Inflation and the Swampland criteria

Chia-Min Lin

National Chin-Yi University of Technology

@ ***NCTS Dark Physics Workshop*** on 1/10

國立勤益科技大學
NCUT
Chinyi Tech

References

Chaotic inflation on the brane and the Swampland Criteria
Chia-Min Lin, Kin-Wang Ng, Kingman Cheung
Phys.Rev.D100(2019) no.2,023545
arXiv:1810.01644

Type I Hilltop Inflation and the Refined Swampland Criteria
Chia-Min Lin
Phys.Rev.D99(2019) no.2,023519
arXiv:1810.11992

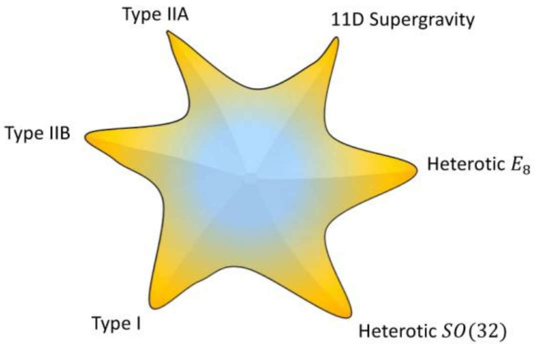
Topological Eternal Hilltop Inflation and the Swampland Criteria
Chia-Min Lin
arXiv:1912.00749

Outline

- What is Swampland (criteria)?
- Motivation?
- Problems?
- Resolution?
- Inflation?
- Eternal inflation
- Conclusion

String theory

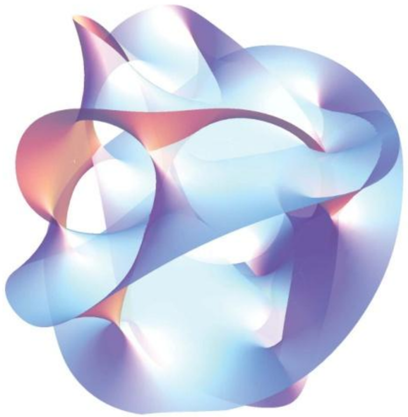
- A candidate of UV completed quantum gravity.
- String theory has no free parameters.
- String theory has no global symmetry.
- De Sitter space is hard to obtain.
- What are the low-energy predictions?



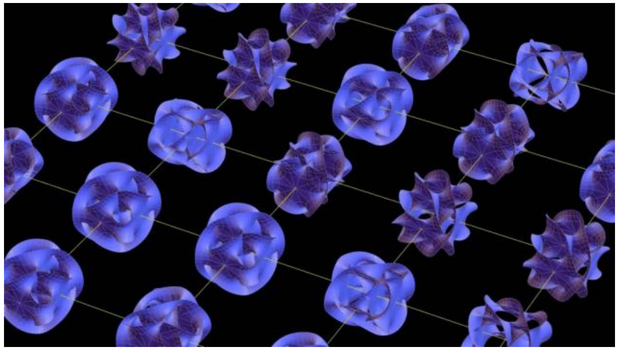
Compactification

- Bosonic string: 26 dimensions
- Superstring: 10 dimensions

Not our world!



$$M_4 \times X$$



Moduli field: deformation of X

4d Minkowski space X Calabi-Yau

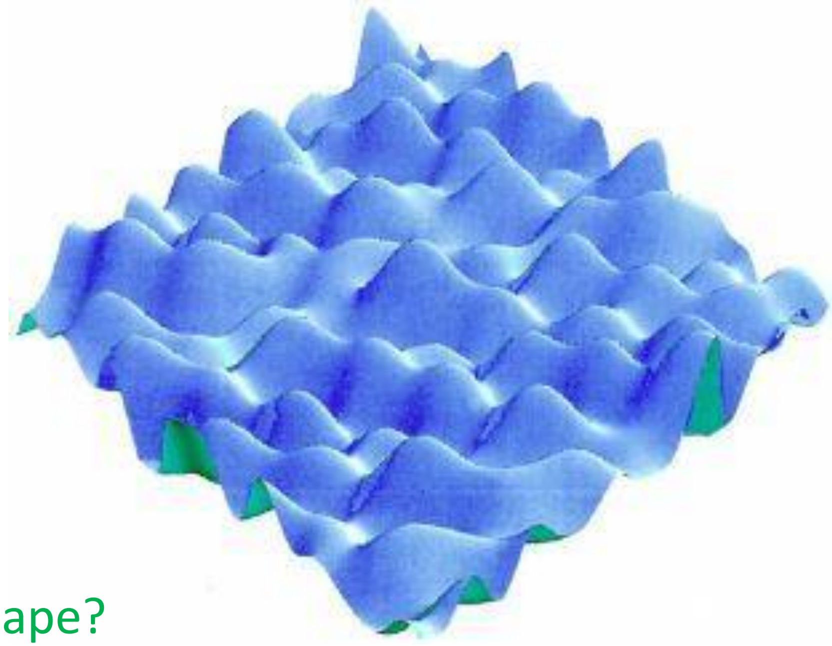
String landscape

- No free parameter but lots of solutions!

$\sim 10^{500}$

$\sim 10^{272000}$

1511.03209 Taylor and Wang



Maybe any EFT can arise from the landscape?
Anything is possible?

Comepare to $$\frac{8.8 \times 10^{28}}{1.6 \times 10^{-33}} = 5.5 \times 10^{61}$$

What is a swampland?

Vafa hep-th/0509212

- Can any (consistent looking) effective field theory be consistent with quantum gravity?
- If yes, what is the use of quantum gravity?
- Most of the EFTs are in the swampland.
- Swampland EFT cannot be UV embedded in quantum gravity.

Motivation

- String theory
- Black hole argument
- Entropy bound
- Holography
- AdS/CFT
- Emergernce proposal

motivate general properties of quantum gravity.

