Quintessence Saves Higgs Instability

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Based on arXiv:1809.05507, with Shi Pi and Misao Sasaki

Beyond the BSM

The 4th Kavli IPMU -Durham IPPP -KEK -KIAS workshop

Outline

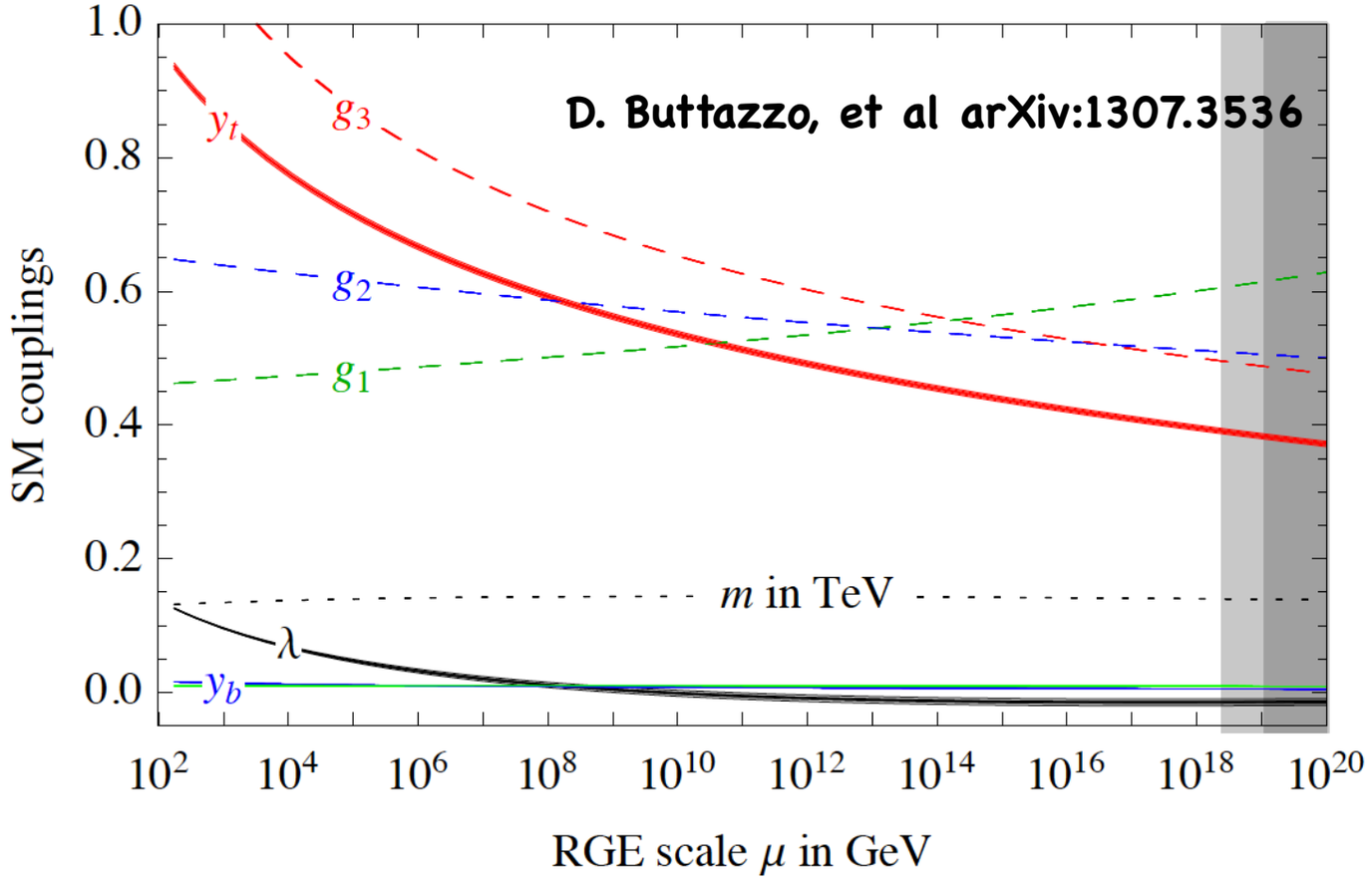
- The Higgs instability problem
- Quintessence-Higgs Model
- Swampland conjecture

Higgs potential and self coupling

In SM, the Higgs potential is:

$$V = \lambda(\mathcal{H}^\dagger\mathcal{H} - v^2)^2 \qquad \lambda \sim 0.13 \quad v \sim 174\ \text{GeV}$$

$$\frac{d\lambda}{d\ln\mu^2} = \frac{1}{(4\pi)^2}\left[\lambda\left(12\lambda + 6y_t^2 - \frac{9g_2^2}{2} - \frac{9g_1^2}{10}\right) - 3y_t^4 + \frac{9g_2^4}{16} + \frac{27g_1^4}{400} + \frac{9g_2^2g_1^2}{40}\right]$$



Higgs potential and self coupling

To study the vacuum structure of the Higgs, RG-improved effective potential:

