Challenges for (string) cosmology in the swampland era

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with Y. Hamada, A. Hebecker & G. Shiu - …, 1812.06097, 1902.01410

Kavli IPMU - Feb 19

invisiblesPlus

Outline

- Motivation:
- The **no-dS Conjecture** and dark energy
  - A challenge to KKLT from 10d
- The **Weak Gravity Conjecture** and axion inflation
- Conclusions

The swampland program

…and some phenomenological applications

String Landscape and the Swampland

- String theory may admit a vast number $\gtrsim 10^{500}$ of 4d solutions
- They represent an enormously rich landscape of EFT
  - Field theoretical ideas in particle physics and cosmology have found their UV realizations in string theory.
  - New scenarios have been uncovered along the way.
- This traditional approach leaves the impression that every consistent-looking EFT can be embedded in string theory

Are there low energy effective theories that are ***not*** embeddable in string theory?

Vafa '05; Ooguri, Vafa, '06; …

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  [Taylor, Wang '17]
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String Landscape and the Swampland

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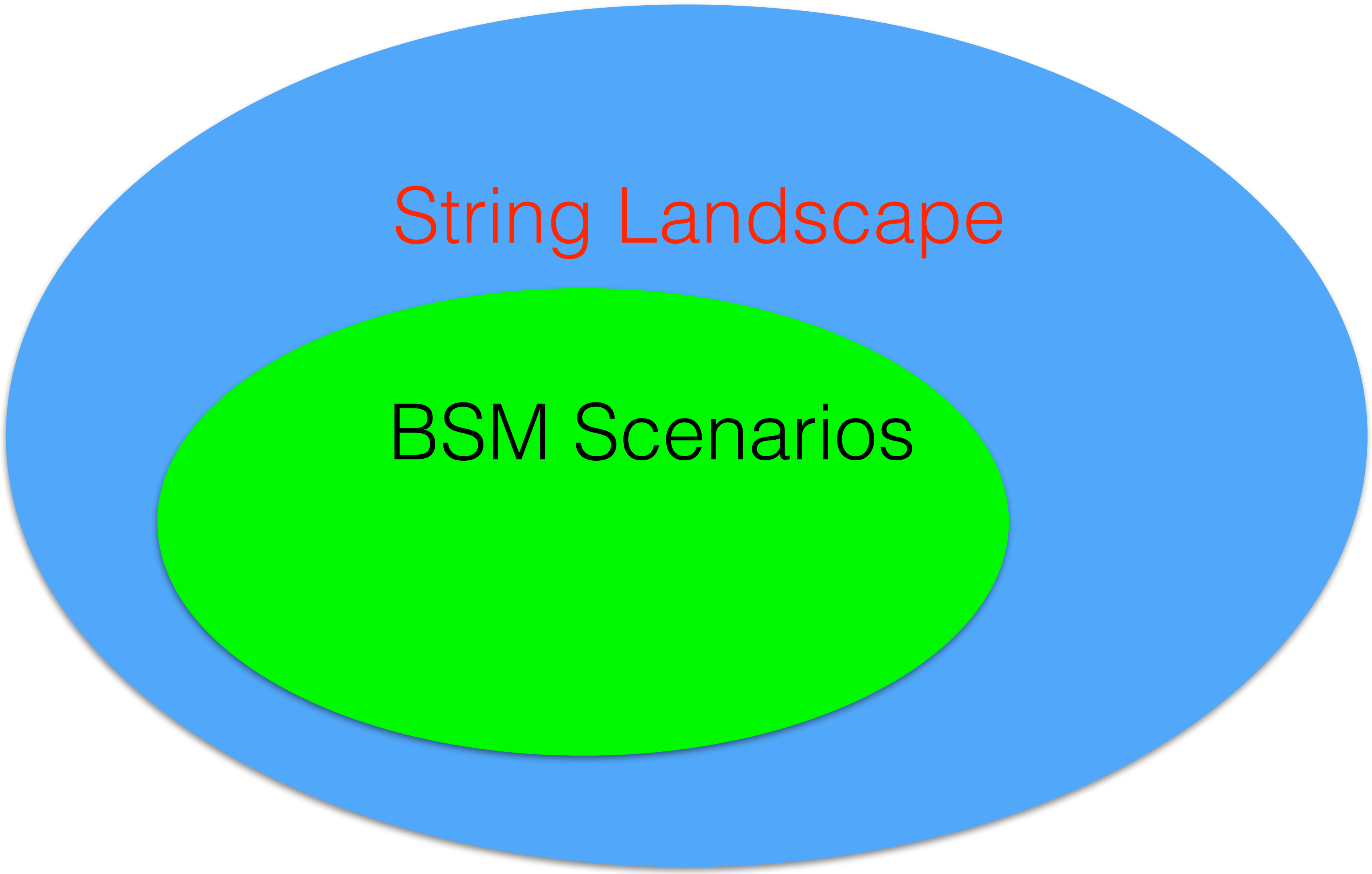

