Quintessence Saves Higgs Instability

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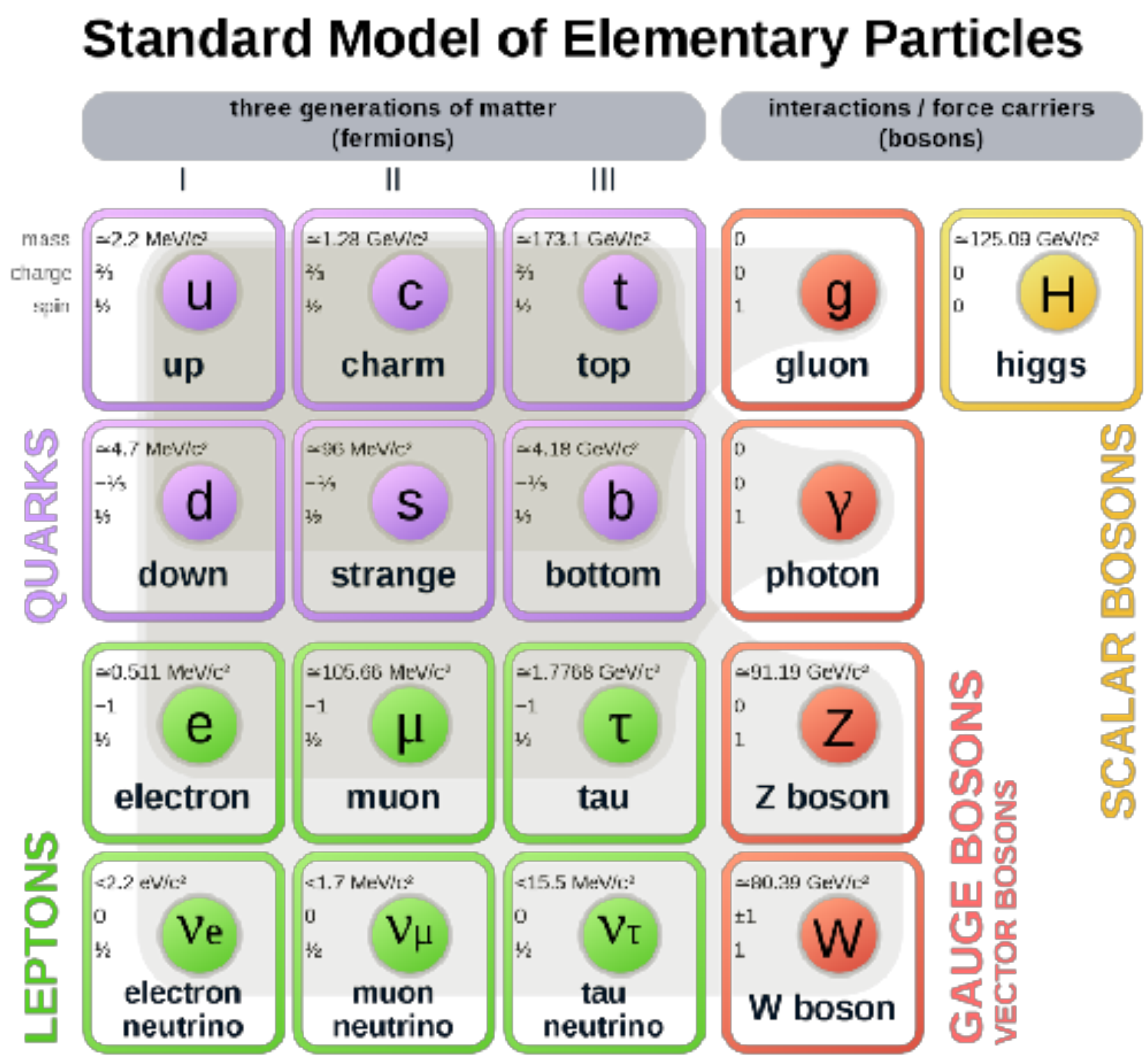
Based on arXiv:1809.05507, with Shi Pi and Misao Sasaki

Berkeley Week

Outline

- The Higgs instability problem
- Origin of Cosmic Acceleration
- Quintessence-Higgs Model
- Swampland conjecture

Standard model

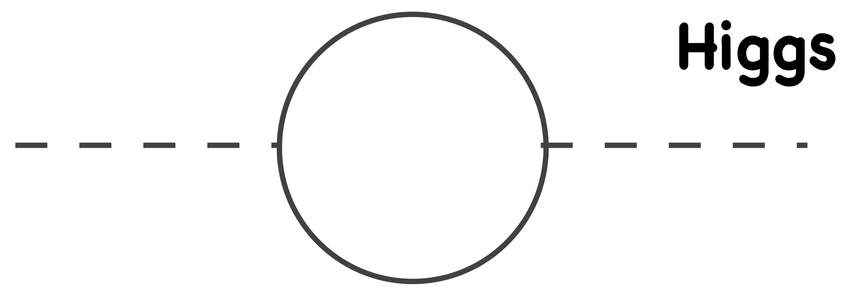


Fundamental law describing low energy scale physics

New Physics is expected

- Hierarchy problem
- Existing of Dark Matter
- Dark Energy
- ……

Hierarchy problem



wilson,1970

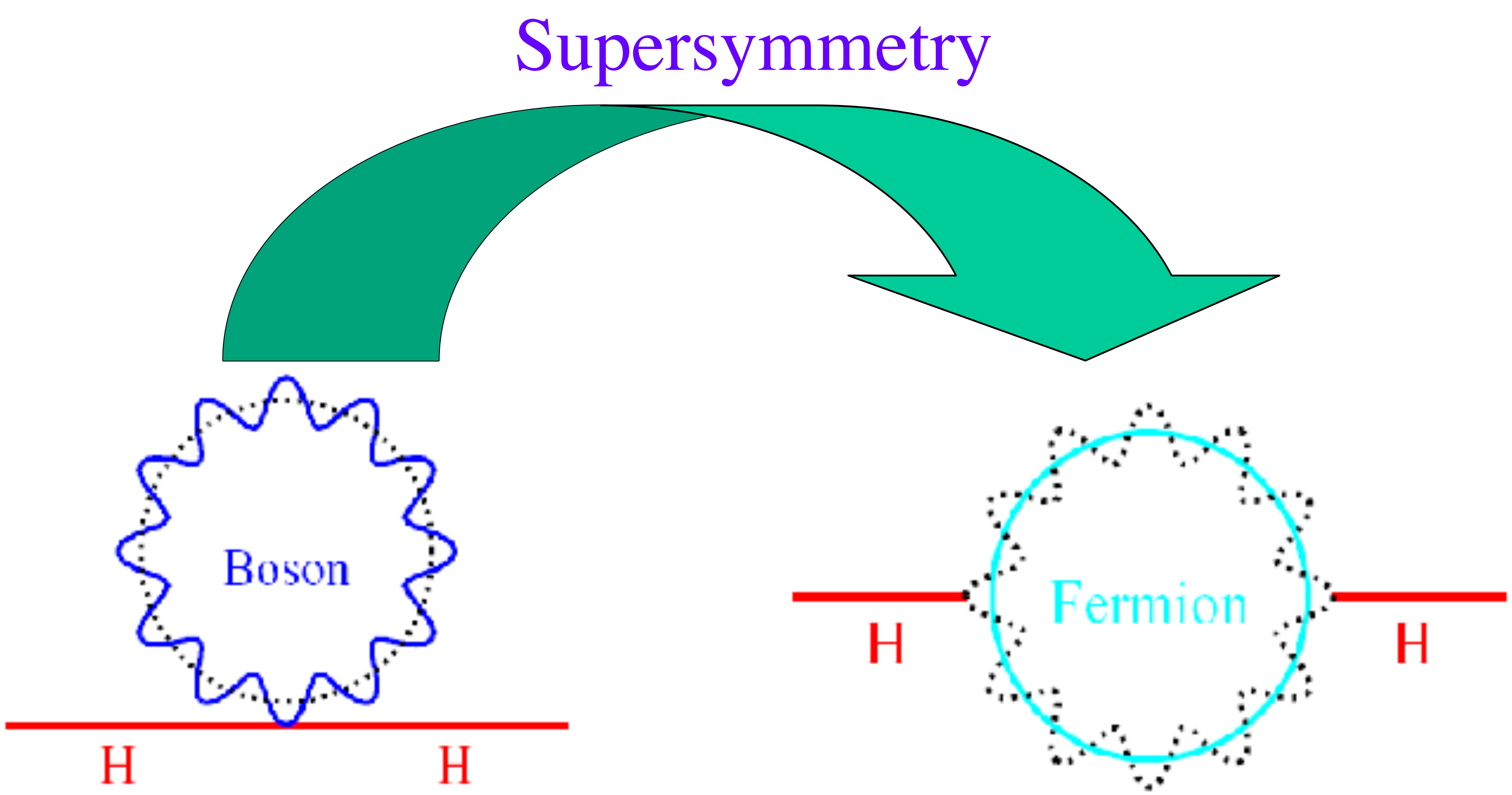
are taken into account. The mass terms for the electron and muon and the weak boson, if any, must also be protected. This requirement means that weak interactions cannot be mediated by scalar particles.[36]

$$m_h^2 = m_0^2 - \delta m^2$$

$$\Lambda^2$$

If $\Lambda^2 \gg m_h^2$, large fine-tuning appears

Supersymmetry provides nice solutions

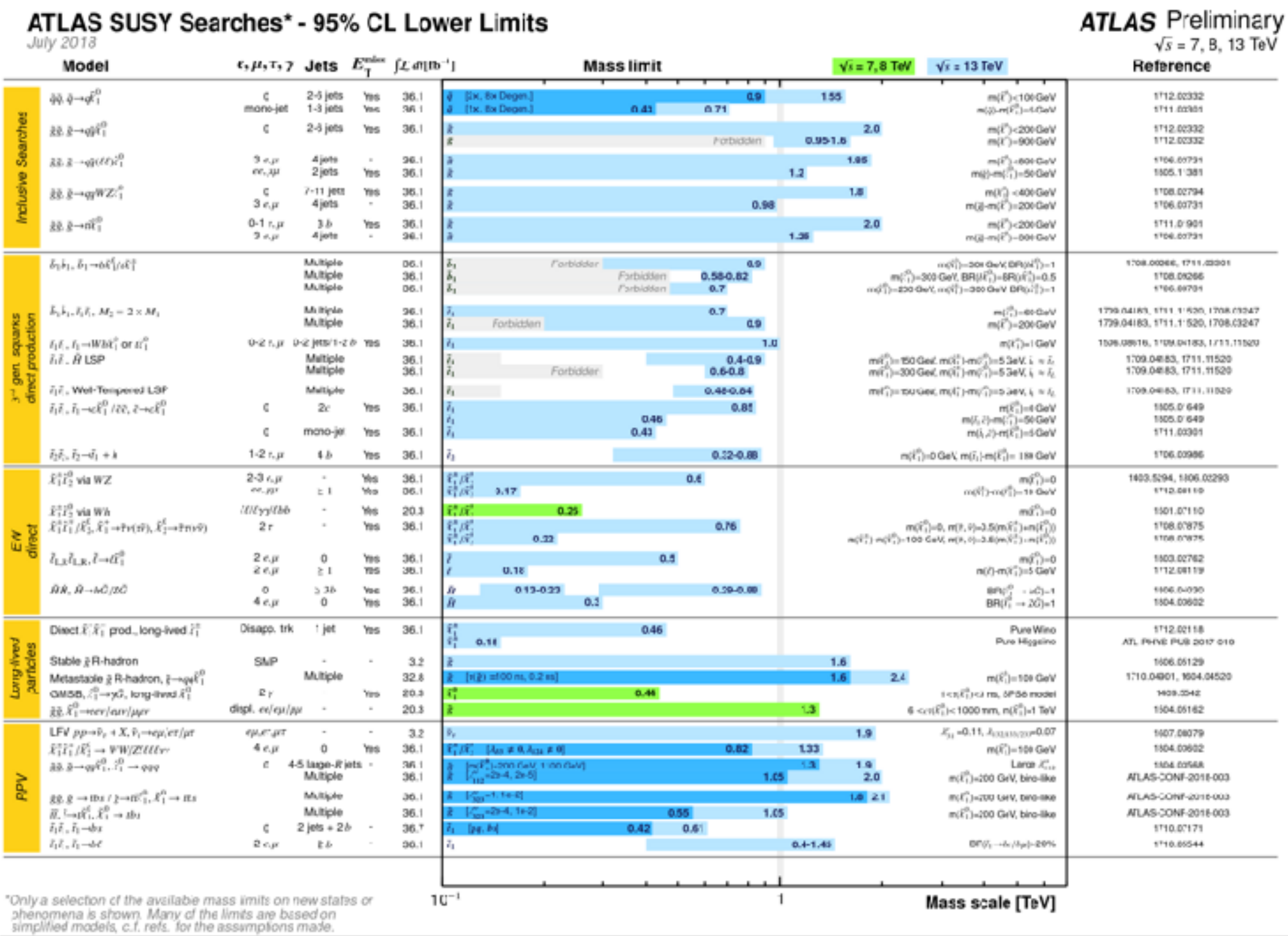


$$\Lambda^2 \to \ln(\Lambda)$$

Prediction: New Particles at TeV scale

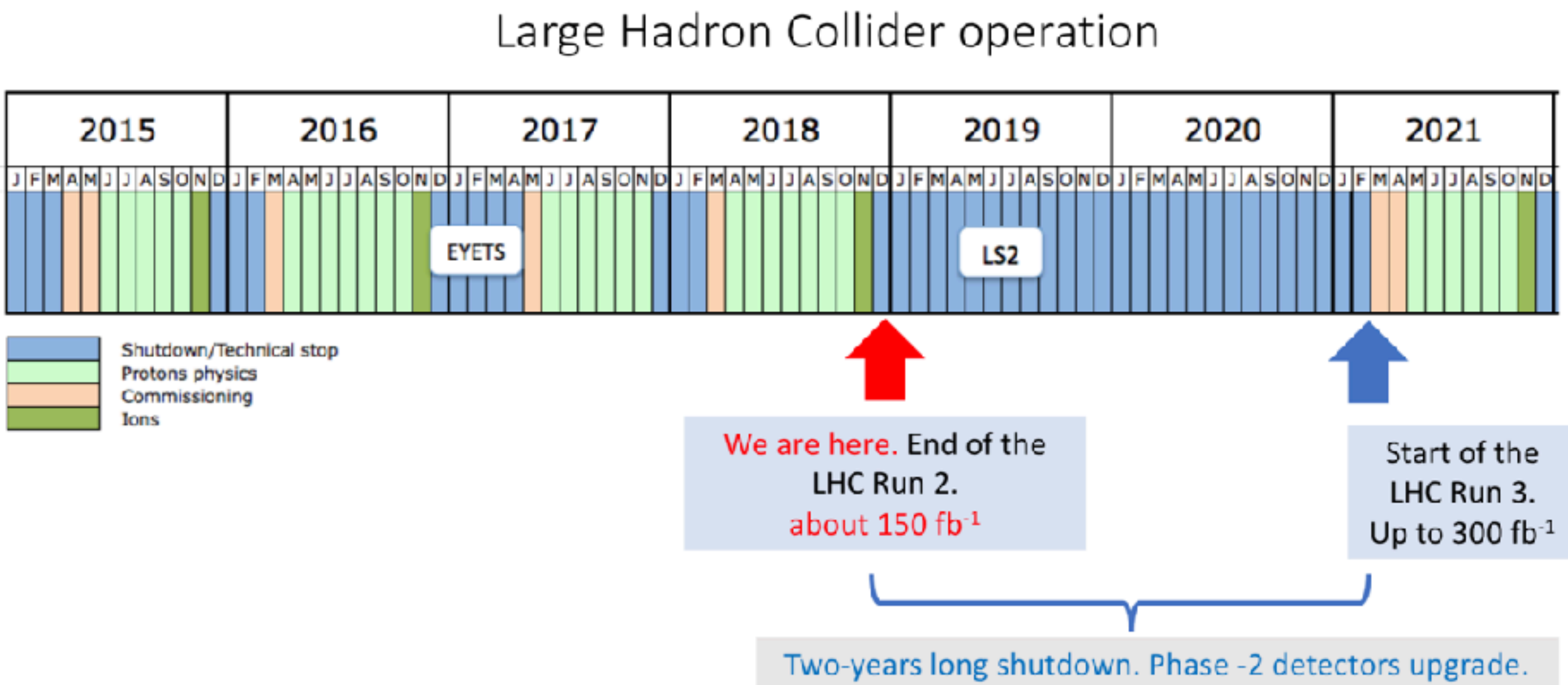
Can be tested at the LHC!