For $h \gg v$

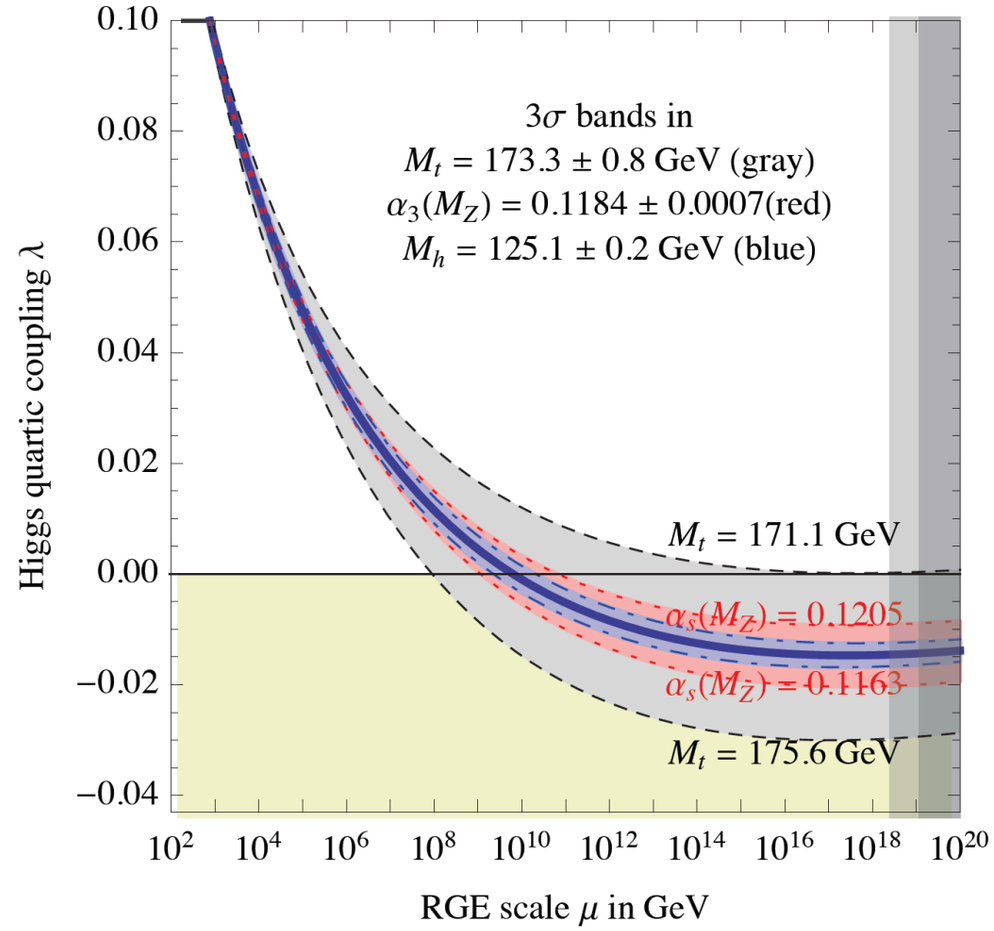
$$V_{\rm eff} = \lambda_{\rm eff}(h)\frac{h^4}{4}$$

$$\lambda_{\rm eff}(h) = e^{4\Gamma(h)}\left[\lambda(\bar{\mu}=h) + \lambda^{(1)}_{\rm eff}(\bar{\mu}=h) + \lambda^{(2)}_{\rm eff}(\bar{\mu}=h)\right]$$

