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

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Rencontres du Vietnam Cosmology

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Modern Cosmology: Inflation & Dark Energy

- **Inflation**
  - Early phase of rapid expansion.
  - Many QFT models.
- **Dark Energy**
  - Causing the current accelerating expansion of the universe.
  - Typically taken to be a cosmological constant.
  - Origin and small scale are very mysterious.

How does recent work in quantum gravity constrain models of these two phenomena and the possibilities of future measurements?

Quantum Gravity & The Swampland

- **The Landscape** – set of all EFTs that can be obtained by some compactification of string theory

- **The Swampland** – set of all EFTs coupled to gravity that are inconsistent with quantum gravity

- **In other words, the swampland is the set of all theories that are not in the string landscape**

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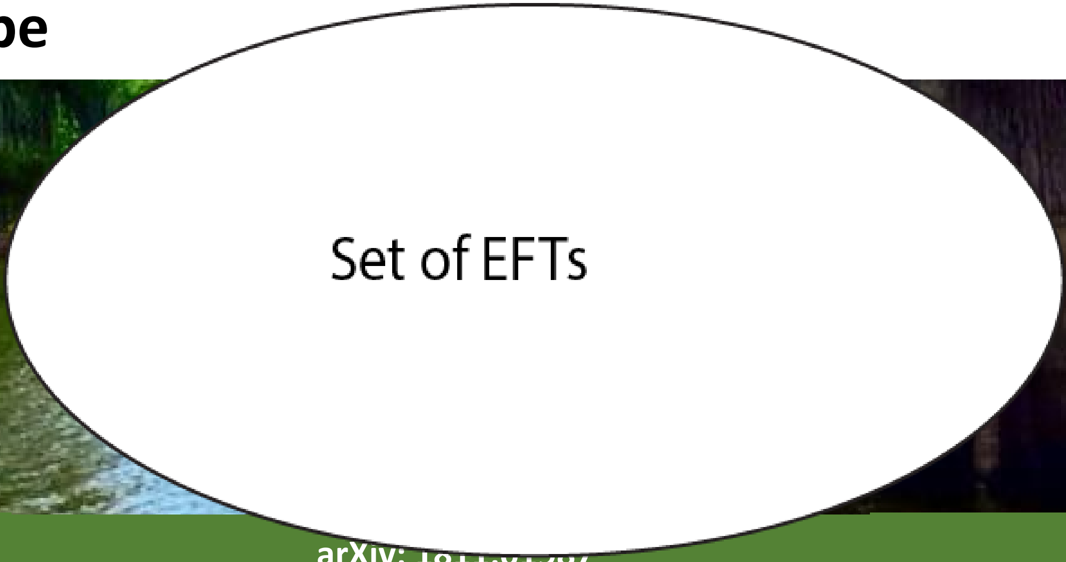

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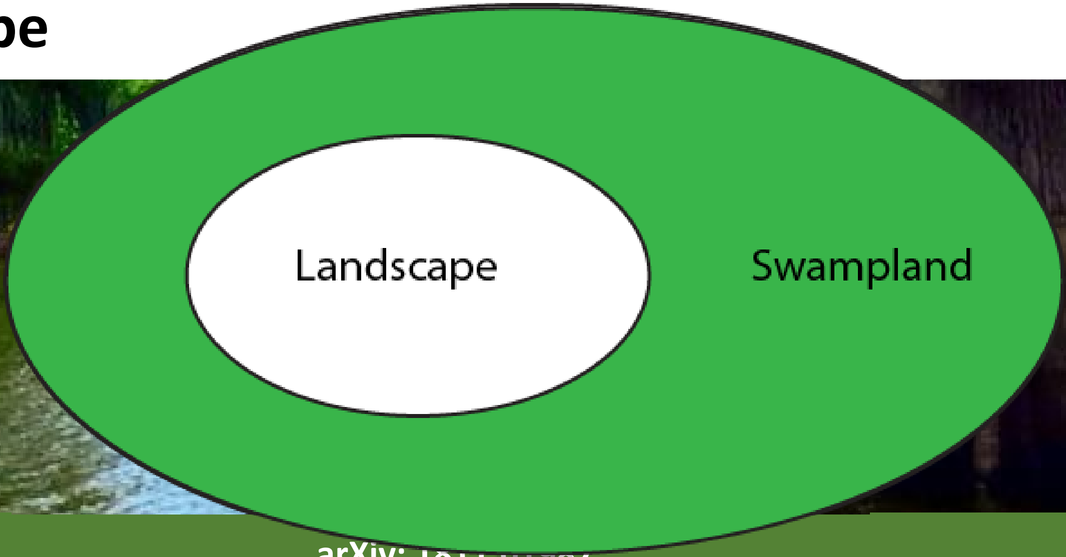

