LIVING AT THE TIP OF THE THROAT

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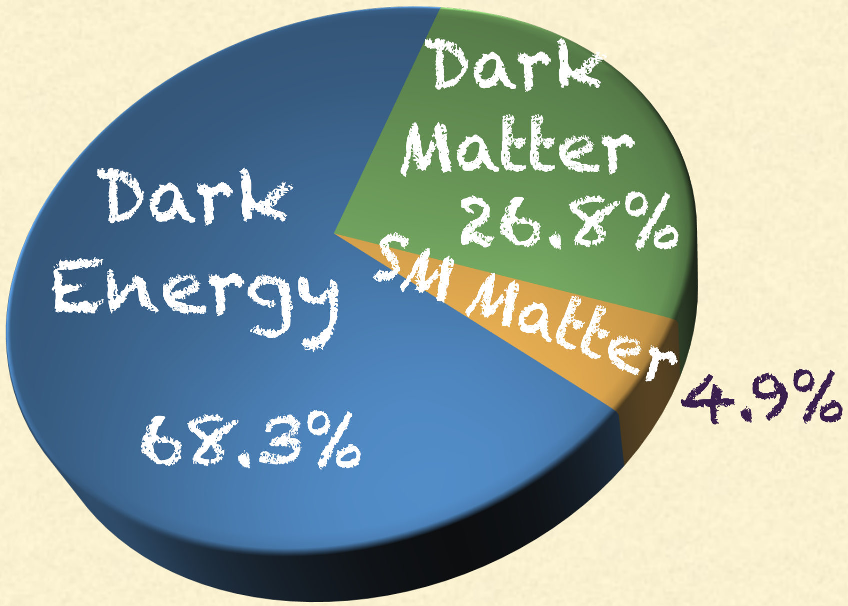
in progress w/Cabo-Bizet, Loaiza-Brito, Olguín-Trejo

THE ΛCDM MODEL OF COSMOLOGY

Cosmology established as a precise science in the last 20 years after first Cosmic Microwave Background (CMB) results from COBE satellite

A phenomenological Standard Model of Cosmology has emerged, in perfect agreement with current observations:

The ΛCDM model (Lambda cold dark matter)



cosmic pie

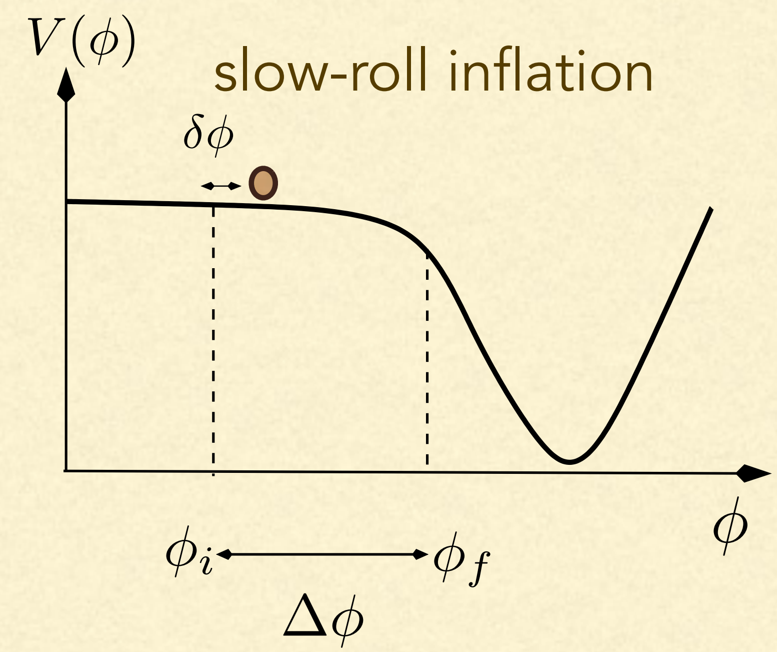
In this model, the universe contains three major components: ***dark energy* (Λ)** *cold dark matter* and ordinary matter.

It is complemented with the ***inflationary** scenario to generate primordial fluctuations that seed large scale structures* we observe today

EARLY TIME ACCELERATION: INFLATION

- A period of quasi exponential accelerated expansion in the very early Universe due to vacuum energy domination.

- Governed by the dynamics of a **single scalar field** with very flat potential: **slow-roll conditions**.



$$\epsilon = \frac{M_P^2}{2}\left(\frac{V'}{V}\right)^2 \ll 1, \qquad \eta = M_P^2 \frac{V''}{V} \ll 1$$

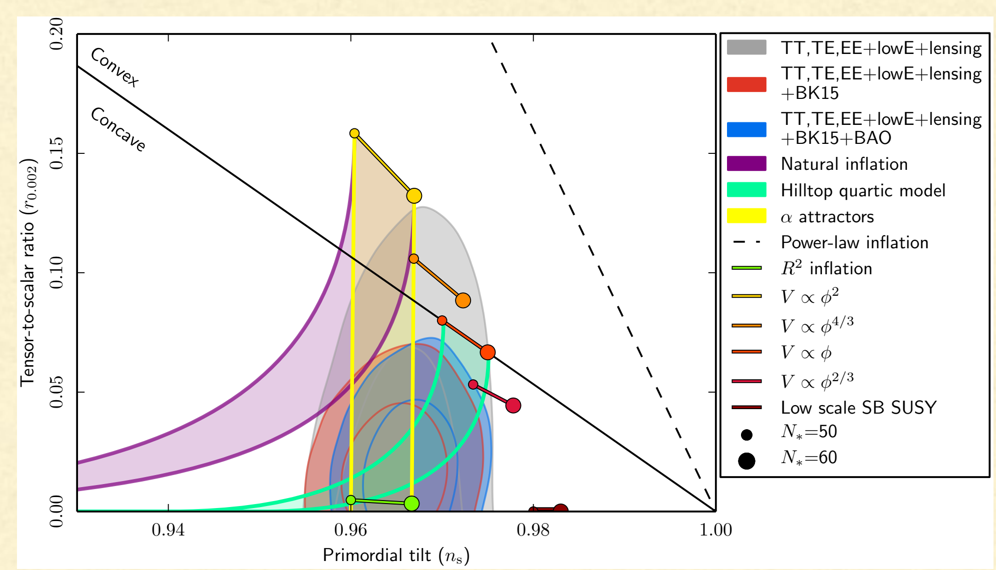
- Simplest inflationary model in agreement with latest observations (Planck/Bicep2/Keck)

Nearly *scale invariant* adiabatic *Gaussian* spectrum of scalar perturbations.

$$(\mathcal{P}_\zeta \sim A_s\, k^{n_s - 1})$$
$$n_s = 1 - 6\epsilon - 2\eta$$
$$r = 16\epsilon$$

$n_s = 0.9649 \pm 0.0042$

$r < 0.036$



[Planck '18]

[BICEP2/Keck '21]

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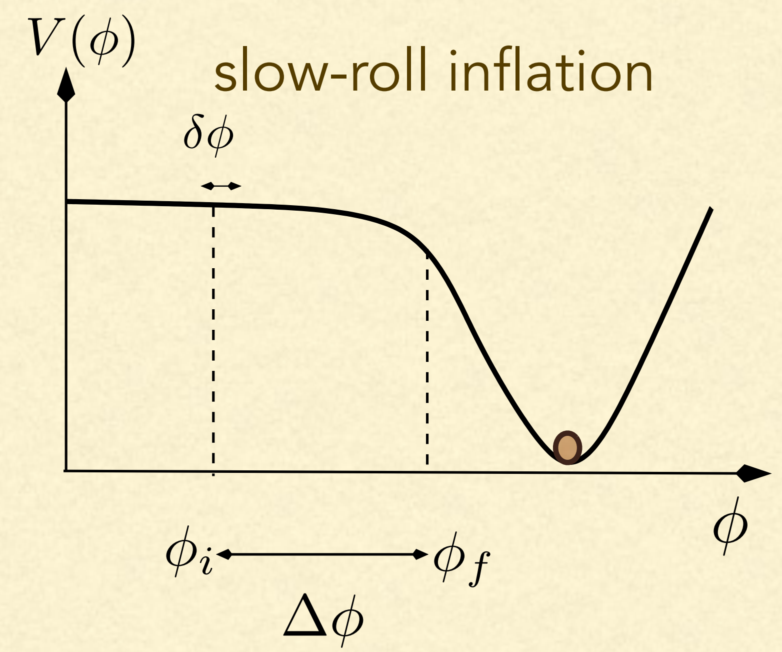

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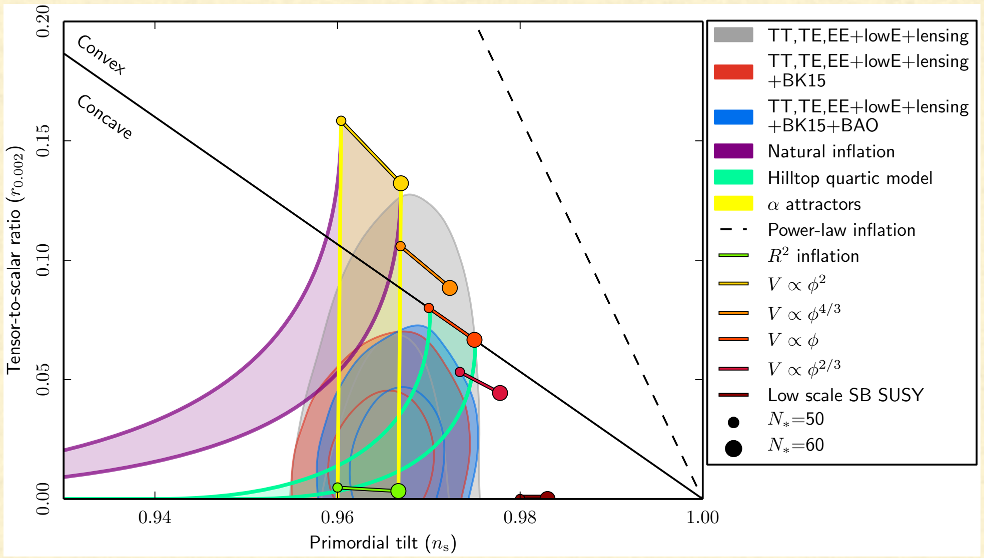

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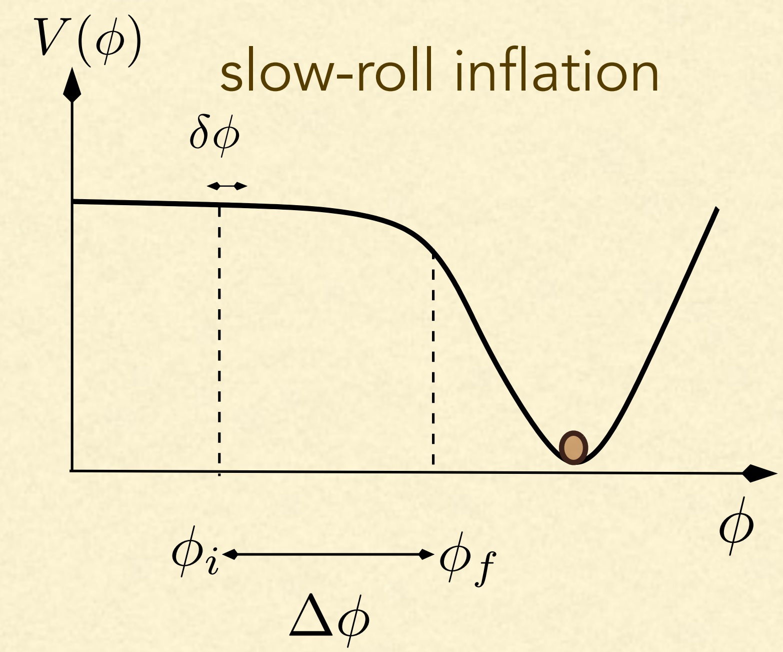

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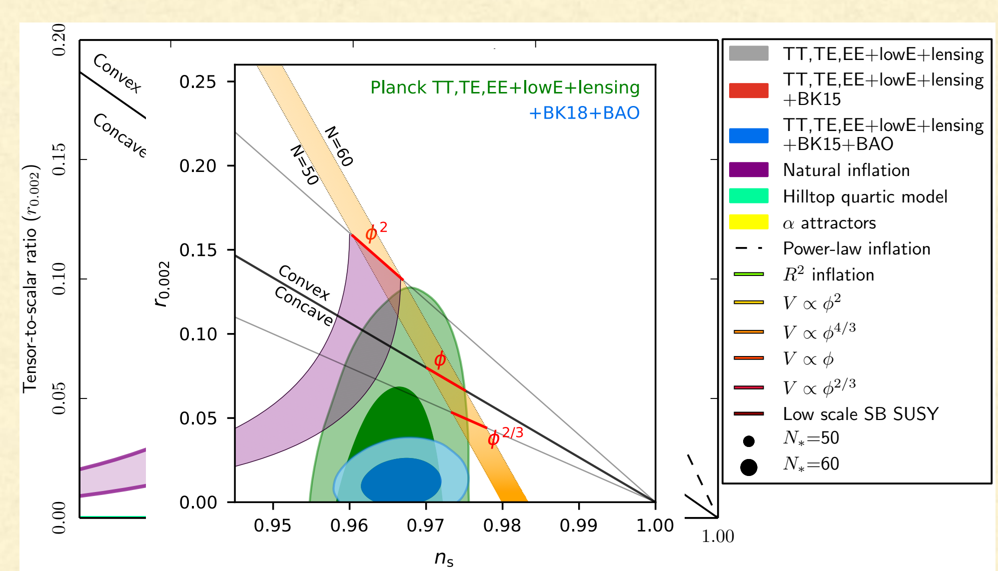


[Planck '18]

[BICEP2/Keck '21]

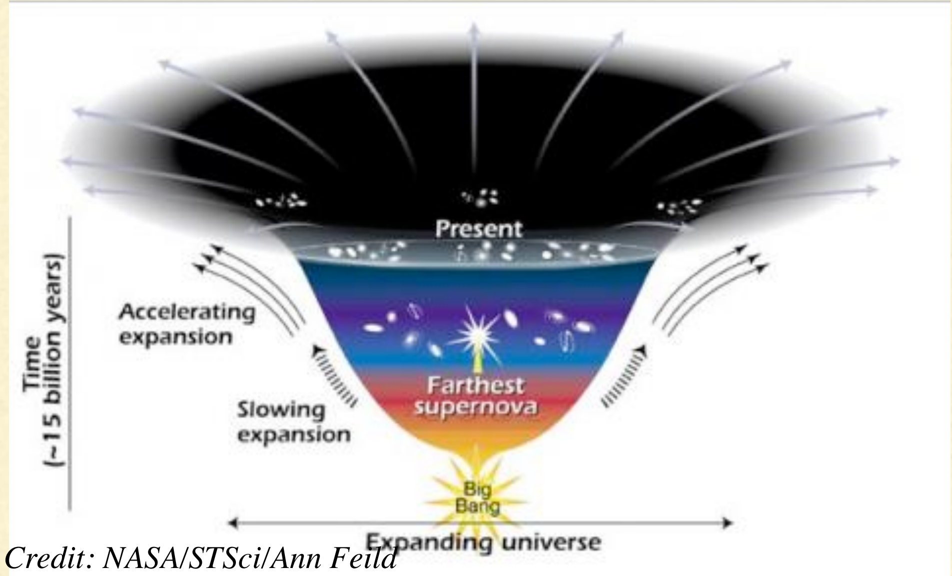
FUNDAMENTAL ORIGIN OF INFLATION?

- The energy scale of the very early universe when cosmic inflation occurred is likely to be extremely high and field range (super)-Planckian.
- Likely to be described in the context of theories beyond the standard model of particle physics, e.g. supergravity and string theory.
- Usually multiple degrees of freedom that could be relevant for inflation and give interesting observational consequences to be tested in forthcoming experiments (e.g. PBHs, gravitational waves, non-Gaussianities, etc.)

LATE TIME ACCELERATION: DARK ENERGY

One of the greatest discoveries of XX century was that of the ***accelerated expansion*** of the universe [Riess et al. '98; Perlmutter et al. '99]

It is also one of the *major puzzles in modern physics*: its cause is often dubbed **dark energy** as its nature is still an mystery.



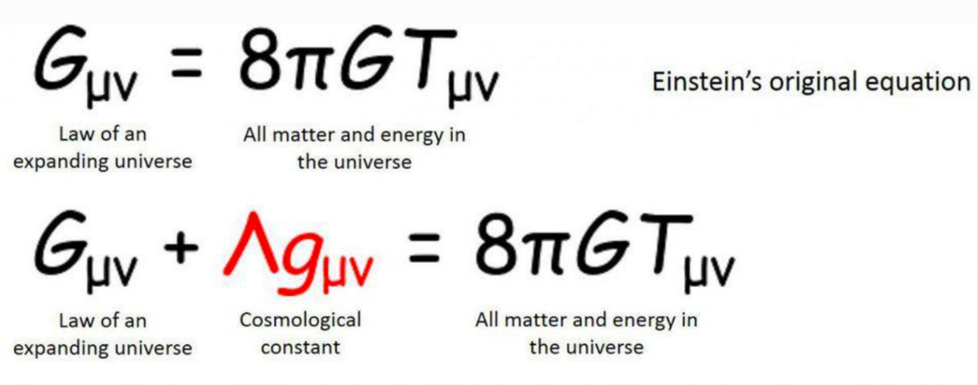
Credit: NASA/STSci/Ann Feild

- Why is its value so small:

$$\rho_{DE} \sim (0.002\,\mathrm{eV})^4$$

$$(\rho_{DE} = 5.96 \times 10^{-27}\mathrm{kg/m^3})$$

The simplest possibility, consistent with data, is a constant energy density: a ***cosmological constant***, Λ



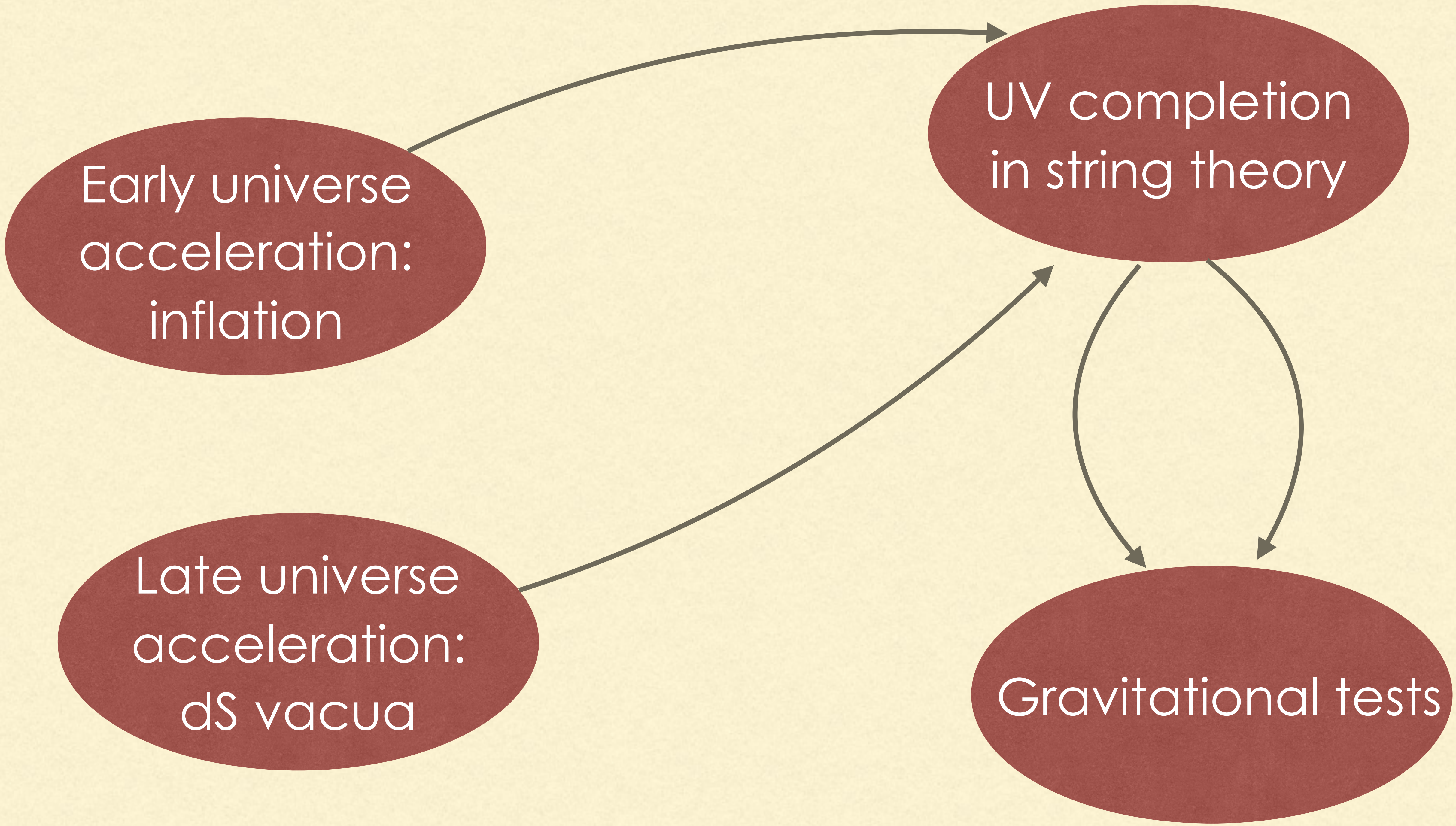
STRING THEORY AND COSMOLOGICAL ACCELERATION

- String theory may help to understand nature of early and late time acceleration

- If string scale is closer to the Planck scale than the TeV scale, it makes it difficult to probe string theory in terrestrial experiments (colliders)

- This strongly motivates the use of observational cosmology to constraint string theory, and of string theory as the foundation for a more complete description of the very early universe.

