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

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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

$$m \sim \exp(-\beta D) \qquad \beta \sim \mathcal{O}(1)$$

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

$$|\nabla V| > cV \qquad c \sim \mathcal{O}(1)$$

$$|\nabla V| = (g^{ij}\partial_i V \partial_j V)^{1/2}$$

Cosmology and the Swampland: Inflation

- Slow Roll parameters

$$\epsilon_V = \frac{1}{2}\left(\frac{V'_\phi}{V_\phi}\right)^2 > \frac{c^2}{2} \qquad \eta_V = \frac{V''_\phi}{V_\phi}$$

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

$$D = \int \sqrt{2\epsilon_V}dN_e \approx \sqrt{2\epsilon_V}N_e > cN_e \qquad D \leq \mathcal{O}(1) \equiv \alpha$$

For 50 e-folds and α=1,

$$c \lesssim \frac{1}{N_e} = 0.02$$

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 Δ 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

$$\min(\nabla_i \nabla_j V) < -c'V \qquad c' \sim \mathcal{O}(1)$$

- 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_{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 $N_2 = N_{tot} - N_1$ e-folds
- Then we require
  - **RdSC Part 1**:

$$\sqrt{2\epsilon_V^{(1)}} \geq c$$

  - **RdSC Part 2 + Spectral tilt**:

$$c' < \frac{1}{2}\left(1 - n_s(k) - 6\epsilon_V^{(2)}\right) \quad \rightarrow c' < \frac{1}{2}\left(1 - n_s(k)\right)$$

  - **Distance**:

$$\sqrt{2\epsilon_V^{(1)}}N_1 + \sqrt{2\epsilon_V^{(2)}}N_2 \leq \alpha \quad \rightarrow \sqrt{2\epsilon_V^{(1)}}N_1 \leq \alpha$$

Cosmology and the (refined) Swampland: Constraints on single-field inflation

- 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 $N_1 < N_{tot}$.

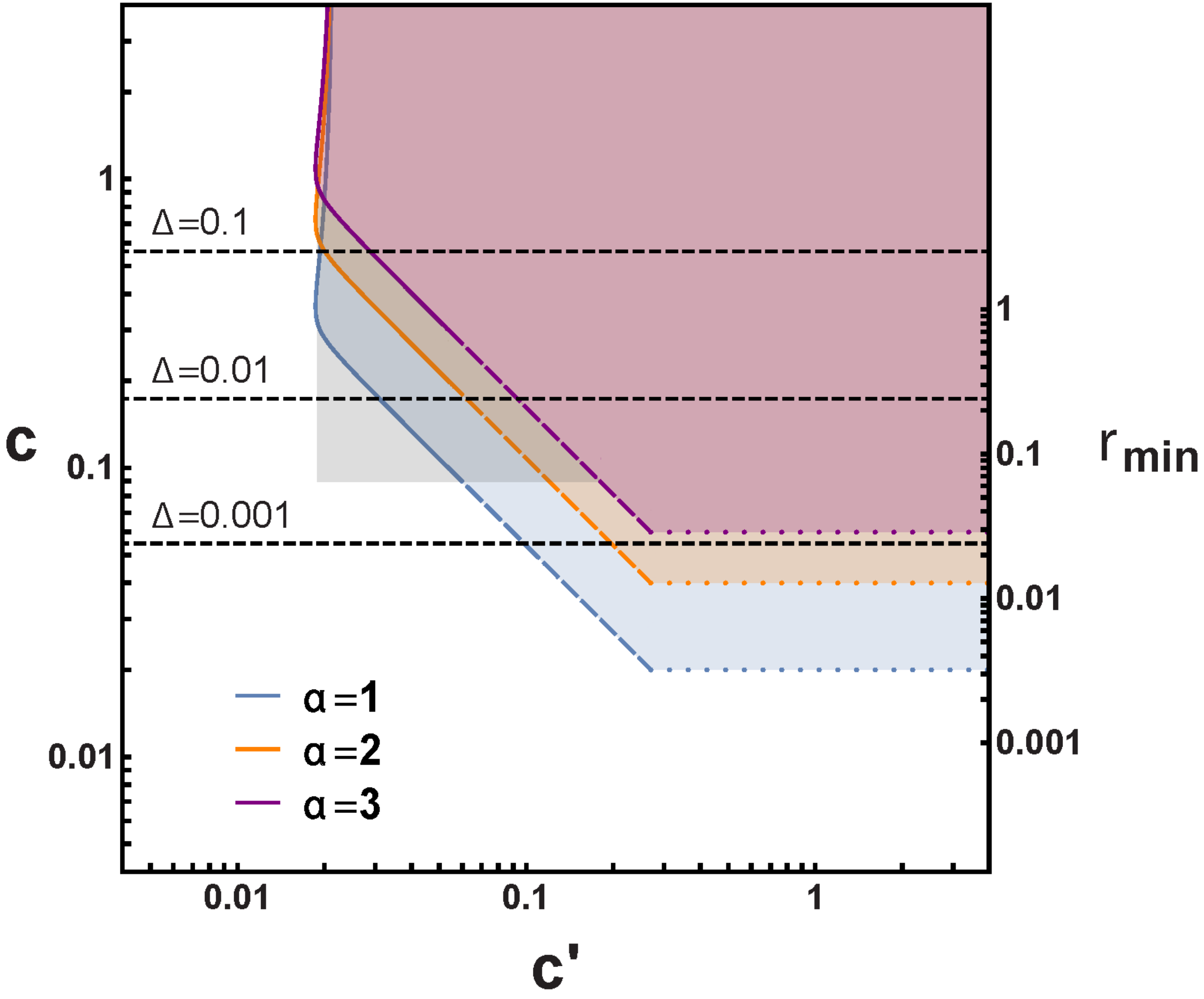
- The running of the scalar spectral tilt can be modelled using PLANCK 2018 data:

$$n_s(k) = 0.9659 - 0.0041 \ln \frac{k}{k_*} \pm \sqrt{0.0040^2 + \left(0.0067 \ln \frac{k}{k_*} \right)^2}$$

to maximize the parameter space for the swampland parameters, we take the 1σ allowed lower end.

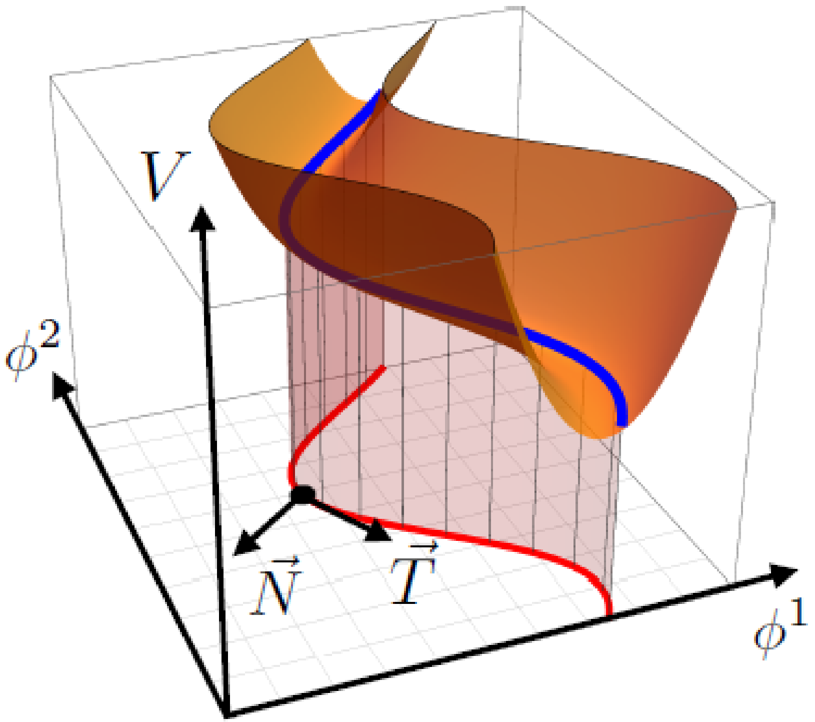
- Also the experimental bound:

$$r_{0.002} < 0.064$$



- 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 $N_1 = N_{tot}$.
- Grey region – excluded by bound on $r_{0.002}$.
- If N_1 is substantial (>5) then the lower bound on Δ 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



[Credit: Hetz & Palma]

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

$$\epsilon_H = -\frac{\dot{H}}{H} \equiv \epsilon \qquad \eta_H = \frac{\dot{\epsilon}}{H\epsilon} \equiv \eta$$

$$\epsilon_V = \frac{1}{2}\frac{g^{ij}V_iV_j}{V^2} = \epsilon\left(1 + \frac{\Omega^2}{9H^2}\right)$$

$$12\eta_V = (c_s^{-2} - 1)\frac{M^2}{H^2} + 2\frac{M^2}{H^2} + 3(4\epsilon - \eta) - 2\left(\left(\frac{M^2}{H^2} - \frac{3}{2}(4\epsilon - \eta)\right)^2 + 9(c_s^{-2} - 1)\frac{M^2}{H^2}\right)^{1/2}$$