No evidence yet



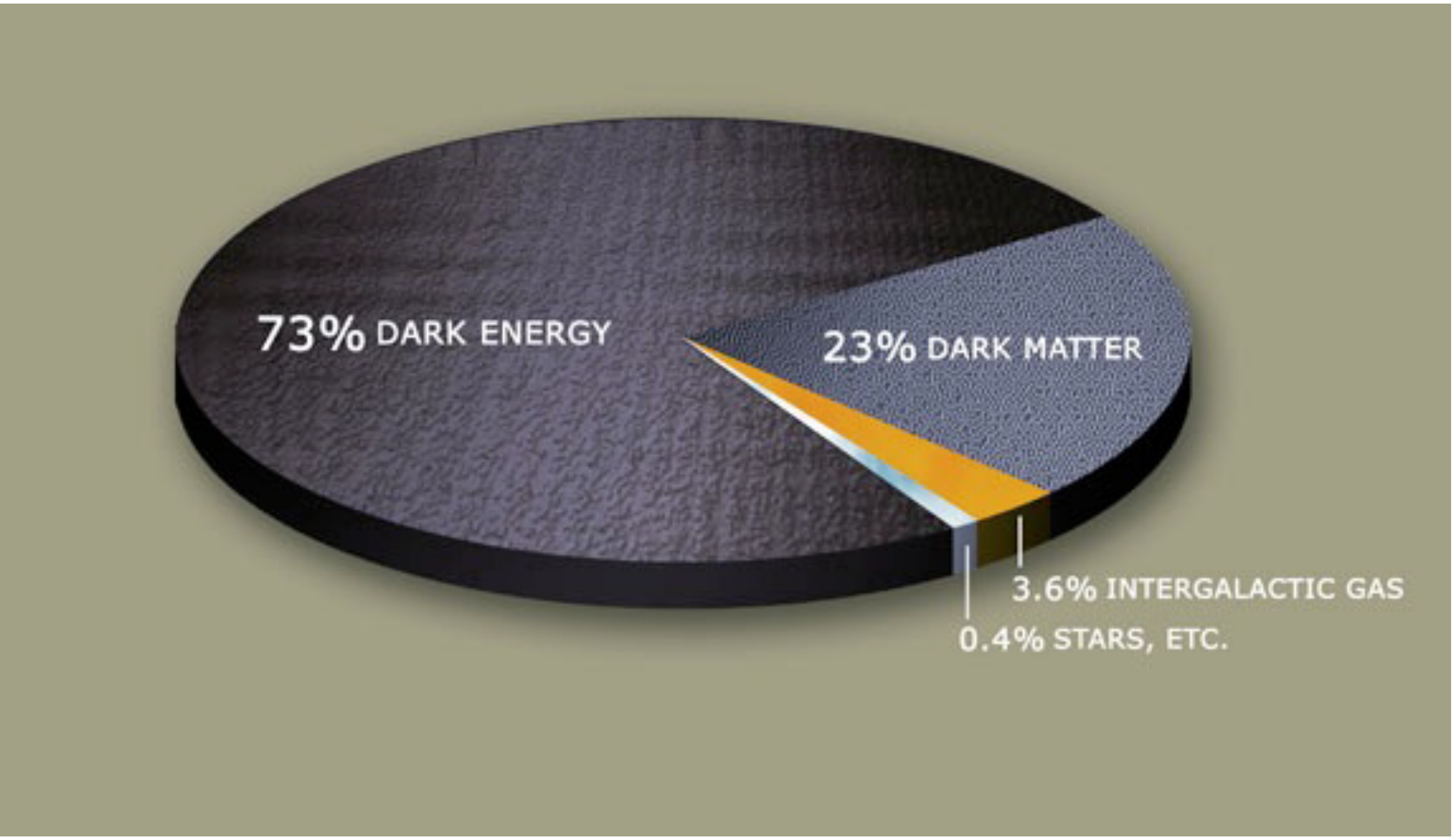
No clue of solution to the hierarchy problem!

LHC shut down for two years



Patience for New Physics appearing

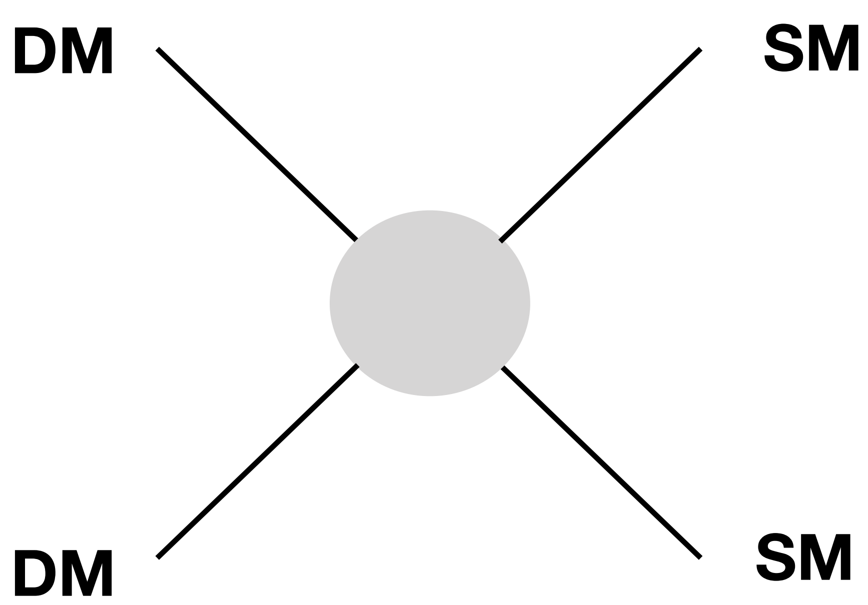
Dark Matter

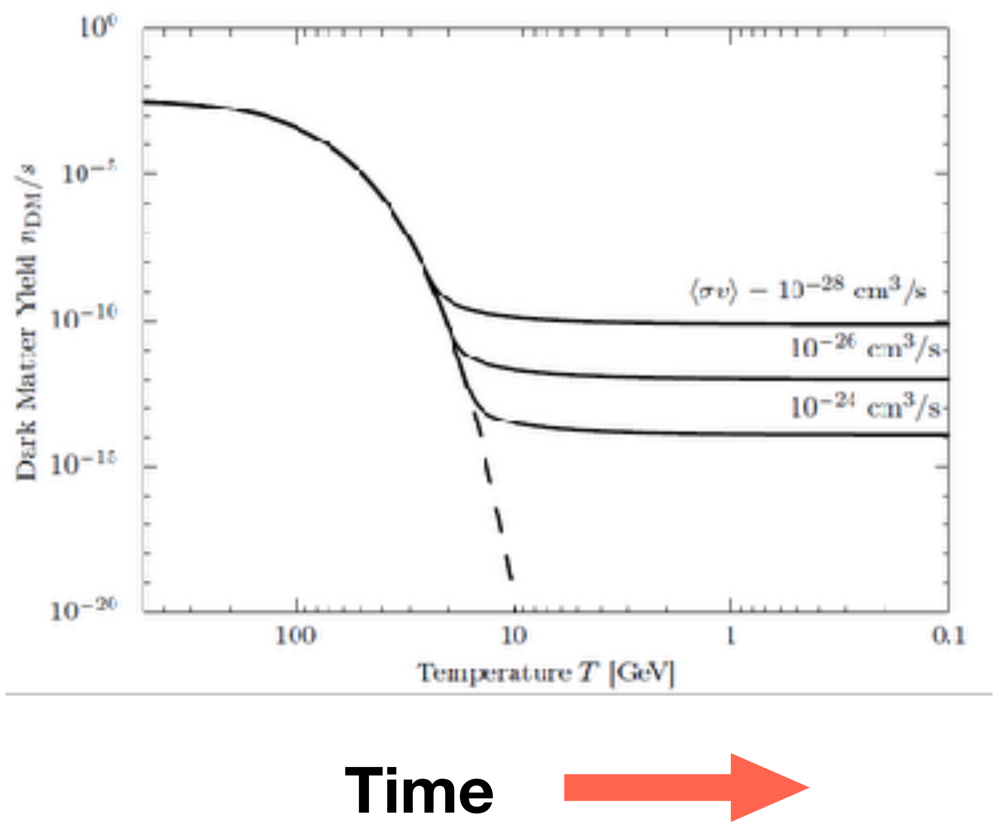


- **Dark Energy 73%**
- **Dark Matter 23%**
- **Baryons 4%**

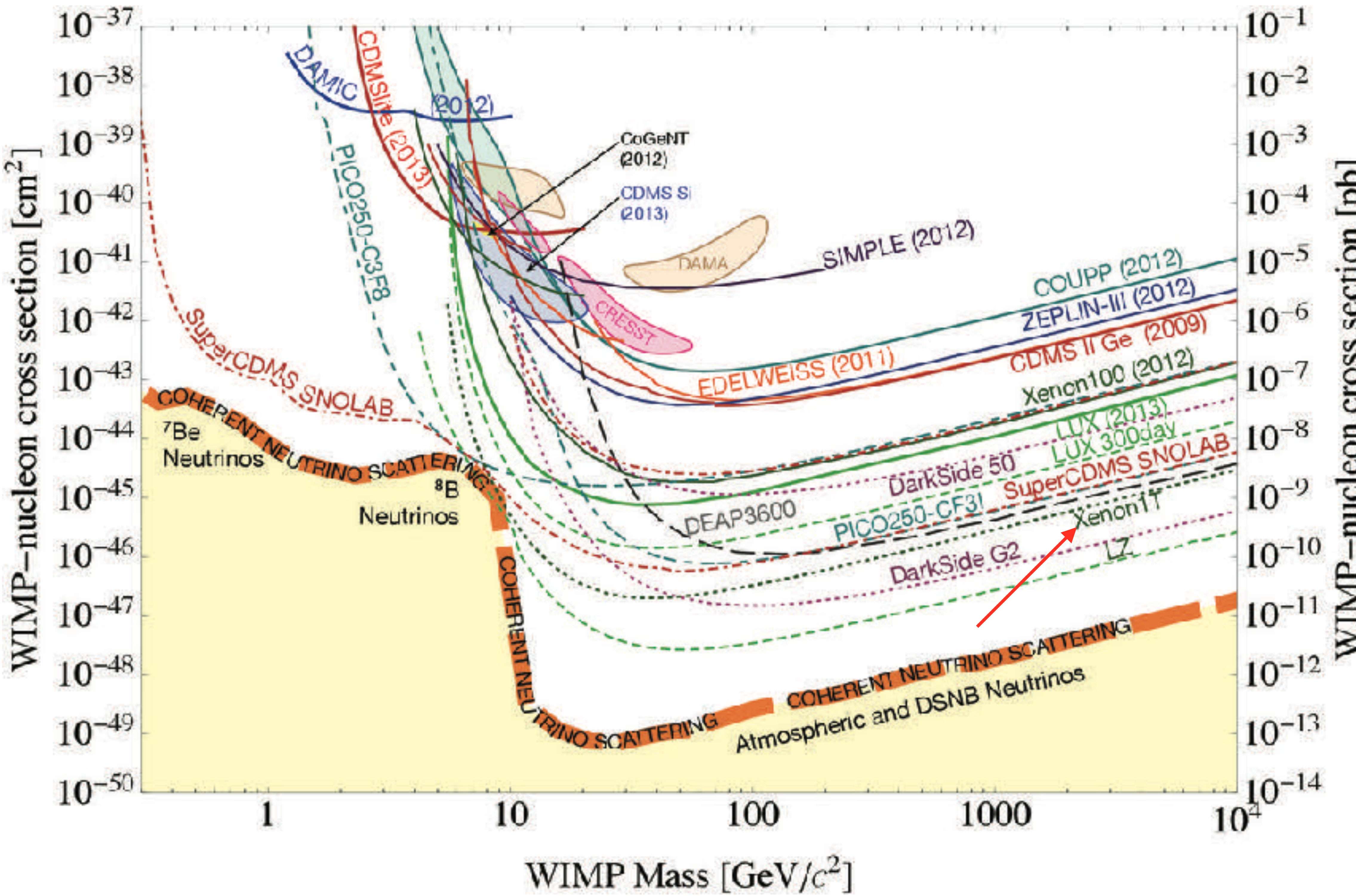
(WIMP)Weekly Interacting Massive Particles

DM annihilation in early universe → Abundance





No signals yet!



Closing to the bottom(neutrino floor)!

