Naturally extended Higgs inflation ready for tests

Dmitry Gorbunov

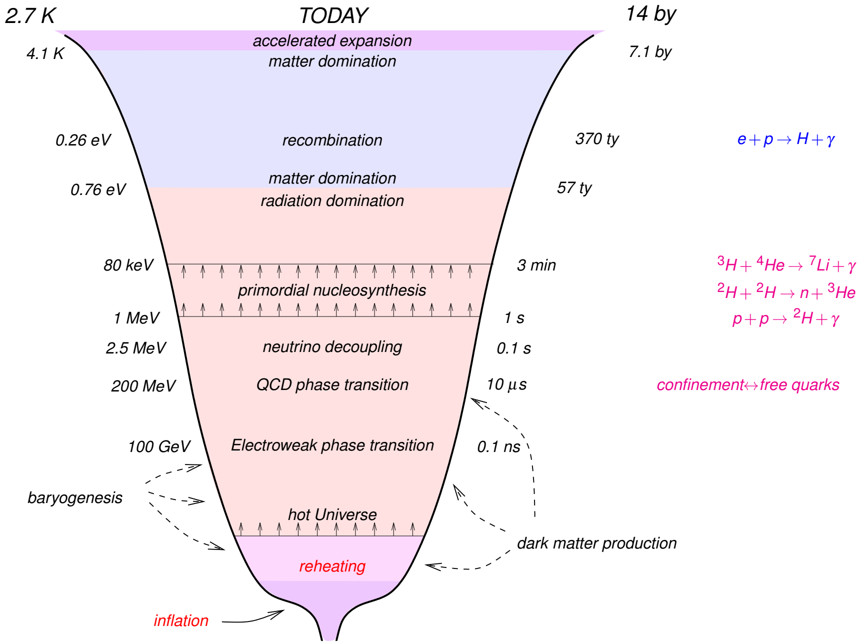
Institute for Nuclear Research of RAS, Moscow

Workshop on New physics paradigm after Higgs and gravitational wave discovering

New Frontiers in Physics, ICNFP 2019, Kolymbari, Crete

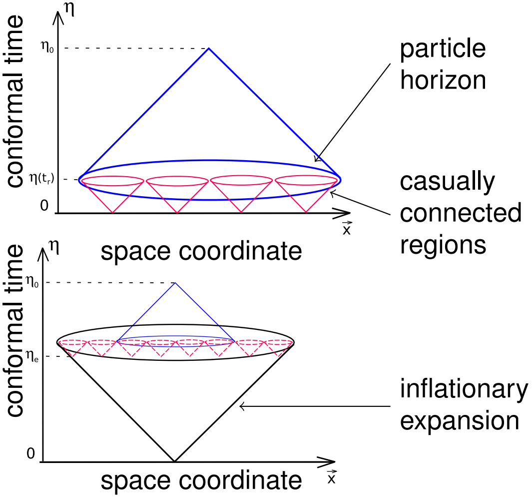
Hot Big Bang within GR and SM: problems

- Dark Matter
- Baryogenesis
- Horizon, Enthropy, Flatness, ... problems
  $l_{H_0}/l_{\mathrm{H},r}(t_0) \sim \sqrt{1+z_r} \simeq 30$
- Singularity at the beginning
- Heavy relics
- Initial perturbations $\delta T/T \sim \delta\rho/\rho \sim 10^{-4}$, scale-invariant
- Dark Energy $0 \neq \Lambda \ll M_{Pl}^4\ M_W^4\ \Lambda_{QCD}^4$ etc ?
- Coincidence problems:
  $$\Omega_B \sim \Omega_{DM} \sim \Omega_\Lambda\ ,$$
  $$\eta_B = n_B/n_\gamma \sim (\delta T/T)^2\ ,$$
  $$T_d^n \sim (m_n - m_p)\ ,$$
  ...
- ΛCDM tensions: H_0?, σ_8? dwarfs? cusps? ... (reionization @ $z \simeq 10$, etc)


