De Sitter Swampland Conjecture and Cosmological Applications

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Based on: **H, Mastui**, **F, Takahashi**, **M, Yamada**, arXiv:1807.1193, arXiv:1809.07286.

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Swampland Conjectures

From kitp.ucsb.edu.

The Swampland refers to a class of low-energy effective theories which fail to be UV completed with quantum gravity.

[H. Ooguri and C. Vafa, Nucl. Phys. B766 (2007) 21]

Swampland Conjectures

The difficulty of de Sitter constructions within string theory lead to the De Sitter Swampland Conjecture: The effective scalar potential for self-consistent theory satisfy the criteria,

$$\frac{|\nabla V|}{V} > c\,, \quad \left(\text{or} \quad \min\left(\nabla\nabla V\right) \leq -\bar{c}\, V\right)^{*}$$

where the dimension-dependent constants $c, \bar{c} \sim \mathcal{O}(1)$ and their precise values depend on the string compactification.

$$\text{De Sitter Swampland Conjecture} \;\Rightarrow\; \text{No dS vacuua or minima}$$

*Note that refined swampland conjecture allows dS maxima.

[G. Obied et al., 1806.08362, H. Ooguri et al., 1810.05506]

Swampland and Cosmology

The De Sitter Swampland Conjecture serverly restricts slow-roll inflation. The current CMB bound $\epsilon < 0.0063$ leads to $c \lesssim 0.11$ and the typical Hubble scale is $H_{\rm inf} \sim 10^{14}$ GeV.

$$c = \mathcal{O}(1) \quad \Rightarrow \quad \text{High-scale inflation}$$

Also, the Swampland conjecture excludes the cosmological constant Λ and supports the quintessence φ for dark energy. Adopting a simple exponential potential $V(\varphi) = \Lambda^4 e^{-c\varphi}$, the current DE bound on c reads $c \lesssim 0.6 - 0.9$.

$$\text{No de Sitter minima} \quad \Rightarrow \quad \text{Quintessence e.g. } V(\varphi) = \Lambda^4 e^{-c\varphi}$$

[Others for the de Sitter swampland conjecture: Higgs potential, QCD axion]

DE/DM isocurvature perturbations

- The high-scale inflation and the quintessence DE leads to the isocurvature perturbations of DE. The DM isocurvature is also induced by the interaction e.g., $m_{\mathrm{DM}} \propto e^{-c'\varphi}$.
- The effect of DE isocurvature perturbations appear only at large scales of the CMB anisotropies and the DE bound is much weaker than the DM one.
- The DM isocurvature perturbations can be induced by quintessence fluctuations $\delta\varphi = H_{\mathrm{inf}}/(2\pi)$, $|\delta\rho_{\mathrm{DM}}/\rho_{\mathrm{DM}}| = |\delta m_{\mathrm{DM}}/m_{\mathrm{DM}}| = |c'|$.
- The Planck observation sets a tight bound on the DM isocurvature and leads to the bound on c':

$$\beta_{\mathrm{iso}} \equiv \frac{\mathcal{P}_{\mathrm{II}}}{\mathcal{P}_{\mathrm{RR}} + \mathcal{P}_{\mathrm{II}}} < 0.038 \quad \Rightarrow \quad |c'| < 1.4 \left(\frac{10^{14}\,\mathrm{GeV}}{H_{\mathrm{inf}}} \right).$$

- Also, an upper bound from fifth-force constraint on interaction between DM and quintessence field leads to $|c'| \lesssim 0.3$.

Possible DM Models

Flatness of quintessence field from DM quantum corrections,

$$|c'| \lesssim \frac{m_\varphi}{\sqrt{G} m_{\rm DM}^2} \simeq c \left(\frac{1 \text{ meV}}{m_{\rm DM}} \right)^2 \quad \Rightarrow \quad m_{\rm DM} \lesssim 1 \text{ meV}$$

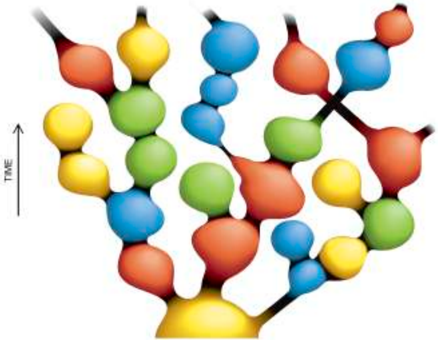
- Fermionic DMs ⇒ Tremaine-Gunn constraint: $m_{\rm DM} \gtrsim \mathcal{O}(100 \text{ eV})$
- Scalar DMs ⇒ Isocurvature perturbation constraints of the CMB are serious for the DMs like axion-like particles.
- Vector DMs ⇒ Isocurvature perturbations of the vector fields are suppressed at large scales and avoids the CMB bounds. The DM density can be naturally induced by the inflationary fluctuations [P. W. Graham et al., Phys Rev D.93.103520]

$$\Omega_{\rm DM} h^2 \simeq 0.1 \left(\frac{m_{\rm DM}}{6 \ \mu\text{eV}} \right)^{1/2} \left(\frac{H_{\rm inf}}{10^{14} \text{ GeV}} \right)^2, \ (\text{Kitajima-san talk})$$

