Sharpening the Boundaries Between Flux Landscape and Swampland by Tadpole Charge

- タドポール電荷によるフラックスランドスケープ/スワンプランドの境界の特徴づけ -

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based on **arXiv:2104.15030** [hep-th]

Main purpose of the talk (in short)

What quantity does characterize

the boundary between Landscape/Swampland

in the 4-dimensional EFT?

Compactifications and Moduli Fields

Compactifications of Type IIB superstring theory

- 10-dimensional (10d) theory
  - Compactify 6d space → 4d effective field theory (EFT)

Moduli fields

- Massless scalar fields = deformations of the internal 6d manifold
  - Complex-structure (cs) moduli ⋯ “shape”
  - Kähler moduli ⋯ “volume”
- Many moduli appear in the EFT

Flux compactifications

- Non-trivial three-form fluxes ⋯ RR, NS-NS (NS) fluxes
- Generate a scalar potential for moduli fields
  - Obtain VEVs ⋯ **Moduli stabilization**

Formulation of the Moduli Stabilization

- Flux compactification → Scalar potential of moduli

  - **Scalar potential**

$$V = e^K \left[K^{i\bar{j}} D_i W \overline{D_{\bar{j}} W} - 3|W|^2 \right]$$

$$K_{i\bar{j}} = \partial_i \partial_{\bar{j}} K$$
$$D_i = \partial_i + K_i$$

  - **Gukov-Vafa-Witten (GVW) type super potential**

$$W_{\mathrm{GVW}} = \int_{\mathrm{CY}} G_3 \wedge \Omega = \underbrace{\int F_3 \wedge \Omega}_{W_{\mathrm{RR}}} - S \underbrace{\int H_3 \wedge \Omega}_{W_{\mathrm{NS}}} \quad (G_3 = F_3 - S H_3)$$

  - **Kähler potential**

$$K = \underline{-4} \log\left[-i(S - \overline{S})\right] - \log\left[-i \int_{\mathrm{CY}} \Omega \wedge \overline{\Omega}\right]$$

specific property of our manifold (introduce later)
-1: usual case (No-scale type)

Tadpole Cancellation Condition (TCC)

- The three-form fluxes are quantized:

$$\int_\Sigma F_3 = N_F \in \mathbb{Z}, \quad \int_\Sigma H_3 = N_H \in \mathbb{Z}.$$

  - These numbers discretize vacua.

- **Tadpole cancellation condition (TCC)** : consistency
  - Fluxes cannot be arbitrary numbers

$$S_{\rm IIB} = S_{\rm NS} + S_{\rm R} + S_{\rm CS} + S_{\rm local}$$

$$\supset -\frac{1}{8}\int \tilde{F}_5 \wedge \star \tilde{F}_5 + \frac{1}{8i{\rm ImS}}\int C_4 \wedge G_3 \wedge \bar{G}_3 + \frac{1}{2}\left(N_{\rm D3} - \frac{1}{2}N_{\rm O3}\right)\mu_3 \int_{\mathbb{R}^{1,3}} C_4,$$

$$(\tilde{F}_5 = dC_4 - \tfrac{1}{2}C_2 \wedge H_3 + \tfrac{1}{2}B_2 \wedge F_3)$$

$$\xrightarrow{\text{Bianchi id.}} \underbrace{\int_{\rm CY} H_3 \wedge F_3}_{\equiv N_{\rm flux}} \underbrace{- N_{\rm D3} + \frac{1}{2}N_{\rm O3}}_{\text{RR charges of D-branes and O-planes}} = 0 \text{: TCC}$$

Problems and Difficulties

- **Only a part of the moduli are stabilized by the fluxes.**
  - No-scale structure ⋯ Kähler moduli are flat directions
    - Non-perturbative effects

- **No principle for flux choices**
  - TCC constrains it but still many degrees of freedom remain

- **Flux Landscape** (flux vacua) Denef, F. and Douglas, M. R., JHEP **0405**, 072 (2004).
  - Set of whole vacua in flux compactifications
  - Estimation: $\sim \mathcal{O}(10^{272000})$ vacua W. Taylor and Y. N. Wang, JHEP **12**, 164 (2015).
  - SM-like models? Statistical approach? M. R. Douglas, JHEP **0503**, 061 (2005).

