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“Gravity as the origin of spontaneous symmetry breaking in an inflationary universe”

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Gravity as the Origin of Spontaneous Symmetry Breaking in the Inflationary Universe

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arXiv: 12xx.xxxx
Work in progress with F. Bezrukov
PRD83, 043511 (2011)
PRD75, 061301(R) (2007) with E. Komatsu

The Inflationary Universe

- Inflation solves flatness, horizon, monopole problems of the big bang theory.
- At the same time, it provides the initial seed of density fluctuations that develop to cosmic structures like galaxies. Since the density fluctuations come from quantum vacuum fluctuations, they obey Gaussian statistics.
- From observations of CMB temperature anisotropy, the amplitude and tilt of the power-spectrum are given by $P_\zeta \sim 10^{-9}$, $n_s \sim 0.96$. It is consistent with Gaussian fluctuations: $-10 < f_{NL} < 74$.

The Standard Model Higgs

- The SM of elementary particles is composed of quarks, leptons, neutrinos, gauge bosons, and Higgs boson.
- The vev of Higgs gives rise to mass to all particles except photons, gluons, and neutrinos.
- From experiments of LHC, the SM Higgs seems to be detected. ATLAS: m ~ 126.5 GeV (5σ); CMS: m ~ 125.3 ± 0.6 GeV (4.9σ)

Is the inflaton Higgs?

- No, if gravity is minimally coupled to the Higgs.
  $P_\zeta \sim 10^4 \lambda \sim 10^2$ too big!

- Yes, if gravity is *non-minimally* coupled to the Higgs.
  [Futamase & Maeda 89; Komatsu & Futamase 99; Bezrukov & Shaposhnikov 08; Barbinsky, Kamenshchik & Starobinsky 08; Germani & Kehagias 10; Germani & YW 11; Kamada, Kobayashi, Yamaguchi & Yokoyama 12; ...]
  $P_\zeta \sim \lambda/\xi^2 \sim 10^{-9}$ for $\xi \sim 5\times10^3$

$$\xi R h^2$$

- How to reheat the Universe? [YW & Komatsu 07; Bezrukov, Gorbunov & Shaposhnikov 09; Garcia-Bellido et al 09; YW 11]

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  $P_\zeta \sim 10^{-4} \lambda M^2/H^2 \sim 10^{-9}$ for $H/M \sim 50$

$$\frac{G^{\mu\nu}}{M^2}\partial_\mu h \partial_\nu h$$

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- How to reheat the Universe? → gravitational inflaton decay [YW & Komatsu 07; 08; Bezrukov, Gorbunov & Shaposhnikov 09; Garcia-Bellido et al 09; YW 11]

