# A Flux-Scaling Scenario for High-Scale Moduli Stabilization in String Theory

Yuta Sekiguchi

LMU and MPI for Physics, Munich

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Blumenhagen, Font, Plauschinn, Fuchs, Herschmann, Wolf, Sekiguchi

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# Motivation for String Phenomenology

According to the recent observations,

a tensor-to-scalar ratio: $r = 0.2$ [BICEP2 '14] and $r < 0.11$ [PLANCK '15]

Also, Lyth bound given by

$$\frac{\Delta\phi}{M_{\rm Pl}} = O(1)\sqrt{\frac{r}{0.01}}$$

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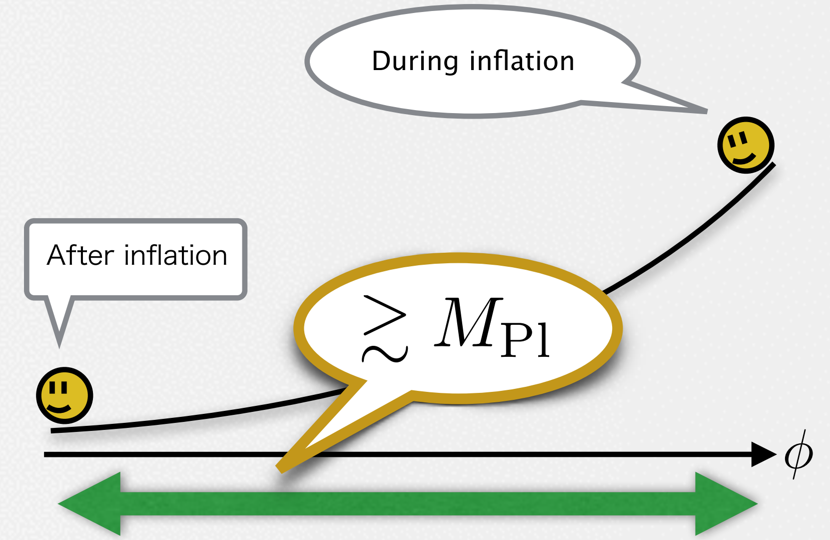


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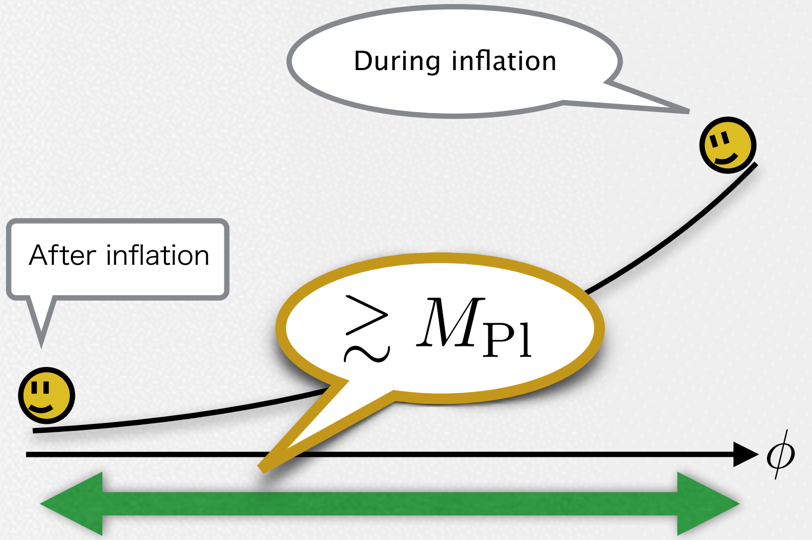


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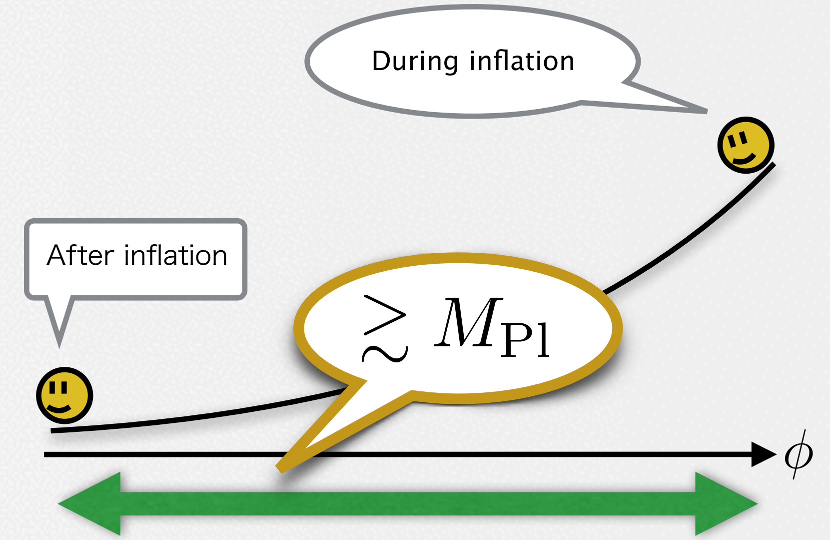