$$\Gamma(h) \equiv \int \gamma(\mu) d\ln\mu$$

γ is the Higgs field anomalous dimension

D. Buttazzo, et al arXiv:1307.3536

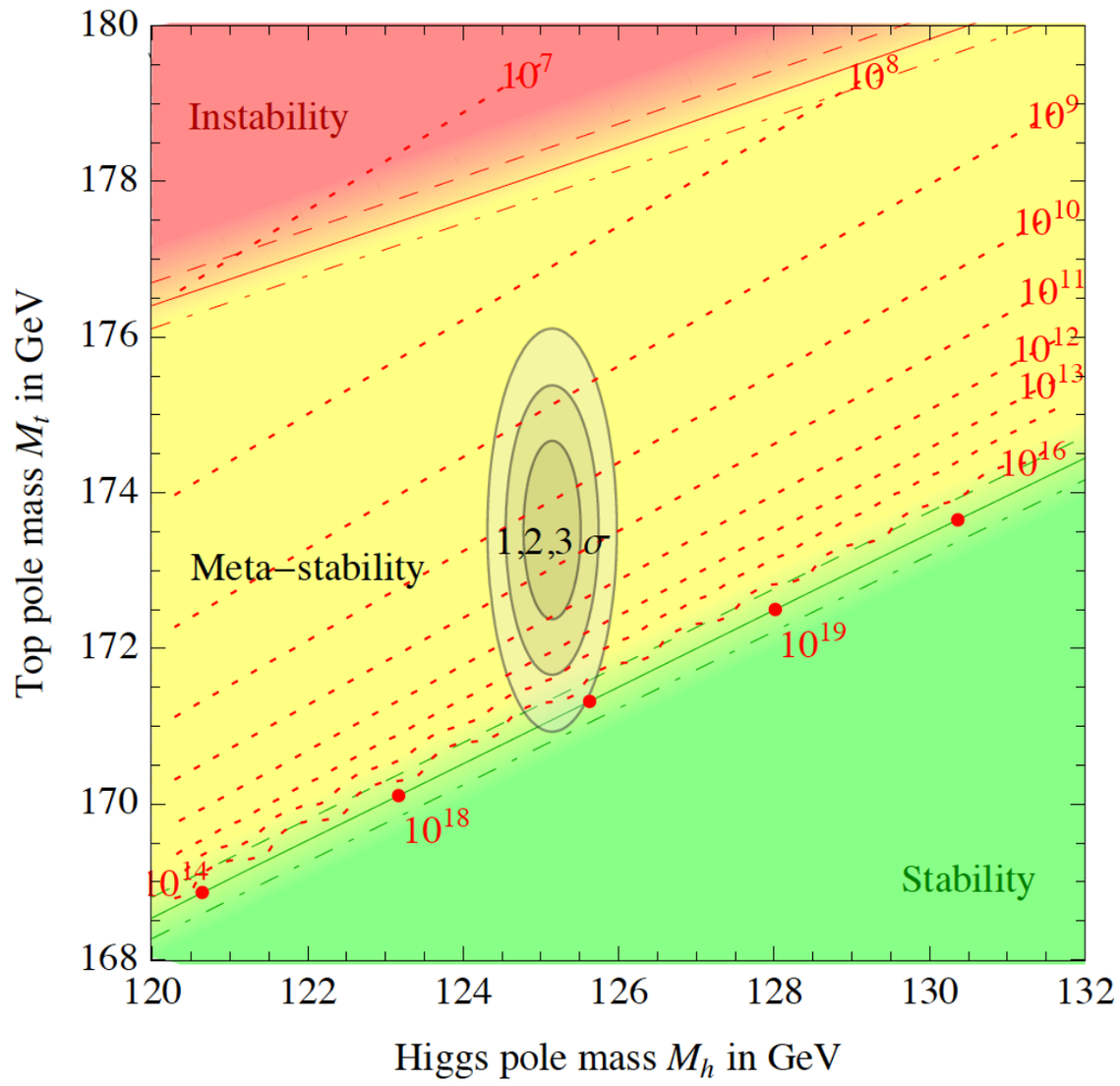


New stable vacuum is developed at high energy scale!

Higgs stability

Should we worried about this?

D. Buttazzo, et al arXiv:1307.3536



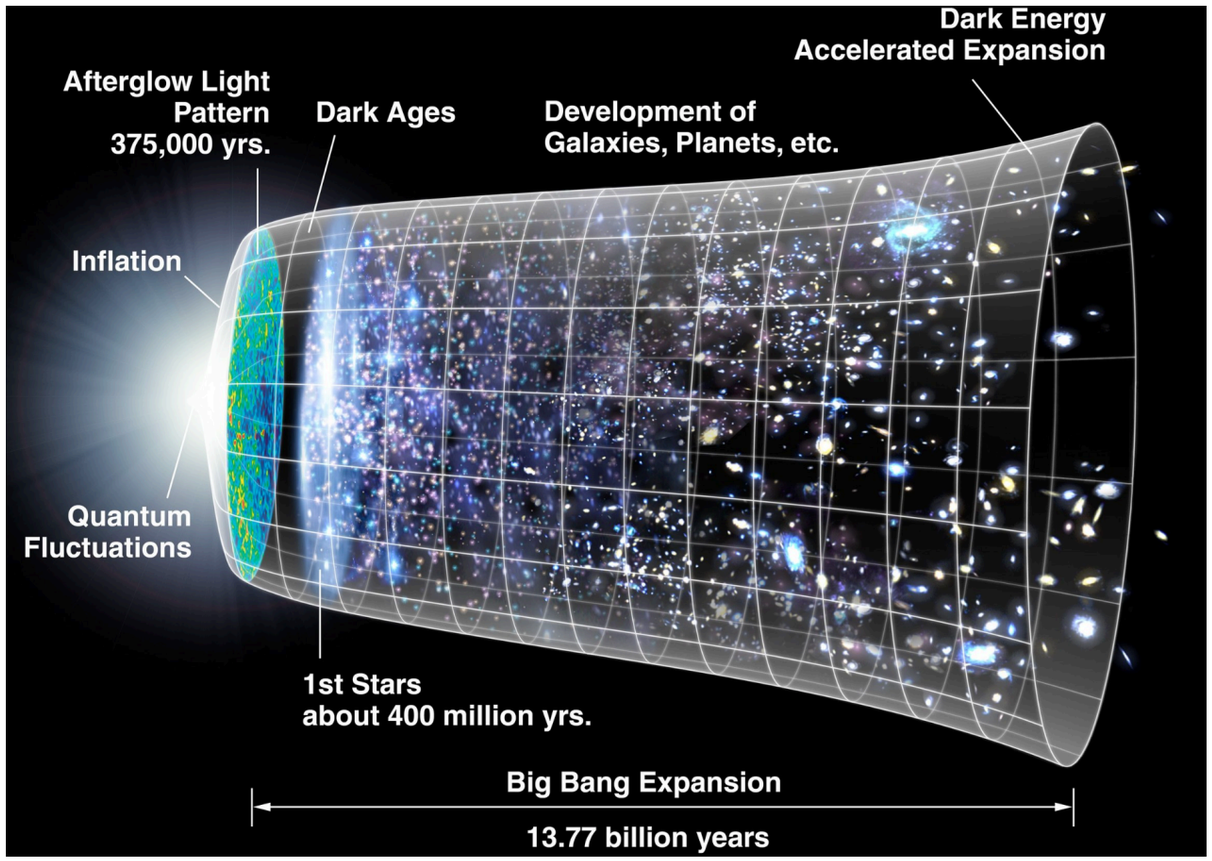
Fortunately for human being: electroweak vacuum is metastable!

(maybe not that fortunate for people who study new physics)