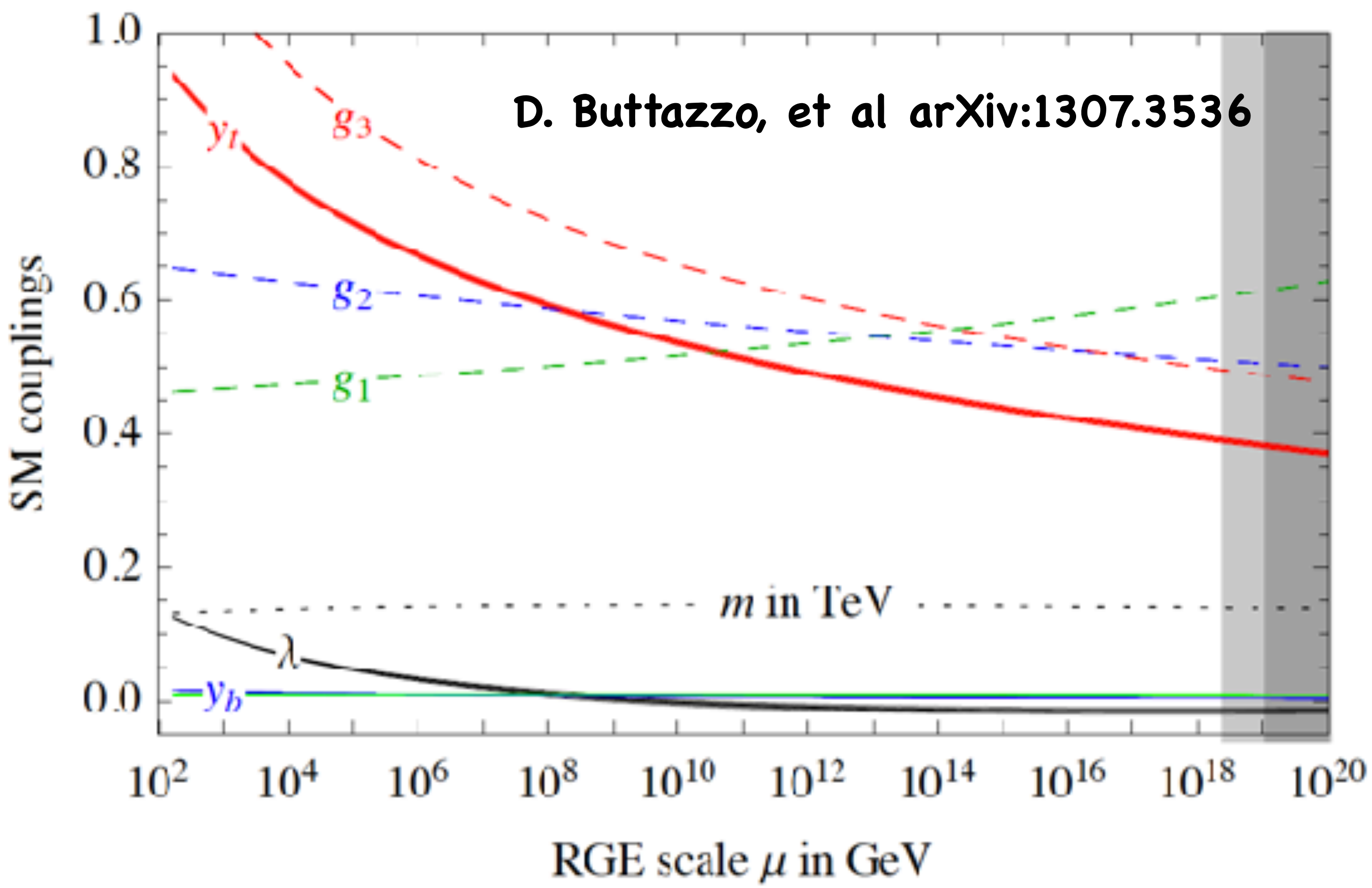
Time to go beyond

Looking into Higgs sector more carefully

In SM, the Higgs potential is:

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

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



y_t: top Yukawa coupling

g_2, g_Y: weak gauge coupling

g_3: strong gauge coupling

Higgs potential and self coupling

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

For $h \gg v$

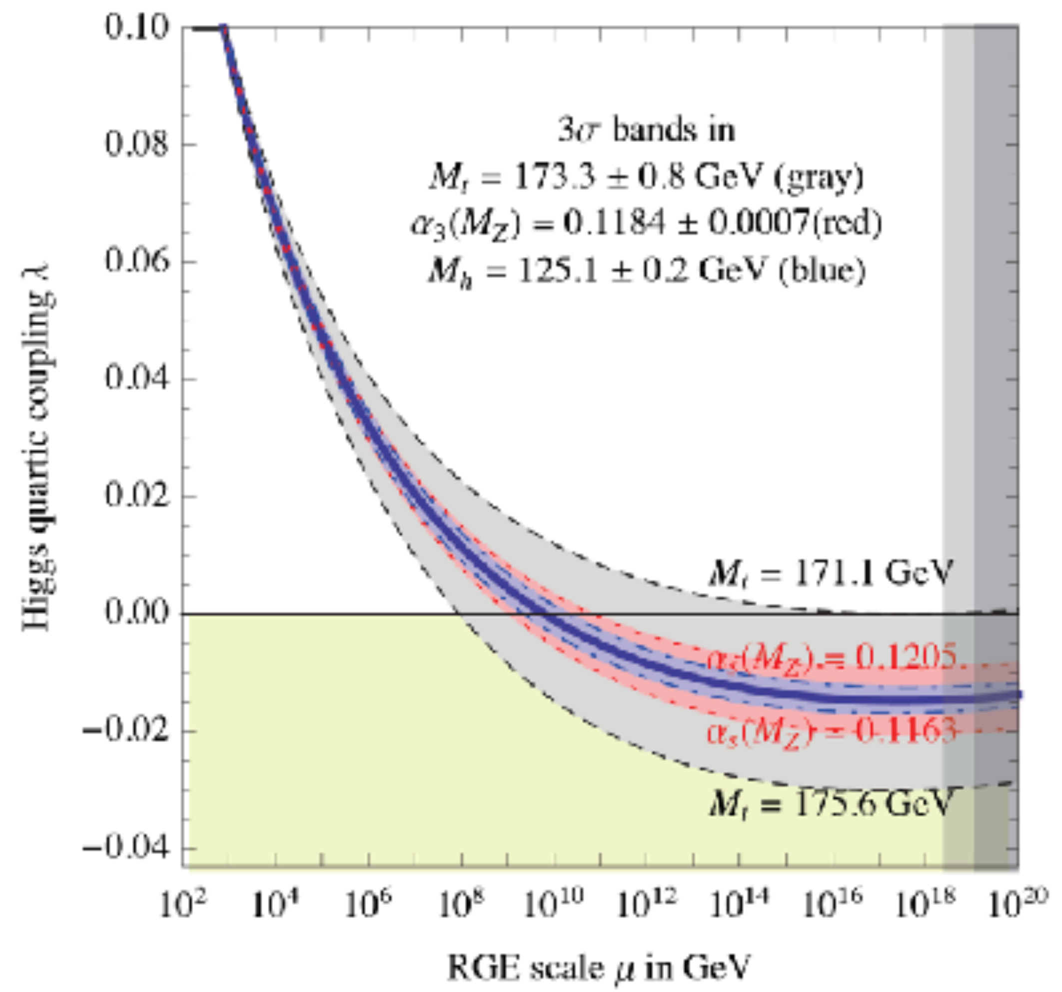
$$V_{\text{eff}} = \lambda_{\text{eff}}(h)\frac{h^4}{4}$$

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

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

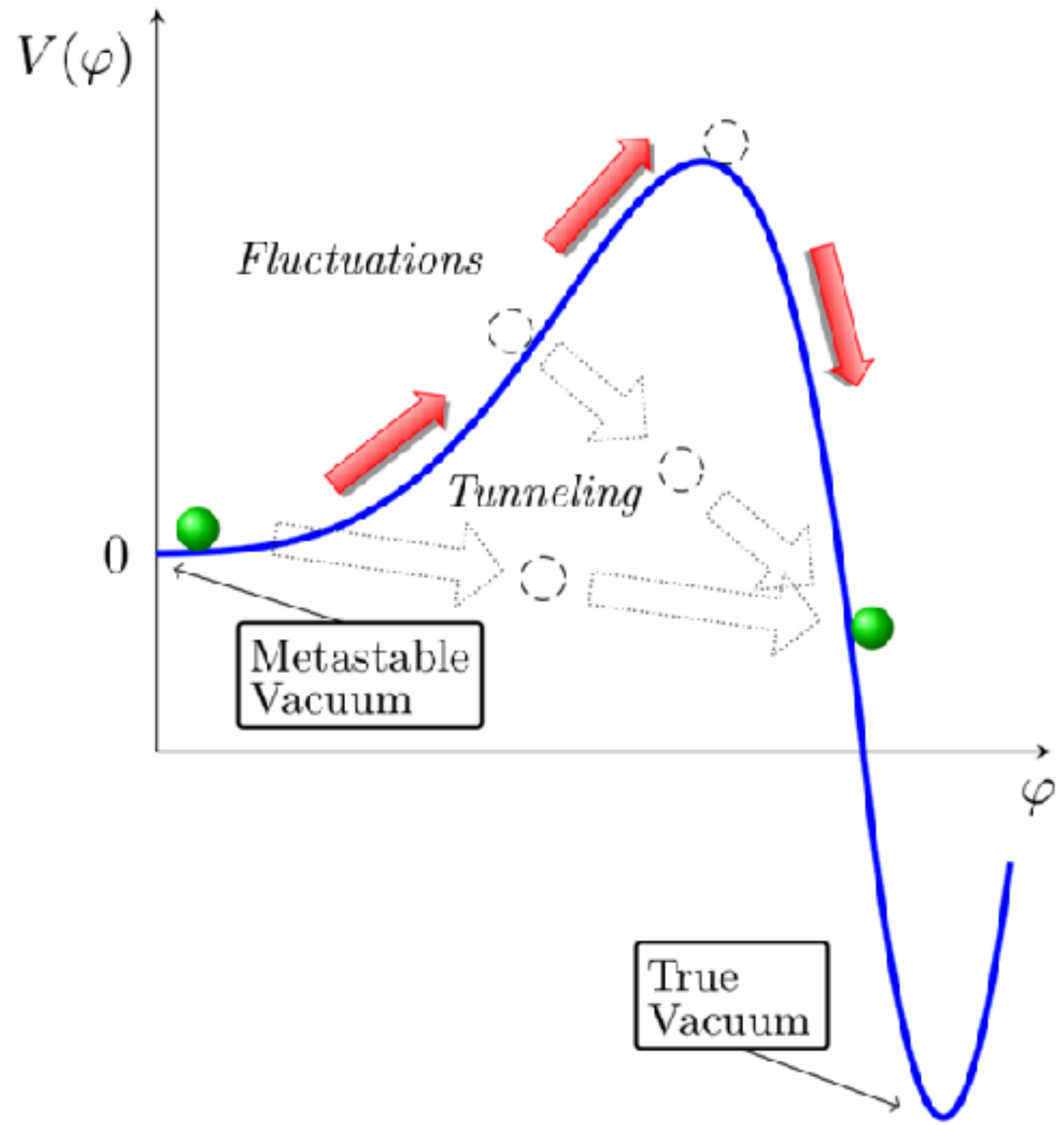
γ is the Higgs field anomalous dimension

D. Buttazzo, et al arXiv:1307.3536



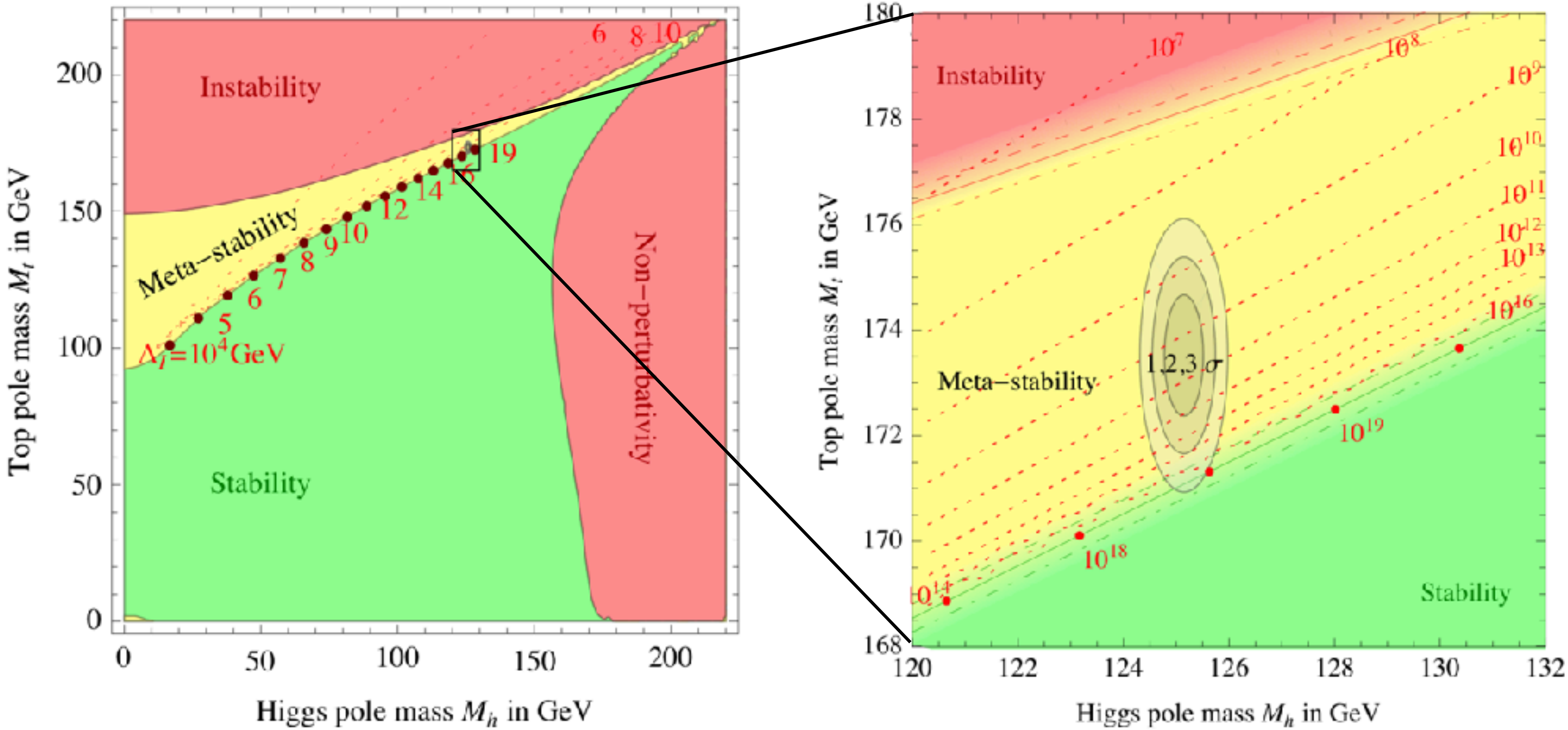
New stable vacuum is developed at high energy scale!