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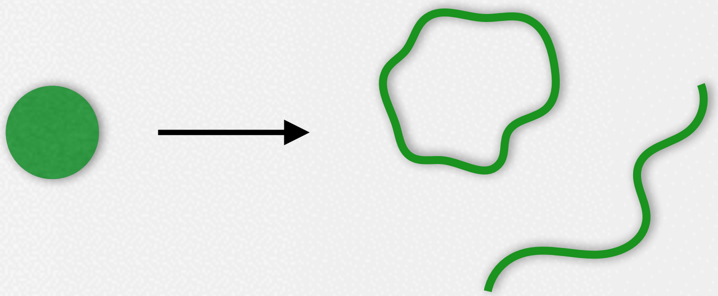
and can provide axion monodromy inflation.

[Hebecker, Kraus, Witkowski '14, Blumenhagen, Plauschinn '14, Marchesano, Shiu, Uranga '14]

- Consider the mechanism to generate axion monodromy inflation in string theory !! → study moduli stabilization !!
- Wish: Implications from string theory fit observables in current or future experiments.

# String Compactifications



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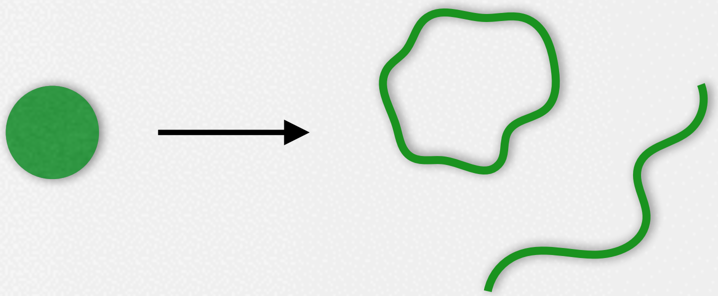

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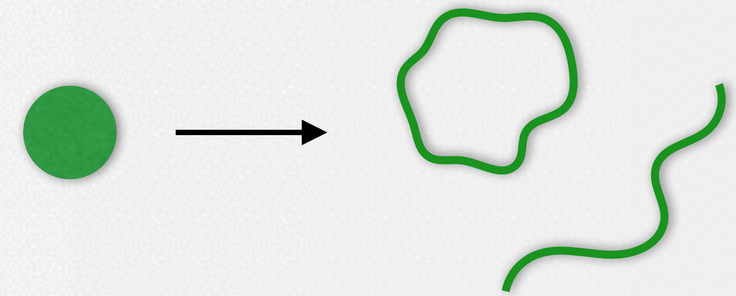

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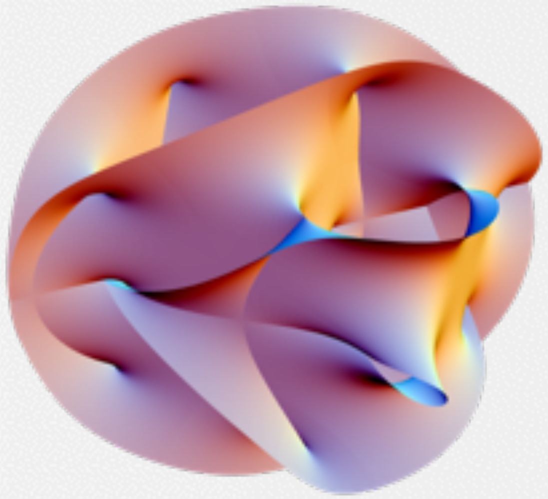
10-dim.
Space-Time

→

4-dim.
Space-Time

x



Compactification space: choose Calabi–Yau threefold (CY3) / (orientifold projection)

Focus on massless spectrum:

→ N=1 Supergravity(SUGRA) in 4-dims.

# Moduli Space and Moduli Stabilization

„Moduli“

- Parameters of the compact space
- obtained by the metric deformation of CY

$$g_{mn} \to g_{mn} + \delta g_{mn} \,, \quad R_{mn}(g + \delta g) = 0\,.$$

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[Grimm, Louis '04]

