Light inflaton completing Higgs inflation

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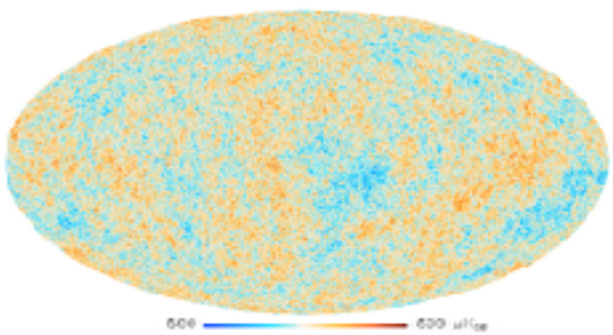
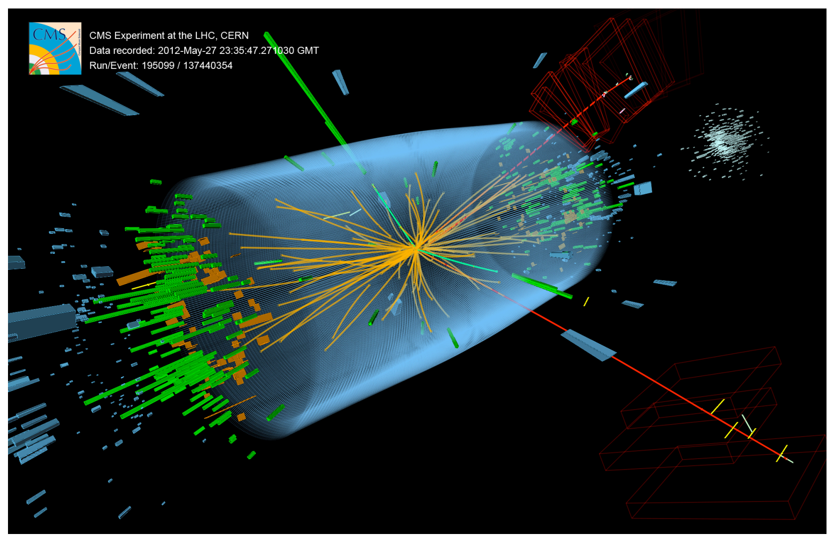
Particle physics in cosmology



Cosmic Microwave Background

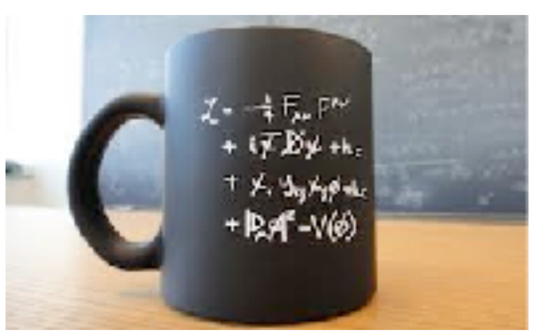
"Slow-roll inflation"

$m_I \ll H$



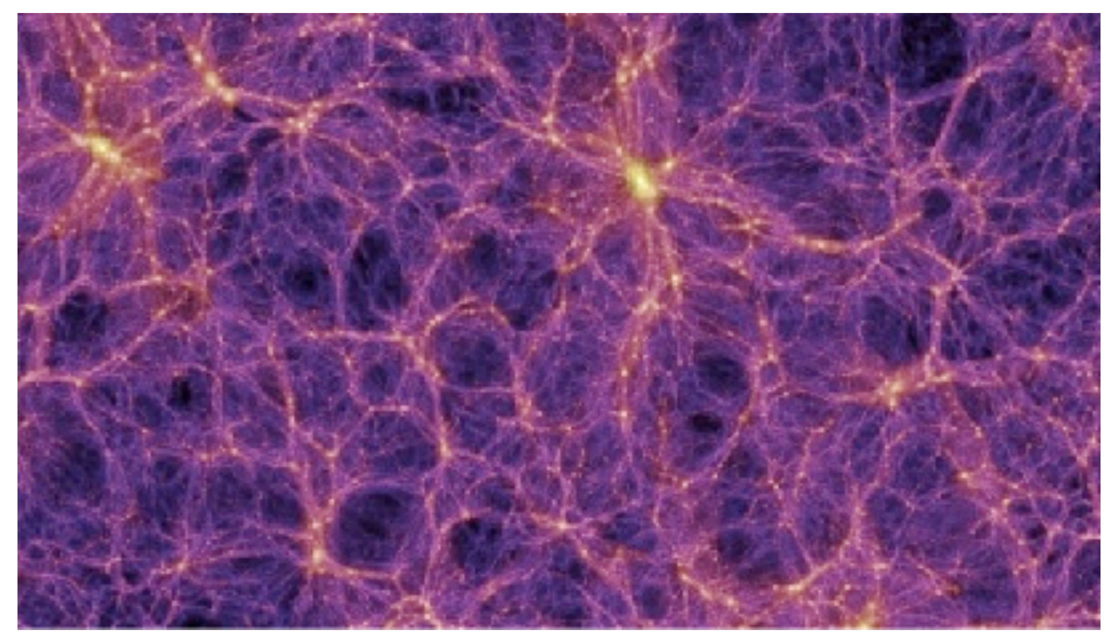
Mass generation

"Higgs boson" $m_H \ll M_P$



?

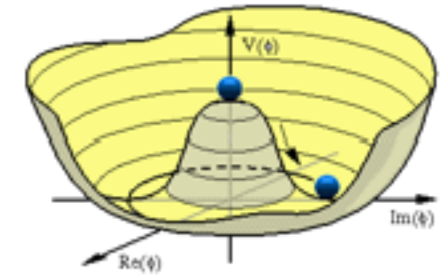
What are the origins of inflation, symmetry breaking, and dark matter?