Higgs stability



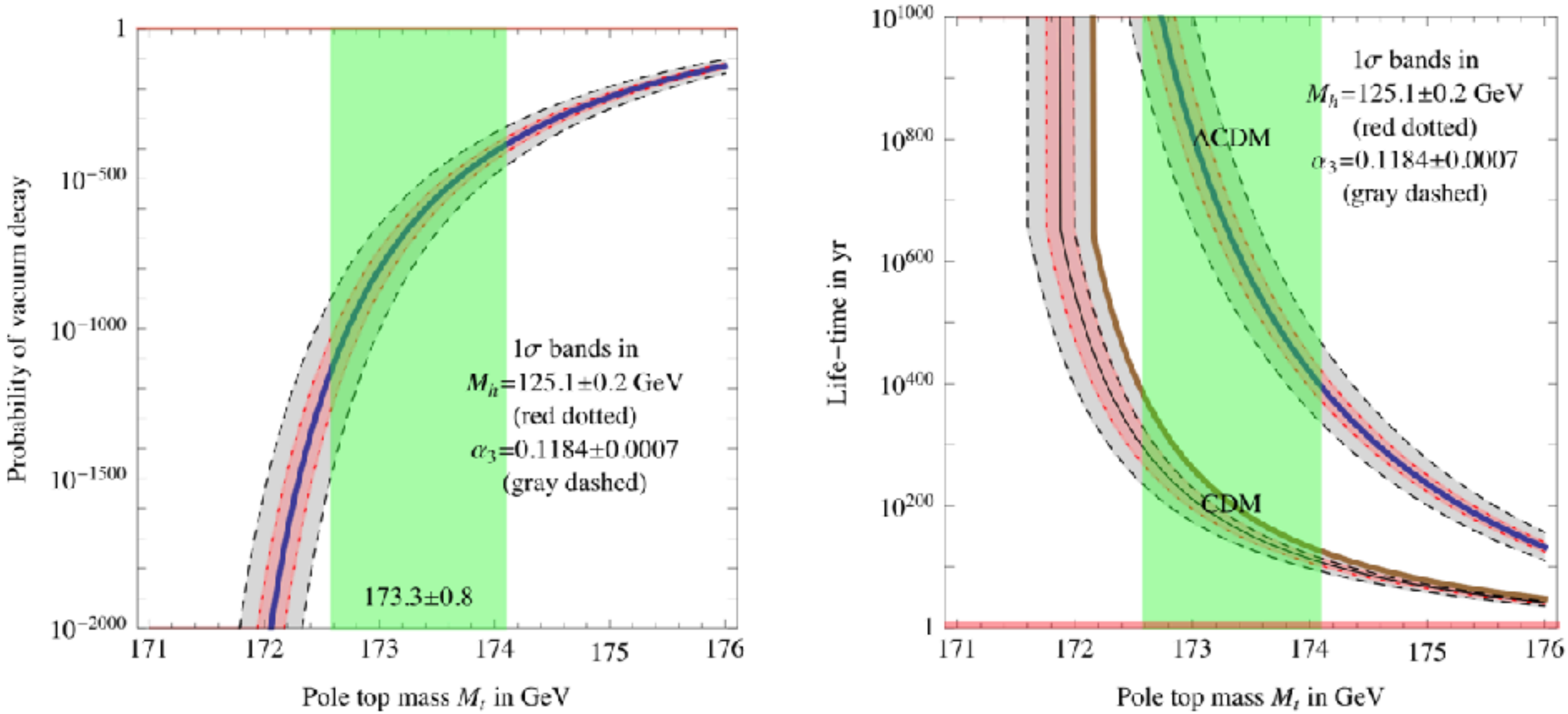
Our universe is at the edge

D. Buttazzo, et al arXiv:1307.3536



Threat in ΛCDM universe

D. Buttazzo, et al arXiv:1307.3536

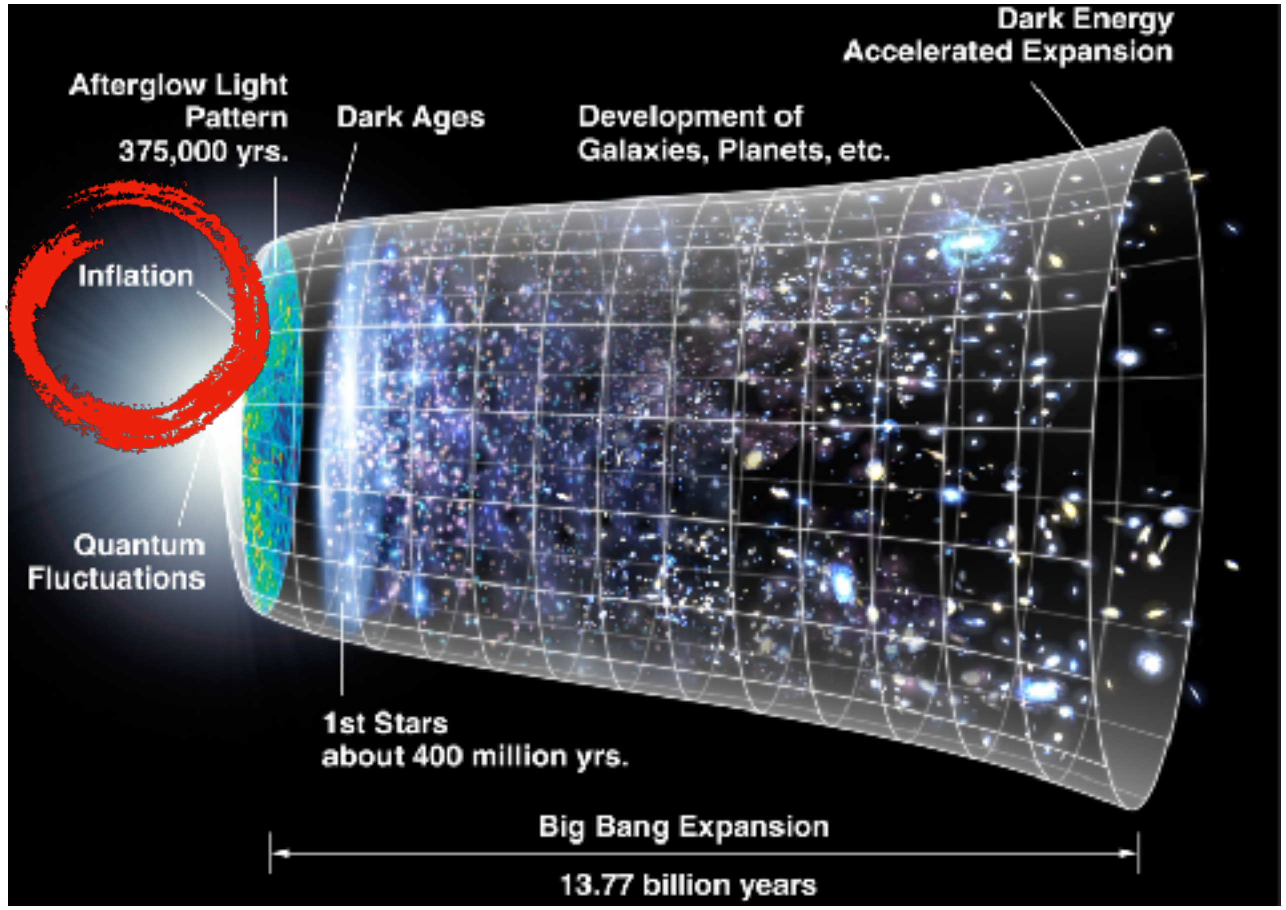


Longer enough, finally decay

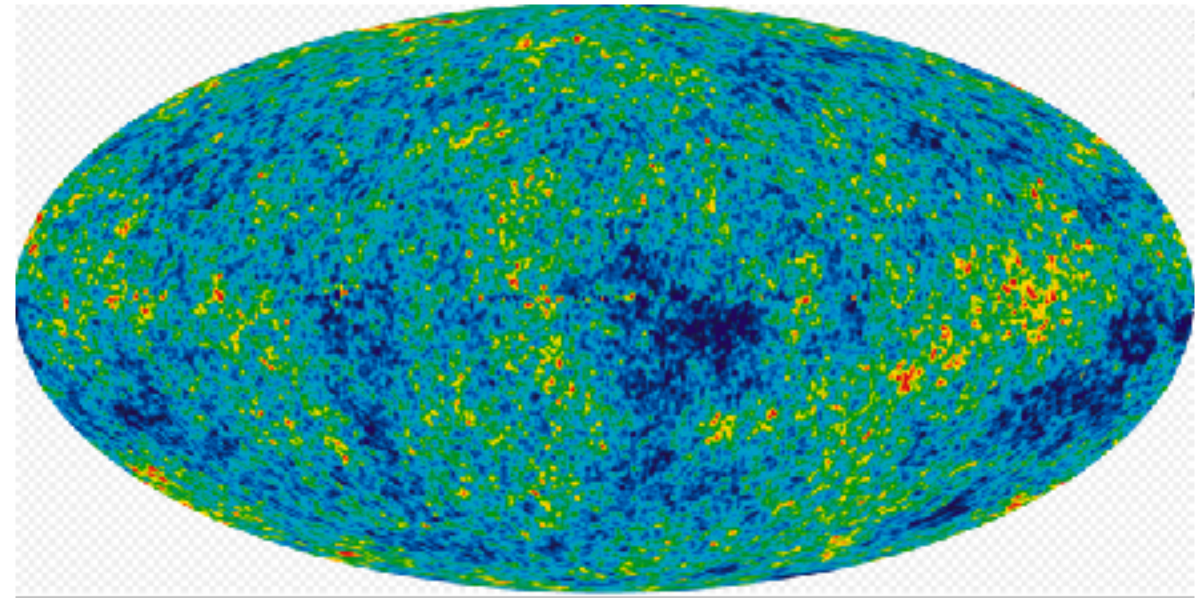
Summary

- We do not have to worry about the threat of vacuum decay in the "near" future.
- However, this is only true in a ΛCDM universe.