| | | axionic | | saxionic | |
|---|---|---|---|---|---|
| $S$ | $=$ | $s$ | $+$ | $i\,c$ | axio-dilaton |
| $U^i$ | $=$ | $v^i$ | $+$ | $i\,u^i$ | complex structure |
| $T_\alpha$ | $=$ | $\tau_\alpha$ | $+$ | $i\,\rho_\alpha + \ldots$ | Kähler |
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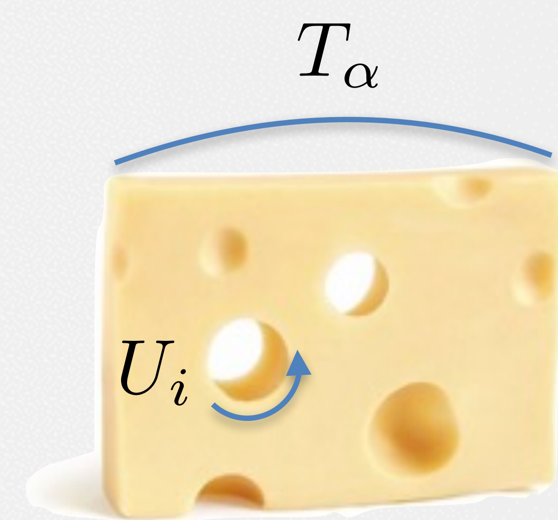

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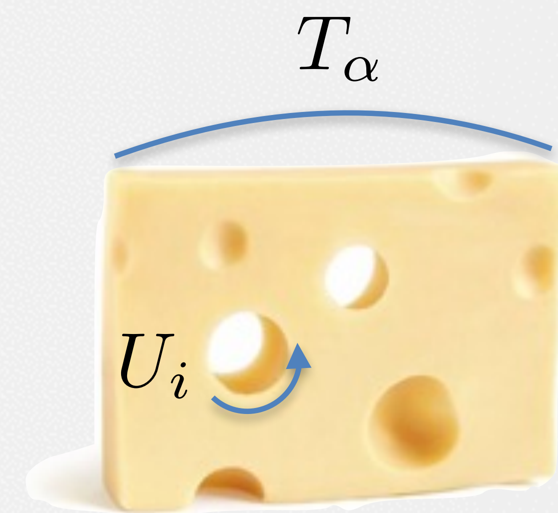


Moduli appear as massless complex scalar fields in 4 dims.

- not discovered in the experiments
- spoils the predictivity of the theory

→ Want to make them as massive as we wish ,or „stabilize" them. = Mass acquirement of Moduli !!

# Fluxes

From the field-content in type IIB string theory, we can construct the field strength.
The field strength defines a non-trivial cohomology class.

**Flux**

- field strength configuration on the $CY_3$
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Fluxes are quantized: $$\int_{\Sigma_3} H_3 \sim h \in \mathbb{Z}$$

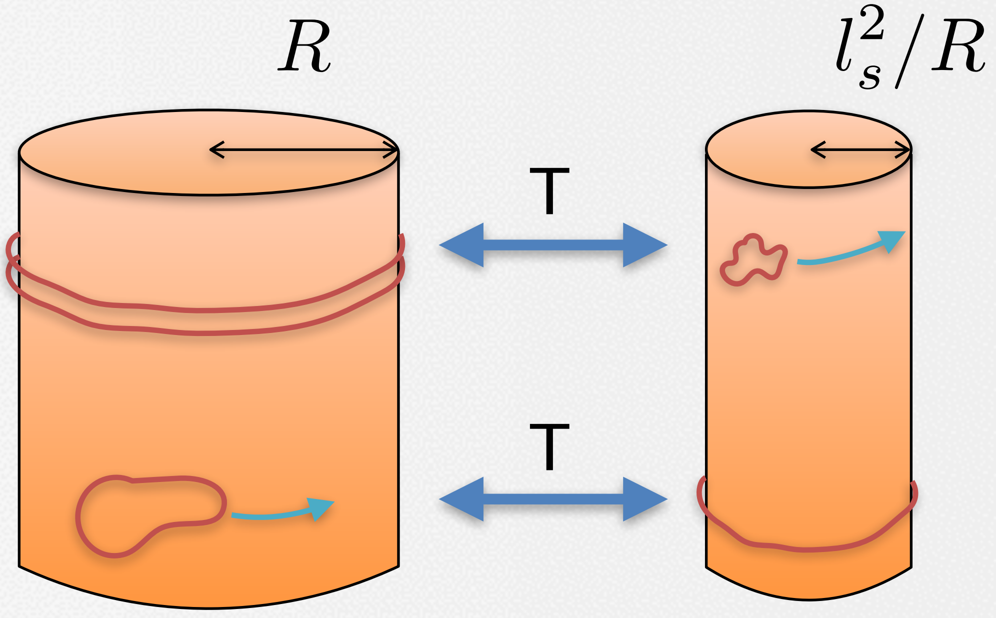
stabilize Moduli!!

