Unitarizing Higgs inflation

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Ref: Gian Giudice, HML, Phys. Lett. B694(2010), 294

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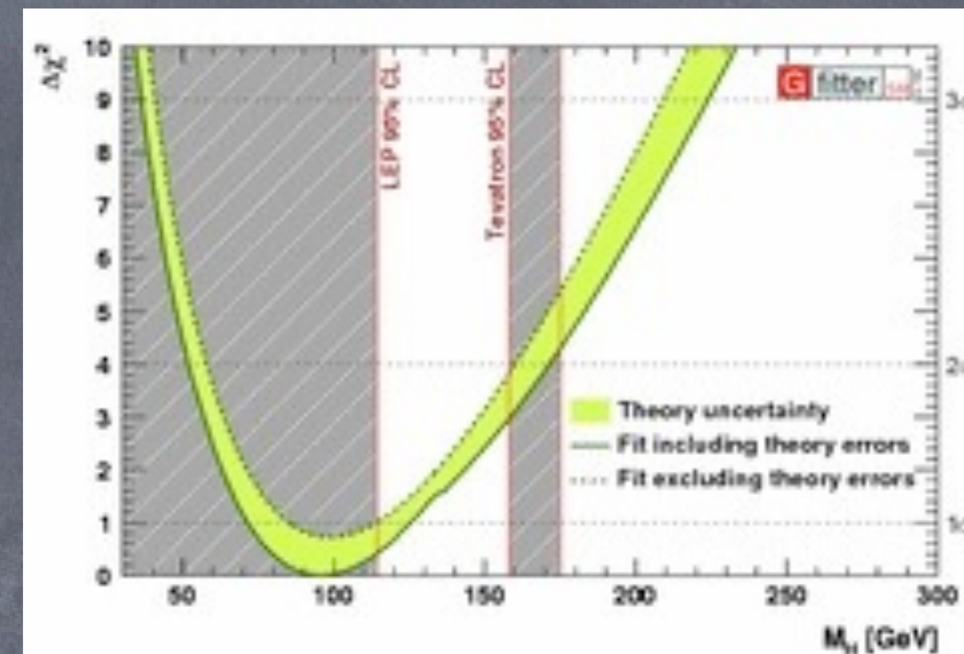
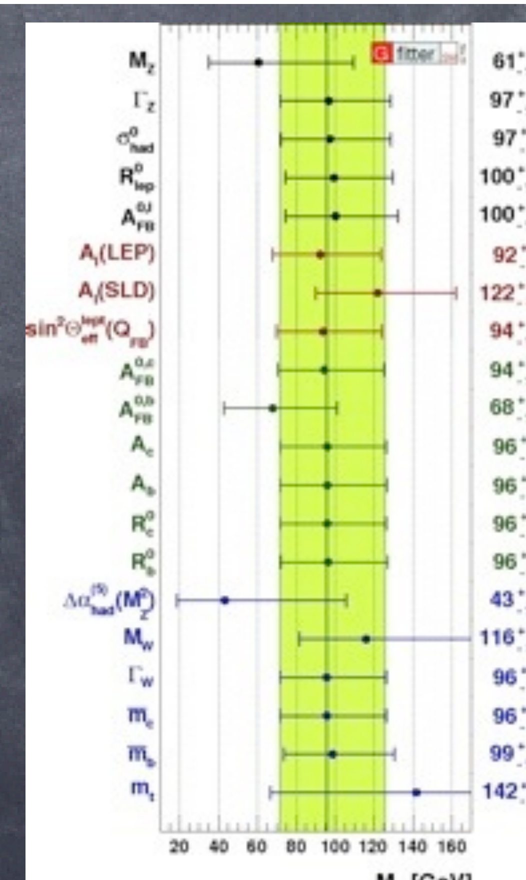
Standard Model Higgs

- Higgs boson triggers electroweak symmetry breaking in SM and unitarizes the SM beyond the electroweak scale.