Inflation in the early universe

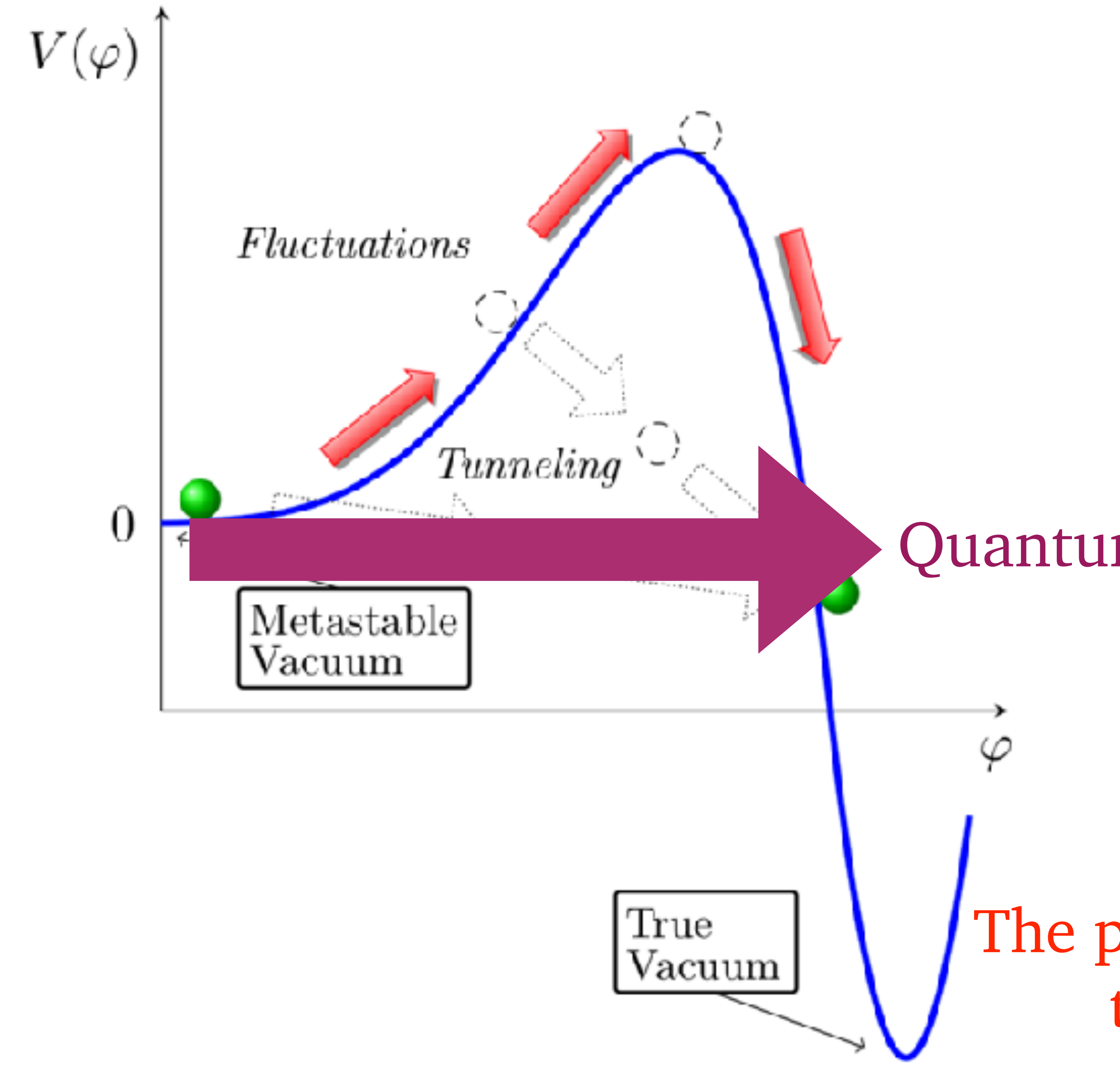


fluctuations in CMB



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

Higgs instability during inflation



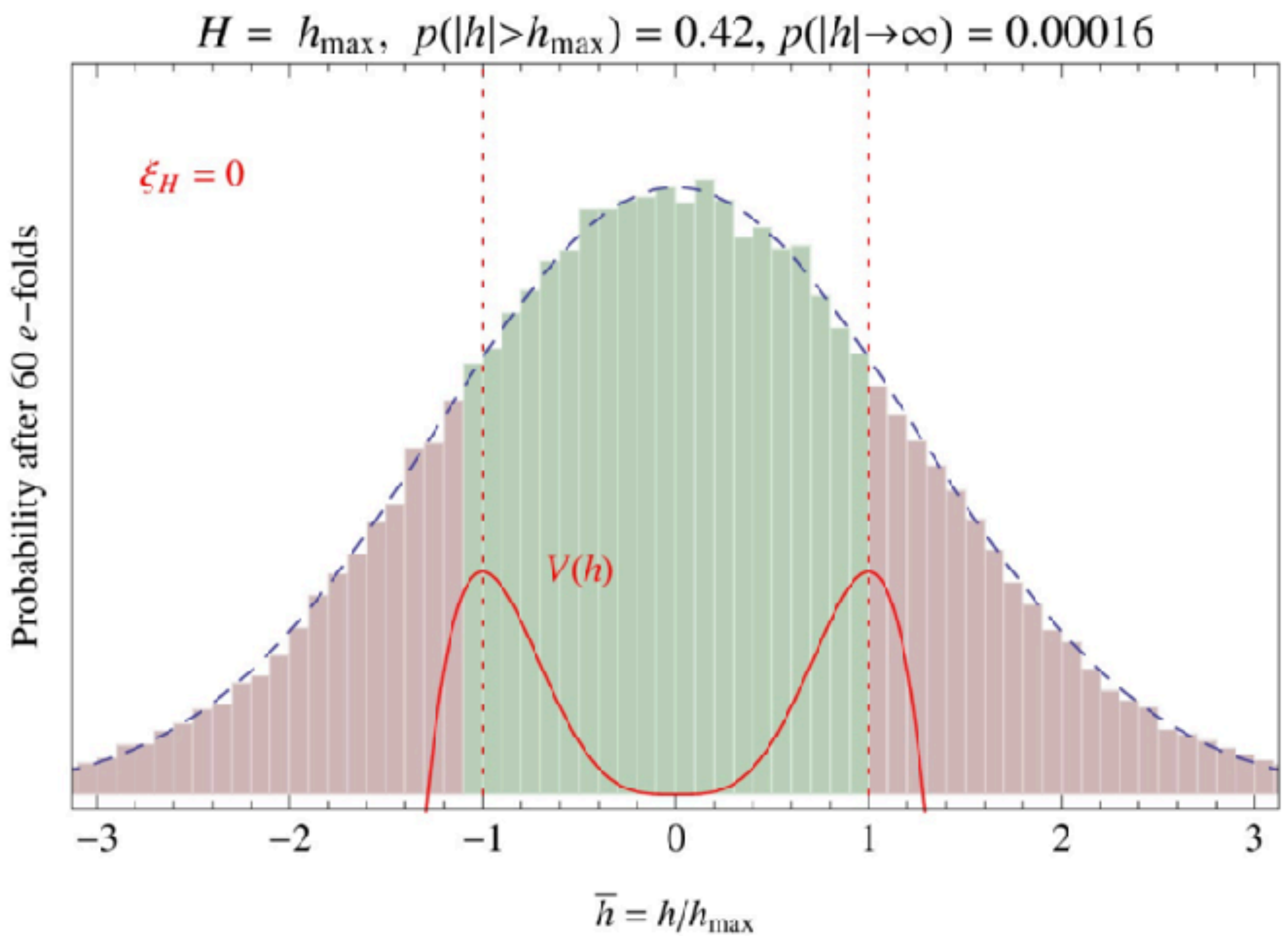
Quantum fluctuations
δφ~H

The probability depends the value of H.

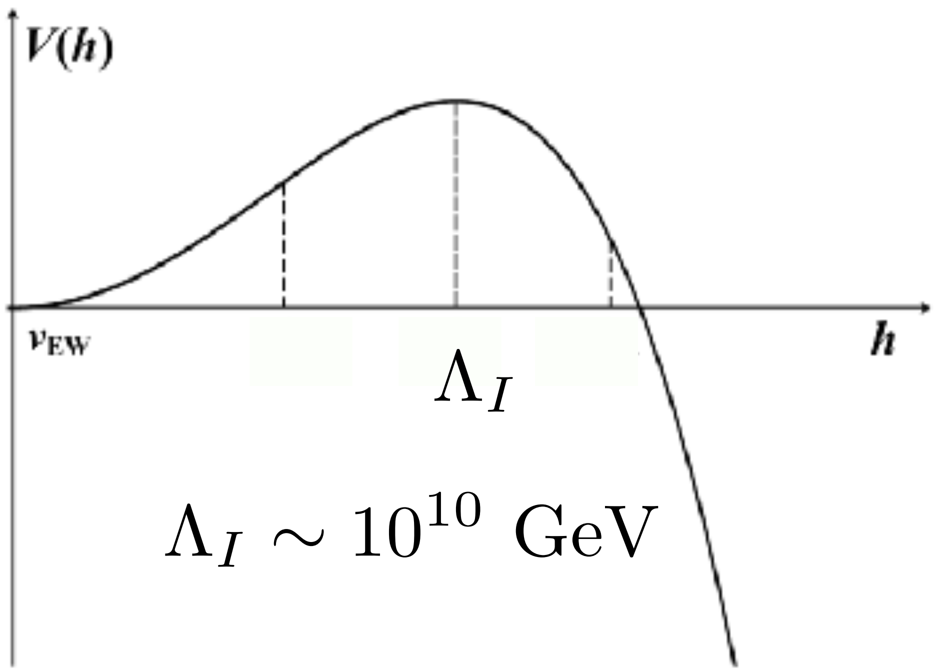
Higgs instability during inflation

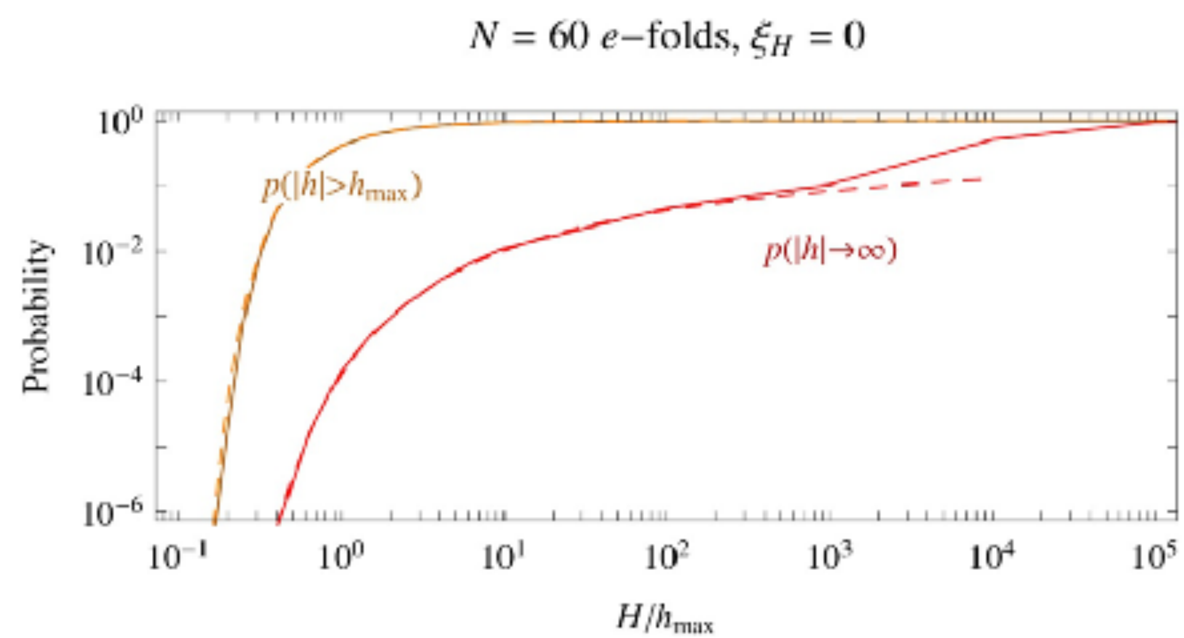
- Even if $H \sim h_{max}$, the probability of ending up in true vacuum is large.

J. R. Espinosa, et al arXiv:1505.04825



Higgs instability during inflation





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

- Low energy scale inflation.

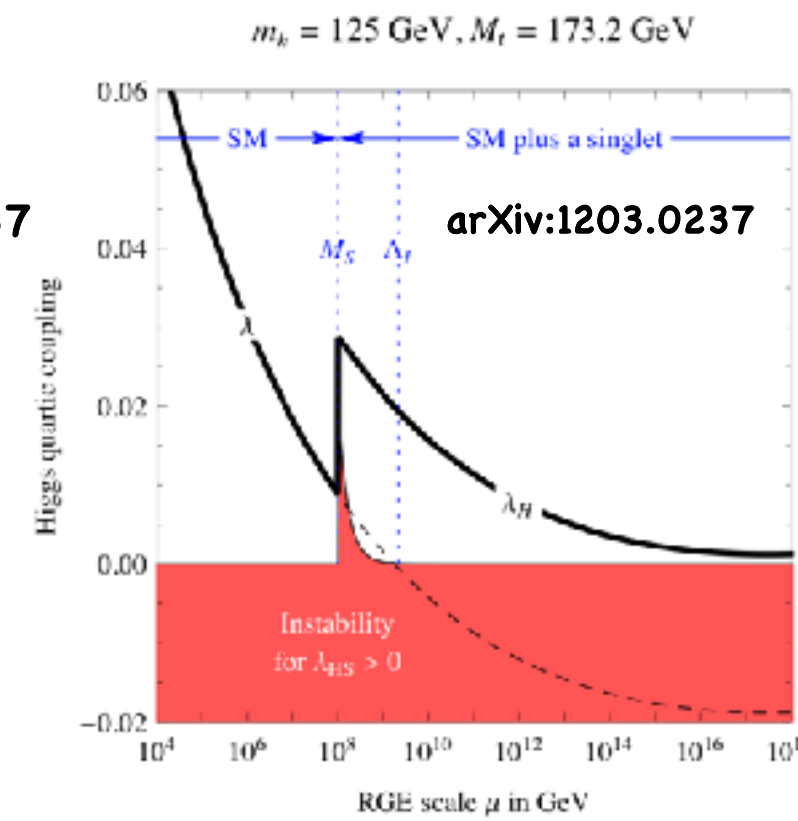
- Non-minimal coupling to gravity.

  Bezrukov et.al. 1403.6078, Hamada et.al. 1403.5043

- 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

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

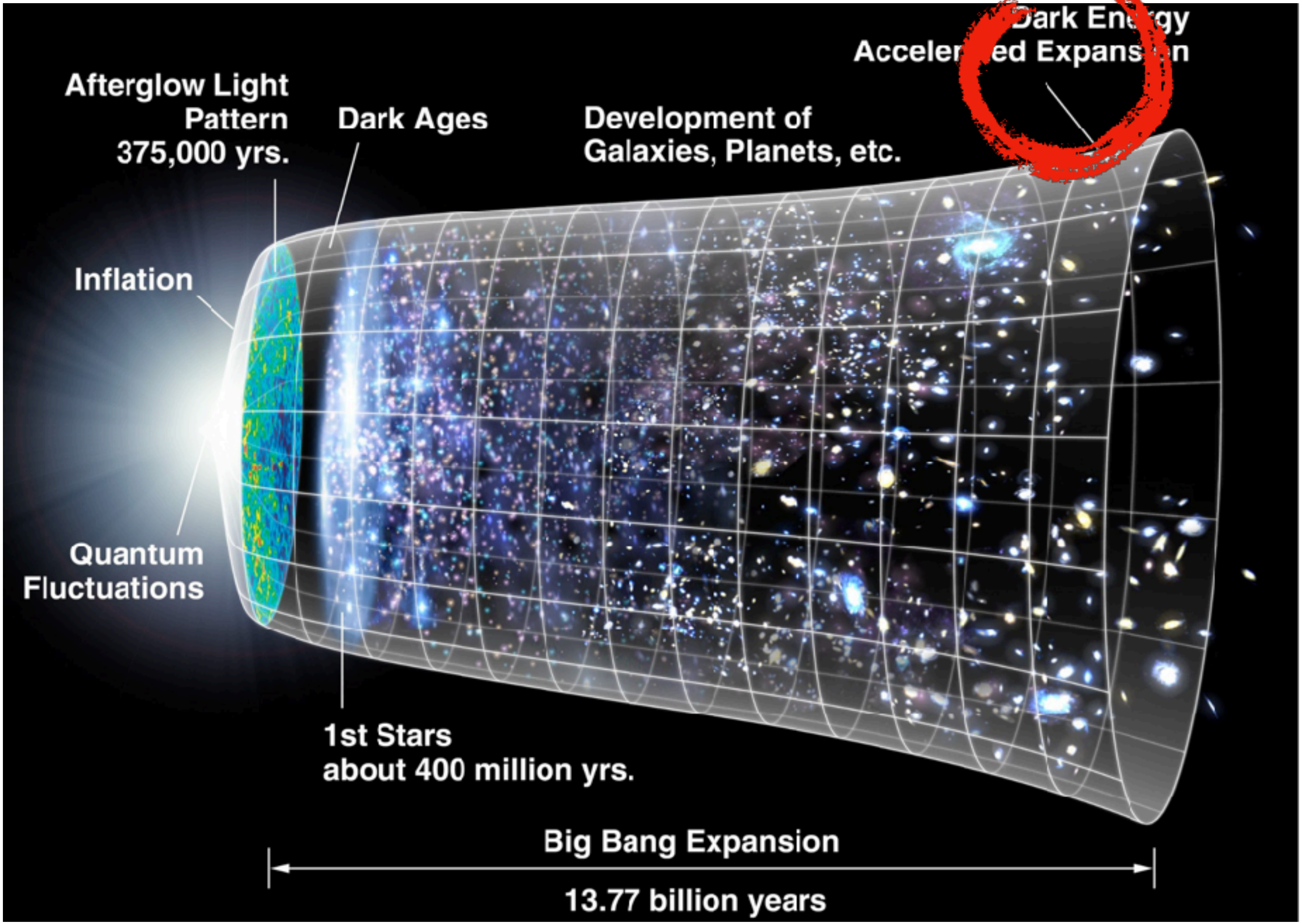


- Add Higgs coupling to inflaton.

