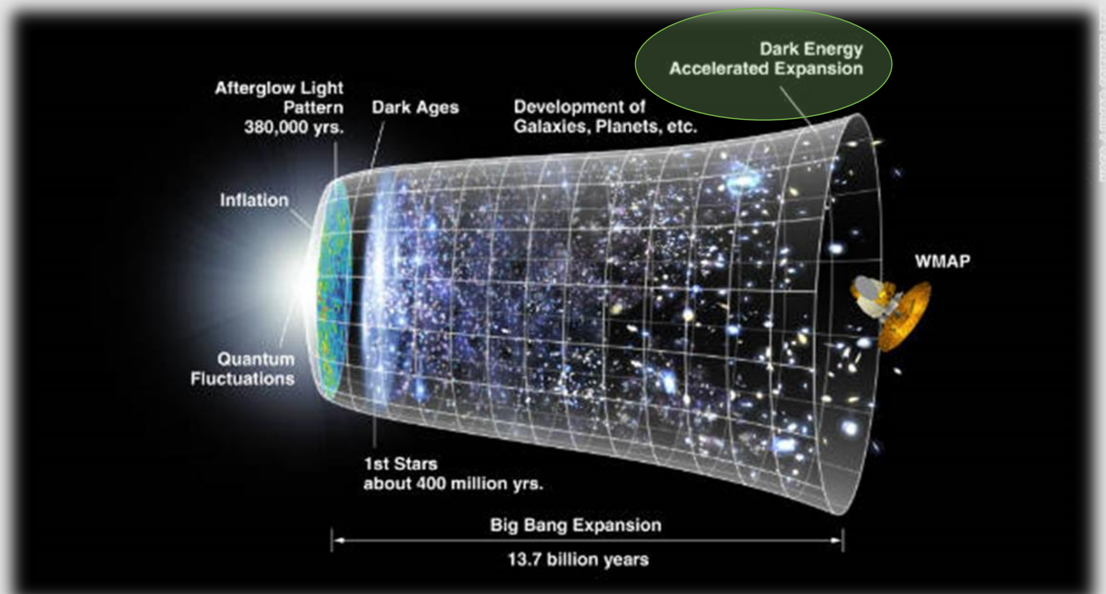
DE-SITTER VACUA FROM A D-TERM GENERATED RACETRACK POTENTIAL IN HYPERSURFACE CALABI-YAU COMPACFITICATIONS

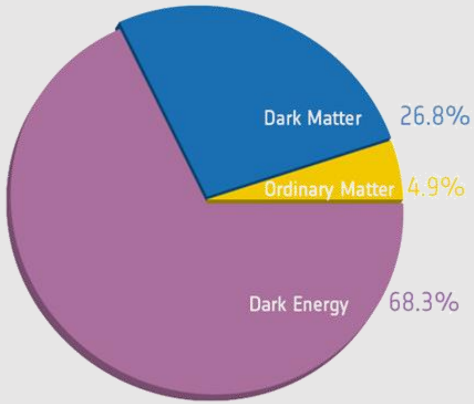
Yoske Sumitomo (住友洋介)
KEK Theory Center, Japan

M. Rummel, YS, JHEP 1501 (2015) 015, arXiv:1407.7580
A. Braun, M. Rummel, YS, R. Valandro, arXiv:1509.06918

Dark Energy

Dominant source for late time expansion

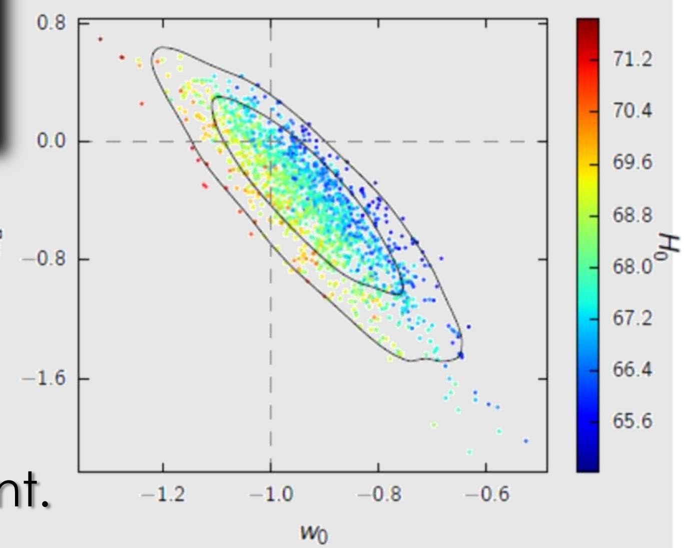




Planck(TT, lowP, lensing)+BAO+JLA+H_0("ext")

$$w = \frac{p}{\rho} = -1.006^{+0.085}_{-0.091}(95\%\ \mathrm{CL})$$

agrees with the positive cosmological constant.



