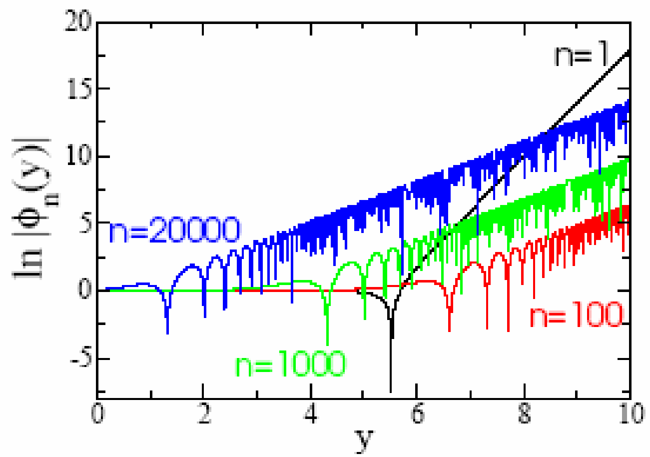
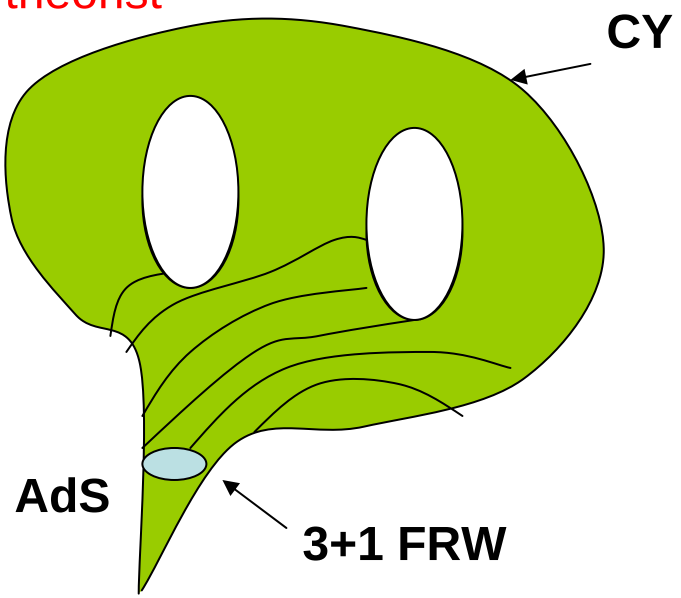



**Figure 4:** Unnormalized wave functions for highly excited KK gravitons with KK numbers $n = 1$, 100, 1000 and 20,000.

# Fluctuations in Cosmology with Compactification

string theorist



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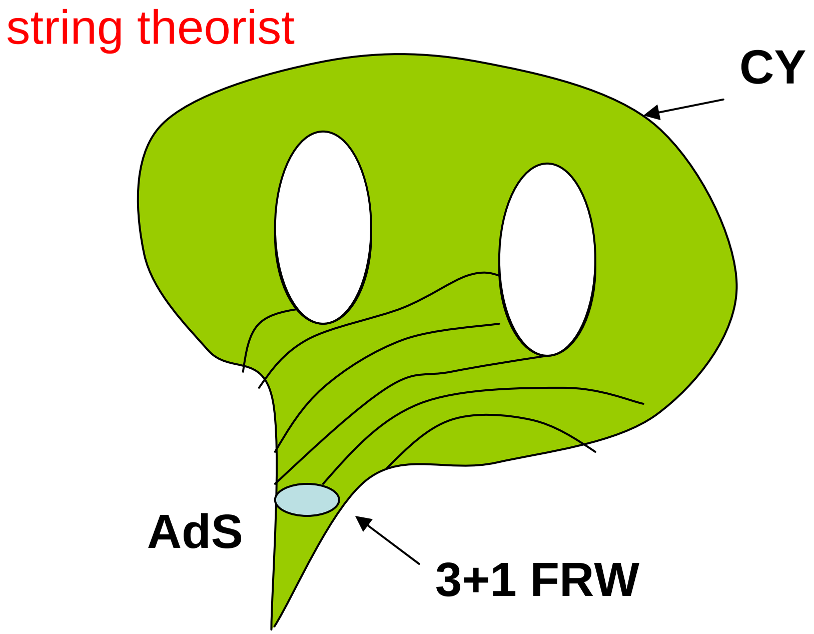
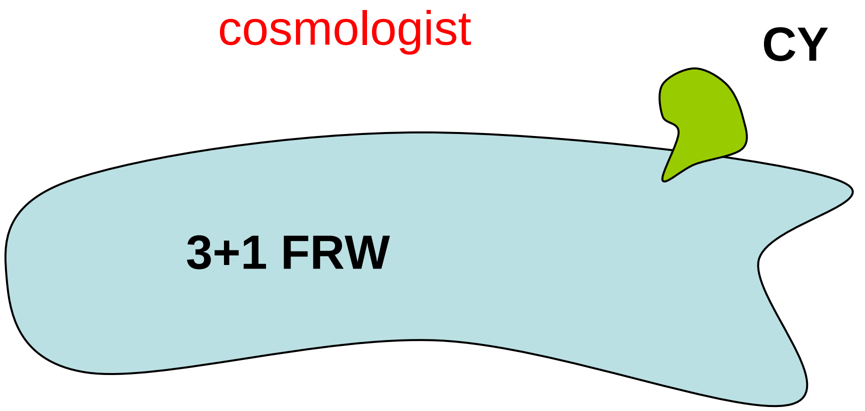
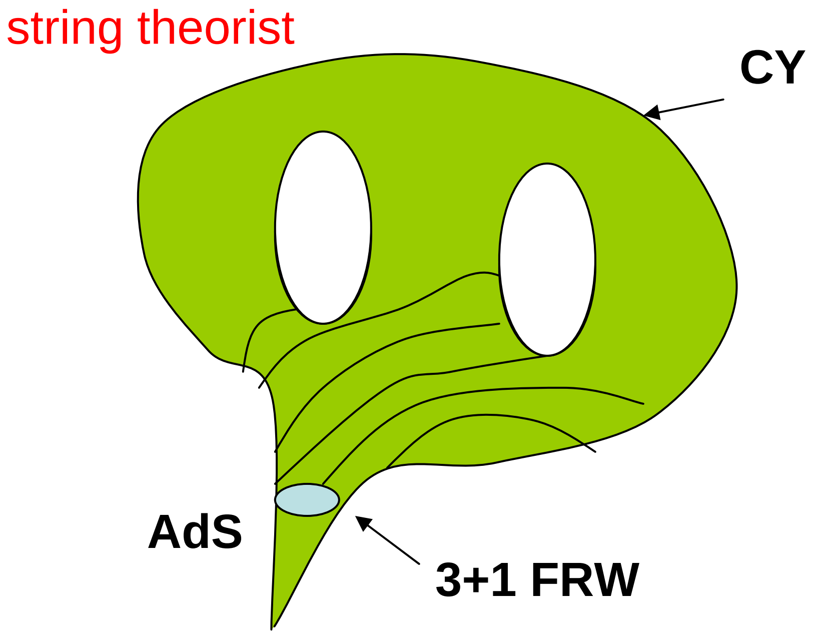
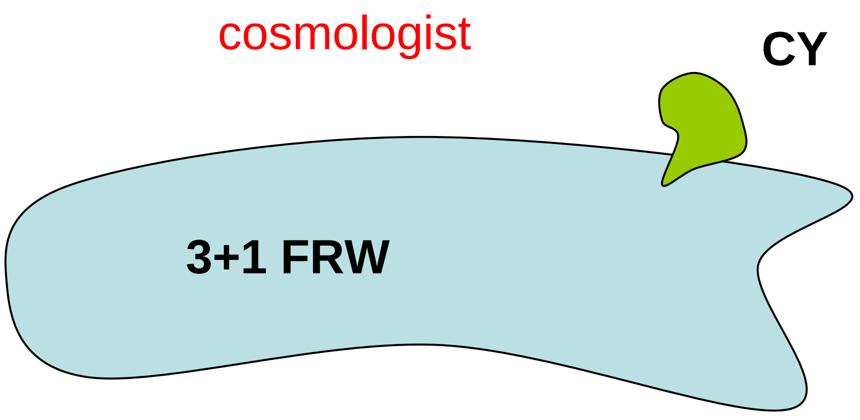
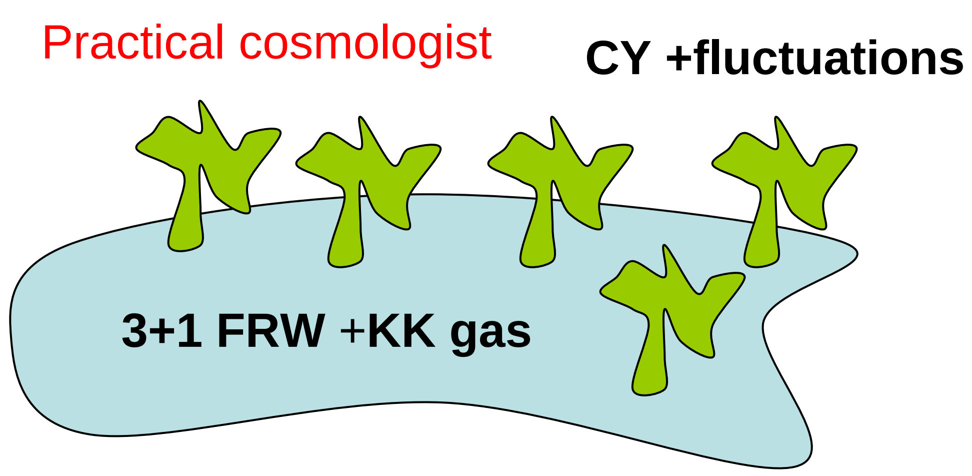