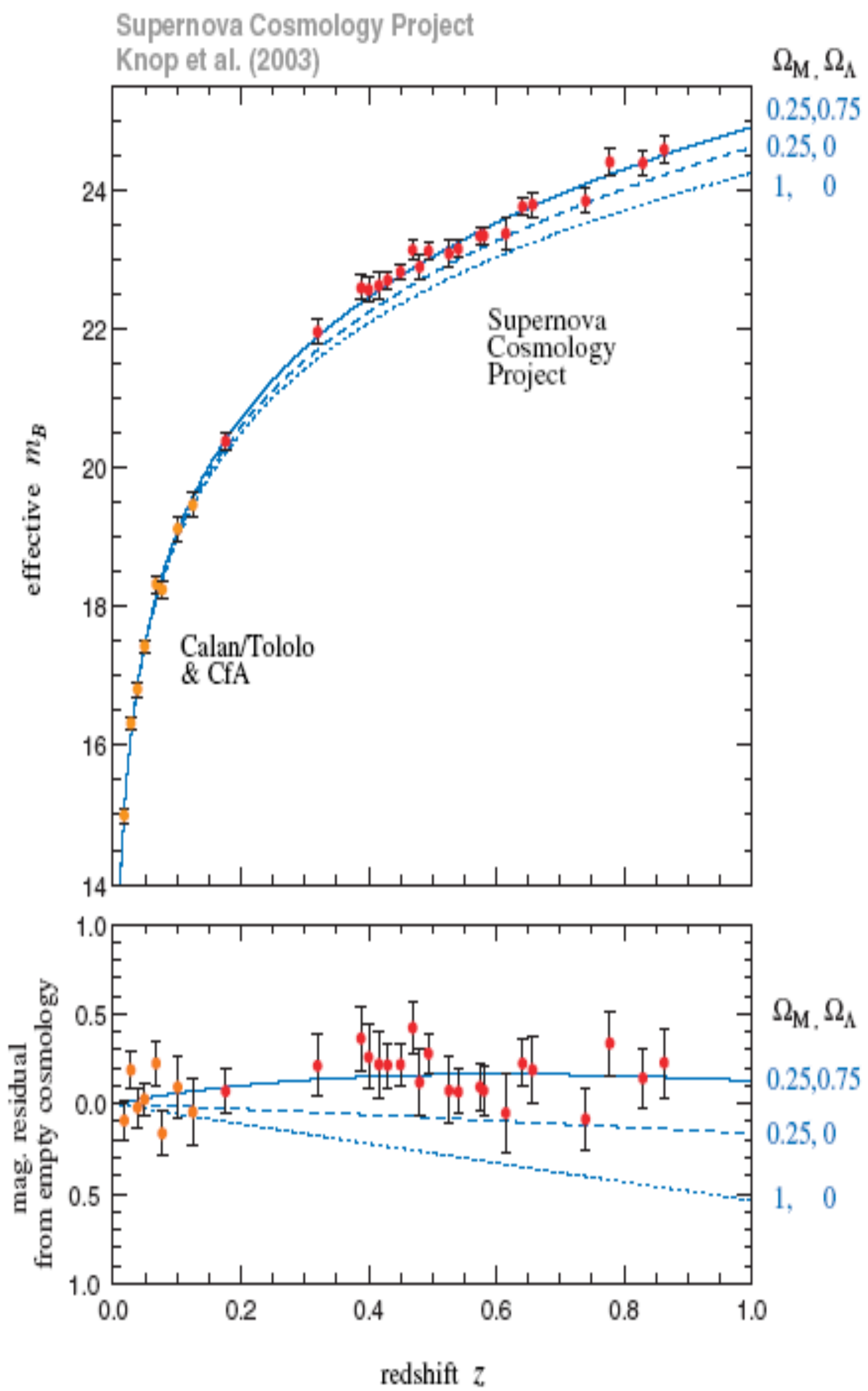
  $\mathcal{L} \supset \xi \phi^2 h^2$ **O. Lebedev, A. Westphal, arXiv:1210.6987**

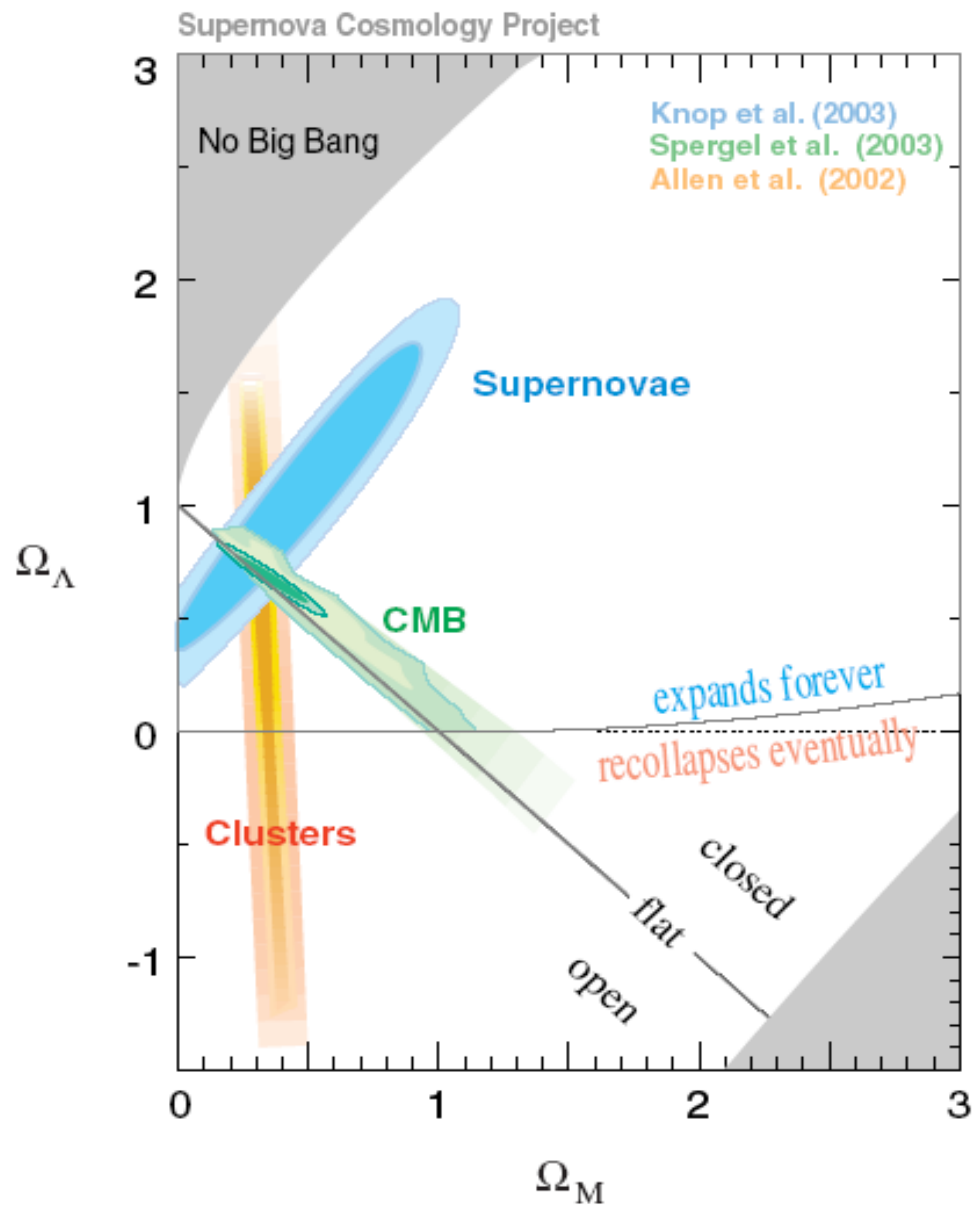
- ……

Late Acceleration of the Universe

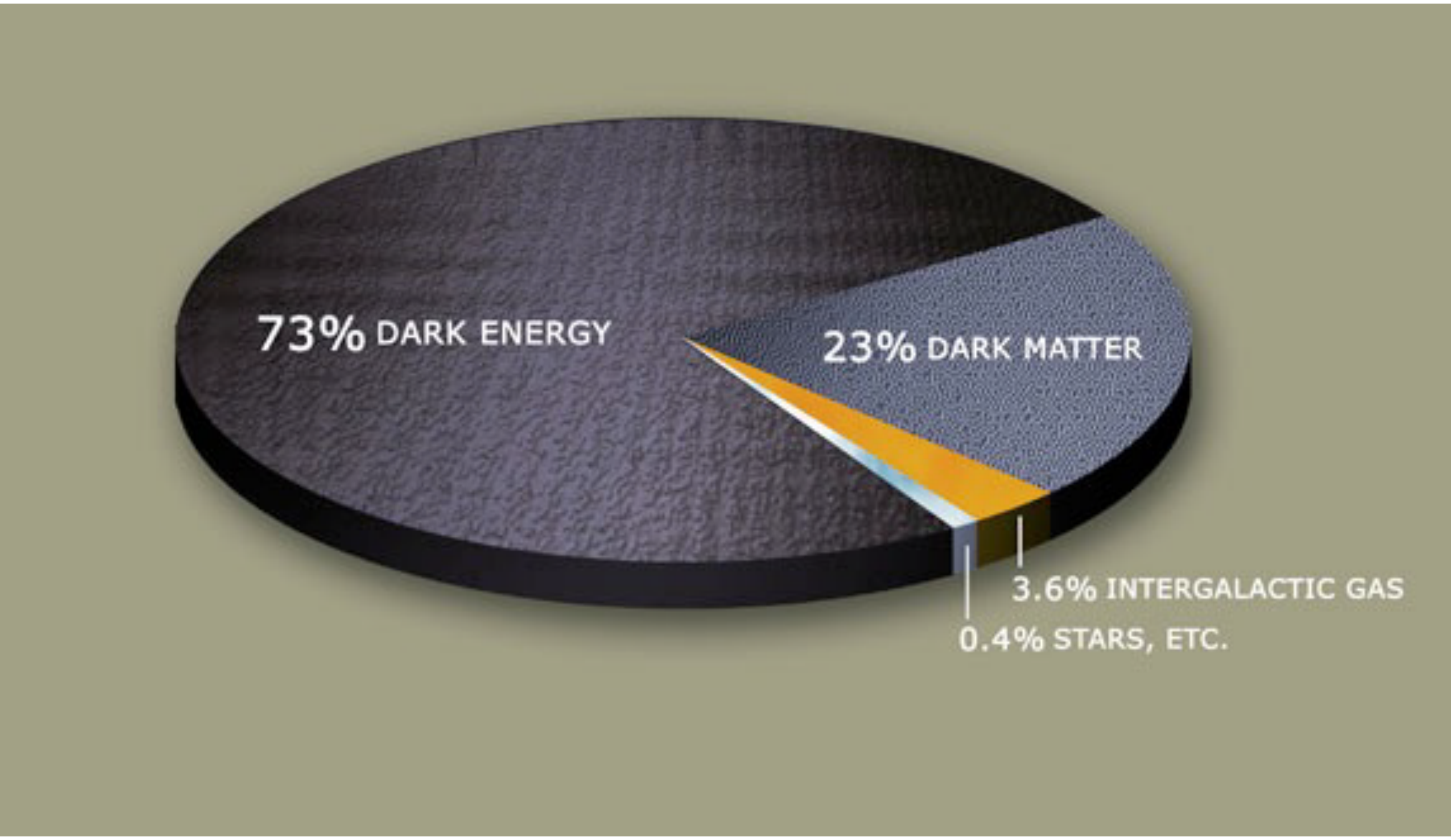


Late Acceleration of the Universe





Dark Energy



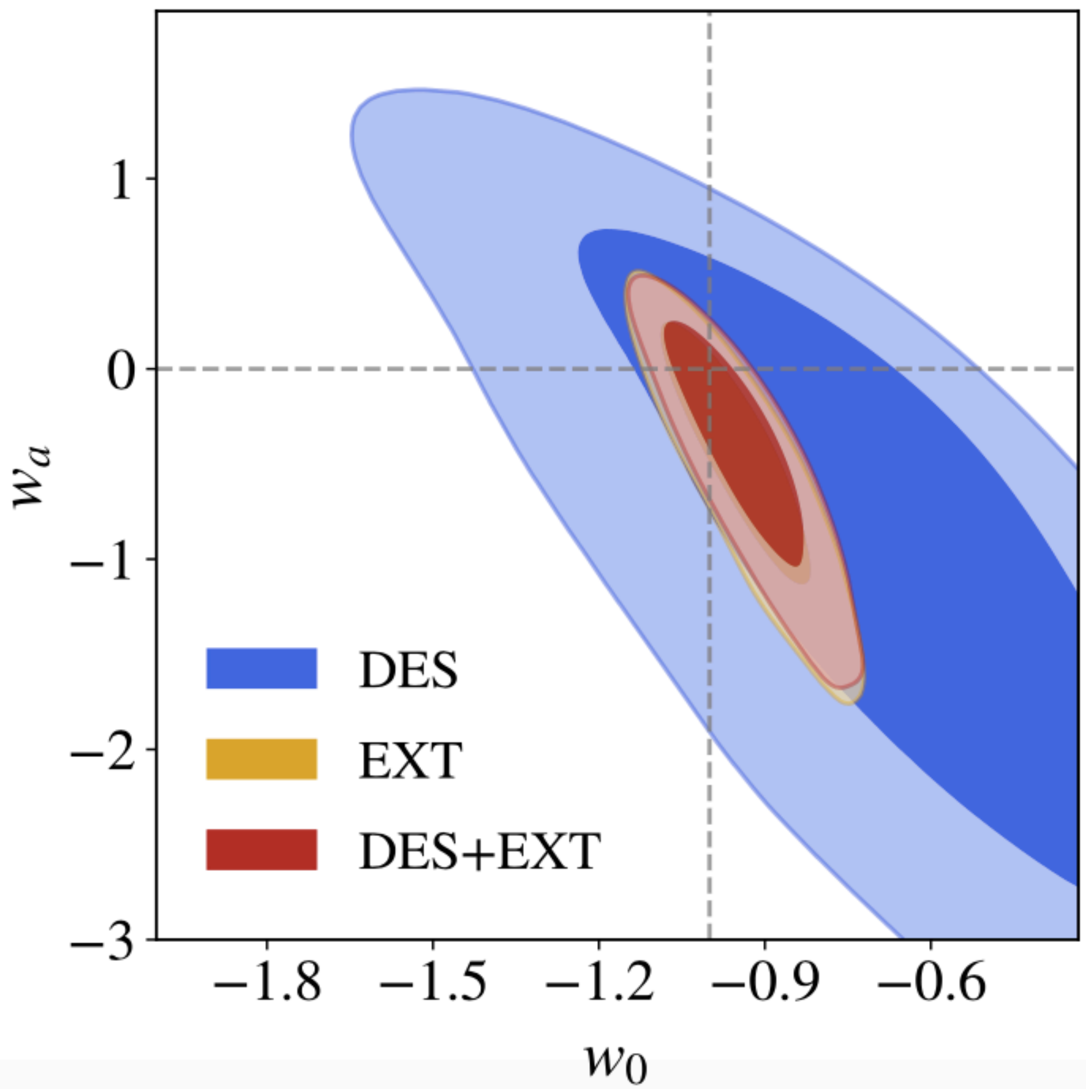
- Dark Energy 73%
- Dark Matter 23%
- Baryons 4%