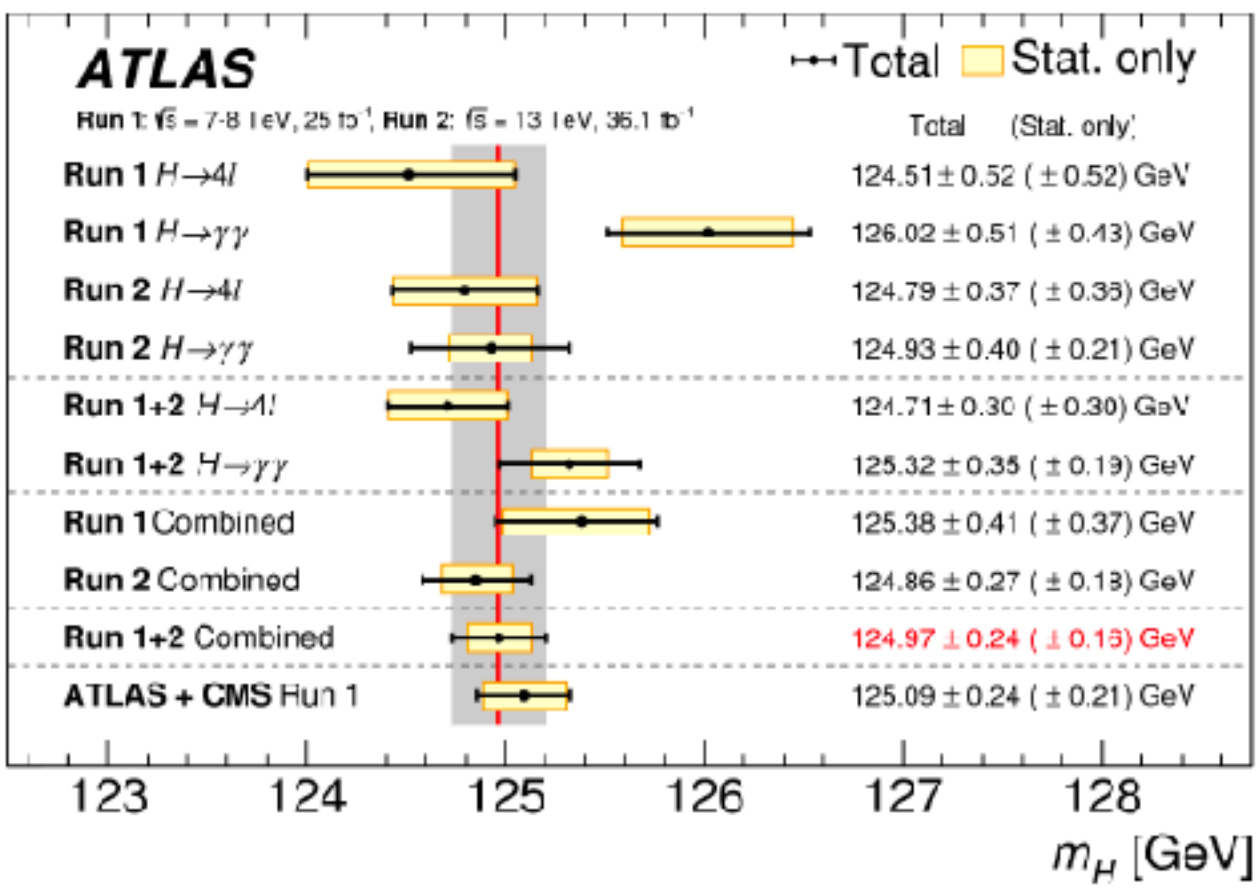
Large-scale structure

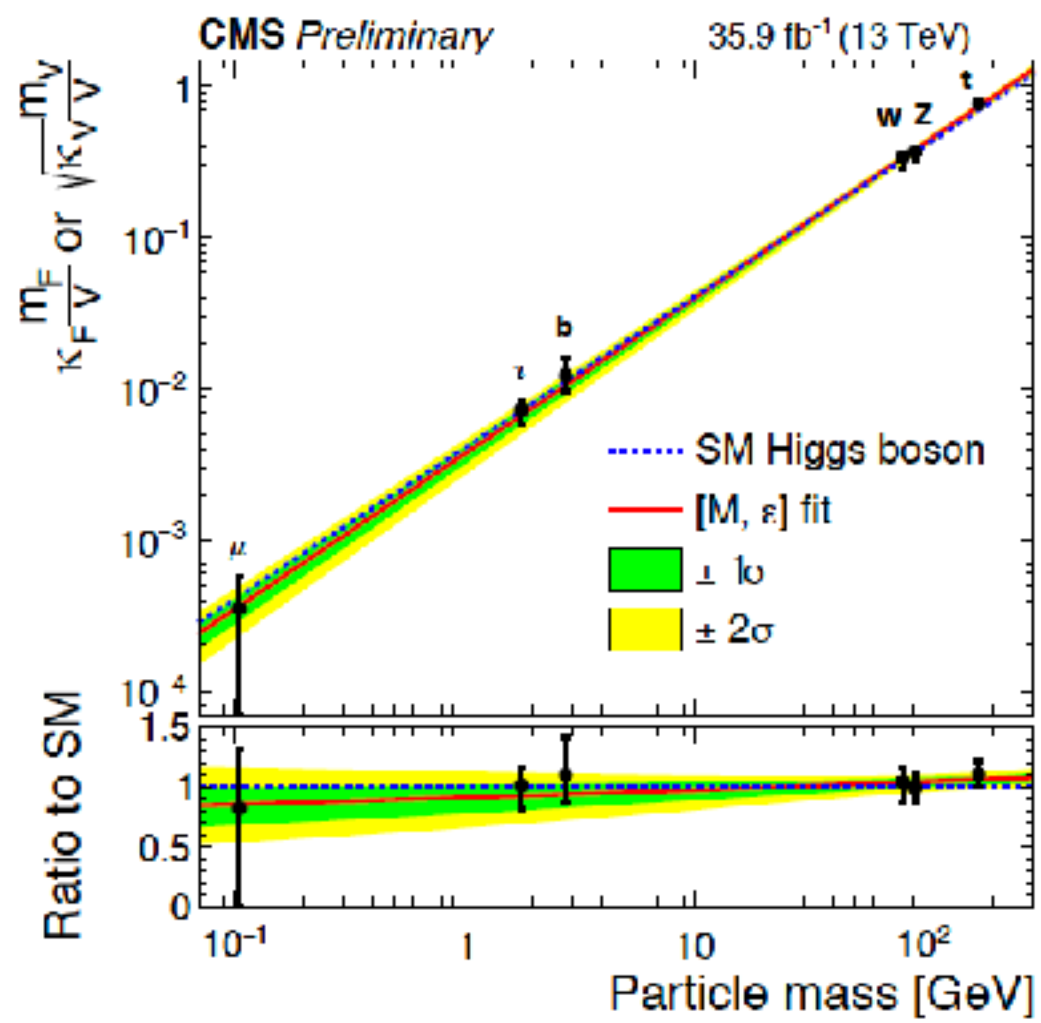
"Dark matter" $\tau_X > 10^{16}\,\mathrm{sec}$

Higgs boson at LHC



- 125GeV Higgs boson is (close to) a fundamental scalar particle, consistent with Higgs couplings predicted in SM.





- Higgs precision is important at HL-LHC and future colliders.
- Is Higgs boson the last piece of the puzzles?

July 5, 2012 | World News | RayKrebs

Higgs Boson May Be Key to Understanding Dark Matter & New Physics?

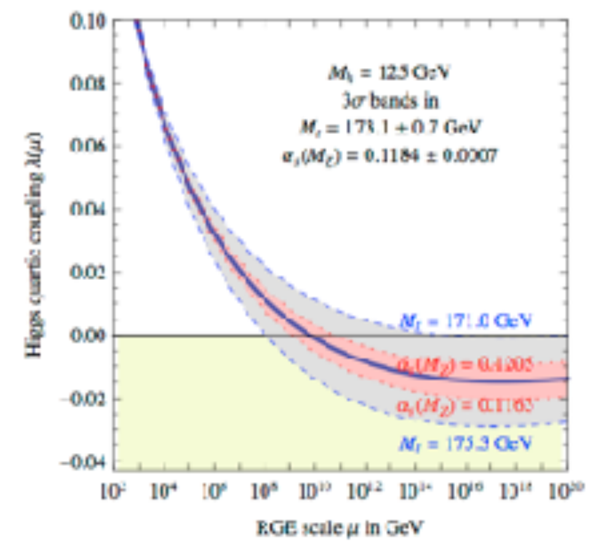
Discovered Higgs boson has a key to open the door to new symmetries and interactions beyond the SM.

Knocking on Higgs's door

- ✔ Hierarchy problem, vacuum instability

$$V = m_H^2 |H|^2 + \lambda |H|^4$$

$$m_H^2 = m_{H,0}^2 - \frac{\kappa^2}{16\pi^2} M_{\rm heavy}^2 \sim (100\,\mathrm{GeV})^2, \;\; \lambda_H > 0$$

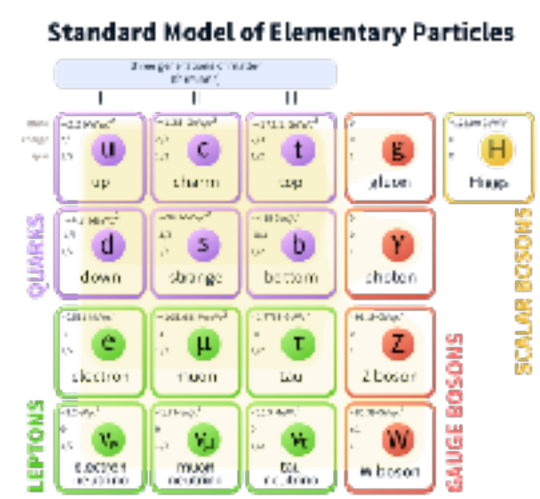


- ✔ Electroweak symmetry breaking $\quad m_H^2 < 0?$

- ✔ Flavor puzzles, baryogenesis

$$H_1 Q_i U_j^c + H_2 Q_i D_j^c + \cdots$$

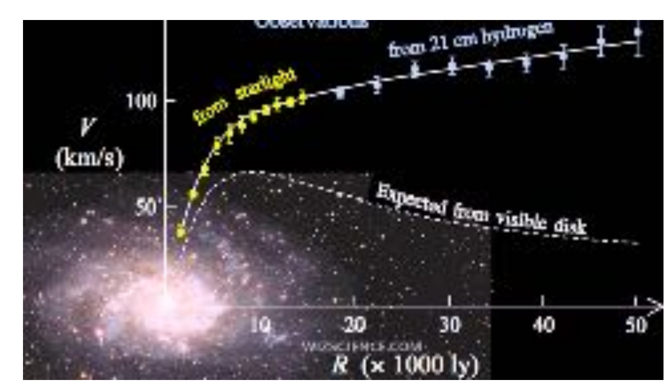
More Higgs?