Swampland Conjectures

- The goal of the swampland program is to find a set of criterion by which one can determine if a given EFT is in the swampland or landscape.
- These criterion are in the form of a set of conjectures:
  - **Old Ideas –** no global symmetries in quantum gravity
  - **Weak Gravity Conjecture** – gravity is the weakest force
  - **Distance Conjecture** – transplanckian field excursions are not allowed
  - **de Sitter Conjecture (dSC) –** no meta-stable de Sitter vacua
  - Many more (AdS conjectures, moduli space conjecture, etc.) + various refinements and modifications of the above
- **These conjectures form a tightly knit web**

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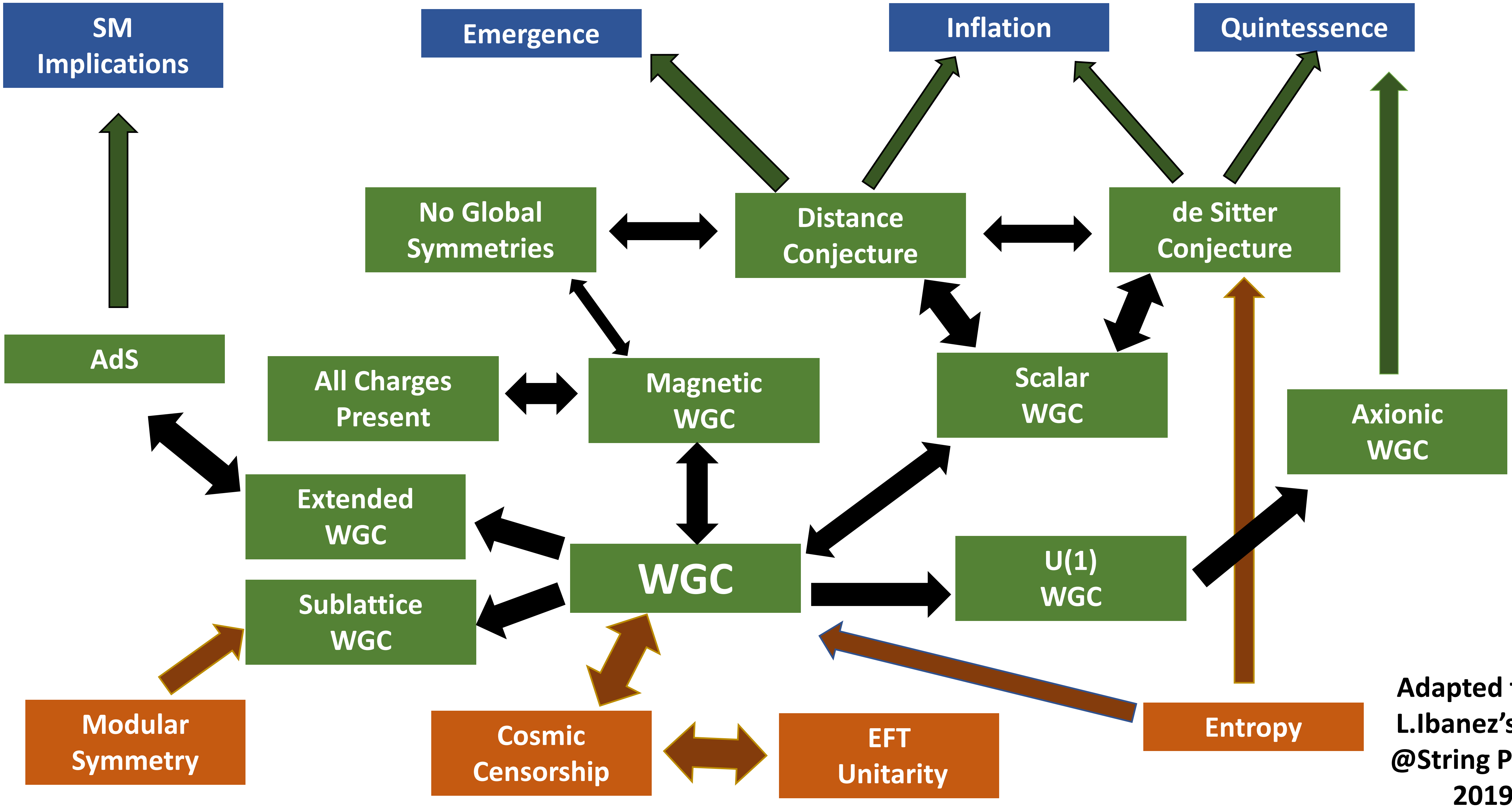

Adapted from L.Ibanez's talk @String Pheno 2019

The Distance Conjecture

- As one traverses a distance D in field space, an infinite tower of light modes appears with mass

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

Therefore, the effective theory breaks down at transplanckian field excursions.

