Swampland Conjectures

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Swampland: recently very popular

1. Distance and de Sitter Conjectures on the Swampland
   DOI: 10.1016/j.physletb.2018.11.018
   References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
   ADS Abstract Service; Link to Article from SCOAP3
   Detailed record - Cited by 138 records 100+

2. De Sitter Space and the Swampland
   CALT-TH-2018-020, IPMU18-0100
   References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
   ADS Abstract Service
   Detailed record - Cited by 245 records 100+
But not just fashion!
Fundamental questions/ideas on QG
But not just fashion!

Fundamental questions/ideas

on QG

... and **our** Universe

myself: ____________________________

**phenomenological constraints/implications**

on **swampland conjectures**
"Pheno/String Collaboration"

村山 - 柳田 - MY 1809.00478
福田 - 齋藤 - 白井 - MY 1810.06532
伊部 - 柳田 - MY 1811.04664
MY 1904.053576 ← Moriond proceeding
白井 - MY 1904.10577

4.5 pages + ref.
Why Swampland?
effective QFT ⇄ experiment

???
Effective QFT $\leftrightarrow$ Experiment

EFT
Quantum Gravity ⟷ effective QFT ⟷ experiment

$\cong$ UV completion

EFT

M/$G_2$, F/$CY_4$, Het/$CY_3$
Quantum Gravity

$\equiv$ UV completion

Effective QFT

Experiment

Swampland [Vafa '05
Ooguri - Vafa '06]

String/QFT
Landscape

EFT

M/G_2

F/CT^3

Het/CY_j
To recap:

given a low-energy EFT

Swampland Conjectures:

Necessary (but NOT sufficient) condition for existence of UV completion in QG (such as string theory)

attempts towards universal prediction from QG
Of course, QG is notoriously difficult
Of course, QG is notoriously difficult.

Clue:
- String theory
- (Semiclassical) GR
- e.g. Black Hole (entropy, Hawking radiation)
- many examples/data duality, AdS/CFT, ...
- precise mathematical checks

Phenomenology
Points to keep in mind

* Gravity is **very crucial** (Mpe finite)

* Often refer to higher-dim. non-renormalizable operators

* All swampland conjectures: conjectures/hypothesis
Points to keep in mind

* Some solid, some speculative

* Combination/Consistency of conjectures crucial

* Some conjectures might not hold generally, but could still be useful
Swampland Conjectures

: Examples
Many conjectures on the market

[review: Brennan, Costa, Vafa '17]

Palti '19

today’s focus:

no global sym.

Weak gravity conj. ← distance conj.

de Sitter conjecture
「No Global Symmetry」

many many works

Misner - Wheeler '57
Polchinski '03
Banks - Seiberg '10
Horkow - Ooguri '18
No exact global sym. in QG

Argument: Consider $U(1)$ global sym.

$\exists$ a state w/ charge $g \gg 1$
No exact global sym. in QG

Argument: Consider $U(1)$ global sym.

$\exists$ a state w/ charge $g \gg 1$
There is no exact global sym. in QG.

**Argument:** Consider $U(1)$ global sym.

$\exists$ a state w/ charge $q \gg 1$

$\Rightarrow$ BH $\Rightarrow$ BH + $\tilde{q}$
Theorem: No exact global sym. in $QG$

Argument: Consider $U(1)$ global sym.

$\exists$ a state w/ charge $g \gg 1$

$BH \Rightarrow BH + g \Rightarrow m \sim \gamma$

$m \text{ indep. of } g$
No exact global sym. in $AG$.

Argument: Consider $U(1)$ global sym.