- ✔ Dark matter

$$\lambda_{HS} |H|^2 S^2$$

WIMP, FIMP, SIMP, …



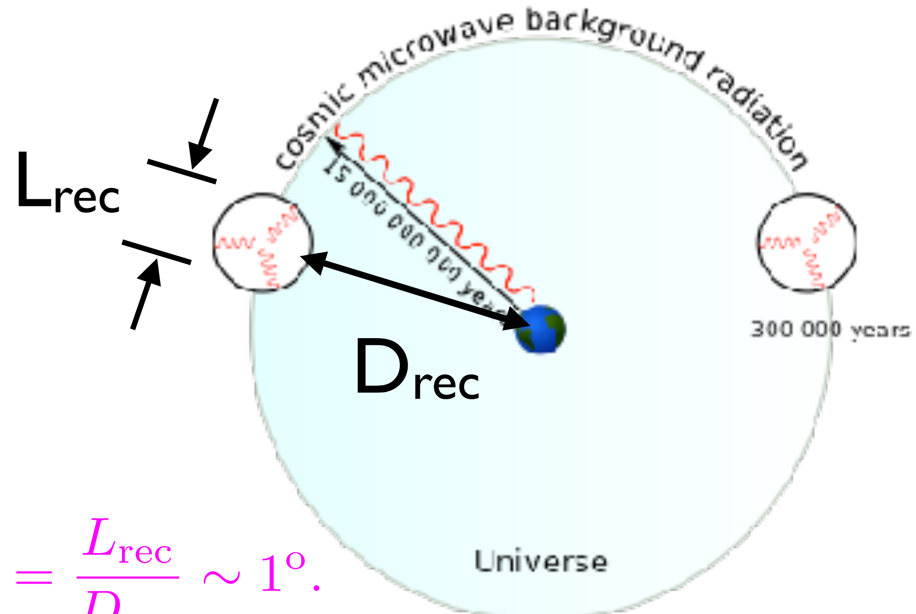
- ✔ Inflation

$$\xi |H|^2 \mathcal{R}$$

Higgs inflation?

Cosmic inflation

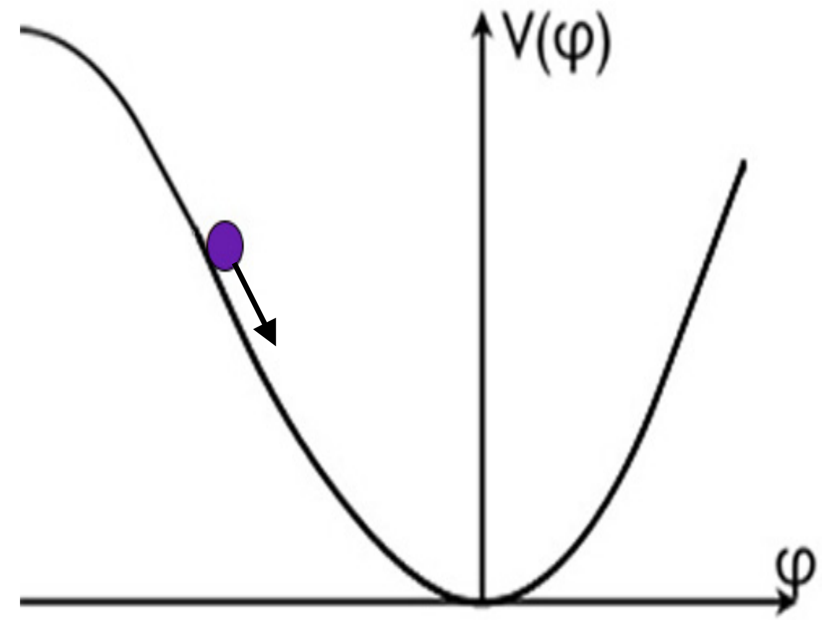
- Exponential expansion with a scalar field "inflaton" explains the initial conditions for Big Bang Cosmology.



$$\theta = \frac{L_{\rm rec}}{D_{\rm rec}} \sim 1^{\rm o}.$$

Causally connected
at recombination

How uniform CMB 1 in 10^4 ?



$$ds^2 = -dt^2 + e^{2Ht} d\vec{x}^2$$

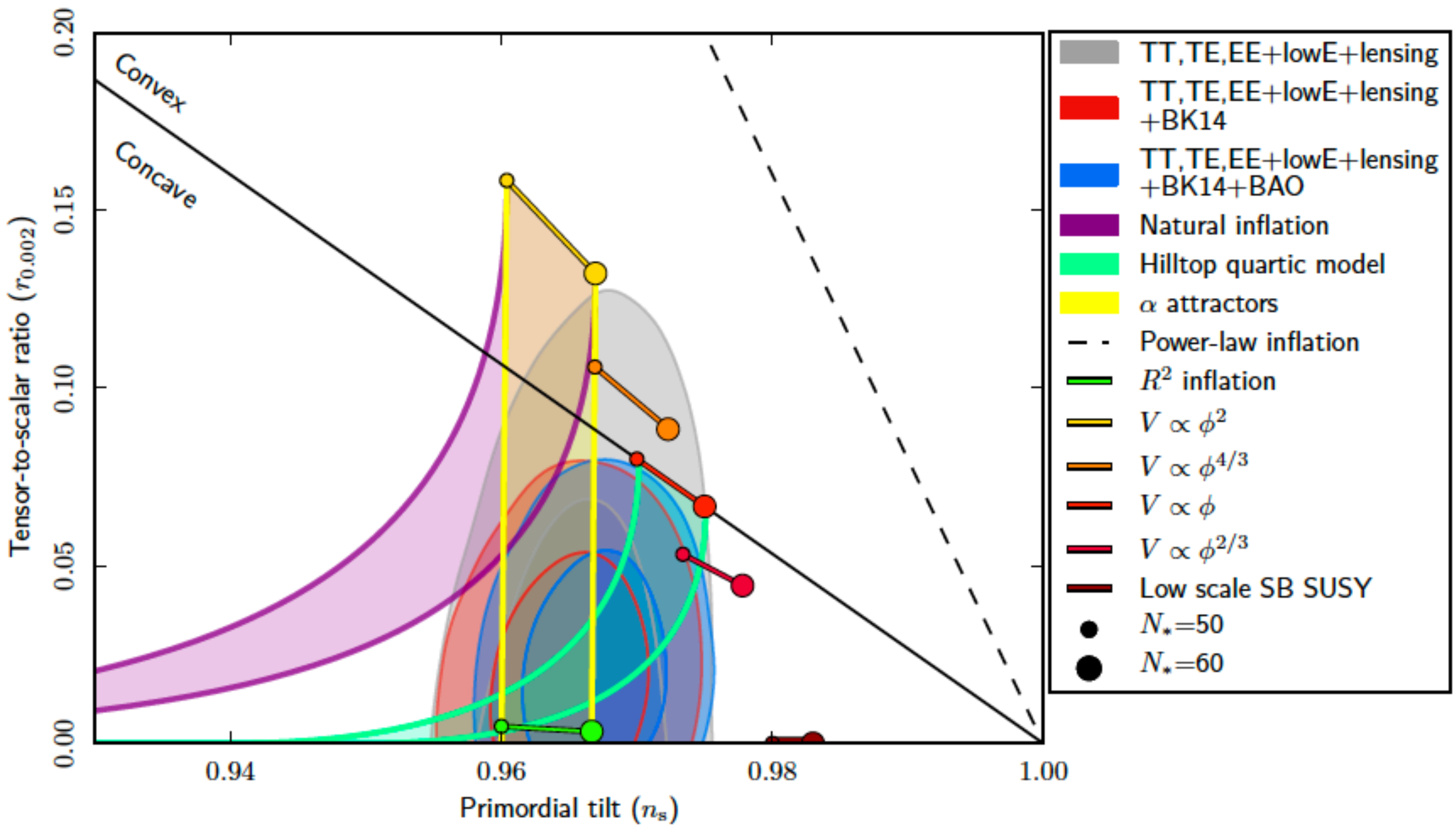
Number of efoldings:

$$N = \int_{t_i}^{t_f} H dt = 60$$

- Slow-roll inflation is confirmed by CMB anisotropies.

$$n_s = 1 - 6\epsilon + 2\eta, \qquad r = 16\epsilon, \qquad \epsilon \sim \frac{(V')^2}{V^2} \ll 1, \quad \eta \sim \frac{V''}{V} \ll 1.$$