# Fluctuations in Cosmology with Compactification



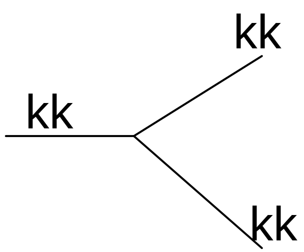
# INTERACTIONS OF KK MODES

bulk action

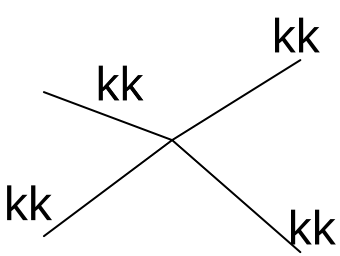
$$S = \frac{M_D^{D-2}}{2} \int d^D x \sqrt{-G}\, (R + 2\,\mathcal{L}) \qquad M_{\rm Pl}^2 = \frac{2\,V_6}{(2\pi)^7\, g_s^2\, \alpha'^4}$$

$$\frac{M_{10}^8 R^5}{2} \int e^{-2y/R}\, \psi_{nL}\, \psi_{n'L'}\, \psi_{n''L''}\, dy \int Q_L^M\, Q_{L'}^{M'}\, Q_{L''}^{M''}\, d\Omega_5 \int \gamma_\mu^{(m)\nu}\, \partial_\sigma \gamma_{\nu\rho}^{(m)}\, \partial^\sigma \gamma^{\mu\rho}_{(m)}\, d^4x$$

$$= \lambda_{3{\rm KK}} \int \gamma_\mu^{(m)\nu}\, \partial_\sigma \gamma_{\nu\rho}^{(m)}\, \partial^\sigma \gamma^{\mu\rho}_{(m)}\, d^4x \ ,$$

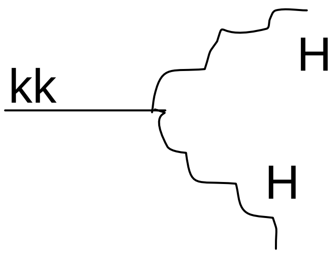



$$\lambda_{3{\rm KK}} \approx \left(\frac{V_6}{R^6}\right)^{1/2} \frac{e^{yt/R}}{M_{\rm Pl}}$$




$$\lambda_{4{\rm KK}} \approx \lambda_{3{\rm KK}}^2$$

## KK-SM particles Interactions




$$\int d^D x \sqrt{-G_{(\text{ind})}}\, G^{\mu\nu}_{(\text{ind})}\, \partial_\mu H\, \partial_\nu H\, \delta^{(6)}(y^c - y^c_b) = \int d^4 x \sqrt{-g(y^c_b)}\, g^{\mu\nu}(y^c_b)\, \partial_\mu \hat{H}\, \partial_\nu \hat{H}$$

$$Q^M_L(\Omega_b)\, \psi_{nL}(y_b) \int d^4 x\, \gamma^{\mu\nu}_{(m)}\, \partial_\mu \hat{H}\, \partial_\nu \hat{H} = \lambda_{\mathrm{KK\,b\,b}} \int d^4 x\, \gamma^{\mu\nu}_{(m)}\, \partial_\mu \hat{H}\, \partial_\nu \hat{H}$$

$\lambda_{\mathrm{KK}\,b\,b}$ vanishes for all $M \neq 0$

$M$ is the projection of the angular momentum along the $z$-axis

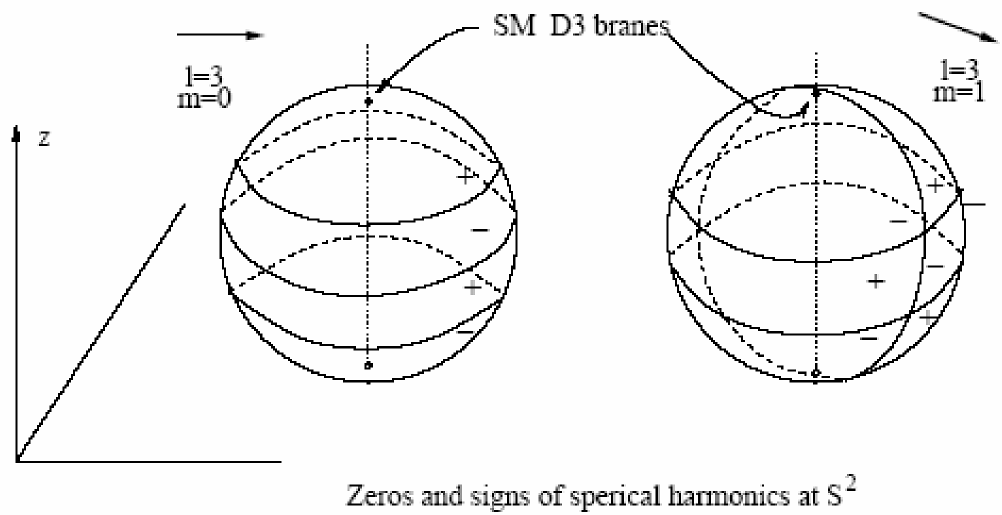
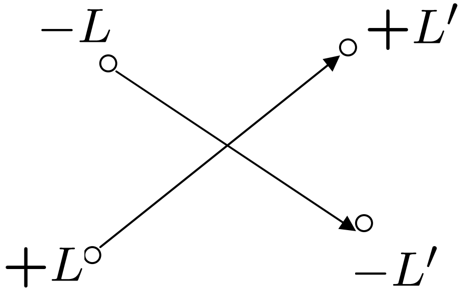



FIG. 1: Zeros and signs on the spherical harmonics on $S^2$. We compare the $M = 0$ with the $M \neq 0$ case. The spherical harmonics with $M \neq 0$ vanish at the two poles. As a consequence, $KK$ modes with nonvanishing angular momentum along the directions whose isometries are left unbroken by the brane are not directly coupled to brane fields (see the main text for details).