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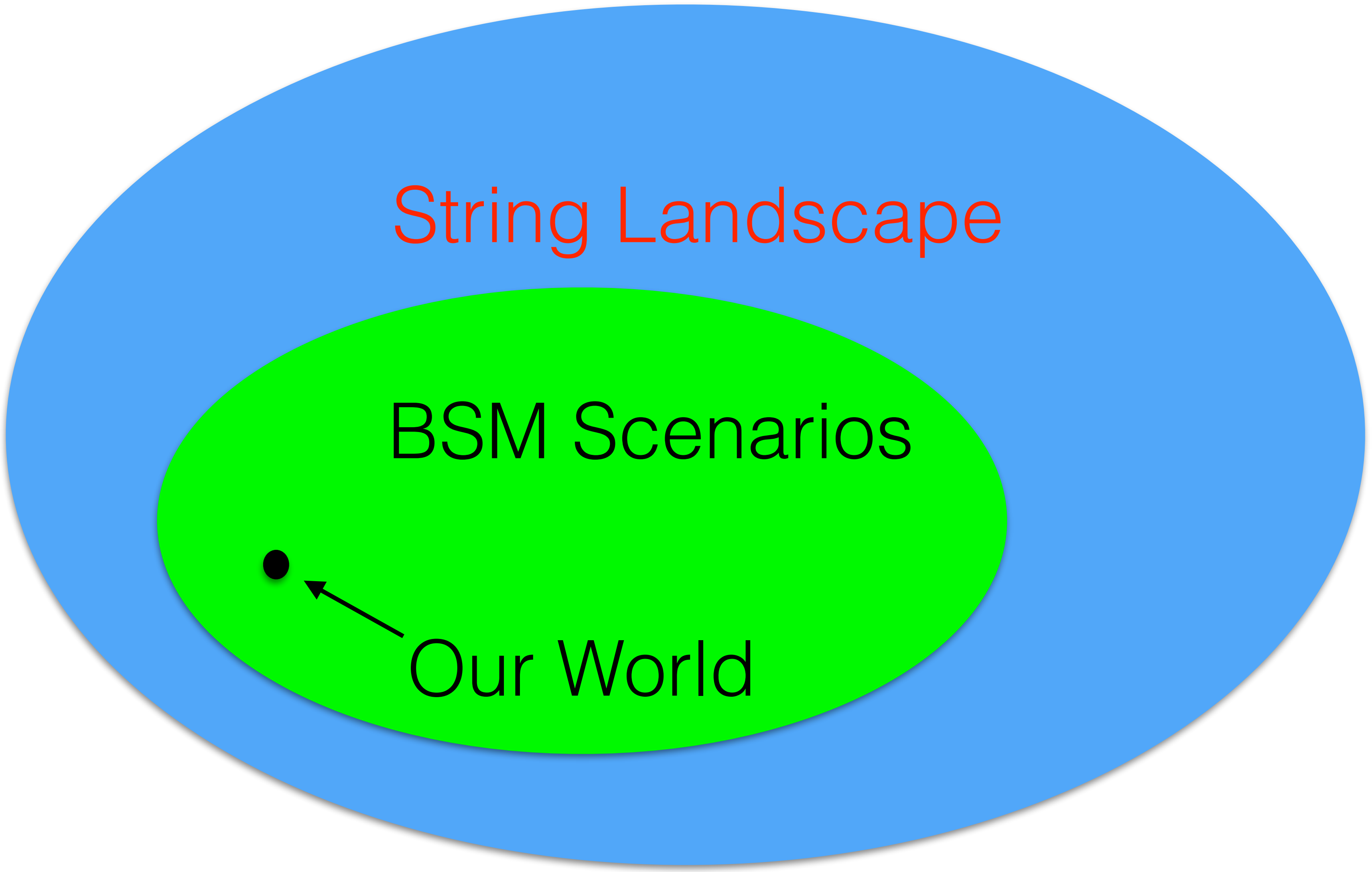
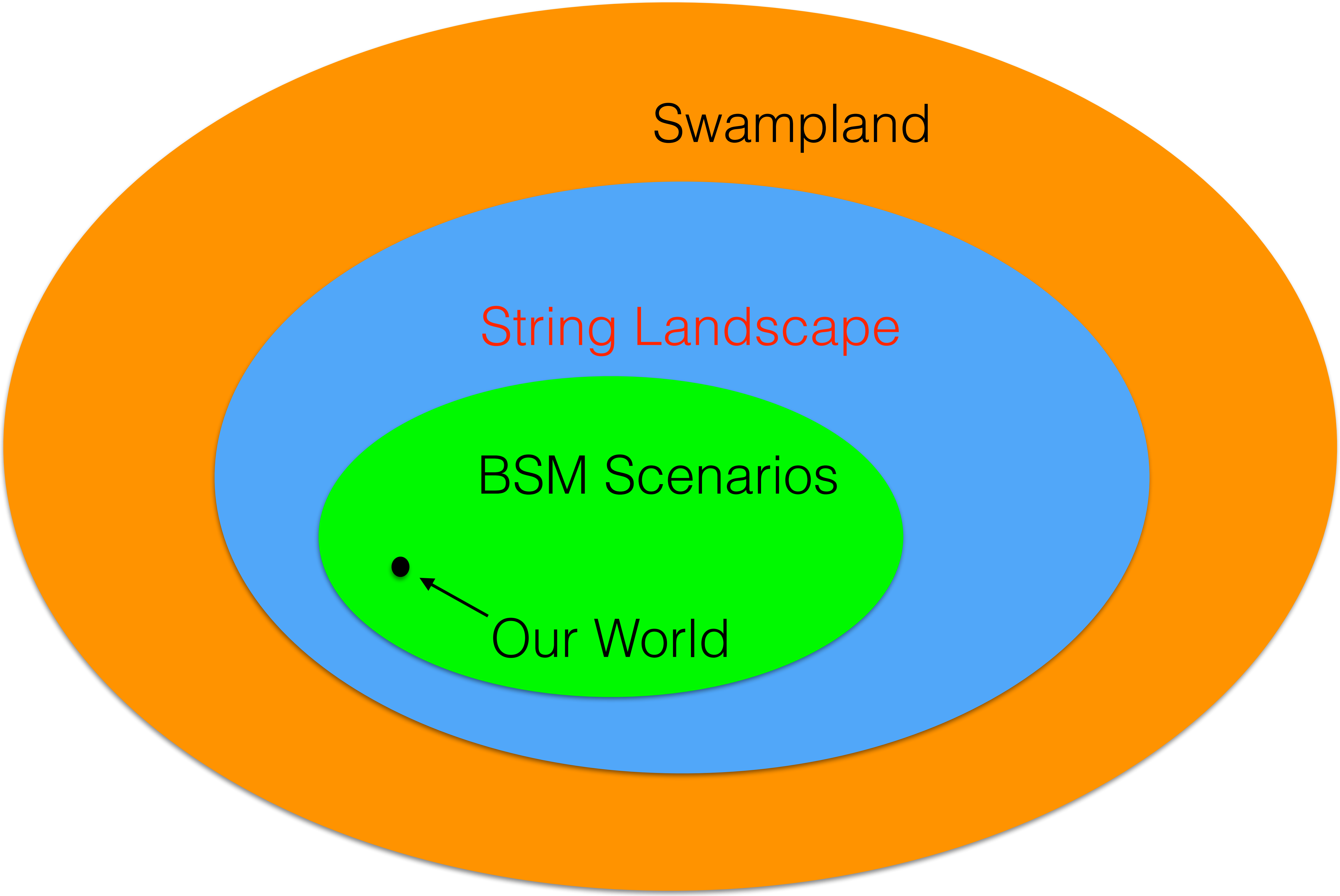


String Landscape and the Swampland



String Landscape and the Swampland

- If there exists a swampland:
  - What properties distinguish landscape vs. swampland EFT's?
  - Are swampland EFT's fundamentally incompatible with quantum gravity? Why?

    String swampland = QG swampland ?

  - What are the implications for phenomenology? Are there BSM proposals that live in the swampland?

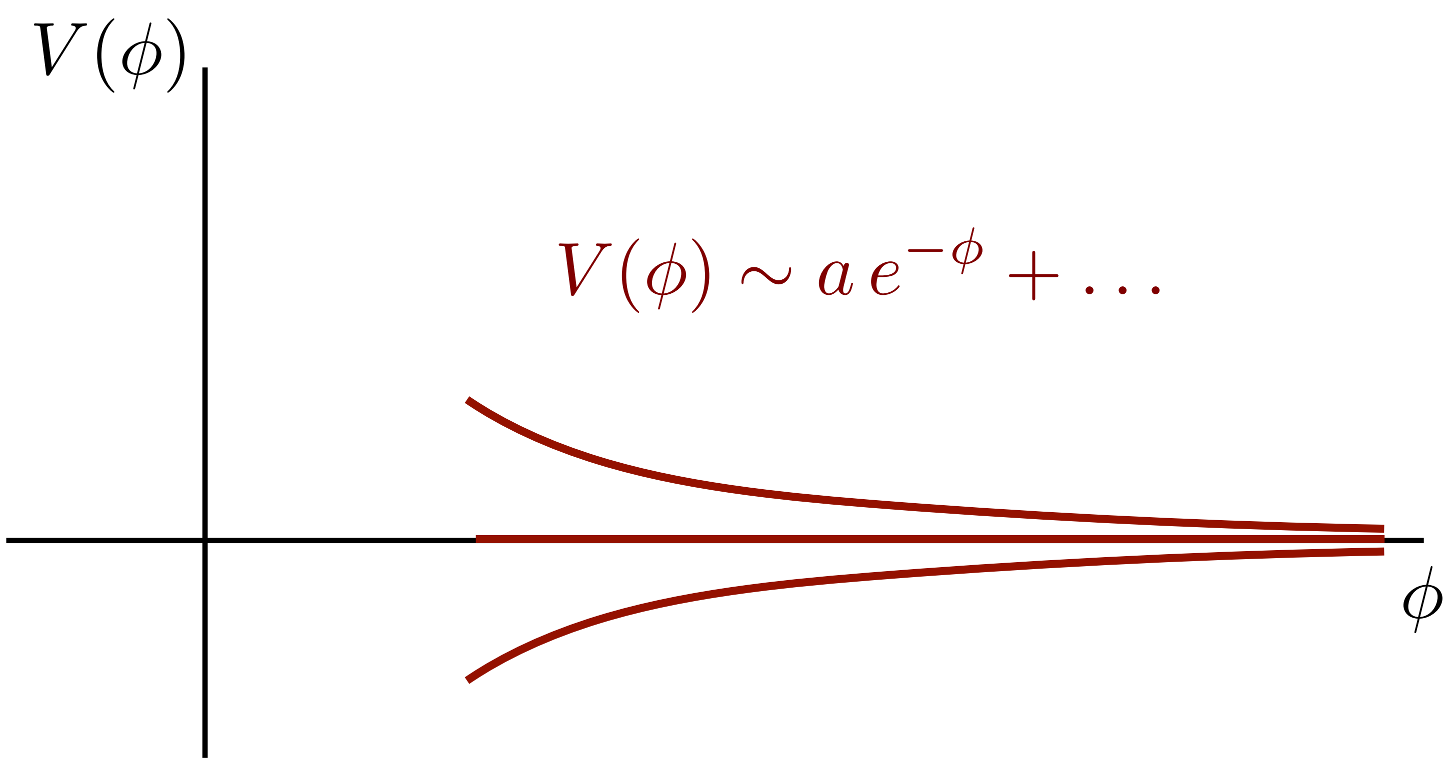
dS vacua and the swampland

dS and the swampland

- It is notoriously difficult to obtain string dS vacua.
- The difficulty can be traced back to the **Dine-Seiberg problem**:

  In string theory, there are no free parameters: coupling constants are vevs of scalar fields (moduli), e.g. $g_s = e^{-\phi}$

  At weak coupling ($\phi \to \infty$), vacuum energy vanishes



- V>0: runaway (quintessence?)
- V=0: flat (massless ϕ)
- V<0: roll to strong coupling

Dine, Seiberg '85

dS and the swampland

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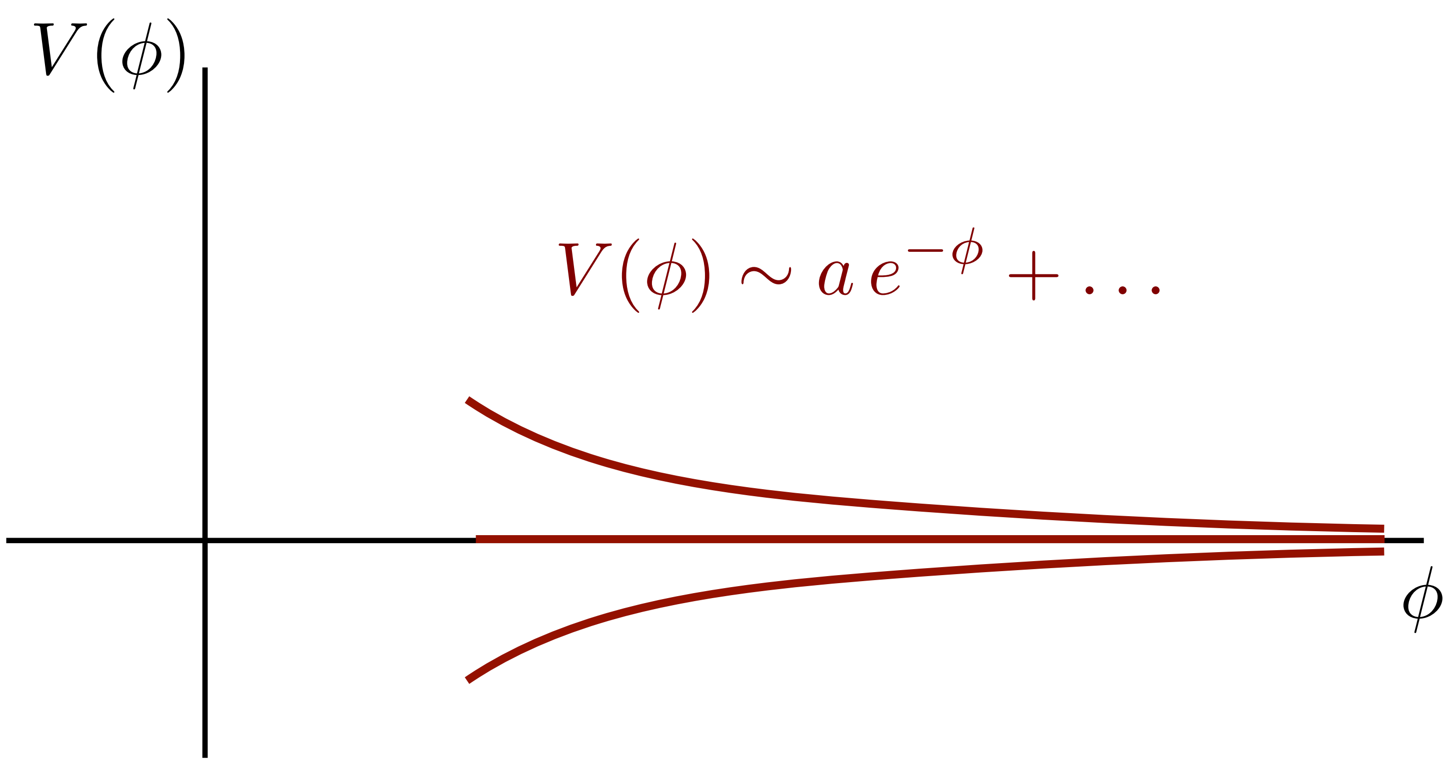


- No vacuum (either AdS, Mink, or dS) at **parametrically** weak coupling exists!

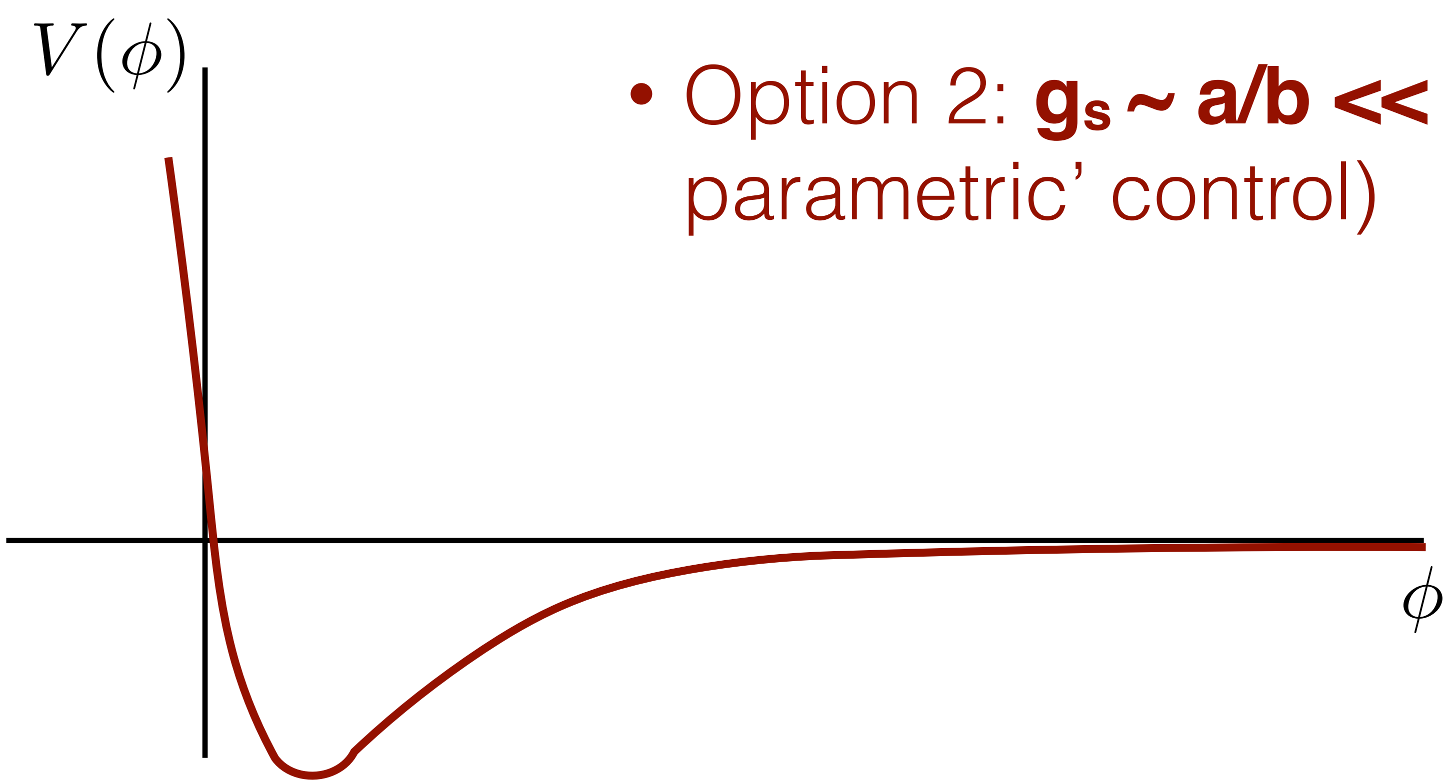
Dine, Seiberg '85

dS and the swampland

- To find a minimum, one needs higher order corrections in the potential, but then perturbativity is endangered

