What does Inflation say about Dark Energy given the Swampland Conjectures?

Jacob M. Leedom
String Phenomenology 2019
6/27/2019

arXiv: 1811.01987
Chien-I Chiang, J.M.L, Hitoshi Murayama
To appear in Physical Review D
Swampland Cosmology: Inflation & Dark Energy

- **Inflation**
  - Early phase of rapid expansion.
  - A number of QFT theories can be used for modelling.

- **Dark Energy**
  - Causing the current accelerating expansion of the universe.
  - Typically taken to be a cosmological constant.

- A priori, these two phenomena are unrelated. Using the Swampland conjectures, one can relate them.

- **Distance Conjecture** – As one traverses a distance D in field space, your EFT eventually breaks down as a tower of light modes appears

\[
m \sim \exp(-\beta D) \quad \beta \sim \mathcal{O}(1)
\]

- **de Sitter Conjecture (dSC)** – The scalar potential of an EFT must satisfy

\[
|\nabla V| > cV \quad c \sim \mathcal{O}(1)
\]

\[
|\nabla V| = (g^{ij} \partial_i V \partial_j V)^{1/2}
\]
Cosmology and the Swampland: Inflation

• Slow Roll parameters

\[ \epsilon_V = \frac{1}{2} \left( \frac{V'_\phi}{V_\phi} \right)^2 > \frac{c^2}{2} \quad \text{and} \quad \eta_V = \frac{V''_\phi}{V_\phi} \]

• Constraint from e-folds, distance conjecture, and dSC:

\[ D = \int \sqrt{2\epsilon_V} dN_e \approx \sqrt{2\epsilon_V} N_e > cN_e \]

For 50 e-folds and \( \alpha=1 \),

\[ c \lesssim \frac{1}{N_e} = 0.02 \]

arXiv:1811.01987
Cosmology and the Swampland: Quintessence & Observation

- Quintessence Dark Energy Equation of State
  \[ 1 + w = \frac{2(V'_Q)^2}{(V'_Q)^2 + 6V_Q^2} > \frac{2c^2}{6 + c^2} \equiv \Delta(c) \]

- The swampland parameter \( c \) should be universal in a given EFT, so we can use the upper bound on \( c \) from applying the distance conjecture to inflation and find that
  \[ \Delta(c) < \Delta(0.02) \sim 10^{-4} \]

- Next generation of experiments (Euclid, LSST, DESI,.. ) will probe \( \Delta \) to \( \sim 10^{-2} \) and it is unlikely that we can probe \( \Delta < 10^{-3} \) in the near future [Heisenberg et al].

- Therefore, even if the swampland conjectures are correct, it is possible we could live in a universe with quintessence but be unable to distinguish it from a cosmological constant.
Refined de Sitter Conjecture

• We will focus on the refinement in [Ooguri et al] & [Garg & Krishnan]

• **Refined de Sitter Conjecture (RdSC):**

  The scalar potential must satisfy either

  \[ |\nabla V| > cV \]

  OR

  \[ \min(\nabla_i \nabla_j V) < -c' V \quad c' \sim \mathcal{O}(1) \]

• Relaxes constraint on inflation:

  \[ D = \int \sqrt{2\epsilon_V} \, dN_e > cN_1 \]
Cosmology and the (refined) Swampland: Single-field Inflation

• We now use the freedom from the RdSC to re-examine the observability of quintessence

• We consider a piecewise inflaton potential with $N_{\text{tot}}$ e-folds that satisfies the first part of the RdSC during the first $N_1$ e-folds and the second of the conjecture during the remaining $N_2 = N_{\text{tot}} - N_1$ e-folds

• Then we require
  • RdSC Part 1:
    \[ \sqrt{2\epsilon_V^{(1)}} \geq c \]
  • RdSC Part 2 + Spectral tilt:
    \[ c' < \frac{1}{2} \left( 1 - n_s(k) - 6\epsilon_V^{(2)} \right) \rightarrow c' < \frac{1}{2} (1 - n_s(k)) \]
  • Distance:
    \[ \sqrt{2\epsilon_V^{(1)}} N_1 + \sqrt{2\epsilon_V^{(2)}} N_2 \leq \alpha \rightarrow \sqrt{2\epsilon_V^{(1)}} N_1 \leq \alpha \]
The constraints on the swampland parameters can be packaged as
\[ (c', c) < \left( \frac{1 - n_s(k)}{2}, \frac{\alpha}{N_1} \right) \]
which is valid so long as \( N_1 < N_{\text{tot}} \).