## KK story




KK particles are thermalized first
SM particles are thermalized much later

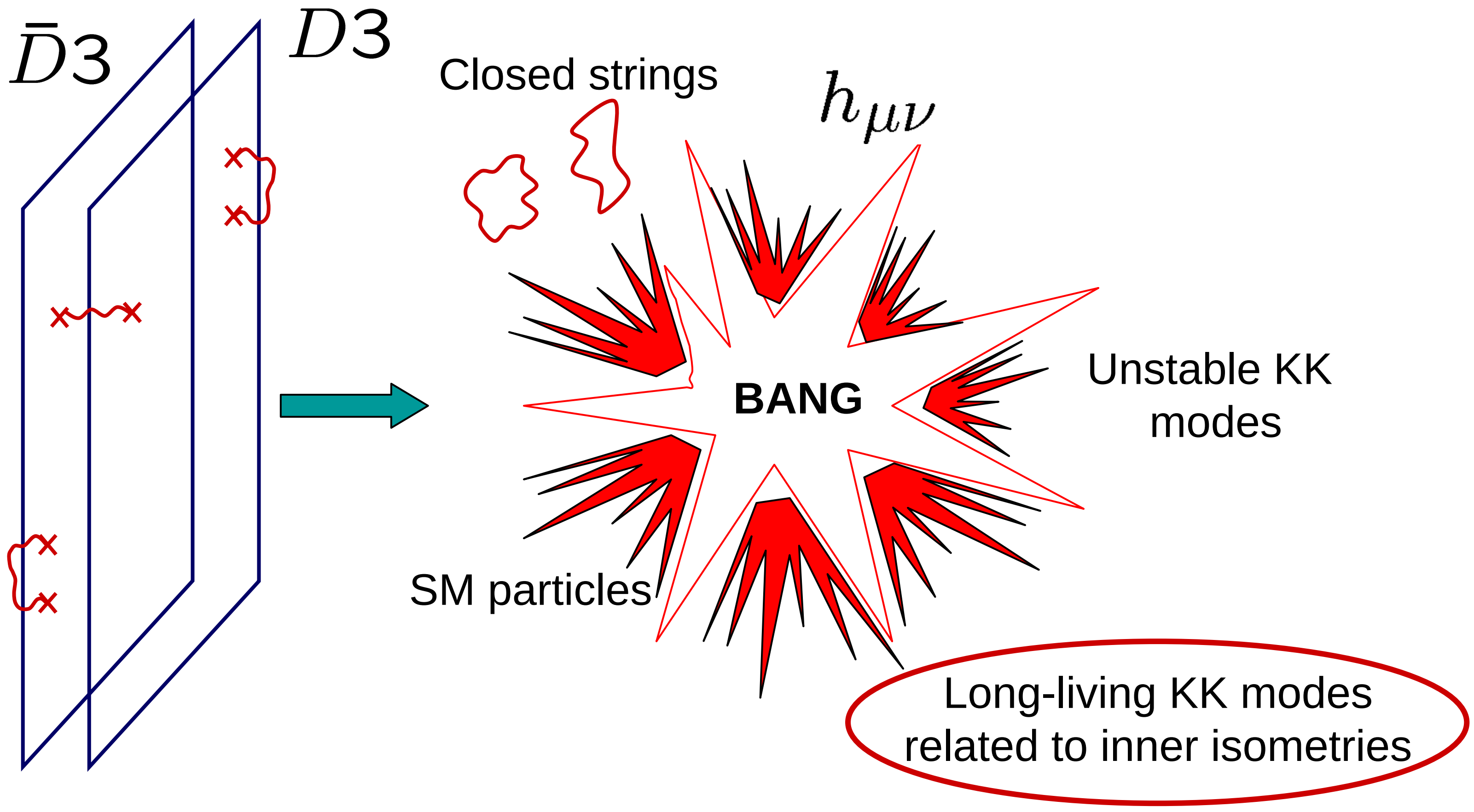
KK from M with isometries
are stable

No complete decay

KK particles freeze out $\Omega_{KK} \gg 1$

# End point of inflation

LK, Yi 05



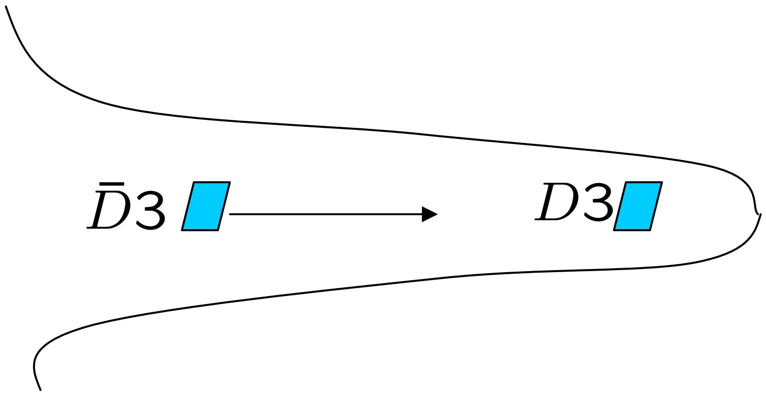

Open strings

between branes are unstable

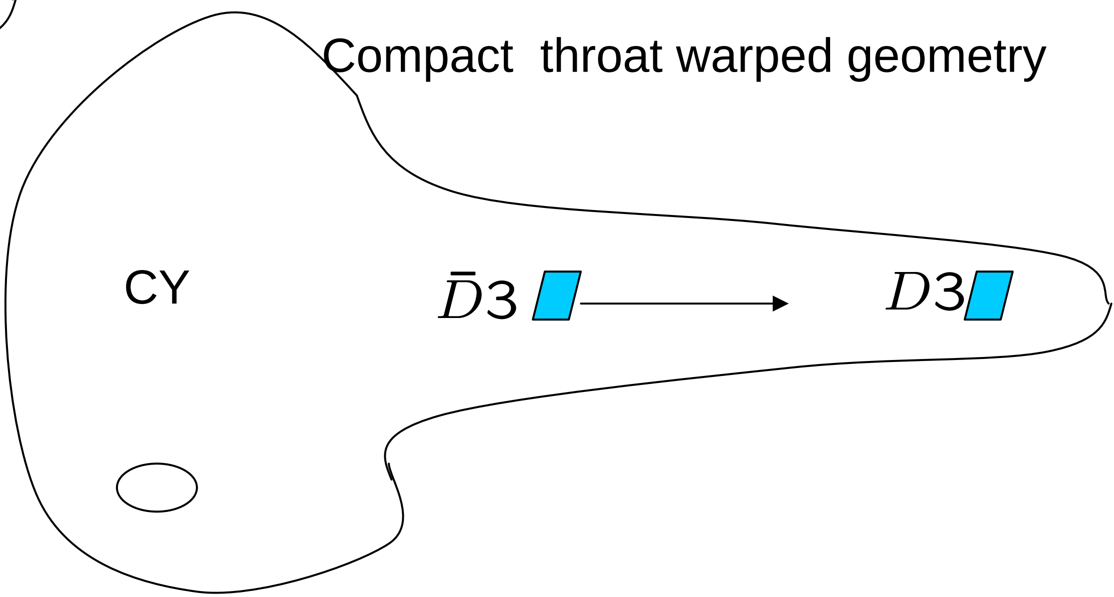
## Resolution?

- Attachment of KS throat to a compact CY
Induces symmetry breaking perturbations.

infinite throat warped geometry




Compact throat warped geometry



## Impact of isometry breaking perturbation on KK modes decay

$$ds^2 = e^{-2y/R}\,\eta_{\mu\nu}\,dx^\mu dx^\nu + dy^2 + R^2\,f_{ij}(\Omega)\,d\theta^i d\theta^j$$

$$ds^2 = e^{-2y/R}\,[1+\epsilon(y)\,w(\Omega)]\,\eta_{\mu\nu}\,dx^\mu dx^\nu + $$

$$+ dy^2 + R^2\,[f_{ij}(\Omega) + \epsilon(y)\,\delta f_{ij}(\Omega)]\,d\theta^i d\theta^j$$

$$\epsilon(y)\,\delta f_{ij}(\Omega_5) \to \sum_{\{L\}} e^{-\alpha_L y/R}\,\delta f_{ij}^{(L)}(\Omega_5)$$