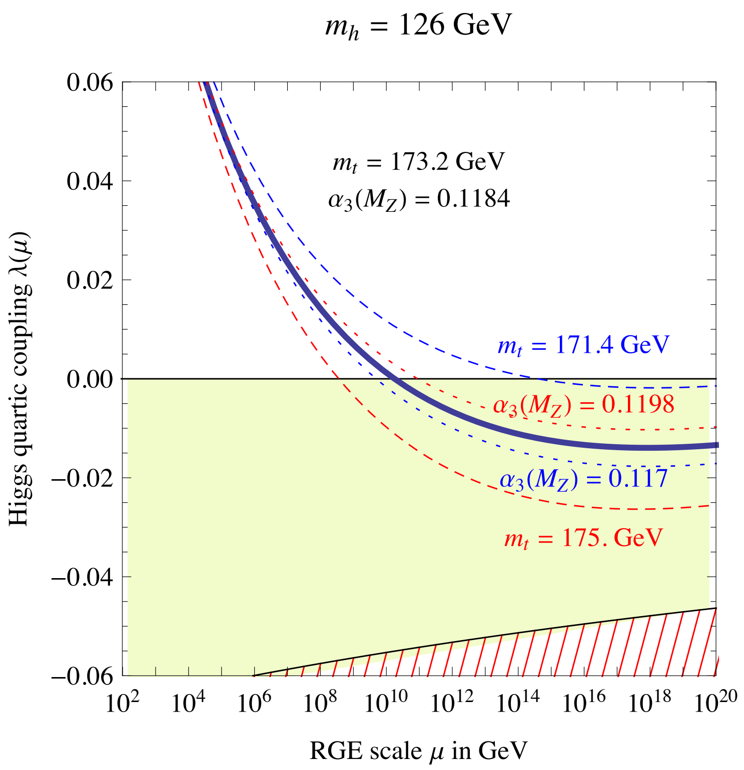
SM Higgs as the inflaton

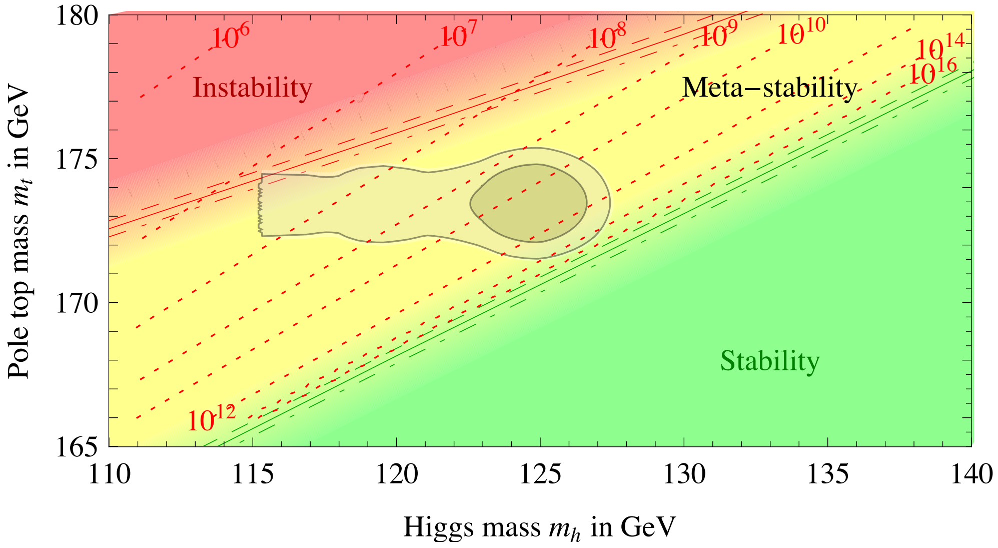
$$\xi R h^2$$

- SM Higgs inflation [Bezrukov & Shaposhnikov 08; Barbinsky, Kamenshchik & Starobinsky 08; ...]
- *Minimalistic* to explain both CMB spectra and LHC data
- Higgs gives masses to gauge bosons and quarks. → Parametric resonance of W, Z happens during oscillations and reheats the Universe [Bezrukov, Gorbunov & Shaposhnikov 09; Garcia-Bellido et al 09]

Meta-stability of SM vacuum at high energy?

[J. Elias-Miro et al 12]



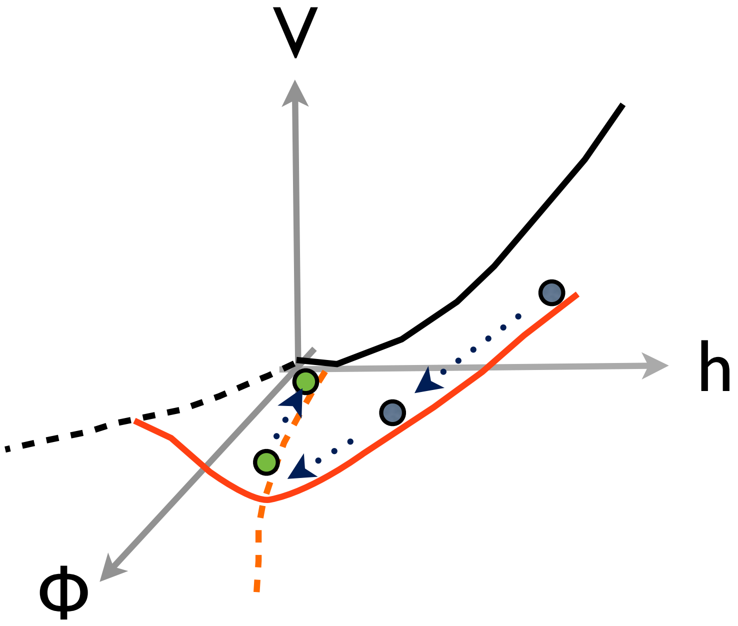


- RG running of λ is sensitive to top mass and strong coupling constant.
- Need additional d.o.f? Bosons change the running of λ positively while fermions do it negatively.

Any other classical condensates during Higgs inflation?