LIVING AT THE TIP OF THE THROAT



PLAN

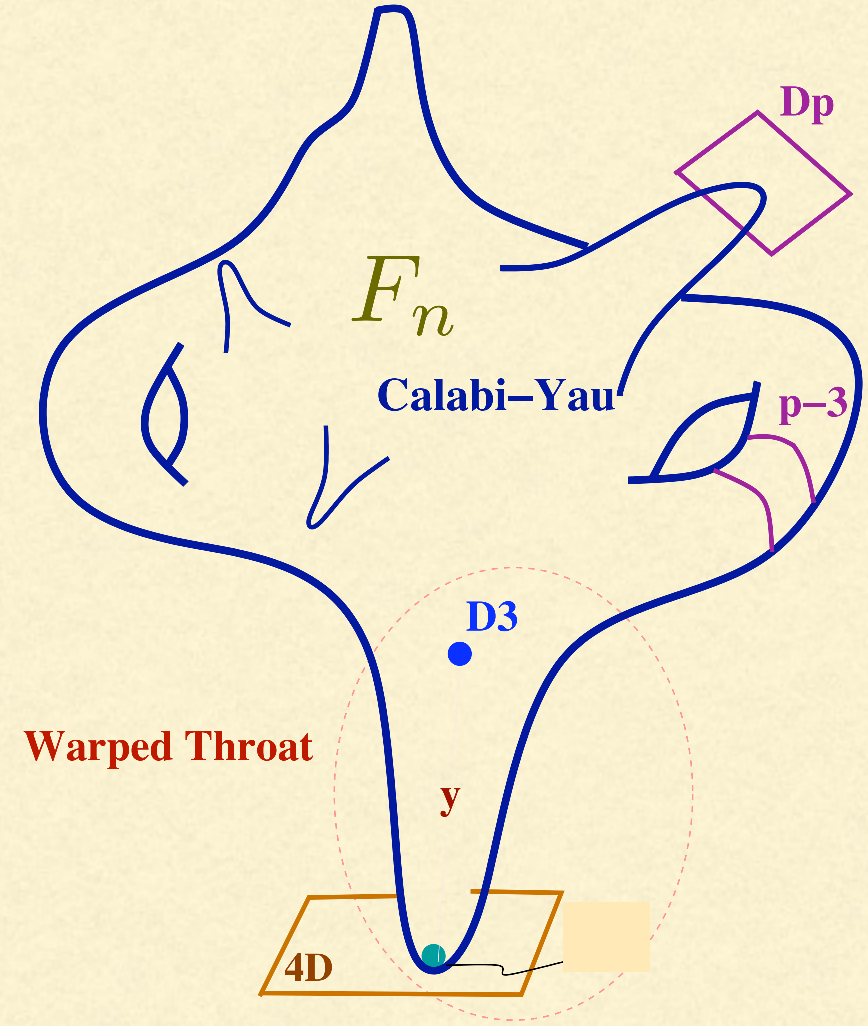
- Flux compactifications and the warped throat
- Early time acceleration: fat inflatons and large turns at the tip of the warped throat
- Late time acceleration: dS in string theory revisited
- Gravity at the tip of the throat
- Summary

TYPE IIB FLUX COMPACTIFICATIONS

[Giddings, Kachru, Polchisnki, '01]

Consider type IIB string theory compactifications with internal fluxes turned on: F_n

- Fluxes backreact **warping** internal CY manifold; new avenues for *phenomenology and cosmology*!
- Fluxes provide **potential** for some of the moduli: *dilaton & complex structure*



TYPE IIB FLUX COMPACTIFICATIONS

[Giddings-Kachru-Polchisnki, '01]

Type IIB string theory in 10D with fluxes and localised sources: D-branes & Orientifolds

$$S_{\rm IIB} = \frac{1}{2{\kappa_{10}}^2}\int d^{10}x\sqrt{-g}\left\{\mathcal{R} - \frac{\partial_M\tau\partial^M\bar\tau}{2({\rm Im}\,\tau)^2} - \frac{G_{(3)}\cdot\bar G_{(3)}}{12\,{\rm Im}\,\tau} - \frac{\tilde F_{(5)}^2}{4\cdot 5!}\right\}$$
$$+\frac{1}{8i{\kappa_{10}}^2}\int\frac{C_{(4)}\wedge G_{(3)}\wedge\bar G_{(3)}}{{\rm Im}\,\tau} + S_{\rm loc}\ .$$

$\tau = C_{(0)} + ie^{-\phi}$ axio-dilaton

$\kappa_{10}^2 = (2\pi)^7(\alpha')^4/2 \equiv \ell_s^8/4\pi$

$g_s = e^{\phi}$

$G_{(3)} = F_{(3)} - \tau H_{(3)}$ 3-form potentials

$\tilde F_5 = F_5 - \frac{1}{2}C_2\wedge H_3 + \frac{1}{2}B_2\wedge F_3.$ 5-form potential

$\tilde F_5 = \star_5 \tilde F_5.$ self-dual

TYPE IIB FLUX COMPACTIFICATIONS: THE CONIFOLD

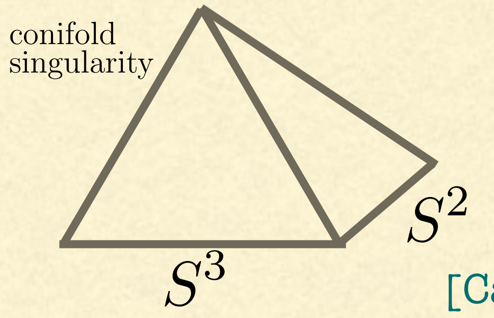
Compactify the extra 6D on a **warped** CY manifold

$$ds^2_{10} = e^{2A(y)}\eta_{\mu\nu}dx^\mu dx^\nu + e^{-2A(y)}\tilde{g}_{mn}dy^m dy^n$$

A variety of SUGRA backgrounds with internal fluxes has been explored in the context of the AdS/CFT correspondence.

The **conifold** is of particular interest: singular non-compact Calabi-Yau 3-fold. Can be seen as a cone over $T^{1,1} = S^3 \times S^2$

$$ds^2_6 = dr^2 + r^2 ds^2_{T^{1,1}}$$



[Candelas-de la Ossa, '89]

THE CONIFOLD

The conical singularity can be smoothed out in two topologically distinct ways, leading to the

[Candelas-de la Ossa, '90; Minasian-Tsimpis, '99; Ohta-Yokono, '99]
[Pando-Zayas, Tseytlin, '00]

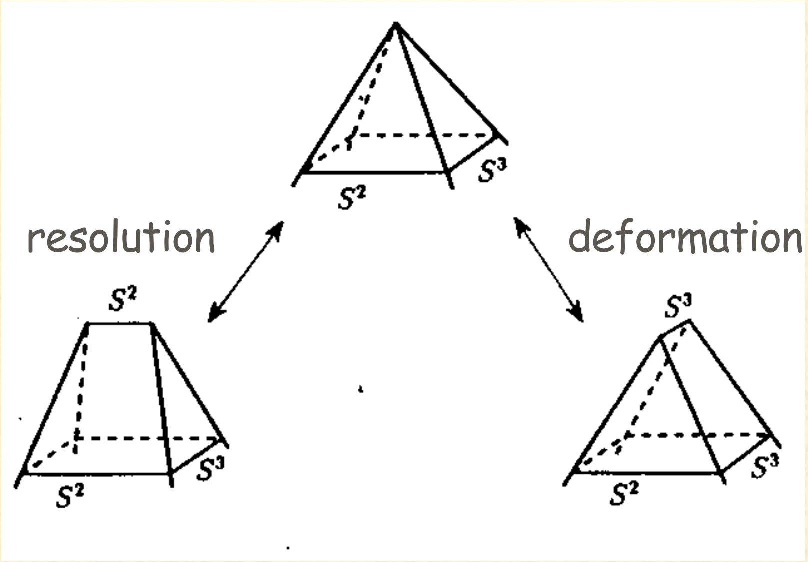
- **deformed conifold** (DC): $S^2 \to 0$

  $$\left(h^{2,1} = 0\,, \quad h^{1,1} = 1\,, \quad z\right)$$

- **resolved conifold** (RC): $S^3 \to 0$

  $$\left(h^{2,1} = 0\,, \quad h^{1,1} = 1\,, \quad u\right)$$

The conifold: singular non-compact Calabi-Yau three-fold

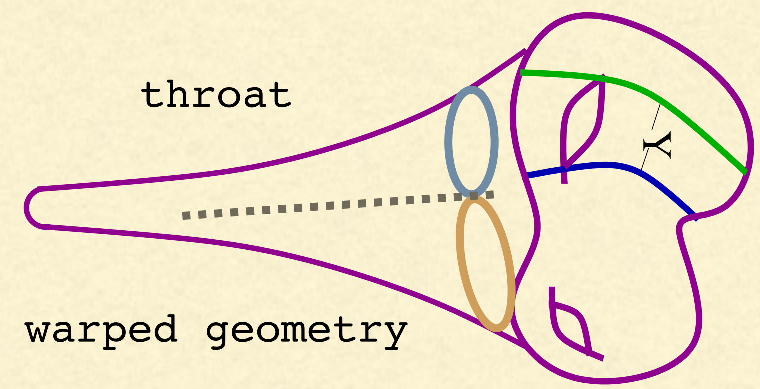


THE WARPED CONIFOLD

When internal fluxes are turned on, backreaction warps 10D spacetime giving rise to throat like geometry

- **warped deformed conifold** (WDC)
  [Klebanov-Strassler, '00] $(F_3, H_3, F_5) \neq 0$

- **warped resolved conifold** (WRC)
  [Pando-Zayas, Tseytlin, '00; Klebanov-Rurugan, '07] $(F_5 \neq 0)$



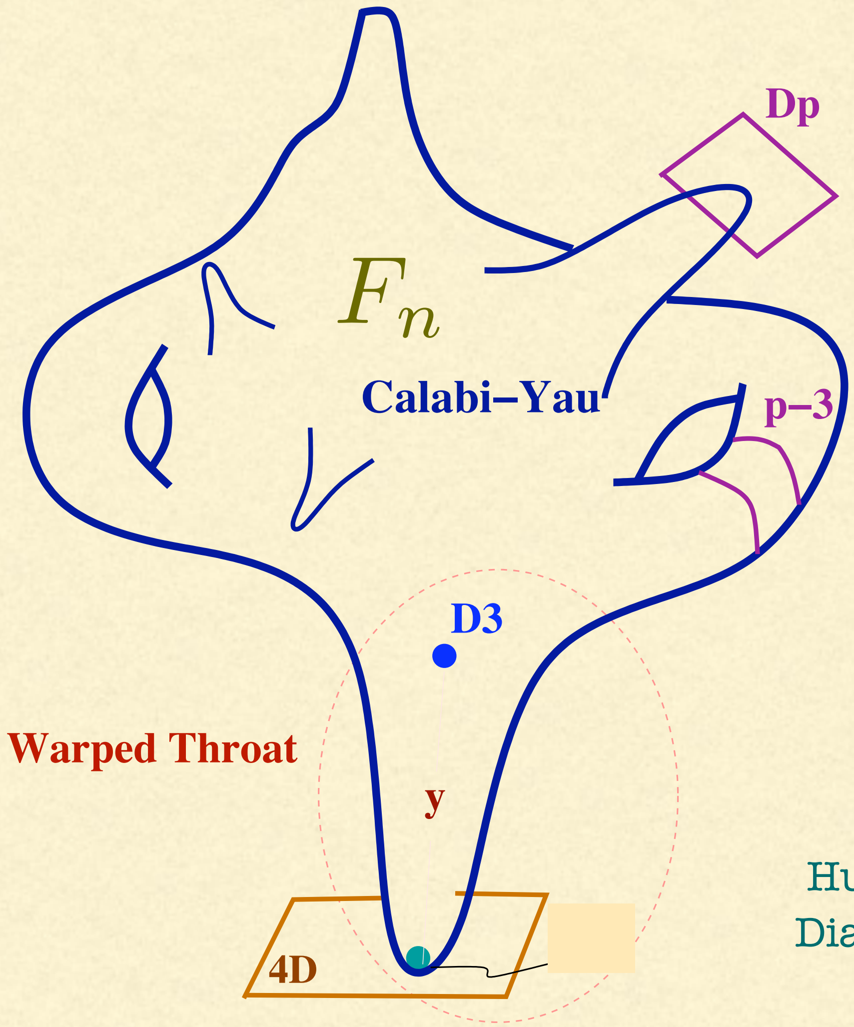
$$ds^2_{10} = e^{2A(y)}\eta_{\mu\nu}dx^\mu dx^\nu + \underset{\textbf{warp factor}}{e^{-2A(y)}}\underbrace{\tilde{g}_{mn}dy^m dy^n}_{\text{DC/RC}}$$

Early universe acceleration: inflation

THE CONIFOLD AND STRING INFLATION

- **D-brane inflation:** a D-brane (anti-D-brane) moves in the internal 6D *warped* space driving inflation*

[Kachru et al, '03; Baumann et al. '06-'10]



- **DBI** inflation: non-standard kinetic terms and warping ➠ inflation with distinctive phenomenology

[Tong, Silverstein, '04; Alishahiha, Tong, Silverstein, '04]

- D3-brane can move in 6D ➠ **multifield** inflation

[w/Gregory, Easson,Mota, Tasinato, '07; Huang, Shiu, Underwood, '07; Chen, Gong, Shiu, '08; Agarwal, Bean, McAllister, Xu, '11; Dias, Frazer, Liddle, '12; McAllister, Renaux-Petel, Xu, '12; Marzouk, Maraio, Seery, '21]

* [For earlier work see: Dvali-Tye, '98; Burgess et al., 01; Dvali, Shafi Solganik, '01]

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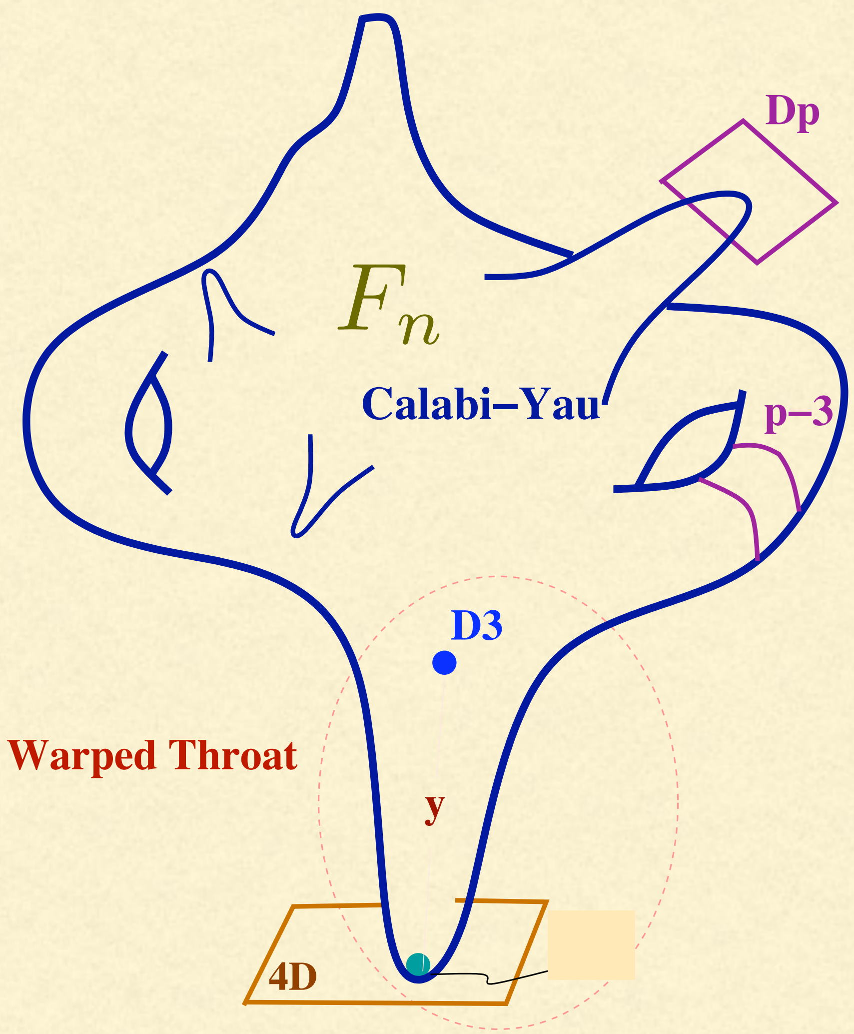


- Higher dimensional Dp-branes wrapping a (p-3)-cycle.
  - **D5** wrapping a 2-cycle in the internal manifold.

    [Kobayashi, Mukohyama, Kinoshita '07; Becker, Leblond, Shandera '07]

  - **D7** brane wrapping 4-cycle.

