Electroweak Quintessence Axion

and

Swampland Conjectures

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PASCoS 2019, Manchester
Based on
arXiv: 1811.04664 [hep-th]

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... and many earlier papers
Dark Energy
Figure 5. $\Lambda$CDM model: 68.3\%, 95.4\%, and 99.7\% confidence regions of the $(\Omega_m, \Omega_{\Lambda})$ plane from SNe Ia combined with the constraints from BAO and CMB. The left panel shows the SN Ia confidence region only including statistical errors while the right panel shows the SN Ia confidence region with both statistical and systematic errors.

Figure 6. $w$CDM model: 68.3\%, 95.4\%, and 99.7\% confidence regions in the $(\Omega_m, w)$ plane from SNe Ia BAO and CMB. The left panel shows the SN Ia confidence region for statistical uncertainties only, while the higher panels show the confidence region including both statistical and systematic uncertainties. We note that CMB and SN Ia constraints are orthogonal, making this combination of cosmological probes very powerful for investigating the nature of dark energy.
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$\Lambda > 0 !$

$\Lambda^4 \simeq O(10^{-12\circ}) M_{pe}^4 \ll M_{pe}^4 !!$
\[ \Lambda^4 \sim 0(10^{-12}) M_{Pl}^4 \ll M_{Pl}^4 \]

while dark energy is IR phenomenon, it is partly about UV QG, string, ...
low-energy EFT

dark energy $\land > 0$

QG/string

observation
dark energy $\wedge > 0$

- low-energy EFT
- observation
- QG/string
low-energy EFT

observation

dark energy \land > 0

QG / string

EFT theorist

QG not needed!
Swampland Conjectures:
[Vafa (05), Ooguri-Vafa (06), ...]
existence of UV completion in QG
constrains low-energy EFT

low-energy EFT

cannot be embedded into UV theory

Swampland

has UV completion

Landscape
low-energy EFT

observation

dark energy $\Lambda > 0$

Oh!

EFT theorist

QG/string

Swampland conjectures
How to Realize $\land$ ?
cosmological constant

$V(\phi)$
cosmological constant vs. quintessence

$V(\phi)$

Ratra–Peebles, Wetterich (88)
Zlatev–Wang–Steinhardt (98)
cosmological constant vs. quintessence

\[ V(\phi) \]

TODAY!!

\[ V(\phi) \]

[ Ratra-Peebles, Wetterich (88)]

[ Zlatev-Wang-Steinhardt (98)]
de Sitter Swampland conjecture

\[ M_{pl} \| \nabla V \| \geq c \sqrt{V} \quad (c \sim O(1), c > 0) \]

excludes dS vacua \((\nabla V = 0, \ V > 0)\)

\[ \Rightarrow \text{motivates quintessence} \quad \text{[Agrawal-Obied-Steinhordt-Vafa (18)]} \]
de Sitter Swampland Conjecture

\[ \text{Obied-Ooguri-Spydyneiko-Vafa (18)} \]

\[ M_{\text{pl}} \| \nabla V \| \geq c \sqrt{V} \quad (c \sim O(1), c > 0) \]

excludes dS vacua \( (\nabla V = 0, V > 0) \)

\[ \implies \text{motivates quintessence Agravahl-Obied-Steinhordt-Vafa (18)} \]

\[ \star \text{speculative, better motivated in asymptotic region} \]

\[ \text{cf. Dine-Seiberg (95), Maldacena-Nunez (00), Wesley-Steinhordt (08), \ldots} \]

Ooguri-Palti-Shiu-Vafa, Hebecker-Wrase (18), \ldots

(This talk does not directly rely on this conjecture)
Quintessence
Q: if quintessence, why flat potential?
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possible answer:

\[ \textit{quintessence axion} \]

\[ \text{[Fukugita-Yanagida (94) Frieman-Hill-Stebbins-Waga (95), Choi (99), ...]} \]

\[ L = \frac{1}{32 \pi^2} \frac{a}{f} \text{Tr} F_{\mu \nu} \tilde{F}^{\mu \nu} \]