- **Difficulties in building Standard Model-like models**
  - Cosmological constant, CP violation, flavor and inflation etc.

Understanding Landscape properties is still challenging!

Swampland Conjectures

- Low energy EFT inconsistent with UV theory
  - In this talk, we call outside of the Landscape the **Swampland**.

- Many **Swampland conjectures** are proposed;

Today's talk

  - **de Sitter (dS) conjecture** G. Obied, H. Ooguri, L. Spodyneiko and C. Vafa, arXiv:1806.08362 [hep-th].
    - Absence of stable dS vacua with all moduli stabilized

$$\mathrm{Min}(\nabla_i \nabla_j V) \leq -c \cdot V \qquad c\text{: } \mathcal{O}(1) \text{ positive constant}$$

  - **AdS/moduli separation conjecture** F. Gautason, V. Van Hemelryck, and T. Van Riet, Fortsch. Phys.67, 1800091 (2019).
    - Limitation on the size of the Moduli mass and AdS radius

$$m_{\text{light}} R_{\text{AdS}} \leq c$$

m_{light}: lightest moduli mass, R_{AdS}: AdS size
c: $\mathcal{O}(1)$ positive constant

  - **AdS distance conjecture** D. Lüst, E. Palti, and C. Vafa, Phys. Lett. B **797**, 134867 (2019).
    - Infinite tower of light KK states appear in the limit $\Lambda \ll 1$.

$$m_{\text{tower}} = c|\Lambda|^{\alpha}$$

m_{tower}: mass scale of the light states
Λ: cosmological constant
c, α: $\mathcal{O}(1)$ positive constant

Purposes of the Study

- **Understanding structure of the Landscape** is still important.
  - e.g., Classification by their cosmological constants

- **Swampland conjectures** were proposed.
  - may explain what does not occur in the Landscape.
  - Proof valid only in some special cases
  - Properties of vacua with all moduli stabilized

- **Inspection of the Swampland conjectures**
  - A background with no Kähler moduli exists: **Mirror dual of** $T^6/(Z_3 \times Z_3)$
  - All the moduli are stabilized only with fluxes.

P. Candelas, E. Derrick and L. Parkes, Nucl. Phys. B 407 (1993) 115.
O. DeWolfe, A. Giryavets, S. Kachru and W. Taylor, JHEP **0507** (2005) 066.
K. Becker, M. Becker and J. Walcher, Phys. Rev. D **76** (2007) 106002.

- **What does support the conjectures?** (if they hold)
  - Sharpen the boundary between Landscape/Swampland

Result: $N_{\rm flux}$ (tadpole charge of fluxes) controls the boundary!

Inspection of the dS conjecture

- The dS conjecture ⋯ No stable dS vacua

- Sign of the scalar potential at minima

We factorize $V = e^K \left(K^{i\bar{j}} D_i W D_j \bar{W} - 3|W|^2\right) \equiv e^K \tilde{V}$

$$\partial_i V = K_i V + e^K \partial_i \tilde{V} = 0 \longrightarrow V = -e^K \frac{\partial_i \tilde{V}}{K_i} \quad \text{(at minima)}$$

→ determined by the Kähler potential (known) and $\partial_i \tilde{V}$

- Function form of the scalar potential (generality)
  - quadratic in the dilaton S
  - $K_{\mathrm{Im}S} < 0, K_{\mathrm{Re}S} = 0$

⟶ We focus on $i = \mathrm{Im}S$ case

N_{flux} appears in the scalar potential

- Expand $\tilde{V}$ with $\mathrm{Im}S$

$$\boxed{\tilde{V} = \frac{1}{2}\partial^2_{\mathrm{ImS}}\tilde{V}(\mathrm{Im}S)^2 - e^{-K_{\mathrm{cs}}}N_{\text{flux}}\mathrm{Im}S + C, \quad C \equiv \tilde{V}\Big|_{\mathrm{Im}S=0} \geq 0}$$