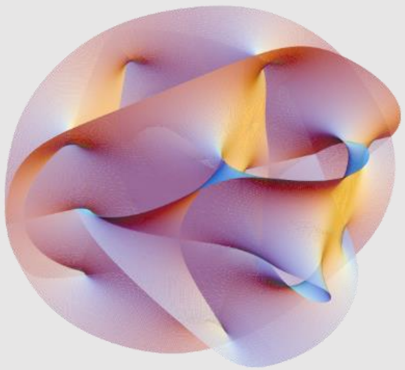
String theory in 10D

A prime candidate of quantum gravity

→ ability to address vacuum energy

String theory has a nice feature: 10D = 4D + 6D

Information of 6D space determines what we have in 4D!



- Light/heavy d.o.f. (moduli fields)
- Sources of potential
- Matters (visible and hidden)

Importantly, we cannot simply select at our will.

→ String theory compactifications impose conditions on SUGRA.

Key points of string cosmology

- Moduli stabilization
- Minimum with positive CC (or DE)
- Consistency of compactifications
- Reasonable parameters
- …

Moduli stabilization

We have to stabilize moduli fields of compactification.

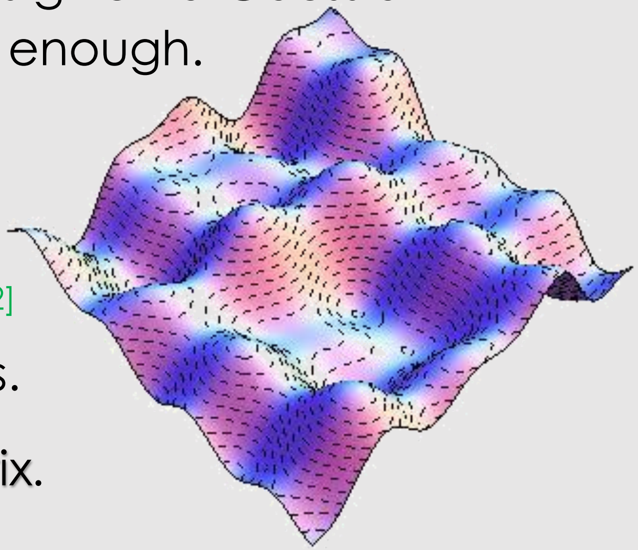
- Reheating for BBN ⟹ $m_\phi \gtrsim \mathcal{O}(10)$ TeV
- Determining parameters in 4D theory

Many moduli fields in string compactification (dilaton, complex structure moduli, Kähler moduli etc.) $N \sim \mathcal{O}(100)$

Probability of stability (eigenvalues $(m_{ij}^2) > 0$) is given a Gaussian suppressed function of # of moduli, if random enough.

$$\mathcal{P} \sim e^{-aN^2}$$

[Aazami, Easther, 05], [Dean, Majumdar, 08], [Borot, Eynard, Majumdar, Nadal, 10], [Marsh, McAllister, Wrase 11], [X. Chen, Shiu, YS, Tye, 11], [Bachlechner, Marsh, McAllister, Wrase 12]



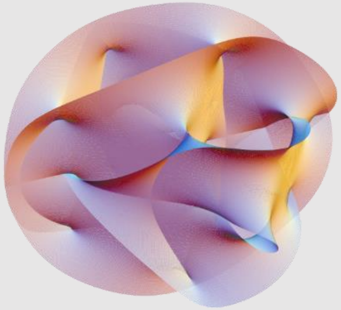
So, when no hierarchy at $N \sim \mathcal{O}(100)$, hopeless.

Need for a hierarchical structure of mass matrix.

Type IIB on Calabi-Yau

A region that is not completely random and works well for cosmology.

