Higgs Inflation
and
the Refined dS Conjecture

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Higgs Inflation

Inflationary Cosmology – Why Inflation?

- "A theory of *exponential expansion* of space in the early universe"
  - Horizon & Flatness Problem

  - Wikipedia
  - Initial Fluctuations → Large Scale Structure

- Each Inflation model has an expected values of spectral index(n_s) and scalar to tensor ration(r).

Inflationary Cosmology – Why Inflation?

- Slow roll parameters

$$\epsilon_V = \frac{M_{\rm pl}^2}{2}\left(\frac{V'}{V}\right)^2$$

$$\eta_V = -M_{\rm pl}^2 \frac{V''}{V}$$

- Relations between $\{n_s, r\}$ & $\{\epsilon_V, \eta_V\}$

$$n_s = 1 - 6\epsilon_V + 2\eta_V$$

$$r = 16\epsilon_V$$

Higgs Inflation

- "The Standard Model Higgs boson as the *inflaton*"

[Fedor Bezrukov, Mikhail Shaposhnikov (2008)]

arXiv:0710.3755

- Non-minimal coupling to Ricci scalar is assumed.

$$S = \int d^4x \sqrt{-g} \left\{ \frac{M_P^2}{2} R + \xi H^\dagger H R + \mathcal{L}_{\rm SM} \right\}$$

Higgs Inflation

$$V_J(h) = \lambda(h^2 - v^2)^2$$

Unitary gauge

$H = h/\sqrt{2}$

$$S = \int d^4x\sqrt{-g}\left\{\frac{M_P^2 + \xi h^2}{2}R - \frac{1}{2}|\partial_\mu h|^2 - V_J(h)\right\}$$

Removing Non-minimal Coupling

Weyl Transformation

$g_{\mu\nu}^E = \Omega^2 g_{\mu\nu}^J$

$\Omega^2 = 1 + \frac{\xi h^2}{M_P^2}$

$$S_E = \int d^4x\sqrt{-g_E}\left\{\frac{1}{2}R_E - \frac{1}{2}F(h)|\partial_\mu h|^2 - \frac{V_J(h)}{\Omega^4}\right\}$$

$$V(h) \approx \begin{cases} \frac{\lambda}{\xi^2}\left(1 + e^{-\sqrt{\frac{2}{3}}h}\right)^{-2} & \text{at} \quad \sqrt{\xi}h_J(h) \gg 1 \\ \lambda\left(h^2 - v^2\right)^2 & \text{at} \quad \sqrt{\xi}h_J(h) \ll 1 \end{cases}$$