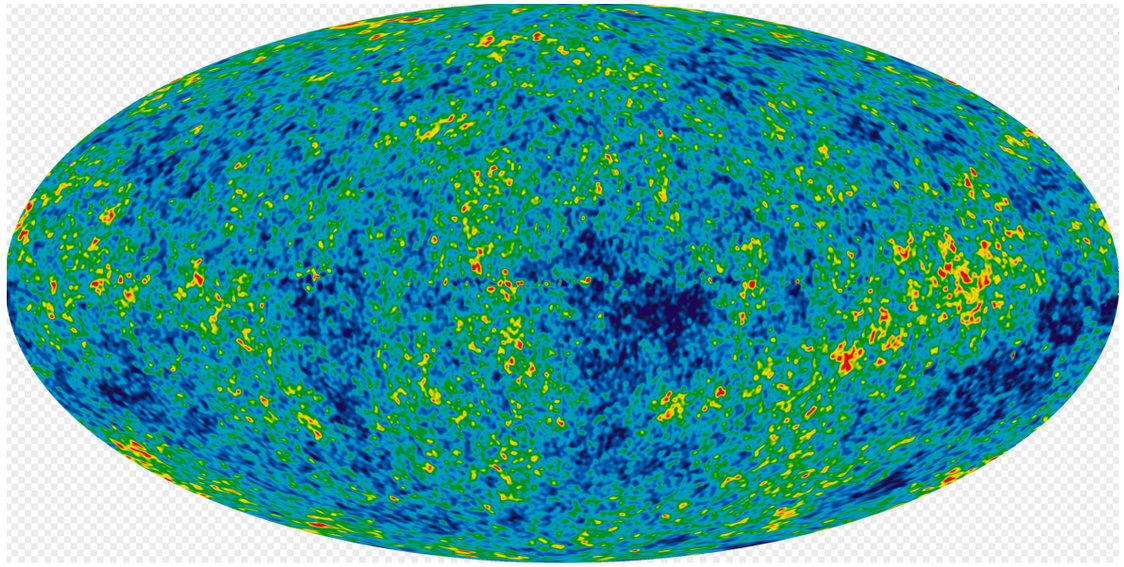
Up to here
No Higgs instability problem

But this is not the end of the story

Inflation

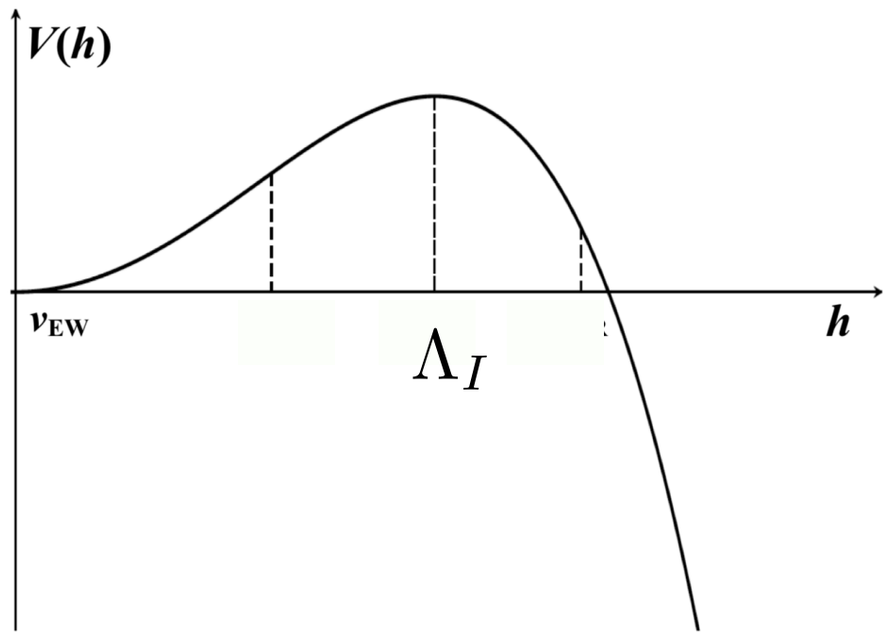


fluctuations in CMB



- Explains the origin of the large-scale structure of the cosmos.
- Horizon problem
- Flatness problem
- Magnetic-monopole problem …

Higgs instability during inflation



$$\Lambda_I \sim 10^{10}\ \mathrm{GeV}$$

Surviving probability per horizon

J. R. Espinosa, et al arXiv:1505.04825

$$P(h < \Lambda_I, N_{\rm tot}) = erf(\frac{\sqrt{2}\pi\Lambda_I}{H_{\rm inf}\sqrt{N_{\rm tot}}}) \qquad erf(x) \simeq 1 - \frac{1}{\sqrt{\pi}x}e^{-x^2}$$

Total $e^{3N_{\rm hor}}$ **horizons**

Surviving probability $1-(1-P)^{e^{3N_{\rm hor}}}$

For $N_{\rm hor} = 60, N_{\rm tot} = 1000,$ we need $H_{\rm inf} < 10^{-2}\Lambda_I$

So-called Higgs instability problem during inflation

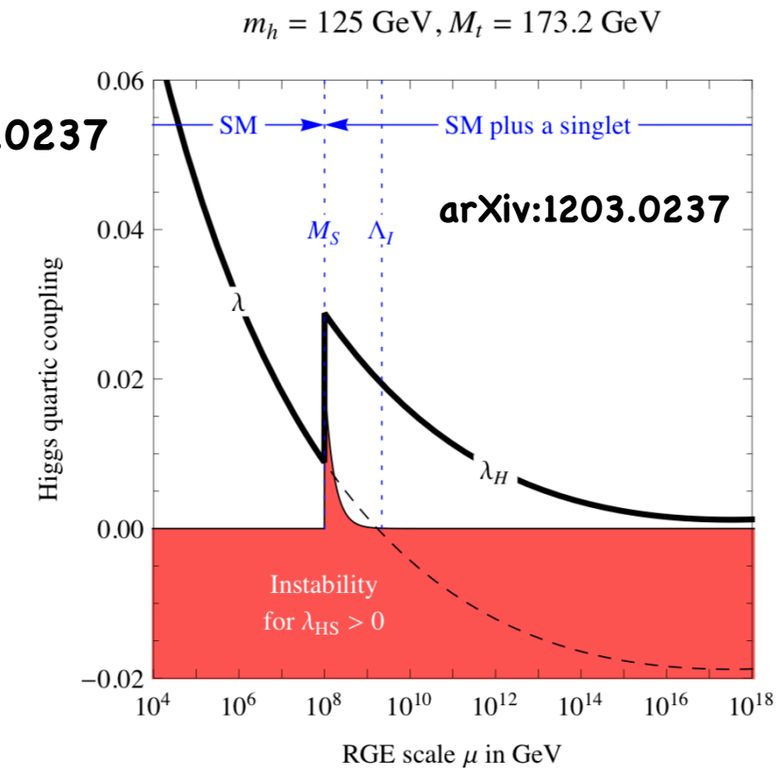
recent review, see arXiv:1809.06923

Some solutions

- Add new field to change Higgs self coupling.