No-scale structure generates a hierarchy:



$$V = V_{\text{Flux}} \quad + \quad V_{\text{NP}} + V_{\alpha'} + \cdots$$

$$\mathcal{O}(\mathcal{V}^{-2}) \quad \gg \quad \mathcal{O}(\ll \mathcal{V}^{-2})$$: CY volume scaling

Also, $V_{\text{Flux}} = e^K \left| D_{S,U_i} W_0 \right|^2$: positive definite

$$D_{S,U_i} W_0 = 0$$

Many moduli are integrated out at high scale.

e.g. CY $\mathbb{P}^4_{[1,1,1,6,9]}$: $h^{1,1} = 2,\ h^{2,1} = 272$

(Hessian) (real part)

$$M \sim \begin{pmatrix} \text{large} & \text{small} \\ \text{small} & \textbf{small} \end{pmatrix} \begin{array}{c} 272+1 \\ 2 \end{array}$$

We have to worry about only few light d.o.f. (Kahler moduli).

Kahler Moduli stabilization

Consider SUGRA F-term scalar potential: $V_F = e^K(|DW|^2 - 3|W|^2)$

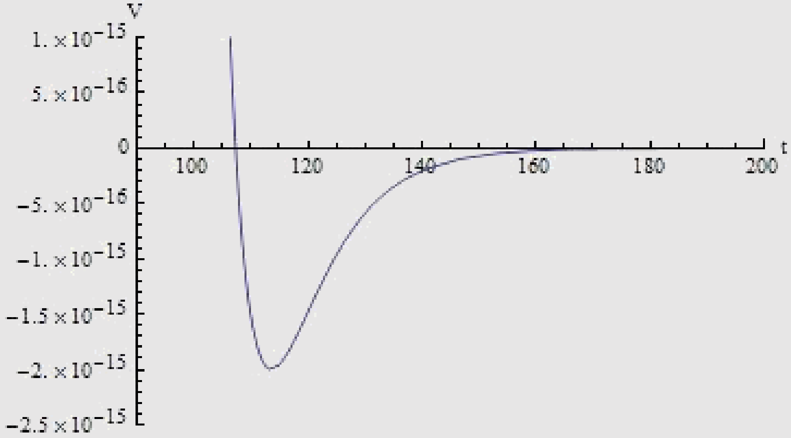
$$K = -2\ln\left(\mathcal{V} + \underline{\frac{\xi}{2}}\right), \qquad W = W_0 + \underline{W_{NP}}$$

α'-correction

non-perturbative effect (instantons etc.)

E.g. KKLT

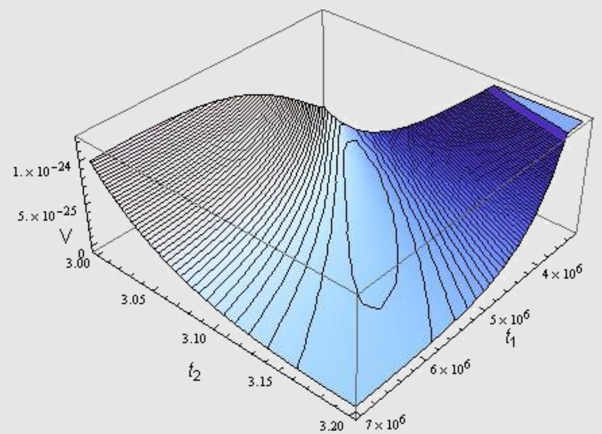
[Kachru, Kallosh, Linde, Trivedi, 03]



$D_I W = 0$: supersymmetric

Large Volume Scenario (LVS)

[Balasubramanian, Beglund, Conlon, Quevedo, 05]



$\partial_I V = 0$: non-sypersymmetric

Both minima stay at AdS

Uplift to dS

Some uplift models

Some proposals keeping stability, but not so many.

- Anti-brane $V = V_{SUGRA} + V_{D3-\overline{D3}}$ [Kachru, Pearson, Verlinde, 01], [KKLT, 03]

  A positive contribution by localized source, suppressed by warping.

- Non-zero minimum of flux potential $V_{\mathrm{Flux}} > 0$ [Saltman, Silverstein, 04]

  Require a suppression to balance with V_{Kahler} (generically $\ll V_{\mathrm{Flux}}$).

- D-term uplift [Burgess, Kallosh, Quevedo, 03], [Cremades, Garcia del Moral, Quevedo, 07], [Krippendorf, Quevedo, 09] [Cicoli, Goodsell, Jaeckel Ringwald, 11]

  A suppressed coefficient is required as $V_D \gg V_{\mathrm{Kahler}}$.

- Dilaton-dependent non-perturbative effects [Cicoli, Maharana, Quevedo, Burgess, 12]

  $V_{up} \propto \frac{e^{-2b\langle s\rangle}}{\mathcal{V}}$: dilaton value $\langle s\rangle$ should be tuned accordingly.