$\exists$ a state w/ charge $q \gg 1$

$g$ should be in BH

but $S_{BH}$ finite $\Rightarrow$ contradiction for $g$ very large
No exact global sym. in QG

e.g. $U(1)_{B-L}$ in SM must be broken by higher-dim. operator e.g. $\frac{\mathbf{888}}{\mathbf{888}} e^{\Lambda^2}$

no constraint (if $\neq 0$)
No exact global sym. in AG

e.g. $U(1)_{B-L}$ in SM must be broken by higher-dim. operator e.g. $\frac{\Lambda^2}{\Lambda^2}$

no constraint (if $\neq 0$)

* approximate global sym. $\Rightarrow$ OK
exact gauge sym.

global sym. $= \infty$ fine-tuning. No free lunch!
No exact global sym. in AQ}

* BH argument does not apply to discrete sym. (such as $\mathbb{Z}_2$)
  but holography argument does

  [Harlow-Ooguri 18]

* even applies to p-form sym.

  [Cordova-Ohmori-Rudelius]
Weak Gravity Conjecture

[Arkani-Hamed, Motl, Nicolis, Vafa '06]
Global Sym.

e \rightarrow 0

NOT ALLOWED
Gauge Sym. $\rightarrow$ Global Sym.

$e : \text{finite limit} \quad e \rightarrow 0$

ALLOWED \hspace{2cm} NOT ALLOWED

Q: Can we choose $e$ to be arbitrary small?
WGC:

\[ \exists a \text{ particle w/ charge } g \]

mass \( m \)

s.t.

\[ e \beta \geq \sqrt{2} \frac{m}{M_{pe}} \]
existence of a particle with charge $q$ and mass $m$ such that:

$$ e \geq \sqrt{2} \frac{m}{M_{pe}} $$

"Gravity as weakest force"

$$ F_{\text{gauge}} = \frac{(e \delta)^2}{4\pi r^2} > F_{\text{gravity}} = \frac{m^2}{8\pi M_{pe}^2} $$
WGC:

\[ \exists a \text{ particle} \left\langle \text{state} \right. \wedge \text{charge } q \wedge \text{mass } m \]

\[ \uparrow \text{can be BH (extremal BH + higher curvature correction)} \]

[\text{Kats- Motl- Padi '06, ...}]

s.t.

\[ e q \geq \sqrt{2} \frac{m}{M_{\text{Pl}}} \]
* original argument: decay of extremal BH
  [AMNV '06]

* checks in string theory compactifications

* many subsequent works, e.g.
  connection with
  
  cosmic censorship [Crisford-Horowitz - Sontos '17]
  holography [e.g. Nakayama-Nomura '15, Montero '19]
(Roughly Speaking)

\( \exists \infty \text{-} \text{many charges } q_1, q_2, \ldots \text{ s.t.,} \)

\( \exists \text{ a particle w/ charge } q_i \)
\( \text{mass } m_i \)

\( \text{s.t. } \left( e q_i \geq \sqrt{2} \frac{m_i}{M_{pe}} \right) \text{ for } \forall i \)
Distance Conjecture

Ooguri-Vafa '06
Baume-Palti '16
Distance Conjecture

Example of global sym. i

shift sym. \( \phi \rightarrow \phi + c \).

[ e.g. many moduli in SUSY ]

can we quantify RG-breaking of

shift sym?
Distance Conjecture

Example of global sym. i
  shift sym. $\phi \rightarrow \phi + c.$
  [e.g., many moduli in SUSY]

Can we quantify RG-breaking of
  shift sym? (cf. monodromy infl.,
  relaxation)

Claim: $\Delta \phi \lesssim \Theta(1) \, M_{\text{Pl}}$
Distance Conjecture

$\Delta \phi$

Field range $\Delta \phi \text{ large}$
Distance Conjecture

$\Delta \phi$

field range $\Delta \phi$ large

$\Rightarrow$ an infinite tower of massless states

$m_n \sim n M_{Pl} e^{-\Theta(1) \frac{\Delta \phi}{M_{Pl}}} \ (n=1,2,...)$
Distance Conjecture

Field range $\Delta \phi$ large

$\Rightarrow$ an infinite tower of massless states

$$m_n \sim n M_{\text{Pl}} e^{-\Theta(1) \frac{\Delta \phi}{M_{\text{Pl}}}} \quad (n=1,2,\ldots)$$

$\Rightarrow$ breakdown of EFT at $\Delta \phi \sim M_{\text{Pl}}$
e.g.: Compactify on $S^1$ with size $R$

Can we take $R \to \infty$?