- Example: Circle Compactification and KK & Winding Modes

$$\mathcal{L} = \frac{\partial_\mu T \partial^\mu \bar{T}}{(T+\bar{T})^2} \qquad T + \bar{T} \sim R^2$$

  - KK Modes:

$$m_{KK} \sim \frac{n}{R}$$

  - Winding Modes:

$$m_{winding} \sim nR$$

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$$\mathcal{L} = \frac{\partial_\mu T \partial^\mu \bar{T}}{(T+\bar{T})^2} \rightarrow g_{T\bar{T}} = \frac{1}{(T+\bar{T})^2} \qquad T+\bar{T} \sim R^2$$

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The de Sitter Conjecture

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

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

$$|\nabla V| = (g^{ij}\partial_i V \partial_j V)^{1/2} \qquad \mathcal{L} \supset g_{ij}\partial^\mu \phi^i \partial_\mu \phi^j$$

- Implications – Dark energy is caused by a quintessence field, not a cosmological constant!
- Why?
  - Fair to say that there is not a single rigorous 4D de Sitter solution of string theory.
  - There exists partial constructions (such as KKLT), but there are concerns over the stability of these scenarios
  - Several no-go theorems that prove dS is impossible in certain scenarios.
  - Not a settled issue and still under much debate.

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:

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

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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 the per cent level, 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

- The original formulation of the dSC was too strong – Higgs and axion potentials were ruled out! [Prof. Yamazaki's talk, Murayama et al]
  - At local maximum: $|\nabla V_{Higgs}| = 0$ but $V_{Higgs} > 0$
- 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

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

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

- The RdSC allows for more freedom – **can this freedom be used to improve the prospects of observing 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**:
  - **RdSC Part 2 + Spectral tilt**:
  - **Distance**:

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  $$c' < \frac{1}{2}\left(1 - n_s(k) - 6\epsilon_V^{(2)}\right) \quad \rightarrow c' < \frac{1}{2}\left(1 - n_s(k)\right)$$
  - **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 $N_1 < N_{tot}$.