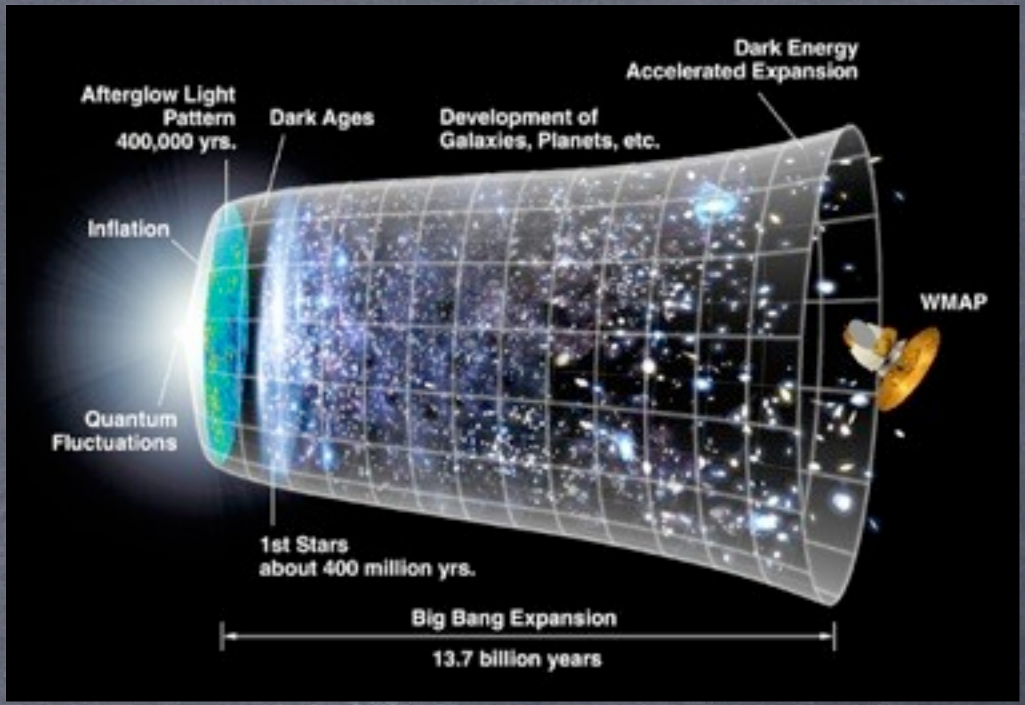
- Light Higgs boson is experimentally favored.
  - LEP/Tevatron exclusions: [95% C.L.]
    $m_H < 114\text{GeV},\ 158\text{GeV} < m_H < 173\text{GeV}$
  - Combined with electroweak precision data: [95(99.5)% C.L.]
    $m_H < 148(197)\text{GeV}$



- Higgs self-coupling is constrained to
  $0.11 < \lambda < 0.18(0.32)$

Cosmic inflation by Higgs boson

- Cosmic inflation has been thought to be driven by an SM singlet scalar.



- CMB data with high precision constrain the inflation models by

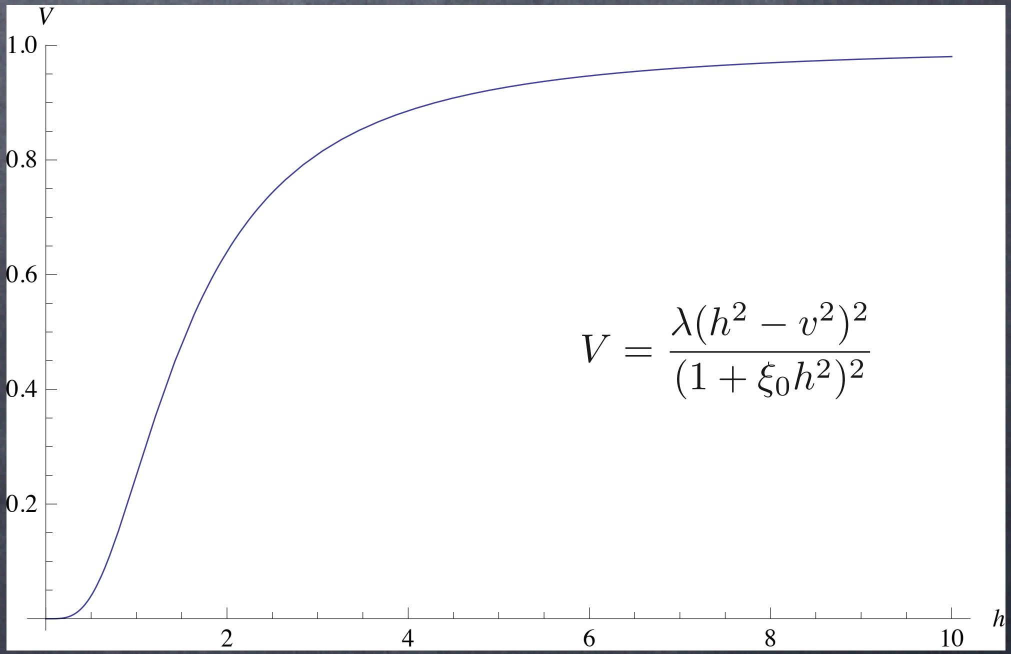
$$n_s = 0.963 \pm 0.012, \quad r < 0.24.$$