$ds^2 = \left(\frac{dR}{R}\right)^2$

$R \to \infty$
e.g.: Compactify on $S^1$ with size $R$.

Can we take $R \to \infty$? 

\[ ds^2 = \left( \frac{dR}{R} \right)^2 \]

$R \to \infty$

Answer: $R \to \infty$ then KK modes light:

\[ m_n \sim \frac{n}{R} \to 0 \]
e.g.: Compactify on $S^1$ with size $R$

Can we take $R \to \infty$?

$$ds^2 = \left(\frac{dR}{R}\right)^2 = dt^2$$

$$R \to \infty$$

$$R = e^{-t}$$

Answer: $R \to \infty$ then KK modes light:

$$m_n \sim \frac{n}{R} = n e^{-t} \to 0$$
e.g.: Compactify on $S^1$ with size $R$ \\
Can we take $R \to \infty$? \\

\[
\text{Answer: } R \to \infty \text{ then KK modes light:}
\]

\[
m_n \sim \frac{n}{R} = n e^{-r} \to 0
\]

(\*: $R \to 0$ : winding strings become light)
Distance Conjecture is originally string-motivated related with Weak Gravity Conjecture Tower originally gravity-motivated

\[ m_n \leq n M_{\text{Pl}} e^{-\theta(1) \Delta \phi} \]

\( (\text{lattice WGC}) \quad \left( \text{w/ } q_n = n \right) \quad \varepsilon_n \sim e^{	heta(1) \Delta \phi} \)

(gauge coupling: VEV of \( \phi \))
today's focus:

No global sym.

Weak gravity conj.  distance conj.

de Sitter conjecture
de Sitter Swampland Conjecture
de Sitter swampland conjecture
[Obied-Ooguri-Sprüngebloek-Vafa (18)]

\[ M_{\text{Pl}} |D\mathcal{V}| \geq c \mathcal{V} \]
Example: de Sitter swampland conjecture

[Obied - Ooguri - Podyneiko - Vafa (18)]

\[ M_{\text{pl}} \sqrt{\sum_{i,j} g_{ij} \partial_i V \partial_j V} \geq \frac{c}{\Theta(1)} \text{ positive constant} \]
* dS vacua excluded \((D V = 0, \ V > 0)\)

* no constraint for \(V < 0\)

\[
\text{(many known (SUSY) AdS vacua in)}
\]
\[
\text{String theory)}
\]
Idea: e.g. 11-D SUGRA

\[ L \sim \int \sqrt{g} \left( R + |G_4|^2 \right) + \ldots \]

\( g_{\mu\nu} \) (metric)

\( C_3 \) (\( dC_3 = G_4 \))

3-form
Idea: e.g. 11D SUGRA

\[ L \sim \int \sqrt{-g} \left( R + |G_4|^2 \right) + \ldots \]

\[ \eta_{\mu
u} \quad \eta^{\mu
u} \]

metric \quad 3-form

compactify on manifold \( X \) w/ overall modulus \( Z \)

\[ ds_{11}^2 = ds_9^2 + e^{2\varphi} ds_{11-d}^2 \]
Idea: e.g. 11D SUGRA

\[ L \sim \int \sqrt{g} \left( R + |G_4|^2 \right) + \cdots \]

\[ g_{\mu \nu} \quad C_3 \quad (dC_3 = G_4) \]

metric \hspace{1cm} 3\text{-form}

compactify on manifold \( X \) w/ overall modulus \( \hat{\tau} \)

\[ ds_{11}^2 = ds_8^2 + e^{2\varphi} \, ds_{11-d}^2 \]

\[ \Rightarrow \text{ } V(\hat{\tau}) = V_R e^{-\lambda_1 \hat{\tau}} + V_A e^{-\lambda_2 \hat{\tau}} \quad (\lambda_1 < \lambda_2) \]
Idea: e.g. 11D SUGRA