Swampland

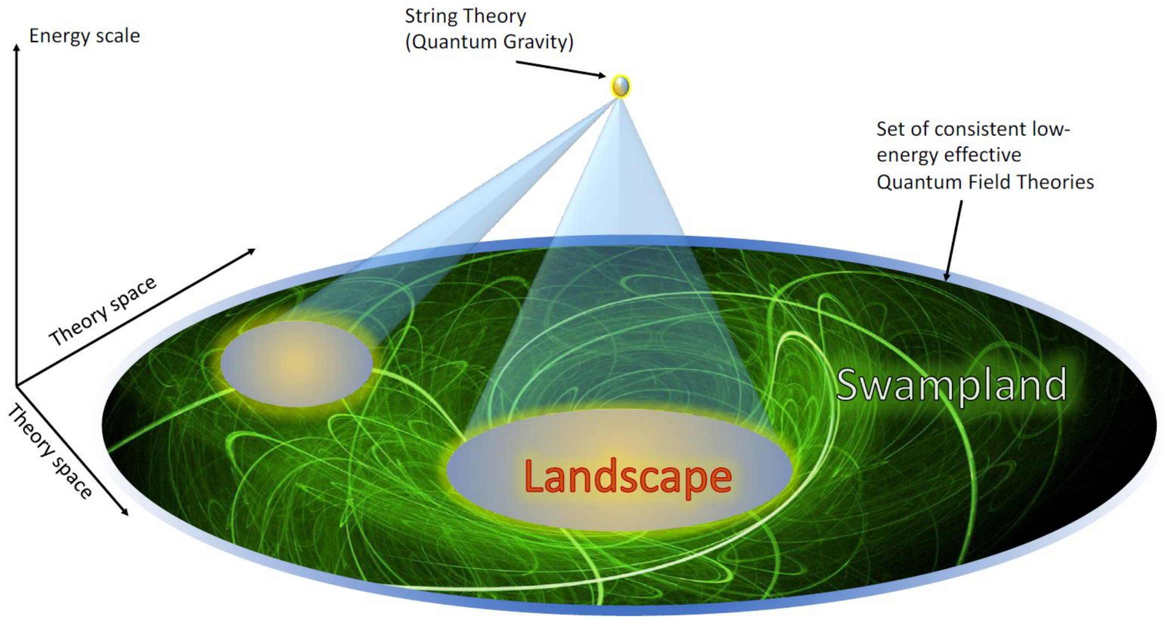


Fig. from 1903.06239

Apparently consistent anomaly-free quantum effective field theories that cannot be UV embedded in quantum gravity.

Swampland Criteria

For a single scalar field

- The distance conjecture

$$\frac{\Delta\phi}{M_P} < O(1)$$

$M_P \to \infty$

Turn off the gravity

- (Refined) de Sitter conjecture

$$M_P \frac{|V'|}{V} > c \sim O(1) \quad \text{or} \quad M_P^2 \frac{V''}{V} < -c' \sim -O(1)$$

Weak gravity conjecture (WGC)

Arkani-Hamed, Motl, Nicolis, Vafa
hep-th/0601001

- Gravity is the weakest force.
- Gauge symmetries vs. Global symmetries

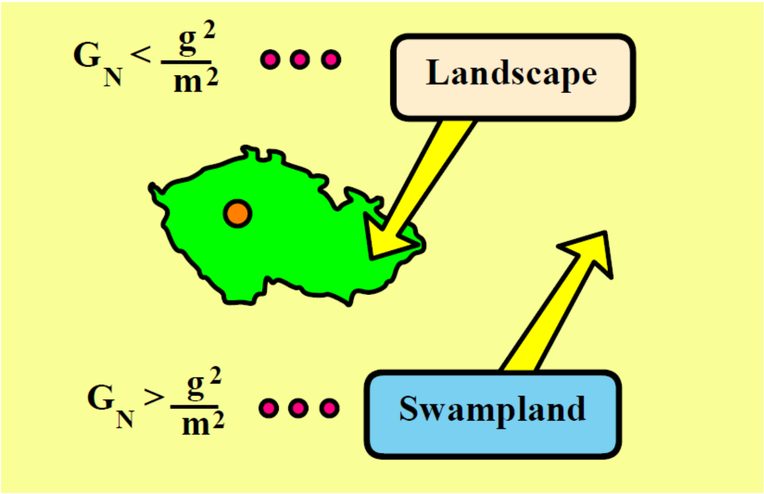
$$F_{Gravity} = \frac{m^2}{8\pi M_P^2 r^2} \qquad F_{EM} = \frac{(gq)^2}{4\pi r^2} \qquad F_{EM} \geq F_{Gravity}$$

$$m \leq \sqrt{2} g q M_P$$

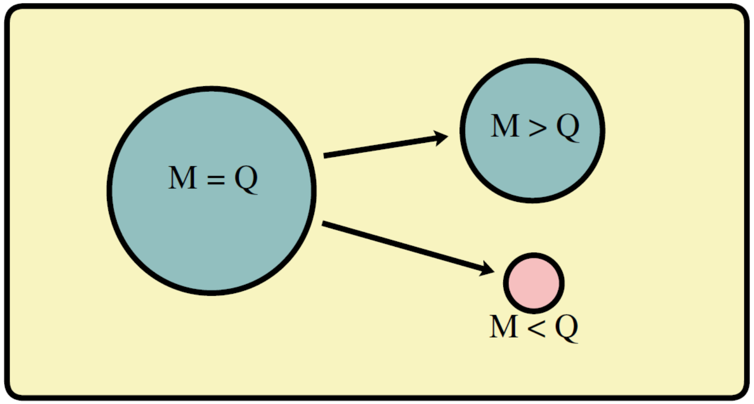
$$m_{mag} \leq \frac{M_P}{g} \qquad m_{mag} \sim \frac{\Lambda}{g^2}$$

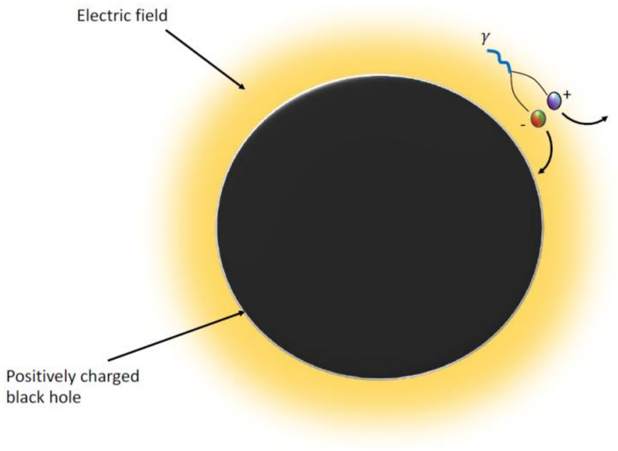
$$\Lambda \leq g M_P$$

A hidden new UV scale



Extremal black hole





There should not exist a large number of exactly stable (extremal) black holes whose stability is not protected by any symmetries.

All black holes should be able to discharge themselves.