Cosmology and the (refined) Swampland: Multi-field Inflation

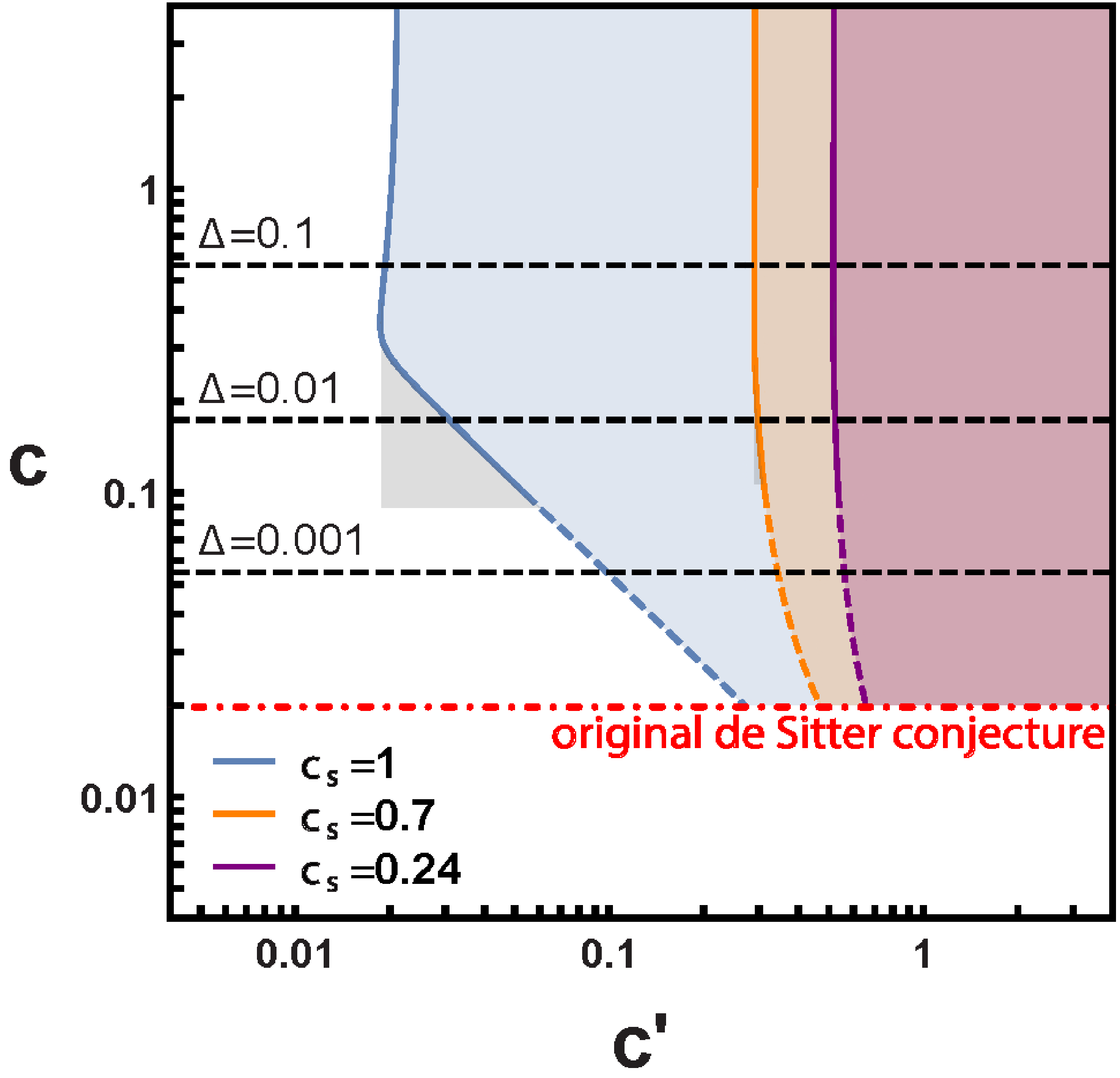
- The expression for the spectral index is changed to incorporate a sound speed that varies with time:

$$n_s = 1 - 2\epsilon - \eta - \kappa \qquad \kappa = \frac{\dot{c}_s}{H c_s}$$

- Tensor to Scalar ratio expression:

$$r = 16\epsilon c_s \qquad c_s^{-2} = 1 + \frac{4\Omega^2}{M^2}$$

- Analysis proceeds as in the single field case.



- α =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).

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!

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