# Geometric and Non-geometric Fluxes

arise from T-duality:

...equivalent physics between
R and the inverse of R

(can be extended to Buscher rule)



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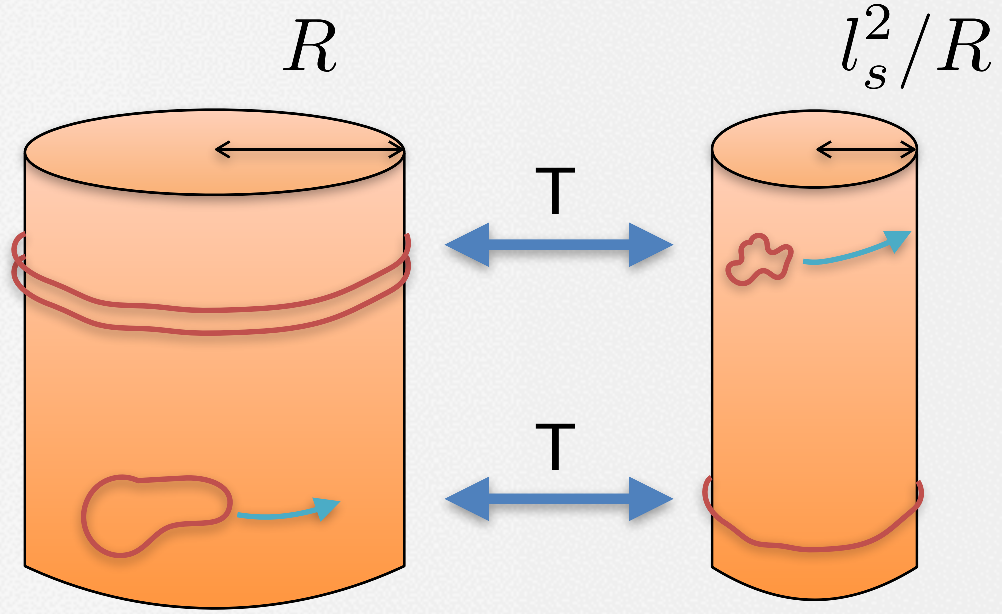


T-duality chain: [Shelton, Taylor, Wecht '07]

$$H_{xyz} \xrightarrow{T^x} F^x{}_{yz} \xrightarrow{T^y} Q^{xy}{}_z \xrightarrow{T^z} R^{xyz}$$

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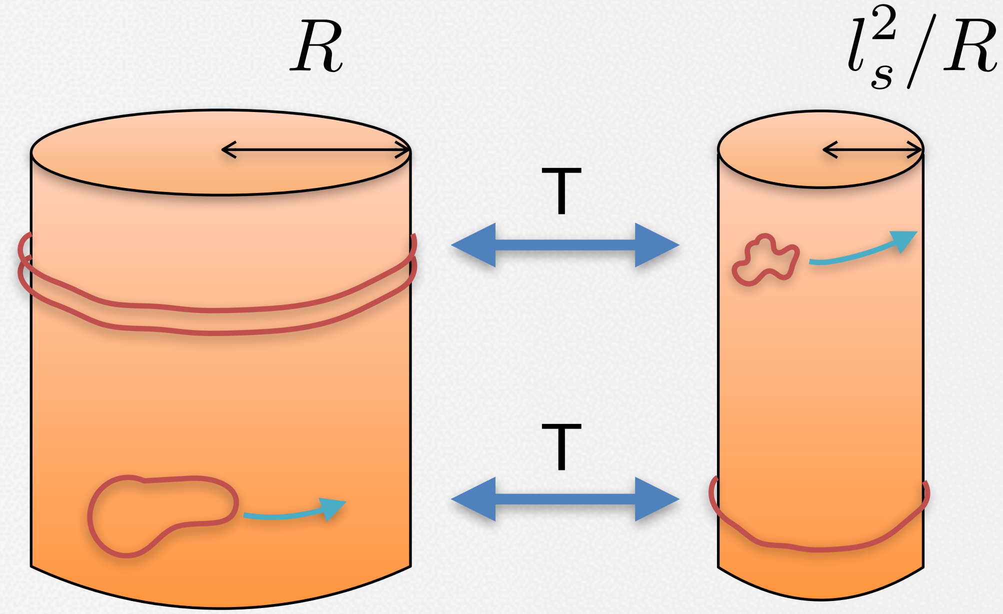


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- $H_{xyz}$: $H_3 = dB_2$
- $F^x{}_{yz}$: geometric
- $Q^{xy}{}_z$: non-geometric
- $R^{xyz}$: non-geometric