Canonical kinetic term

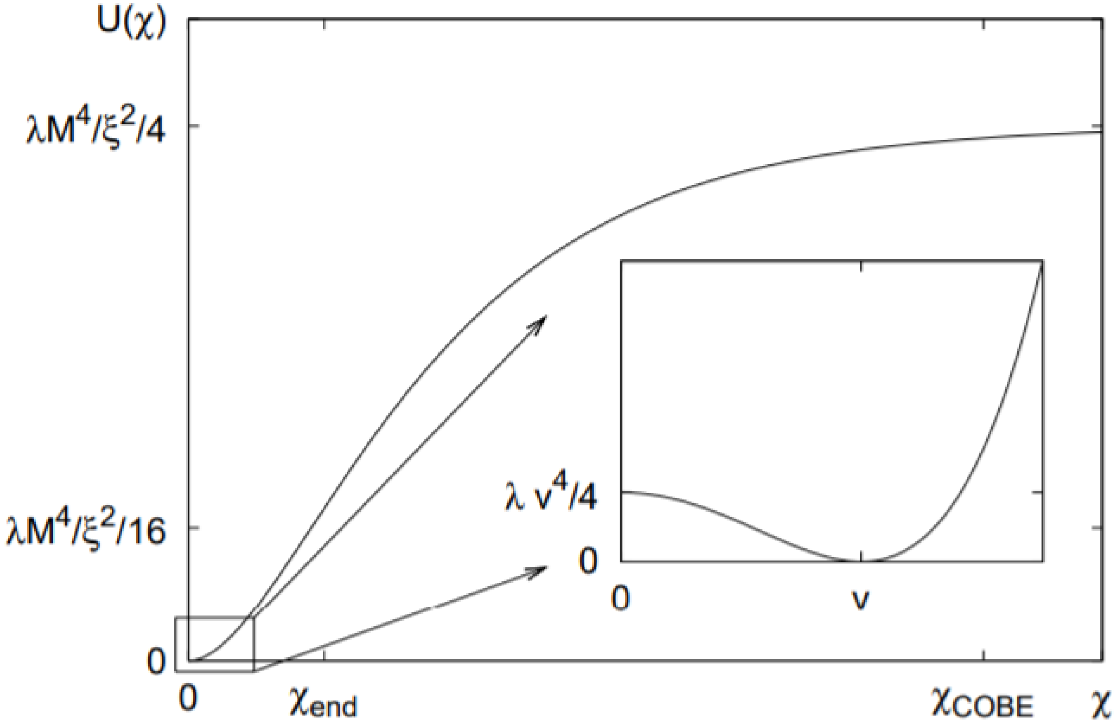
Field Redefinition

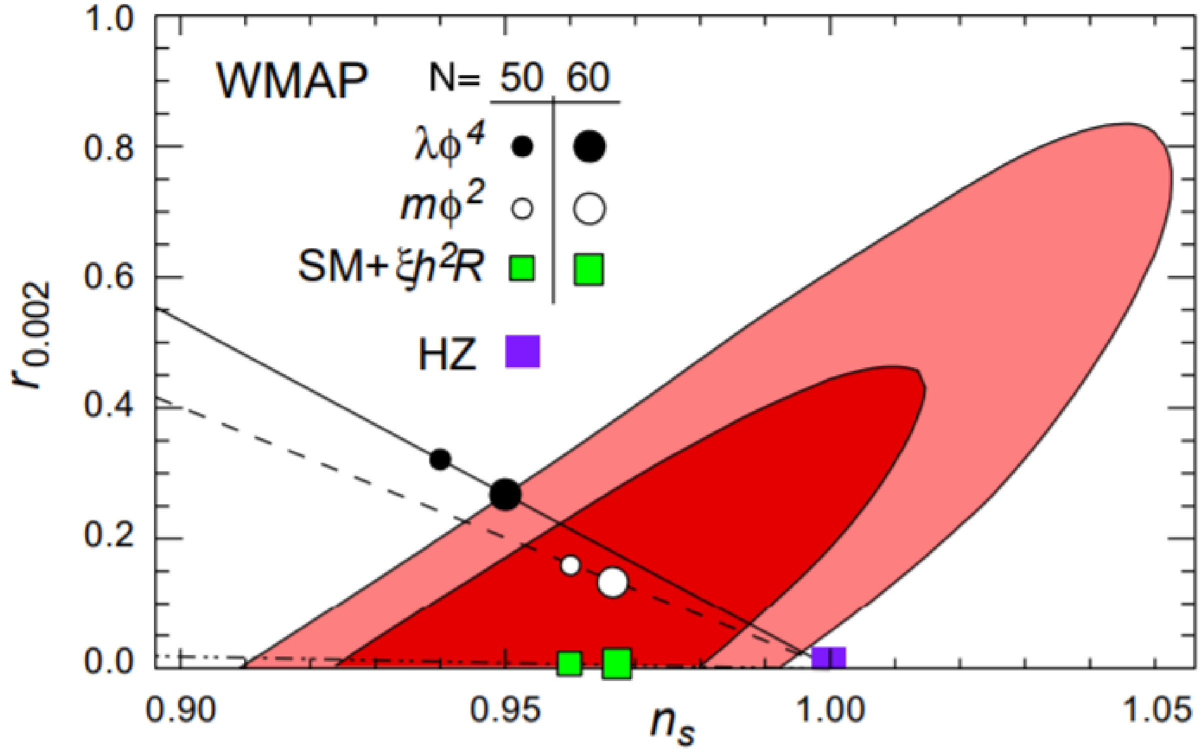
$$F(h) = \frac{\Omega^2 + 6\xi^2 h^2}{\Omega^4} = \frac{1 + \left(\xi + 6\xi^2\right)h^2}{(1 + \xi h^2)^2}$$

$$\frac{dh_E}{dh} \equiv \sqrt{F(h)} = \sqrt{\frac{\Omega^2 + 6\xi^2 h^2}{\Omega^4}}$$

Higgs Inflation

[Fedor Bezrukov, Mikhail Shaposhnikov, 2008]