O. Aharony, Y. E. Antebi and M. Berkooz, "Open string moduli in KKLT compactifications," (2005) [arXiv:hep-th/0508080].

$$\epsilon(y) = e^{-\alpha y/R} \qquad \alpha = \sqrt{28} - 4 = 1.29$$

# Fluctuations in Cosmology with Compactification

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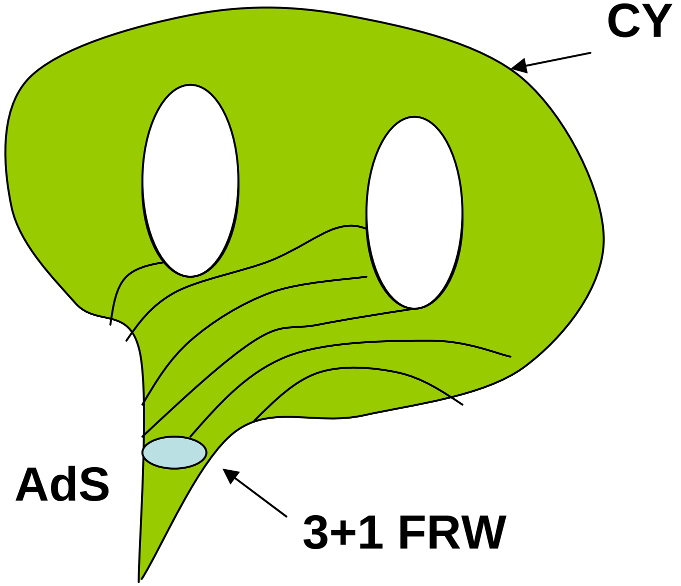
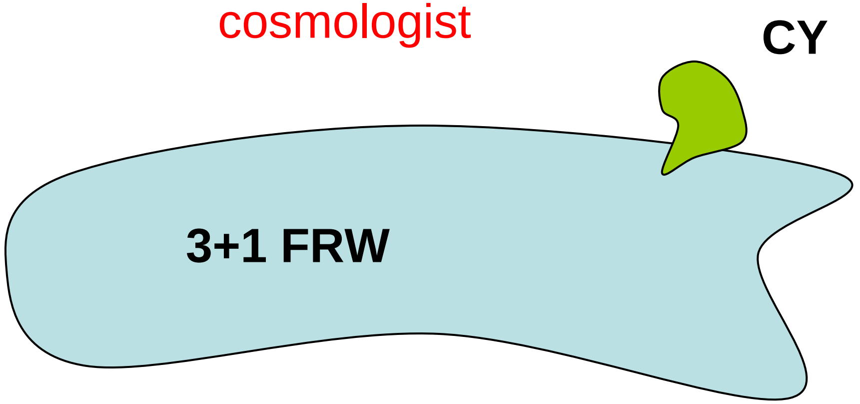
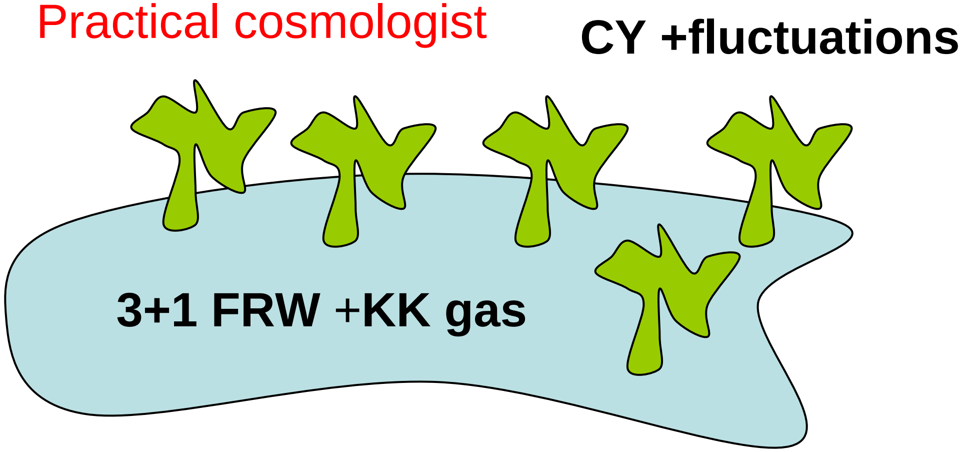
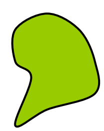



cosmologist




Practical cosmologist



KK atom

$$\Phi_m(y^c) = \sum_{L,M} Y_L^M(\Omega)\, \psi_{m,L}(y)$$

## KK Modes of the Throat with Isometry Breaking Perturbations

$$[H_0 + V]\ \Phi_m = m^2\, e^{-2y/R}\, \Phi_m$$

$$H_0 = -\frac{\partial}{\partial y}\left[e^{-4y/R}\,\frac{\partial}{\partial y}\right] - e^{-4y/R}\,\frac{\nabla^2_{(f)}}{R^2}$$

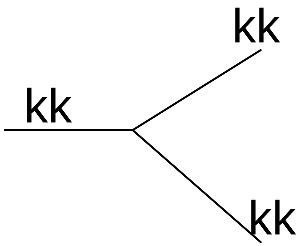
$$\begin{aligned} V = \epsilon\, w\, H_0 \ &-\ e^{-4y/R}\,\frac{d\epsilon}{dy}\left(2w + \frac{1}{2} f^{kl}\delta f_{kl}\right)\frac{\partial}{\partial y} \\ &-\ \frac{e^{-4y/R}}{R^2}\,\epsilon\left[\partial_i\left(2w + \frac{1}{2} f^{kl}\delta f_{kl}\right) f^{ij}\,\partial_j - \frac{1}{\sqrt{f}}\,\partial_i\left(\sqrt{f}\delta f^{ij}\partial_j\right)\right] \end{aligned}$$

# KK Modes of the Throat with Isometry Breaking Perturbations

$$\Phi^M_{nL}(y,\Omega_5) = (1+\mathcal{O}(\epsilon))\;\psi_{nL}(y)\,Q^M_L(\Omega_5) + \frac{1}{4}\sum_{\substack{n',L',M' \\ m_{n'L'}\neq m_{nL}}} \frac{M_{10}^8 R^5\, V^{M'M}_{n'L'nL}}{m^2_{nL}-m^2_{n'L'}}\,\psi_{n'L'}(y)\,Q^{M'}_{L'}(\Omega_5)+\ldots$$

$$V^{MM'}_{nLn'L'} = \int dy\, d\Omega_5\, \psi_{nL}(y)\, Q^M_L(\Omega_5)\, V\, \psi_{n'L'}(y)\, Q^{M'}_{L'}(\Omega_5)$$

$$\begin{aligned}\delta\,\Phi^M_{nL}(y,\Omega_5) &= \frac{1}{4}\frac{M_{10}^8 R^5\, V^{M'M}_{n'L'nL}}{m^2_{nL}-m^2_{n'L'}}\,\psi_{n'L'}(y)\,Q^{M'}_{L'}(\Omega_5)+\ldots \\ &\approx \frac{e^{-(1+\alpha)y_t/R}}{M_{\rm Pl}}\left(\frac{V_6}{R^6}\right)^{1/2} e^{2y/R}\,J_{\nu'}\left(m_{n'L'}Re^{y/R}\right)\,Q^{M'}_{L'}(\Omega_5)+\ldots\end{aligned}$$

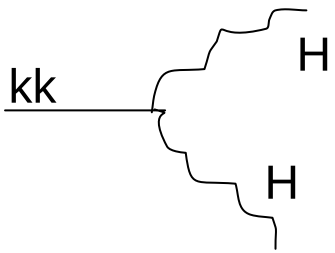



$$\lambda_{3\mathrm{KK}} \approx \left(\frac{V_6}{R^6}\right)^{1/2} \frac{e^{y_t/R}}{M_{\mathrm{Pl}}}$$

First order correction

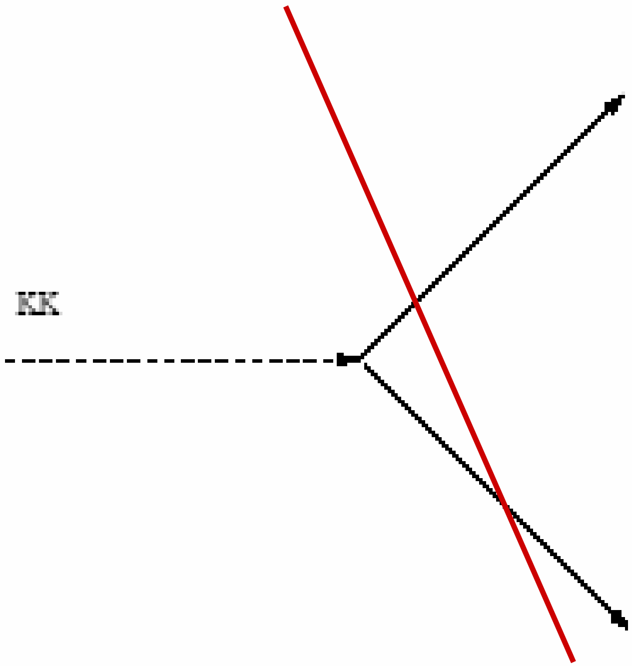
$$\lambda^{(\epsilon)}_{3\,\mathrm{KK}} = \int dy\, e^{-2y/R}\, \epsilon(y)\, \psi_{nL}\, \psi_{n'L'}\, \psi_{n''L''} \int d\Omega_5 \left(w + \frac{1}{2} f^{kl} \delta f_{kl}\right) Q^{M}_{L}\, Q^{M'}_{L'}\, Q^{M''}_{L''} + \ldots$$