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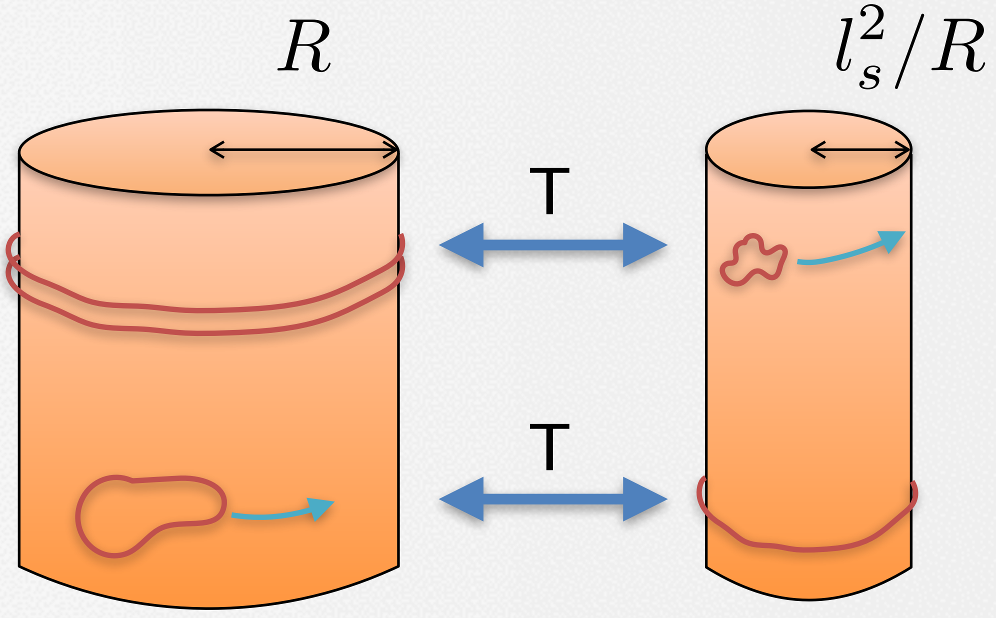


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Twisted differential:

$$d \longrightarrow \mathcal{D} = d - H\wedge - F\circ - Q\bullet - R\llcorner$$

extends the superpotential etc.

# S-dual non-geometric $P$-flux [Aldazabal et al. '06, '10]

arises from S-duality: $S \to \frac{aS - ib}{icS + d}\,, \quad \begin{pmatrix} C_2 \\ B_2 \end{pmatrix} \to \begin{pmatrix} a & b \\ c & d \end{pmatrix} \begin{pmatrix} C_2 \\ B_2 \end{pmatrix}$

$ad - bc = 1$

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For the S-duality invariance, we need a counter-part for non-geom. $Q$-flux in the SL(2,Z) doublet:

$$\begin{pmatrix} Q \\ P \end{pmatrix} \to \begin{pmatrix} a & b \\ c & d \end{pmatrix} \begin{pmatrix} Q \\ P \end{pmatrix}$$

Geometric and non-geometric fluxes are incorporated into the superpotential !!

# The F-term scalar potential

The scalar potential in N=1 4-dim. Supergravity:

$$V = \frac{M_{\rm Pl}^4}{4\pi}\, e^K \Big( K^{I\bar{J}} D_I W D_{\bar{J}} \overline{W} - 3 \big|W\big|^2 \Big)$$

$I(\bar{J})$ = (anti-)holomorphic moduli

with

Kähler potential:

$$K = -\ln(-i \int \Omega \wedge \overline{\Omega}) - \ln(S + \overline{S}) - 2 \ln \mathcal{V}$$

[Grimm, Louis '04]

Covariant derivative:

$$D_I W = \partial_I W + (\partial_I K) W$$

# The flux-induced superpotential [Gukov, Vafa, Witten '01]

$$W = \int_{CY_3} \left[ \mathfrak{F} + (d - H\wedge)\Phi_{\rm c}^{\rm ev} \right]_3 \wedge \Omega$$

$$\mathfrak{F} = \langle dC_2 \rangle\,, \quad \Phi_{\rm c}^{\rm ev} = iS - iG^a\omega_a - iT_\alpha \tilde{\omega}^\alpha$$

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+ S-dual covariance

$$\begin{aligned}W=\;&-\;\left(\mathfrak{f}_\lambda X^\lambda-\tilde{\mathfrak{f}}^\lambda F_\lambda\right)+i\,S\left(h_\lambda X^\lambda-\tilde{h}^\lambda F_\lambda\right)\\&-\;i\,G^a\left(f_{\lambda a}X^\lambda-\tilde{f}^\lambda{}_a F_\lambda\right)+i\,T_\alpha\left(q_\lambda{}^\alpha X^\lambda-\tilde{q}^{\lambda\alpha}F_\lambda\right)\\&+\;\left(S\,T_\alpha+\tfrac{1}{2}\kappa_{\alpha bc}G^bG^c\right)\left(p_\lambda{}^\alpha X^\lambda-\tilde{p}^{\lambda\alpha}F_\lambda\right)\end{aligned}$$

extra term (quadratic)!!