- **Coefficient of the linear term is N_{flux} !**
  - 10d consistency appears in the 4d potential in the nontrivial way
  - The structure remains even in the no-scale type potential

- Implication of N_{flux} for resulting vacua
  - Restricted by the TCC condition

- N_{flux} can be a messenger of the consistency

Implication of N_{flux} for resulting vacua

- Example: existence of a stable Minkowski vacuum
  - If exists,

$$\langle \mathrm{Im} S \rangle = \frac{N_{\text{flux}}}{e^{K_{\text{cs}}} \partial^2_{\mathrm{Im}S} \tilde{V}}$$

with $\partial^2_{\mathrm{Im}S} V > 0 \Leftrightarrow \partial^2_{\mathrm{Im}S} \tilde{V} > 0$ (stability condition)

→ Since $\mathrm{Im} S = {g_s}^{-1}$, $N_{\text{flux}} > 0$ is required.

- Stable dS vacuum?
  - Again, N_{flux} is constrained (by a complicated relation).

→ **TCC should be linked to the dS conjecture.**

  - Numerical calculation would show the relation explicitly.

Numerical search of stable dS vacua

- Search configurations
  - Fluxes: $-20 \leq \#(\text{flux}) \leq 20$ with $0 \leq N_{\text{flux}} \leq 300$

    - Tadpole cancellation condition (TCC): $N_{\text{flux}} \leq 12$
      - Vacua with $N_{\text{flux}} > 12$ should fall into the Swampland

        (from 10d viewpoint)

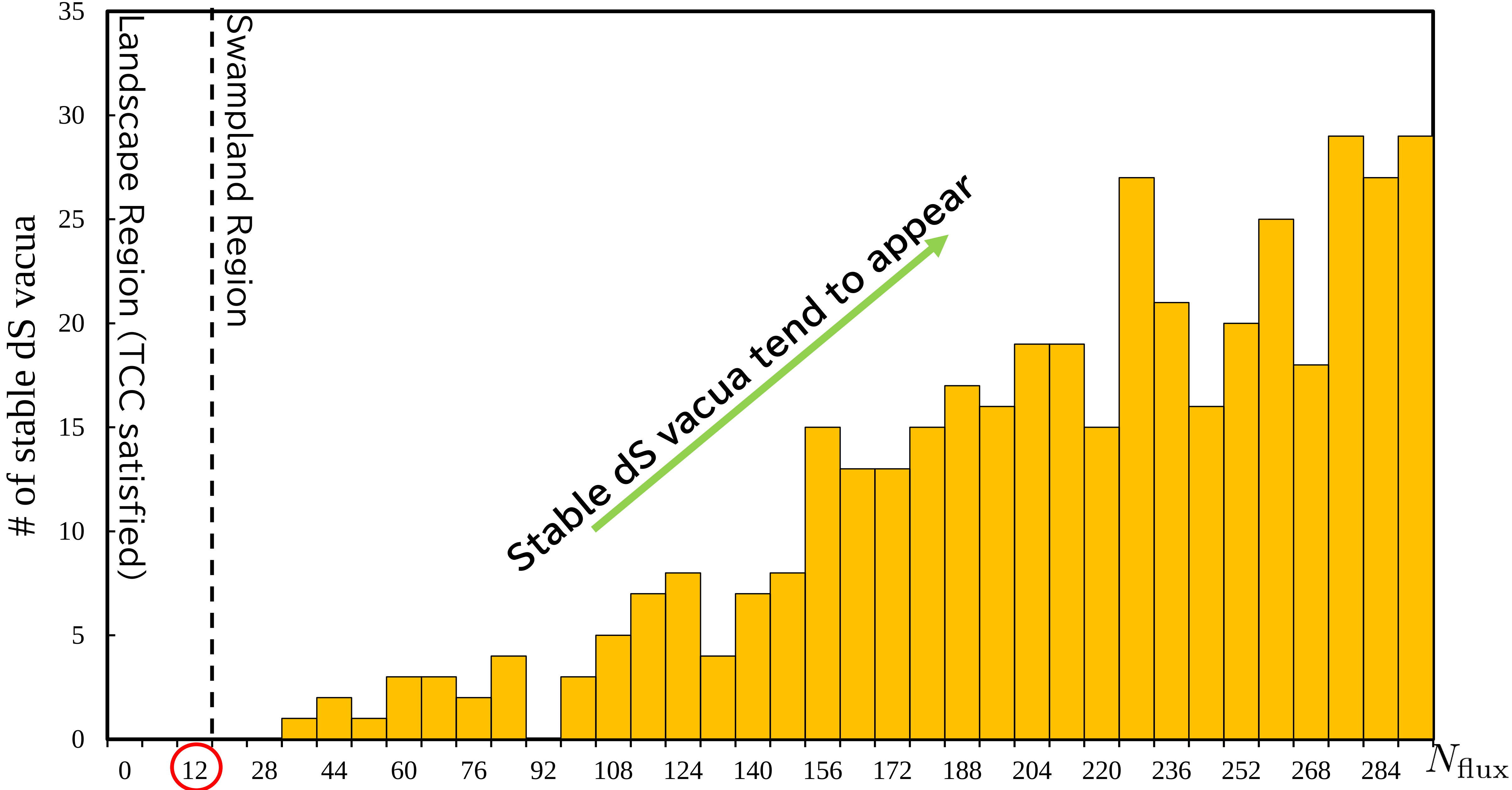
  - # of flux patterns: 7.9×10^9
  - # of minima found: 6.7×10^8