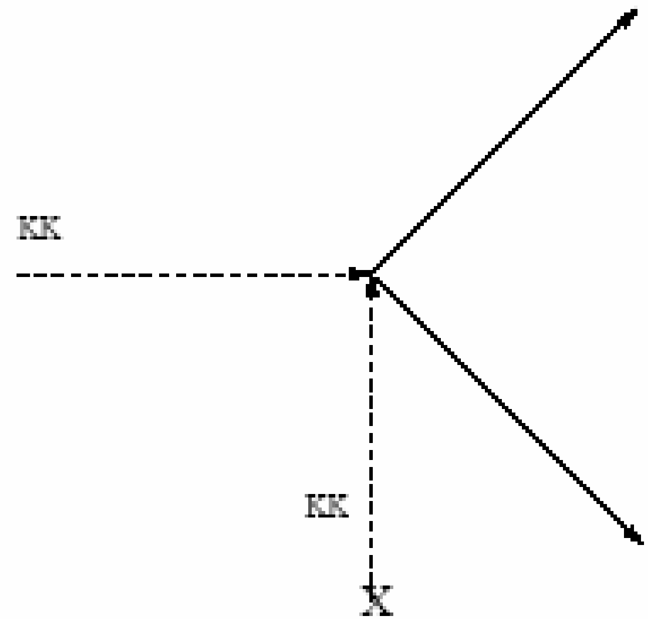
$$\lambda^{(\epsilon)}_{3\,\mathrm{KK}} \approx \left(\frac{V_6}{R^6}\right)^{1/2} \frac{e^{(1-\alpha)y_t/R}}{M_{\mathrm{Pl}}}$$




$$\lambda^{(\epsilon)}_{\mathrm{KK\,b\,b}} = \frac{1}{4} \sum_{\substack{n',L' \\ m_{n'L'} \neq m_{nL}}} \frac{M_{10}^8 R^5}{m_{nL}^2 - m_{n'L'}^2} V^{0M}_{n'L'nL}\, \psi_{n'L'}(y_b)\, Y^0_{L'}(\theta_b = 0) + \ldots$$

$$\lambda^{(\epsilon)}_3 \equiv \left(\frac{V_6}{R^6}\right)^{1/2} \frac{e^{(1-\alpha)y_t/R}}{M_{\rm Pl}}$$


KK


KK
KK
X

## RELIC ABUNDANCES

freeze-out temperature $T_f$

$$\frac{\Gamma_{\mathrm{KK}_L\,\mathrm{KK}_{-L}\to \mathrm{b\,b}}}{H} \sim 0.1\,\lambda_3^4\, m^3\, M_p\, \left(\frac{m}{T}\right)^{1/2} \mathrm{e}^{-m/T}$$

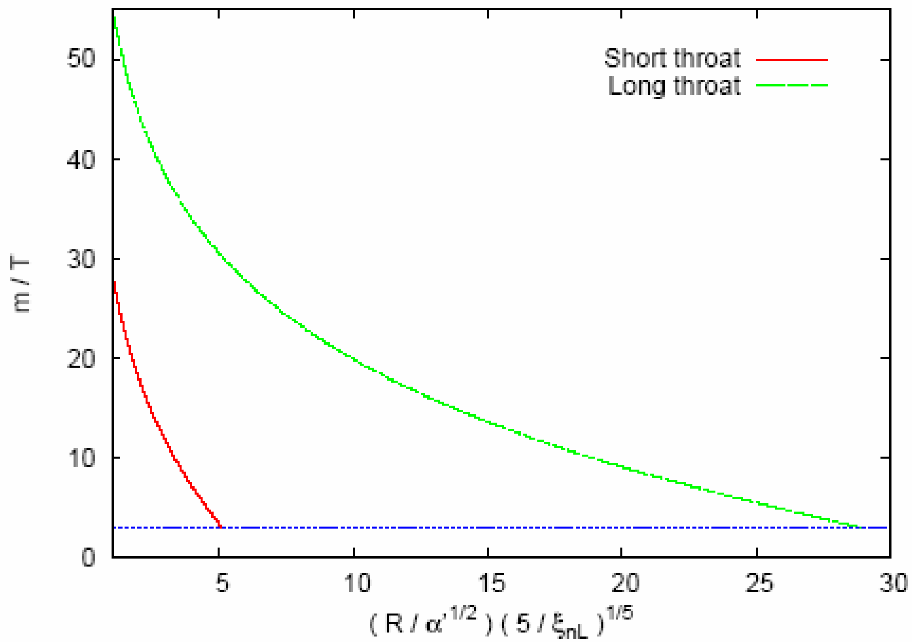



FIG. 3: Estimate for the $m/T$ ratio at which the scatterings $\mathrm{KK}_L + \mathrm{KK}_{-L} \to b + b$ freeze out. The value is strongly sensitive to the ratio $R/\sqrt{\alpha'}$.

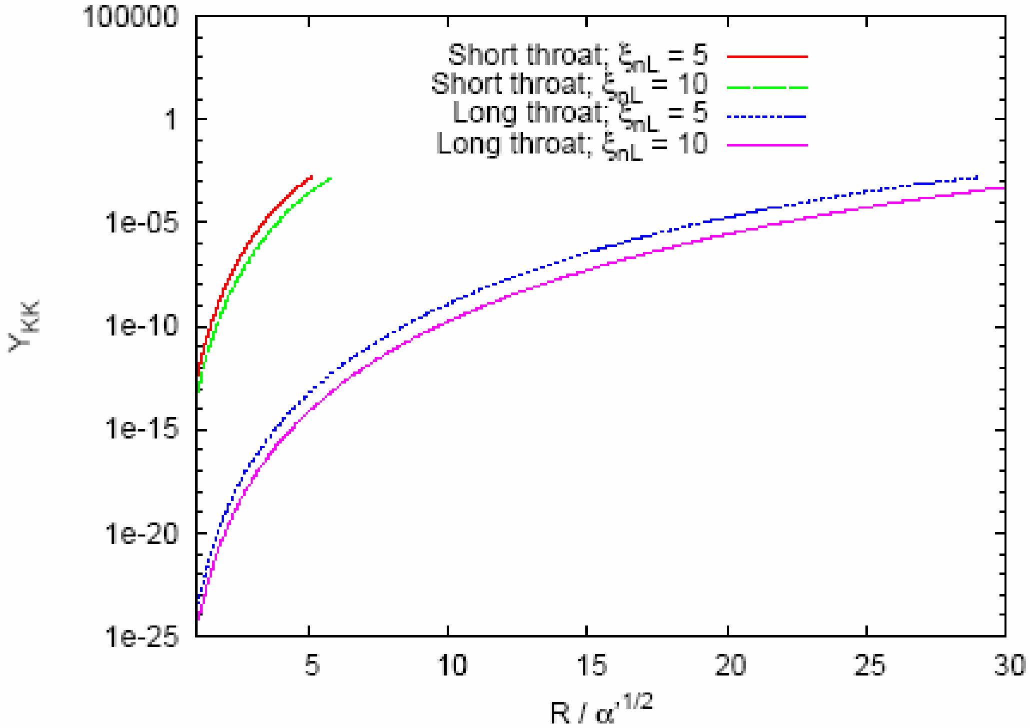



FIG. 4: Relic abundance for the $KK_L$ species as function of parameter $R/\sqrt{\alpha'}$. We note that the lightest modes are more abundant than the heavier ones.