- non-Abelian gauge field
- dynamic \( \Theta \) angle
- (\( \hat{x} \) this is the ONLY coupling of \( a \))
shift symmetry

$$a \rightarrow a + (\text{const.})$$

broken by non-pert. effect

$$V(a) = \wedge^4 \cos \left( \frac{a}{fa} \right) + \ldots$$

$$M_{pl}^4 e^{-\frac{2\pi}{\alpha}} \ll M_{pl}^4 \quad (\alpha = \frac{g^2}{4\pi})$$
shift symmetry
\[ a \rightarrow a + \text{(const.)} \]

broken by non-pert. effect

\[ V(a) = \Lambda^4 \cos \left( \frac{a}{f a} \right) + \cdots \]

\[ M_{\text{pl}}^4 e^{-2\pi/\alpha} \ll M_{\text{pl}}^4 \quad (\alpha = \frac{g^2}{4\pi}) \]

Q: which non-Abelian gauge field?
why particular value of \( \alpha \)?
Surprisingly, electroweak SU(2) gauge group in the standard model does the job!!

\[
\alpha_2(M_Z) \sim \frac{1}{29} \quad \longrightarrow \quad \alpha_2(M_{\text{pl}}) \sim \frac{1}{48}
\]
Surprisingly, electroweak $SU(2)$ gauge group in the standard model does the job!

\[ \alpha_2(M_Z) \sim \frac{1}{29} \quad \implies \quad \alpha_2(M_{pl}) \sim \frac{1}{48} \]

\[ \Lambda \sim M_{pl} e^{-\frac{2\pi}{\alpha_2(M_{pl})}} \sim O\left(10^{-130}\right) M_{pl} \]

\(\star\) dominant contribution comes from small-size instanton

electroweak quintessence axion scenario

[ Fukugita-Yanagida (94), Nomura-Watari-Yanagida (00), McLerran-Pisarski-Skokov (12), ...]
Q: Isn't the EW $\theta$-angle unphysical?

$\theta$ can be rotated away by anomalies of

$(B+L)$ - global symmetry [cf. Anselm-Johansen (92)]

A. $(B+L)$ - sym. is broken by higher-dim. operator, e.g.

$L \supset \frac{1}{2} g g g g l$

[Anselm-Johansen (92)]

(cf. no exact global symmetry in QFT)

[Misner-Wheeler (57), ... Polchinski (83), Banks-Seiberg (10), Harlow-Ooguri (18), ...]
Weak Gravity Conjecture
Weak gravity conjecture implies

\[ f \leq \frac{M_{\text{Pl}}}{S_{\text{inst}}} \sim \mathcal{O}(10^{-2}) M_{\text{Pl}} \ll M_{\text{Pl}} \]

\[ S_{\text{inst}} = \frac{2\pi}{\alpha_2(M_{\text{Pl}})} \approx 300 \]
Weak gravity conjecture implies

\[ f \lesssim \frac{M_{\text{Pl}}}{\sin \theta} \sim \mathcal{O}(10^{-2})M_{\text{Pl}} \ll M_{\text{Pl}} \]

\[ S_{\text{inst}} = \frac{2\pi}{\alpha_2(M_{\text{Pl}})} \approx 300 \]

However, we need small quintessence mass

\[ m^2 \sim \frac{\Lambda^4}{f^2} \sim \frac{H_0^2 M_{\text{Pl}}^2}{f^2} \lesssim H_0^2 \]

\[ \implies f \gtrsim M_{\text{Pl}} \text{ needed} \]
Hilltop Quintessence? [Dutta-Scherrer (’08), \ldots]

Choose

\[ \delta a = |a - f_{\Pi}| \ll f_{\Pi} \]

to avoid too much rolling

However, this requires

\[ O \left( \exp \left( \frac{M_{\text{Pl}}}{f} \right) \right) \sim O \left( e^{100} \right) \]

fine-tuning

[see e.g. Choi (’99), Svrcek (’06), Ibe-Yanagida-MY (’18)]
We can ameliorate the fine-tuning by modifying RG flow by heavy particles

\[ \alpha_2(M_Z) \sim \frac{1}{29} \quad \Rightarrow \quad \alpha_2(M_{\text{pl}}) \sim \frac{1}{48} \]

\[ S_{\text{inst}} \sim \frac{2\pi}{\alpha_2(M_{\text{pl}})} \sim 300 \]
We can ameliorate the fine-tuning by modifying RG flow by heavy particles.

\[ \alpha_2(M_Z) \sim \frac{1}{29} \quad \text{RG} \]

\[ \alpha_2(M_Z) \sim O(1) \]

w/ heavy \[ S_{\text{inst}} \sim O(10) \] particles
We can ameliorate the fine-tuning by modifying RG flow by heavy particles.