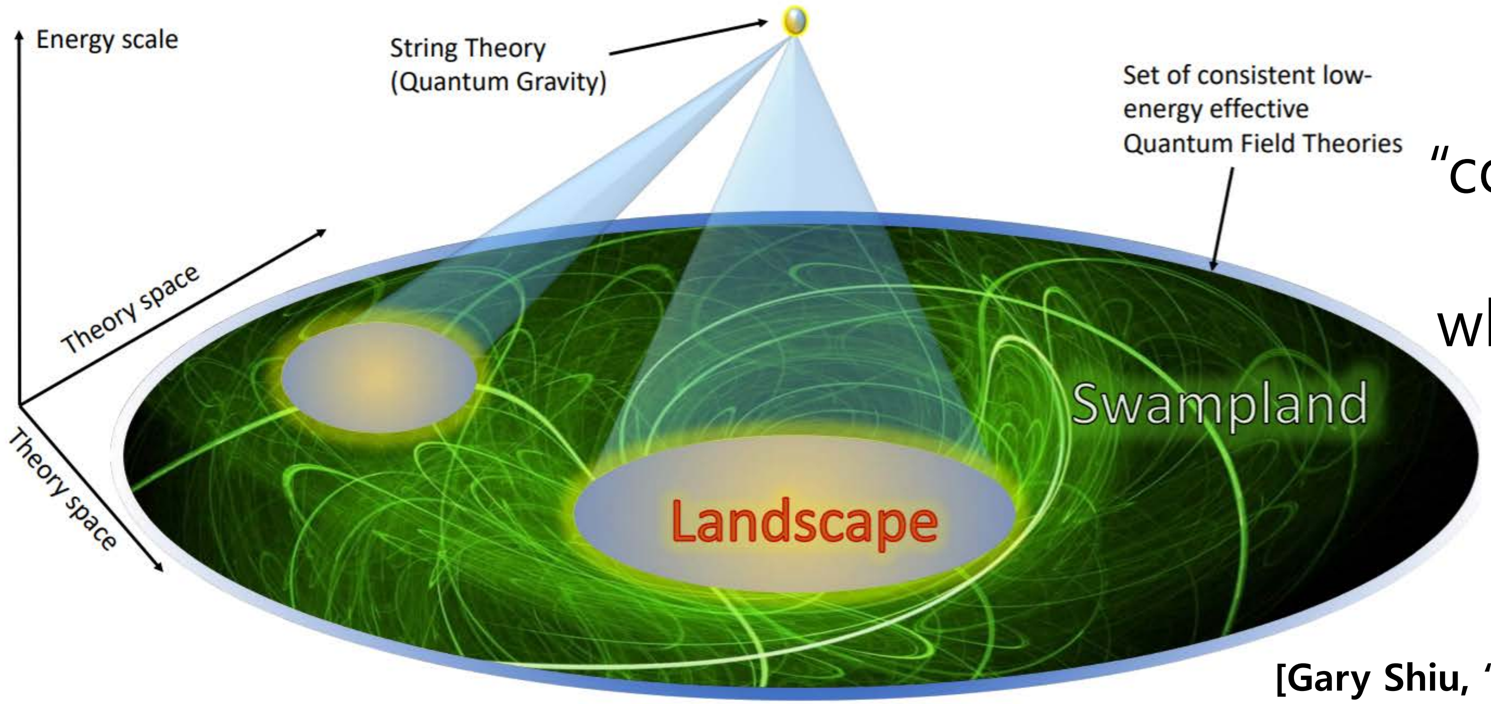
$N \simeq 60 \qquad \xi \simeq 47200\sqrt{\lambda}$

Inflationary predictions : $n_s \simeq 0.966 \quad r \simeq 0.0034$

De Sitter Conjecture

Swampland Conjecture

- For a quantum gravity theory (string theory) to be consistent with low energy effective theory (standard model), so-called *Swampland Conjecture* has to be satisfied. **[C. Vafa (2005)]** **arXiv:hep-th/0509212**



"consistent-looking semiclassical effective field theories, which are actually *inconsistent*."

[Gary Shiu, "QG and the Swampland"]