- The dS conjecture holds – no dS vacua exist in the Landscape
  - <u>However, the dS vacua appear in the region $N_{\text{flux}} > 12$</u>.
    The number of them increases as N_{flux} becomes larger.

→ Quantity characterizing the boundary between Landscape/Swampland in the 4d EFT is…

$\boxed{N_{\text{flux}} \quad \text{(or TCC)}}$

Stable dS vacua are more likely to appear with larger N_{flux}



$N_{\rm flux}$ and AdS/moduli scale separation

- $N_{\rm flux}$ is also related to moduli masses and Λ;

  - Moduli mass matrix in SUSY AdS vacua (isotropic tori)

$$\frac{M^2_{\rm phys,AdS}}{\Lambda_{\rm AdS}} = \begin{pmatrix} \frac{2}{3} - \frac{19}{108}|x|^2 & \frac{2}{9}\bar{y} & -\frac{x}{2\sqrt{3}} - \frac{x\bar{y}}{9\sqrt{3}} & \frac{\bar{x}}{6\sqrt{3}} \\ \frac{2}{9}y & \frac{2}{3} - \frac{19}{108}|x|^2 & \frac{x}{6\sqrt{3}} & -\frac{x}{2\sqrt{3}} - \frac{\bar{x}y}{9\sqrt{3}} \\ -\frac{x}{2\sqrt{3}} - \frac{\bar{x}y}{9\sqrt{3}} & \frac{\bar{x}}{6\sqrt{3}} & -\frac{7}{3} - \frac{1}{36}|x|^2 & 1 \\ \frac{x}{6\sqrt{3}} & -\frac{\bar{x}}{2\sqrt{3}} - \frac{x\bar{y}}{9\sqrt{3}} & 1 & -\frac{7}{3} - \frac{1}{36}|x|^2 \end{pmatrix},$$

with $x \equiv (S - \bar{S})(\tau - \bar{\tau})\frac{D_\tau W_{\rm NS}}{W}, y \equiv (S - \bar{S})(\tau - \bar{\tau})\frac{\overline{D_\tau W_{\rm NS}}}{W}.$

  - $N_{\rm flux}$ in the SUSY AdS vacua

$$\frac{N_{\rm flux}}{\Lambda_{\rm AdS}} = \frac{8({\rm Im}S)^3}{3}\left(8 - \frac{|x|^2}{3}\right)$$