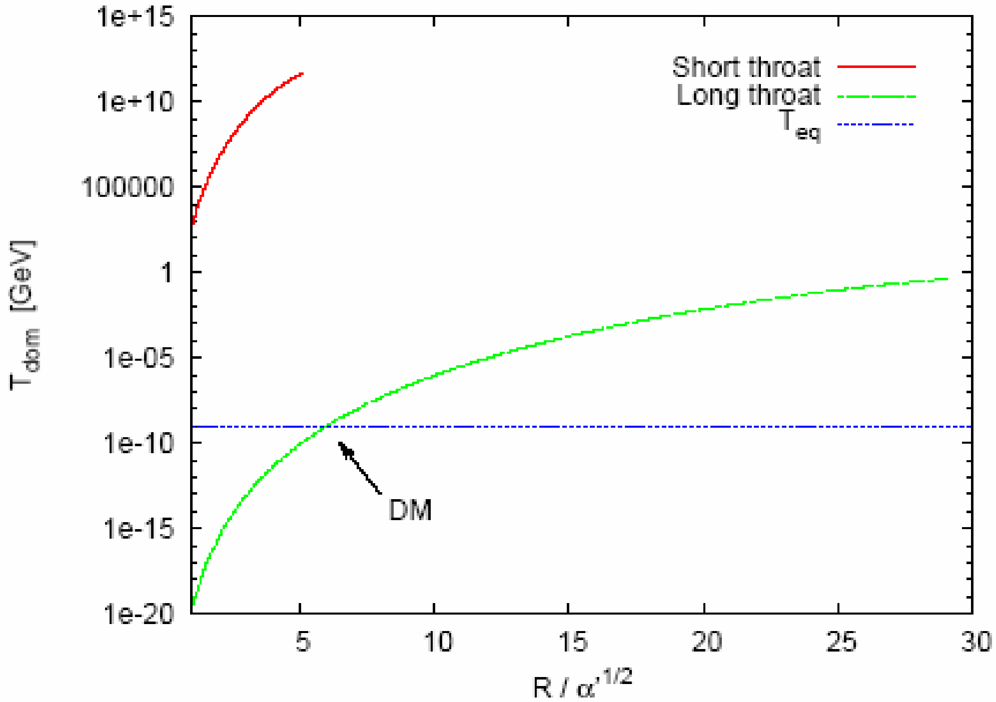



FIG. 5: Temperature of the universe at which the relic $KK_L$ particles start to dominate, (provided they have not decayed yet) as function of $R/\sqrt{\alpha'}$. The temperature $T_{eq} \simeq 7.4 \cdot 10^{-10}\,\mathrm{GeV}$ at the moment of matter–radiation equality is also shown for comparison. In the long throat, for $R/\sqrt{\alpha'} \simeq 6$, the KK modes can be the dark matter candidate.

## PHENOMENOLOGICAL CONSTRAINTS

Limits from BBN

Limits from astrophysical $\gamma$-ray backgrounds

Darm Matter $\Omega_m$

## Short throat $e^{-A} \sim 10^{-4}$

Lifetime is shorter but abundance is higher.
Require decay before BBN $10^{-2}$sec

$$\tau \simeq \frac{1}{\Gamma_{\rm tot}} \simeq 1.1 \times 10^{-27}\,{\rm s}\,\left(4 \times 10^3\right)^{2(\alpha-1.29)} \left(\frac{R}{5\sqrt{\alpha'}}\right)^{9-6\alpha} \left(\frac{R}{V_6^{1/6}}\right)^{6\alpha}$$

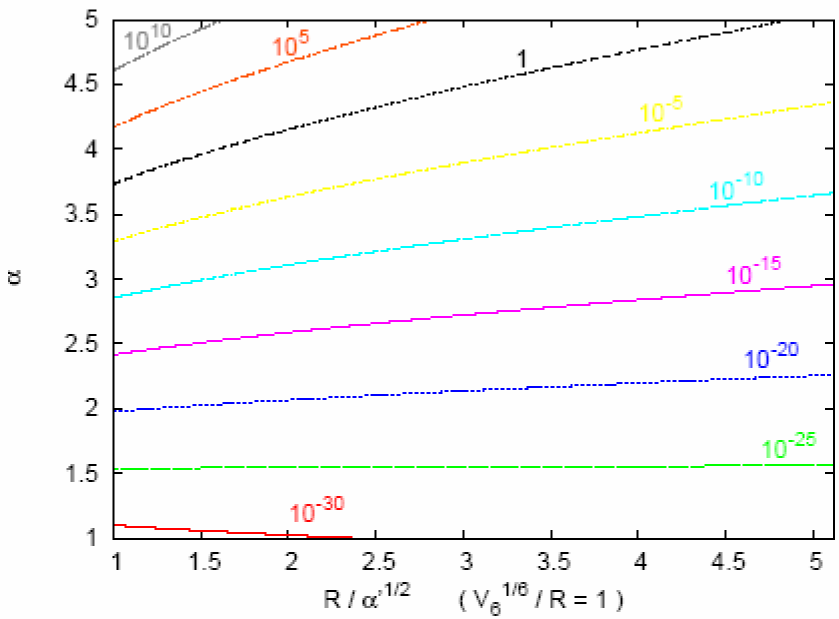



FIG. 6: Curves of lifetime (labelled by seconds) of the $KK_L$ particles in the short throat case, as function of $\alpha$ and $R/\sqrt{\alpha'}$. For definiteness, we have fixed $V_6^{1/6}/R = 1$ in this plot. Higher values of this ratio correspond to a shorter lifetime, cf. Eq. (88).

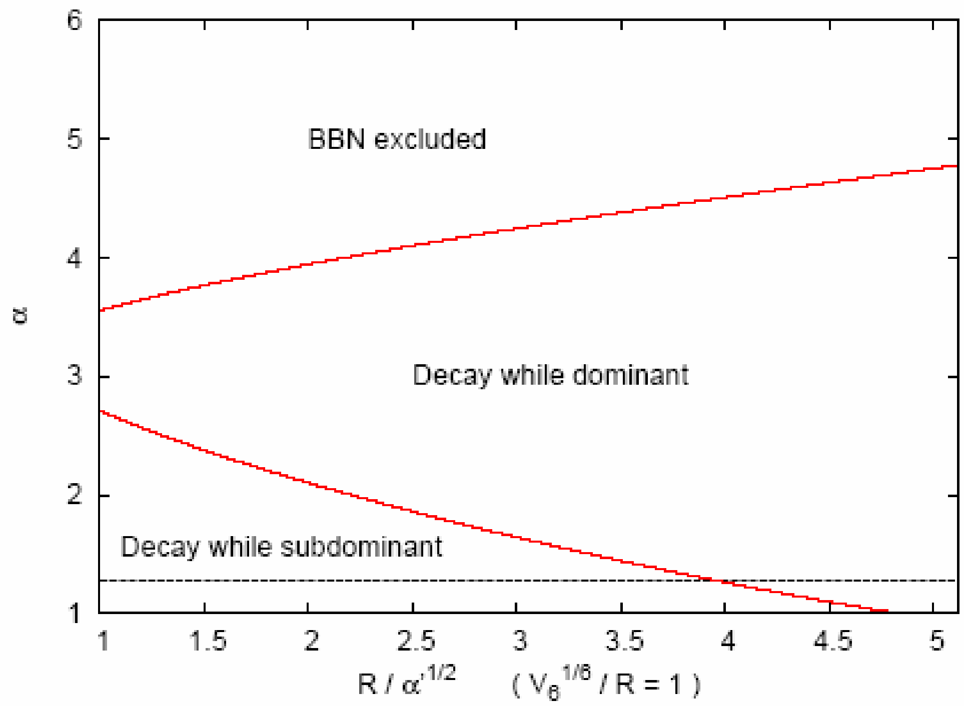



FIG. 8: Different scenarios for the decay of the $KK_L$ particles in the short throat, for the fixed value $V_6^{1/6}/R = 1$. The horizontal line corresponds to the reference value $\alpha = 1.29$.

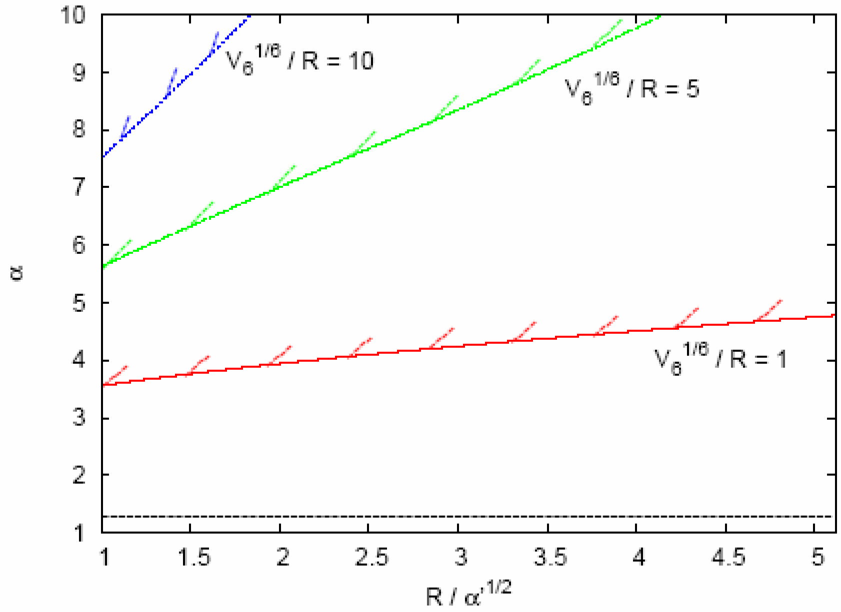



FIG. 7: BBN limit $\tau < 10^{-2}$ s for three reference values of the ratio $V_6^{1/6}/R$ for the short throat. For each case, regions above the lines (greater lifetime) are excluded. The horizontal line at $\alpha = 1.29$ corresponds to the reference value.