de Sitter(dS) Derivative Conjecture

- (Refined) de Sitter derivative conjecture

[G. Obied, H. Ooguri, L. Spodyneiko, and C. Vafa (2018)]
arXiv:1806.08362

De Sitter space
In quantum gravity

$$M_P ||\nabla V|| \geq c_1 V$$

OR

Black hole entropy argument
Distance conjecture

[H. Ooguri, E. Palti, G. Shiu, and C. Vafa (2018)]
arXiv:1810.05506

$$M_P^2 \min \left(\nabla_i \nabla_j V \right) \leq -c_2 V$$

$$c_1, c_2 : \mathcal{O}(1)$$

Analysis & Results

Bound from the Observation

De Sitter conjecture ⇔ Slow roll parameters

$$F_1(h) \equiv \frac{|dV/dh|}{V} \qquad F_2(h) \equiv \frac{d^2V/dh^2}{V}$$

$$n_s = 1 - 6\epsilon_V + 2\eta_V = 1 - 3F_1(h_*)^2 + 2F_2(h_*)$$

$$r = 16\epsilon_V = 8F_1(h_*)^2$$

REMINDER

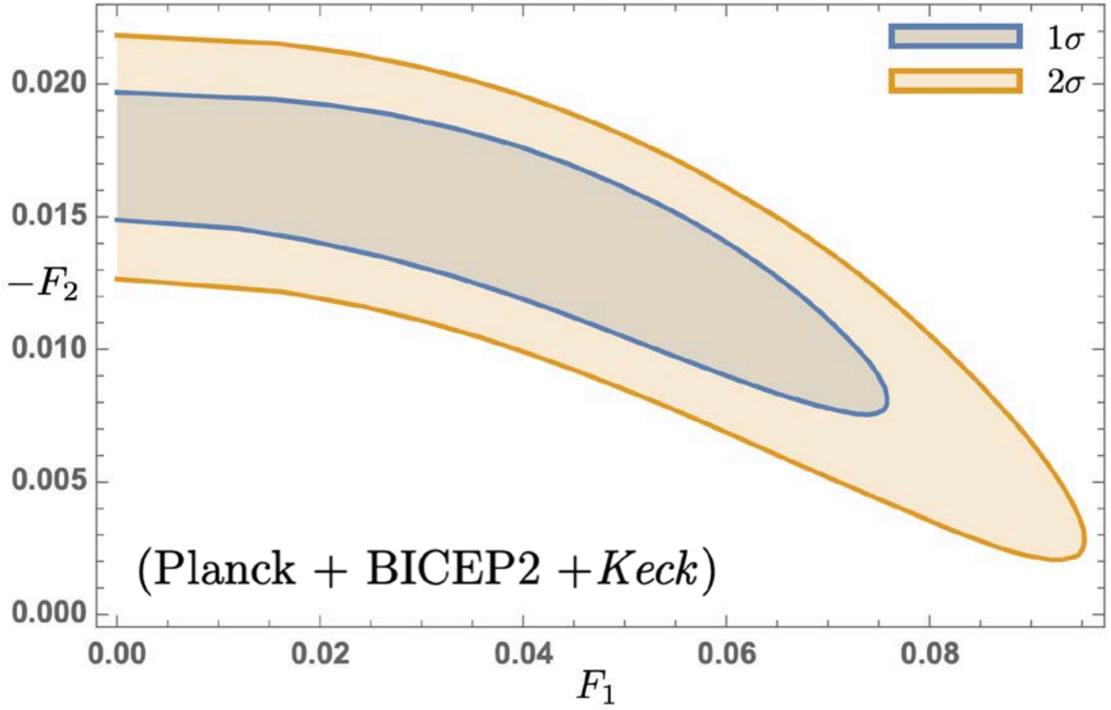
$$M_P||\nabla V|| \geq c_1 V$$

$$M_P^2 \min(\nabla_i \nabla_j V) \leq -c_2 V$$

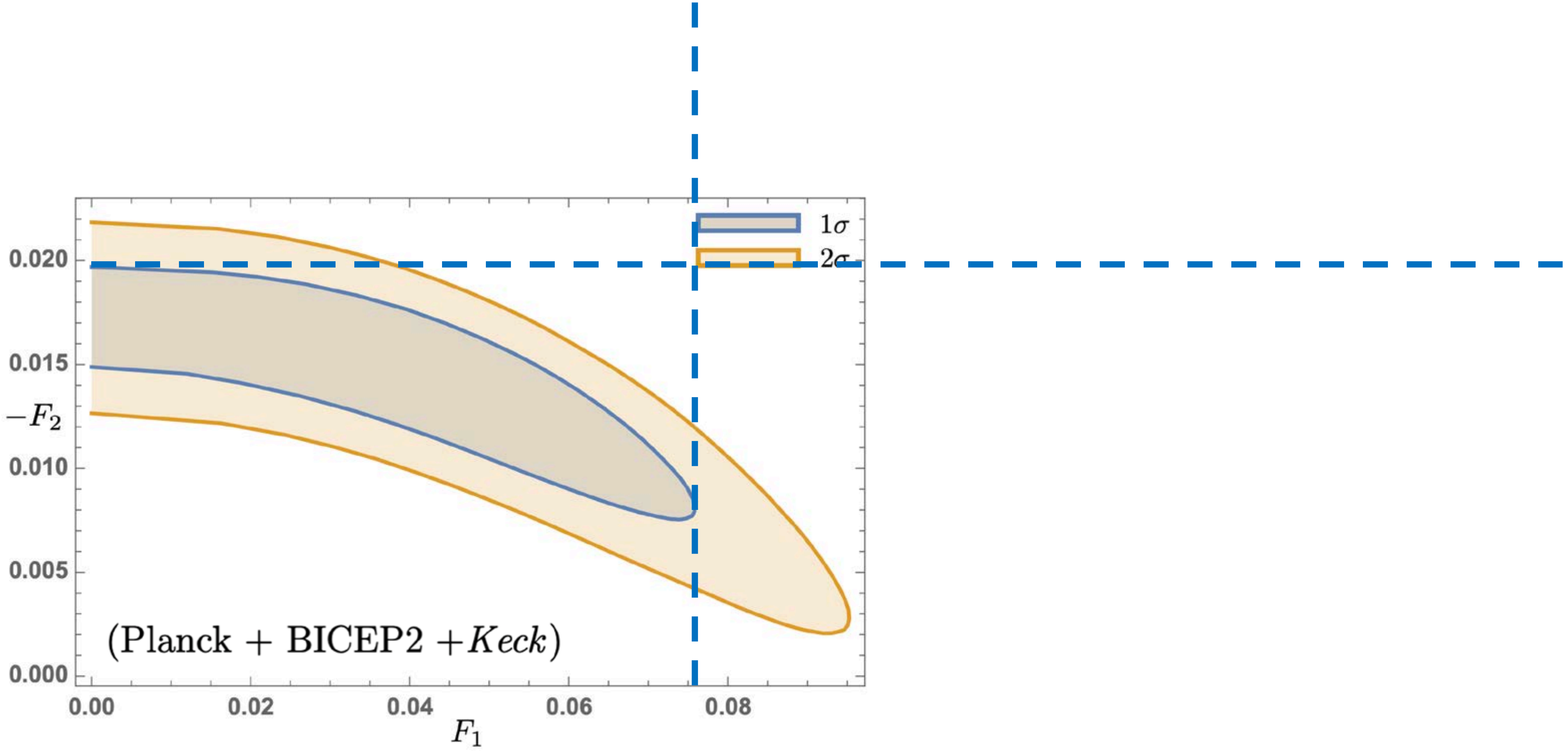
Equivalently,

$$c_1 \leq F_1(h_*) = \sqrt{2\epsilon_V} = \sqrt{\frac{r}{8}} \qquad c_2 \leq -F_2(h_*) = -\eta_V = \frac{1 - n_s - 3r/8}{2}$$