J. Elias-Miró, J. R. Espinosa, G. F. Giudice, Hyun Min Lee, A. Strumia, arXiv:1203.0237

$$V_0 = \lambda_H \left(H^\dagger H - v^2/2\right)^2 + \lambda_S \left(S^\dagger S - w^2/2\right)^2 + 2\lambda_{HS} \left(H^\dagger H - v^2/2\right)\left(S^\dagger S - w^2/2\right)$$



- Add Higgs coupling to inflaton.

O. Lebedev, A. Westphal, arXiv:1210.6987

$$\mathcal{L} \supset \xi \phi^2 h^2$$

- Higgs self coupling is dynamical: changing with time.

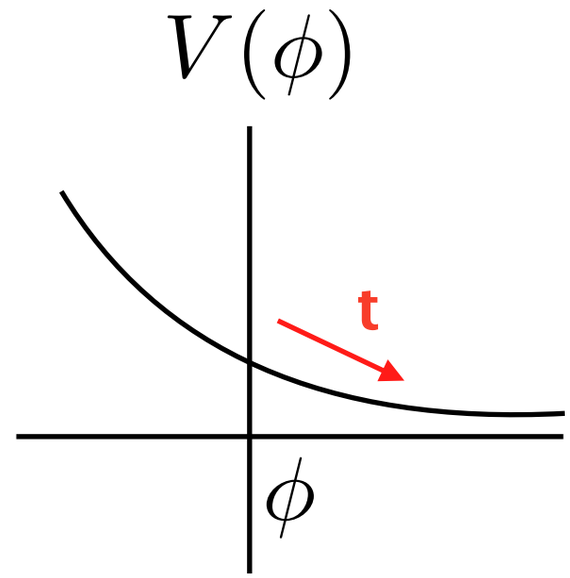
C. Han, Shi Pi and Misao Sasaki, arXiv:1809.05507

Do we have a dynamical field at hand?

Quintessence as an explanation of dark energy

E. J Copeland, A. R Liddle, D. Wands, arXiv:9711068

$$V(\phi) = e^{-\xi\phi}\Lambda_0$$



Smaller in future, larger in the past!
Fit our requirement perfectly.

Quintessence-Higgs Model

F. Denef, A. Hebecker, T. Wrase, arXiv:1807.06581

$$V(\phi, \mathcal{H}) = e^{-\xi\phi}\left(\lambda\left(|\mathcal{H}|^2 - v^2\right)^2 + \Lambda\right) \quad (\xi > 0)$$

Potentially solve the higgs instability problem,

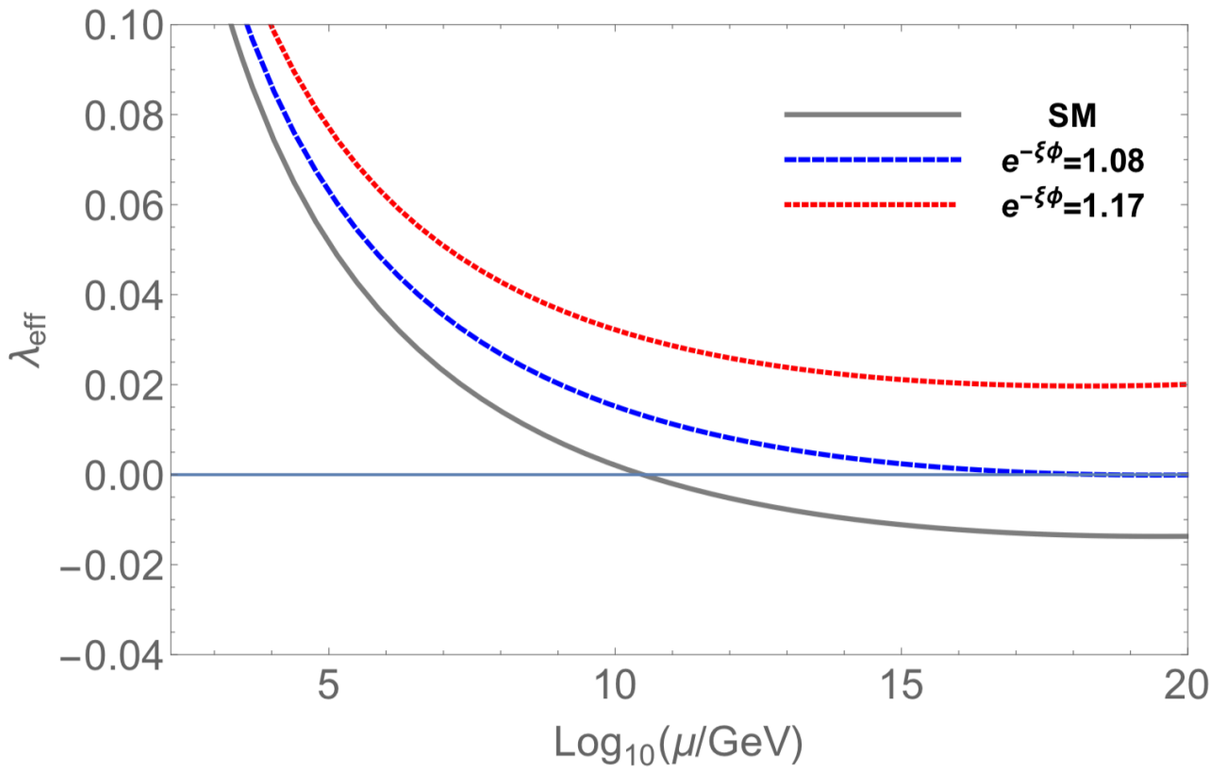
- **How large enhancement do we need?**
- **Whether quintessence provide such a factor?**
- **How to test it?**

How large enhancement do we need?