Swampland Distance Conjecture

hep-th/0605264 Ooguri and Vafa

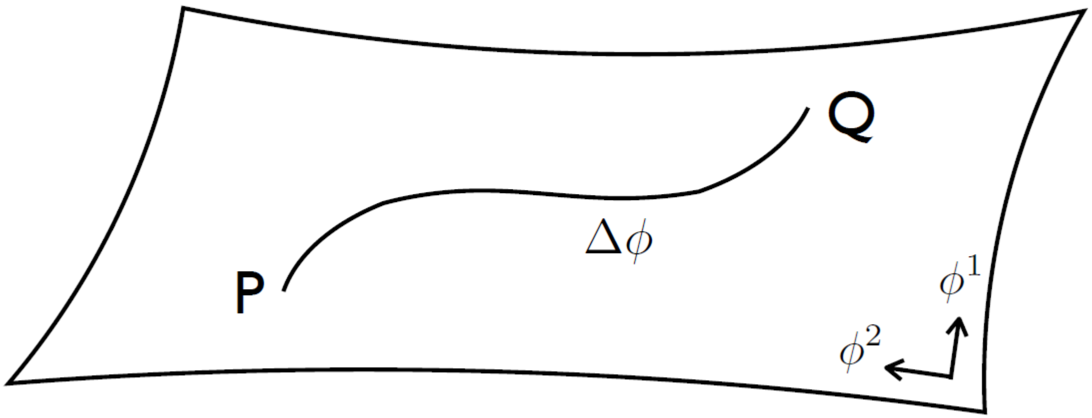
There exists an infinite tower of states with mass scale M such that

$$M(Q) < M(P) e^{-\alpha \frac{d(P,Q)}{M_P}}$$

$$\Lambda_{\text{cut-off}} \sim \Lambda_0 \, \exp(-\lambda \Delta\phi)$$

if

$$d(P,Q) \geq M_P$$

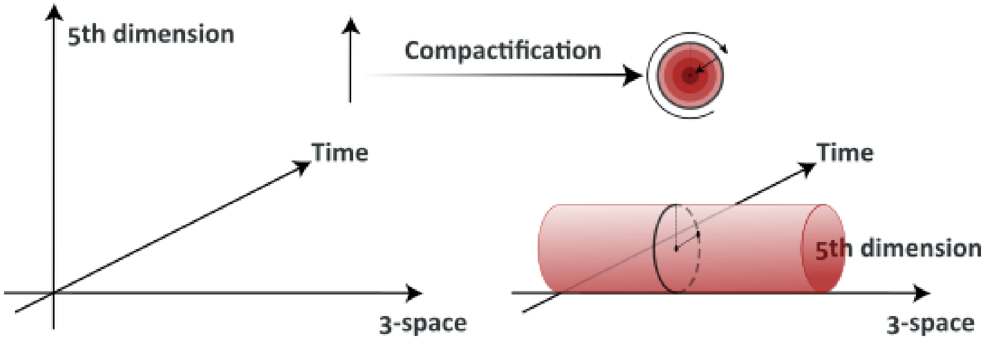


Kaluza-Klein (KK) mode

y compactified in a circle $$y = y + 2\pi R$$

$$\phi(x,y) = \sum_{n=-\infty}^{\infty} e^{iny/R} \phi^{(n)}(x)$$

$$M_{KK}{}^{2} = \left(\frac{n}{R}\right)^{2}$$



String theory: T-duality

$$\left(M_{n,w}^{(s)}\right)^2 = \left(\frac{n}{R}\right)^2 + \left(\frac{wR}{\alpha'}\right)^2$$

$$T \equiv \frac{1}{2\pi\alpha'}$$

$$2\pi RT = \frac{R}{\alpha'}$$

$$R \leftrightarrow \frac{\sqrt{\alpha'}}{R}$$

Variation of a scalar field

$$M_{KK} \sim e^{\alpha\phi}$$

$$M_w \sim e^{-\alpha\phi}$$

$$\alpha = \sqrt{2}\left(\frac{d-1}{d-2}\right)^{\frac{1}{2}} > 0$$

$$D = d + 1$$

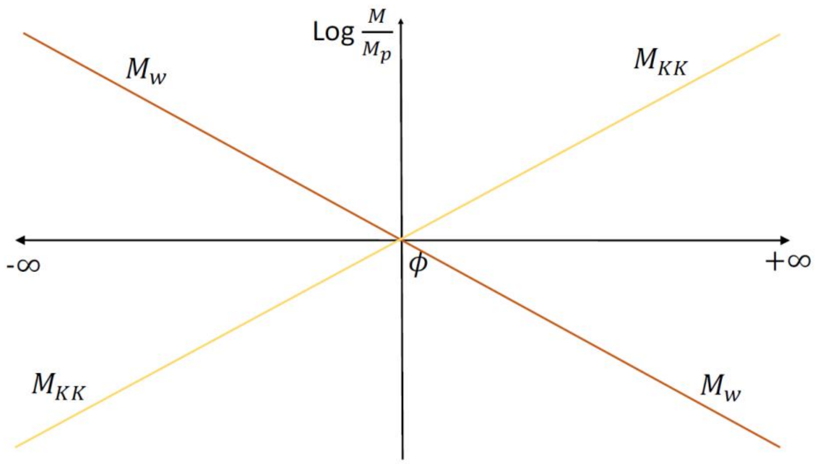


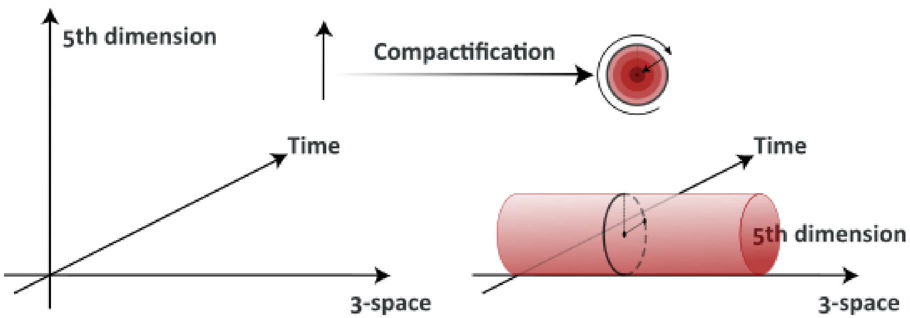
Fig. from 1903.06239

$$M(\phi_i + \Delta\phi) \sim M(\phi_i)e^{-\alpha|\Delta\phi|}$$

Compactification with gauge fields

$$M_{KK} \sim g^{(A)} \sim e^{\alpha\phi}$$

$$M_{w} \sim g_{(V)} \sim e^{-\alpha\phi}$$



$$ds^2 = e^{2\alpha\phi} g_{\mu\nu} dX^{\mu} dX^{\nu} + e^{2\beta\phi}(dX^{d} + A_{\mu} dX^{\mu})^2$$