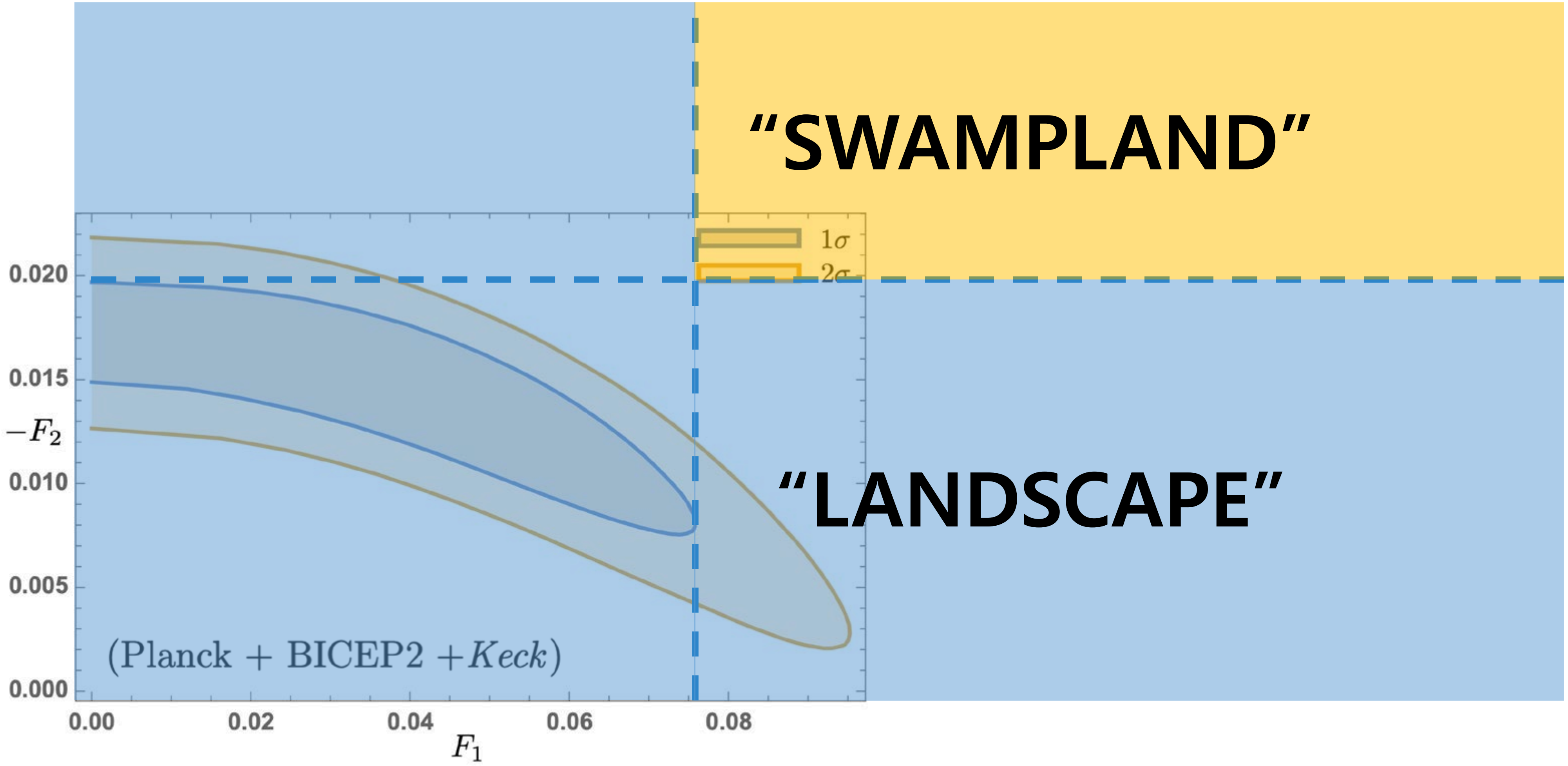
Bound from the Observation



Bound from the Observation



Bound from the Observation



Bound from the Higgs inflation

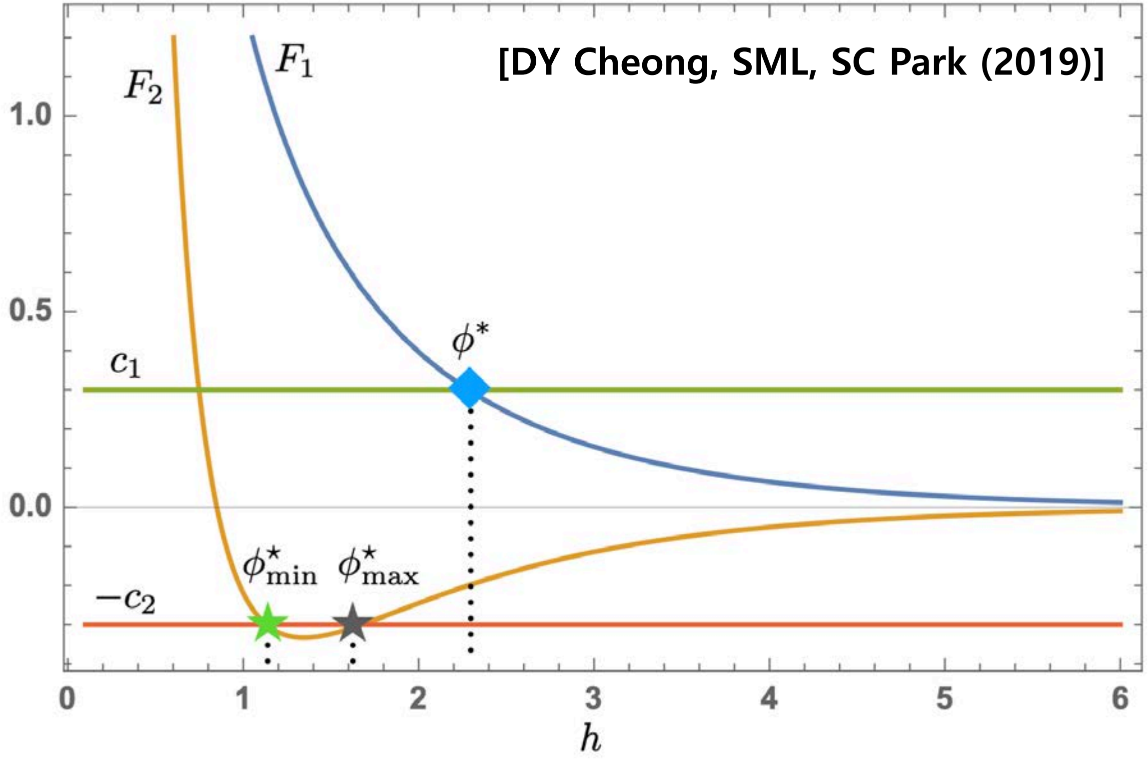
Condition1.

$$F_1(h) \geq c_1 \Leftrightarrow h \leq \phi^* = F_1^{-1}(c_1)$$

Condition2.