## Long throat $e^{-A} \sim 10^{-16}$

$$\tau \simeq \frac{1}{\Gamma_{\rm tot}} \simeq 3 \times 10^{13}\,{\rm s}\ \left(8 \times 10^{14}\right)^{2(\alpha-1.29)} \left(\frac{R}{5\sqrt{\alpha'}}\right)^{9-6\alpha} \left(\frac{R}{V_6^{1/6}}\right)^{6\alpha}$$

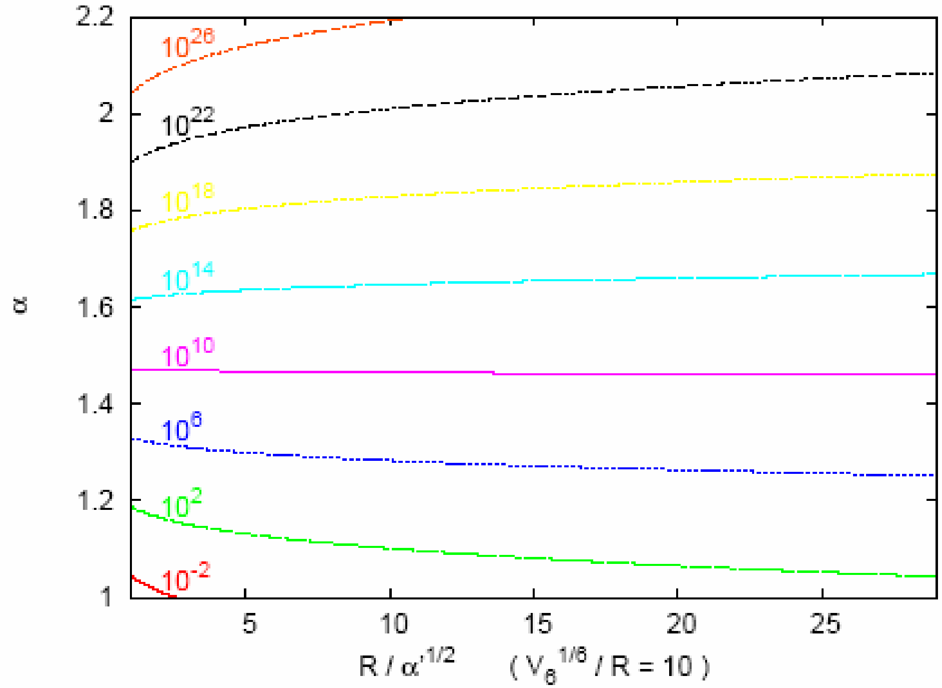



FIG. 9: Lifetime (in seconds) of the KK$_L$ particles in the long throat. For definiteness, we have fixed $V_6^{1/6}/R = 10$ in this plot. Higher (shorter) values of this ratio correspond to a shorter (longer) lifetime, cf. Eq. (90).

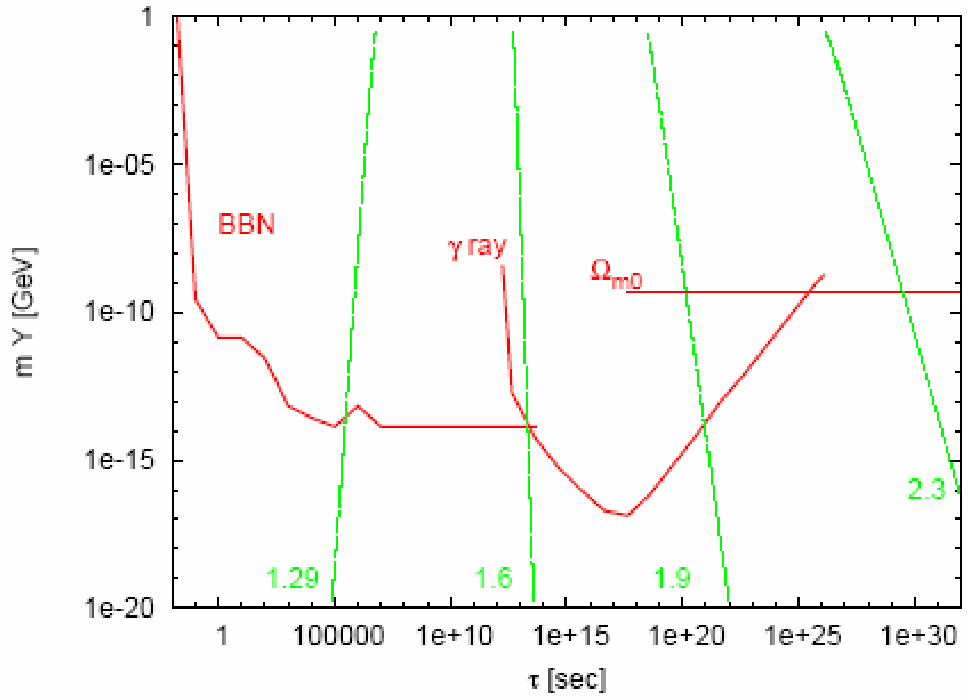



FIG. 10: Combined upper bound on the mass $m$ times the abundance $Y$ for an unstable particle with lifetime $\tau$. The BBN limit is taken from [29], while the bound from the diffuse $\gamma$ ray background from [31]. The horizontal line denoted by $\Omega_{m0}$ is the limit imposed by requiring that the energy density of the KK particle does not exceed the dark matter $\Omega$. The other curves represent the values of $\tau$ and $m\,Y$ obtained in the long throat, for $V_6^{1/6}/R = 10$, for different values of $\alpha$ (indicated on the lines) and of $R/\sqrt{\alpha'}$ ($mY$ is an increasing function of $R/\sqrt{\alpha'}$).

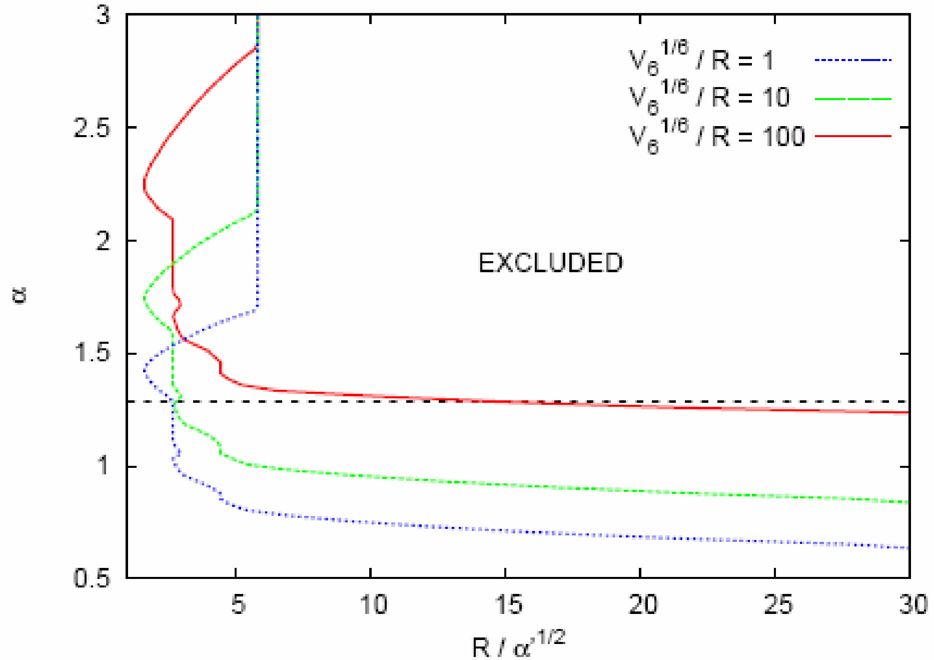



FIG. 11: Final exclusion region for the parameter in the long throat. The three lines correspond to three reference value of $V_6^{1/6}/R$. For each case, values of the parameters on the right of the corresponding curve conflict with the phenomenological limits shown in Fig. 10. The highest values of $\alpha$ shown result in $\mathrm{KK}_L$ particles with a much longer lifetime than the age of the universe. In this case, the only relevant bound is that the energy density of the $\mathrm{KK}_L$ particles does not exceed the one of dark matter in our universe. The horizontal line corresponds to $\alpha = 1.29$