A_{μ} KK gauge field

$V_{\mu} \equiv B_{[\mu d]}$ From the Kalb-Ramond B-field

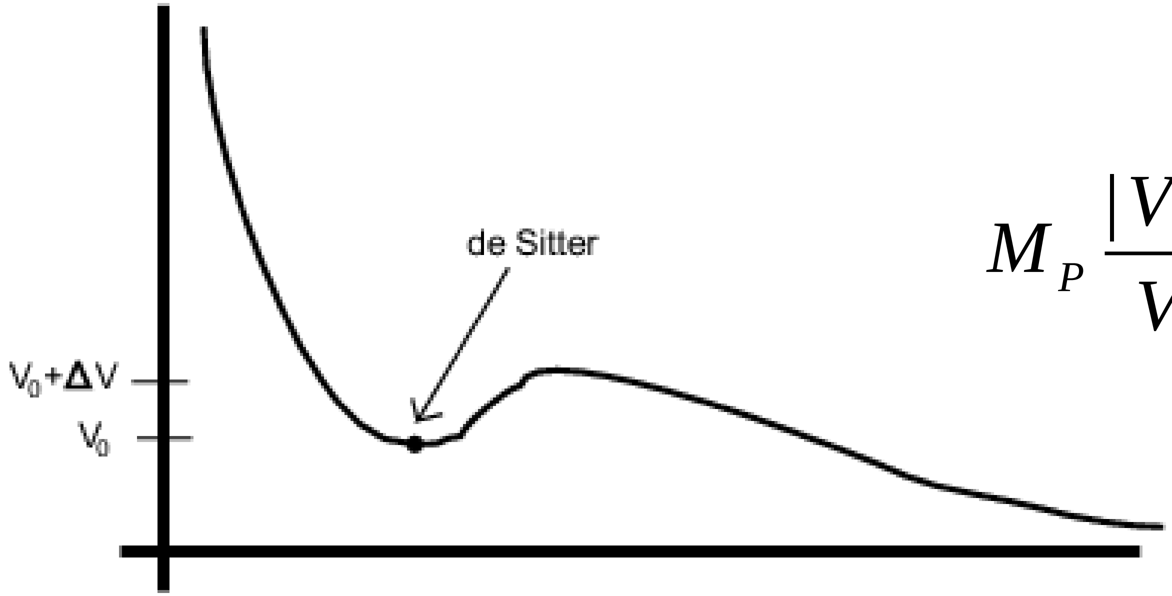
There are connections between swampland conjectures and weak conjecture.

Swampland de Sitter Conjecture

Obied, Ooguri, Spodyneiko, and Vafa 1806.08362

- (meta-)stable de Sitter vacuum belongs to the swampland.

(Original version)

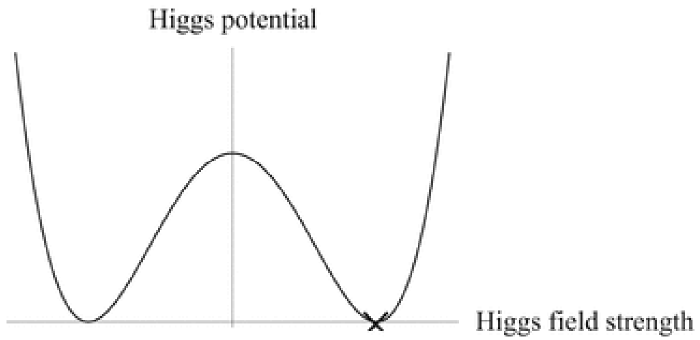


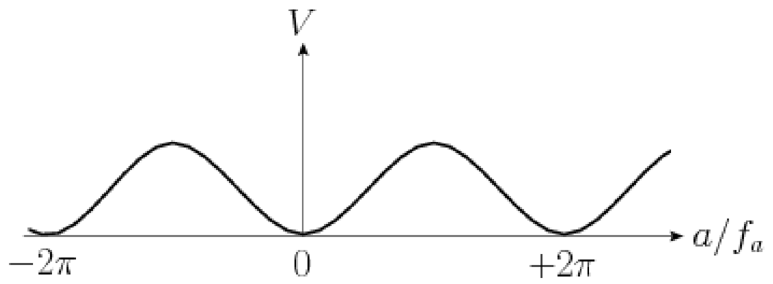
$$M_P \frac{|V'|}{V} > c \sim O(1)$$

What is the problem?

- Higgs
- QCD axion
- Cosmological constant
- (metastable) De Sitter vacua
- Hilltop Inflation

All in the swampland?



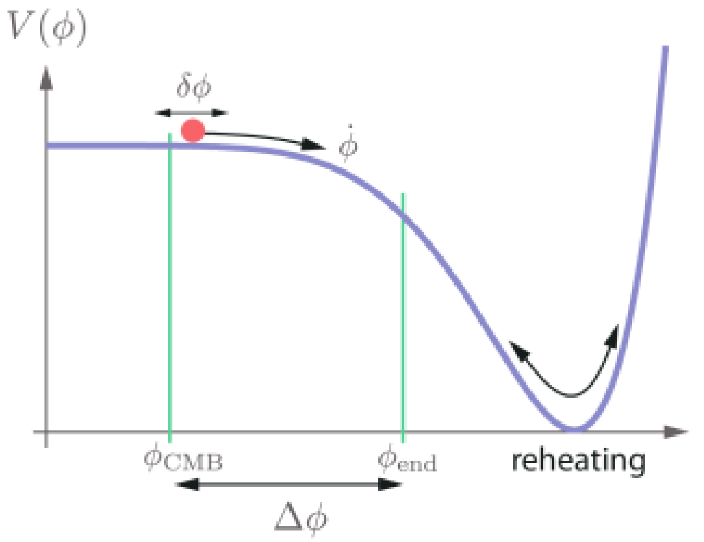


Inflation

$$\ddot{\phi} + 3H\dot{\phi} + V' = 0$$

Slow-roll parameters:

$$\varepsilon \equiv \frac{1}{2} M_P^2 \left(\frac{V'}{V} \right)^2 \qquad \eta \equiv M_P^2 \frac{V''}{V}$$