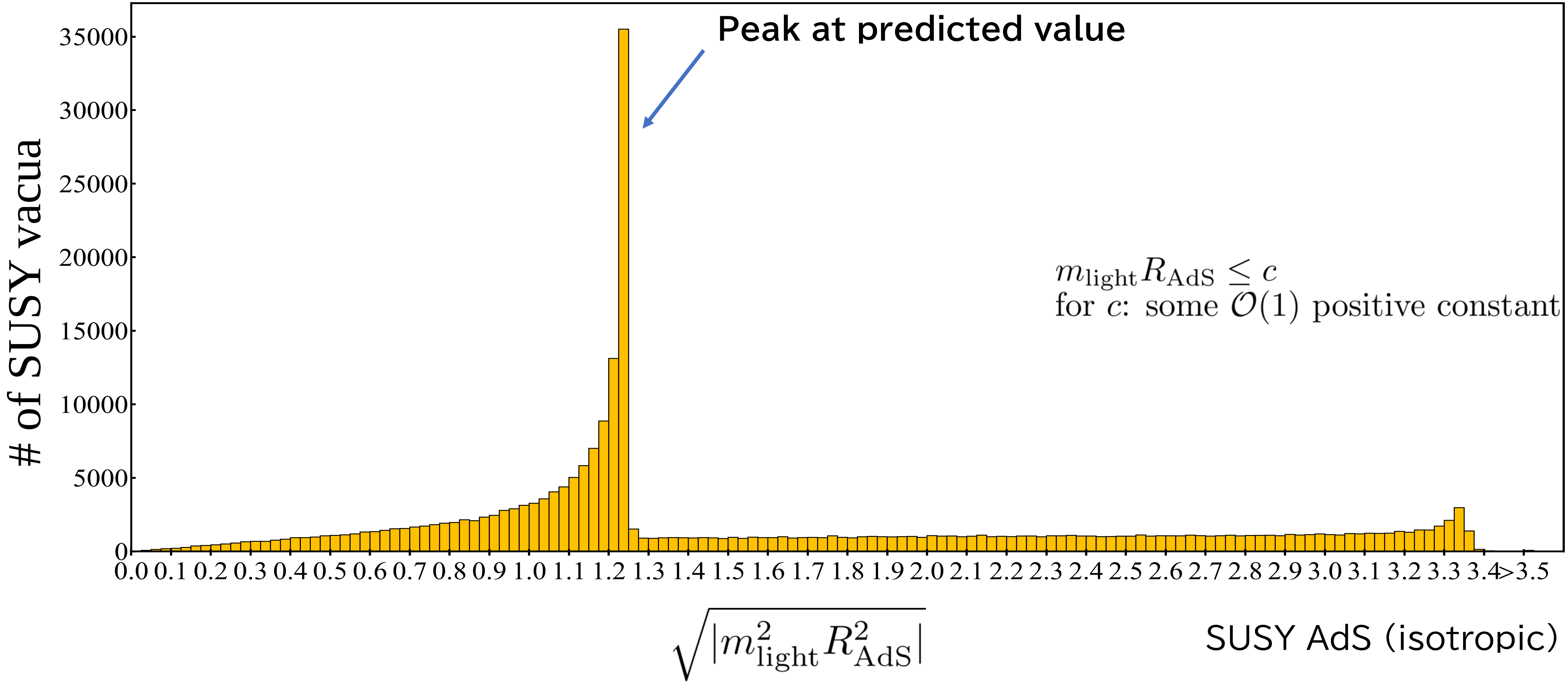
→ These are linked via x

  - Prediction

$$|m_{\rm light}R_{\rm AdS}| \simeq \frac{\sqrt{6}}{2} \simeq 1.22$$

with $8({\rm Im}S)^2\Lambda_{\rm AdS} \gg 9N_{\rm flux}, {\rm Arg}x = {\rm Arg}y$

N_{flux} supports the AdS/moduli scale separation conjecture



SUSY AdS (isotropic)

Summary and Conclusions

- $N_{\rm flux}$ is a parameter restricted by the 10d consistency (TCC).

In this talk, we pointed out;

- Appearing in the 4d EFT in the nontrivial way
- The Swampland conjectures are related to $N_{\rm flux}$.
  - $N_{\rm flux}$ as a **messenger**; resulting vacua notice its inconsistency via $N_{\rm flux}$.
  - Landscape/Swampland boundary in the 4d EFT is controlled by $N_{\rm flux}$.
- Implying the importance of TCC in proving conjectures

Thank you all for your attention!

More details in 2104.15030