Just effectively change the higgs self coupling $\lambda'(v) = \lambda(v)e^{-\xi\phi}$

$$\lambda_{\rm eff}(h) = e^{4\Gamma(h)}\left[\lambda'(h) + \lambda^{(1)}(h) + \lambda^{(2)}(h)\right]$$

C. Han, Shi Pi and Misao Sasaki, arXiv:1809.05507



$$e^{-\xi\phi} > 1.08 \pm 0.02$$

Whether quintessence provide such a factor?

C. Han, Shi Pi and Misao Sasaki, arXiv:1809.05507

$$H^2 = H_0^2 \left[\Omega_{\gamma 0} \left(\frac{a_0}{a} \right)^4 + \Omega_{m0} \left(\frac{a_0}{a} \right)^3 + e^{-\xi\phi} \left(\frac{\lambda \left(|\mathcal{H}|^2 - v^2 \right)^2}{3 M_{\rm Pl}^2 H_0^2} + \Omega_{\Lambda 0} \right) \right],$$

$$0 = \ddot{\phi} + 3H\dot{\phi} - \xi e^{-\xi\phi} \left(\lambda \left(|\mathcal{H}|^2 - v^2 \right)^2 + \Lambda \right),$$

$$e^{\xi\phi} = \left(\frac{\Omega_{m0}}{\Omega_{\Lambda 0}} \right)^{\frac{\xi^2}{3}} - \frac{\xi^2}{3} \left[1 + \mathcal{O}\left(\frac{\lambda}{g_{s*\rm EW}} \left(\frac{v}{T_{\rm EW}} \right)^4 \right) \right]$$

$$\xi > 0.35 \pm 0.05$$

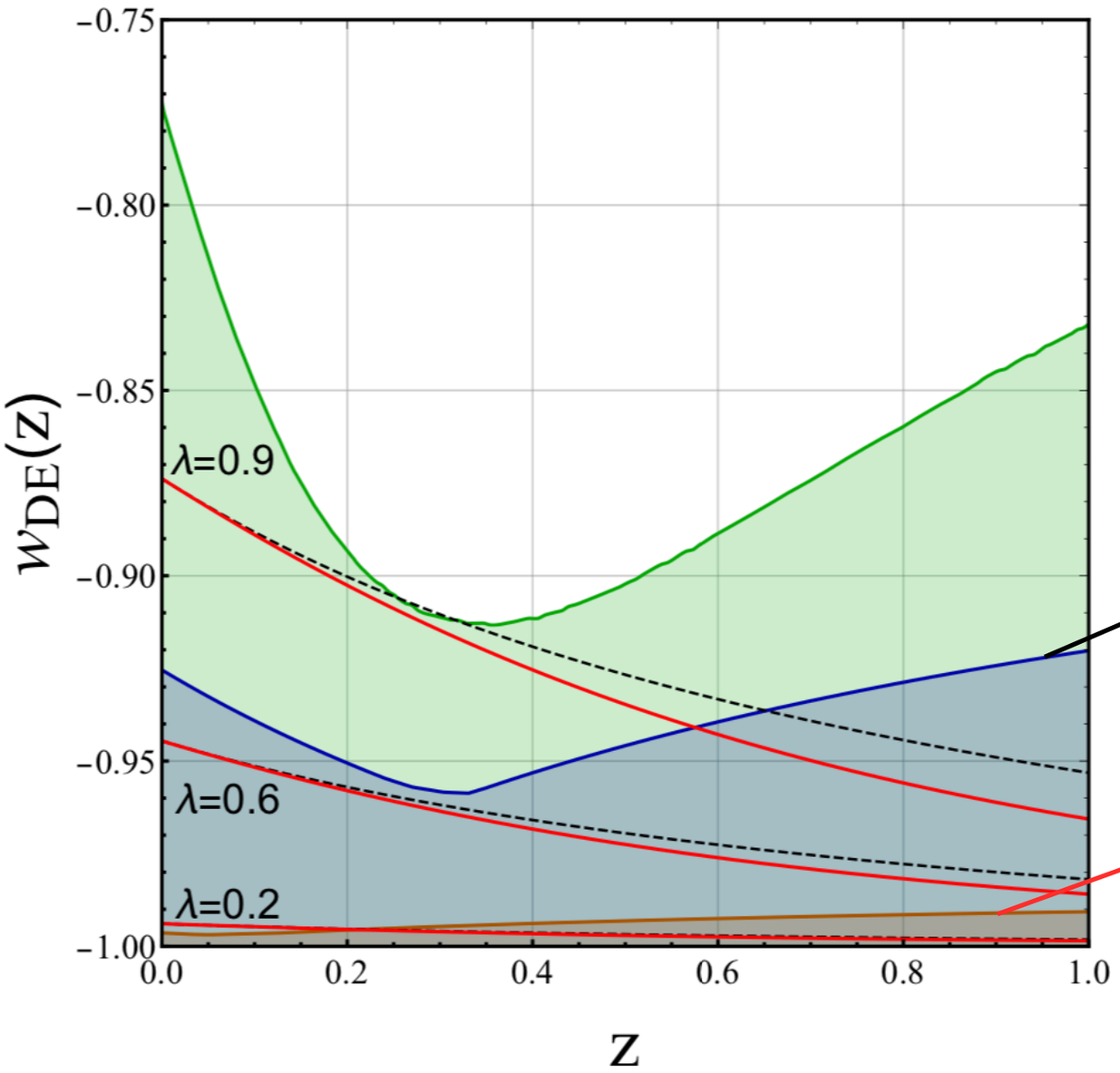
From Planck 2018

Ω_Λ	0.679 ± 0.013
$\Omega_{\rm m}$	0.321 ± 0.013

How to test it?