- Higgs boson with non-minimal coupling to gravity has been proposed as the inflaton.

[Beyrukov, Shaposhnikov(2007)]

$$\mathcal{L} = \frac{1}{2}\mathcal{R} + \xi_0 |\mathcal{H}|^2 \mathcal{R} - |D_\mu \mathcal{H}|^2 - \lambda\Big(|\mathcal{H}|^2 - \frac{v^2}{2}\Big)^2$$

$$\text{with } \xi_0 \simeq 50000\sqrt{\lambda}.$$



Unitarity problem in Higgs inflation

[Burgess, Trott, Lee(2009,2010); Barbon, Espinosa(2009)]

- However, large non-minimal coupling violates unitarity by

$$\frac{1}{\Lambda}|\mathcal{H}|^2\Box h^\mu_\mu \quad \text{or} \quad \frac{1}{\Lambda^2}(\partial_\mu|\mathcal{H}|^2)^2 \quad \text{at} \quad \Lambda = \frac{M_P}{\xi_0} \sim 10^{14}\text{GeV}.$$

- Unitarity violation signals the breakdown of effective field theory above unitarity scale.
- Hubble scale is close to unitarity scale and Higgs vev during inflation is higher than unitarity scale.
- So, Higgs inflation is sensitive to new physics appearing at unitarity cutoff.

Higgs inflation as a non-linear sigma model

- Higgs kinetic term is a non-linear sigma model type,

$$\mathcal{L}_{\rm kin} = -\frac{1}{2(1+\xi_0\vec{\phi}^2)}\Big(\delta_{ij} + \frac{6\xi_0^2\phi_i\phi_j}{1+\xi_0\vec{\phi}^2}\Big)\partial_\mu\phi_i\partial^\mu\phi_j.$$

- The kinetic term is linearized by introducing a real sigma scalar with constraint $\sigma^2 = \vec{\phi}^2 + \frac{1}{\xi_0}$ as [κ: Lagrange multiplier, F(0)=0.]

$$\mathcal{L}_{\rm kin} = -\frac{1}{2\xi_0\sigma^2}\Big[(\partial_\mu\vec{\phi})^2 + 6\xi_0(\partial_\mu\sigma)^2\Big] - \kappa(x)F(\sigma^2 - \vec{\phi}^2 - \frac{1}{\xi_0})$$

- Replacing κ by a constant parameter, the sigma scalar is promoted as a dynamical field with appropriate potential F.

- The kinetic term is Euclidean 5D AdS with isometry $SO(1,5)/SO(5)$.

- For $F(y)=\frac{y^2}{4\xi_0^2\sigma^4}$, the full action is equivalent to

$$\mathcal{L}=\frac{1}{2}\xi_0\sigma^2 R-|D_\mu\mathcal{H}|^2-\frac{1}{4}\kappa\Big(\sigma^2-2|\mathcal{H}|^2-\frac{1}{\xi_0}\Big)^2-\lambda\Big(|\mathcal{H}|^2-\frac{v^2}{2}\Big)^2.$$

- Minimizing the sigma potential at $\langle\sigma\rangle\simeq\frac{1}{\xi_0}$ for $\frac{1}{\xi_0}\gg\frac{v}{M_P}$, fixes the Planck mass.