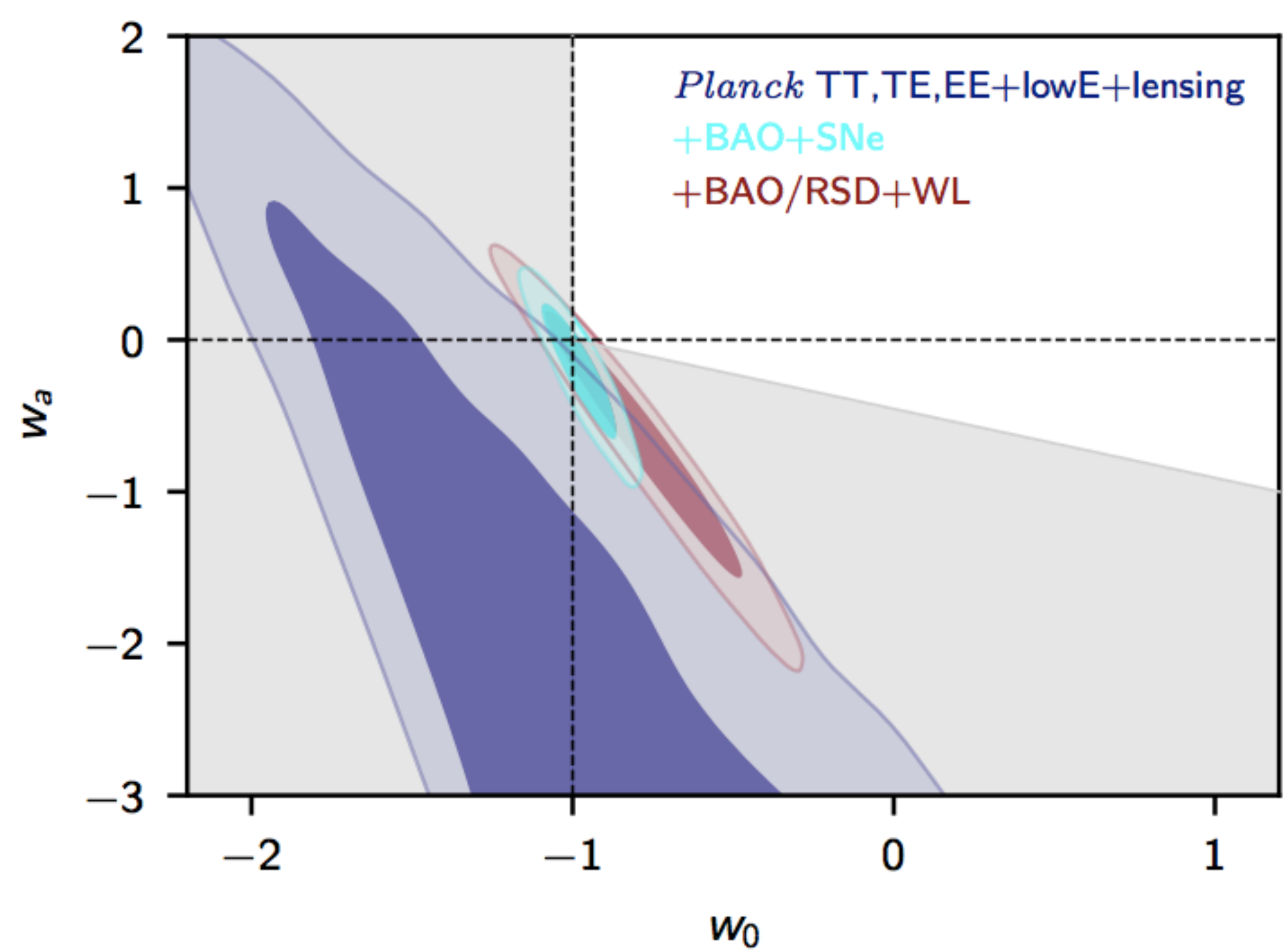
Cosmology constant vs Scalar Field (Quint…)

Observation

$$w(a) = w_0 + (1-a)w_a$$

Parameter	*Planck*+SNe+BAO	*Planck*+BAO/RSD+WL
w_0	-0.961 ± 0.077	-0.76 ± 0.20
w_a	$-0.28^{+0.31}_{-0.27}$	$-0.72^{+0.62}_{-0.54}$
H_0 [km s^{-1}Mpc^{-1}]	68.34 ± 0.83	66.3 ± 1.8
σ_8	0.821 ± 0.011	$0.800^{+0.015}_{-0.017}$
S_8	0.829 ± 0.011	0.832 ± 0.013
$\Delta\chi^2$	-1.4	-1.4



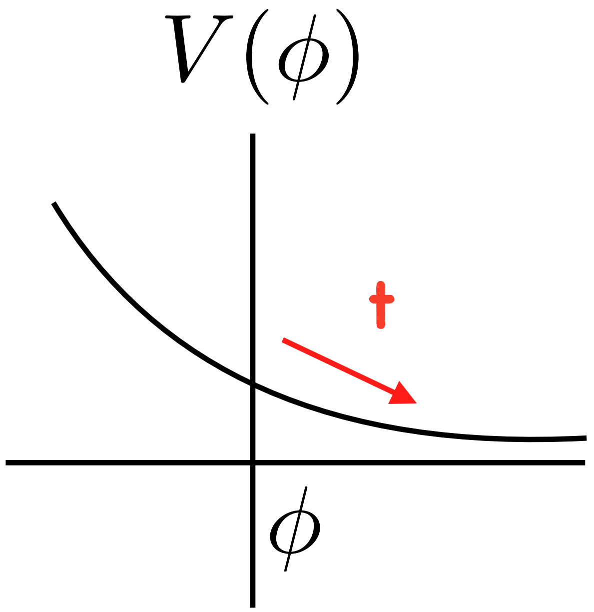


A quintessence model

Quintessence as an explanation of dark energy

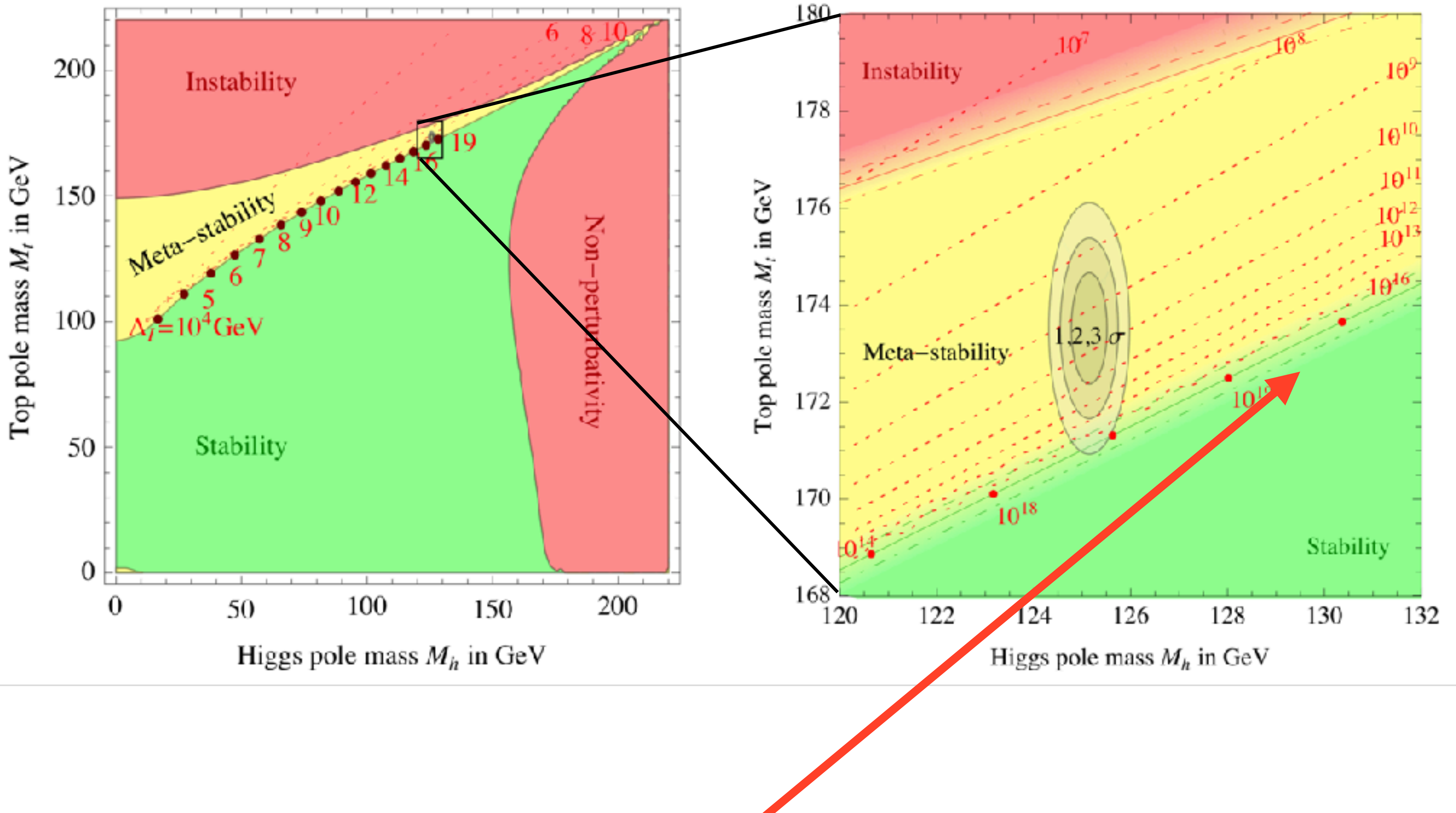
E. J Copeland, A. R Liddle, D. Wands, arXiv:9711068

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



Smaller in future, larger in the past!

Recall the Higgs instability problem



If Higgs mass(self coupling) is larger in the past, no Higgs instability problem!

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,

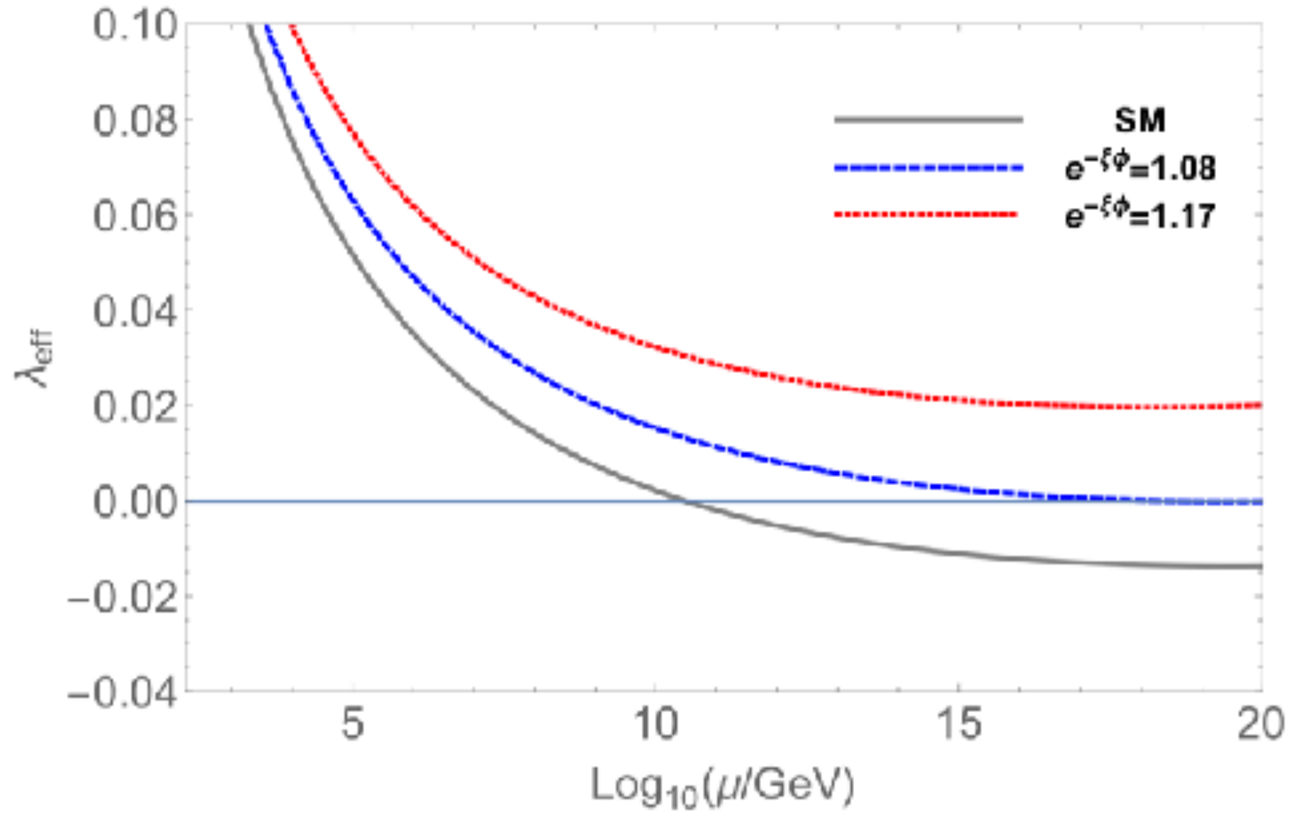
- **How large enhancement is needed?**
- **How much quintessence can provide?**
- **How to test?**

How large enhancement is needed?

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

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

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



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

How much quintessence can provide?