Dark energy experiment already exclude $\xi > 0.6$

Y. Akrami, R. Kallosh, A. Linde, V. Vardanyan, arxiv:1808.09440

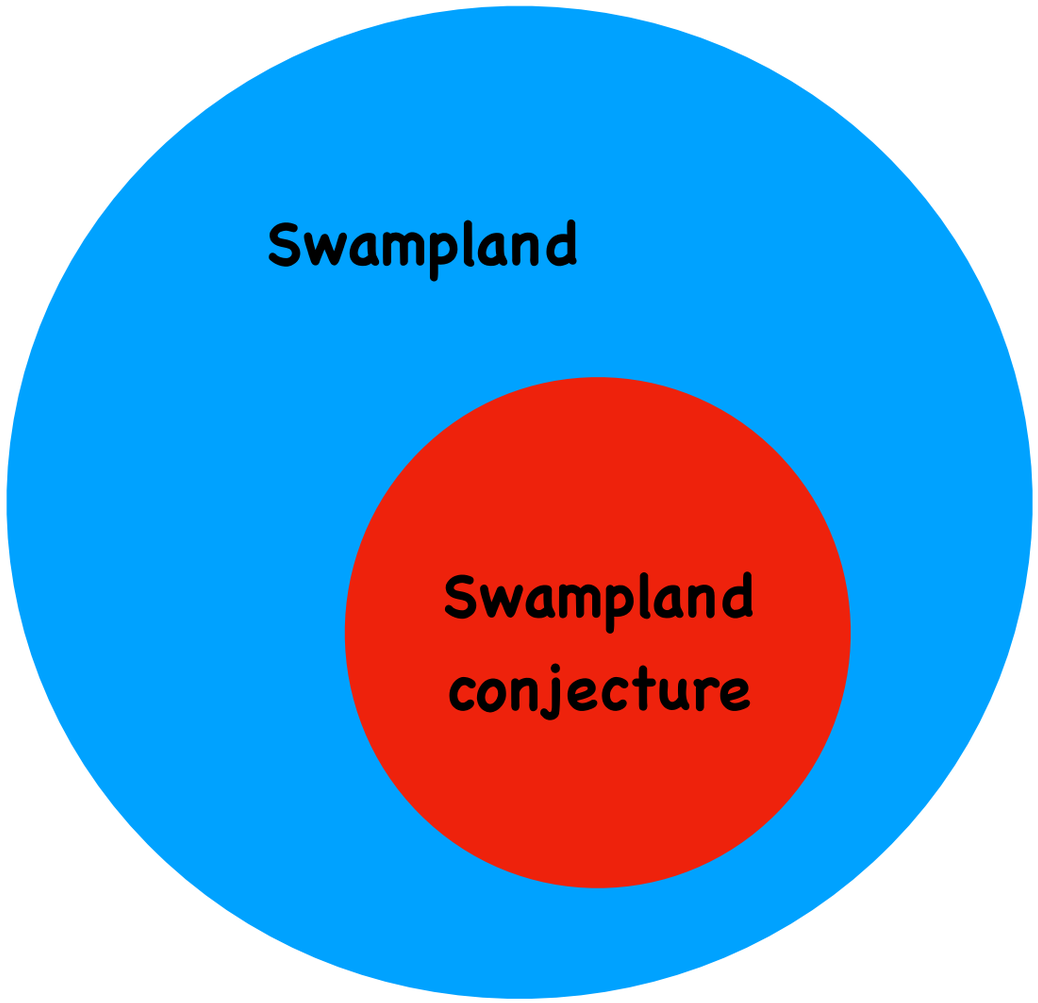


Exclusion limit combing SNeIa, CMB, BAO, H_0

Future reach: Euclid and the SKA (large-scale structure surveys) (within 10 years)

Swampland Conjecture(my own understanding)

All the theories not consistent with quantum gravity is swampland.



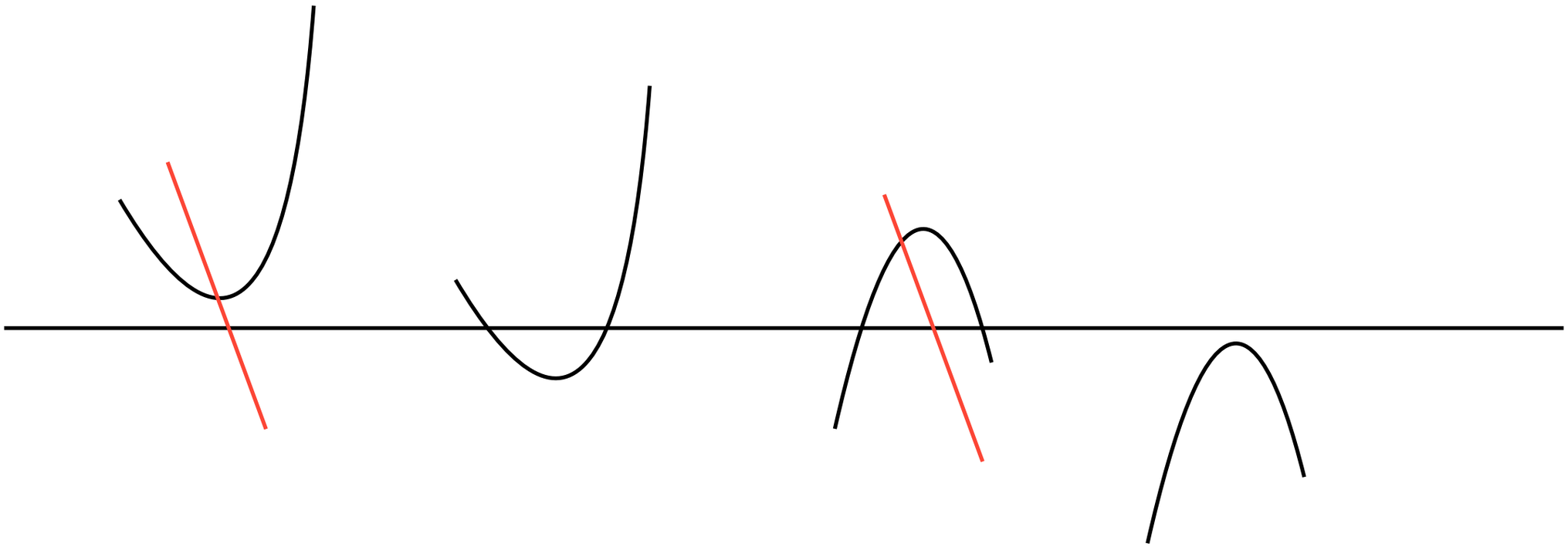
G. Obied, H. Ooguri, L. Spodyneiko, C. Vafa, arXiv:1806.08362