- Scalar condensate:
  - Heavy → integrated out; It may leave features on CMB spectra.
  - Light → frozen but affect inflationary dynamics later; It may become Dark Matter (if stable) after inflation.
- Vector condensate → anisotropy [M. Watanabe, Kanno & Soda 09; ...]
- Can they be curvatons?
- Do they change dynamics and reheating process?

“*Spontaneous symmetry breakdown*” due to gravity



$$V \sim \lambda h^4 - \xi R h^2 + m^2\phi^2$$

$$v \sim \pm\sqrt{\frac{\xi R}{\lambda}} \sim \pm\sqrt{\frac{\xi}{\lambda}}\frac{m\phi_*}{M_p}$$

$$\sim 10^3 m \quad \text{for} \quad \phi_* \sim M_p$$

- Light scalar dominates energy density after inflation. → Higgs acquires non-trivial vev due to *negative mass term*. It diminishes the amplitude of Higgs oscillations, and reheating proceeds perturbatively.

Reheating with light scalar condensates

- Decay channels: Φ, W, Z, top → kinematically allowed? If not, Higgs decays mainly into Φ (tree), γ, gluon (loop) gravitationally. [YW 11]

$$\Gamma(h \to WW) \sim \Gamma(h \to ZZ) \sim g_2^2 m_W \qquad \Gamma(h \to \bar{t}t) \sim y_t^2 m_t$$

$$m_i \sim g_i \sqrt{|\hat{h}| M_p/\xi} \sim g_i v \qquad m_{\hat{h}} \sim \sqrt{\lambda} M_p/\xi$$

$$T_{\rm reh} \sim 0.1 \sqrt{\Gamma M_p}$$

- Light scalars become Dark Matter if they are stable. If unstable, they must decay before BBN.

Gravitational inflaton decay [YW 11]

$$g_{\mu\nu}(x) \to \hat{g}_{\mu\nu}(x) = \Omega^2(x) g_{\mu\nu}(x)$$

$$\approx g_{\mu\nu} + g_{\mu\nu}\frac{F(v)\sigma}{M_{Pl}^2}$$

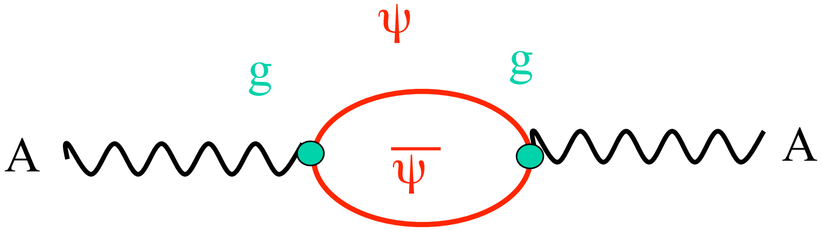
Conformal invariance: local scale invariance

Mass term explicitly breaks scale invariance.

$$T_{m\ \mu}^{\mu}[\hat{g}_{\mu\nu}] = -\frac{\Omega}{\sqrt{-\hat{g}}}\frac{\delta S_m[\hat{g}_{\mu\nu}]}{\delta\Omega}$$

Conformal invariant field:

- Massless spin-½ fields
- Conformally coupled massless spin-0 fields
- Gauge fields (classical level)