    [Kobayashi, Mukohyama, Kinoshita '07]

D5/D7 moving in more than one dimension: multifield

* [For earlier work see: Dvali-Tye, '98; Burgess et al., 01; Dvali, Shafi Solganik, '01]

MULTI FIELD INFLATION, RECENT DEVELOPMENTS

In multifield inflation, a new inflationary attractor arises characterised by **strongly non-geodesic** trajectories

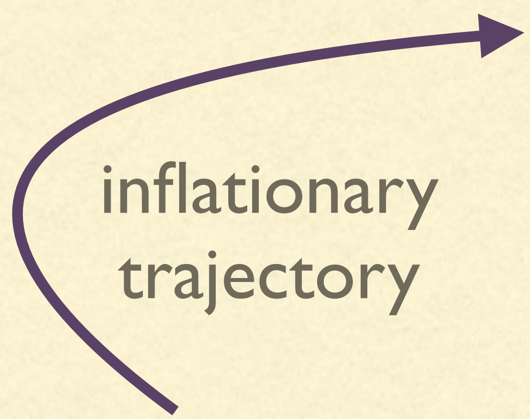
[Achúcarro, Bjorkmo, Brown, Hetz, Palma, Christodoulidis, Marsh, Roest, Renaux-Petel, Sfakianakis, Turzyński, 15-19]

- Departure from geodesic measured by **turning rate** ω which should vary slowly during slow-roll inflation

[Aragam, Paban, Rosati, '20]

new slow-roll parameter

$$\nu \equiv \frac{\dot{\omega}}{H\omega}\,, \qquad \nu \ll 1$$



$\omega \gg 1$ Strongly non-geodesic attractor

together with usual slow-roll conditions $\epsilon, \eta \ll 1$

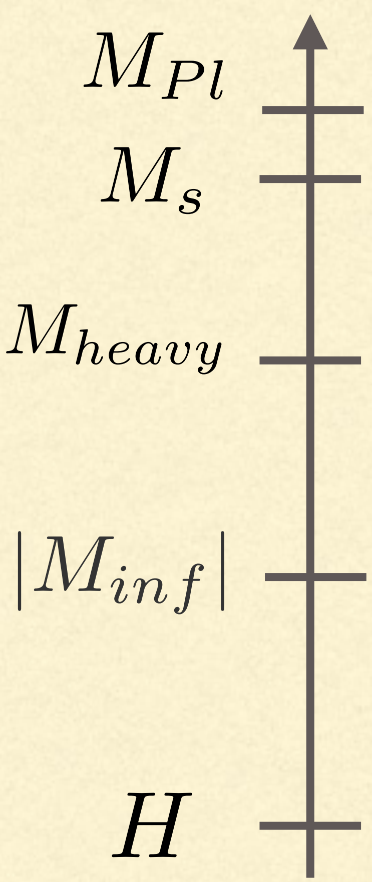
- Interesting phenomenology, in particular for *sharp turns*

FAT INFLATION

[w/Chakraborty, Chiovoloni, Loaiza, Niz '19]

Contrary to standard belief, **inflaton masses** can *all* be **larger** than Hubble scale: **fat**. Steep potentials are ok

[w/Chakraborty et al. '19;
w/Aragam, Chivoloni, Paban, Rosati, '21]



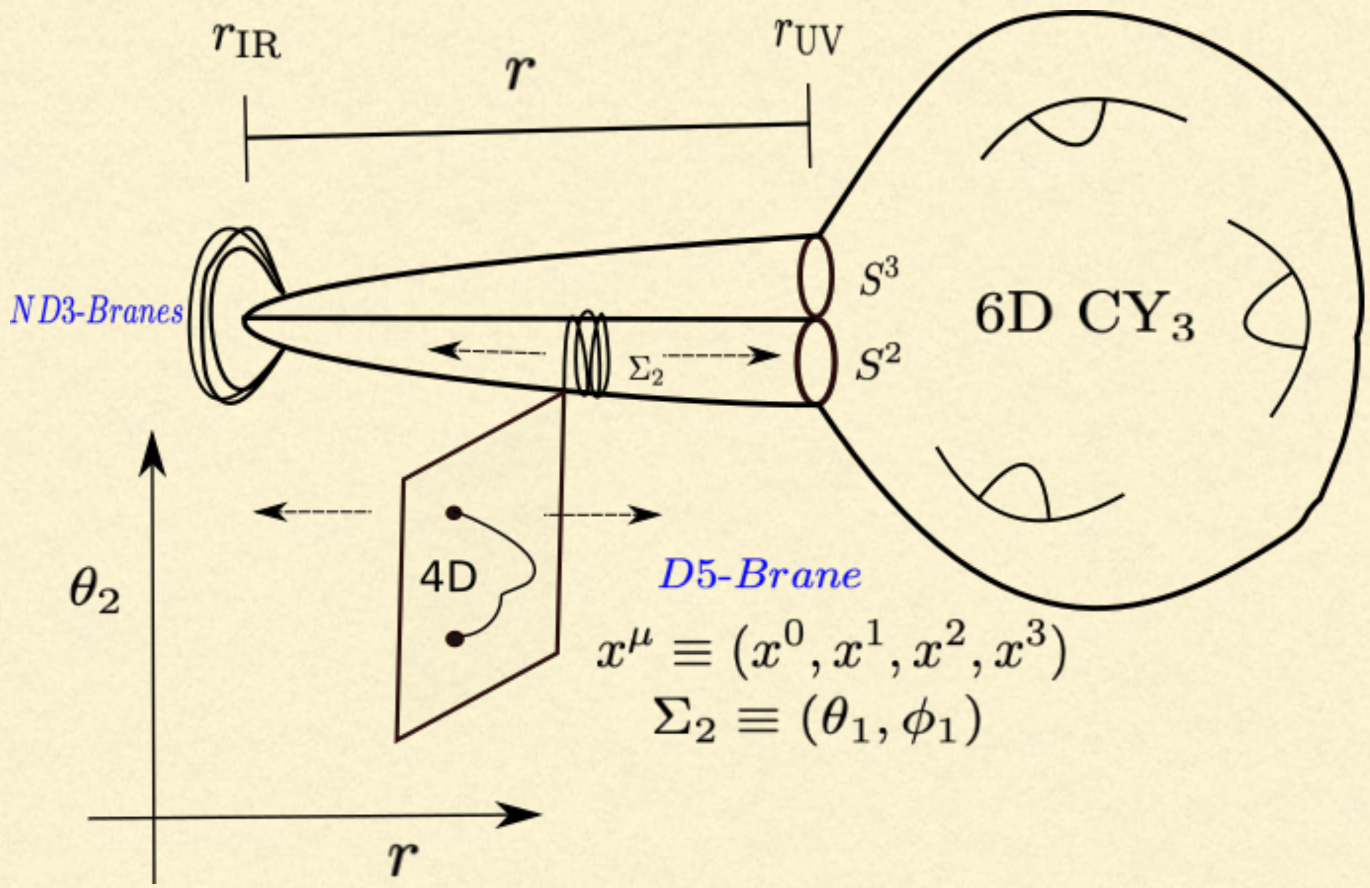
$$H < |M_{inf}| < M_{heavy} \qquad (\forall \;\; \phi^a)$$

$$\eta_V \equiv M_{\rm Pl}^2 \left| \text{min eigenvalue} \left(\frac{\nabla^a \nabla_b V}{V} \right) \right| \gg 1$$

FAT INFLATION IN STRING THEORY

[w/Chakraborty, Chiovoloni, Loaiza, Niz ’19]

- Consider a *warped* compactification in type IIB string theory. A probe **D5-brane** moving in the radial and angular directions in a **warped resolved conifold**



[Single field case: Kenton-Thomas, ’14]

WARPED GEOMETRY AND D5-BRANE DYNAMICS

- The 10D metric for the WRC is given by

[Pando Zayas, Tseytlin, 00; Klebanov, Murugan, '07]

$$ds^2 = \underbrace{\mathcal{H}^{-1/2}}_{\text{Warp factor}}(\rho, \theta_2) ds^2_{FRW} + \mathcal{H}^{1/2}(\rho, \theta_2) \underbrace{ds^2_{RC}}_{\text{6D resolved conifold metric}} \, ,$$

- Probe D5-brane dynamics is described by

$$S_5 = \; -T_5 p \int_{\mathcal{W}_6} d^6\xi \sqrt{-\det(P_6 \left[g_{ab} + B_{ab} + \underset{q}{\underline{2\pi\alpha' F_{ab}}}\right])} \; + \mu_5 p \int_{\mathcal{W}_6} P_6 \left[C_6 + C_4 \wedge (B_2 + 2\pi\alpha' F_2)\right]$$

$T_5 = \mu_5 g_s^{-1}$ $\qquad$ ($g_s =$ string coupling)

$\mu_5 = \left[(2\pi)^5 \ell_s^6\right]^{-1}$ $\qquad$ ($\ell_s =$ string scale)

$p =$ wraping number

$$V(r, \theta) = \phi(r) + \gamma(\overline{\Phi}_-(r) + \Phi_h(r, \theta))$$

$$\gamma = 4\pi^2 \ell_s^2 p q T_5 g_s$$

[Kenton-Thomas, '14; Bauman et al. '07-10]

D5-BRANE FAT INFLATION: THE ACTION

At the end of the day, the 4D action takes the form

$$S_4 = \int d^4x\sqrt{-\mathrm{g}}\left[\frac{M_{\rm Pl}^2}{2}R_4 + \frac{1}{2}g_{ij}v^i v^j - V(r,\theta)\right]$$

where

$$g_{ij} = 4\pi p T_5 \mathcal{F}^{1/2}\mathrm{diag}\left(\frac{r^2+6u^2}{r^2+9u^2}, \frac{1}{6}(r^2+6u^2)\right), \qquad v^i = (\dot r, \dot\theta_2)\,, \qquad \left(M_{Pl}^2 = V_w\left(\frac{1}{2}(2\pi)^7 g_s^2\ell_s^8\right)^{-2}\right)$$

$$\mathcal{F} \equiv \frac{\mathcal{H}}{9}(r^2+3u^2)^2 + (\pi\ell_s^2 q)^2\,,$$

$$\mathcal{H} = \left(\frac{L_{T^{1,1}}}{3u}\right)^4\left(\frac{2}{\rho^2} - 2\ln\left(\frac{1}{\rho^2}+1\right)\right), \qquad L_{T^{1,1}}^4 = \frac{27\pi}{4}N g_s \ell_s^4\,. \qquad (\rho = r/3u)$$

$$V(r,\theta) = V_0 + 4\pi p T_5 \mathcal{H}^{-1}\left[\mathcal{F}^{1/2} - \ell_s^2\pi q g_s\right] + \gamma\left[\overline{\Phi}_- + \Phi_h\right], \qquad (\gamma = 4\pi^2\ell_s^2 pqT_5 g_s)$$

$$\overline{\Phi}_- = \frac{5}{72}\left[81\left(9\rho^2-2\right)\rho^2 + 162\log\left(9\left(\rho^2+1\right)\right) - 9 - 160\log(10)\right]$$

$$\Phi_h = a_0\left[\frac{2}{\rho^2} - 2\log\left(\frac{1}{\rho^2}+1\right)\right] + 2a_1\left[6 + \frac{1}{\rho^2} - 2(2+3\rho^2)\log\left(1+\frac{1}{\rho^2}\right)\right]\cos\theta + \frac{b_1}{2}\left(2+3\rho^2\right)\cos\theta\,.$$

D5-BRANE FAT INFLATION: THE POTENTIAL

$$S_4 = \int d^4x\sqrt{-\mathrm{g}}\left[\frac{M_{\rm Pl}^2}{2}R_4 + \frac{1}{2}g_{ij}v^iv^j - V(r,\theta)\right]$$

With

$$g_{ij} = \mathrm{diag}(g_{rr}(r), g_{\theta\theta}(r))$$

non-trivial field space curvature

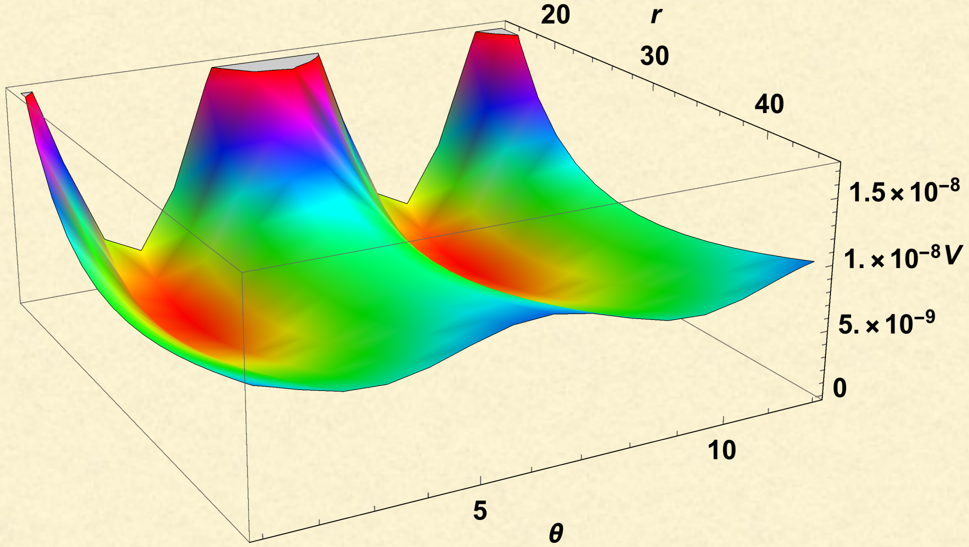
$$\mathbb{R} \neq 0$$

$$V(r,\theta) = V(r) + W(r)\cos\theta$$

Instantaneous decay constant

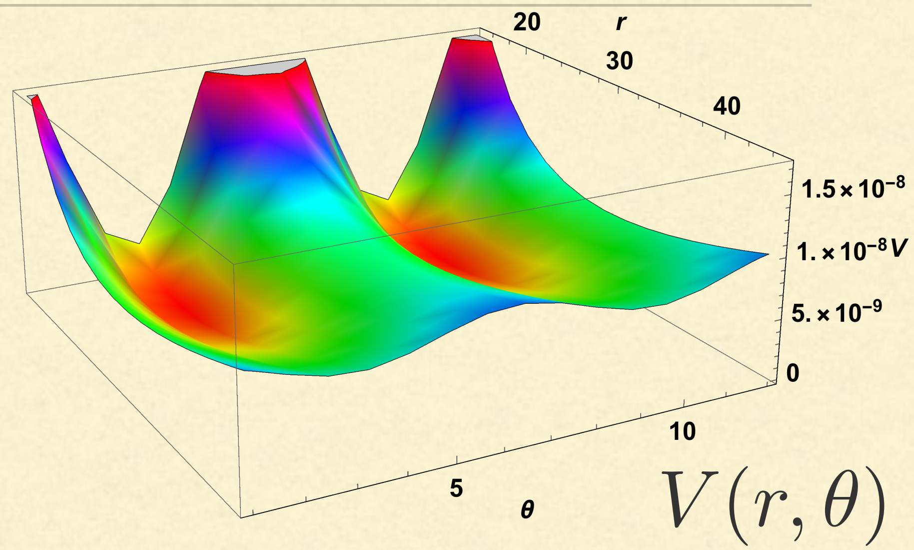
$$f = \sqrt{g_{\theta\theta}(r)}$$

$V(r,\theta)$



D5-BRANE FAT INFLATION: PARAMETERS

Parameters and constraints



$V(r, \theta)$

- String theory models of inflation relay on 4D LEEFT, weakly coupled, perturbative string expansion

$$g_s < 1\,, \quad L/\ell_s > 1$$

- For a 4D effective field theory description to be valid during inflation, requires compactification scale smaller than string scale $(L_c/\ell_s > 1)$

- Thus we require the hierarchy:

$$\lesssim M_{KK} \lesssim M_s \lesssim M_{Pl}$$

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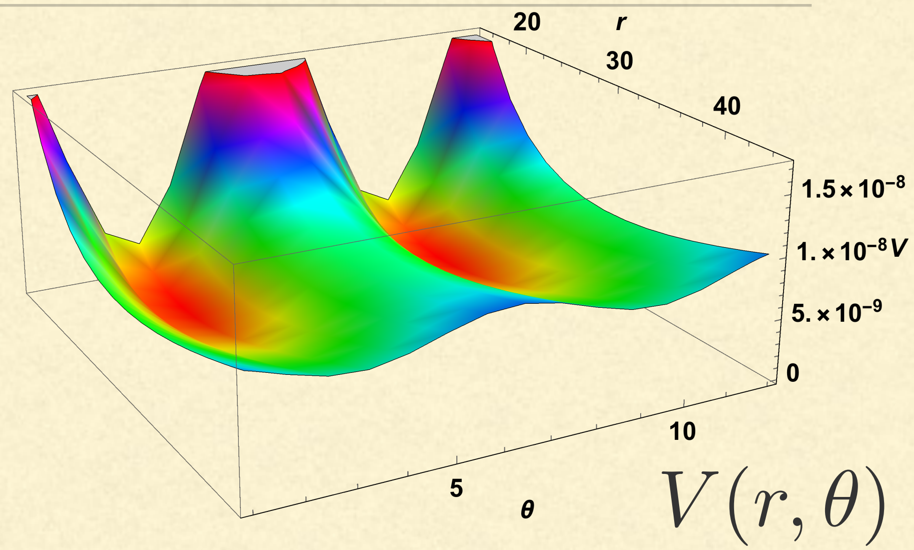

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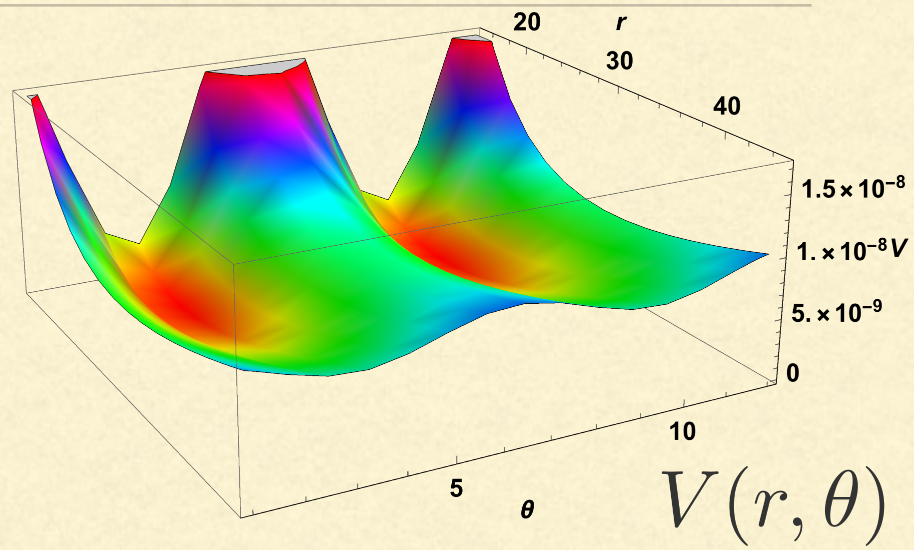