# Angular KK modes from the long throat can be dark matter candidate

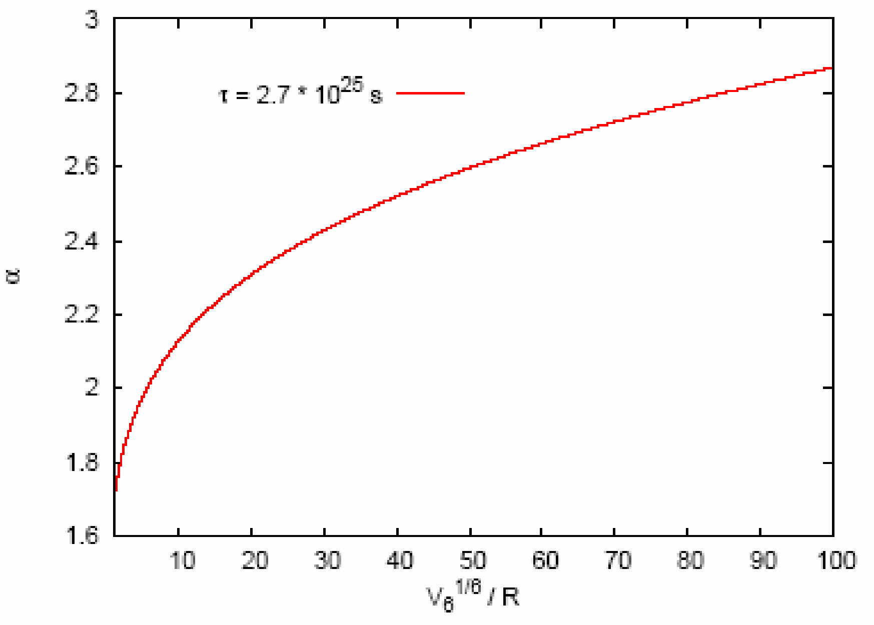



FIG. 12: Angular KK modes can be the dark matter candidate for $R/\sqrt{\alpha'} \simeq 6$ and for the values of the parameters $\alpha$ and $V_6^{1/6}/R$ above the line shown in the plot, corresponding to a lifetime of the KK particles greater than about $3 \cdot 10^{25}$ s (to avoid the limit from the diffuse $\gamma$ ray background, cf. Fig. 10). For $V_6^{1/6}/R > 1$ this occurs for relatively large values of $\alpha > 1.7$.

# Issues with multiple throats

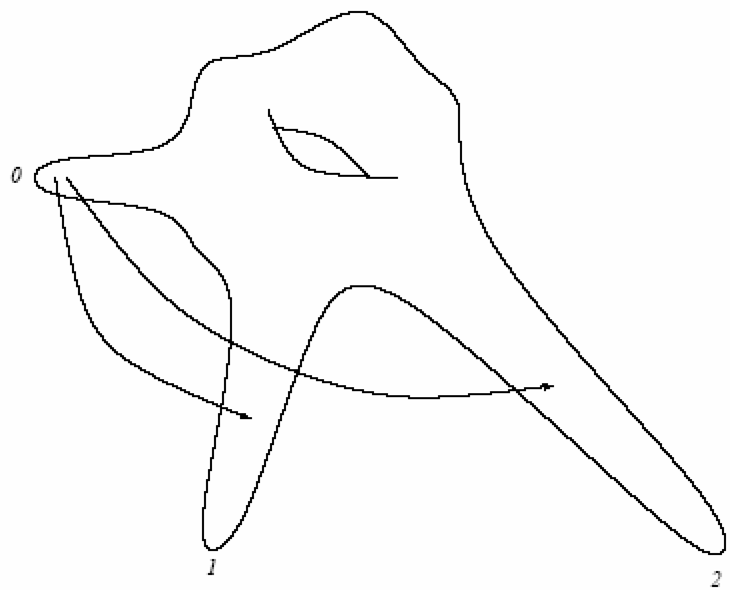



Figure 4: KK modes in the inflation throat deposit energy to lower energy throats. The branching ratio will be largely determined by how throats are distributed in the internal manifold with respect to the inflation throat and less sensitive to the field content of each throat. Energy deposited in throat 1 will later decay to throat 2, but at much more suppressed rate because its mass scale is far lower than that of the inflation throat.

# Model wave equation of angular KK modes in the bulk

$$\left(\partial_y^2 + m_{KK}^2 - \frac{p^2}{R^2}\right)\Phi_m = 0$$

the angular KK modes

are exponentially suppressed in the bulk

$$\Phi_m \sim e^{-p(L)|y|/R}$$

exponentially suppresses the tunneling rate.

a Standard Model throat can be cloaked by a horizon of a black hole produced by tunneling of the excited Kaluza-Klein modes from the Inflationary throat.

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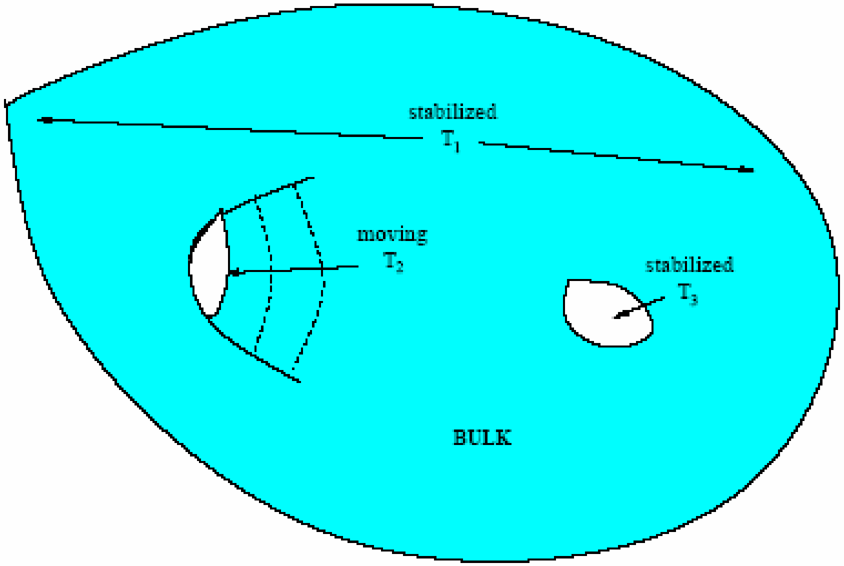
a Standard Model throat can be cloaked by a horizon of a black hole produced by tunneling of the excited Kaluza-Klein modes from the Inflationary throat.

At large enough energy density

$$\epsilon > \epsilon_{cr} \simeq \frac{MK}{\alpha'^2 g_s^2} e^{-4A} \qquad (1)$$

cascading gauge theory undergoes
a deconfining phase transition manifested in a
formation of BH horizon in KS geometry

# Kahler moduli Inflation (Conlon&Quevedo hep-th/050912)
# Roulette Inflation-Kahler moduli/axion
# (Bond, LK, Prokushkin&Vandrevange hep-th/0612197)



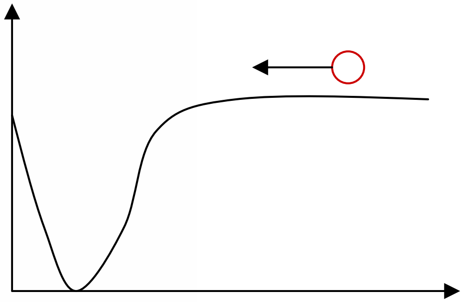



Figure 1: Schematic illustration of the ingredients in Kähler moduli inflation. The four-cycles of the CY are the Kähler moduli $T_i$ which govern the sizes of different holes in the manifold. We assume $T_3$ and the overall scale $T_1$ are already stabilized, while the last modulus to stabilize, $T_2$, drives inflation while settling down to its minimum. The imaginary parts of $T_i$ have to be left to the imagination. The outer $3+1$ observable dimensions are also not shown.