$$V(\phi) = -a\, e^{-\phi} + b\, e^{-2\phi} + \ldots \qquad \Longrightarrow \qquad g_s = e^{-\phi_0} = \frac{a}{2b}$$

- Option 1: $g_s \sim a/b \sim 1$ strong coupling (no control)!
- Option 2: **$g_s \sim a/b << 1$** AdS at small coupling ('non-parametric' control)

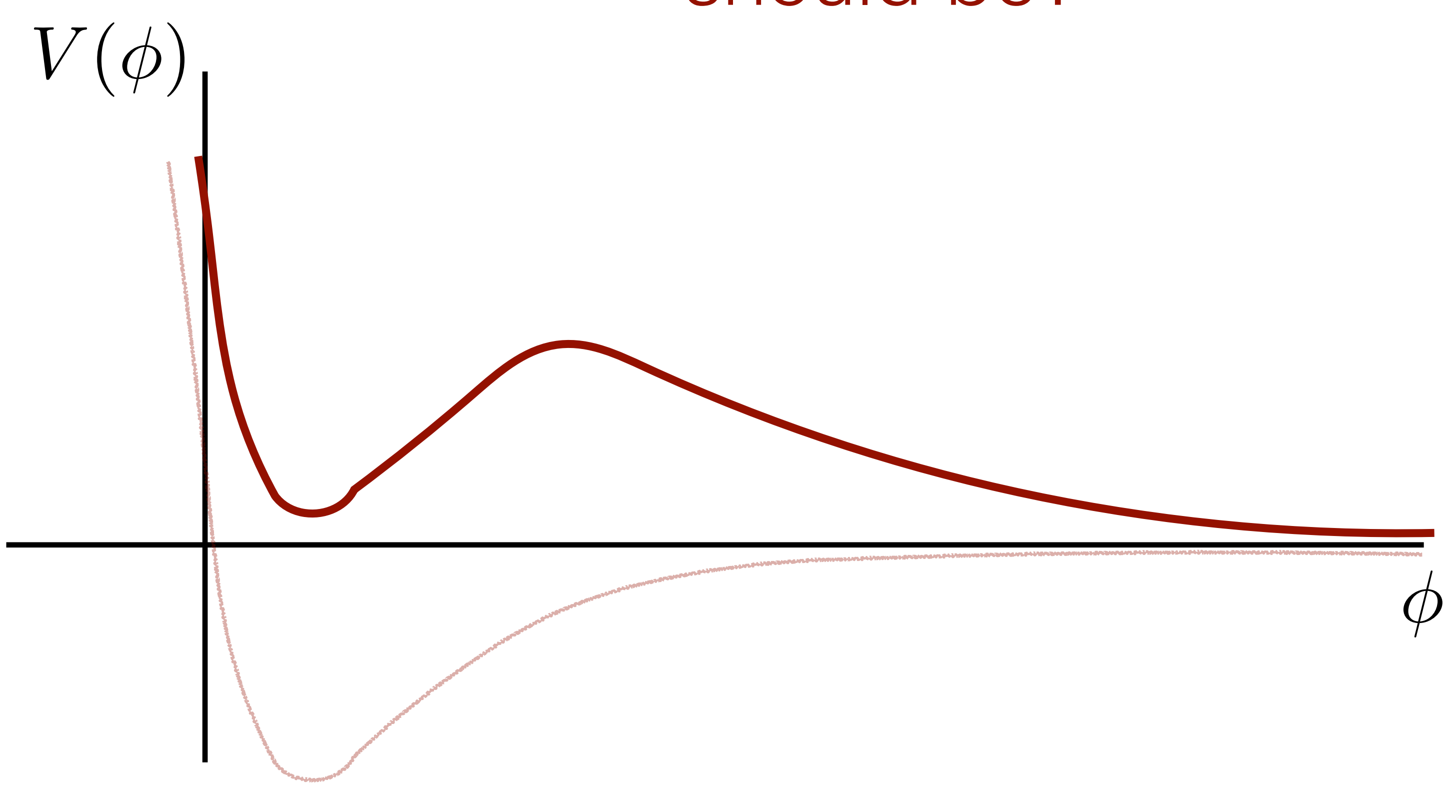


dS and the swampland

- To find a minimum, one needs higher order corrections in the potential, but then perturbativity is endangered

$$V(\phi) = a\, e^{-\phi} - b\, e^{-2\phi} + c\, e^{-3\phi} + \dots$$

- With one more term, one can obtain potentials with dS minima at $g_s << 1$. Not ideal, but who said it should be?



Moduli stabilization and constructions of vacua (AdS, Mink or dS) exploit this mechanism

GKP '01, KKLT '03, LVS '05

dS and the swampland

- Recent suggestion: in every direction in moduli space, the potential must satisfy **asymptotically**

$$|\nabla V(\phi)| \geq \alpha V \qquad\qquad \alpha \sim \mathcal{O}(1)\,,\ \phi \to \infty$$

Obied, Ooguri, Spodyneiko, Vafa '18

This behaviour arises naturally in string theory, and is required asymptotically by swampland conjectures. Ooguri, Palti, Shiu, Vafa '18

- **De Sitter swampland conjecture:** this must hold (with minor qualifications) throughout moduli space, forbidding dS vacua.

dS vacua (KKLT, LVS)	vs.	dS swampland conjecture
Necessarily complicated Vacuum energy		Simple but speculative Quintessence

A challenge to KKLT from 10d

KKLT from 10d perspective

- Two main proposals to obtain positive vacuum energy in string compactifications **KKLT** and LVS scenarios

Kachru et al. ‘03,
Balasubramanian et al. ‘05

Despite thorough scrutiny since proposed, they have resisted strong criticism rather well: no definitive inconsistency found.

On the other hand, no explicit construction developed so far.

c.f. Danielsson, Van Riet ‘18

- If (strong) no-dS conjecture holds they should be pathological

Renewed interest and attacks on KKLT and LVS.