\[ L \sim \int \sqrt{g} \left( R + |G_4|^2 \right) + \ldots \]

\[ g_\mu^\nu \quad C_3 \quad (dC_3 = G_4) \]

metric 3-form

compactify on manifold \( X \) w/ overall modulus \( \tau \)

\[ ds^2 = ds_9^2 + e^{2\tau} ds_{11-d}^2 \]

\[ V(\tau) = V_R e^{-\lambda_2 \tau} + V_A e^{-\lambda_1 \tau} \quad (\lambda_1 < \lambda_2) \]

\[ |\partial_\tau V| \geq \min(\lambda_1, \lambda_2) \cdot \lambda_1 = \frac{6}{\sqrt{(d-2)(11-d)}} \]
Assumption

- GR (no $\alpha$/$g_s$ correction)
- extra dimension

cf. dS no-go thm [Maldacena-Nunez '00]
[Steinhardt-Wesley '08]

no-go on slow-roll inflation
[Hertzberg-Kachru-Taylor-Tegmark '07, ...]
Assumption
- GR (no $\alpha'/g_5$ correction)
- extra dimension

cf. dS no-go thm [Maldacena-Nunez '00, Steinhardt- Wesley '08]

no-go on slow-roll inflation
[Hertzberg-Kachru-Taylor-Tegmark '07, ...]

[OOSV] claimed this holds generally / anywhere
even when various corrections are important
If true, dS conjecture has dramatic consequences.

*multiverse* gone? [cf. Takahashi–Matsui '18, Kinney '18, Redelius '19]

*eternal inflation*
If true, dS conjecture has dramatic consequences.

* multiverse gone?
* eternal inflation
* quintessence?

[cf. Takahashi–Matsui '18, Kinney '18, Redelius '19]

[Ratra–Peebles '88, Weirenich '88, Caldwell–Dave–Steinhardt '97]

Future observation (e.g., Euclid/WFIRST/LSST, ...
"Controversy"
String Theory May Create Far Fewer Universes Than Thought

Some physicists claim the popular landscape of universes in string theory may not exist.

By Clara Moskowitz on July 30, 2018
THEORETICAL PHYSICS

Dark Energy May Be Incompatible With String Theory

A controversial new paper argues that universes with dark energy profiles like ours do not exist in the “landscape” of universes allowed by string theory.
ds conjecture is in sharp tension w/ claimed construction of ds vacua metastable
e.g. [Kachru - Kallosh - Linde - Trivedi ’03]
The dS conjecture is in sharp tension with the claimed construction of metastable dS vacua. For example, [Kachru-Kallosh-Linde-Trivedi '03].

It is true that KKLT has many subtle parts. For example, $\overline{O3}$ uplift/susy (no sust dS).

\[ \text{AdS} \rightarrow \Rightarrow \text{dS} \]
Technically: difficult to control corrections

\[ V \sim e^{-c_1 \phi} + e^{-c_2 \phi} + e^{-c_3 \phi} + \ldots \]

Same order?

[Dine-Selberg '85]

 Proposal of classical dS in IIA +08
[\text{Córdova-De Luca-Tomasiello '08}]

Seem to be removed by Maldacena-Nunez-type no-go
[Cribiori-Junghans '19]
I myself do not see sharp-enough argument against metastable vacua

dS conjecture as a general statement rather speculative
I myself do not see sharp-enough argument against metastable vacua
dS conjecture as a general statement rather speculative

... but can still be useful in asymptotic/weak coupling corner of QG landscape

[I prefer a positive approach:
an opportunity to learn something]
Bottom-up constraints