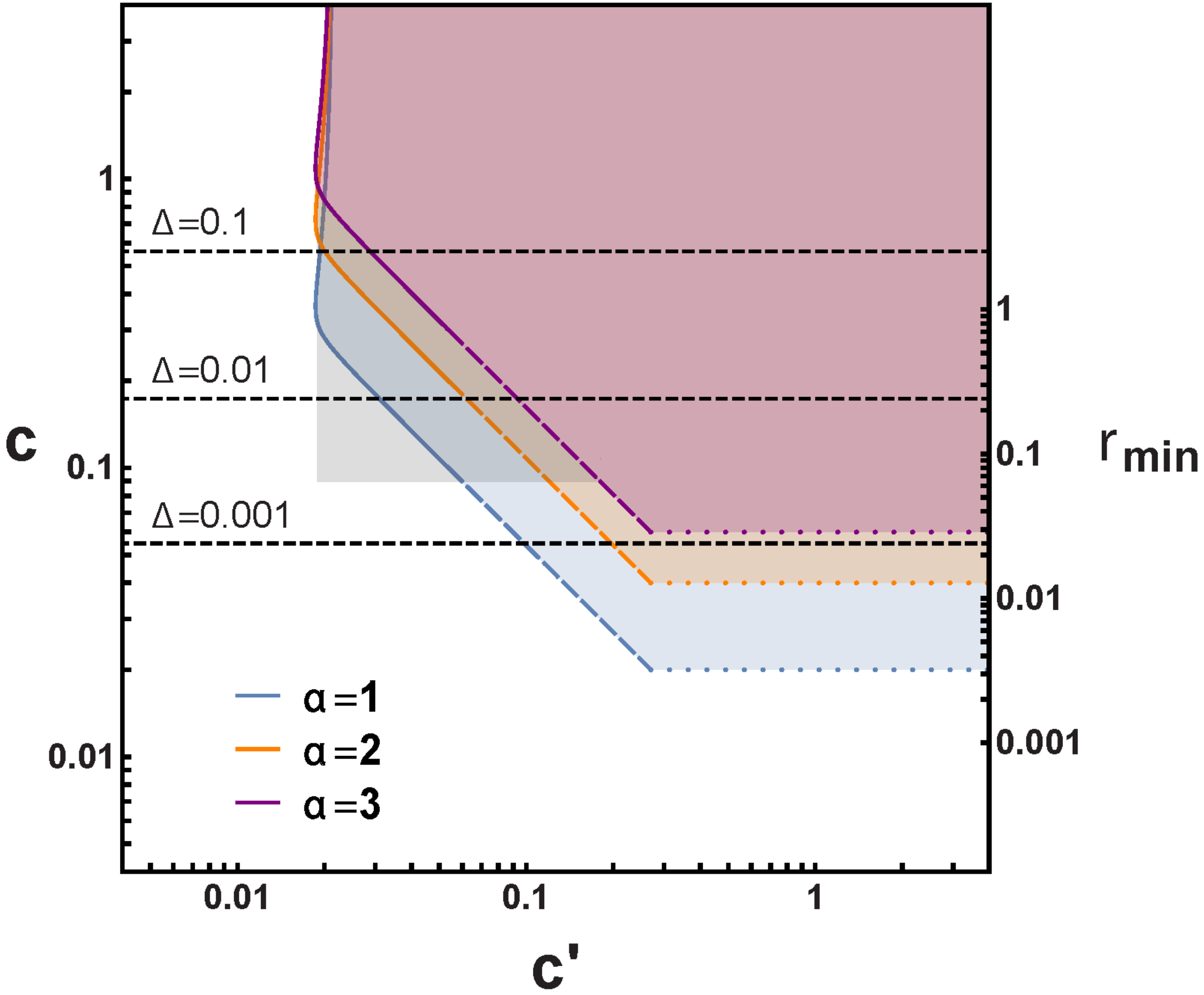
- The running of the scalar spectral tilt can be modelled using PLANCK 2018 data:

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

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

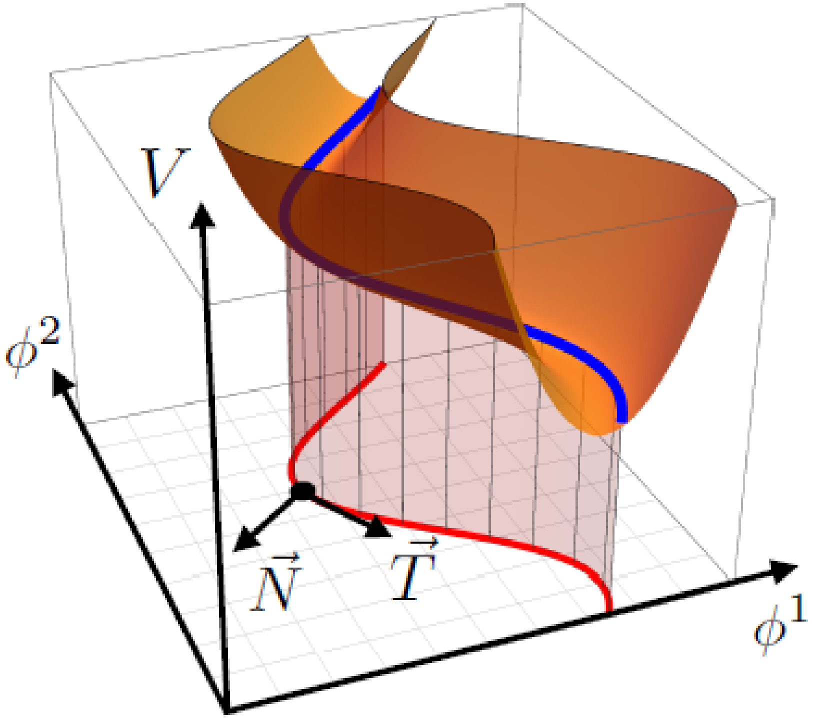
- Also the experimental bound:

$$r_{0.002} < 0.064$$



- 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:

$$\epsilon_H = -\frac{\dot{H}}{H^2} \equiv \epsilon \qquad \eta_H = \frac{\dot{\epsilon}}{H\epsilon} \equiv \eta$$