- I will **only** address criticism to KKLT based on a 10d proposal

Whether the dS conjecture holds or not will not be discussed

Moritz, Retolaza, Westphal ’17, ’18
Moritz, Van Riet, ‘18
Gautason, Van Hemelryck, Van Riet ‘18

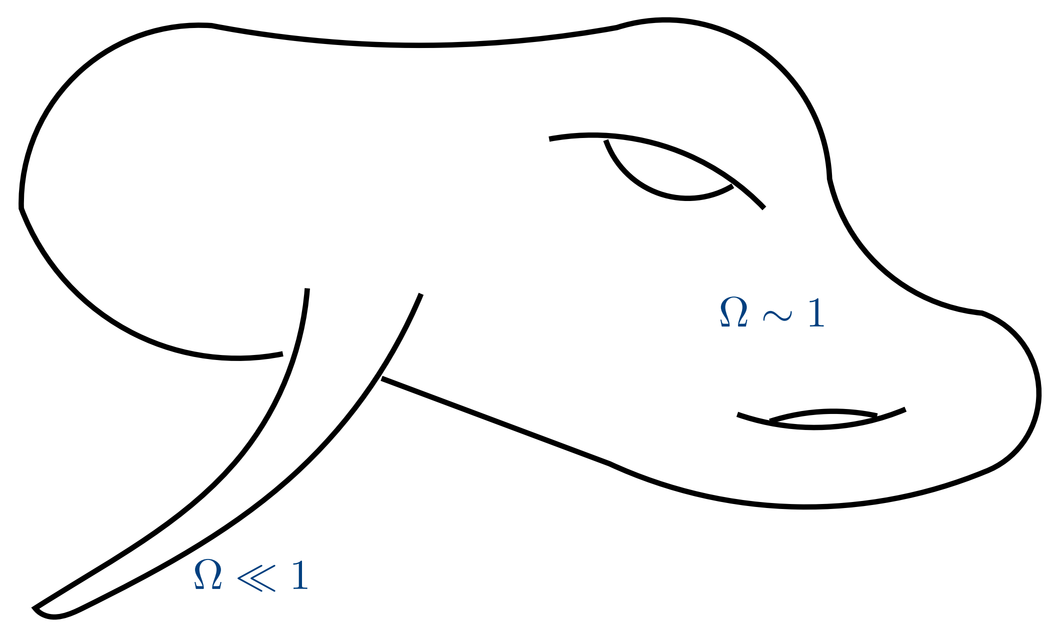
KKLT from 10d perspective

- KKLT review: obtain the 4d effective potential of a type IIB compactification with one Kahler (volume) modulus T.

Step 0: consider a GKP-type setup (warped compactification to Minkowski with O7-planes, D3/D7-branes and fluxes)

$$V(T) = 0$$

(no-scale, c.s. stabilised)



$$ds^2_{10} = \Omega^2(y)\, \eta_{\mu\nu}\, dx^\mu\, dx^\nu + g_{mn}\, dy^m\, dy^n$$

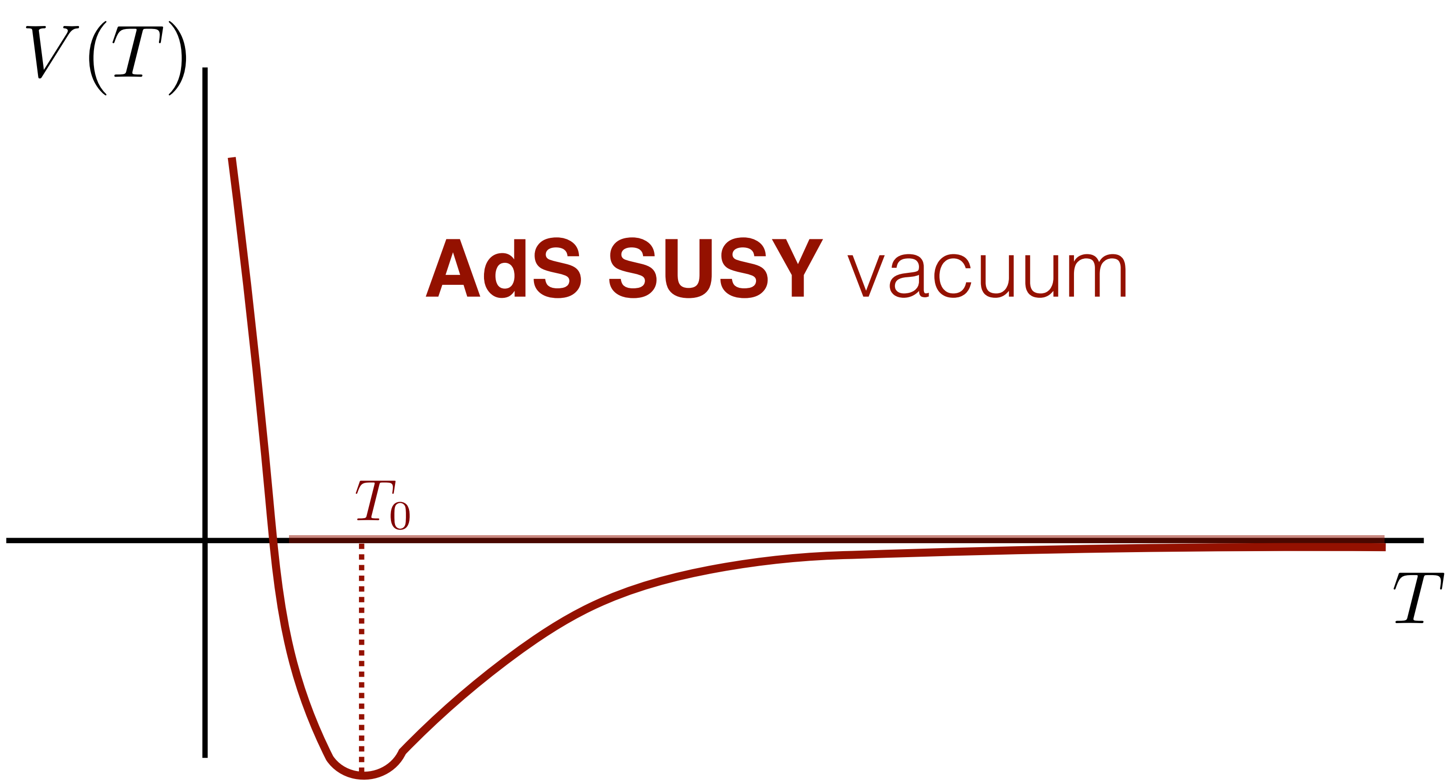
Giddings, Kachru, Polchinski '01

KKLT from 10d perspective

- KKLT review: obtain the 4d effective potential of a type IIB compactification with one Kahler (volume) modulus T.

Step 1: take into account non-perturbative effects, e.g. gaugino condensation on D7-branes

$$\langle\lambda\lambda\rangle \sim e^{-aT} \qquad \Longrightarrow \qquad V(T) \sim \frac{1}{T}e^{-2aT} - \frac{2}{T^2}W_0 e^{-aT}$$



W_0: flux superpotential

$$W_0 \sim e^{-aT_0}$$

Computational control:

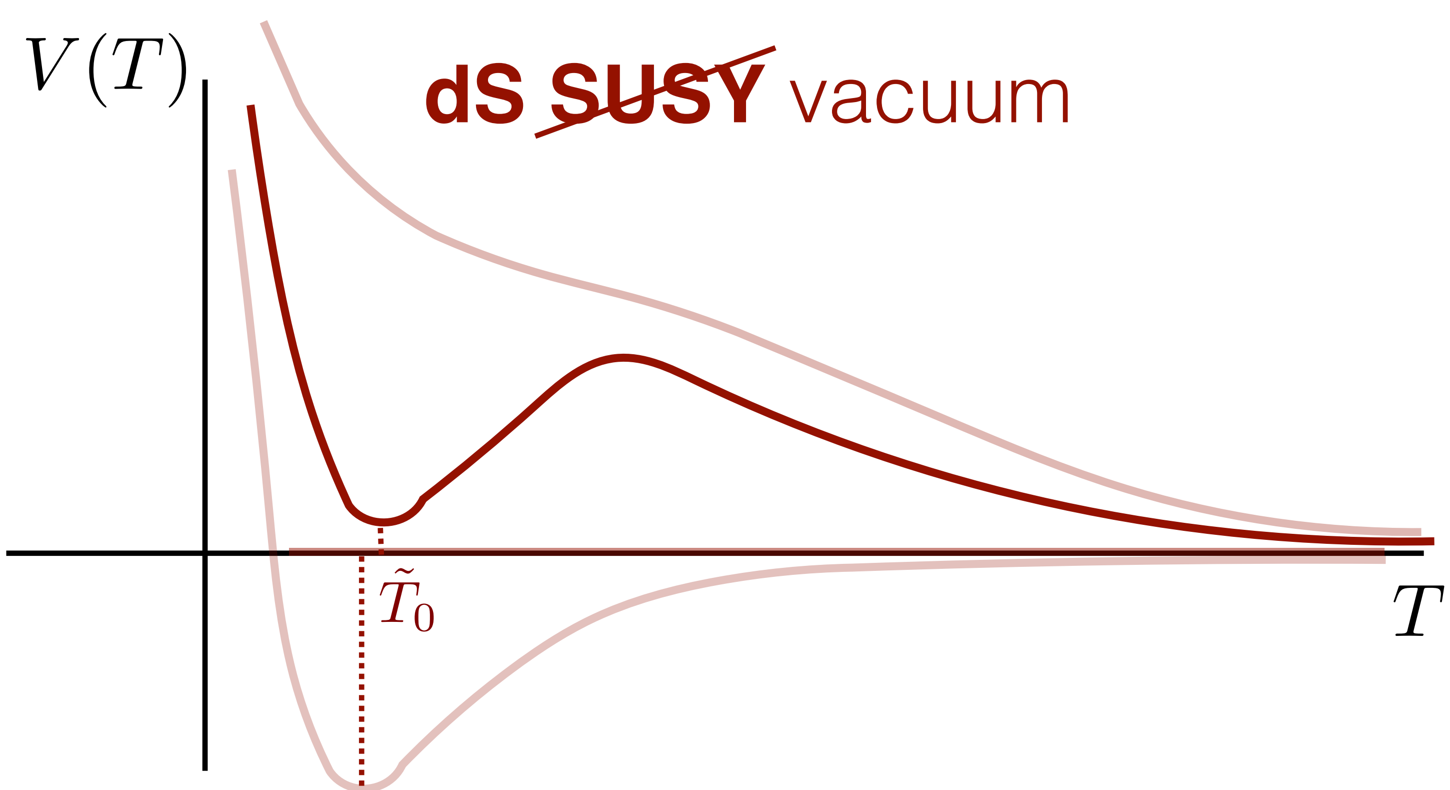
$$a\,T_0 > 1 \implies W_0 \ll 1$$

KKLT from 10d perspective

- KKLT review: obtain the 4d effective potential of a type IIB compactification with one Kahler (volume) modulus T.

Step 2: introduce anti-D3-brane at the tip of the throat

$$V(T) \sim \frac{1}{T}e^{-2aT} - \frac{2}{T^2}W_0 e^{-aT} + \frac{\mu_3}{T^2}$$



μ_3 <<1: warped D3-tension

If μ_3 not small enough

⇒ runaway

KKLT from 10d perspective

- The KKLT proposal, in particular gaugino condensation effects, is formulated in terms of the 4d effective potential

  Difficult to implement in the 10d theory, where E3-brane effects would need to be taken into account

- The 10d perspective (the 10d Einstein equations) are often useful to derive no-go theorems

  Maldacena, Nuñez ‘00

  Recently, an approach to include gaugino condensation effects in the classical 10d picture has been proposed

  Baumann et al. ’06, ‘10

  It has been claimed that this picture shows “flattening” effects missed in the 4d perspective, challenging KKLT dS-uplifts

  Moritz, Retolaza, Westphal ’17, ’18
  Moritz, Van Riet, ‘18
  Gautason, Van Hemelryck, Van Riet ‘18

KKLT from 10d perspective

- Consider Einstein equation in 10d and its trace over 4d indices:

$$\mathcal{R}_{MN} = T_{MN} - \frac{1}{8} g_{MN} T^L_L \implies R^\mu_\mu = \frac{1}{2}\left(T^\mu_\mu - T^m_m\right) \equiv -2\Delta$$

- For a warped ansatz: $ds^2_{10} = \Omega^2(y)\ (\eta_{\mu\nu}\, dx^\mu\, dx^\nu + g_{mn}\, dy^m\, dy^n)$

$$\mathcal{V}_6\, \mathcal{R}(\eta) = \int d^6y \sqrt{g}\ \Omega^8(y)\, \mathcal{R}(\eta) = -2 \int d^6y \sqrt{g}\ \Omega^{10}(y) \Delta$$

Useful for no-go theorems: positivity arguments on Δ constrain compactifications with $\mathcal{R}(\eta) \geq 0$.

Maldacena, Nuñez '00

- GKP warped compactifications (KKLT step 0) have $\mathcal{R}(\eta)=0$ (Minkowski compactification)

KKLT from 10d perspective

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- **KKLT (0)**: GKP Minkowski solution

$$\mathcal{V}_6\,\mathcal{R}(\eta) = \frac{1}{2}\int d^6y\,\sqrt{g}\;\Omega^{10}(y)\Delta = 0$$

KKLT from 10d perspective

$$\mathcal{V}_6\,\mathcal{R}(\eta) = \int d^6y\,\sqrt{g}\;\Omega^8(y)\,\mathcal{R}(\eta) = -2\int d^6y\,\sqrt{g}\;\Omega^{10}(y)\Delta$$

- **KKLT (1&2)**: include gaugino condensate and anti D3-brane effects

$$\mathcal{V}_6\,\mathcal{R}(\eta) \approx -2\int d^6y\,\sqrt{g}\;\Omega^{10}(y)\left(\Delta^{\langle\lambda\lambda\rangle} + \Delta^{\overline{D3}}\right)$$

$\Delta^{\lambda\lambda}$ proposal: include $\langle\lambda\lambda\rangle \sim e^{-aT}$ as a source in the D7-brane action and compute the corresponding $\Delta^{\text{(gaugino)}}$

$$S_{\lambda\lambda} \sim \int_{X_6} G_3 \wedge \Omega_3\,\overline{\lambda\lambda}\,\delta_{D7} + \text{c.c.} \quad\Longrightarrow\quad \Delta^{\langle\lambda\lambda\rangle} = \frac{1}{2}\left(\mathcal{L}_{\langle\lambda\lambda\rangle} - g^{mn}\frac{\delta\mathcal{L}_{\langle\lambda\lambda\rangle}}{\delta g^{mn}}\right)_{\langle\lambda\lambda\rangle\sim e^{-aT}}$$

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Problem: the G_3-flux sourced by a localised gaugino condensate is divergent. Integrating it out leads to S ~ δ(0), (UV-regularization dependent)!!

KKLT from 10d perspective

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$\boldsymbol{\Delta^{\overline{D3}}}$: easily estimated from the $\overline{\text{D3}}$-brane worldvolume-action

Claim: both $\Delta^{\lambda\lambda}$ and $\Delta^{\overline{D3}}$ are strictly positive (at least when Kahler moduli are stabilized)

Claimed to be due to flattening of the potential upon $\overline{\text{D3}}$-uplift

Moritz, Retolaza, Westphal '17

KKLT from 10d revisited

Hamada, Hebecker, Shiu, PS ’18, ‘19

KKLT from 10d revisited

- To solve the puzzle, need first to regularise the divergent action (inspired by similar divergences in Horava-Witten theory)

Essential ingredients captured by 5d toy model on $M_4 x S^1$ of a bulk one-form flux $G_1=d\phi$ coupled to a source <λλ> localised on the circle

$$S \sim \int \Big(G_1 \wedge *G_1 - 2\, G_1 \wedge *\langle\lambda\lambda\rangle\delta(y)dy \Big)$$

$$\Longrightarrow \qquad G_1 = \langle\lambda\lambda\rangle\delta(y)dy \qquad \Longrightarrow \qquad S \sim \langle\lambda\lambda\rangle^2\delta(0)$$

Resolution required by SUSY: complete to perfect-square form

$$S \sim \int \Big(G_1 - \langle\lambda\lambda\rangle\delta(y)dy \Big) \wedge * \Big(G_1 - \langle\lambda\lambda\rangle\delta(y)dy \Big)$$

$$\Longrightarrow \qquad G_1 = \langle\lambda\lambda\rangle\delta(y)dy + G_1^{(0)} \qquad \Longrightarrow \qquad S \sim \int G_1^{(0)} \wedge * G_1^{(0)}$$