Higgs

\[ V_H = \lambda \left( H^2 - V^2 \right)^2 \]

has local maximum @ \( H = 0 \)

\[ \partial_H V_H = 0 \quad \forall \lambda > 0 \]

already in tension with dS conjecture

[Denef-Hebecker-Wrase '18]
EW modification? [Murayama-Yanagida-Y 98]

e.g., real scalar $S$ in addition to $H$

$$V_{H,S} = \lambda (H^2 - V^2)^2 + \kappa (S - \alpha) (H^2 - \omega^2) + \frac{m^2 S^2}{2} + \lambda_S S^4$$

$$\left( 2s V \rightarrow 0 \quad \text{at} \quad H = 0 \right)$$

no longer extremal pt

no longer extremal pt

$H$ direction

$S$ direction

$H = 0$

$S$
EW modification? [Murayama–Yanagida–Y 18]  
egg, real scalar $S$ in addition to $H$

$$V_{H,S} = \lambda (H^2 - V^2)^2 + \kappa (S - \alpha) (H^2 - \omega^2) + \frac{m^2}{2} S^2 + \Lambda_S^4$$

minimum

- $H(a) = \frac{k^2 \omega^2 - k \mu^2 u - 2k \mu^2 V^2}{k^2 - 2k \mu^2}$, $S(a) = \frac{k u + 2k \lambda v^2 - 2k \lambda \omega^2}{k^2 - 2k \mu}$

- $V|_{H(a), S(a)} = 0$

but another extremal point ($DV = 0$): $H(b) = 0$, $S(b) = \frac{\omega^2 k}{m^2}$

We need

- $V|_{H(b), S(b)} \leq 0$ (3 conditions incompatible!!!)
EW modification? [Murayama-Yanagida-Y 18]

e.g. real scalar $S$ in addition to $H$

$$V_{H,S} = \lambda (H^2 - V^2)^2 + K (S - \alpha) (H^2 - \omega^2) + \frac{m^2}{2} S^2 + \Lambda_S^4$$

and (in 0)

no longer extremal pt

extremal pt

extremal point

$H$ direction

$S$
More generally no-go thm against EW modification even for multiple fields

[Murayama-Yanagida-Y 78]

(\: still contrived loopholes, but unlikely \:)
Coupling to Quintessence: [Denef-Hebecker-Wrase '18]

\[ V_{H,Q}(H,Q) = e^{-\frac{c}{M_{\text{Pl}}} \frac{Q}{e}} V_H(H) \]

always rolls in \( Q \)-direction
Coupling to Quintessence: [Denef-Hebecker-Wrase '18]

\[ V_{H,Q}(H,Q) = e^{-\frac{cQ}{M_{Pl}}} V_{H}(H) \]
always rolls in \( Q \)-direction

But then Higgs VEV depends on \( Q \) and hence time-dependent quantum correction \( (\frac{M_{Pl}}{m_e} \text{ time variation} \)

\( (\text{fifth force searches}) \)

[Ibe-Hamaguchi-Moroi '18]

\( \Rightarrow \) original dS conjecture "excluded"
Refined dS Conjecture

Modify the condition s.t.

\( V > 0, \ \nabla V = 0, \ \nabla^2 V < 0 \) allowed
Refined dS Conjecture

Modify the condition s.t.
\[ V > 0, \ \Delta V = 0, \ \Delta^2 V < 0 \ \text{allowed} \]

* [Gorg-Krishnan, Ooguri-Palti-Shiu-Vafa '18]

\[ \left| \Delta V \right| \geq c \ V \ \text{or} \ \min (\Delta_i \Delta_j V) \geq -c' V \]

\( (c, c': \text{positive } \Theta(1)) \)

* [Murayama-Yanagida-Y '18]

\[ \left| \Delta V \right| \geq c \ V \ \text{when} \ \Delta^2 V \geq 0 \]
Distance Conj. \rightarrow dS Conj. ?

* distance conjecture required for dS Conj

\[
V(\phi) = m^2 \phi^2 \\
\nabla_\phi V > V \\
\Rightarrow \phi \leq M_{Pl}
\]
Argument by [Ooguri-Palti-Shiu-Vafa '18]
Consider quasi-dS $\exists \phi V \sim e^V$
Argument by [Ooguri–Palti–Shiu–Vafa ’18]

Consider quasi-dS $\exists \phi V \sim c V$.