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$$\begin{aligned} W = \; & - \; \left( \mathfrak{f}_\lambda X^\lambda - \tilde{\mathfrak{f}}^\lambda F_\lambda \right) + i\, S \left( h_\lambda X^\lambda - \tilde{h}^\lambda F_\lambda \right) \\ & - \; i\, G^a \left( f_{\lambda a} X^\lambda - \tilde{f}^\lambda{}_a F_\lambda \right) + i\, T_\alpha \left( q_\lambda{}^\alpha X^\lambda - \tilde{q}^{\lambda\alpha} F_\lambda \right) \\ & + \; \left( S\, T_\alpha + \tfrac{1}{2} \kappa_{\alpha b c} G^b G^c \right) \left( p_\lambda{}^\alpha X^\lambda - \tilde{p}^{\lambda\alpha} F_\lambda \right) \end{aligned}$$

Design and analyze models!

# Flux-Scaling Scenario

A representative example:

$$K = -3\ln(T+\overline{T}) - \ln(S+\overline{S})$$

$$\tilde{\mathfrak{f}}\,,h\,,q \in \mathbb{Z}$$

$$\begin{aligned} W &= i\tilde{\mathfrak{f}} + ihS + iqT \\ &= i\tilde{\mathfrak{f}} + ihs + iq\tau - \underbrace{(hc+q\rho)}_{\equiv\,\theta} \end{aligned}$$

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→The resulting scalar potential:

$$V = \frac{M_{\rm Pl}^4}{4\pi\cdot 2^4}\left[\frac{(h\,s-\tilde{\mathfrak{f}})^2}{s\,\tau^3} - \frac{6\,h\,q\,s + 2q\,\tilde{\mathfrak{f}}}{s\,\tau^2} - \frac{5\,q^2}{3\,s\,\tau} + \frac{\theta^2}{s\,\tau^3}\right]$$

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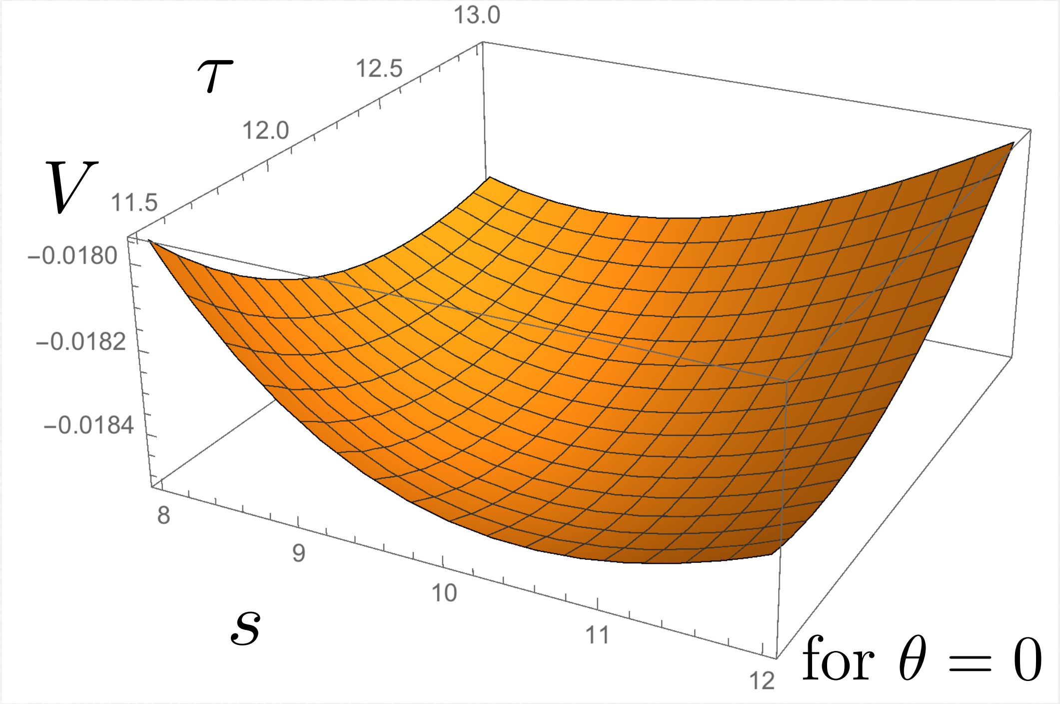
Check:

- minimal point (vacuum) and minimum: $\frac{\partial V}{\partial \bullet} = 0\,,\quad V_{\rm min}?$ if < 0 → AdS!!
- F-term supersymmetry breaking: $D_I W \neq 0\,?$
- tachyon-free (stability): $\frac{\partial^2 V}{\partial\bullet\,\partial\circ} \lessgtr 0\,?$
- mass eigenvalues.