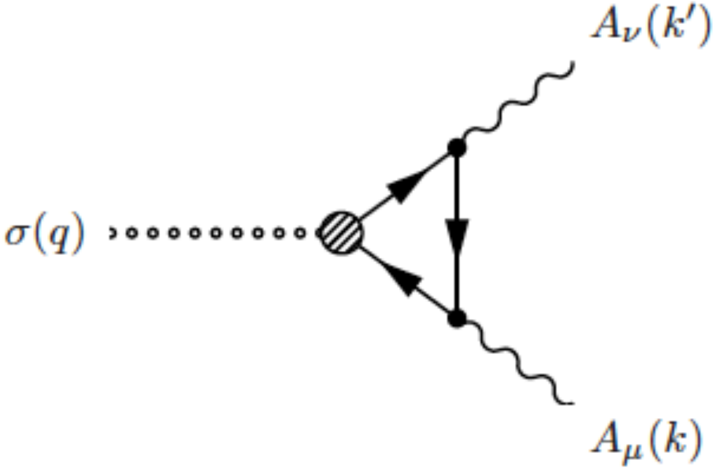


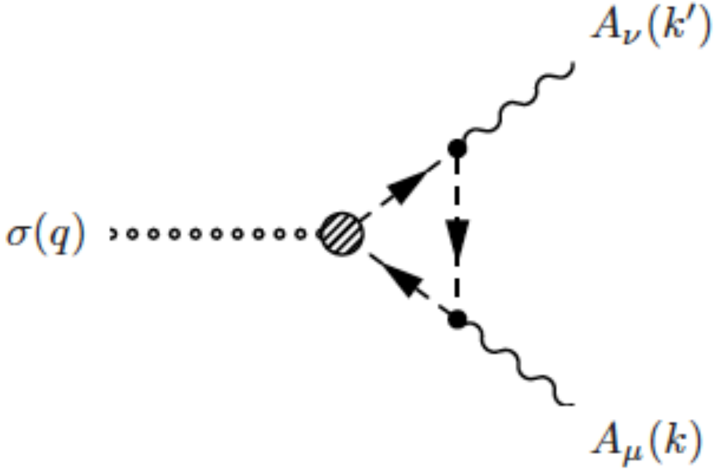
$$\mathcal{L}_{\rm int} = \sqrt{-g}\frac{F_1(v)\sigma}{2M_{Pl}^2}T^{\mu}_{{\rm m}\mu}$$

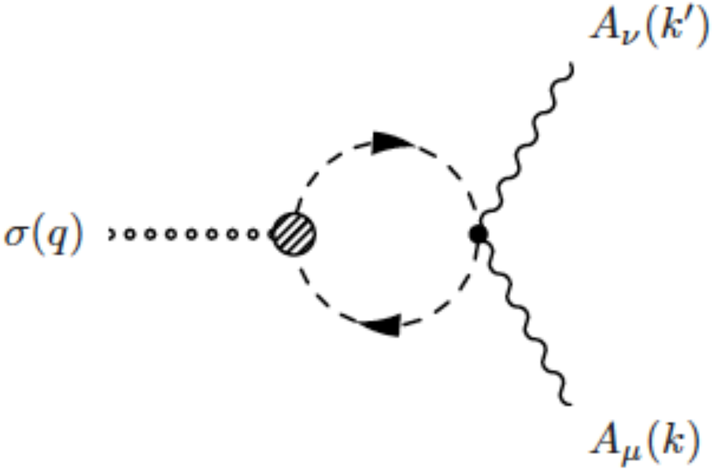
$$T^{\mu}_{{\rm m}\mu} = \underbrace{\sum_{s=1}^{N_\chi} 2\left[-(D_\mu\chi_s)^* D^\mu\chi_s + 2U(\chi_s^*\chi_s)\right] + \sum_{f=1}^{N_\psi} m_f\bar{\psi}_f\psi_f}_{\text{at the classical level}} + \boxed{\frac{\beta_h(g)}{2g}F_{\mu\nu}F^{\mu\nu}}$$

Gauge trace anomaly: lowest order decay channel to photons

two-photon decay of the Higgs







Summery of decay rates

Femions

$$\Gamma(\sigma \to \bar{\psi}\psi) \simeq \frac{N_\psi [F_1(v)]^2 m_\sigma m_\psi^2}{32\pi M_{Pl}^4}$$

Scalars

$$\Gamma(\sigma \to \chi_+ \chi_-) \simeq \frac{N_\chi [F_1(v)]^2 m_\sigma^3}{64\pi M_{Pl}^4}$$

← Probably most efficient.

Gauge fields

$$\Gamma(\sigma \to 2A_\mu) = \frac{\alpha^2 [F_1(v)]^2 m_\sigma^3}{1024\pi^3 M_{\mathrm{Pl}}^4} \left| \sum_{f=1}^{N_\psi} 2 I_f \left(\frac{m_\sigma^2}{m_f^2} \right) + \sum_{s=1}^{N_\chi} \left(2 + \frac{m_\sigma^2}{m_s^2} \right) I_s \left(\frac{m_\sigma^2}{m_s^2} \right) \right|^2$$

*Pre*heating with light scalar condensates?

- Gravitationally induced couplings cannot be so large since they are essentially Planck-suppressed.
- Direct couplings to the scalar are assumed to be small. Of course, yes in principle.

Conclusions and future work...

- SM Higgs inflation can be saved by additional scalars.
- However, *SSB due to gravity* may occur after inflation if the scalar dominates energy density.
- Reheating occurs naturally.
- Works left: Dark Matter abundance, Baryogenesis, ...