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for light inflation

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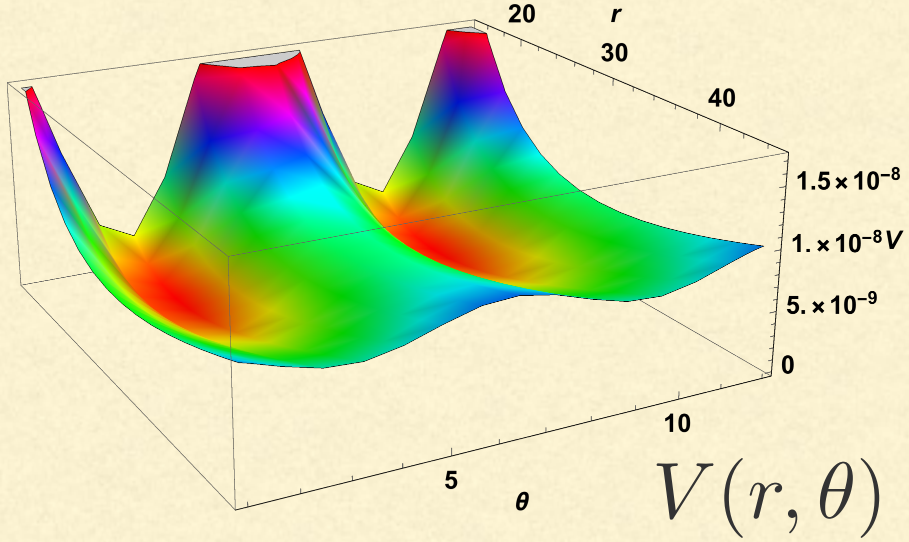

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for fat inflation

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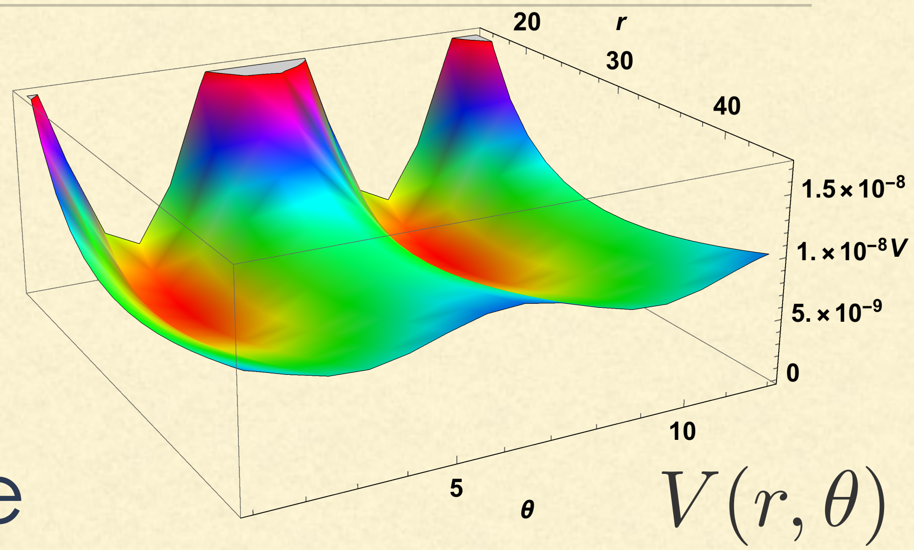


$V(r,\theta)$

- The parameter, u, is the natural length of the throat, so $u > \ell_s$
- The constants (a_0, a_1, b_1) appearing in the potential are undetermined but small. (Coefficients of indep. solutions of the Laplace equation on the RC)
- The parameters (p,q) are the D5-brane wrapping and flux numbers, and N is the number of D3-branes sourcing the RC geometry. Backreaction constraints require

[Becker, Leblond, Shandera, '07; Kooner, S. Parameswaran, IZ, '15]

$$N \gg 1\,, \qquad p \ll 12N(2\pi)^2\mathcal{H}^{-1/2}\frac{\ell_s^2}{r^2}\,, \qquad pq \ll 4\pi N \qquad \left(\mathcal{H}_{min}^{-1/2} = \mathcal{H}_{tip}^{-1/2}\right)$$

D5-BRANE FAT INFLATION

- We fix the parameters (g_s, N, u) to ensure hierarchy of scales:

$$M_c \lesssim M_s \lesssim M_{Pl}$$

- Vary the parameters (p, q), keeping track of the backreaction constraints.

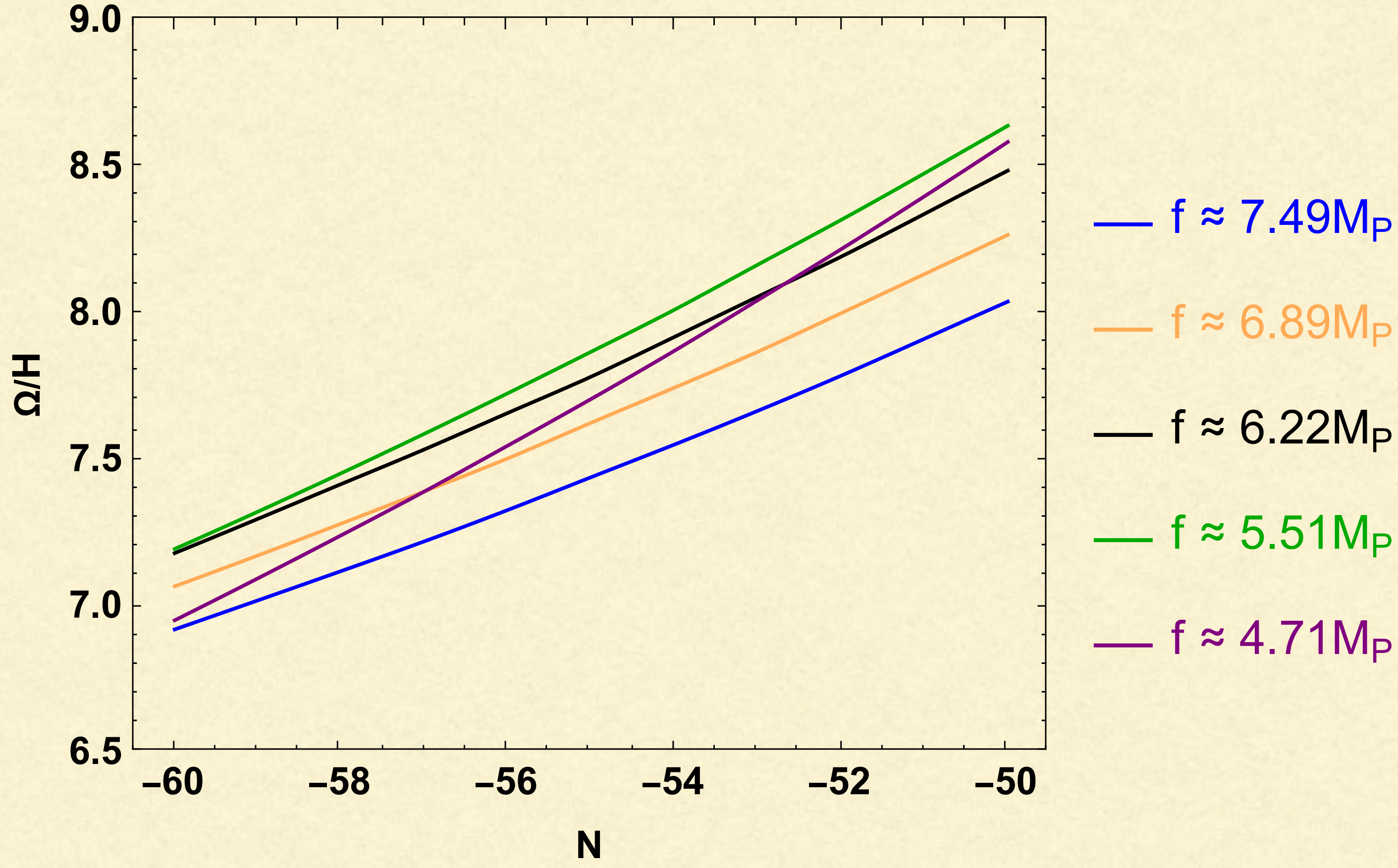
- We then choose the coefficients (a_0, a_1, b_1) such that the amplitude of the scalar perturbations matches with observations.

N	g_s	ℓ_s	u	q	a_0	a_1	b_1
1000	0.01	501.961	$50\ell_s$	1	0.001	0.0005	0.001

$$(M_s \sim 10^{-3} M_{Pl}, \;\; M_c \sim 10^{-4} M_{Pl}, \;\; H \sim 10^{-5} M_{Pl})$$

D5-BRANE FAT INFLATION: TURNING RATE

- Slow-roll Inflation lasts for at 60-efolds or more for wide range of parameters
- Natural-like inflation with large turning rate: $\omega > 1$



$$f = \sqrt{g_{\theta\theta}(r)}$$

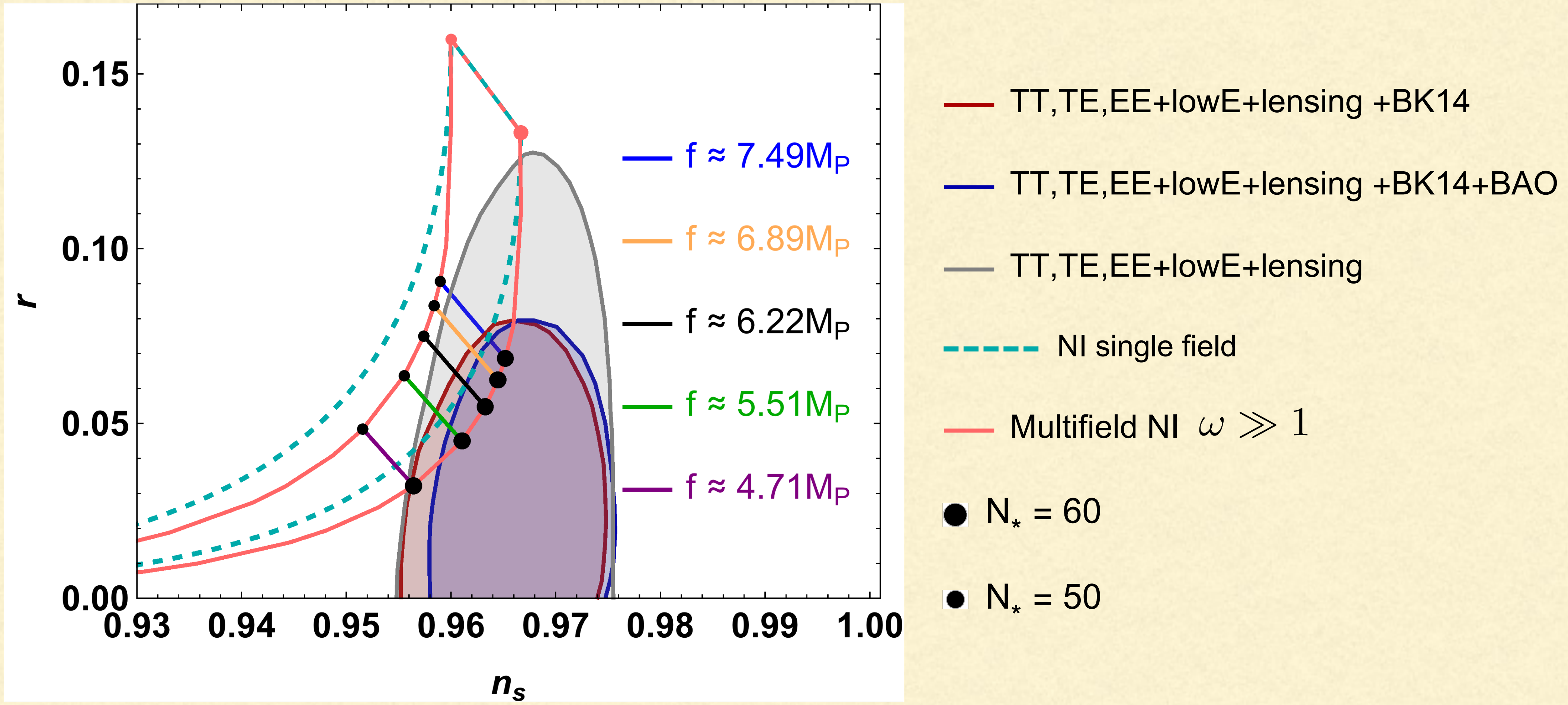
p	f/M_{Pl}
7	7.49
6	6.89
5	6.22
4	5.51
3	4.71

Instantaneous decay constant

- Inflatons are **fat:** $\lambda_{-}/H^2 \sim 10$

D5-BRANE FAT INFLATION: COSMOLOGICAL PARAMETERS

- Cosmological parameters: clear departure from single field

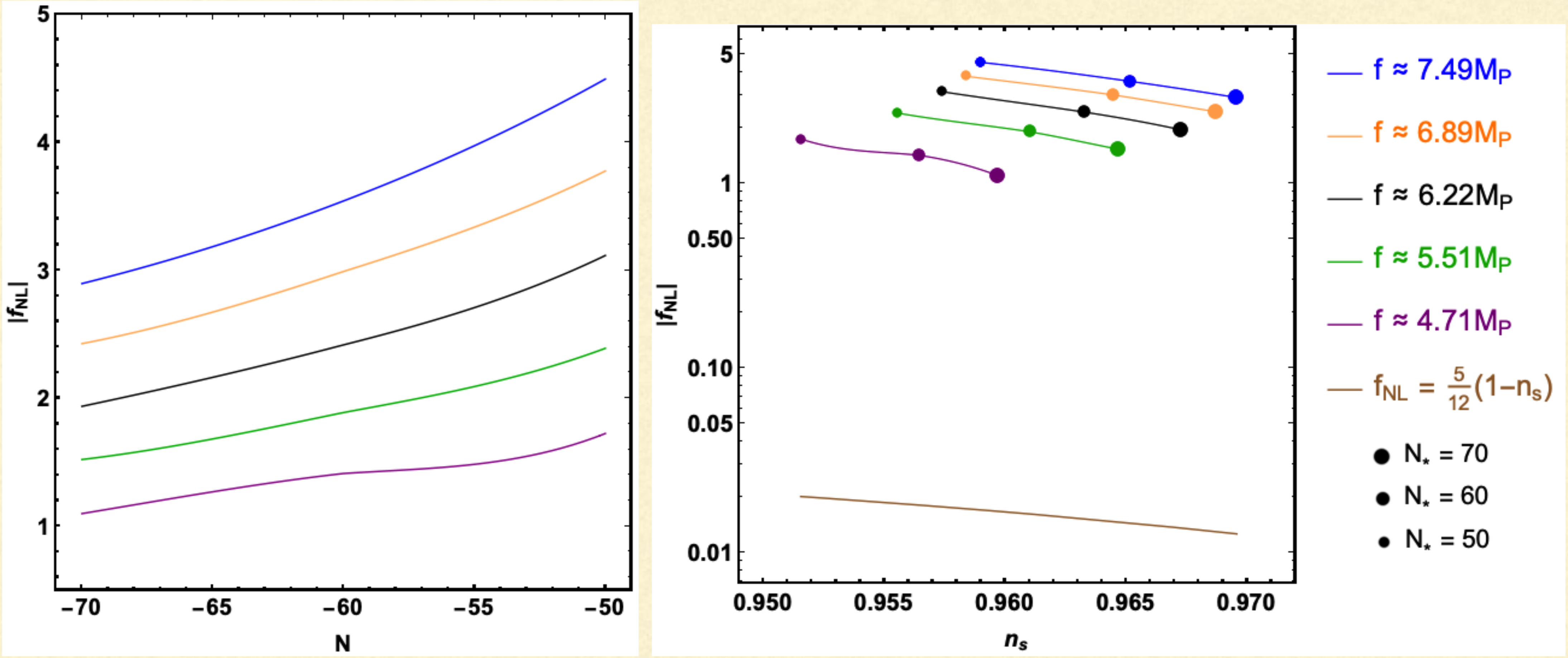


D5-BRANE FAT INFLATION: NON-GAUSSIANITY

- Distinguishable from single field via non-Gaussianity

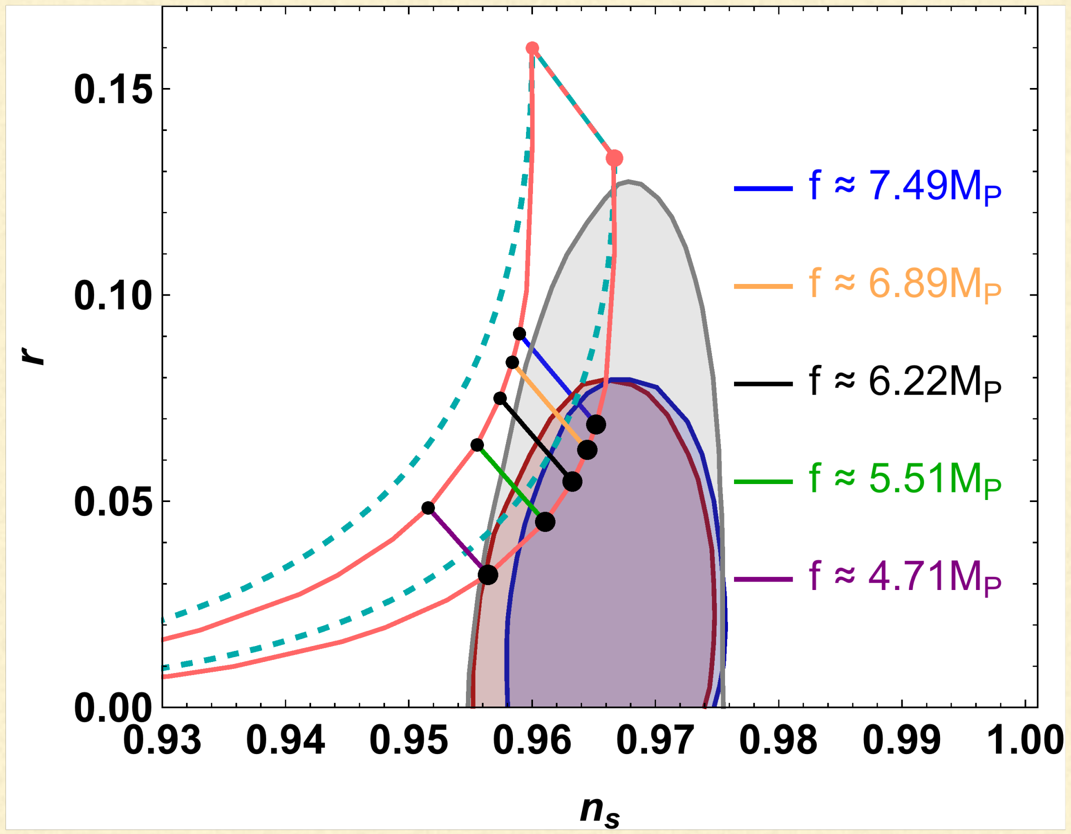
$$f_{\rm NL} = -\frac{5}{6}\frac{\mathrm{N}^{,i}\mathrm{N}^{,j}\mathrm{N}_{;ij}}{(\mathrm{N}_{,k}\mathrm{N}^{,k})^2}\,,$$

[Kaiser, Mazenc, Sfakianakis, '12]