\[ \alpha_2(MZ) \sim \frac{1}{29} \rightarrow S_{\text{inst}} \sim O(10) \text{ or even } O(1) \]

But... this spoils the successful estimate for

\[ \Lambda^4 \sim M_{\text{pl}}^4 e^{-S_{\text{inst}}} \sim O(10^{-120}) M_{\text{pl}}^4 \]
Supersymmetric Miracle
Consider MSSM w/ \( m_{susy} \sim O(\text{TeV}) \)

EW \( \theta \)-angle
Consider MSSM w/ $m_{susy} \sim O(\mathrm{TeV})$

EW $\Theta$-angle $\sim$ (B+L)-breaking

dim 5 op. $\underline{QQQL}$

dangerous for proton decay

[Sakai-Yanagida, Weinberg (82)]
Consider MSSM w/ $m_{susy} \sim O(\text{TeV})$

EW $\theta$-angle $\sim (B+L)$-breaking
dim 5 op. QQQQ

dangerous for proton decay

[Sakai-Yanagida, Weinberg (82)]

impose Frogatt-Nielsen sym.
with breaking parameter

$\epsilon \sim \frac{\langle \phi_{W} \rangle}{M_{\phi}} \sim \frac{1}{17}$

for quark/lepton mixing matrix
\[ \alpha_2(M_{\text{pl}}) \bigg|_{\text{MSSM}} = \frac{1}{23} \quad \text{cf.} \quad \alpha_2(M_{\text{pl}}) \bigg|_{\text{SM}} = \frac{1}{48} \]

\[ \Lambda^4 \sim e^{-\frac{2\pi}{\alpha_2(M_{\text{pl}})}} \]
\[ \alpha_2(M_{\text{pl}}) \bigg|_{\text{MSSM}} = \frac{1}{23} \quad \text{cf.} \quad \alpha_2(M_{\text{pl}}) \bigg|_{\text{SM}} = \frac{1}{48} \]

Instanton calculus gives \([\text{Nomura-Watori-Yanagida (00)}]\)

\[ \Lambda^4 = e^{-\frac{2\pi}{\alpha_2(M_{\text{pl}})}} \epsilon^{10} \frac{3}{4} M_{\text{SWY}} M_{\text{pl}} \]

\[ \approx \mathcal{O}(10^{-120}) \] \( M_{\text{pl}}^4 \) !!

\[ \epsilon = \frac{1}{17}, \quad m_{\text{SWY}} \approx \text{TeV} \]
Now, back to inclusion of heavy particles ....
Include a pair $X, \bar{X}$ of heavy particles with intermediate mass $M_X$.

$$\alpha_2^{-1}(M_{PL}) \big|_{X\bar{X}} = \alpha_2^{-1}(M_{PE}) + \frac{2 Tr}{2\pi} \log \frac{M_X}{M_{PE}}$$

$\omega$ Dynkin index
Include a pair $X, \bar{X}$ of heavy particles with intermediate mass $M_X$

$$\alpha_2^{-1}(\text{M}_{\text{Pl}}) \bigg|_{X \bar{X}} = \alpha_2^{-1}(\text{M}_{\text{Pl}}) + \frac{2 \text{Tr}}{2\pi} \log \frac{M_X}{\text{M}_{\text{Pl}}}$$

Heavy particles also generate extra zero modes

Insertion of operators $M_X X \bar{X}$

$$\sim \left( \frac{M_X}{\text{M}_{\text{Pl}}} \right)^{2 \text{Tr}}$$
It turns out 2 effects cancel out,
[Nomura-Wataru-Yanagida (00)]

\[ \Lambda^4 \big|_{x \bar{x}} \sim e^{-\frac{2\pi}{\alpha_2(M_{\text{pl}})}} \left( \frac{M_X}{M_{\text{pl}}} \right)^{2TR} e^{1.0 m_{\text{susy}}^3 M_{\text{pl}}} \]

\[ = \Lambda^4 \big|_{\text{MSSM}} \]

WGC 😊

We can change the RG running of \( \alpha_2 \)
while keeping the size of \( \Lambda^4 \) robust 😊.
We have many choices for heavy particles

\[ \text{s.t. } \Delta^2(M_{\text{pl}}) = 4 \pi \]