Perfectly finite

$G^{(0)}$ subject to flux quantization

Horava, Witten '96; Horava '96; Mirabelli, Peskin '97

KKLT from 10d revisited

- Analogously, complete the divergent action coupling G_3-flux to D7-gauginos into a perfect-square form

$$S_{G_3\lambda\lambda} \sim \int \Big(G_3 \wedge * \overline{G_3} - G_3 \wedge \overline{\lambda\lambda}\, \delta_{D7} * \Omega_3 + \text{c.c.} \Big)$$
$$\longrightarrow \int \Big| G_3 - \lambda\lambda\, \delta_{D7}\, \overline{\Omega}_3 \Big|^2$$

Looks good but there is a problem: in $\delta_{D7}\Omega_3$ is not closed, so

$$G_3 = \lambda\lambda\, \delta_{D7} * \overline{\Omega}_3 \qquad \Longrightarrow \qquad dG_3 \neq 0$$

~~Bianchi identity~~

Action still divergent

KKLT from 10d revisited

- Analogously, complete the divergent action coupling G_3-flux to D7-gauginos into a perfect-square form

Way out: project the source onto the subspace of closed forms (drop its co-exact component), with projector $\mathcal{P}$

$$S_{G_3\lambda\lambda} \sim \int \left| G_3 - \lambda\lambda\,\delta_{D7}\,\overline{\Omega}_3 \right|^2 \longrightarrow \int \left| G_3 - \mathcal{P}\big(\lambda\lambda\,\delta_{D7}\,\overline{\Omega}_3\big) \right|^2$$

- Perfectly finite action
- G3 equations of motion unmodified
- Upon integrating out G3: $S_{G_3\lambda\lambda} \sim \int \left| G_3^{(0)} - \frac{\lambda\lambda}{A_\perp}\,\overline{\Omega}_3 \right|^2$

Correctly reproduces results expected from 4d SUGRA (including GVW superpotential).

Hamada, Hebecker, Shiu, PS ’18
Kallosh ‘19

KKLT from 10d revisited

- Given this finite action, one can revisit the 10d analysis of KKLT

$$\mathcal{V}_6\,\mathcal{R}(\eta) = -2\int d^6y\,\sqrt{g}\;\Omega^{10}(y)\Delta$$

Where $\Delta = \frac{1}{4}\left(-T^{\mu}_{\mu} + T^{m}_{m}\right) = \frac{1}{2}\left(\mathcal{L} - \underbrace{g^{mn}\frac{\delta\mathcal{L}}{\delta g^{mn}}}\right)$ = scaling inner volume T

- 10d KKLT **pre-uplift**: consider a scaling of form $\langle\lambda\lambda\rangle \sim e^{-aT}$ and compute $\Delta^{(\mathrm{gaugino})}$ from the finite 10d action

$$\mathcal{V}_6\mathcal{R}_\eta \sim -\,a\,T^2\left(T\,e^{-2aT} - W_0\,e^{-aT}\right) + \frac{1}{2}\,T^2 e^{-2aT}$$

On-shell, **same as KKLT** AdS result in a subtle way

$$\mathcal{V}_6\,\mathcal{R}_\eta \sim \frac{1}{2}\,T^4\,\underbrace{\frac{\partial V_{\langle\lambda\lambda\rangle}}{\partial T}} + T^3 V_{\langle\lambda\lambda\rangle} \xrightarrow{\text{on-shell}} T_0^3\,V_{\langle\lambda\lambda\rangle}(T_0)$$

Vanishes on-shell iff no other contributions to V(T), e.g. $\overline{\mathrm{D3}}$'s

KKLT from 10d revisited

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- 10d KKLT **uplift**: add D3-branes at tip of throat. $\Omega^8(y_0)\Delta^{\overline{D3}} << 1$

$\Delta^{\overline{D3}}$ contribution is negligible. Uplift???

$$\mathcal{V}_6\, \mathcal{R}_\eta \sim \frac{1}{2} T^4 \underbrace{\frac{\partial V_{\langle\lambda\lambda\rangle}}{\partial T}} + T^3 V_{\langle\lambda\lambda\rangle} \xrightarrow{\text{on-shell}} -\tilde{T}_0^4 \left[\frac{\partial V_{\overline{D3}}}{\partial T}\right]_{\tilde{T}_0} + \tilde{T}_0^3 V_{\langle\lambda\lambda\rangle} = \tilde{T}_0^3\, V_{\text{tot}}(\tilde{T}_0)$$

No longer vanishes: small shift in minimum $T_0 \to \tilde{T}_0$ induced by D3 backreacts on $\Delta^{(\text{gaugino})}$ and generates **KKLT uplift**!!

Conclusions

- We have addressed and dispelled recent criticism on the KKLT scenario using 10d Einstein equations

Moritz et al. '17, '18 ; Gautason et al. '18

- We proposed a λ^4-action counter-term to the D7-brane action.

  Avoid previous divergences and reproduce 4d SUGRA results

c.f. Kallosh '19

- Compared the 4d and 10d approaches to KKLT

  We have shown the general on-shell equivalence:

  4d Einstein + Kahler moduli e.o.m. $\Longleftrightarrow$ 10d Einstein eq.

c.f. Giddings, Maharana '05
see Gautason et al. '19 for different treatment and results

  Our action leads to the standard 4d KKLT (gaugino) potential

  In 10d: while Δ^{D3}, $\Delta^{(gaugino)} > 0$ individually. Uplift arises by backreaction of D3-branes on $\Delta^{(gaugino)}$ which changes signs

Hamada, Hebecker, Shiu, PS '18, '19; c.f. Carta, Moritz, Westphal '19

The Weak Gravity Conjecture

QG and Global Symmetries

- **Global symmetries** are expected to be violated by gravity:

- **No hair theorem:** Hawking radiation is insensitive to Q.
  ➡ <u>Infinite</u> number of states (remnants) with $m \lesssim M_p$
  ➡ Violation of entropy bounds. At finite temperature (e.g. in Rindler space), the density of states blows up.

Susskind '95

- **Swampland conjecture**: theories with exact global symmetries are not UV-completable.

- In (perturbative) string theory, all symmetries are gauged

The Weak Gravity Conjecture

- We have argued that global symmetries are in conflict with Quantum Gravity

- Global symmetry = gauge symmetry at g=0

  - It is not unreasonable to expect problems for gauge theories in the weak coupling limit: g -> 0

- When do things go wrong? How? …

The Weak Gravity Conjecture

- The conjecture:

Arkani-Hamed, Motl, Nicolis, Vafa '06

"Gravity is the Weakest Force"

- For every long range gauge field there exists a particle of charge q and mass m, such that

$$q > \frac{m}{M_p}$$

  - What evidence is there for the conjecture?
  - What does it imply for phenomenology?

Why WGC?