Fat natural inflation

N	g_s	ℓ_s	u	q	a_0	a_1	b_1
1000	0.01	501.961	$50\ell_s$	1	0.001	0.0005	0.001



p	$f/M_{\rm Pl}$
7	7.49
6	6.89
5	6.22
4	5.51
3	4.71

$$\mathbb{R} - 3 \times 10^4 M_{Pl}^{-2}$$

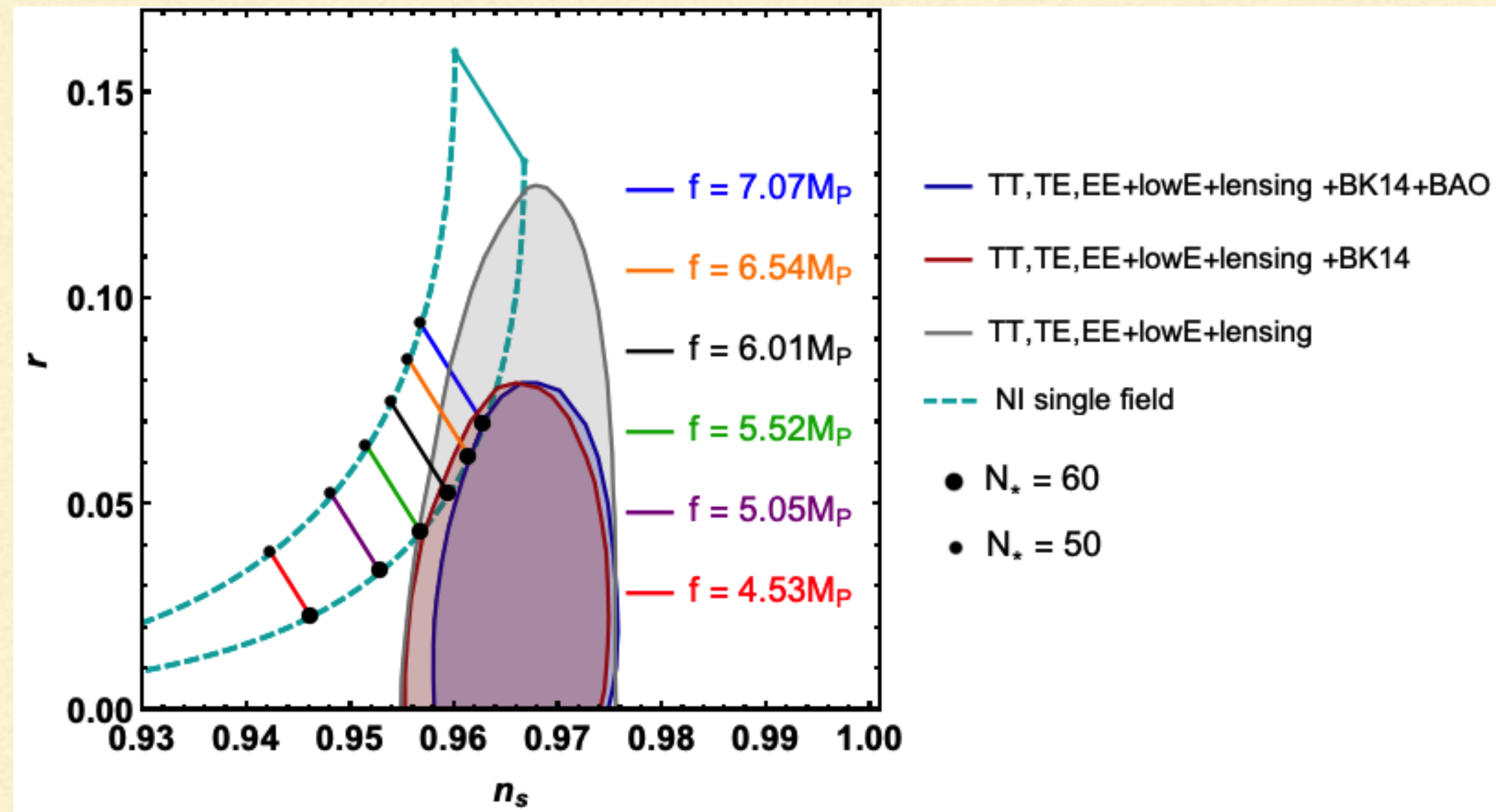
$$\lambda_- / H^2 \sim 10$$

$$\omega \sim 10$$

$$f_{NL} \sim \mathcal{O}(1)$$

Light natural inflation

N	g_s	q	u	ℓ_s	a_0	a_1	b_1
1000	0.01	70	$50l_s$	501.961	0.1	0.0001	0.0001



p	$f/M_{\rm Pl}$
90	7.07
77	6.54
65	6.01
55	5.52
46	5.05
37	4.53

$$\mathbb{R} \sim -10^2 M_{\rm Pl}^{-2}$$

$$\lambda_1 / H^2 \sim 0.1$$

$$\omega \sim 0.4$$

$$f_{NL} \sim \mathcal{O}(10)$$

MULTIFIELD D-BRANE INFLATION

- Multifield inflation has new inflationary attractor with (strongly) non-geodesic trajectories.
- Light fields are not needed, *all* fields can be heavy. Avoid η_V-problem
- Fat D5-brane model has challenges that would need to be addressed in a more complete model (moduli stabilisation, heaviest inflaton a bit too heavy)
- Fat trajectories in D3-anti-D3-brane multi-field inflation seem difficult
- Transient large turns ➠ interesting pheno (PBHs, GWs)?

[sugra case: Bhattacharya, IZ, '22]

Late time acceleration: dS vacua

DE SITTER SPACE

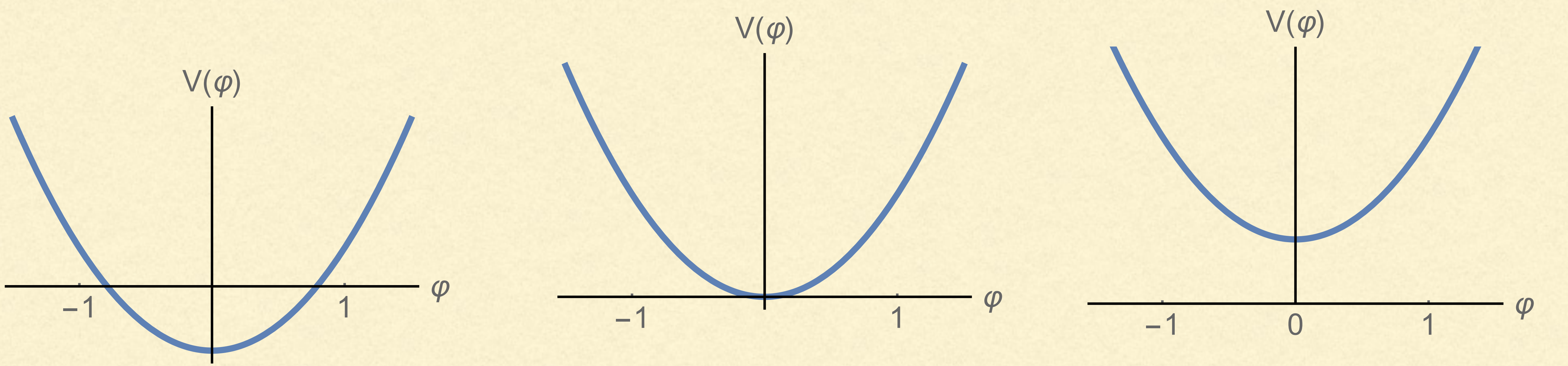
Cosmological constant problem aside, ***de Sitter space*** in string theory and pure supergravity challenging to find

$$G_{\mu\nu} = 8\pi G T_{\mu\nu}$$

Law of an expanding universe — All matter and energy in the universe — Einstein's original equation

$$G_{\mu\nu} + \Lambda g_{\mu\nu} = 8\pi G T_{\mu\nu}$$

Law of an expanding universe — Cosmological constant — All matter and energy in the universe



$\Lambda < 0$ *AdS* $\Lambda = 0$ *Minkowski* $\Lambda > 0$ *dS*

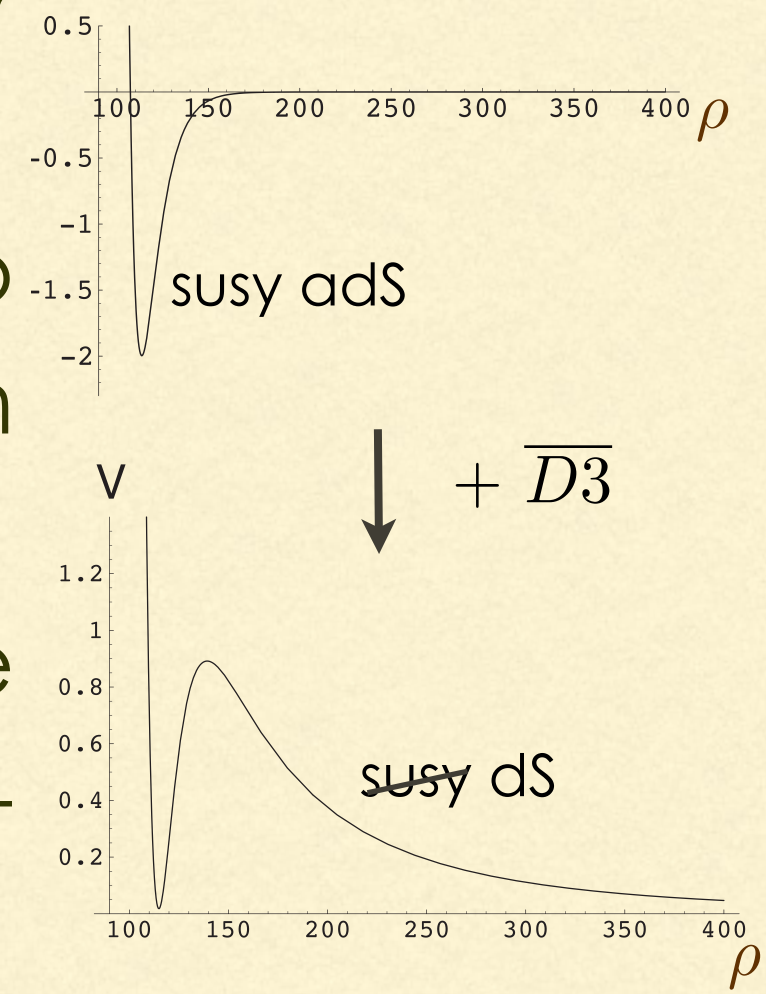
DS VACUA IN STRING THEORY: KKLT

[Kachru, Kallosh, Linde, Trivedi, '03]

Flux compactification in type IIB: N=1 sugra

[Giddings, Kachru, Plochinski, '01]

- 1) Fluxes generate a potential for dilaton and complex structure moduli
- 2) Add non-perturbative terms to stabilise Kähler moduli: only adS can be obtained
- 3) Uplift the minimum to a dS, positive vacuum energy by adding an anti-D3-brane

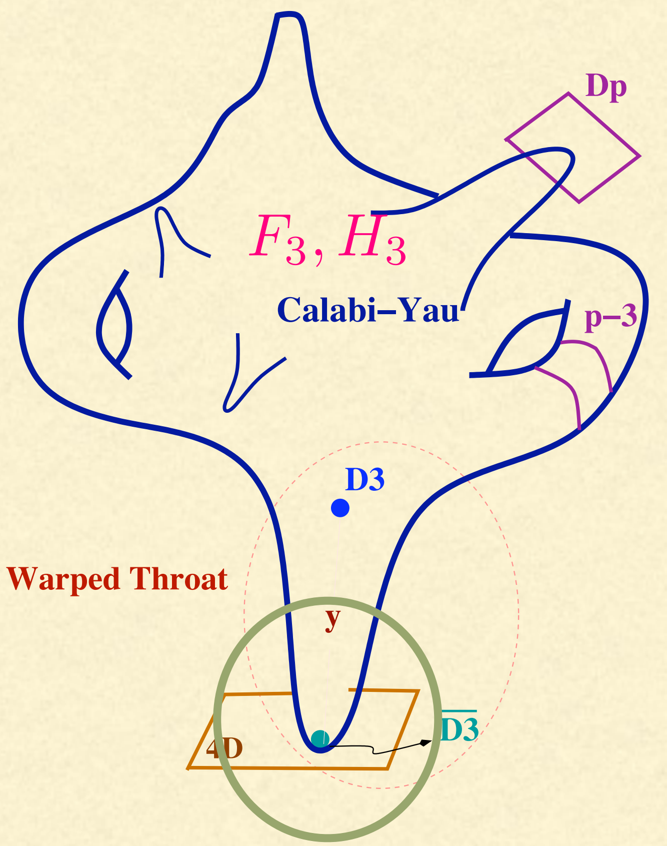


REVISITING KKLT STEP 1

- *Near the conifold point*, 6D metric well approximated by Klebanov-Strassler warped deformed conifold solution

[Klebanov-Strassler, '00]

$$ds^2_{10} = e^{2A(y)}\eta_{\mu\nu}dx^\mu dx^\nu + e^{-2A(y)}\underbrace{\tilde{g}_{mn}dy^m dy^n}_{\text{KS}}$$



- Kähler metric for deformation modulus is *corrected* due to *strong* warping.

[Giddings-Maharana '05; **Douglas-Shelton-Torroba, '07**; Frey-Torroba-Underwood-Douglas, '08]

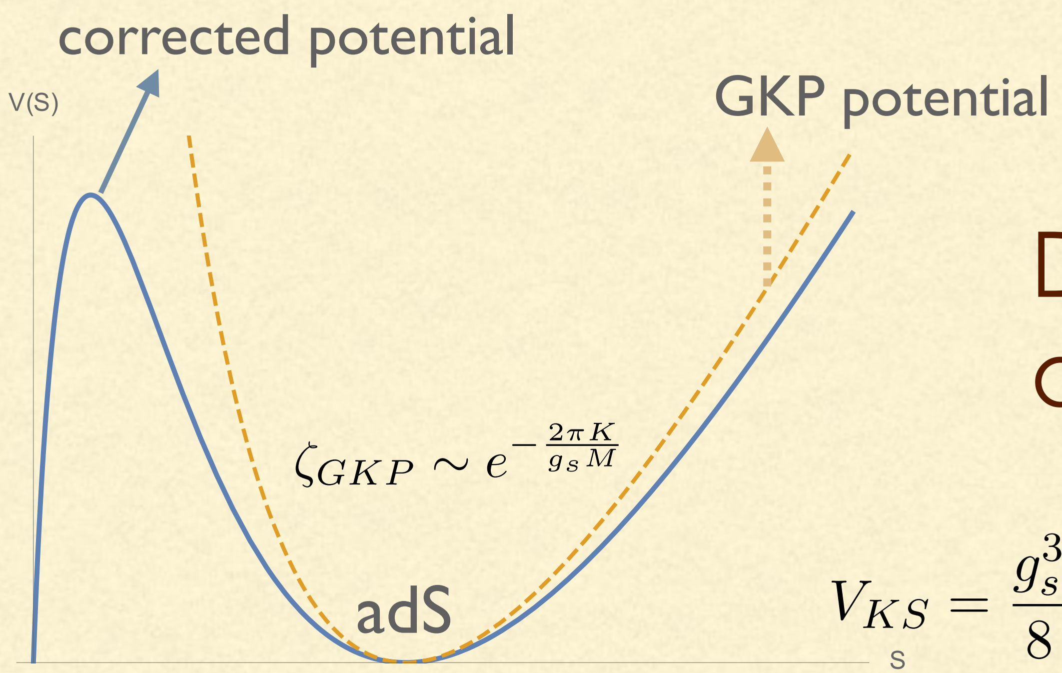
$$\mathcal{K}(z,\bar{z}) = \frac{l_s^6}{\pi||\Omega||^2 V_6}\left[|z|^2\left(\log\frac{\Lambda_0^3}{|z|}+1\right) + \frac{9c'(g_sM)^2}{(2\pi)^4\mathcal{V}^{2/3}}|z|^{2/3}\right]$$

REVISITING KKLT STEP 1

- Deformation conifold modulus, S, becomes light and might be destabilised by uplifting anti-D3 brane potential

$\left(z = S/\ell_s^3 = \zeta e^{i\theta}\right)$

[Bena, Dudas, Graña, Lüst, '18; Blumenhagen, Kläwer, Schlechter, '19; Bena, Buchel, Lüst, 19; Dudas, Lüst, '19; Randall, '19; Crinò, Quevedo, Valandro, '20]



near the conifold point,

$z \ll 1$

DST strong warping correction dominates

$$V_{KS} = \frac{g_s^3}{8}\frac{g_s}{\mathcal{V}^2}\left(\log\frac{\Lambda_0^3}{|z|} + \frac{1}{(2\pi)^4}\frac{c'(g_s M)^2}{\mathcal{V}^{2/3}|z|^{4/3}}\right)^{-1}\left|\frac{M}{2\pi}\log\frac{\Lambda_0^3}{z} - \frac{K}{g_s}\right|^2 M_p^4$$

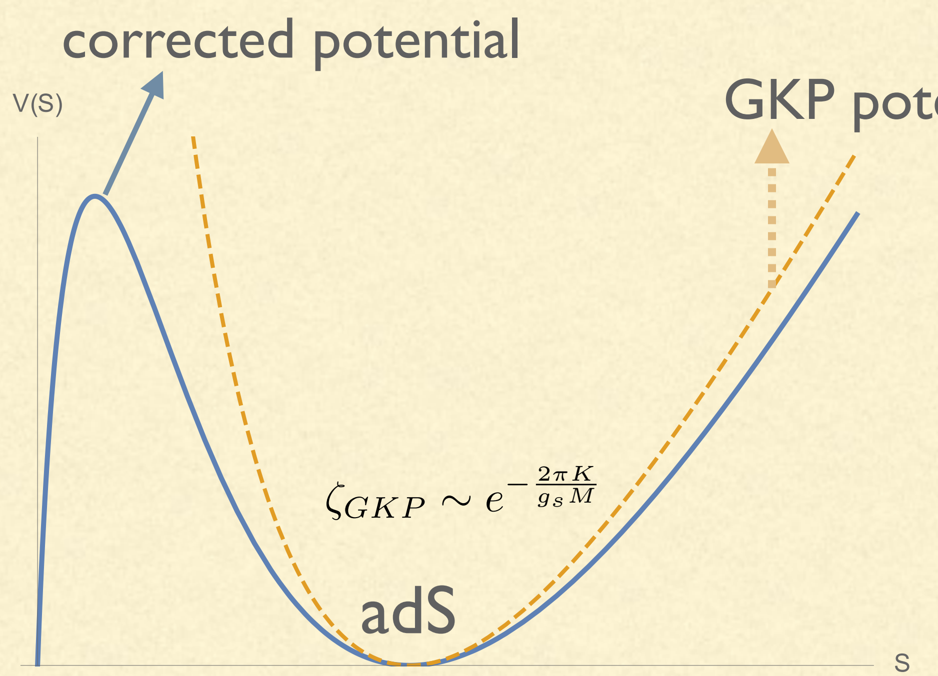
REVISITING KKLT STEP 1

- Deformation conifold modulus, S, becomes light and might be destabilised by uplifting anti-D3 brane potential

[Bena, Dudas, Graña, Lüst, '18; Blumenhagen, Kläwer, Schlechter, '19; Bena, Buchel, Lüst, 19; Dudas, Lüst, '19; Randall, '19; Crinò, Quevedo, Valandro, '20]