(Bousso Bound)

$S \leq S_{GH} \sim R^2 \sim \frac{1}{H^2} \sim \frac{1}{V}$

dS entropy
Consider quasi-dS $\exists \phi V \sim c V \quad (c \ll 1)$

(Bousso Bound)

$S \leq S_{GH} \sim R^2 \sim \frac{1}{H^2} \sim \frac{1}{V}$

$dS$ entropy

$S = S(N, R) \sim N^p R^8$

# of species $\rightarrow$ dS

$N, R \gg 1$
Argument by [Ooguri, Palti, Shiu, Vafa '18]

Consider quasi-dS \( \mathcal{D} V \sim e V \)

\[ (\text{Bousso Bounded}) \]

\[ S \leq S_{GH} \sim R^2 - \frac{1}{4H^2} \sim \frac{1}{V} \]

\[ S = S(N, R) \sim N^p R^8 \]

\[ \Rightarrow \quad \# \text{ of species} \quad \text{dS Radius} \quad N, R \gg 1 \]

When \( \Delta \Phi \) large, tower of states \( \frac{m_n}{M_{pl}} \sim n e^{-b \Delta \Phi} \)

\[ \rightarrow N \sim \Lambda_{\text{cutoff}} \frac{e^{b \Delta \Phi}}{e^{-b \Delta \Phi}} \sim e \]

\[ \left[ \ast \text{ assume light states dominates (a fraction of) entropy} \right] \]
Argument by [Ooguri–Palti–Shiu–Vafa ’18]

Consider quasi-\(dS\)

\[ 2\phi V \sim c V \]

d\(S\) entropy

\[ S \leq S_{GH} \sim R^2 \sim \frac{1}{H^2} \sim \frac{1}{V} \]

\[ S = S(N, R) \sim N^p R^q \]

\[ N \sim e^{b\phi} \]

\[ V \leq e^{-c\phi} \]

\[ (c \sim \frac{2bp}{2q}) \]
Argument by [Ooguri–Palti–Shiu–Vafa ’18]

Consider quasi-dS $\exists \phi V \sim cV$

dS entropy

$$S \leq S_{GH} \sim R^2 \sim \frac{1}{H^2} \sim \frac{1}{V}$$

$$S = S(N, R) \sim N^p R^q$$

$$N \sim e^{b \Delta \phi}$$

$$V \leq e^{-c \Delta \phi}$$

For absence of tachyons

$$\min (\nabla^2 V) \geq -\frac{\Theta(1)}{R^2} \sim -c' V$$

$\Theta$ curvature coupling
Argument by [Hebecker-Wrase (18)]

* distance conjecture: tower of light states

\[ nM \sim n M_{\text{pe}} e^{-b \phi} \quad (n = 1, 2, \ldots) \]
[Hebecker-Wrase (18)]

* distance conjecture: tower of light states

\[ n m \sim n M_p e^{-b \phi} \quad (n = 1, 2, \ldots) \]

* below cutoff \( \Lambda \), \[ N \sim \frac{\Lambda}{m} \] states
[Hebecker-Wrase (18)]

* distance conjecture: tower of light states

\[ n \Lambda \sim n M_{pe} e^{-b \phi} \quad (n = 1, 2, \ldots) \]

* below cutoff \( \Lambda \), \( N \sim \frac{\Lambda}{m} \) states

* cutoff \( \Lambda \) smaller than \( M_{pe} \):

\[ \frac{1}{\Lambda^2} \sim \frac{N}{M_{pe}^2} \]
[Hebecker- Wrase (18)]

* distance conjecture: tower of light states
  \[ n \propto n \, M_{\text{pe}} \, e^{-b \phi} \quad (n = 1, 2, \ldots) \]

* below cutoff \( \Lambda \), \( N \sim \frac{\Lambda}{m} \) states

* cutoff \( \Lambda \) smaller than \( M_{\text{pe}} \):
  \[ \Lambda \gtrsim H = \sqrt{\frac{V}{3 M_{\text{pe}}^2}} \]
  \[ \frac{1}{\Lambda^2} \sim \frac{N}{M_{\text{pe}}^2} \]
[Hebecker- Wrase (18)]