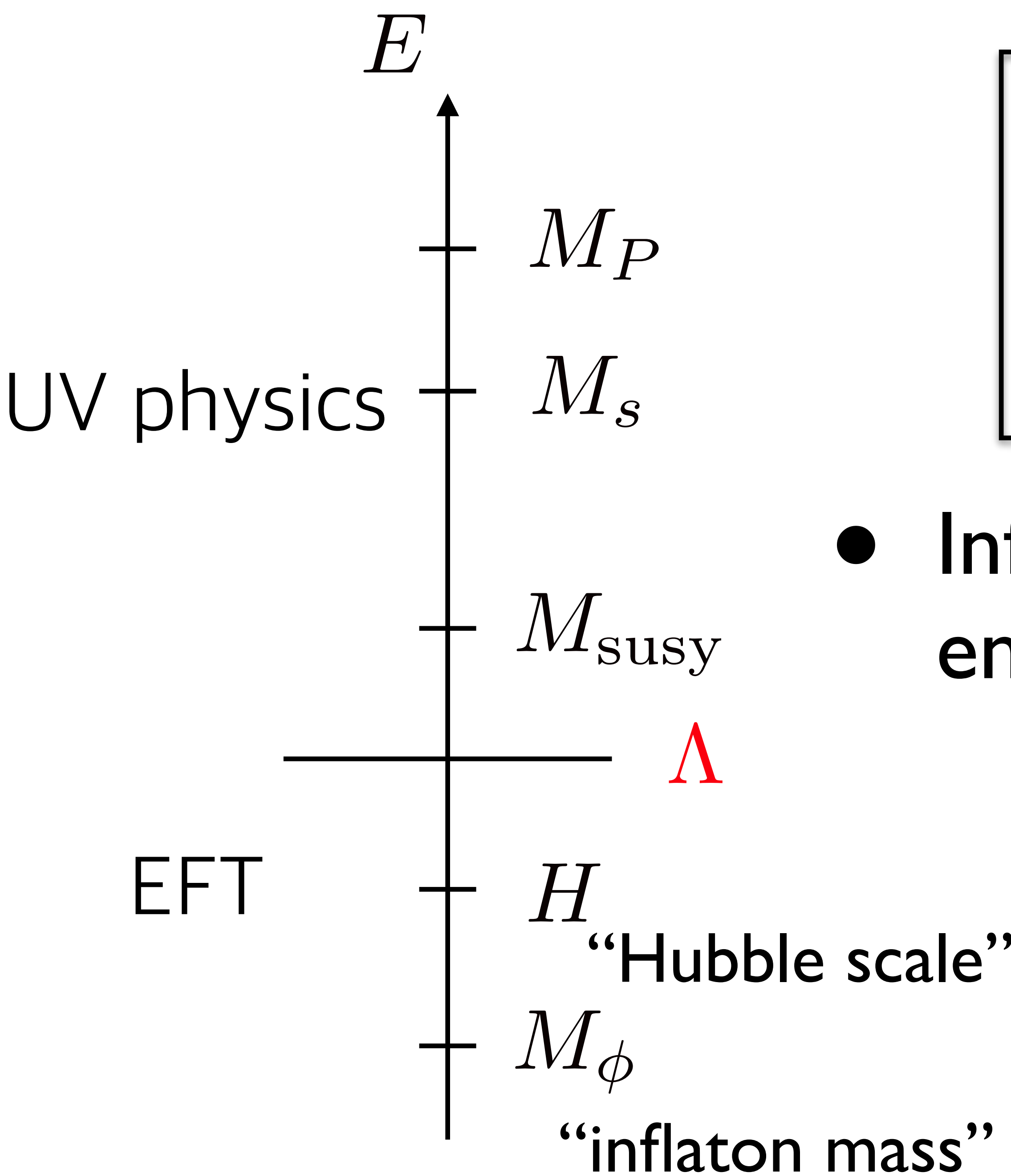
Planck data



$n_s = 0.9659 \pm 0.0041$ $\quad r_{0.002} < 0.10$ (95 % CL, *Planck* TT+lowE+lensing)

$n_s = 0.9653 \pm 0.0041$ $\quad r_{0.002} < 0.064$ (95 % CL, *Planck* TT,TE,EE +lowE+lensing+BK14) .

Inflation as EFT



$$\epsilon \sim \frac{(V')^2}{V^2} \ll 1, \quad \eta \sim \frac{V''}{V} \ll 1.$$

$$\Rightarrow \quad M_\phi \ll H \sim \sqrt{V} \ll \Lambda$$

- Inflation is Effective field theory valid at energies much below UV cutoff.

$$\mathcal{L} = \frac{1}{2}(\partial_\mu \phi)^2 - \frac{1}{2} m_\phi^2 \phi^2 - \frac{1}{3} B\phi^3 - \frac{1}{4}\lambda \phi^4 - \sum_{n=1}^{\infty} \frac{c_n \phi^{n+4}}{\Lambda^n}.$$

- What controls UV physics (or unitarity) for entire range of inflaton fields?

Questions

- What is inflaton?

  axion, dilaton, moduli, wilson-line, Higgs boson, ….

- How is inflaton potential flat enough?

  shift, scale, supersymmetry, gauge, ….

- How does it interact with the rest? $\Rightarrow$ Reheating

  effects on CMB? distinguishable?
  testable at colliders? dark matter? baryogengesis?

- In this talk, we consider the possibility of Higgs inflation and its consistency & UV completion.

Higgs = inflaton?

- Minimally coupled Higgs boson:

$$\mathcal{L} = \sqrt{-g}\Big(\frac{1}{2}\mathcal{R} - |D_\mu H|^2 - \lambda_H |H|^4 - m_H^2 |H|^2 - V_0\Big)$$

$\lambda_H |H|^4$ inflation: $\lambda_H \sim 10^{-12}$

$m_H^2 |H|^2$ inflation: $m_H^2 \sim (10^{13}\,\mathrm{GeV})^2$

But, $m_h = \sqrt{2\lambda_H}\, v = 125\,\mathrm{GeV}$ $\Rightarrow$ $\lambda_H = 0.13$

$$v = \sqrt{-\frac{m_H^2}{\lambda_H}} = 246\,\mathrm{GeV} \quad \Rightarrow \quad m_H^2 = -(98\,\mathrm{GeV})^2$$

cf. inflection point: small running quartic coupling.

$$\lambda_H(h) = \lambda(\mu_c) + \frac{g_{\rm SM}^4}{(16\pi^2)^2}\ln\Big(\frac{h}{\mu_c}\Big), \qquad \lambda(\mu_c) \ll 1, \quad \mu_c \sim M_P.$$

$\Rightarrow$ Too small number of efoldings.

Higgs inflation

[Bezrukov, Shaposhnikov (2007)]

- Add a non-minimal coupling for Higgs boson to the SM.

$$\mathcal{L} = \sqrt{-g}\Big(\frac{1}{2}\mathcal{R} + \boxed{\xi|H|^2\mathcal{R}} - |D_\mu H|^2 - \lambda_H(|H|^2 - v^2/2)^2\Big)$$

$$\Rightarrow \quad \mathcal{L}_E = \sqrt{-g_E}\Big(\frac{1}{2}\mathcal{R}(g_E) - \underline{\frac{3\xi^2}{\Omega^2}(\partial_\mu|H|^2)^2 - \frac{1}{\Omega}|D_\mu H|^2} - \frac{V}{\Omega^2}\Big)$$

$$g_{\mu\nu} = \Omega^{-1} g_{E,\mu\nu}, \quad \Omega = 1 + 2\xi|H|^2$$

Non-canonical kinetic terms

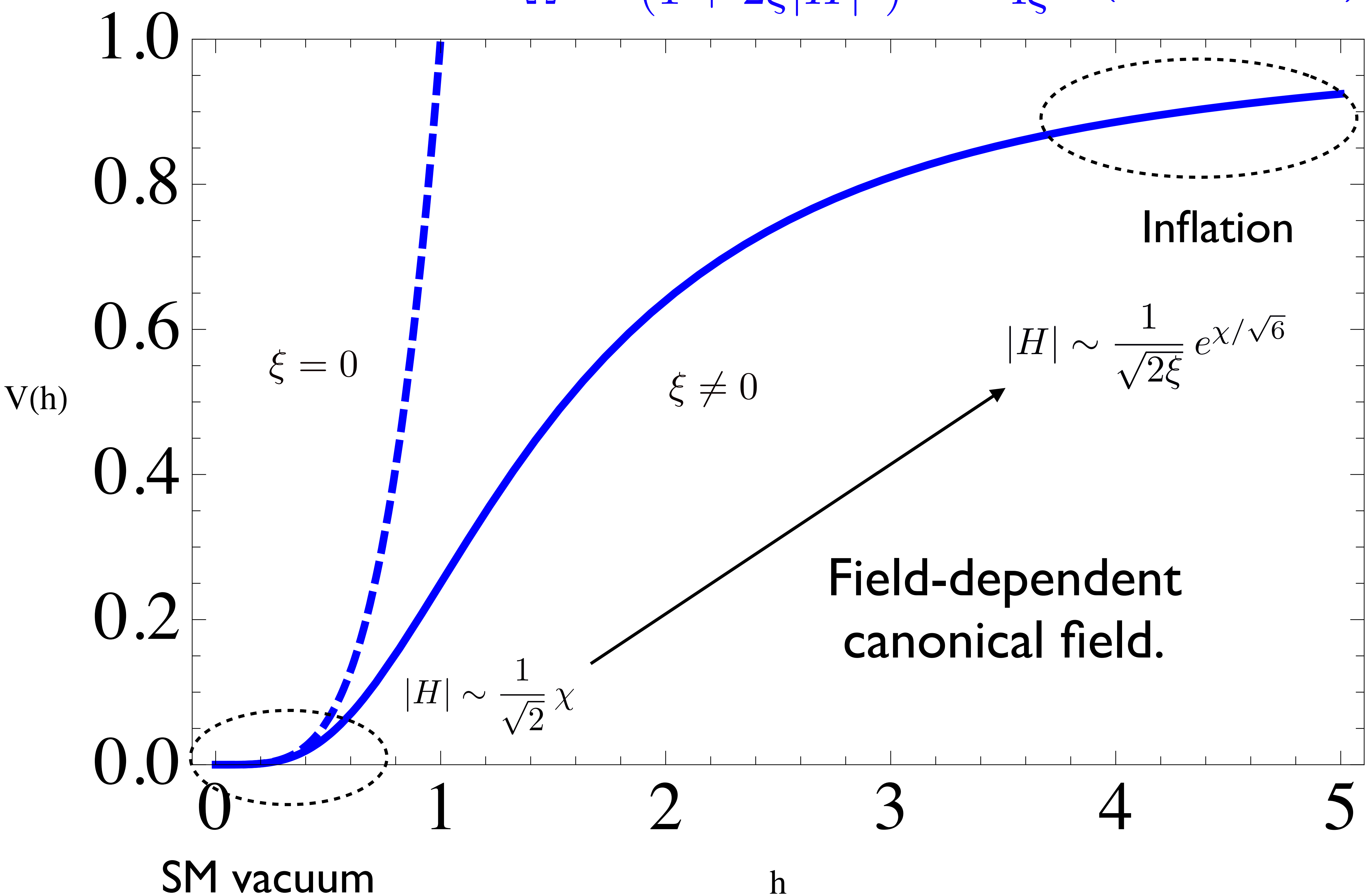
Higgs boson can drive cosmic inflation, with definite predictions.