# Flux-Scaling Scenario

We found a non-supersymmetric AdS minimum: $(s, \tau, \theta) = (-\frac{\tilde{\mathfrak{f}}}{h}, -\frac{6\tilde{\mathfrak{f}}}{5q}, 0)$

$$V_{\min} = -\frac{50}{27}\frac{hq^3}{\tilde{\mathfrak{f}}^2}\frac{M_{\rm Pl}^4}{4\pi\cdot 2^4} < 0 \text{ (AdS)}$$



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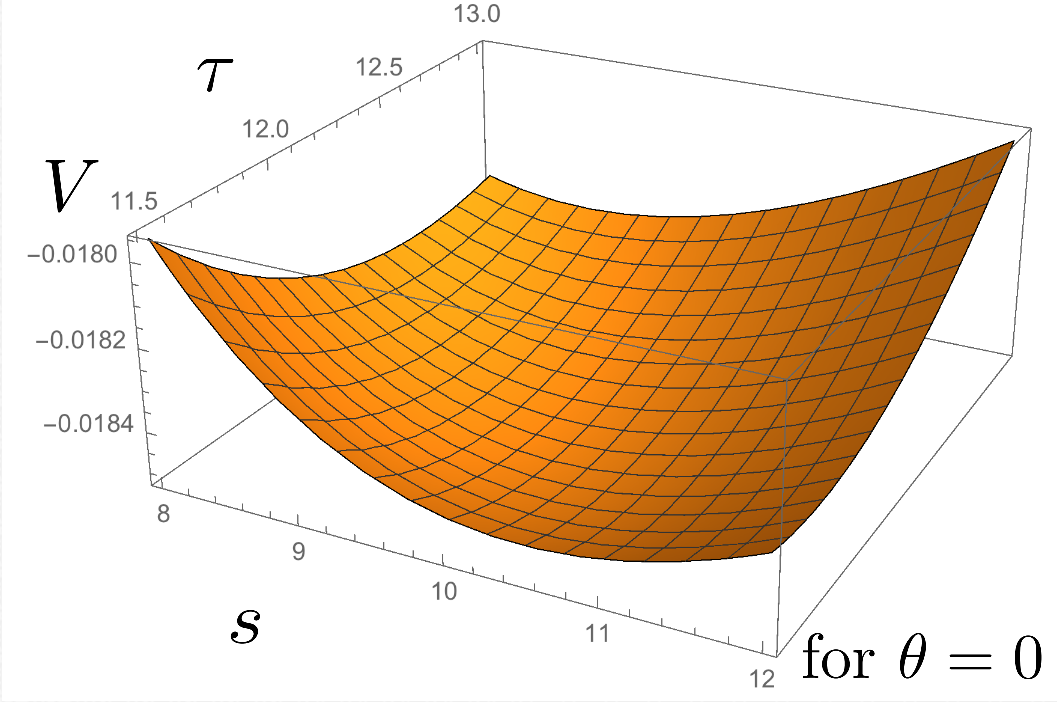


Also,

- Tachyon-free ✔
- Mass eigenstates:

> • the same flux-scale
> • one lightest axion!!

$$M^2_{{\rm mod},i} = \mu_i \frac{hq^3}{\tilde{\mathfrak{f}}^2}\frac{M_{\rm Pl}^2}{4\pi\cdot 2^4}\,, \qquad \mu_i \approx (\underbrace{6.2,\, 1.7}_{\rm saxionic};\, \underbrace{3.4,\, 0}_{\rm axionic})$$

- Gravitino mass:

$$M^2_{\frac{3}{2}} \approx 0.833\, \frac{hq^3}{\tilde{\mathfrak{f}}^2}\frac{M_{\rm Pl}^2}{4\pi\cdot 2^4}$$

> high-scale susy breaking!

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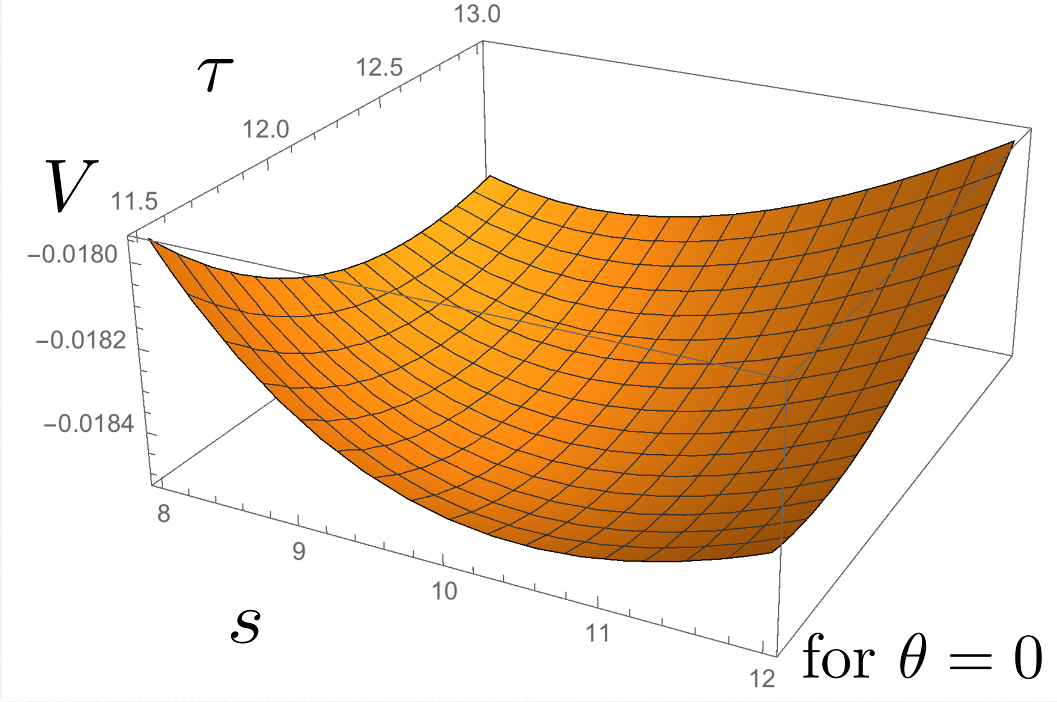