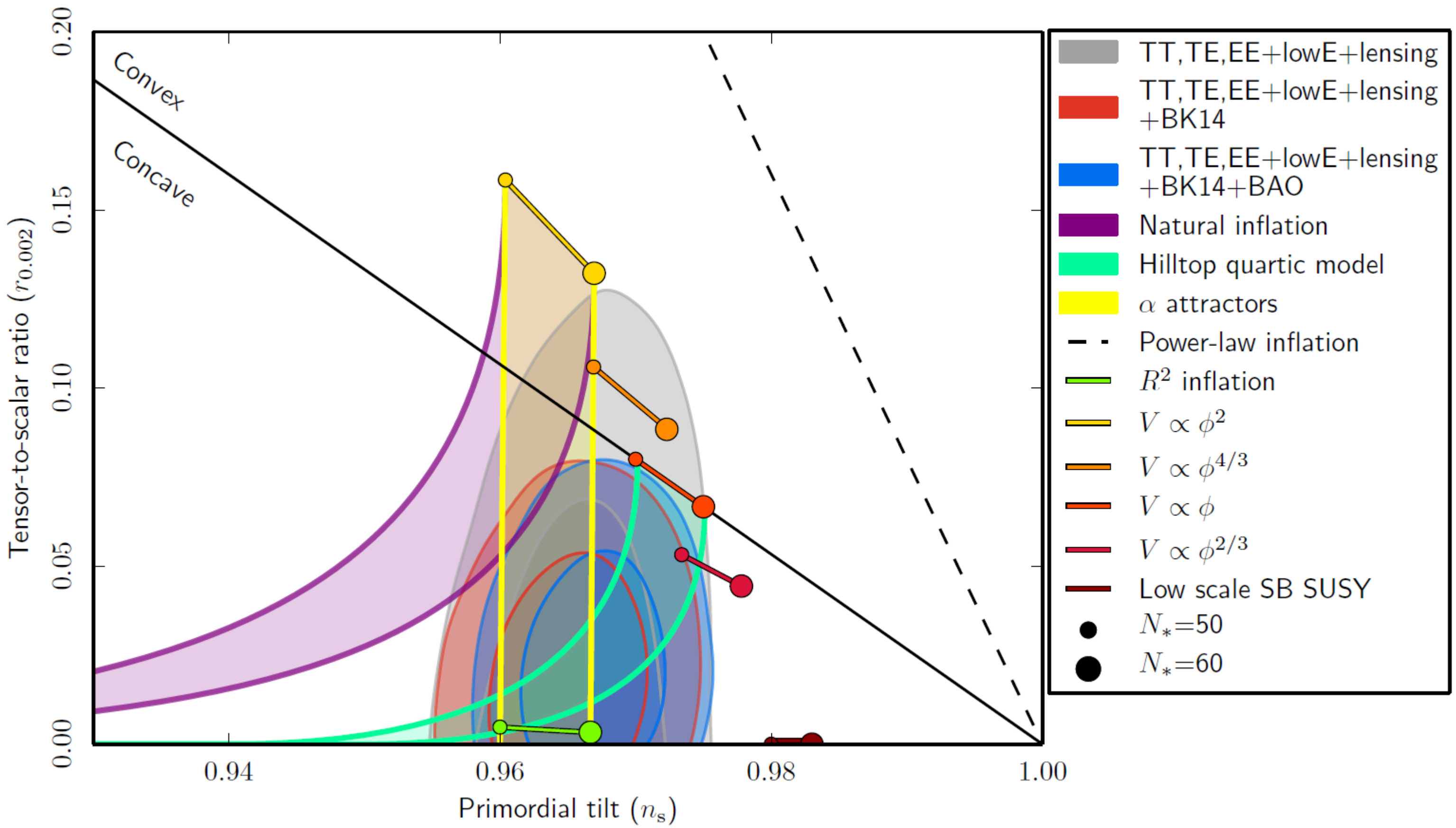


$$n_s = 1 - 6\varepsilon + 2\eta$$

$$r = 16\varepsilon$$

PLANCK 2018

1807.06211

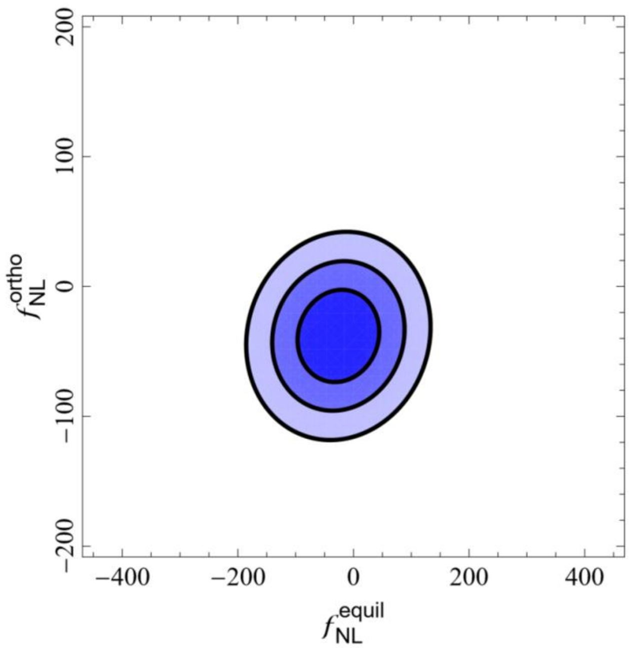


Primordial non-Gaussianity?

PLANCK 2018 1905.05697

$$f_{NL}^{local} = -0.9 \pm 5.1$$

…do not detect any significant signals.



Our stringent tests of many types of non-Gaussianity are fully consistent with expectations from the standard single-field slow-roll paradigm and provide strong constraints on alternative scenarios.

Inflation is in the swampland?

$$N = \frac{1}{M_P^2}\int \frac{V}{V'} d\phi \simeq \frac{\frac{\Delta\phi}{M_P}}{M_P \frac{V'}{V}}$$

Inflation does not happen?

$$\frac{\Delta\phi}{M_P} < O(1)$$

$$M_P \frac{|V'|}{V} > c \sim O(1)$$

Tensor to scalar ratio

$$\epsilon = \frac{1}{2}\left(\frac{V'}{V}\right)^2 = \frac{1}{2}c^2$$

$$M_P \frac{|V'|}{V} > c \sim \mathcal{O}(1)$$

$$r = 16\epsilon = 8c^2 \lesssim 0.06$$

$$c \lesssim 0.087$$

Too big?

Literatures

- A note on Inflation and the Swampland (1807.05445), Kehagias and Riotto
- The string swampland constraints require multi-field inflation (1807.04390), Achucarro and Palma
- A note on Single-field Inflation and the Swampland Criteria (1809.03962), Das
- Avoiding the string swampland in single-field inflation: Excited initial states (1809.01277) (Brahma and Hossain)
- The Zoo Plot Meets the Swampland: Mutual (In)Consistency of Single-Field Inflation, String Conjectures, and Cosmological Data (1808.06424), Kinney, Vagnozzi, and Visinelli

Here, we show that the swampland conjectures are inconsistent with existing observational constraints on single-field inflation. … Extension to non-canonical models such as DBI Inflation does not significantly weaken the bound.