The running of the scalar spectral tilt can be modelled using PLANCK 2018 data:
\[ n_s(k) = 0.9659 - 0.0041 \ln \frac{k}{k_*} \pm \sqrt{0.0040^2 + \left(0.0067 \ln \frac{k}{k_*}\right)^2} \]
to maximize the parameter space for the swampland parameters, we take the 1\(\sigma\) allowed lower end.

Also the experimental bound:
\[ r_{0.002} < 0.064 \]
• Solid Lines – running of the spectral index up to $N_1 \sim 10$.
• Dashed Lines – continued running of spectral index to $N_1 \sim 50$.
• Dotted lines – Distance conjecture constraint when $N_1 = N_{\text{tot}}$.
• Grey region – excluded by bound on $r_{0.002}$.
• If $N_1$ is substantial (>5) then the lower bound on $\Delta$ is just below observability.
• If $N_1$ is small, then quintessence can easily be bounded from below such that it is observable.
• Tension with the notion that both $c$ and $c'$ are both $O(1)$.
Cosmology and the (refined) Swampland: Multi-field Inflation

- In a multi-field inflation model, the Hubble and potential slow roll parameters are related in a more complicated manner:

\[ \epsilon_H = -\frac{\dot{H}}{H} \equiv \epsilon \quad \eta_H = \frac{\dot{\epsilon}}{H \epsilon} \equiv \eta \]

\[ \epsilon_V = \frac{1}{2} \frac{g^{ij} V_i V_j}{V^2} = \epsilon \left(1 + \frac{\Omega^2}{9H^2}\right) \]

\[ 12 \eta_V = (c_s^{-2} - 1) \frac{M^2}{H^2} + 2 \frac{M^2}{H^2} + 3(4\epsilon - \eta) - 2 \left(\frac{M^2}{H^2} - \frac{3}{2}(4\epsilon - \eta)\right)^2 + 9(c_s^{-2} - 1) \frac{M^2}{H^2}\]
Cosmology and the (refined) Swampland: Multi-field Inflation

• The expression for the spectral index is changed to incorporate a sound speed that varies with time:

\[ n_s = 1 - 2\epsilon - \eta - \kappa \]

\[ \kappa = \frac{\dot{c}_s}{Hc_s} \]

• Tensor to Scalar ratio expression:

\[ r = 16\epsilon c_s \]

\[ c_s^{-2} = 1 + \frac{4\Omega^2}{M^2} \]

• Analysis proceeds as in the single field case.
• $\alpha = 1$ for all regions.
• Blue region is the same as single field.
• For lower sound speeds, one can have $N_1 \sim 10$ and force quintessence to be observable.
• Both $c$ and $c'$ can be $O(0.1)$. 

\[ c_s = 1 \]
\[ c_s = 0.7 \]
\[ c_s = 0.24 \]
Conclusions

• The refined de Sitter conjecture allows for the possibility of forcing quintessence to be observable.

• Single-Field Inflation
  • Concave down inflaton potentials are favored.
  • Tension with the notion that $c$ and $c'$ are both $O(1)$.

• Multi-Field Inflation
  • Reduced sound speed can force observable quintessence.
  • Furthermore, $O(1)$-ish parameters can be accommodated.

• Better understanding of $c$ and $c'$ essential to further constraining observables

• Don’t lose hope!
References

  Prateek Agrawal, Georges Obied, Paul J. Steinhardt, Cumrun Vafa – arXiv 1806.09718
• [5]. David Andriot, Christoph Roupec – arXiv: 1811.08889
• [7]. Daniel Baumann – arXiv: 0907.5424