✓ $\frac{\Delta T}{T} \sim 10^{-4} \Rightarrow \frac{\sqrt{\lambda_H}}{\xi} = 2\times 10^{-5}$ "Large non-minimal coupling"

✓ $n_s = 1 - \frac{2}{N} = 0.966, \quad r = \frac{12}{N^2} = 0.0033$ "Consistent with Planck data"

Higgs potential

$$\frac{V}{\Omega} = \frac{\lambda_H |H|^4}{(1+2\xi|H|^2)^2} \sim \frac{\lambda_H}{4\xi^2}\left(1 - e^{-\frac{2}{\sqrt{6}}\chi}\right)$$



Power counting for EFT

[Burgess, HML, Trott (2009)]

- Truncate the effective action in scalar-tensor gravity.

$$-\frac{\mathcal{L}_{\rm eff}}{\sqrt{-g}} = v^4 V(\theta) + \frac{M_p^2}{2} g^{\mu\nu}\Big[W(\theta)\, R_{\mu\nu} + G_{ij}(\theta)\, \partial_\mu\theta^i\partial_\nu\theta^j\Big]$$
$$+A(\theta)(\partial\theta)^4 + B(\theta)\, R^2 + C(\theta)\, R\, (\partial\theta)^2 + \frac{E(\theta)}{M^2}\, (\partial\theta)^6 + \frac{F(\theta)}{M^2}\, R^3 + \cdots .$$

- Identify interactions from field expansions in EFT.

$$\theta^i(x) = \vartheta^i(x) + \frac{\phi^i(x)}{M_p} \quad \text{and} \quad g_{\mu\nu}(x) = \hat{g}_{\mu\nu}(x) + \frac{h_{\mu\nu}(x)}{M_p}$$

- Validity of semi-classical approximation: $\dot{h}/h,\ H \ll M$

cutoff

$$\text{Quantum action}: \ \Gamma = \int d^4x \mathcal{L}_{\rm eff}(\text{background}) + \hbar\Delta\Gamma,$$

"power counting" in EFT : $\Delta\Gamma \ll \Gamma$

$\Rightarrow$ Effective interactions are constrained.

Trouble with large coupling

- Effective Higgs interactions

[Han, Willenbrock (2004); Burgess, HML, Trott (2009,2010); Barbon, Espinosa (2009); Hertzberg (2010)]

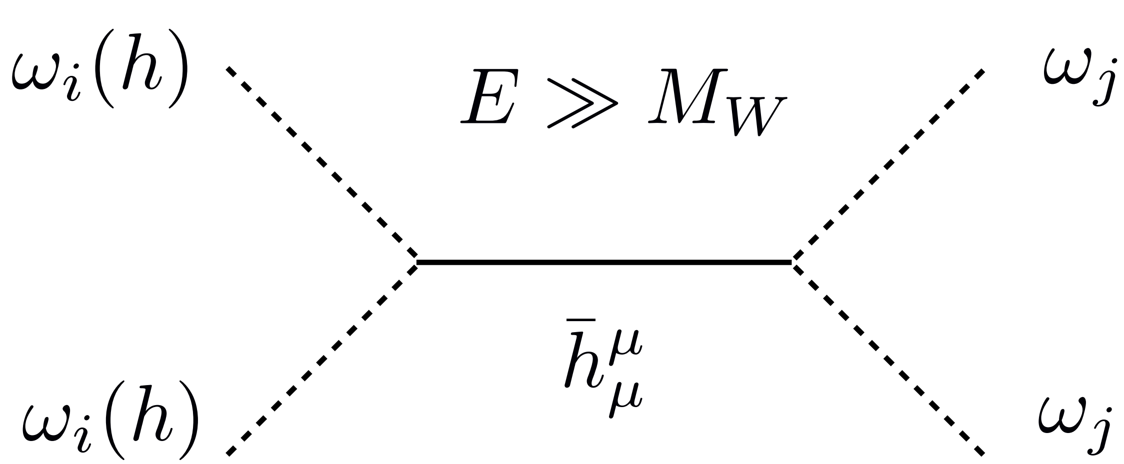
$$H = \frac{1}{\sqrt{2}} \begin{pmatrix} -\omega_2(x) - i\omega_1(x) \\ \varphi(x) + h(x) + i\omega_3(x) \end{pmatrix}, \quad g_{\mu\nu}(x) = \hat{g}_{\mu\nu}(x) + \frac{h_{\mu\nu}(x)}{M_P}.$$

$$\Longrightarrow \quad \mathcal{L}_{\rm int} = \frac{1}{4}\left(\omega_1^2 + \omega_2^2 + \omega_3^2 + (\varphi + h)^2\right) \boxed{\frac{\xi}{\Lambda}} \left(\Box \bar{h}^\mu_\mu + 2\partial^\alpha \partial^\beta \bar{h}_{\alpha\beta} + \cdots\right).$$

cf. Einstein frame:

$$\mathcal{L}_{\rm eff} = \frac{2\xi}{M_P^2} |H|^2 |D_\mu H|^2 - \boxed{\frac{3\xi^2}{M_P^2}} \partial_\mu (H^\dagger H) \partial^\mu (H^\dagger H) + \frac{4\lambda_H \xi}{M_P^2} |H|^6 + \cdots$$

- Perturbative unitarity is violated at small scales.



$$\mathcal{M}_{\omega_i \omega_i \to \omega_j \omega_j} \sim \frac{\xi^2 E^2}{M_P^2},$$

Unitarity bound ~ Hubble scale,

$$E \lesssim \frac{M_P}{\xi} \quad \text{vs} \quad H_{\rm inf} \sim \frac{\sqrt{\lambda_H} M_P}{\xi}.$$

Saving Higgs inflation

[Giudice, HML (2010)]