Brane world cosmology

A motivation: heterotic M theory, 11D SUGRA compactified on S_1/Z_2

Inflation on the brane

$$H^2 = \frac{1}{3M_P}\rho\left[1+\frac{\rho}{2\Lambda}\right],$$

Maartens, Wands, Bassett, and Heard
hep-ph/9912464

$$M_4 = \sqrt{\frac{3}{4\pi}}\left(\frac{M_5^2}{\sqrt{\Lambda}}\right)M_5,$$

At high energies, Hubble expansion is faster.

$$\epsilon \equiv \frac{1}{2}\left(\frac{V'}{V}\right)^2 \frac{1}{\left(1+\frac{V}{2\Lambda}\right)^2}\left(1+\frac{V}{\Lambda}\right),$$

$$\eta \equiv \left(\frac{V''}{V}\right)\left(\frac{1}{1+\frac{V}{2\Lambda}}\right).$$

$$\Lambda \gtrsim 5.0 \times 10^{-53}$$

3-brane tension

Inflation on the brane

$$N = \int_{\phi_e}^{\phi_i} \left(\frac{V}{V'}\right)\left(1 + \frac{V}{2\Lambda}\right) d\phi.$$

$$P_R = \frac{1}{12\pi^2}\frac{V^3}{V'^2}\left(1 + \frac{V}{2\Lambda}\right)^3.$$

$$n_s = 1 + 2\eta - 6\epsilon.$$

$$\alpha = \frac{dn_s}{d\ln k} = -\frac{dn_s}{dN}.$$

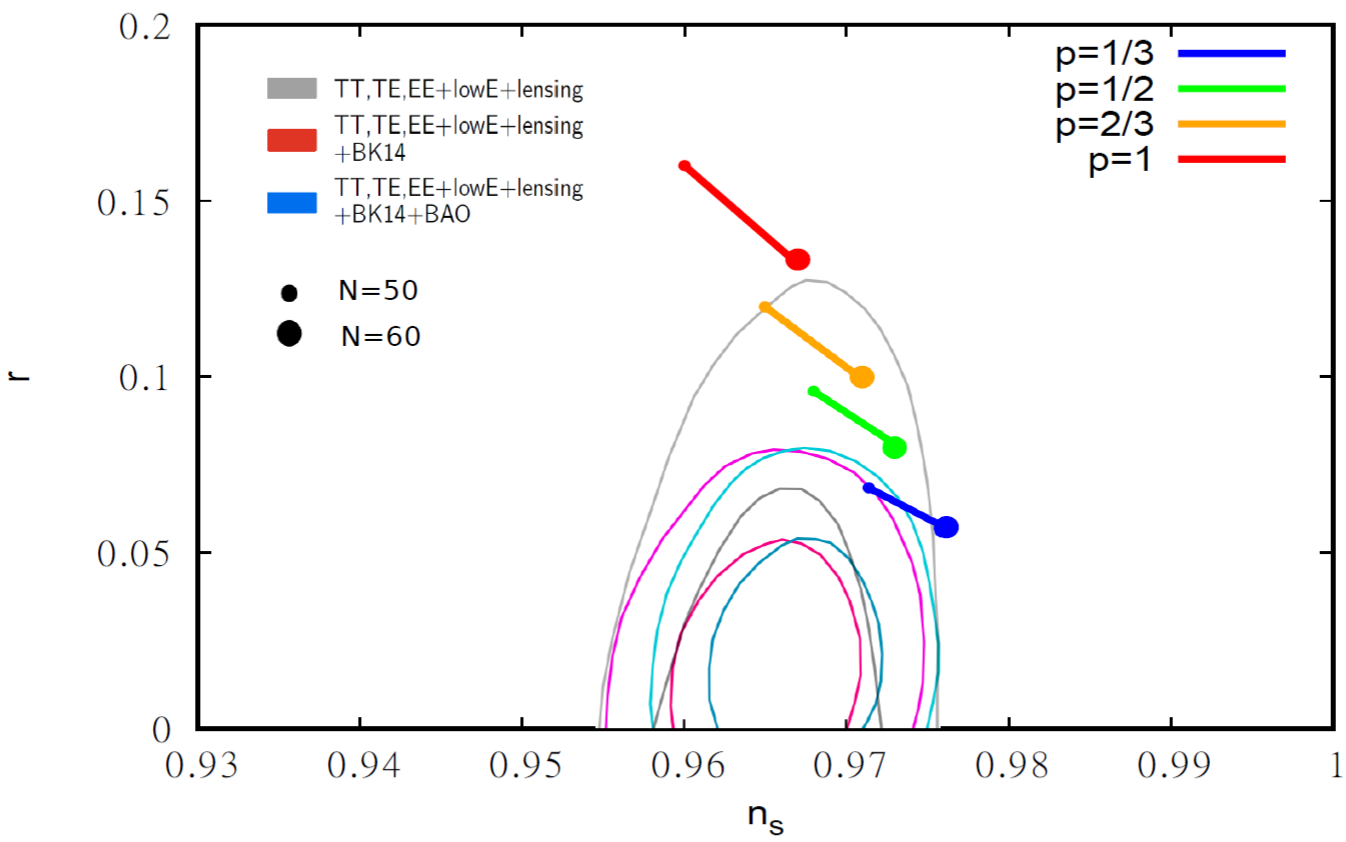
Chaotic inflation on the brane

$$V = a\phi^p.$$

$$V/\Lambda \gg 1$$

High energy limit.