- Expanding the sigma field as $\sigma=\frac{1}{\xi_0}+\bar{\sigma}$, the non-minimal coupling induces only the Planck-suppressed interactions,

$$\mathcal{L}=\frac{1}{2}h^{\mu\nu}\Box h_{\mu\nu}+\frac{1}{2}h^\mu_\mu\Box h^\nu_\nu+(2\bar{\sigma}+\bar{\sigma}^2)\Box h^\mu_\mu+\cdots$$

UV complete Higgs inflation

- Sigma-model type UV completion persists for the most general Z_2 invariant Lagrangian with dimension-4 interactions,

$$\mathcal{L} = \frac{1}{2}\Big(\tilde{M}^2 + \xi\tilde{\sigma}^2 + 2\zeta|\mathcal{H}|^2\Big)\mathcal{R} - \frac{1}{2}(\partial_\mu\tilde{\sigma})^2 - |D_\mu\mathcal{H}|^2$$
$$-\frac{1}{4}\kappa\Big(\tilde{\sigma}^2 - \tilde{\Lambda}^2 - 2\alpha|\mathcal{H}|^2\Big)^2 - \lambda\Big(|\mathcal{H}|^2 - \frac{v^2}{2}\Big)^2.$$

- $v \ll \tilde{M}, \tilde{\Lambda}$: usual fine-tuning of Higgs mass.
- $\zeta \sim \mathcal{O}(1) \ll \xi$ to avoid the reappearance of unitarity problem.
- All the non-renormalizable interactions are suppressed by the Planck scale.

Dynamics of UV complete inflation

- In vacuum, $m_\sigma \sim \frac{M_P}{\xi} \gg m_H$ so integrating out the sigma scalar leads to the Higgs inflation model with effective non-minimal coupling, $\xi_0 = \alpha\xi + \zeta$.

- During inflation, $m_{\tilde{H}} \sim \frac{M_P}{\sqrt{\xi}} \gg m_{\tilde{\sigma}}$ due to the large Higgs background so the heavy scalar $\tilde{H} = \frac{\Lambda}{\sigma} H$ decouples.

- Slow-roll inflation occurs along the flat direction,

$$\phi^2 \simeq \frac{\kappa\alpha}{\lambda + \kappa\alpha^2}\,\sigma^2. \qquad [\phi = \sqrt{2}|\mathcal{H}|]$$

- After integrating out the heavy scalar, the inflaton potential for $\sigma = \frac{1}{\xi}\,e^{\chi/\sqrt{6}}$ becomes

$$V = V_0\Big(1 - e^{-2\chi/\sqrt{6}}\Big)^2, \quad V_0 = \frac{1}{4\xi^2}\Big(\frac{\lambda\kappa}{\lambda + \kappa\alpha^2}\Big).$$

Comparison to Higgs inflation

- For N=60, the predictions for the spectral index and tensor to scalar ratio are similar to Higgs inflation:

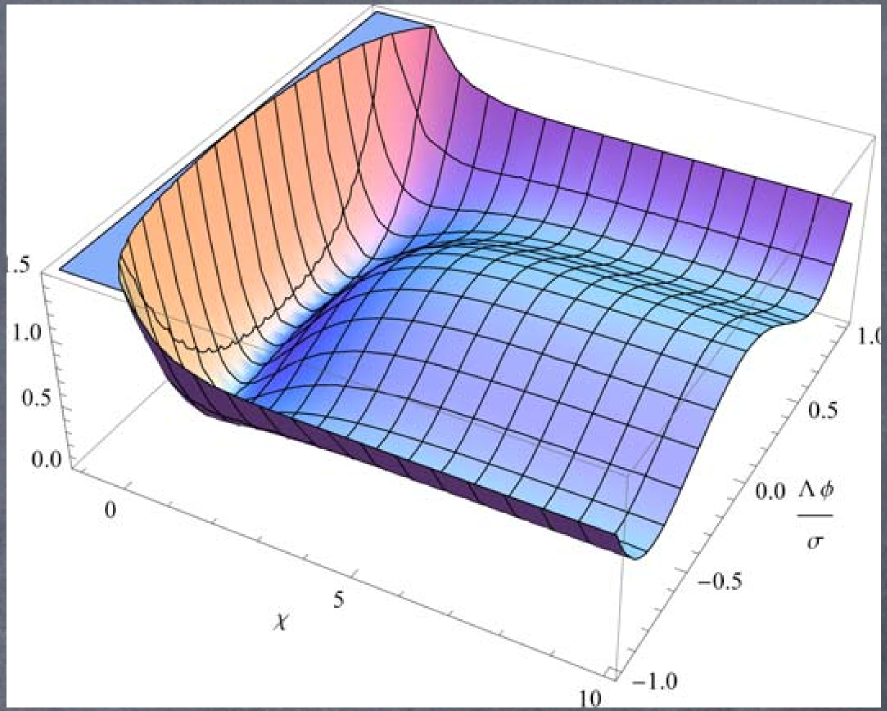
$$n_s \simeq 0.966, \quad r = 3.2 \times 10^{-3}.$$