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

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

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

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

$$\xi > 0.35 \pm 0.05$$

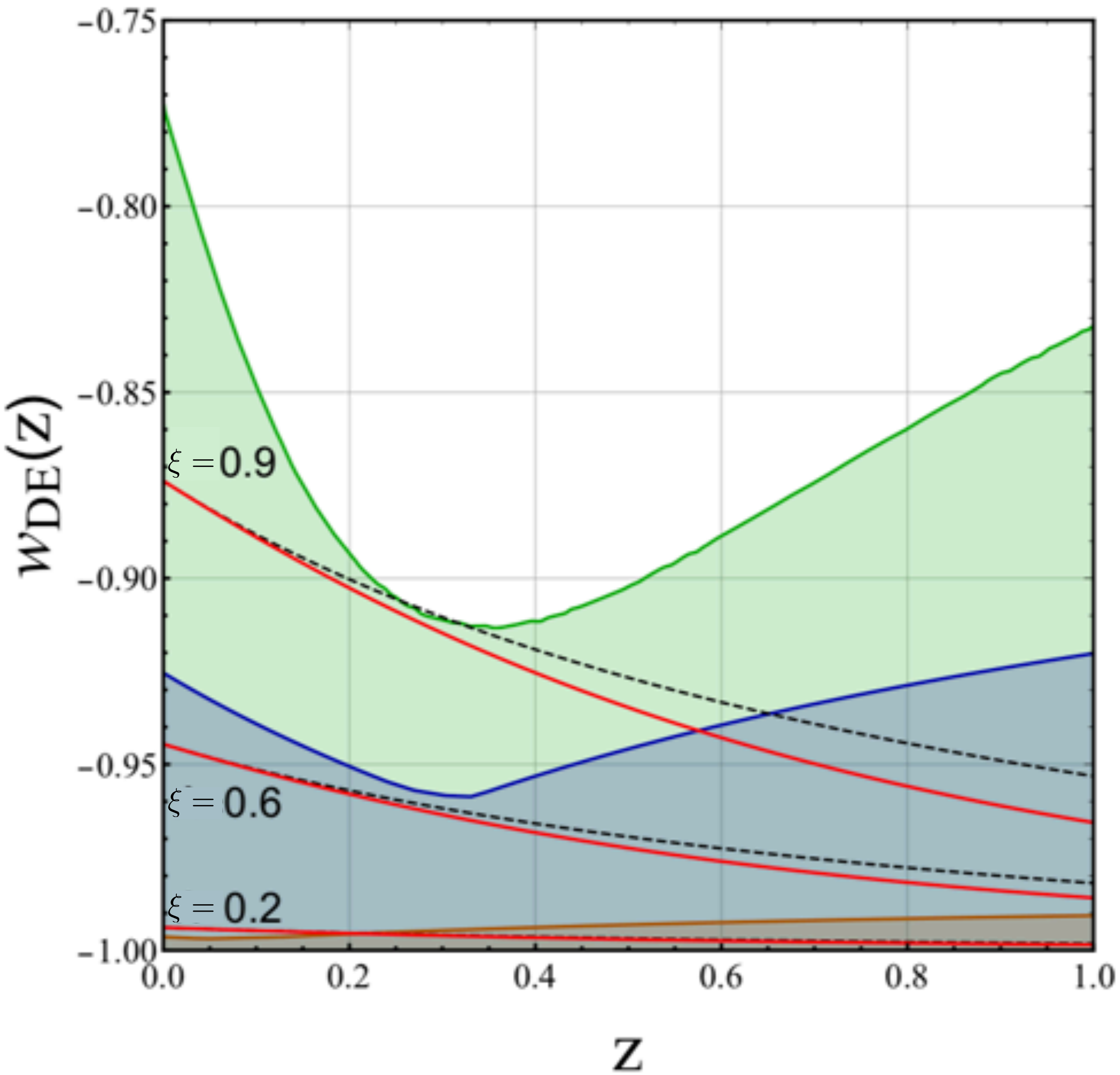
From Planck 2018

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

How to test?

Dark energy experiment already exclude $\xi > 0.6$

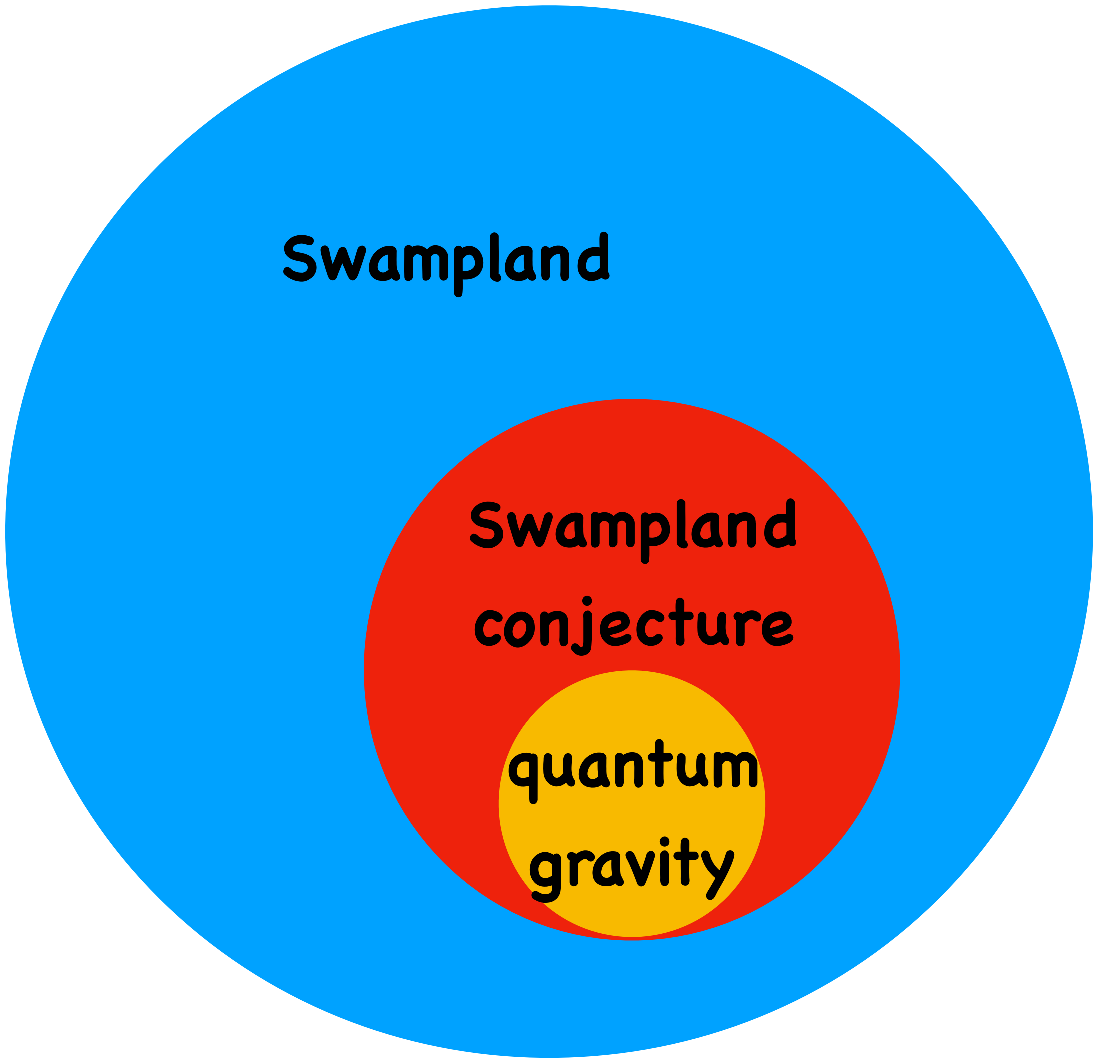
Y. Akrami, R. Kallosh, A. Linde, V. Vardanyan, arxiv:1808.09440



Exclusion limit combing SNeIa, CMB, BAO, H_0

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

To be swampland or not to be swampland?



- What is Swampland?
- The set of low energy physics models which look consistent but ultimately are not when coupled to gravity, is called the "swampland." ——Vafa

Swampland conjecture: a quantum gravity theory should satisfy:

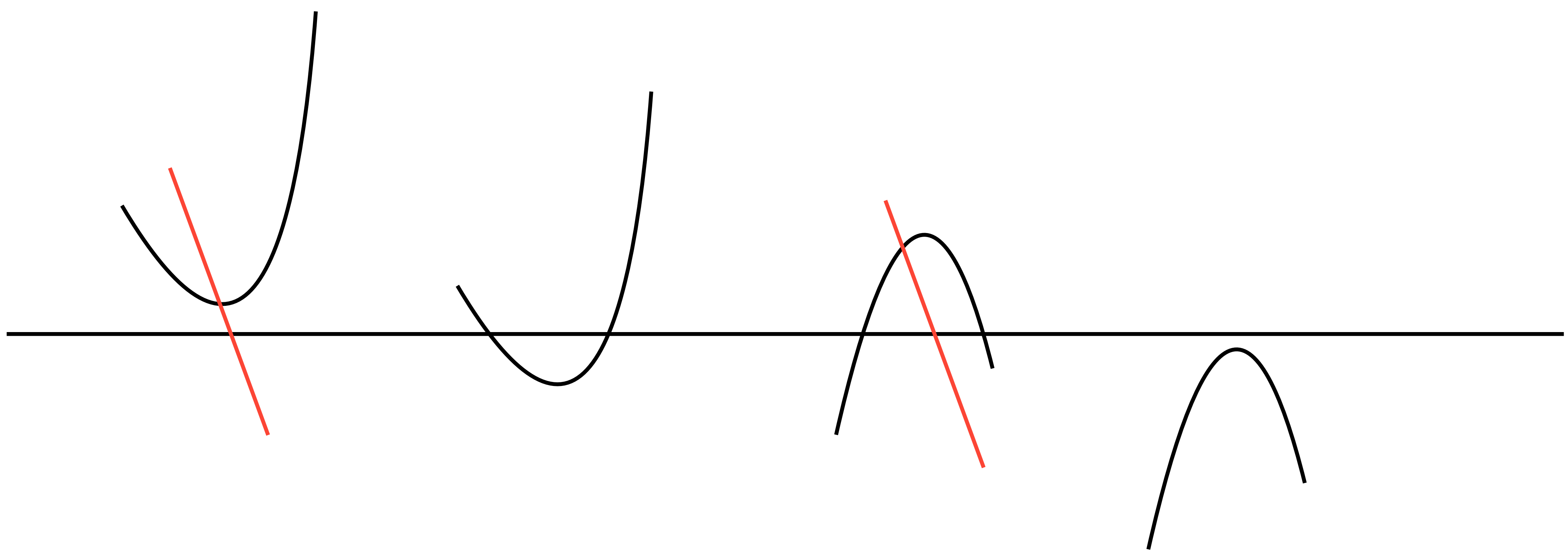
G. Obied, H. Ooguri, L. Spodyneiko, C. Vafa, arXiv:1806.08362

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

$$||\nabla V_{\rm total}|| = \sqrt{\sum_{i,j} g^{ij}_{\rm conf}(\partial_{\phi_i} V_{\rm total})(\partial_{\phi_j} V_{\rm total})}\,,$$

Swampland Conjecture

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



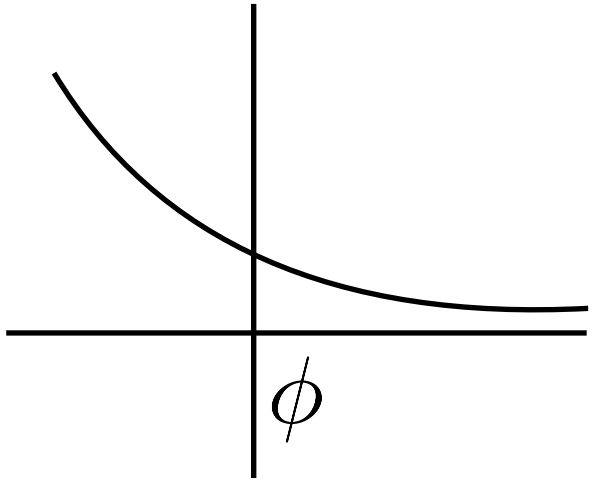
Implications I: dark energy

Cosmological constant do not exist!

$$V = \Lambda$$

Dark energy should be explained dynamically:

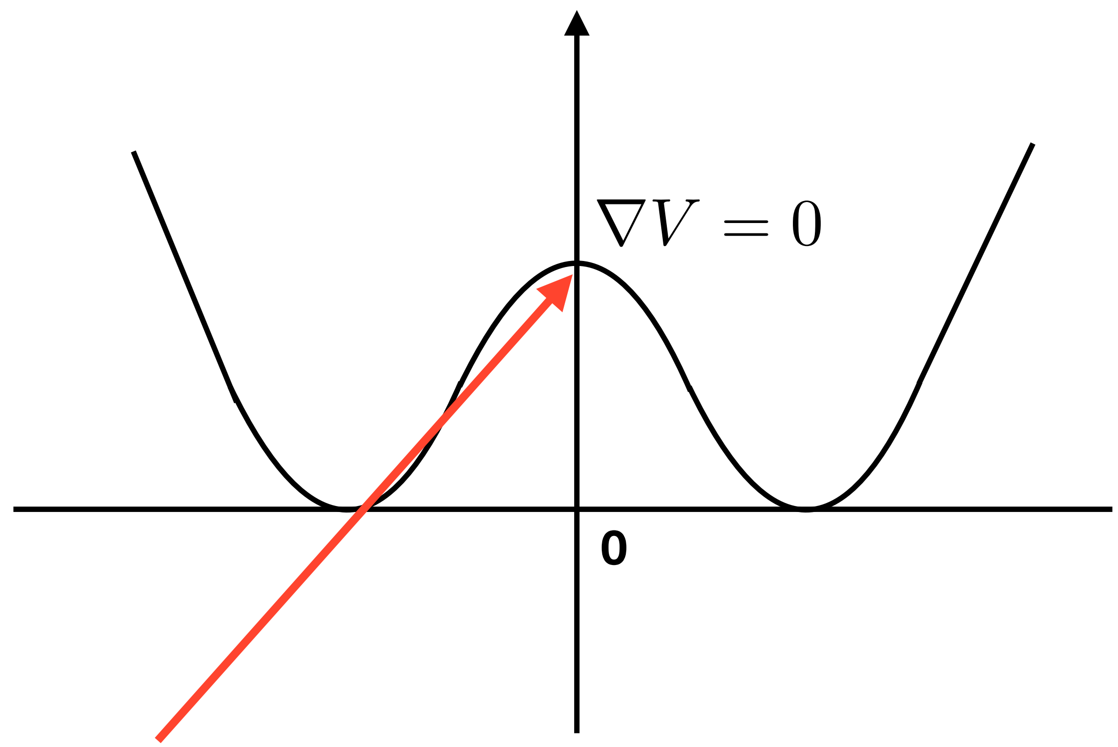
Quintessence: $$V = \Lambda e^{-\xi\phi}$$



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

Implications II: Higgs

Higgs sector need to be enlarged!



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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 is consistent with the swampland conjecture.
- It can be tested by cosmology observations.

Happy New Year!