A suppression of coefficient is required.

(due to different volume dependence)

D-TERM GENERATED RACETRACK UPLIFT

M. Rummel, YS, JHEP 1501 (2015) 015, arXiv:1407.7580

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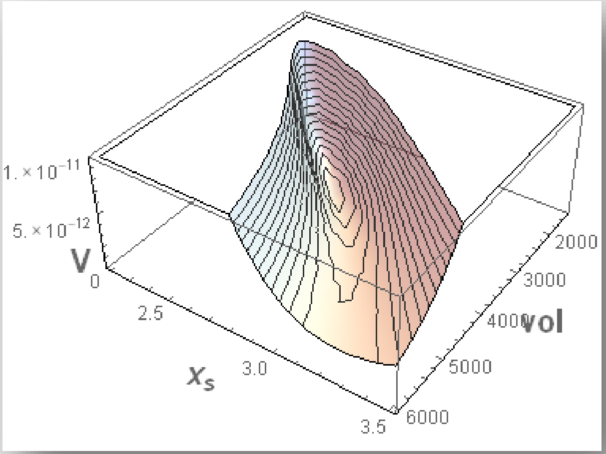
D-term generated racetrack uplift

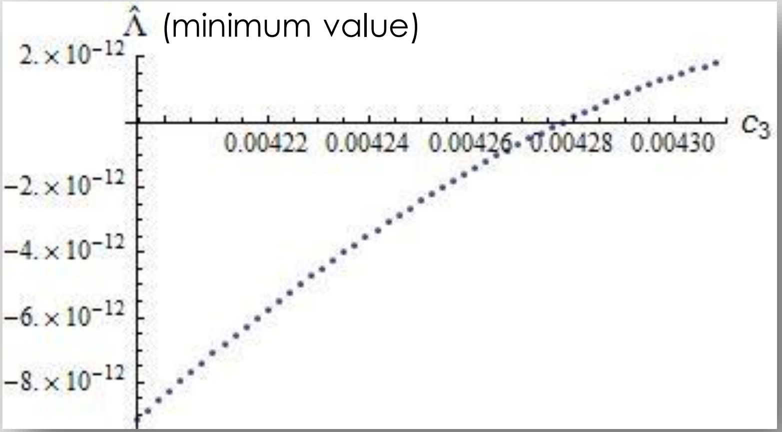
[Rummel, YS, 14]

Effective potential:

$$\hat{V} \sim \underbrace{\frac{3\xi}{4\mathcal{V}} + \frac{4c_s x_s}{\mathcal{V}^2} e^{-x_s} + \frac{2\sqrt{2}c_s^2\sqrt{x_s}}{3\mathcal{V}} e^{-2x_s}}_{\text{LVS stabilization at AdS}} + \underbrace{\frac{4\beta c_a x_s}{\mathcal{V}^2} e^{-\beta x_s}}_{\text{uplift}} + \cdots$$

When $\boldsymbol{c_s = -0.01}$, $\xi = 5$, $\boldsymbol{\beta = 5/6 \sim 0.83}$, and increase c_a





Minkowski point: $\boldsymbol{c_a \sim 4 \times 10^{-3}}, \mathcal{V} \sim 3240, x_s \sim 3.07.$

$|c_s| \sim |c_a|$ special suppression is not required when $\beta \sim 1.$

Analytically, $\beta < 1, c_a > 0$ are required for uplift.

Key idea: D-term constraint

D-term potential imposes a constraint at high scale.

$V = V_F + V_D$ $\qquad$ $V_D \gg V_F$ $\quad$ generating a heavy mass

In string theory compactifications,

Magnetized D7-branes wrapping a Calabi-Yau four-cycle

$$\Rightarrow \quad V_D = \frac{1}{\mathrm{Re}(f_D)} {\xi_D}^2 \qquad \xi_D = \frac{1}{\mathcal{V}} \int J \wedge D_D \wedge \mathcal{F}_D$$

w/ matters stabilized accordingly

A choice of flux $\mathcal{F}_D$ would give

$$V_D \propto \frac{1}{\mathrm{Re}(f_D)} \frac{1}{\mathcal{V}^2} \left(\sqrt{\beta\, x_s} - \sqrt{x_a}\right)^2$$

so a constraint: $x_a = \beta\, x_s$

Then, a racetrack is generated (different from simple racetrack).

$$V_F \ni \hat{C}_s e^{-x_s} + \hat{C}_a\, e^{-x_a} + \cdots \quad \Rightarrow \quad \hat{C}_s e^{-x_s} + \hat{C}_a\, e^{-\beta\, x_s} + \cdots$$

Values of β

The value of β determines how much suppression we need.