**E.g.**

1. 3 SU(2) triplets
   at \( O(10^7 \text{ GeV}) \)

2. 1 SU(2) triplet
   1 SU(3) octet
   at \( O(10^{12} \text{ GeV}) \)
   + 4 pairs of SU(5) \( 5, \overline{5} \)
   at \( O(1 \text{ TeV}) \)
More Swampland Conjectures
de Sitter Conjecture
\[ V(\alpha) \sim \Lambda^4 \cos \left( \frac{\alpha}{f} \right) \] has local maximum, hence violates original dS conjecture

\[ M_{\text{pe}} \| D V \| \geq c V \]

Murayama - Yanagida - MY (18)
See also Denef - Hebecker - Wrase, Conlon, Choi - Chwye - Sin (18)
\[ V(\alpha) \sim \Lambda^4 \cos(\frac{\alpha}{f}) \] has local maximum, hence violates original dS conjecture

\[ \text{M}_{\text{pl}} \parallel \nabla V \parallel \geq c' V \]

\[ \text{Murayama - Yanagida - MY (18)} \]
\[ \text{See also Dinef - Hebecker - Wrase, Conlon, Choi - Chwoy - Sin (18)} \]

However, consistent with refined dS conjecture

\[ \text{M}_{\text{pl}} \parallel \nabla V \parallel \geq c' V \text{ or } \text{M}_{\text{pl}}^2 \text{ min}(\nabla^2 V) \geq c' V \]

\[ \text{Garg - Krishnan, Murayama - Yanagida - MY, Ooguri - Palti - Shiu - Vafa, ... (18)} \]
\[ \text{See also Fukuda - Saito - Shirai - MY (18)} \]
Scalar  WGC
*Some versions of weak gravity conjecture with scalar fields claim [Palti (17), Shirai-MY (19)]

"F_{scalar} > F_{gravity}"

This requires $O(1)$ coupling of quintessence to SM particles, and is highly constrained by fifth-force searches [⋯, Shirai-MY (19)]
No non-sust AdS
SM + Majorana neutrinos on $S^1$ creates AdS$_3 \times S^1$ vacua \cite{Arkani-Hamed:2007fq,Dubovsky:2007xk,Nicolis:2008in,Villadoro:2007uv}, which is conjecturally forbidden \cite{Ooguri:2016otz,IBANEZ1977241}.

This "problem" removed by two light bosons (EW axion and QCD axion) \(\sim\) observation?
\[ \pi_1 = 0 \]
The axion is complexified into saxion $S$

\[ \text{[ in SUSY/ swampland conjecture (Ooguri-Vafa '06)]} \]

\[ (\Pi_i(S') = \mathbb{Z}, \Pi_i(C) = 0) \]

Saxion decay causes moduli/Polonyi problem

This can be saved e.g. by enhancing the coupling w/ inflection [Linde ('96)]

\[
\begin{align*}
\frac{\phi}{M_p} & \quad 1 \\
0.8 & \quad 0.8 \\
0.6 & \quad 0.6 \\
0.4 & \quad 0.4 \\
0.2 & \quad 0.2 \\
-0.2 & \quad 0.2
\end{align*}
\]

\[
\begin{align*}
\frac{\phi}{M_p} & \quad 1 \\
0.8 & \quad 0.8 \\
0.6 & \quad 0.6 \\
0.4 & \quad 0.4 \\
0.2 & \quad 0.2 \\
-0.2 & \quad 0.2
\end{align*}
\]
Summary
electroweak quintessence axion

\[ \Lambda^t \sim M_{pe}^2 e^{-\frac{2\pi}{\alpha_2(M_{pe})}} \sim O(10^{-130}) M_{pl}^4 \]
* Electro-weak Quintessential Axion:
  
  simple scenario to explain $\Lambda^4 \sim 10^{-120} M_{Pl}^4$

* Consistent w/ de Sitter swampland conjecture

* Consistency w/ weak gravity conjecture
  requires fine-tuning into hilltop region

* However, fine-tuning ameliorated in MSSM + heavy matter (SUSY miracle) (robust)
low-energy EFT

observation

EW Quintessence Axion

swampland conjectures

QFT/String
low-energy EFT

PA

observation

COS

$S$

swampland conjectures

QG/string

EW Quintessence Axion