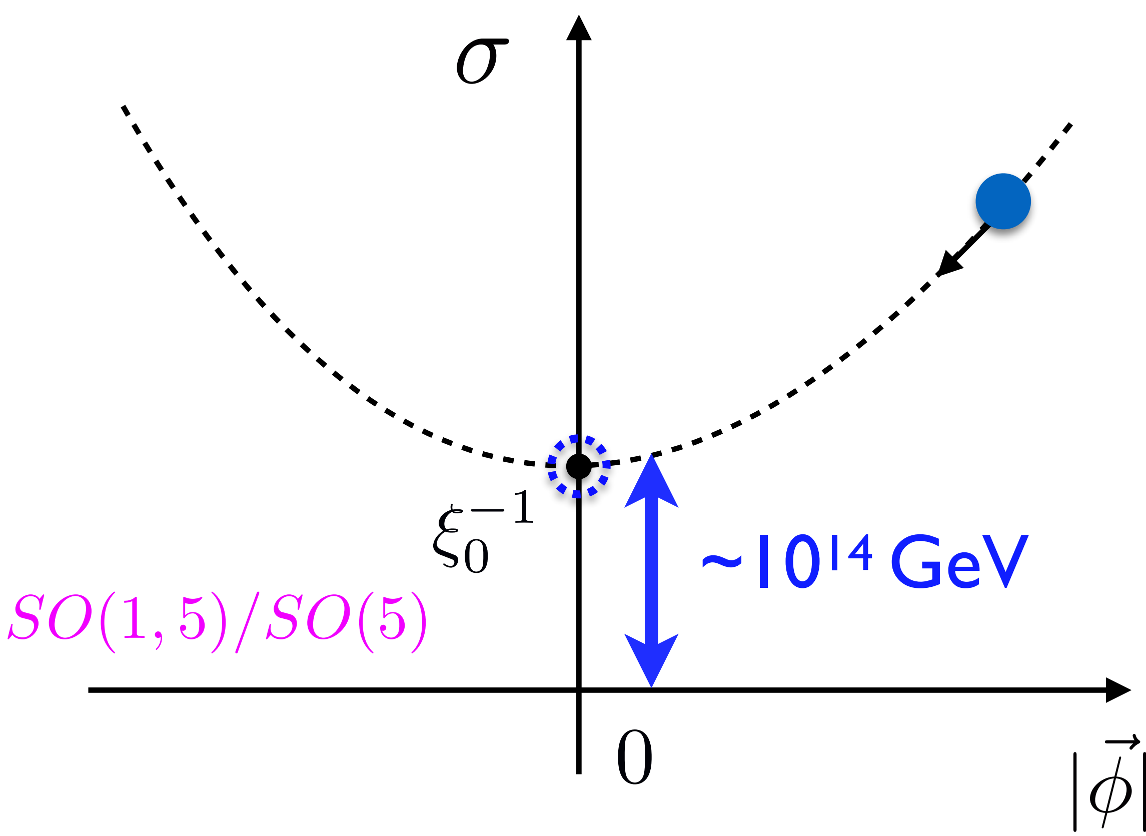
"Induced gravity" $\mathcal{L}_J = \sqrt{-g}\left[\underline{\xi_0\sigma^2\mathcal{R}} - \frac{1}{2}(\partial_\mu\sigma)^2 - \lambda\left(\sigma^2 - \vec{\phi}^2 - \xi_0^{-1}\right)^2\right]$

$\int D\psi\, e^{iS(g,\psi)} = e^{i\int d^4x\sqrt{-g}(M_P^2\mathcal{R}+\cdots)}$ [Zee, Smolin (1979)]

➡ Integrate out "sigma field": $\mathcal{L}_{\rm eff} = \sqrt{-g}(1+\xi_0\vec{\phi}^2)\mathcal{R}$

~Higgs inflation as EFT.

Full theory: Higgs moves in hyperbolic space!



➡ The same predictions as in Higgs inflation.

Physical sigma mass is tied up to inflation scale.

$m_\sigma^2 = 4\lambda H^2 \sim (10^{13}\,\mathrm{GeV})^2$

Comparison to Starobinsky

- Starobinsky R² model is dual to a scalar-tensor theory.

[Starobinsky (1984); Giudice, HML (2014)]

$$\mathcal{L}=\sqrt{-g}\left(\frac{R}{2}+\xi^2 R^2\right) \Longleftrightarrow \mathcal{L}=\sqrt{-g}\Big(\frac{R}{2}+\frac{1}{2}\xi\sigma^2 R-\frac{1}{16}\sigma^4\Big)$$

Hubbard-Stratonovich transf.

- Starobinsky model as a UV completion?

[Y. Ema (2017); Gorbunov, Tokareva (2018)]

$$\mathcal{L}=\sqrt{-g}\Big(\frac{1}{2}(1+\xi_H h^2+\underline{\xi\sigma^2})R-\frac{1}{2}(\partial_\mu h)^2-\underline{\frac{1}{16}}\sigma^4-V(h)\Big)$$

$$\Longrightarrow \mathcal{L}=\sqrt{-g}\Big(\frac{1}{2}\xi\hat\sigma^2 R-\frac{1}{2}(\partial_\mu h)^2-\frac{1}{16}\Big(\hat\sigma^2-\frac{\xi_H}{\xi}h^2-\frac{1}{\xi}\Big)^2-V(h)\Big)$$

$\xi\hat\sigma^2=1+\xi_H h^2+\xi\sigma^2$: Equivalent to a sigma-field model.

Higher curvature terms such as R³ would spoil unless suppressed.

[Giudice, HML, in progress]

General sigma inflation

[HML (2018)]

Introduce a linear non-minimal coupling in the sigma model.

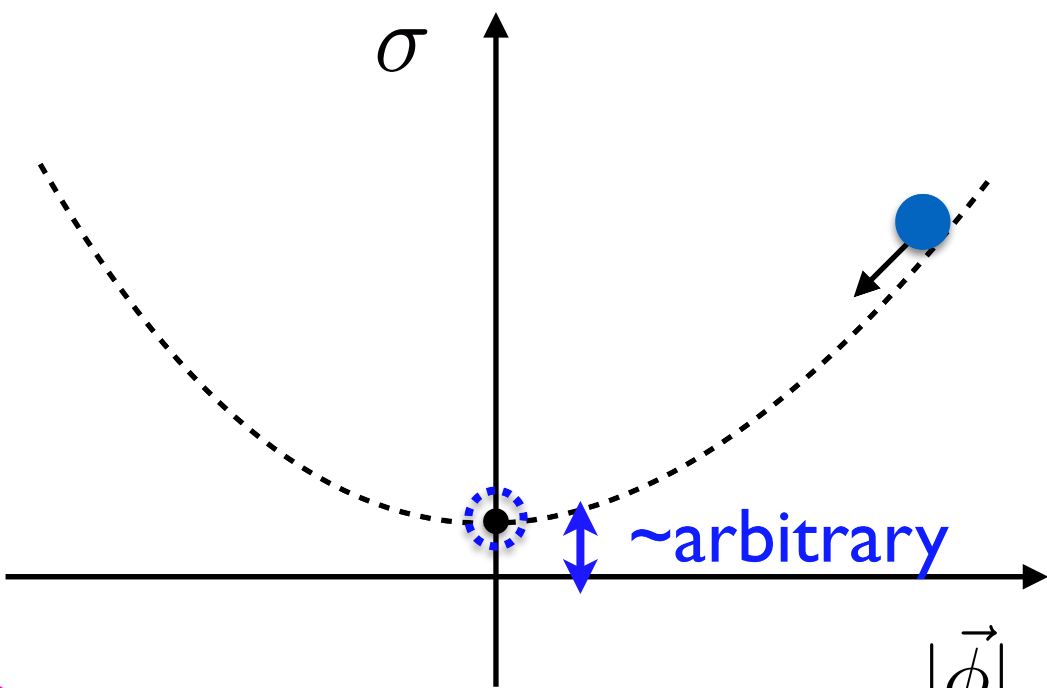
$$\mathcal{L}_J = \sqrt{-g}\Big[\underbrace{(1+\xi_1\sigma+\xi_0\sigma^2)}_{=\Omega}\mathcal{R} - \frac{1}{2}(\partial_\mu\sigma)^2 - \frac{1}{2}m_\sigma^2\sigma^2 - \lambda(\sigma^2-\vec{\phi}^2)^2\Big]$$

Stable gravity:	$\xi_1^2 < 4\xi_0$
Unitarity up to Planck scale:	$\xi_1 \sim \sqrt{\xi_0}$