[**H, Mastui**, **F, Takahashi**, **M, Yamada**, arXiv:1809.07286]

Eternal Inflation and Multiverse

Multiverse from Andrei Linde, Stanford University

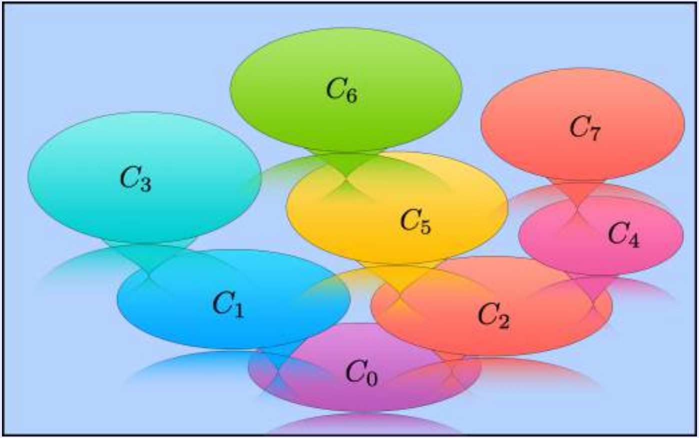


- The most intriguing properties of the inflationary paradigm is that inflation can be eternal. Once the eternal inflation begins, it never ends and continues to create an infinite number of bubble or pocket universes with the different vacua of the landscape.

  [A. D. Linde, Mod. Phys. Lett. A1, 81 (1986), Phys. Lett. B175, 395 (1986).]

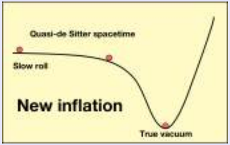
Multiverse and Anthropic Principle

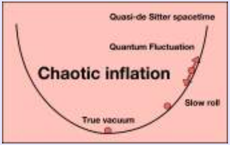
Eternal Inflation + String Landscape $\Rightarrow$ Finetuning Problem



Eternal Inflation vs Swampland

- De Sitter Swampland Conjecture forbids de Sitter vacua or minima.
- The old/hilltop eternal inflation is inconsistent with this criteria.





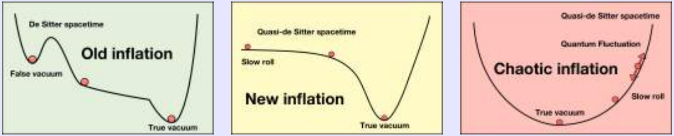
- The chaotic eternal inflation is only possible for $c \sim \mathcal{O}(0.01)$ and the typical Hubble parameter $H_{\rm inf}$ during the eternal inflation is parametrically close to the Planck scale,

$$\frac{\langle\delta\phi\rangle_{\rm quantum}}{\langle\delta\phi\rangle_{\rm classical}} = \frac{H^2}{2\pi|\dot{\phi}|} \gtrsim 1 \quad \Rightarrow \quad 2\pi c \lesssim \frac{H_{\rm inf}}{M_P} < 1/\sqrt{3}.$$

[**H, Mastui**, **F, Takahashi**, arXiv:1807.1193]

Conclusion

- The De Sitter Swampland Conjecture forbids the de Sitter vacua or minima, and tightly restricts the slow-roll inflation and prefers the quintessence scenario (Refined conjecture can relax these bounds).
- The high-scale inflation and quintessence scenario for the dark energy are favored in this conjecture. This scenario leads to DE or DM isocurvature perturbations from the inflationary quintessence fluctuations and favors the vector DM with $m_{\rm DM} \sim \mathcal{O}(10)\ \mu\text{eV}$.
- The De Sitter Swampland Conjecture also constraints the eternal inflation scenarios and the Multiverse.



- The chaotic eternal inflation is only possible for $c \sim \mathcal{O}(0.01)$ and the Hubble parameter is tightly constrained, $2\pi c \lesssim H_{\rm inf}/M_{\rm P} < 1/\sqrt{3}$.