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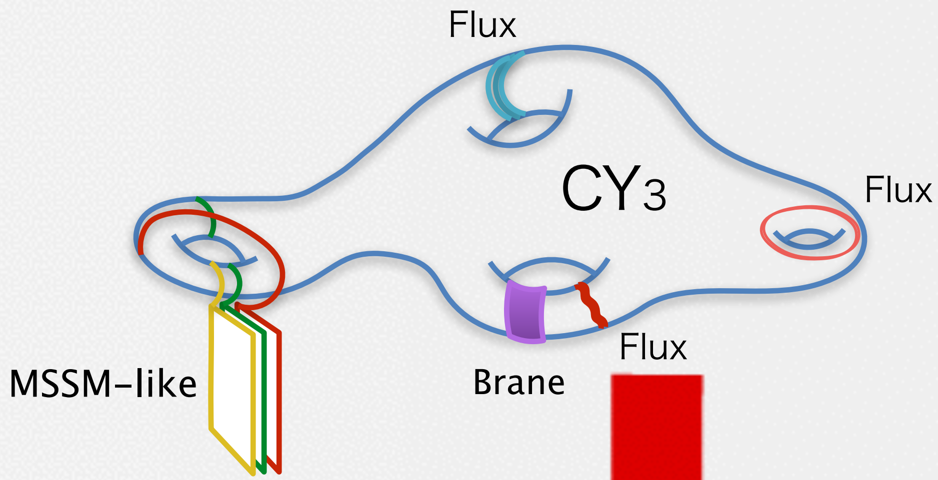
Additionally,

Soft masses in sequestered scenario:

- Gravity-mediated gaugino masses: $M_a \sim \left(\frac{q}{h}\right)^{\frac{3}{4}} M_{\frac{3}{2}} \sim \left(\frac{M_{KK}}{M_s}\right)^6 M_{\frac{3}{2}}$
- Anomaly-mediated gaugino masses: $M_a^{\rm anom} \sim \frac{M_{\rm KK}}{M_{\rm Pl}} M_{\frac{3}{2}}$




- suppressed relative to the gravitino mass
- gaugino masses in the intermediate regime

# Conclusions and Outlook

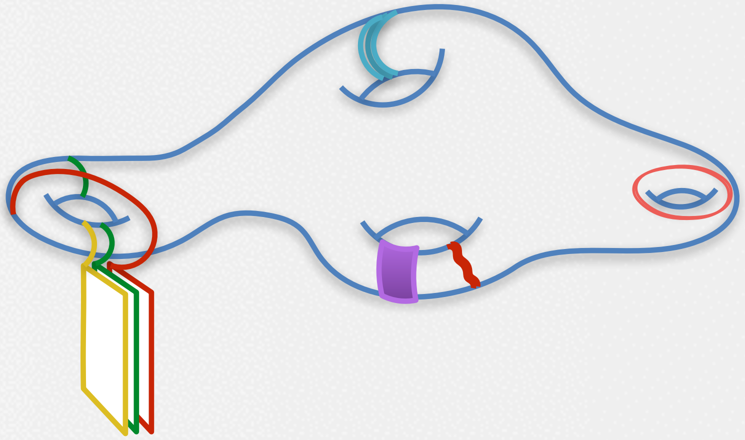
## Conclusions:

In the type IIB Calabi-Yau orientifold including (non-)geometric fluxes,

- Systematically analyzed the flux-induced scalar potential yielding non-supersymmetric AdS minima, where moduli and the mass scale can be parametrically controlled.
- Stabilized almost all the moduli except some massless axions
- Obtained the suppressed gaugino masses relative to the gravitino mass

## Open questions:

- Uplift to stable dS-vacua ? → [Blumenhagen, Damian, Font, Herschmann, Sun ’15]
- Uplift to a 10D full solution of string theory ?
- Inclusion of KK-mass and string states ?



Thank you!