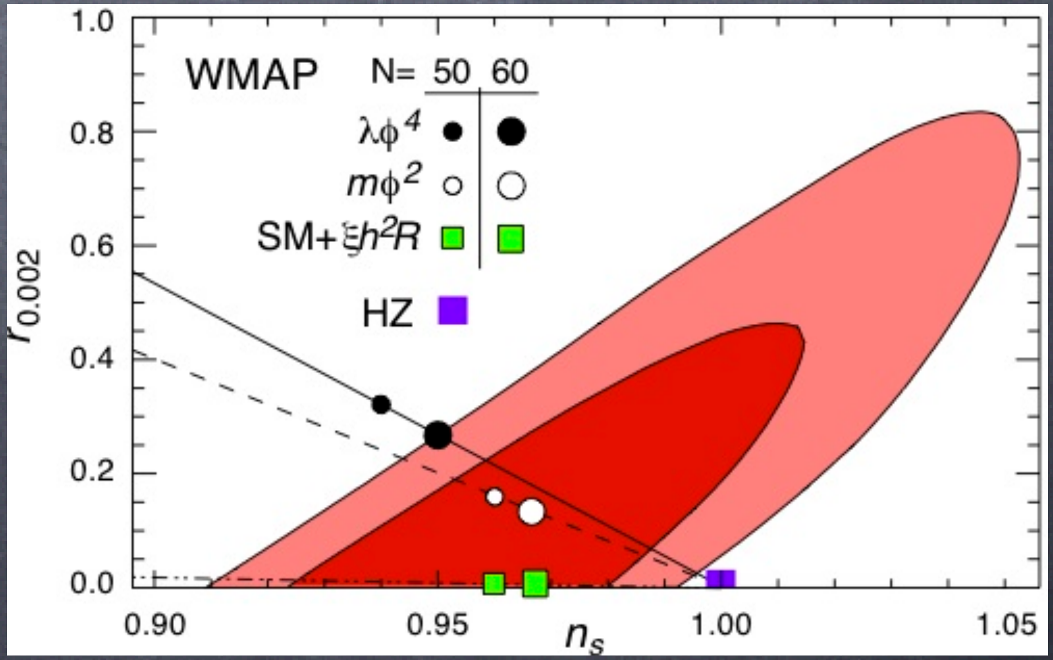
- COBE normalization requires

$$\frac{\xi_0}{\sqrt{\lambda}} \simeq 50000 \left(1 + \frac{\lambda}{\kappa\alpha^2}\right)^{-1/2}.$$

- For $\lambda \ll \kappa\alpha^2$, the constraint coincides with the result of Higgs inflation.

- Both Higgs and sigma scalars participate in reheating.





[from Bezrukov, Shaposhnikov (2007)]

Conclusion

- We proposed a simple extension of the SM Higgs inflation in which a sigma scalar unitarizes up to Planck scale.
- Inflation occurs along the flat direction with sigma and Higgs scalars being of comparable size.
- Inflation vacuum energy depends on unknown couplings of the sigma scalar.
- If the Higgs self-coupling at inflation scale is much smaller than 1, the Higgs inflation becomes insensitive to new physics. A small Higgs self-coupling can be consistent with the Higgs mass bound due to RG running.
- Our result is applicable to similar inflation models with large non-minimal couplings.