* distance conjecture: tower of light states

\[ n \sim n \, M_{pe} \, e^{-b \phi} \quad (n=1, 2, \ldots) \]

* below cutoff \( \Lambda \), \( N \sim \frac{\Lambda}{m} \) states

* cutoff \( \Lambda \) smaller than \( M_{pe} \):

\[ \Lambda \geq H = \sqrt{\frac{V}{3 \, M_{pe}^2}} \]

\[ \sim \frac{V}{M_{pe}^4} \leq e^{-\frac{2b\phi}{3}} \]
* Since we use distance conjecture, asymptotic region $\Delta \phi \sim M_{pl}$

* Inequality:

$$V \leq e^{-\alpha(1) \Delta \phi}$$

[cf. Dine–Selberg]

saturated?
today's focus:

No global sym.

Weak gravity conj. \( \Rightarrow \) distance conj.

de Sitter conjecture ???
In refined version
no constraint on Higgs/axion/SSB

Inflation: \( \epsilon_V \geq c'^2 / 2 \) or \( Z_V \leq -c' \)

[Fukuda-Saito-Shirai-Y 18, ---]

* e-folding OK (concave region)

* \( N_s, r \) difficult for single-field (canonical kinetic term)

\[
\begin{align*}
N_s - 1 & \approx -6 \leq 2 \eta \approx 0.03 - 0.04 \quad (c' \approx 0.01) \\
r & = 16 \epsilon \leq 0.064 \\
Z & \approx -0.01
\end{align*}
\]

* \( c, c' \approx 1 \) OK for multi-field (e.g., curvaton)
Ho Tension
Figures:

Figure 1: Recent values of $H_0$ as a function of publication date since the Hubble Key Project (adapted from Beaton et al. 2016). Symbols in blue represent values of $H_0$ determined in the nearby universe with a calibration based on the Cepheid distance scale. Symbols in red represent derived values of $H_0$ based on an adopted cosmological model and measurements of the CMB. The blue and red shaded regions show the evolution of the uncertainties in these values, which have been decreasing for both methods. The most recent measurements disagree at greater than 3-$\sigma$. (Freedman '17)
flat $- \Lambda$CDM

Early

- Planck: $67.4^{+0.5}_{-0.5}$
- DES+BAO+BBN: $67.4^{+1.1}_{-1.2}$

Late

- SH0ES: $74.0^{+1.4}_{-1.4}$
- CCHP: $69.8^{+1.9}_{-1.9}$
- MIRAS: $73.6^{+3.9}_{-3.9}$
- H0LiCOW: $73.3^{+1.7}_{-1.8}$
- MCP: $74.8^{+3.1}_{-3.1}$
- SBF: $76.5^{+4.0}_{-4.0}$

Early vs. Late: $6.1\sigma$

73.3$^{+0.8}_{-0.8}$ combining all

73.9$^{+1.0}_{-1.0}$ with Cepheids: $5.8\sigma$

72.5$^{+1.2}_{-1.2}$ with TRGB: $4.0\sigma$

73.8$^{+1.4}_{-1.3}$ with MIRAS: $4.4\sigma$

[Verde-Treu-Riess '19]
Is Ho tension consequence of distance conj.??
Early-time solution

Early Dark Energy [Poulin-Smith-Kamionkowski '18]

- Behaves as DE to raise CMB $H_0$
- Then decays rapidly (faster than radiation) @ $z \sim 5000$
Early-time solution

Early Dark Energy

- Behaves as DE to raise CMB $H_0$
- then decays rapidly (faster than radiation)