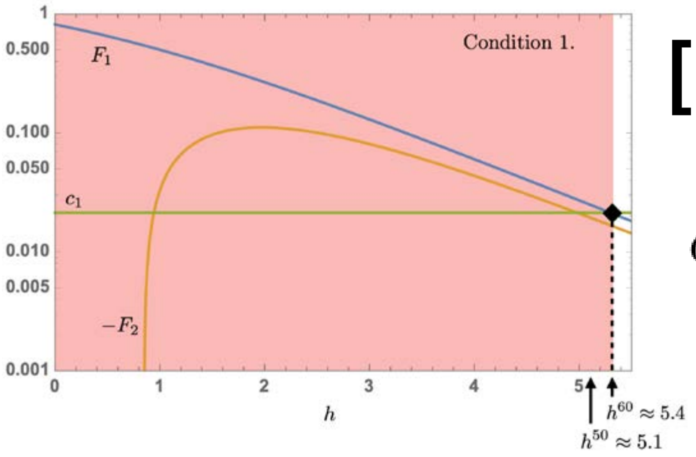
$$F_2(h) \leq -c_2 \Leftrightarrow h \in [\phi^\star_{\rm min}, \phi^\star_{\rm max}]$$

$$\phi^\star_{\rm min}, \phi^\star_{\rm max} : F_2^{-1}(-c_2)$$



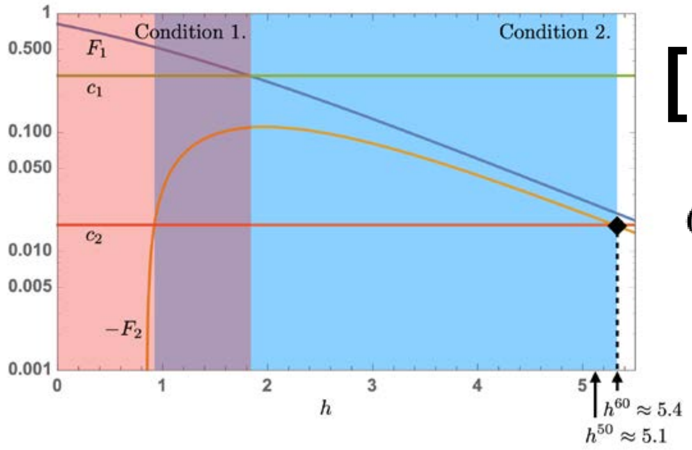
For 60(50) e-folds, $h_* \approx 5.4(5.1)$

Bound from the Higgs inflation



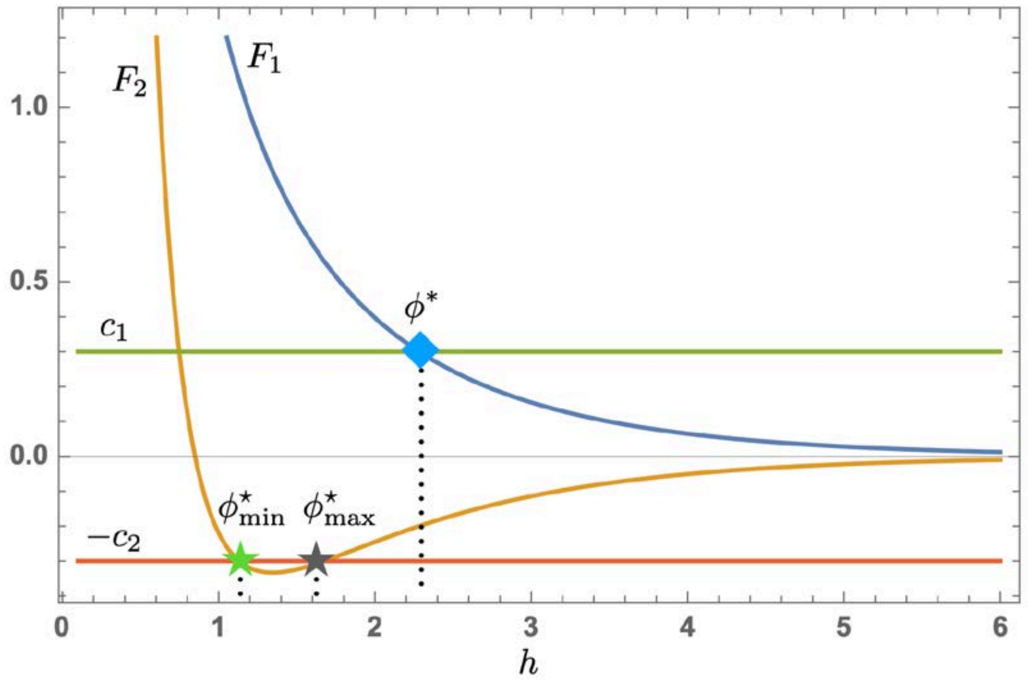
[Case1]