Several lines of argument have been taken (so far):

- Holography [Nakayama, Nomura, ’15];[Harlow, ‘15];[Benjamin, Dyer, Fitzpatrick, Kachru, ‘16];[Montero, Shiu, PS, ’16];[Montero, ’18]
- IR Consistencies (unitarity & causality) [Cheung, Remmen, ’14]; [Andriolo, Junghans, Noumi, Shiu, ’18];
- Cosmic Censorship [Horowitz, Santos, Way, ‘16]; [Cottrell, Shiu, PS, ’16]; [Crisford, Horowitz, Santos ’17],[Horowitz, Santos ’19]
- Axion Black Holes [Hebecker, PS, ’17]; [Montero, Uranga, Valenzuela, ’17]
- Black hole entropy: [Cottrell, Shiu, PS, ’16, ’17];[Fisher, Mogni, ’17];[Hod, ’17];[Cheung, Liu, Remmen, ’18]

Suggestive evidence, but no definitive proof of WGC found so far

Phenomenological application:

Axion inflation

WGC and axions

- Consider a U(1) gauge theory in 5d, and compactify on S to 4d. Upon dimesional reduction: $A_M(x, x_4) \to (A_\mu(x), \phi(x))$

$$S = \int d^5x \, \frac{-1}{4g_5^2} F_{MN}F^{MN} \quad \longrightarrow \quad \int d^4x \left(\frac{-1}{4g_4^2} F_{\mu\nu}F^{\mu\nu} - \frac{1}{2}\partial_\mu\phi\partial^\mu\phi \right)$$

The gauge symmetry leads to an axion shift symmetry $\phi = \phi + c$

- Topologically non-trivial Euclidean configurations (instantons) with charged fields wrapping the 5d circle generate a potential

$$V(\phi) = e^{-S_{inst}} \cos\left(\frac{\phi}{f}\right)$$

$$S_{inst} = 2\pi R m_5$$
$$f = q_5\sqrt{2\pi R}$$

- The 5d WGC for charged particles $m_5 < q_5 M_{p,5d}^3$ translates into:

$$\boxed{f \cdot S_{inst} \leq M_p}$$

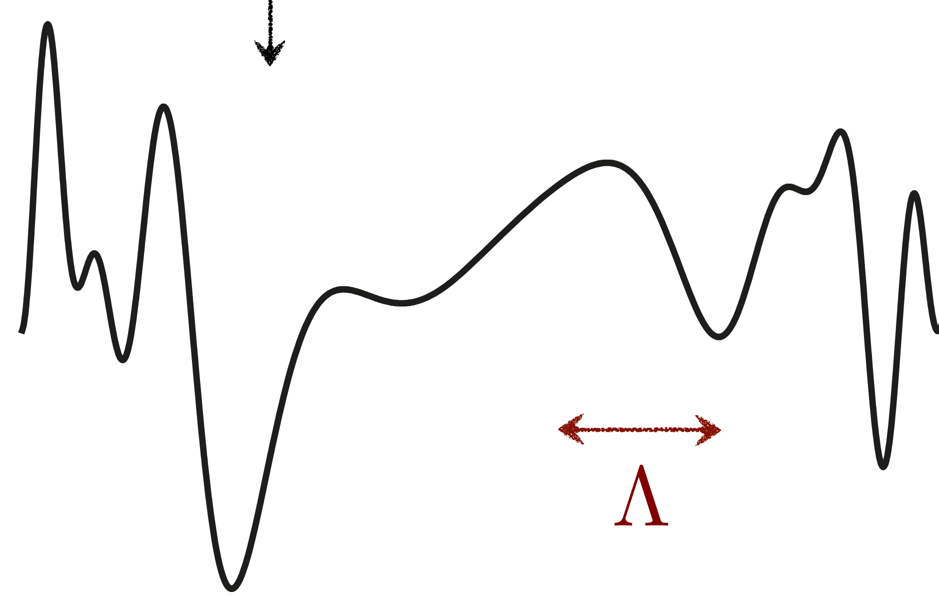
More generally, using T-duality:
Brown, Cottrell, Shiu, PS, ‘15

WGC and inflation

UV sensitivity of large field inflation: $\Delta\phi > M_P$

$$\mathcal{L}_{\text{eff}}[\phi] = \frac{1}{2}(\partial\phi)^2 - \frac{1}{2}m^2\phi^2\left(1 + \sum_{i=1}^{\infty} c_i \frac{\phi^{2i}}{\Lambda^{2i}} + \cdots\right)$$

$c_i \sim \mathcal{O}(1)$



WGC and inflation

- Axions are ideal candidates for large field inflation: protected by a perturbatively exact global symm.

$$\phi \sim \phi + c \quad \Longrightarrow \quad V^{(p)} = 0$$

Natural Inflation:
Freese et. al '90

- Non-perturbative potential

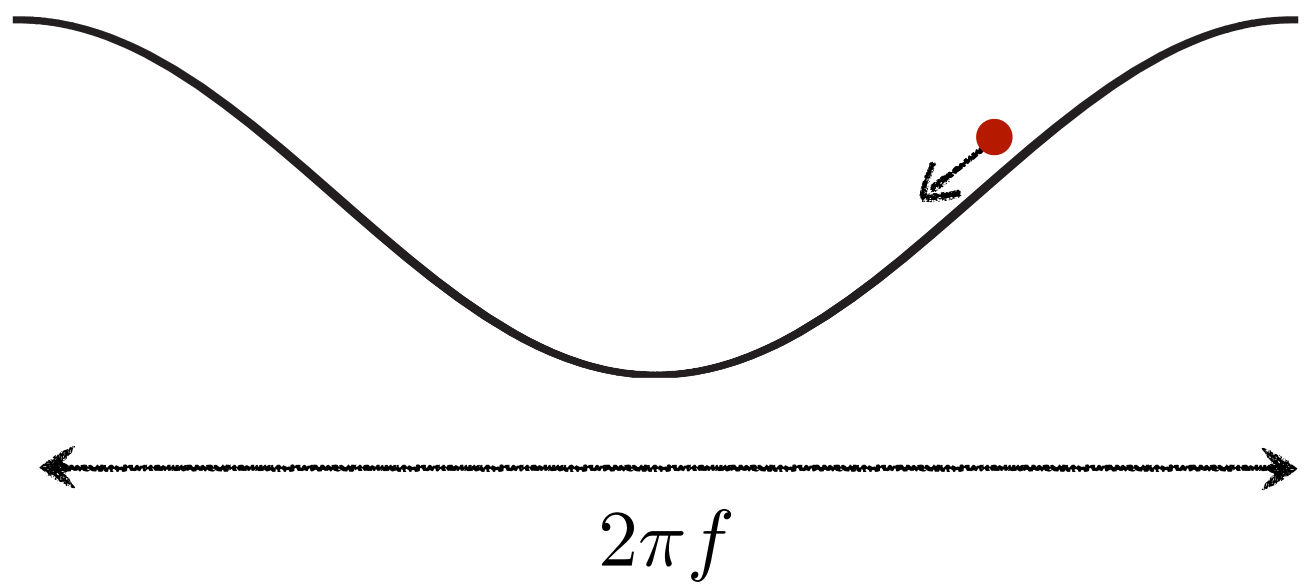
$$V(\phi) = \Lambda^4 \sum_k e^{-kS_{inst}} \left[1 - \cos\left(\frac{k\phi}{f}\right)\right]$$

- Broken shift symmetry: $\phi \sim \phi + c \quad \longrightarrow \quad \phi + 2\pi f$
- $e^{-S_{inst}}$ is expected to be (non-perturbatively) small

WGC and inflation

- Inflation with axions:

$$V(\phi) \propto e^{-S_{inst}} \left[1 - \cos\left(\frac{\phi}{f}\right)\right] + \cancel{\sum_{k>1} e^{-kS_{inst}} \left[1 - \cos\left(\frac{k\phi}{f}\right)\right]}$$



- Simplest natural inflation: slow roll and pert. control

$$f > M_p\,, \quad e^{-S_{inst}} \ll 1 \quad \Longrightarrow \quad \boxed{f \cdot S_{inst} > M_p}$$

WGC and inflation

- Effective models of natural inflation in tension with WGC

Arkani-Hamed et al. ‘06

- Thorough searches for transplanckian axions in the string landscape have not been successful.

Banks et al. ’03 …

- Models with multiple axions (N-flation, KNP-alignment,…) have been proposed to obtain large field ranges
  - The WGC in all direction in charge space (i.e. requiring all extremal black holes to be unstable) constrains these models

Brown, Cottrell, Shiu, PS, ’15…

- Loopholes exist, actively being studied.

- Axion monodromy is a possible alternative not addressed by the WGC. It is subject to other swampland conjectures