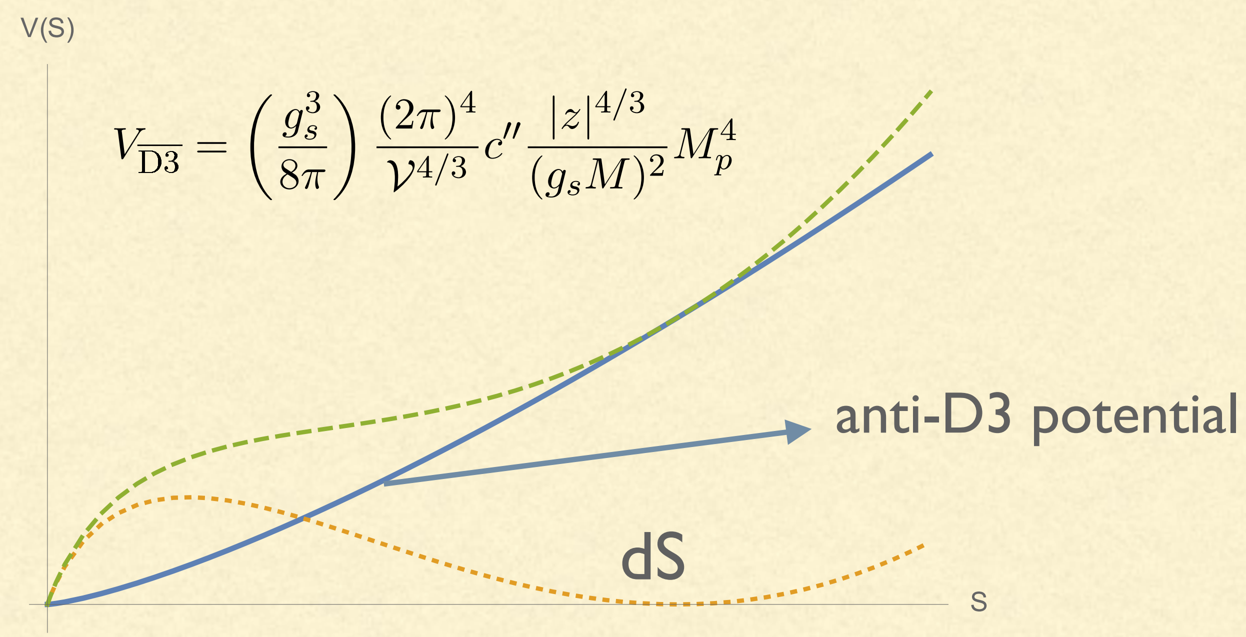
- Stability of anti-D3 uplifted minimum requires large fluxes, threatening tadpole cancellation

[Braun, Valandro, '20; Bena, Blåbäck, Graña, Lüst, '20-21]



$$\zeta_{GKP} \sim e^{-\frac{2\pi K}{g_s M}}$$

$$+\ \overline{D3}$$



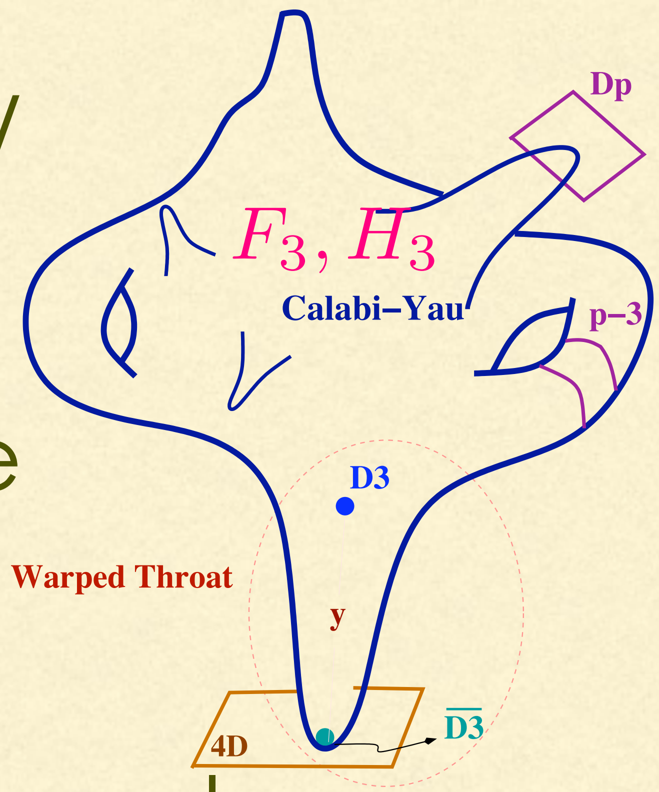
$$V_{\overline{\rm D3}} = \left(\frac{g_s^3}{8\pi}\right)\frac{(2\pi)^4}{\mathcal{V}^{4/3}}c''\frac{|z|^{4/3}}{(g_sM)^2}M_p^4$$

TADPOLE CANCELLATION

- Orientifold compactifications contain O3/O7-planes. Need to cancel tadpoles.

- Fluxes contribute to the D3-brane charge as well as D7-branes.

- Requiring to cancel total charges in the internal CY space from D-branes, O-planes and fluxes:



$$N_{flux} = \frac{N_{O3}}{2} + \frac{\chi(D_{O7})}{2} - 2N_{D3}$$

$$N_{flux} \propto \int_{CY} F_3 \wedge H_3$$

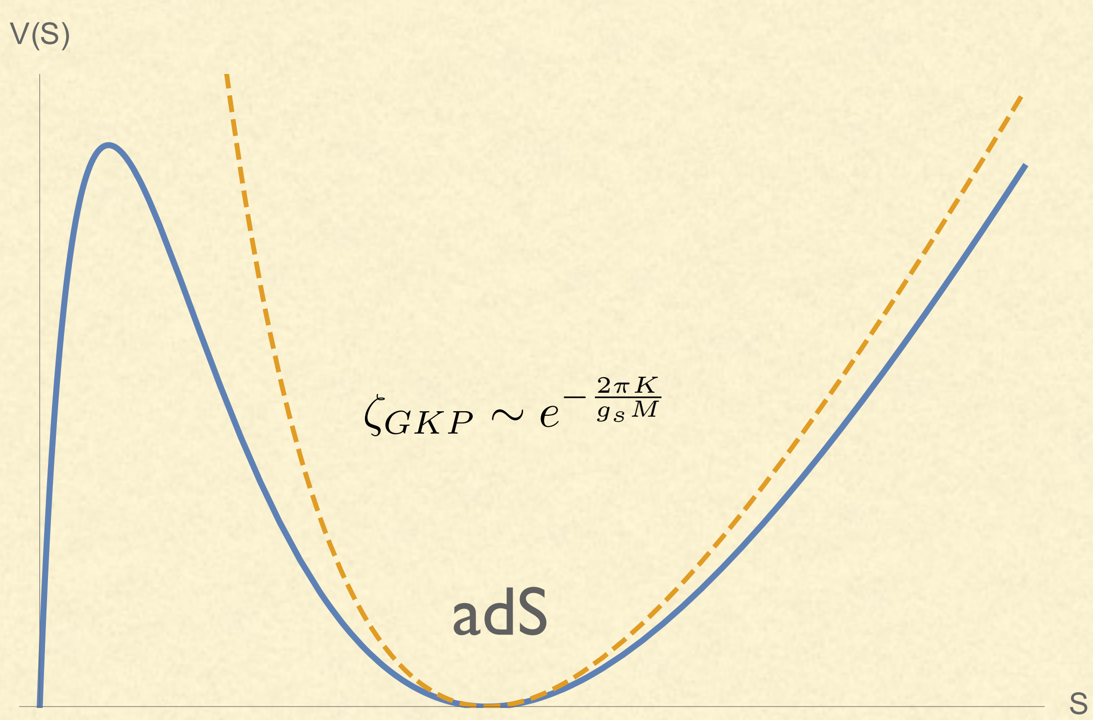
$$\frac{1}{(2\pi\alpha)^2\alpha'}\int_A F_3 = M$$

$$\frac{1}{(2\pi\alpha)^2\alpha'}\int_B H_3 = K$$

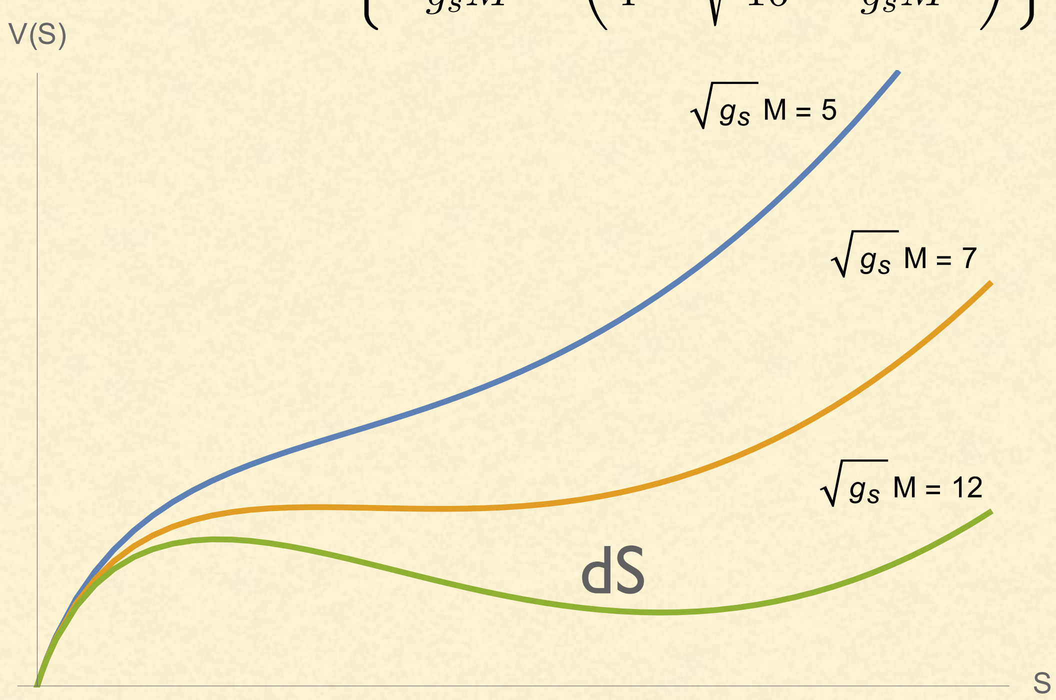
UPLIFTING RUNAWAYS

Strongly warped regime: deformation conifold potential runaway as adS ➠ dS $(c' = 1.18, c'' = 1.75)$ [Bena, Dudas, Graña, Lüst, '18]

$$\zeta_{min} = \Lambda_0^3 \ \exp\left\{-\frac{2\pi K}{g_s M} - \left(\frac{3}{4} \pm \sqrt{\frac{9}{16} - \frac{4\pi c' c''}{g_s M^2}}\right)\right\}$$



➠



$$MK \gtrsim 500$$

$$MK \gtrsim 100$$

[Bena, Blåbäck, Graña, Lüst, '20-21]

(N_{flux} =MK)

[Crinò, Quevedo, Valandro, '20]

NEW DS IN WEAKLY WARPED REGIME

[Bento-Chakraborty-Parameswaran-IZ, '21]

How generic is this? What happens in the **weakly warped** regime? That is,

$$\mathcal{K}(z,\bar{z}) = \frac{l_s^6}{\pi||\Omega||^2 V_6}\left[|z|^2\left(\log\frac{\Lambda_0^3}{|z|}+1\right)+\frac{9c'(g_sM)^2}{(2\pi)^4\mathcal{V}^{2/3}}|z|^{2/3}\right]$$

Flux potential:

$$V_{KS} = \frac{g_s^3}{8}\frac{g_s}{\mathcal{V}^2}\left(\log\frac{\Lambda_0^3}{|z|}+\frac{1}{(2\pi)^4}\frac{c'(g_sM)^2}{\mathcal{V}^{2/3}|z|^{4/3}}\right)^{-1}\left|\frac{M}{2\pi}\log\frac{\Lambda_0^3}{z}-\frac{K}{g_s}\right|^2 M_p^4$$

Anti-D3 potential gets also modified $(c_{D3}=0,1)$

$$V_{\overline{\text{D3}}} = c_{D3}\left(\frac{g_s^3}{8\pi}\right)\frac{2}{\mathcal{V}^2}\left\{1+\frac{1}{(2\pi)^4}\frac{2}{c''}\frac{(g_sM)^2}{\mathcal{V}^{2/3}|z|^{4/3}}\right\}^{-1} M_p^4$$

NEW DS IN WEAKLY WARPED REGIME

[Bento-Chakraborty-Parameswaran-IZ, '21]

Weakly warped regime: new dS solution, present also for small KM $z = \zeta e^{i\theta}, \; x \equiv \log \frac{\Lambda_0^3}{\zeta}$

$$V = V_{KS} + V_{\overline{D3}} = \frac{\delta_1 C}{\mathcal{V}^{4/3}} \Lambda_0^4 e^{-\frac{4}{3}x} \left[(1+\beta)^{-1}(1-\epsilon x)^2 + c_{D3}\delta_2 \left(1 + \delta_3 \mathcal{V}^{2/3} \Lambda_0^4 e^{-\frac{4}{3}x}\right)^{-1} \right]$$

$$\varepsilon = \frac{g_s M}{2\pi K}, \quad \delta_1 = \frac{g_s^3}{8} \times \frac{K^2}{g_s}, \quad \delta_2 = \frac{g_s^3}{8\pi} \times c'' \frac{c'}{\delta_1} = \frac{1}{\pi} \times c'' c' \frac{g_s}{K^2}, \quad \delta_3 \equiv \frac{(2\pi)^4}{2} \frac{c''}{(g_s M)^2}$$

$$\beta \equiv \frac{\mathcal{V}^{2/3} \log \frac{\Lambda_0^3}{\zeta}}{\frac{c'}{(2\pi)^4} \frac{(g_s M)^2}{\zeta^{4/3}}} = C\, \mathcal{V}^{2/3} \Lambda_0^4 \, x e^{-\frac{4}{3}x}, \qquad C = \frac{(2\pi)^4}{c'(g_s M)^2}$$

- Strongly warped regime $\beta \ll 1$ (previous work)

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- Weakly warped regime $\beta \gg 1$ (our work)

NEW DS IN WEAKLY WARPED REGIME

[Bento-Chakraborty-Parameswaran-IZ, '21]

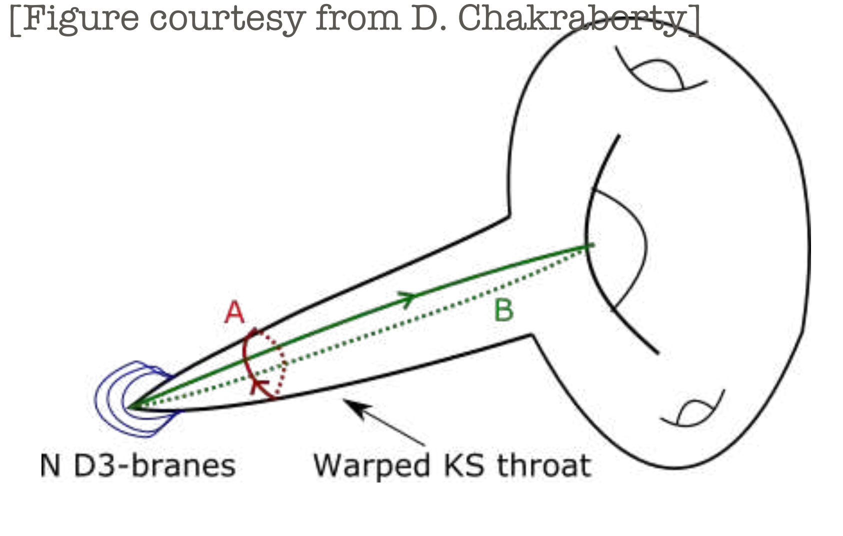
Weakly warped regime: new dS solution, present also for small KM

$$V \approx \frac{\delta_1}{\mathcal{V}^2}\frac{1}{x}\left[\left(1-\frac{1}{\beta}\right)\left(1-\varepsilon x\right)^2 + \beta c_{D3}\delta_2\left(1+\delta_3\mathcal{V}^{2/3}\Lambda_0^4 e^{-\frac{4}{3}x}\right)^{-1}\right]$$

This has a minimum at

$$\zeta_{min} \approx \Lambda_0^3 \exp\left\{-\frac{2\pi K}{g_s M} - \frac{16 K c_{D3}}{12\pi^2 c' M \Lambda_0^4 \mathcal{V}^{2/3}}\right\}$$

[Figure courtesy from D. Chakraborty]



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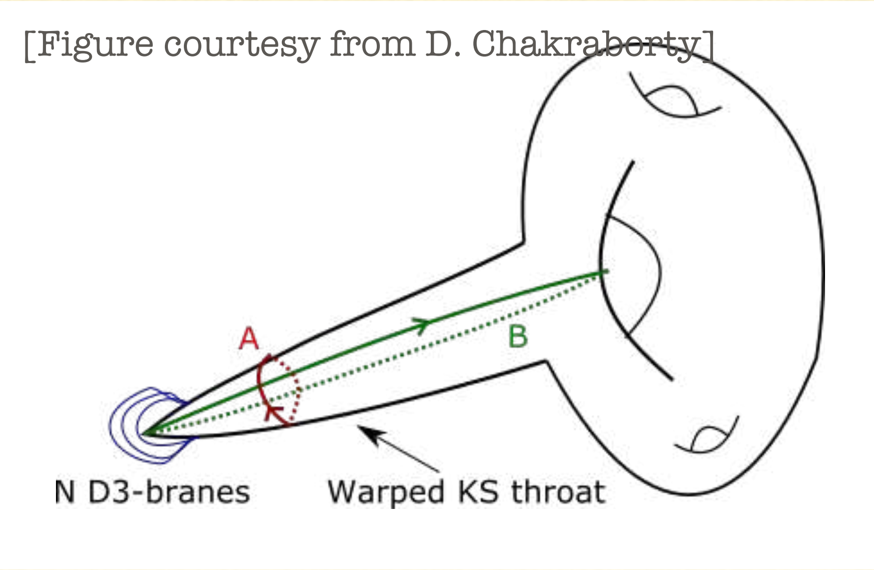

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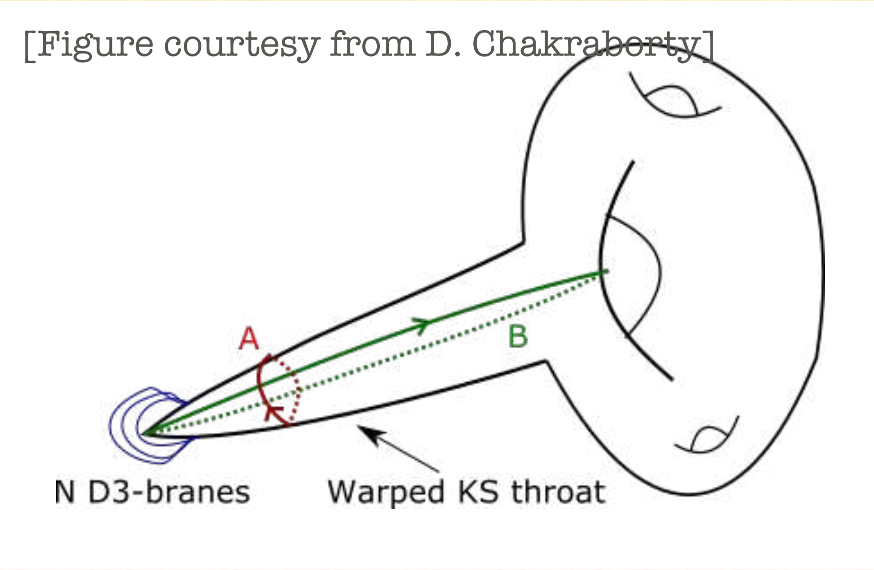

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small shift of the GKP solution

So long as β is large enough, there is always a solution.
Thus anti-brane does not destabilise the conifold modulus.
Tadpole can be small