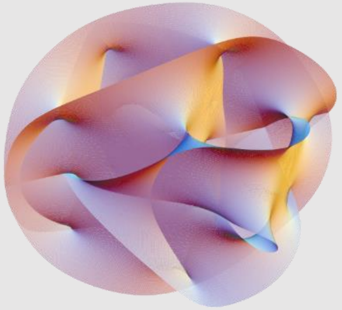
$$V \ni \hat{C}_s e^{-x_s} + \hat{C}_a\, e^{-\beta\, x_s} + \cdots \qquad\qquad (x_a = \beta\, x_s)$$

If $\beta = 0.9$, almost no suppression of coefficients for uplift $|\hat{C}_s| \sim |\hat{C}_a|$.

Parameter β is determined by geometry and fluxes.

Constraints from consistency of CY compactifications:

- ✓ Two instantons (on rigid divisors)
- ✓ D-term (anomalous U(1)) that relates two moduli $x_{s,a}$
- ✓ Quantized fluxes on integral basis
- ✓ Charge cancellations (no D3, D5, D7 tadpoles)
- ✓ No anomaly (Freed-Witten)



We assume that open-string moduli are stabilized at $\langle \phi_i \rangle \neq 0$ for simplicity.
(hidden matters)

An example

[Braun, Rummel, YS, Valandro, 15]

- Intersections

$$I_3 = 2D_v^3 + D_s^3 + 2D_a^3 \quad \Longrightarrow \quad \mathcal{V} \propto \frac{1}{3} x_v^{3/2} - \frac{\sqrt{2}}{3} x_s^{3/2} - \frac{1}{3} x_a^{3/2}$$

Swiss-Cheese type

- Instantons (rank one)

Euclidean D3 on rigid divisors D_s, D_a $\Longrightarrow$ $W = W_0 + A_s e^{-x_s} + A_a e^{-x_a}$

- O7-plane, a D7-brane (D-term)

$D_{O7} = 4D_v - 3D_s - 2D_a, \qquad D_D = 4D_{O7}$ $\Longrightarrow$ no D7-tadpole

- Quantized fluxes (no Freed-Witten anomaly)

$$\mathcal{F}_{s,a} = 0, \qquad \mathcal{F}_D = \frac{D_s}{2} - \frac{D_a}{2} \quad \Longrightarrow \quad \begin{aligned} Q_{D3}^{tot} &= Q^{F_3,H_3} + Q^{O7} + Q^{D7} + Q^{O3} \\ &= Q^{F_3,H_3} - 526 \end{aligned}$$

- D-term constraint

$$\xi_D = \frac{1}{\mathcal{V}} \int_{D_D} J \wedge \mathcal{F}_D = 0 \quad \Longrightarrow \quad x_a = \beta\, x_s, \qquad \beta = \frac{8}{9}$$

Successful de-Sitter!

Scanning Calabi-Yau for β

[Braun, Rummel, YS, Valandro, 15]

Using the data of 6D toric Calabi-Yau hypersurfaces,

[Kreuzer, Skarke, 00], [Altman, Gray, He, Jejjala, Nelson 14]

Three moduli $(h^{1,1} = 3, \quad \mathcal{V}, x_s, x_a)$

Total: 244 (polytopes)

Suitable geometry and successful flux: 32 (13%)

Four moduli $(h^{1,1} = 4, \quad \mathcal{V}, x_s, x_a, x_b)$

Total: 1197 (polytopes)

Suitable geometry and successful flux: 191 (16%)

Possible β values

$$\beta = \frac{49}{50}(= 0.98), \frac{121}{128}(\sim 0.95), \frac{225}{242}(\sim 0.93), \ldots$$

good β, good realizability

There are several other setups too.

Summary & Discussion

- 6D geometry determines 4D physics.
- Moduli stabilization, minimum vev, consistency, naturalness should be taken into account for string cosmology.
- D-term generated racetrack model uplifts potential successfully. (Simple racetrack does not.)
- Almost no suppression required in parameters if $\beta \sim 1$.
- 6D Calabi-Yau data suggests that $\beta \sim 1$ is ubiquitous.
- Open-string moduli need not to be $\langle \phi_i \rangle \neq 0$ in other types of Calabi-Yau.