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

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

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

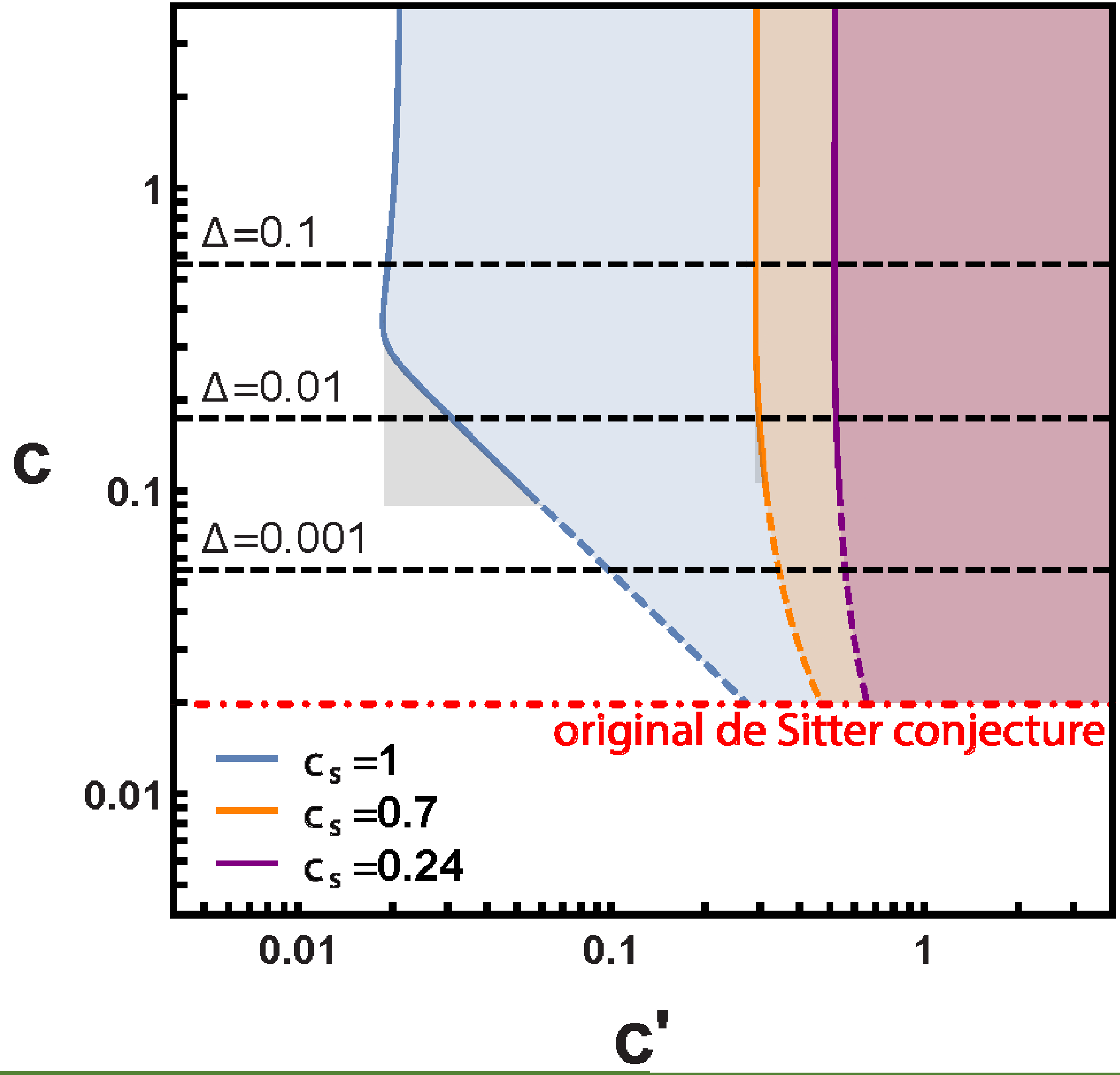
- The expression for the spectral index is changed to incorporate a sound speed that varies with time:

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

- 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 ~10 and force quintessence to be observable.
- Both c and c' can be O(0.1).

Conclusions

- The Swampland Program provides new and exciting ways to try and tie cosmology and low energy physics to UV physics.
- Although the dSC requires that dark energy is some form of quintessence, the RdSC allows for agreement with current bounds as well as allowing for the possibility of forcing quintessence to be detectable in future experiments
  - 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.
- Theory: Better understanding of c and c' essential to further constraining models and observables
- Experiment: Measurements of the dark energy equation of state are also essential – don't lose hope and get lost in the swamp!

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