NEW DS IN WEAKLY WARPED REGIME: VOLUME STABILISATION

Volume can be stabilised in the large volume scenario

$$\mathcal{K}/M_p^2 = k_0 - 2\log\left[\mathcal{V} + \frac{\xi}{g_s^{3/2}}\right] - \log\left(-i(\tau-\bar{\tau})\right) + k_1|z|^2\left(\log\frac{\Lambda_0^3}{|z|}+1\right) + \frac{k_2}{\mathcal{V}^{2/3}}|z|^{2/3}\,,$$

$$W/M_p^3 = w_1\left(W_0 e^{i\sigma} + \left[-\frac{M}{2\pi i}z\left(\log\frac{\Lambda_0^3}{z}+1\right) - i\frac{K}{g_s}z\right] + Ae^{-aT_s}\right)$$

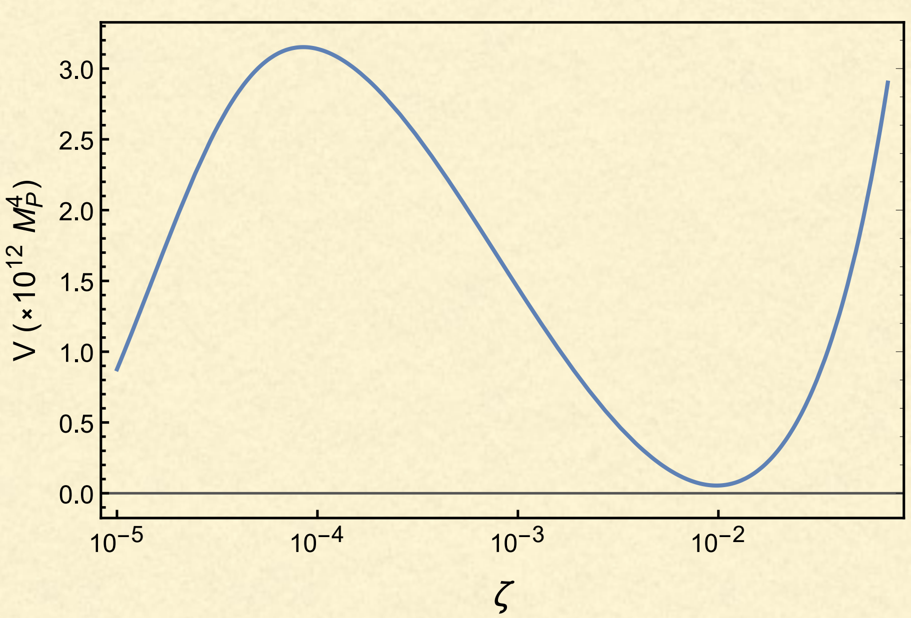
[Bento-Chakraborty-Parameswaran-IZ, '21]

- Weakly warped regime

W_0	σ	g_s	M	K	Λ_0	κ_s	χ	a	A
1200	0	0.17	16	2	1	$\frac{\sqrt{2}}{9}$	-260	$\frac{\pi}{3}$	1200

τ_s	τ_b	ζ	V_{crit}	$m_1^2 \sim m_\zeta^2$	$m_2^2 \sim m_{\tau_s}^2$	m_3^2
10.42	700	9.7×10^{-3}	5.44×10^{-14}	2.38×10^{-8}	7.36×10^{-6}	8.98×10^{-13}
10.85	960	9.8×10^{-3}	6.68×10^{-14}	9.24×10^{-9}	3.11×10^{-6}	-2.57×10^{-13}

$\mathcal{V}$	M_s	m_{KK}	$m_{3/2}$	M_s^w	m_{KK}^w
1.86×10^4	2.21×10^{-3}	4.30×10^{-4}	1.32×10^{-4}	2.20×10^{-3}	1.34×10^{-3}
2.98×10^4	1.75×10^{-3}	3.14×10^{-4}	8.21×10^{-5}	1.74×10^{-3}	1.06×10^{-3}



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$$W/M_p^3 = w_1\left(W_0 e^{i\sigma} + \left[-\frac{M}{2\pi i}z\left(\log\frac{\Lambda_0^3}{z}+1\right) - i\frac{K}{g_s}z\right] + Ae^{-aT_s}\right)$$

[Bento-Chakraborty-Parameswaran-IZ, '21]

- Weakly warped regime

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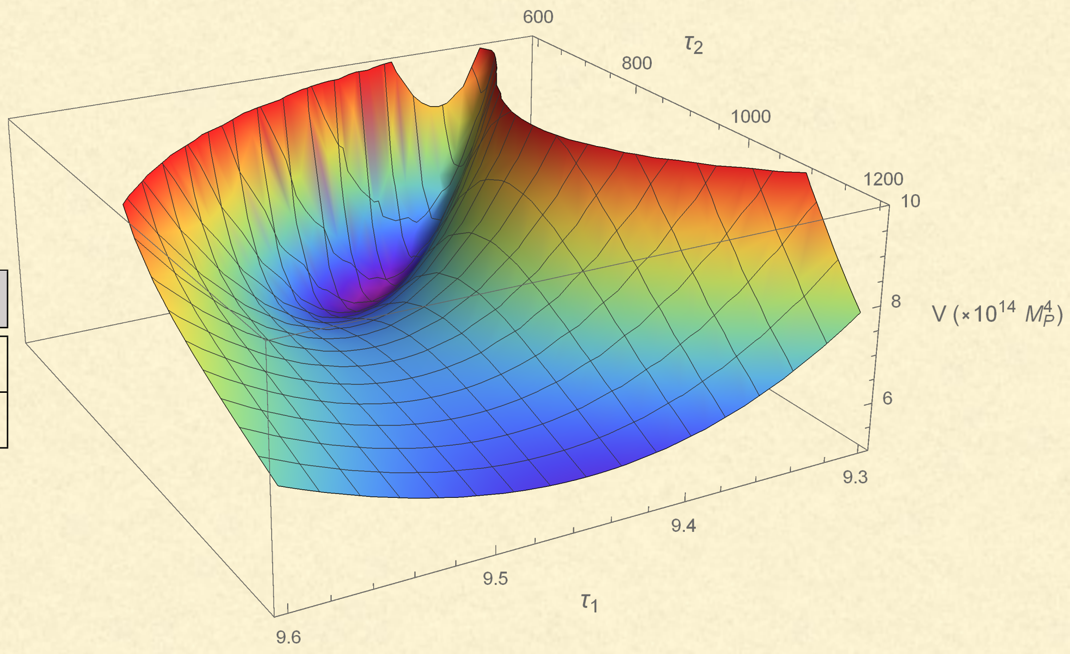
10.85	960	9.8×10^{-3}	6.68×10^{-14}	9.24×10^{-9}	3.11×10^{-6}	-2.57×10^{-13}

$\mathcal{V}$	M_s	m_{KK}	$m_{3/2}$	M_s^w	m_{KK}^w
1.86×10^4	2.21×10^{-3}	4.30×10^{-4}	1.32×10^{-4}	2.20×10^{-3}	1.34×10^{-3}
2.98×10^4	1.75×10^{-3}	3.14×10^{-4}	8.21×10^{-5}	1.74×10^{-3}	1.06×10^{-3}



NEW DS IN WEAKLY WARPED REGIME

- A new dS solution arises in the weakly warped regime of the warped flux compactification.

- Small shift from GKP minimum, not destabilised by anti-D3 brane!

- Tadpole $(MK = 32)$ can be much smaller. Stronger bound comes from supergravity approximation ($g_s < 1$)

$$g_s M > 1$$

UPLIFTING RUNAWAYS IN THE MIRROR QUINTIC

- In most works, dilaton has been assumed to be fixed; no concrete compact CY; focus on M, K fluxes.
- GKP solution requires at least 3 types of fluxes to stabilise dilaton. Can these change results?
- Use concrete compact CY, the mirror quintic, to address these questions

[w/Cabo-Bizet, Olguín-Trejo, Loaiza-Brito, in progress]

FLUX COMPACTIFICATIONS ON THE MIRROR QUINTIC

- The mirror quintic is a compact CY, with a single CS z:

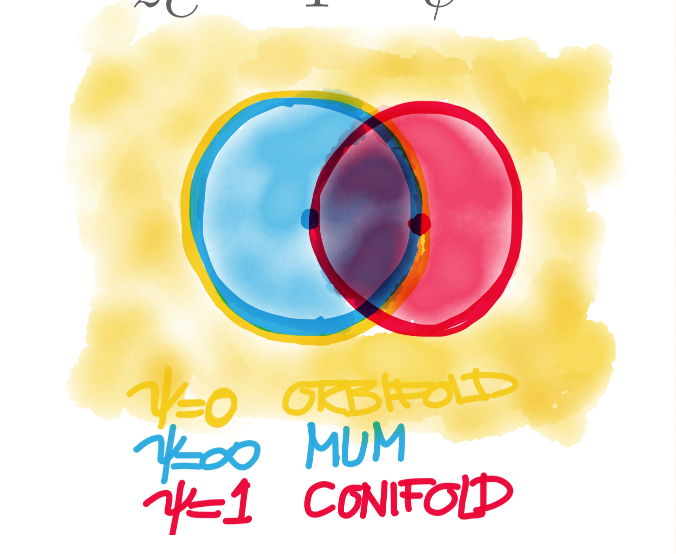
[Candelas-de la Ossa-Green-Parkes, '91]

$$h^{2,1} = 1, \quad h^{1,1} = 101, \quad \underbrace{b_3 = 4}_{\text{four 3-cycles}}$$

- It has three critical points: *conifold, large complex structure and orbifold* the singular points are located at:

  - **the conifold:** $z_C = 0$
  - the LCS: $z_C = 1$
  - the orbifold: $z_C = \infty$

$z_C = 1 - \psi^{-5}$



FLUX COMPACTIFICATIONS ON THE MIRROR QUINTIC

We can turn on 3-form fluxes on the four 3-cycles to stabilise the dilation and complex structure

Denote the fluxes as

$$(F^I_{(3)}, F_{(3)I}) = (F_1, F_2, F_3, F_4),$$
$$(H^I_{(3)}, H_{(3)I}) = (H_1, H_2, H_3, H_4),$$

Such that

$$\frac{1}{(2\pi)^2\alpha'}\int_{A^I} F_{(3)} = (F_1, F_2)\,, \qquad \frac{1}{(2\pi)^2\alpha'}\int_{A^I} H_{(3)} = (H_1, H_2)\,,$$
$$\frac{1}{(2\pi)^2\alpha'}\int_{B_I} F_{(3)} = (F_3, F_4)\,, \qquad \frac{1}{(2\pi)^2\alpha'}\int_{B_I} H_{(3)} = (H_3, H_4)\,.$$

In our notation:

$$F_1 = M\,, \quad H_3 = K\,, \quad H_4 = K'$$

STRONGLY WARPED REGIME ON THE MIRROR QUINTIC

[w/Cabo-Bizet, Olguín-Trejo, Loaiza-Brito, in progress]

We consider the modification of the Kähler potential by DST to stabilise the dilation and deformation modulus explicitly

$$K(z,\bar{z},\tau,\bar{\tau}) = -\ln\left[-i\left(\tau-\bar{\tau}\right)\right] - \ln\left[-i\bar{\Pi}^T\Sigma\Pi\right] - 2\ln\left[\mathcal{V}\right] + \frac{C}{(\tau-\bar{\tau})^2}|z|^{2/3},$$

$$W(z,\tau) = F_1\Pi_3 + F_2\Pi_4 - F_3\Pi_1 - F_4\Pi_2 + \tau\left(H_3\Pi_1 + H_4\Pi_2 - H_1\Pi_3 - H_2\Pi_4\right),$$

where

$$\Pi \sim \begin{pmatrix} A_0\, z \\ a_0 + b_0\, z \\ c + d\, z + a\, z\ln z \\ a_1 + b_1\, z \end{pmatrix}, \quad \Sigma = \begin{pmatrix} 0 & \mathbb{1}_{k\times k} \\ -\mathbb{1}_{k\times k} & 0 \end{pmatrix} \quad k = 1 + h^{2,1}$$

and

$$C \equiv -4\frac{9\, c' F_1^2}{8\pi(2\pi)^4\mathcal{V}^{2/3}}$$

MODULI STABILISATION ON THE MIRROR QUINTIC

[w/Cabo-Bizet, Olguín-Trejo, Loaiza-Brito, in progress]

As shown in GKP, two stabilise the dilaton, we need to turn on at least three fluxes: (F_1, H_3, H_4) $((M, K, K'))$

Next, we add the contribution from the anti-D3 brane

$$V_{\overline{\mathrm{D3}}} = \frac{M_{\mathrm{Pl}}^4}{8\pi} \frac{(2\pi)^4 c''}{(g_s F_1)^2} \frac{|z|^{4/3}}{\mathcal{V}^{4/3}} = \frac{M_{\mathrm{Pl}}^4}{8\pi} D\, |z|^{4/3} (\tau - \bar{\tau})^2 \,, \qquad D \equiv -\frac{(2\pi)^4 c''}{4\, F_1^2\, \mathcal{V}^{4/3}}$$

$(z = re^{i\theta})$ $\quad (\tau = C_0 + e^{-\phi} = t_1 + it_2)$ $\quad (g_s = e^{\phi_0})$

$r_o,\, r,\, r_f$	$\theta_o,\, \theta,\, \theta_f$	t_1	t_2	$\vec{F},\, \vec{H}$	$\vec{F}\Sigma\vec{H}$	KM
$7.76 * 10^{-3}$	-142.74	7.78	2.41	$(15, 3, 4, -5)$	3526	3510
$7.75 * 10^{-3}$	-142.74	7.78	2.41	$(12, -7, 234, 1)$		
$9.03 * 10^{-5}$	-142.85	7.01	3.05			
$1.50 * 10^{-5}$	61.03	4.61	1.82	$(40, 28, -3, 10)$	5073	5120
$1.18 * 10^{-5}$	61.35	4.61	1.82	$(-5, 9, 128, 1)$		
$1.16 * 10^{-5}$	61.07	4.61	1.82			

Very large tadpole required to keep solutions!

STRONG WARPING CORRECTION REVISITED

- Compact uplifted dS solutions are possible
- Solutions with three fluxes (M,K,K') alone, seem harder to obtain (require large tadpole)
- DST correction is valid at, and infinitesimally far from the GKP minimum (on-shell)
- However, stability argument relies on features of off-shell potential of the deformation modulus
- Understanding of the potential away from minimum is needed

[Lüst, Randall, '22]

STRONG WARPING CORRECTION REVISITED

[Lüst, Randall, '22]

- Computed the potential for the deformation modulus for finite field displacements
- Considered the additional constraints that arise in warped compactifications

$$\delta_S A = \frac{1}{8}\delta_S \tilde{g}$$

$$\tilde{\nabla}^n\Big[\delta_S\tilde{g}_{nm} - \tilde{g}_{mn}\big(\delta_S\tilde{g} - 4\delta_S A\big)\Big] - 2\tilde{g}^{nk}\,\partial_n A\Big[\delta_S\tilde{g}_{km} - \tilde{g}_{km}\big(\delta_S\tilde{g} - 8\delta_S A\big)\Big] = \delta_S T_m = 0$$

for one-parameter family of warp factors and Ricci-flat metrics on the deformed conifold,

$$A(y^m, S)\,, \quad \tilde{g}_{mn}(y^m, S)$$

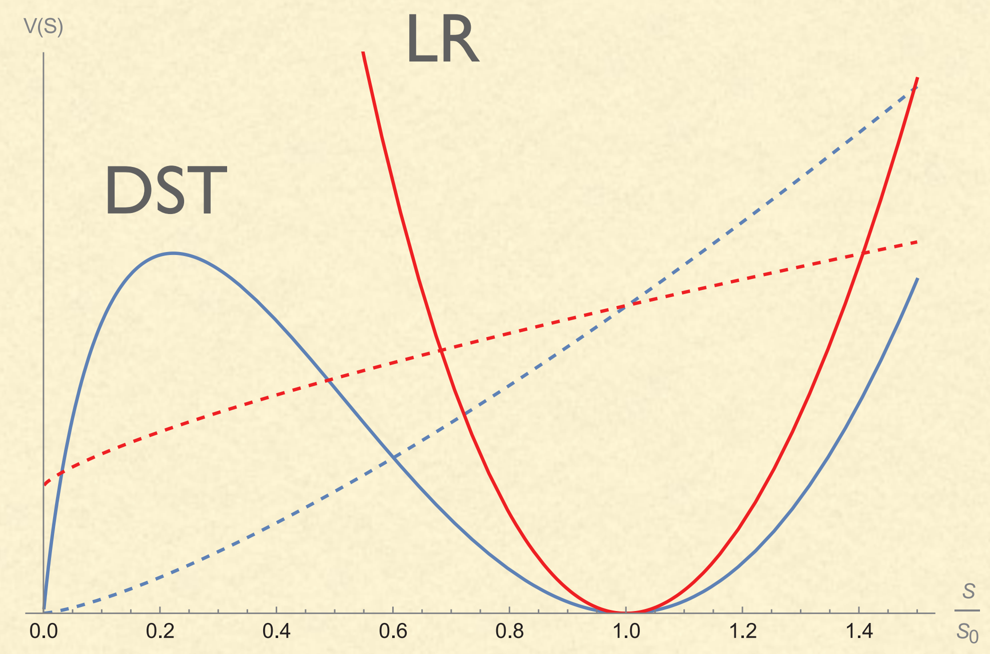
STRONG WARPING CORRECTION REVISITED

[Lüst, Randall, '22]

- Solved these constraints to compute directly the full off-shell potential for the conifold deformation parameter of the KS geometry.
- The resulting potential as it only has one critical point at the supersymmetric minimum

both with and without the anti-brane perturbation.

$$V_{\text{flux}} = \frac{1}{4\kappa_{10}^2} \int d^6y \frac{e^{4A}}{\operatorname{Im}\tau_{\text{IIB}}}\left[G_3 \wedge \tilde{\star}_6 \overline{G}_3 + iG_3 \wedge \overline{G}_3\right]$$



STRONG WARPING CORRECTION REVISITED

[Lüst, Randall, '22]

- Solved these constraints to compute directly the full off-shell potential for the conifold deformation parameter of the KS geometry.

- The resulting potential as it only has one critical point at the supersymmetric minimum both with and without the anti-brane perturbation.