Swampland conjecture: a quantum gravity theory should satisfy:

$$|\nabla V|/V > c, c \sim O(1) \qquad ||\nabla V_{\rm total}|| = \sqrt{\sum_{i,j} g^{ij}_{\rm conf} (\partial_{\phi_i} V_{\rm total})(\partial_{\phi_j} V_{\rm total})}\ ,$$

Swampland Conjecture

$$|\nabla V|/V > c, c \sim O(1)$$



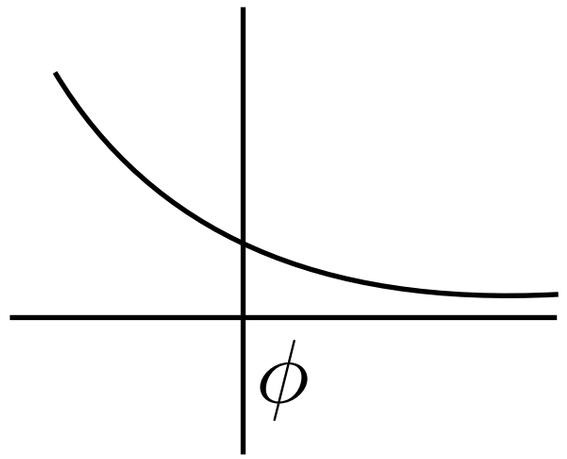
Implications I: dark energy

Cosmological constant do not exist!

$$V = \Lambda$$

Dark energy should be explained dynamically:

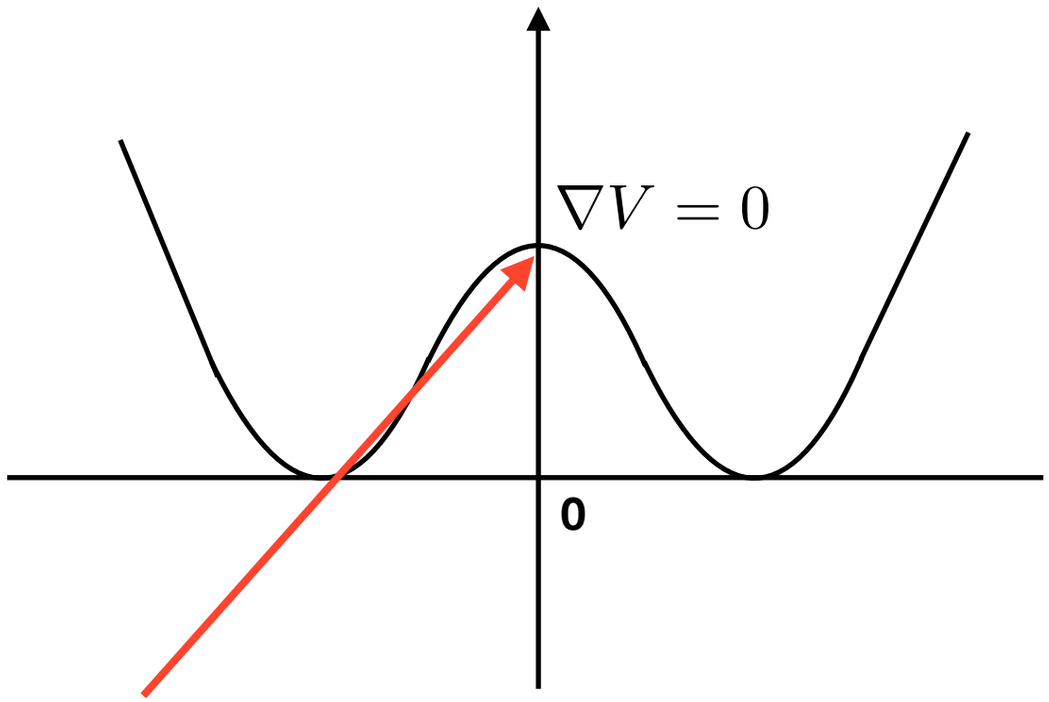
Quintessence: $V = \Lambda e^{-\xi\phi}$



$$\nabla V/V = \xi$$

Implications II: Higgs

Higgs sector need to be enlarged!



Not consistent!

Quintessence-Higgs Model

F. Denef, A. Hebecker, T. Wrase, arXiv:1807.06581

$$V(\phi, \mathcal{H}) = e^{-\xi\phi}\left(\lambda\left(|\mathcal{H}|^2 - v^2\right)^2 + \Lambda\right) \quad (\xi > 0)$$

$$|\nabla_H V = 0|, \ |\nabla_\phi V| = \xi V \qquad |\nabla V|/V = \xi$$

Summary

- The Higgs instability can be solved in Quintessence-Higgs Model.
- It may be tested within 10 years.
- UV completion?