@ $z \approx 5000$

\[ V(\phi) \sim (1 - \cos \frac{\phi}{f})^n \text{ (e.g. } n = 3) \]

\[ \phi \sim 0 \]

\[ \chi \text{ matter } V(\phi) \sim \phi^2 \text{ has } \Gamma \ll m \sim H_{z=5000} \]
Consider instead ultralight axion [Kaloper ’19]

\[ f \sim M_p \quad (\text{WGC } f \lesssim M_p) \]
Consider instead ultralight axion \cite{Kaloper-19} \( f \sim M_{pe} \) (WGC \( f \lesssim M_{pe} \))

\[ V(\phi) \sim \phi^2 \ (\text{matter}) \] near bottom, but

\[ \Delta \phi \sim M_{pe} \rightarrow \text{light modes } \chi \]

distance \( L > e^{-\Delta \phi} \chi \chi \)
Consider instead ultralight axion \cite{kaloper19}

\[ f \sim M_{\text{Pl}} \quad \text{(WGC } f \lesssim M_{\text{Pl}}) \]

\[ V(\phi) \sim \phi^2 \text{ (matter) near bottom, but} \]

* \[ \Delta \phi \sim M_{\text{Pl}} \Rightarrow \text{light modes } \chi \]
  
  distance (\text{distance } L \gtrsim e^{-\Delta \phi} \chi \chi) \]

* Parametric resonance

* Enhancement by \[ N_{\chi} \sim e^{\Delta \phi} \]
Consider instead ultralight axion \[ \text{[Kaloper '19]} \]
\[ \uparrow f \sim M_{pe} \quad (\text{WGC } f \leq M_{pe}) \]

\[ V(\phi) \sim \phi^2 \text{ (matter) near bottom, but} \]

\* \( \Delta \phi \sim M_{pe} \implies \text{light modes } \chi \]
\( \text{distance } (L > e^{-\Delta \phi} \chi \chi) \text{ conj.} \]

\* Parametric resonance

\* Enhancement by \( N\chi \sim e^{\Delta \phi} \text{ conj.} \)

\[ \implies \Gamma \sim H_{Z=5000} \]
**Late-time solution**

distance conjecture for Quintessence Dark Energy $Q$

tower of states $= \text{Dark Matter} P_{DM}(Q) \sim \rho_{DM} e^{-Q}$
Late-time solution

distance conjecture for Quintessence Dark Energy $Q$

tower of states $=$ Dark Matter $PDM(Q) \sim PDM e^{-Q}$

※ fifth-force constraint marginal

※ improves $H_0$ tension

[Agrawal-Obied-Varfa '19]
Naturalness?
naturalness needs to be revisited.
naturalness needs to be revisited:
No Free Parameter in QG

Any parameter (e.g. $Y_{\text{quark}, \Theta_{\text{ACP}}, \ldots}$):

VEV of moduli (e.g. axion) dynamically determined

(or fixed by some (QG) consistency)
Finite # of Moduli in QG
(typically ~ O(100))

⇒ ∞ - relations for higher-dim. op.

\[ L = L_0 + \sum_i 2 \left( \frac{\Theta_i}{M_{pl}} \right)^{\Delta \Theta_i - 4} \]

only finite independent

(cf. Heckman - Vafa '19)
Finite # of Moduli in QG
(typically $\sim O(100)$)

$\Rightarrow$ infinite relations for higher-dim. op.

$$L = L_0 + \sum_i \frac{2i O_i}{M_{pl} \Delta o_i - 4}$$

only finite independent

[No global sym, but "fine-tuned"
There IS free lunch!]
Summary
Swampland conjectures:

QG constraints on low-energy physics

essence of QG/string ⇔ phenomenology of EFT

Please do use the conjectures in your next paper!! (esp. young folks!)
緊急告知!!
Today:

Covered only limited aspects of "standard" material... 😞
* 名古屋大学にて集中講義
「沼地予想とその現象論」

2019年 9月30日(月) ～ 10月2日(水)
(4×3 ≈ 12 h)

(※詳細は追って名大物理HPより)
* 科研費研究員公募 (予定)!!
(予定) 2019年秋公募
2020年4月以降 ～ 2023年3月 (3年)
IPMU 1人, KEK 1人

KEK
北野
山田

IPMU
山崎

hep-ph
hep-lat
hep-th