Predictions



Refined de Sitter conjecture

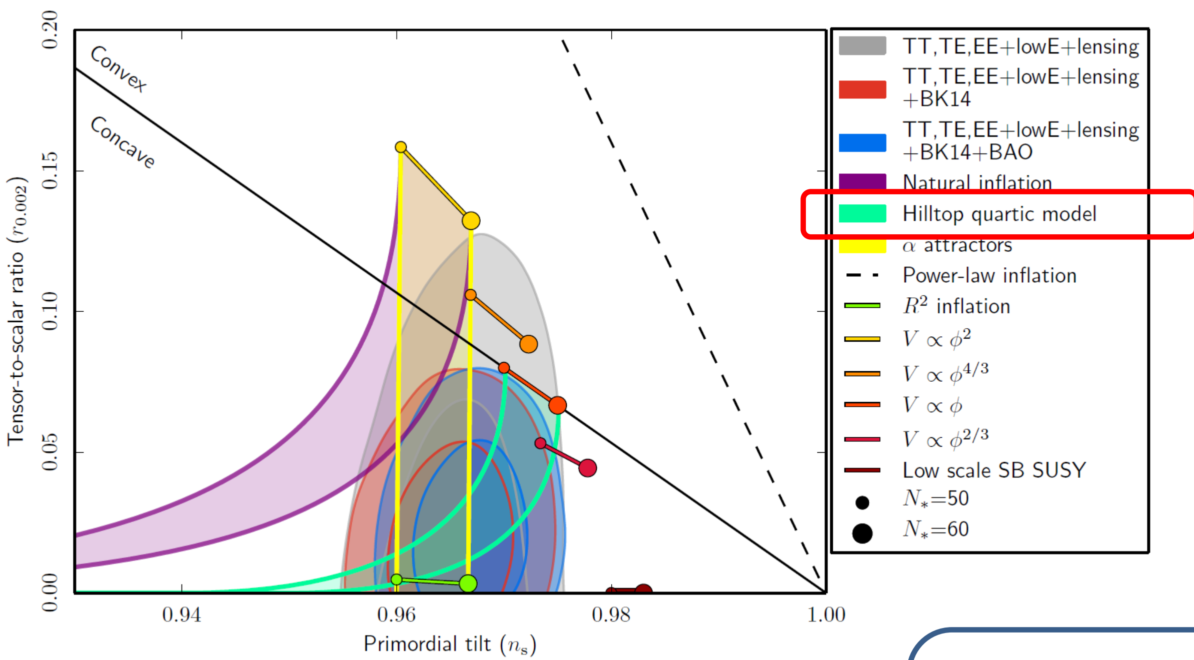
Ooguri, Palti, Shiu, Vafa 1810.05506

Garg, Krishnan 1807.05193

$$M_P \frac{|V'|}{V} > c \sim O(1) \quad \text{or} \quad M_P^2 \frac{V''}{V} < -c' \sim -O(1)$$

⇒ Higgs (and perhaps hilltop inflation) can satisfy it.

Hilltop quartic model?



$$V = V_0 - \lambda \phi^4$$

$$V'(\phi = 0) = V''(\phi = 0) = 0$$

It is in the swampland.

Type I Hilltop inflation

$$V(\phi) = V_0 - \frac{1}{2}m^2\phi^2 - \lambda\frac{\phi^p}{M_P^{p-4}} \equiv V_0\left(1+\frac{1}{2}\eta_0\frac{\phi^2}{M_P^2}\right) - \lambda\frac{\phi^p}{M_P^{p-4}},$$

$$\eta_0 \equiv -\frac{m^2 M_P^2}{V_0}.$$

$$P_\zeta = \frac{1}{12\pi^2}\left(\frac{V_0}{M_P^4}\right)^{\frac{p-4}{p-2}} e^{-2\eta_0 N}\frac{\left[p\lambda(e^{(p-2)\eta_0 N}-1)+\eta_0 x\right]^{\frac{2p-2}{p-2}}}{\eta_0^{\frac{2p-2}{p-2}}(\eta_0 x - p\lambda)^2}$$

$$n_s - 1 = 2\eta = 2\eta_0\left[1 - \frac{\lambda p(p-1)e^{(p-2)\eta_0 N}}{\eta_0 x + p\lambda(e^{(p-2)\eta_0 N}-1)}\right]$$

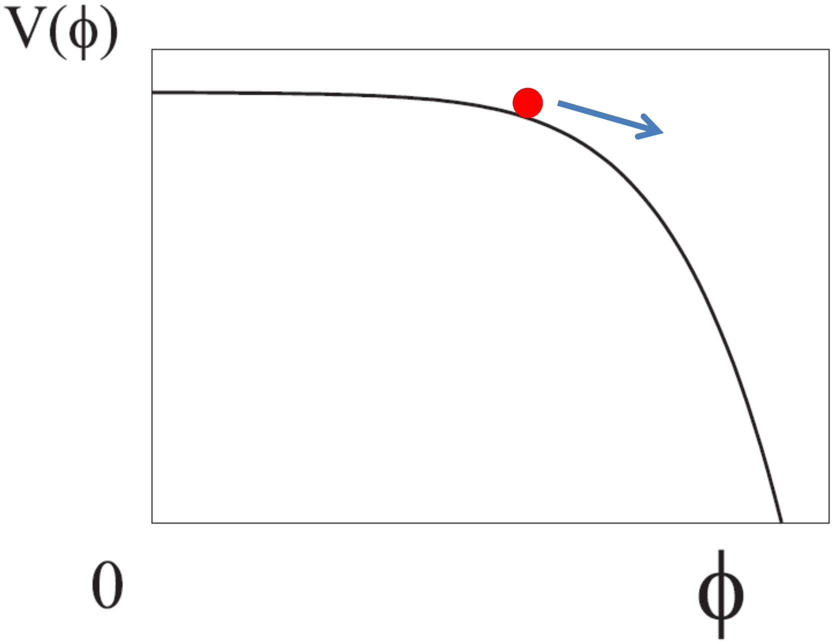
$$\alpha = 2\eta_0^2\lambda p(p-1)(p-2)\frac{e^{(p-2)\eta_0 N}(\eta_0 x - p\lambda)}{\left[\eta_0 x + p\lambda(e^{(p-2)\eta_0 N}-1)\right]^2}.$$

Hilltop inflation

$$\frac{\Delta\phi}{M_P} < O(1)$$

$$M_P^2 \frac{V''}{V} < -c' \sim -O(1)$$

$$M_P^2 \frac{V''}{V} \sim -O(10^{-2})$$



Fine-tuning?

Hilltop inflation on the brane

$$\varepsilon = \frac{M_P^2}{2}\left(\frac{V'}{V_0}\right)^2 \frac{1}{\left(\frac{V_0}{4\Lambda}\right)}$$

$$\frac{V_0}{\Lambda} \gg 1$$

$$\Lambda = 6\pi \frac{M_5^6}{M_P^2}$$

$$\eta = M_P^2 \left(\frac{V''}{V_0}\right) \frac{1}{\left(\frac{V_0}{2\Lambda}\right)}$$

$$H^2 = \frac{V}{3M_P^2}\left(1 + \frac{V}{2\Lambda}\right)$$

$$\ddot{\phi} + \boxed{3H\dot{\phi}} + V' = 0$$

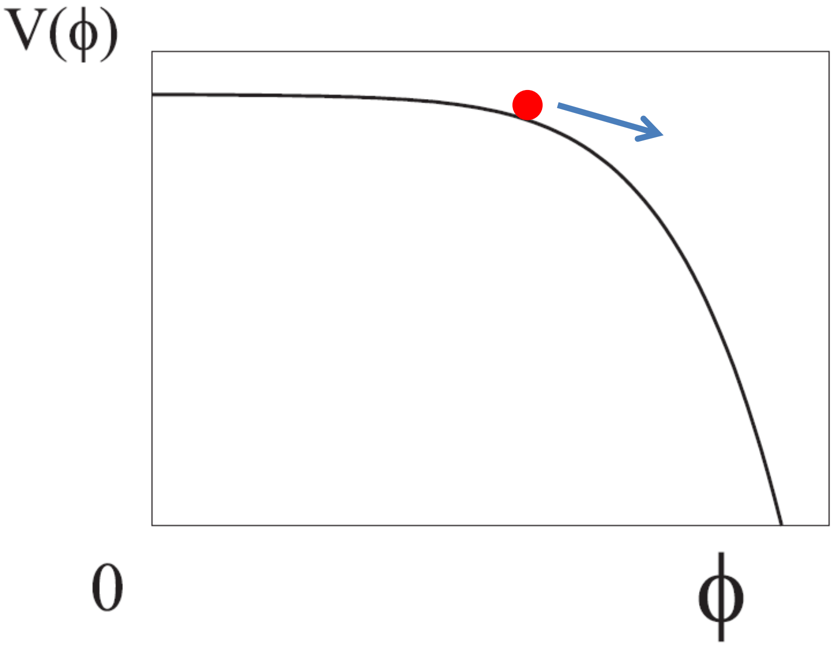
Friction is enhanced.