Large graviton mixing or kinetic term,

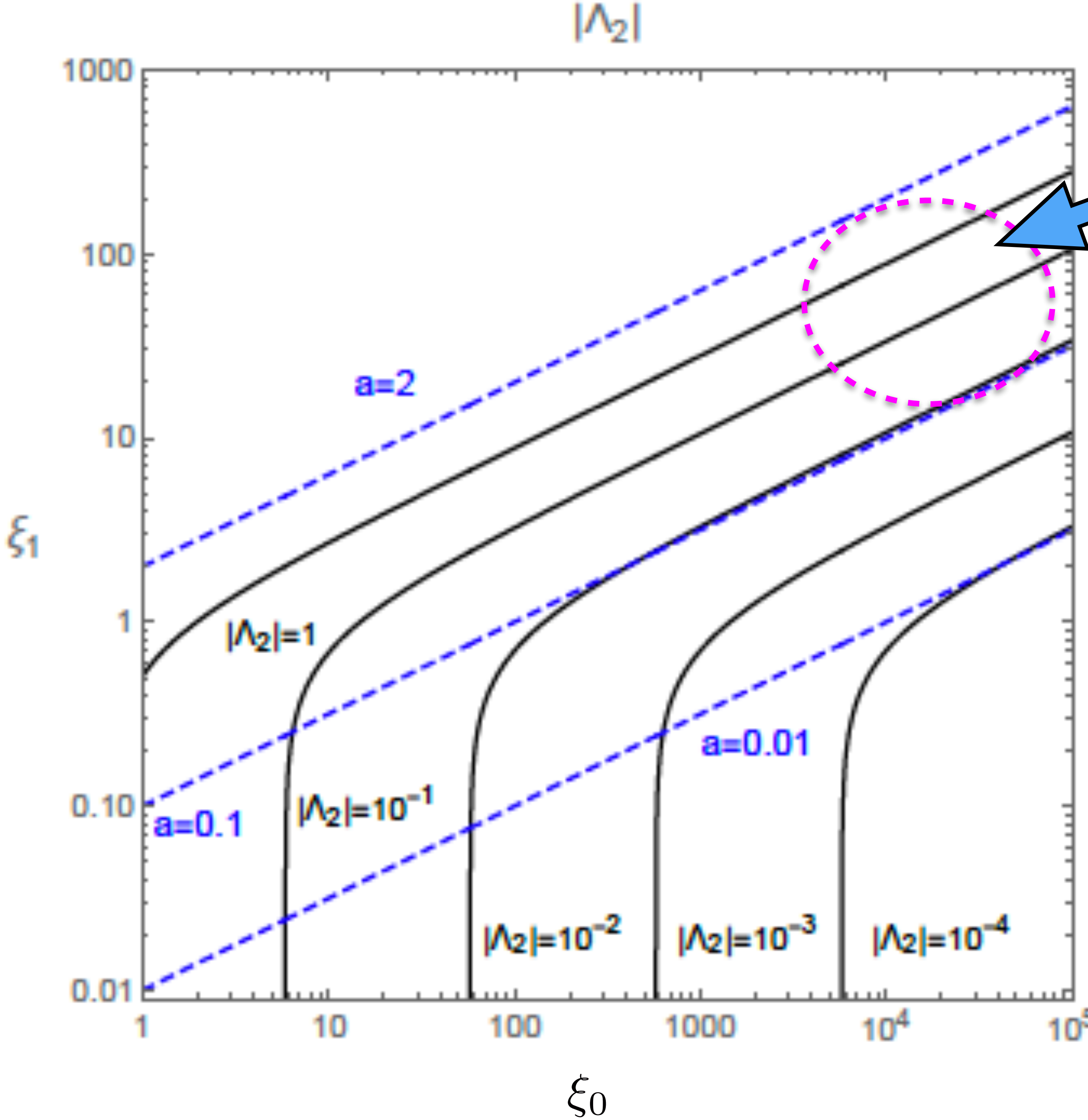
$$\mathcal{L}_J \supset \xi_1\sigma\delta\mathcal{R} = \xi_1\sigma\Box h + \cdots$$

$$\mathcal{L}_E \supset -\frac{3}{4}\frac{\Omega'^2}{\Omega^2}(\partial_\mu\sigma)^2 = -\frac{3}{4}\xi_1^2(\partial_\mu\sigma)^2 + \cdots$$



$\Rightarrow$ Suppressed interactions or large cutoff scale;
sigma mass can be arbitrarily small.

Λ_2 : Unitarity scale



Favored region

$$a = \frac{\xi_1}{\sqrt{\xi_0}} \sim 1$$

Higgs EFT from sigma field

[HML (2018)]

Integrate out "sigma field" in general sigma models.

$$\mathcal{L}_J = \sqrt{-g}\Big[(1+\xi_1\sigma+\xi_0\sigma^2)\mathcal{R} - \frac{1}{2}(\partial_\mu\sigma)^2 - \frac{1}{2}m_\sigma^2\sigma^2 - \lambda(\sigma^2 - a\vec{\phi}^2)^2\Big]$$

$$\mathcal{L}_{\rm eff} = \sqrt{-g}\Bigg[1 + \xi_1\sqrt{a\vec{\phi}^2 - \frac{m_\sigma^2}{\lambda}} + a\xi_0\vec{\phi}^2\Bigg]\mathcal{R}$$

$$\vec{\phi}^2 \ll |m_\sigma^2|/\lambda: \quad \mathcal{L}_{\rm eff} = \sqrt{-g}\Big[(1+a\xi_0\vec{\phi}^2)\mathcal{R} - \frac{1}{2}\lambda_{\rm eff}(\vec{\phi}^2)^2\Big]$$

$\lambda_{\rm eff} = \lambda_\phi - a\lambda$: stabilize Higgs vacuum

"Higgs inflation in EFT"

$$\vec{\phi}^2 \gg |m_\sigma^2|/\lambda: \quad \mathcal{L}_{\rm eff} = \sqrt{-g}\Big[1 + a\xi_1\sqrt{\vec{\phi}^2} + a\xi_0\vec{\phi}^2\Big]\mathcal{R}$$

Higgs inflation with non-analytic linear term.

Inflation dynamics

Take the most general Lagrangian for sigma field + Higgs:

$$\frac{\mathcal{L}}{\sqrt{-g}} = \frac{1}{2}M_P^2\Big(1+\frac{\xi_1\sigma}{M_P}+\frac{\xi_2\sigma^2}{M_P^2}+\frac{\xi_\phi\phi^2}{M_P^2}\Big)R-\frac{1}{2}(\partial_\mu\sigma)^2-\frac{1}{2}(\partial_\mu\phi)^2-V_J(\sigma,\phi)$$

with $V_J(\sigma,\phi)=\frac{1}{2}m_\phi^2\phi^2+\underline{\frac{1}{4}\lambda_\phi\phi^4}+\frac{1}{2}m_\sigma^2\sigma^2-\mu\sigma\phi^2+\frac{1}{3}\alpha\sigma^3+\underline{\frac{1}{2}\lambda_{\sigma\phi}\sigma^2\phi^2+\frac{1}{4}\lambda_\sigma\sigma^4}.$

Two field dynamics for inflation: $\xi_1\sigma+\xi_2\sigma^2+\xi_\phi\phi^2\gg 1$

$$\boxed{\begin{aligned} e^{\frac{2}{\sqrt{6}}\chi} &= \xi_1\sigma+\xi_2\sigma^2+\xi_\phi\phi^2, \\ \tau &= \frac{\phi}{\sigma}. \end{aligned}}$$

Scale-free limit:
mass terms irrelevant.

$$\frac{\mathcal{L}}{\sqrt{-g}} \approx \frac{1}{2}\Big[1+\frac{1}{6}\frac{1+\tau^2}{\xi_2+\xi_\phi\tau^2}\Big](\partial_\mu\chi)^2+\frac{1}{\sqrt{6}}\frac{\tau(\xi_2-\xi_\phi)}{(\xi_2+\xi_\phi\tau^2)^2}(\partial_\mu\chi)(\partial^\mu\tau)$$
$$+\frac{1}{2}\frac{\xi_\phi^2\tau^2+\xi_2^2}{(\xi_2+\xi_\phi\tau^2)^3}(\partial_\mu\tau)^2 \;-\; V_0\left(1-2a\,e^{-\frac{1}{\sqrt{6}}\chi}-(2+a^2)\,e^{-\frac{2}{\sqrt{6}}\chi}\right)$$

with $V_0 = \dfrac{\lambda_\phi\tau^4+2\lambda_{\sigma\phi}\tau^2+\lambda_\sigma}{4(\xi_2+\xi_\phi\tau^2)^2}, \quad a = \dfrac{\xi_1}{(\xi_2+\xi_\phi\tau^2)^{1/2}}.$

Single-field inflation

Stabilize the tau field: $\xi_2 \gg \xi_\phi = \mathcal{O}(1)$ (no unitarity problem)

$$(1)\ \tau = \sqrt{-\frac{\lambda_{\sigma\phi}}{\lambda_\sigma}}\ :\ \lambda_\phi > 0\,,\ \lambda_{\sigma\phi} < 0\,,$$
$$(2)\ \tau = 0\ :\ \lambda_\phi > 0\,,\ \lambda_{\sigma\phi} > 0\,,$$
$$(3)\ \tau = \infty\ :\ \lambda_\phi < 0\,,\ \lambda_{\sigma\phi} < 0\,,$$
$$(4)\ \tau = 0, \infty\ :\ \lambda_\phi < 0\,,\ \lambda_{\sigma\phi} > 0\,.$$

$$(1):\ V_0 = \frac{1}{4}\frac{\lambda_\phi\lambda_\sigma - \lambda_{\sigma\phi}^2}{\lambda_\sigma\xi_\phi^2 + \lambda_\phi\xi_2^2 - 2\lambda_{\sigma\phi}\xi_\phi\xi_2} = \frac{1}{4\xi_2^2}\Big(\lambda_\sigma - \frac{\lambda_{\sigma\phi}^2}{\lambda_\phi}\Big),\ ✓$$
$$(2):\ V_0 = \frac{\lambda_\sigma}{4\xi_2^2},\ ✓$$
$$(3):\ V_0 = \frac{\lambda_\phi}{4\xi_\phi^2},\ ✗$$
$$(4):\ V_0 = \frac{\lambda_\sigma}{4\xi_2^2}\ ✓ \quad \text{or} \quad \frac{\lambda_\phi}{4\xi_\phi^2},\ ✗$$

Unstable Higgs vacuum

Inflaton is Higgs-sigma mixed or sigma-field only.