- However, it would be useful to have an explicit expression of the N=1 supersymmetry Kähler potential

$$K_{\text{warp}}(S, \bar{S})$$

to bring the new potential in the form of an N= 1 supergravity with W_{flux}

STRONGLY WARPED REGIME KÄHLER POTENTIAL

[w/Cabo-Bizet, Olguín-Trejo, Loaiza-Brito, in progress]

We follow the procedure of DST to find an expression for the Kähler metric, $K_{z\bar{z}}$

$$K_{z\bar{z}} = \frac{i}{||\Omega||^2 V_6} \int_{conifold} h\, \chi_S \wedge \chi_{\bar{S}}\,,$$

where the (2,1)-form for KS is given by

$$\chi_S = g^3 \wedge g^4 \wedge g^5 + d[F(\eta)(g^1 \wedge g^3 + g^2 \wedge g^4)] - id[f(\eta)(g^1 \wedge g^2) + k(\tau)(g^3 \wedge g^4)],$$

$$F(\eta) = \frac{\sinh\eta - \eta}{2\sinh\eta}, \quad f(\eta) = \frac{\eta\coth\eta - 1}{2\sinh\eta}(\cosh\eta - 1), \quad k(\eta) = \frac{\eta\coth\eta - 1}{2\sinh\eta}(\cosh\eta + 1).$$

STRONGLY WARPED REGIME ON THE MIRROR QUINTIC REVISITED

[w/Cabo-Bizet, Olguín-Trejo, Loaiza-Brito, in progress]

We follow the procedure of DST to find an expression for the Kähler metric, $K_{z\bar{z}}$

$$K_{z\bar{z}} = \frac{i}{||\Omega||^2 V_6} \int_{conifold} h\, \chi_S \wedge \chi_{\bar{S}}\,,$$

Metric becomes

$$K_{z\bar{z}} = \frac{2}{\pi ||\Omega||^2 V_6} \left(\int d\eta \frac{d}{d\eta} \{h\, [f + F(k-f)]\} - \int d\eta \frac{dh}{d\eta} [f + F(k-f)] \right), \qquad h \approx \frac{e^{-4A}}{\mathcal{V}^{2/3}}$$

can use the warp factor found by LR

$$\partial_\tau e^{-4A(\tau,S)} = 2^{\frac{2}{3}} \frac{g_s(\alpha' M)^2}{|S|^{\frac{4}{3}}} \frac{\tau \coth\tau - 1}{\sinh^2\tau} \frac{\sinh 2\tau - 2\tau}{(\sinh 2\mathcal{T} - 2\mathcal{T})^{2/3}} \partial_\tau \mathcal{T} \qquad (\eta \equiv \tau)$$

with

$$\mathcal{T}(\tau, S) = F^{-1}\left[F(\tau) - \log\frac{S}{S_0}\right], \qquad F(t) = \frac{1}{2}\log\left[\sinh(2t) - 2t\right] \qquad \left(\mathcal{T}(\tau,S) = \tau\left(\frac{S_0}{S}\right)^{2/3} + \mathcal{O}(\tau^3)\right)$$

STRONGLY WARPED REGIME ON THE MIRROR QUINTIC REVISITED

[w/Cabo-Bizet, Olguín-Trejo, Loaiza-Brito, in progress]

We can perform the integral numerically for different values of the deformation modulus $z = S/\ell_s^3$ $\quad (\ell_s^2 = (2\pi)^2\alpha')$

$$I = -\int d\eta \, \frac{de^{-4A(z,\eta)}}{d\eta}[f + F(k-f)]$$

We perform a suitable fit of this function to find the Kähler metric in the (off-shell) strong regime

$$K_{z\bar{z}} = \frac{8(2)^{2/3}\ell_s^6}{\pi|\Omega|^2 V_6}\frac{(g_s F_1)^2}{(2\pi)^4\mathcal{V}^{2/3}}\left(\frac{A}{|z|^{4/3}} + \frac{B}{|z_0|^{4/3}}\right)e^{-a\frac{|z_0|^{2/3}}{|z|^{2/3}}}$$

with

$$A = 0.151421\,, \quad B = 0.456719\,, \quad a = 1.187543$$

Kähler potential can now be obtained by integration

STRONGLY WARPED REGIME ON THE MIRROR QUINTIC REVISITED

[w/Cabo-Bizet, Olguín-Trejo, Loaiza-Brito, in progress]

The Kähler potential can now be obtained by integration and we can use it to stabilise the deformation modulus and dilation in the strongly warped regime

$$K(z,\bar{z},\tau,\bar{\tau}) = -\ln\left[-i\left(\tau-\bar{\tau}\right)\right] - \ln\ \left[-i\,\bar{\Pi}^T\Sigma\Pi\right] - 2\ln\left[\mathcal{V}\right] + K_{\rm warp}(z,\bar{z},\tau,\bar{\tau}),$$

$$W(z,\tau) = F_1\Pi_3 + F_2\Pi_4 - F_3\Pi_1 - F_4\Pi_2 + \tau\left(H_3\Pi_1 + H_4\Pi_2 - H_1\Pi_3 - H_2\Pi_4\right)\ ,$$

The anti-D3 potential get's modified according to

$$V_{\overline{D3}} = \frac{(2\pi)^4}{8\pi}\,\frac{|z_0|^{4/3}}{(g_s\,F_1)^2}\,\frac{2^{1/3}}{I(0,z)}\,\frac{M_{Pl}^4}{\mathcal{V}^{4/3}}$$

$$I(0,z) = a\left(\frac{z_0}{z}\right)^b\ , \qquad\qquad b\sim 0.44$$

DS AT THE TIP OF THE THROAT

- First step to write the off-shell potential in terms of N = 1 supergravity
- Tadpole can be small, no instability triggered. Constraint of flux $\sqrt{g_s}M$ no longer applies.
- Could instability appear farther away from the minimum?
- dS vacua a la KKLT remain an interesting possibility
- Further constraints, relax of assumptions, etc?

Gravitational tests

GRAVITY AT THE TIP OF THE THROAT

[Bento-Chakraborty-Parameswaran-IZ, '22]

- Warped throats have open new possibilities for cosmology and phenomenology
- For example, our universe can confined on a D-brane at the tip of a warped throat
- It is thus interesting to study its effects on the gravitational sector of the 4D EFT.
- As a first step, we focus on the corrections to the Newtonian potential, which can be compared to observations across diverse scales

GRAVITY AT THE TIP OF THE THROAT

[Bento-Chakraborty-Parameswaran-IZ, '22]

- Consider type IIB supergravity in 10D, compactify on a warped CY 3-fold
- Find the corresponding KK tower of tensor modes, which describes an infinite set of massive spin-2 fields in 4D
- We use these results to compute the **corrections to the Newtonian** gravitational **potential** due to the massive tower and **compare** these predictions with current **experimental constraints**.

[Gravitational waves & Extra dimensions (past 5 years): Reinoud Jan Slagter '17; Andriot, Lucena Gómez, '17; Chakraborty, Chakravarti, Bose, SenGupta, '17; Megías, Nardini, Quirós, '18; Kwon, Lee, Tolla, '19; Andriot, Tsimpis, '19; Du, Tahura, Vaman, Yagi, '20; Andriot, Marconnet, Tsimpis, '21; Ferko, Satishchandran, Sethi, '21

GRAVITY AT THE TIP OF THE THROAT

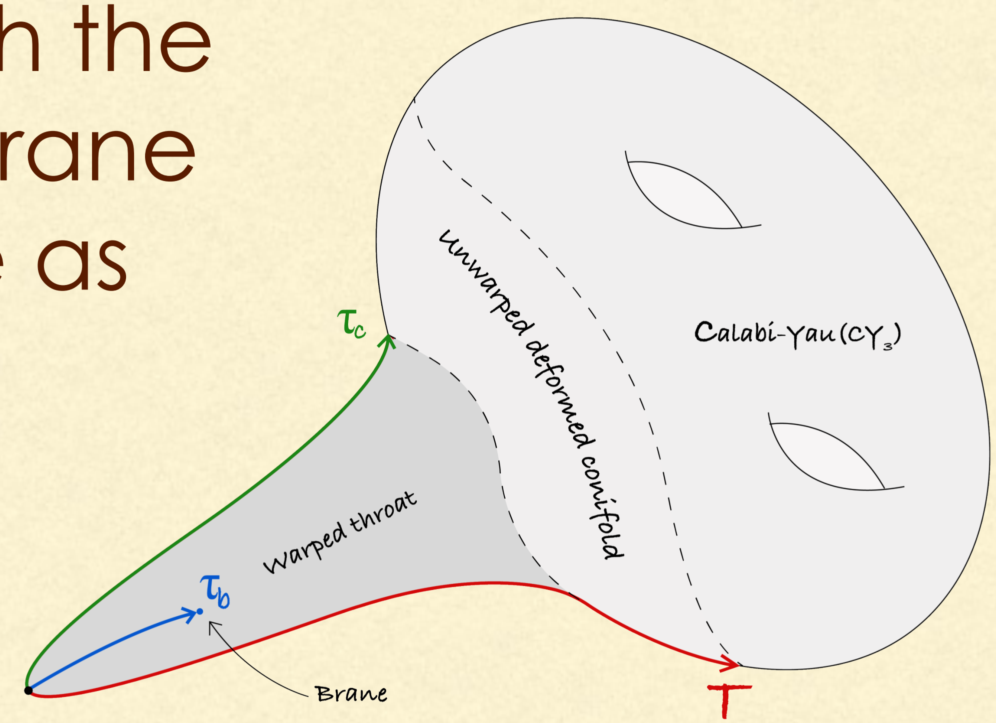
[Bento-Chakraborty-Parameswaran-IZ, '22]

Consider a braneworld scenario, with the Standard Model localised on a D3-brane at $y_{\rm b}$ in the warped compact space as

Unwarped conifold transition ($\tau_c < \tau <$ T)

Vanishing boundary conditions on CY3 ($\tau =$ T)

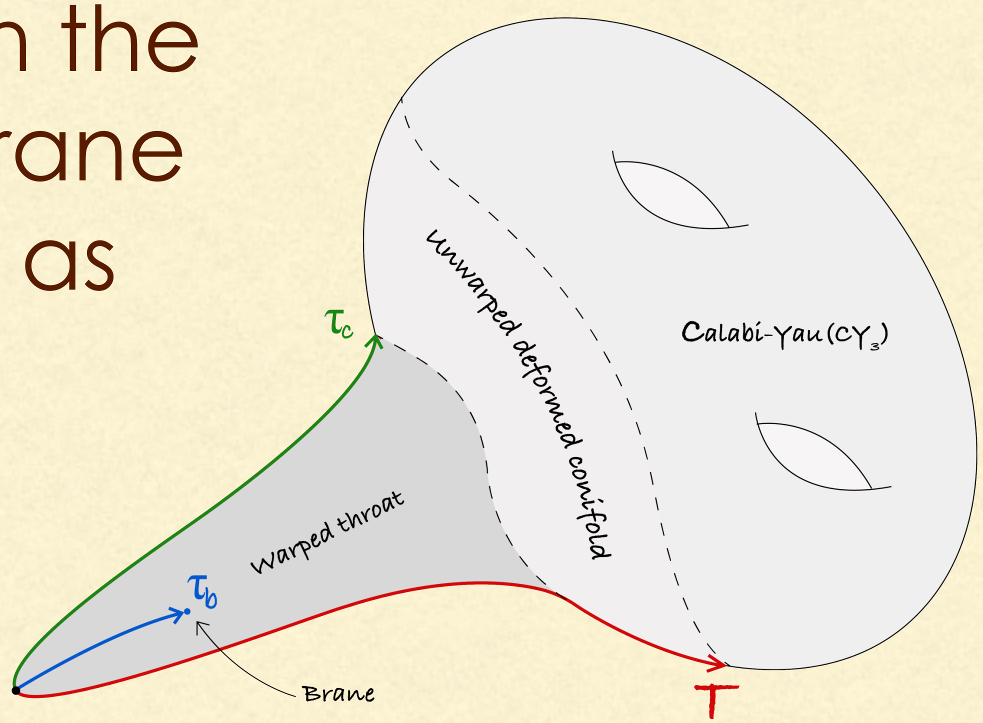
(3+1)-brane somewhere in the throat ($\tau <$ T)



GRAVITY AT THE TIP OF THE THROAT

[Bento-Chakraborty-Parameswaran-IZ, '22]

Consider a braneworld scenario, with the Standard Model localised on a D3-brane at $y_{\rm b}$ in the warped compact space as



The Newtonian potential can be parameterised as

range

$$V = G_N \frac{m_1 m_2}{r}\left(1 + \alpha\, e^{-r/\lambda}\right)$$

strength

$$(\tau_c, T, g_s, M, \mathcal{H}, \tau_b)$$

$$\alpha = \frac{(2\pi)^2}{(g_s M)^3}\frac{2A(\tau_b,\tau_c,T)}{I(\tau_c)^{3/2}} H_{\tau_c}(\tau_b)^{-1/2}\frac{g_s^2}{\mathcal{H}^2}\,,$$

$$\lambda^{-1} = \frac{\mathcal{H}}{2^{1/6}}\frac{2\pi}{\sqrt{g_s M}}\frac{H_{\tau_c}(\tau_b)^{1/4}}{I(\tau_c)^{1/4}}\frac{\mu(\tau_c,T)}{l_p}\,.$$

$$\mathcal{H} \equiv H_{\tau_c}(\tau_b)^{-1/4}\frac{g_s}{\sqrt{4\pi \mathcal{V}_w}}$$

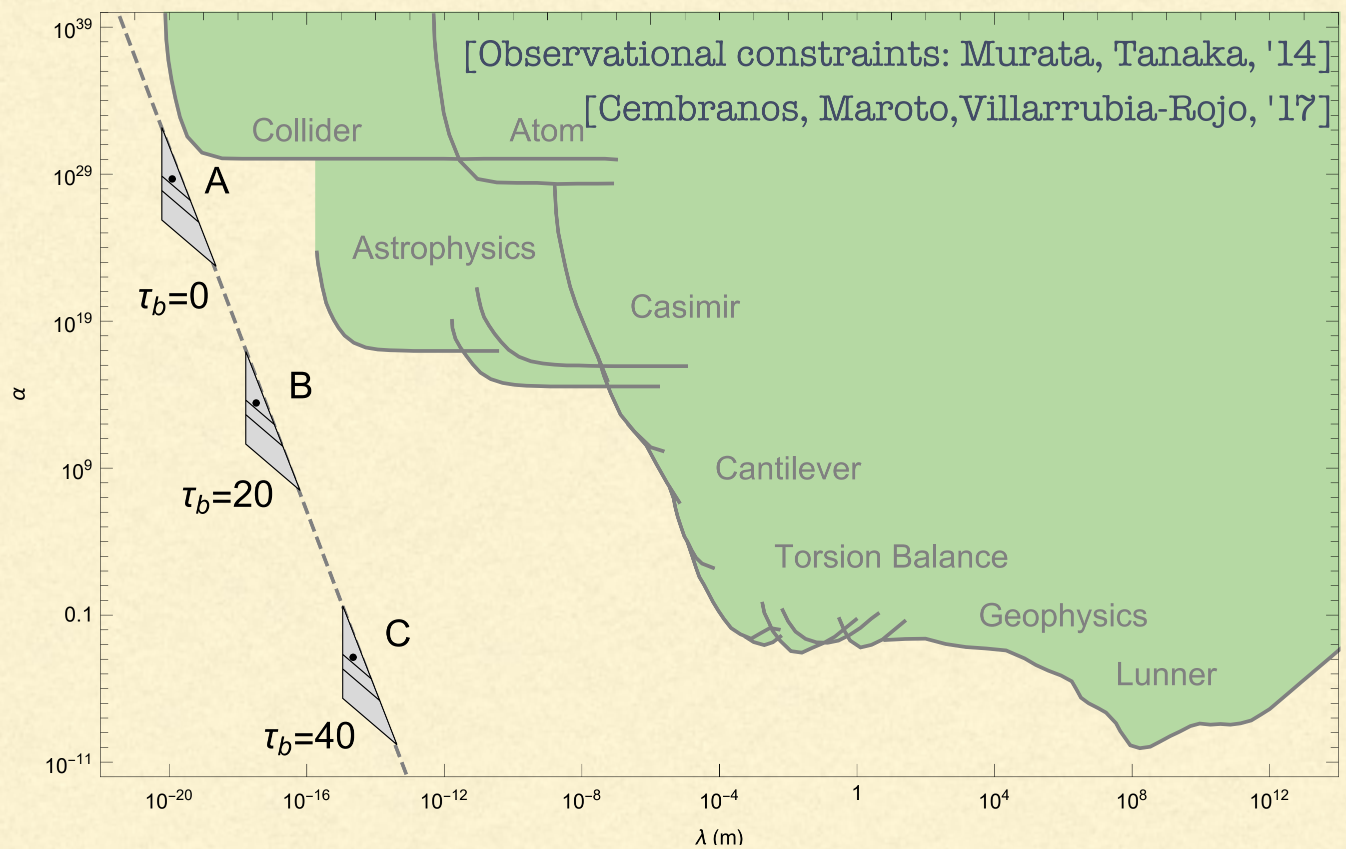
$$H = 1 + \frac{e^{-4A}}{\mathcal{V}^{2/3}}$$

GRAVITY AT THE TIP OF THE THROAT

[Bento-Chakraborty-Parameswaran-IZ, '22]

We can compare our predictions with the available experimental constraints

$$V = G_N \frac{m_1\, m_2}{r} \left(1 + \alpha\, e^{-r/\lambda}\right)$$

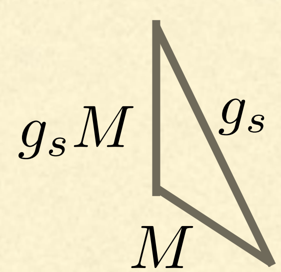


$(\mathcal{H} = 10^{-15}\,, \quad (A,B,C):\ g_s = 0.2, M = 20)$

$M < 32, 100, 1000$

Triangle regions:

$g_s M > 1$	Supergravity (α')
$g_s < 1$	String loop expansion
$M < M_{max}$	D3 Tadpole



SUMMARY

String theory warped compactifications offer rich new avenues to explore cosmological questions

In particular for early and late time acceleration: inflation and dark energy

Future is bright in terms of test of cosmological as well as gravitational implications!

Several questions still open!

MULTI FIELD INFLATION AND THE SWAMPLAND

Recently proposed *asymptotic dS conjectures* require

$$\frac{\nabla V}{V} \geq \frac{c}{M_{\rm Pl}} \qquad \text{or} \qquad \frac{\min(\nabla^a \nabla_b V)}{V} \leq -\frac{c'}{M_{\rm Pl}^2}$$

In multi field inflation, these conditions can be satisfied:

- If inflation occurs along *strongly non-geodesic attractor*, the first condition can be satisfied, while second condition may or not be satisfied

[Hetz, Palma, '16; Achúcarro, Palma, '18]

$$\epsilon_V \approx \epsilon \left(1 + \frac{\omega^2}{9}\right) \gtrsim \mathcal{O}(1)$$

if turn rate is large

$$\left(\epsilon_V \equiv \frac{M_{\rm Pl}^2}{2} \frac{V^a V_a}{V^2}\right)$$

MULTI FIELD INFLATION AND THE SWAMPLAND

Recently proposed *asymptotic dS conjectures* require

$$\frac{\nabla V}{V} \geq \frac{c}{M_{\rm Pl}} \qquad \text{or} \qquad \frac{\min(\nabla^a \nabla_b V)}{V} \leq -\frac{c'}{M_{\rm Pl}^2}$$

In multi field inflation, these conditions can be satisfied:

- If inflaton satisfies, $H^2 \ll \lambda \leq V_{TT}$, one can show that $\omega \gg 1$ and first condition may be satisfied
- If inflaton satisfies, $\left|\lambda/H^2\right| \gg 1$ (tachyonically fat), second condition is satisfied

[w/Chakraborty et al. '19;
w/Aragam, Chivoloni, Paban, Rosati, '21]

DE SITTER SWAMPLAND CONJECTURE

- The scalar potential in the LEEFT of any consistent quantum gravity must satisfy *either*:

[Danielsson, Van Riet '18;
Obied, Ooguri, Spodyneiko, Vafa '18;
Garg, Krishnan '18; Ooguri, Palti, Shiu, Vafa '18]

$$\frac{\sqrt{\nabla^i V \nabla_i V}}{V} \gtrsim \frac{c}{M_{Pl}} \quad \text{or} \quad \frac{\min(\nabla^i \nabla_j V)}{V} \lesssim -\frac{c'}{M_{Pl}^2}$$

for some universal constants c, c' > 0 of order 1.

- Rules out metastable dS, allows sufficiently unstable dS