$$\phi^* \geq h_* \Leftrightarrow c_1 \leq F_1(h_*)$$

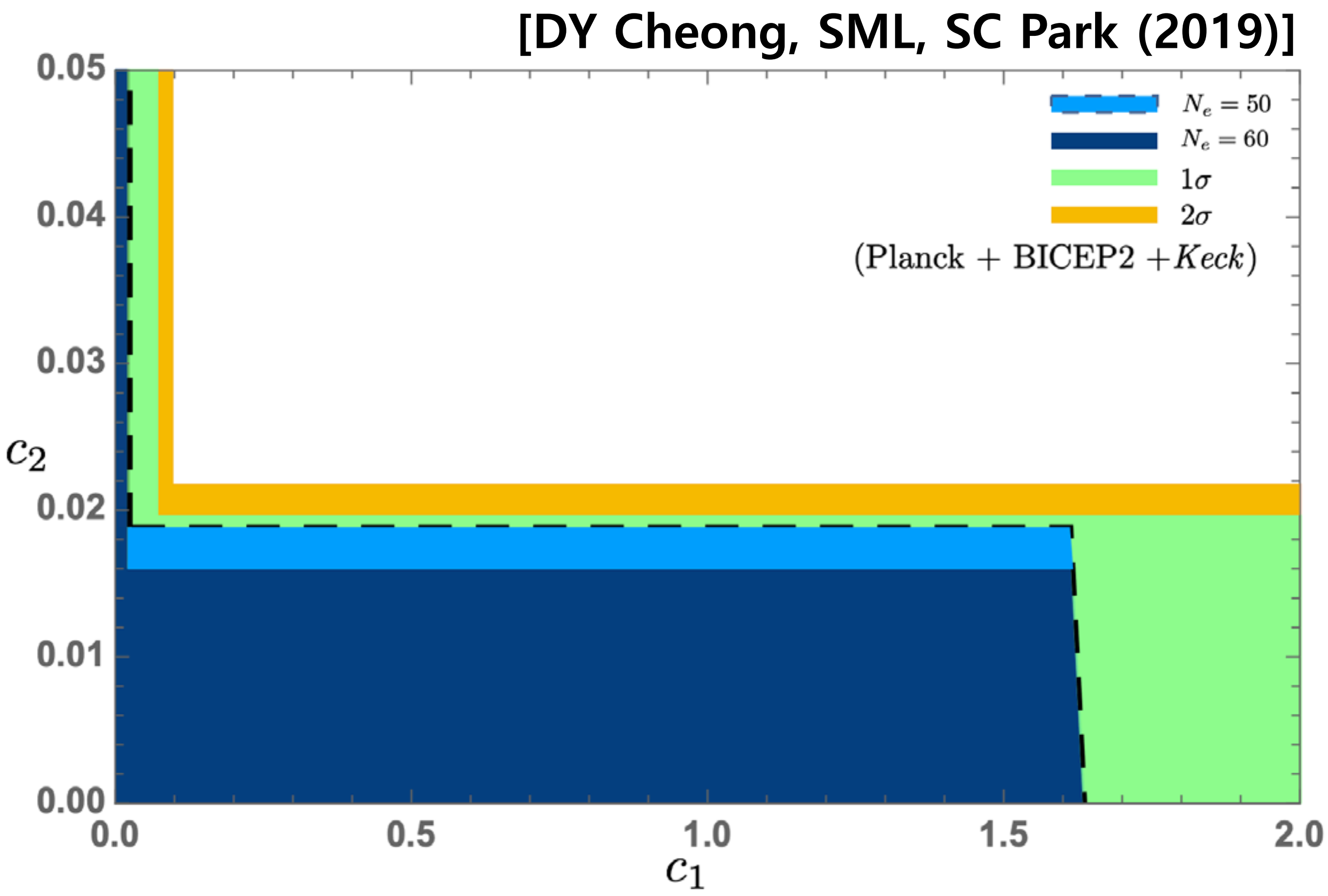


[Case2]

$$\phi^\star_{\max} \geq h_* \text{ and } \phi^* \geq \phi^\star_{\min}$$
$$\Leftrightarrow c_2 \leq -F_2(h_*) \text{ and } c_1 \leq F_1(\phi^\star_{\min})$$



Results & Implications



- c_1 & $c_2 \sim O(1)$ is not satisfied simultaneously just from the observation
- Requirement of $c_2 \sim O(1)$ is not strict
  → Still possible to be in the landscape
- In HI case, absolute bound for c_1 is ~1.6
- Adding Condition2 is crucial for HI to be in the landscape

Summary

- Recently proposed dS conjecture provides the direct criterion for the consistency between QG and the low energy effective theories.

- Slow-roll single field Inflation models can be in the landscape region, although it is in the disfavored region. ($c_2 \sim O(0.01)$)

  → More precise statement/argument is demanded.

- Other inflationary models (e.g. quintessence, multi-field inflation) are also needed to be considered.

THANK YOU!

ありがとうございます