Swampland conjectures can be satisfied.

Eternal inflation

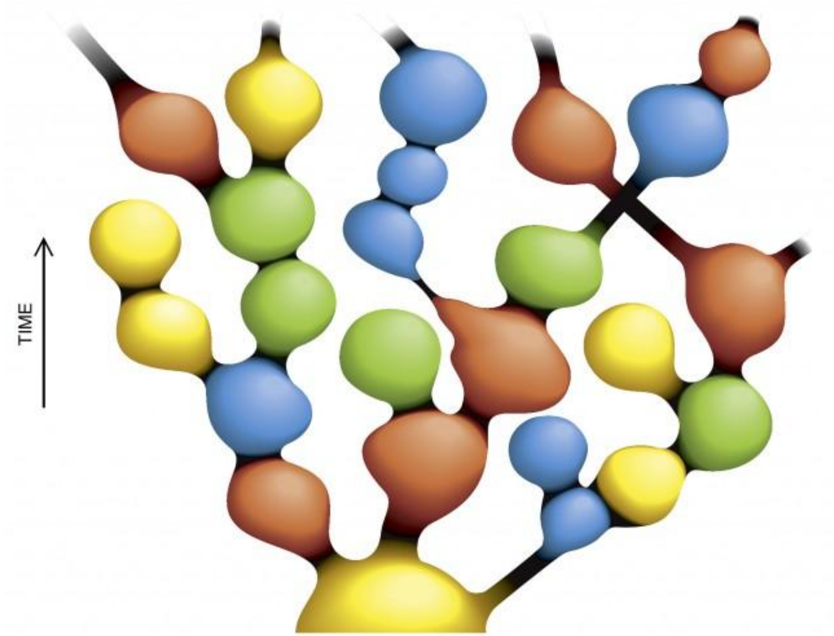
- Old eternal inflation
- Stochastic eternal inflation
- Topological eternal inflation
- Other possibilities?

Stochastic eternal inflation



$$\delta\phi \sim \frac{H}{2\pi}$$

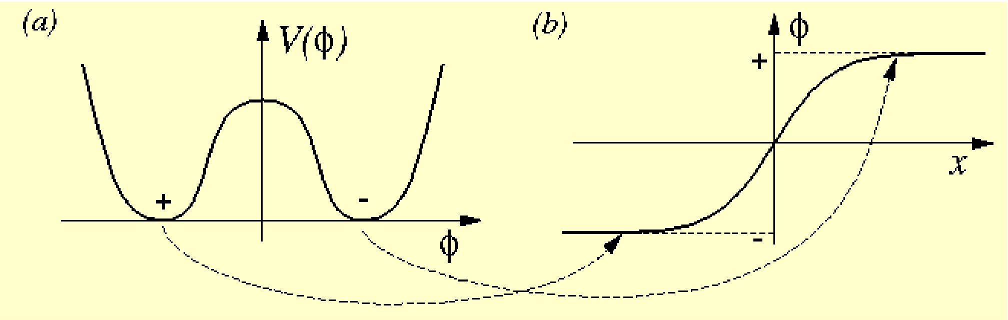
Eternal inflation



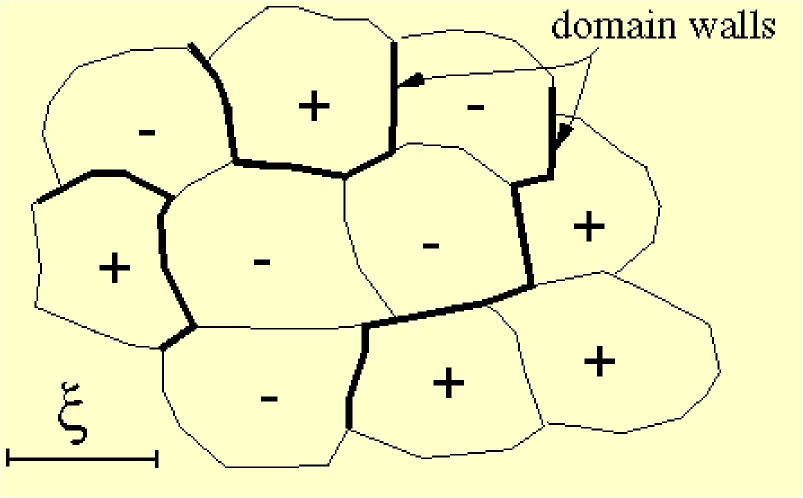
Is eternal inflation in the swampland?

- Matsui & Takahashi 1807.11938
- Dimopoulos 1810.03438
- Kinney 1811.11698
- Brahma & Shandera 1904.10979
- Wang & Brandenberger & Heisenberg 1907.08943
- Ridelius 1905.05198
- Blanco-Pillado & Deng & Vilenkin 1909.00068

Kibble mechanism



$$V(\phi)=\frac{1}{4}\kappa(\phi^2-M^2)^2$$



Kibble mechanism

Topological eternal inflation

$$V(\phi) = \frac{1}{4}\kappa(\phi^2 - M^2)^2$$

$$\delta > \frac{1}{H}$$

$$M \geq M_P$$

This contradicts the distance conjecture:

$$\frac{\Delta\phi}{M_P} < O(1)$$

Topological eternal inflation on the brane

$$M > M_P \sqrt{\frac{6\Lambda}{V_0}} \qquad \frac{V_0}{\Lambda} \gg 1$$

This can satisfy the distance conjecture:

$$\frac{\Delta\phi}{M_P} < O(1)$$

Conclusion

- Chaotic inflation on the brane can satisfy the swampland criteria.
- Hilltop inflation on the brane can satisfy the swampland criteria.
- Topological eternal inflation on the brane can satisfy the swampland criteria.