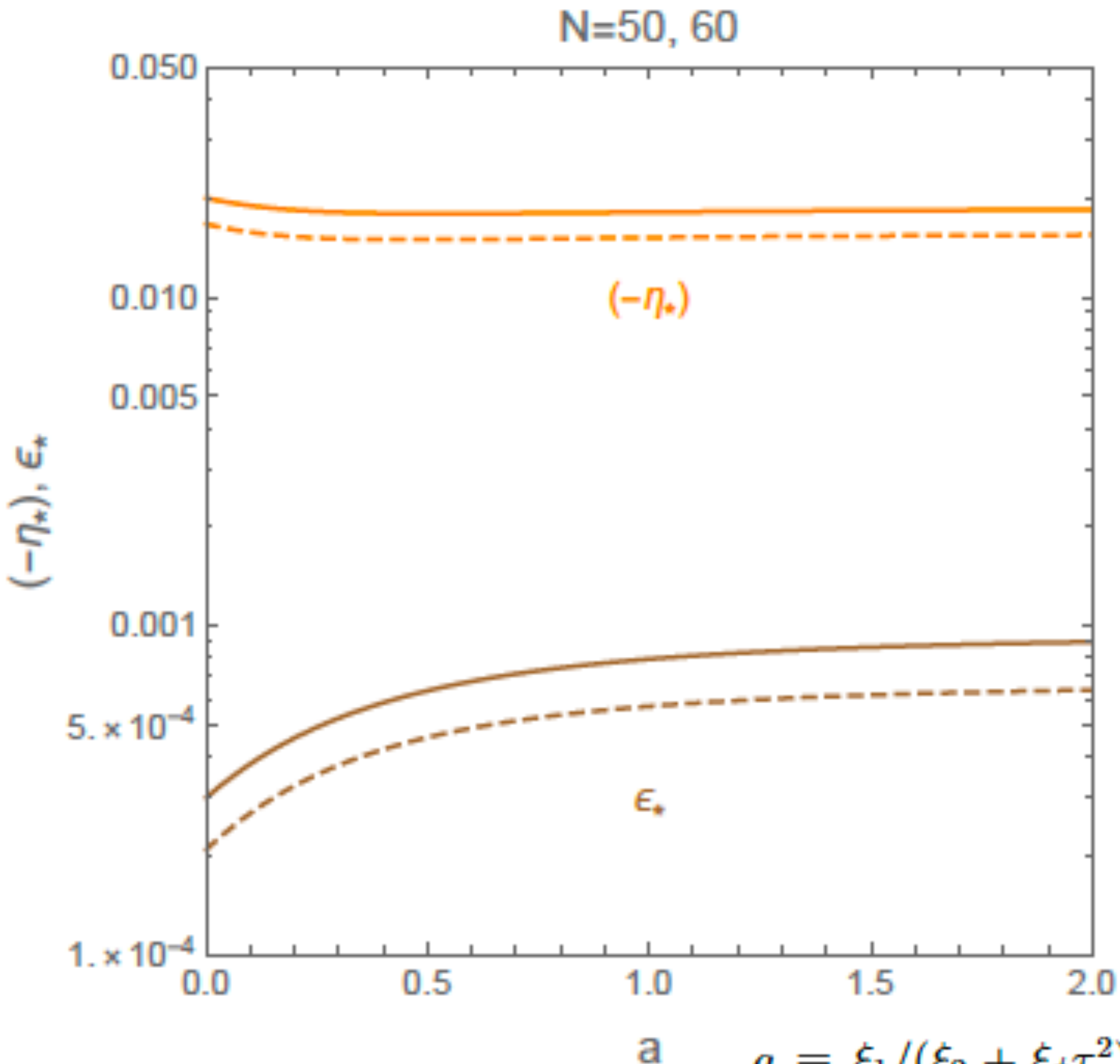
Effective Lagrangian for single-field inflation:

$$\frac{\mathcal{L}_{\rm eff}}{\sqrt{-g_E}} = \frac{1}{2}R(g_E) - \frac{1}{2}(\partial_\mu\chi)^2 - V_0\left(1 - 2a\,e^{-\frac{1}{\sqrt{6}}\chi} - (2 + a^2)\,e^{-\frac{2}{\sqrt{6}}\chi}\right).$$

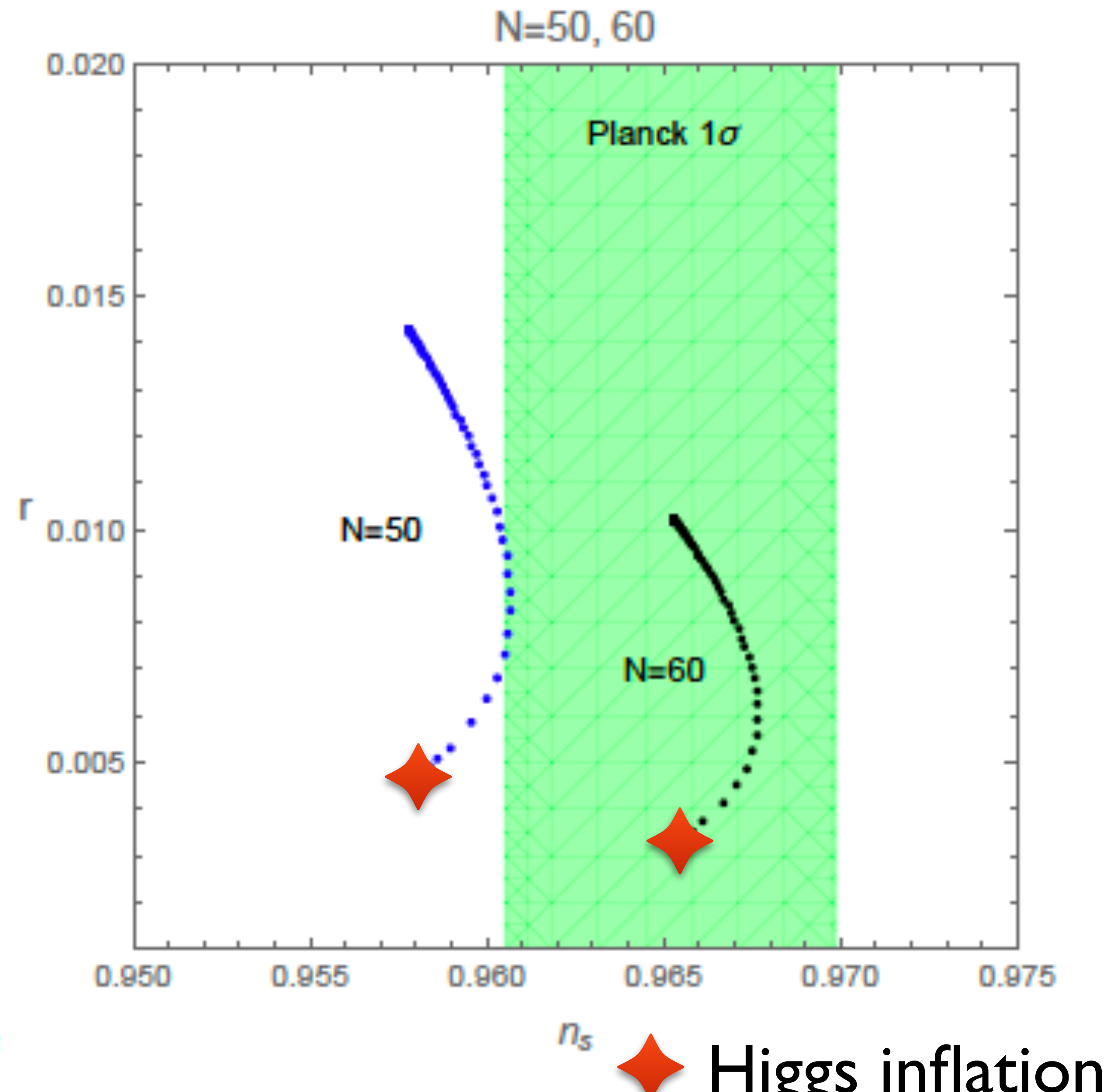
$$\boxed{a = \frac{\xi_1}{(\xi_2 + \xi_\phi\tau^2)^{1/2}}.}$$

extra terms

Deviation from Higgs inflation



$a \equiv \xi_1/(\xi_2 + \xi_\phi \tau^2)^{1/2}$



The higher unitarity scale, the more deviation up to r=0.01.

Tensor-to-scalar ratio testable at future CMB experiments.

Conclusions

- Higgs inflation needs a UV completion, for which the general form of sigma models is proposed.
- Sigma field coupling to Higgs can solve vacuum instability problem as well as unitarize Higgs inflation.
- Large linear non-minimal coupling of the sigma field leads to sizable deviation in the tensor mode up to r=0.01 from Higgs inflation.
- Light sigma field (inflaton) could play a role for electroweak phase transition and Higgs production.