2.7 K
TODAY
14 by
accelerated expansion
4.1 K
matter domination
7.1 by
0.26 eV
recombination
370 ty
$e + p \to H + \gamma$
matter domination
0.76 eV
radiation domination
57 ty
80 keV
3 min
$^3H + {}^4He \to {}^7Li + \gamma$
primordial nucleosynthesis
$^2H + {}^2H \to n + {}^3He$
1 MeV
1 s
$p + p \to {}^2H + \gamma$
2.5 MeV
neutrino decoupling
0.1 s
200 MeV
QCD phase transition
10 μs
confinement↔free quarks
100 GeV
Electroweak phase transition
0.1 ns
baryogenesis
hot Universe
dark matter production
reheating
inflation

Inflationary solution of Hot Big Bang problems

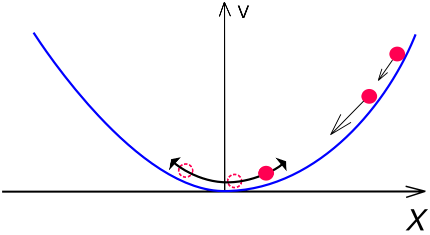
- no initial singularity in dS space
- all scales grow exponentially, including the radius of the 3-sphere
  the Universe becomes exponentially flat
- any two particles are at exponentially large distances
  no heavy relics
  no traces of previous epochs!
- no particles in post-inflationary Universe
  to solve entropy problem we need post-inflationary reheating



Chaotic inflation at large fields: graceful entrance

in all domains of Planck size
each of the form of inflaton energy
fluctuates similarly

Chaotic inflation, A.Linde (1983), A.Linde (1984)



$$\frac{1}{2}\dot{\phi}^2 \sim \frac{1}{2}(\partial_i \phi)^2 \sim V(\phi) \lesssim M_{\rm Pl}^4$$

If $V(\phi)$ dominates by chance

$$\ddot{\phi} - \Delta\phi/a^2 + 3H\dot{\phi} + V'(\phi) = 0$$

for power-law potential at $\phi > M_{Pl}$

$$V \simeq \text{const}$$

“slow roll” solution

$$H^2 = \frac{8\pi}{3M_P^2} V(\phi)\,, \quad a(t) \propto e^{Ht}$$

Chaotic inflation at large fields: graceful exit

If $V(\phi)$ dominates by chance

Chaotic inflation, A.Linde (1983), A.Linde (1984)

$$\ddot{\phi} - \Delta\phi/a^2 + 3H\dot{\phi} + V'(\phi) = 0$$

for power-law potential at $\phi > M_{Pl}$

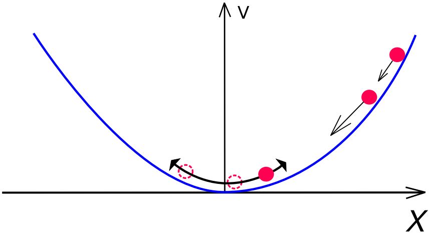
$$V \simeq \text{const}$$

"slow roll" solution

$$H^2 = \frac{8\pi}{3M_P^2} V(\phi)\,, \quad a(t) \propto e^{Ht}$$

valid while slow roll conditions

$$M_P^2 \frac{V''}{V} \ll 1\,, \quad M_P^2 \frac{V'^2}{V^2} \ll 1$$



Inflaton must couple to Standard Model fields

to reheat the Universe after inflation

The idea is great,

but is not verifiable
except for the 3d-flatness

Does it make the idea wrong...?

Unexpected bonus: generation of perturbations

- Quantum fluctuations of wavelength λ of a free massless field φ have an amplitude of $\delta\varphi_\lambda \simeq 1/\lambda$
- In the expanding Universe: $\lambda \propto a$

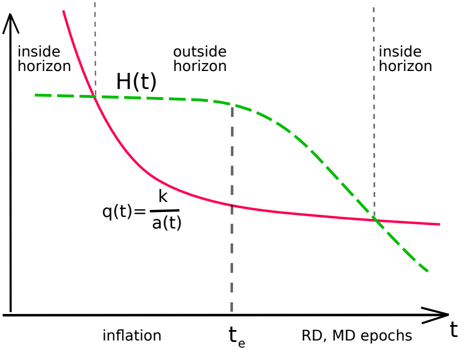
  inflation: $l_H \sim 1/H = \text{const}$, so modes "exit horizon"
  Ordinary stage: $l_H \sim 1/H \propto t$, $l_H/\lambda \nearrow$, modes "enter horizon"

Evolution at inflation

- inside horizon: $\lambda < l_H$
  $\lambda \propto a \Rightarrow$ $\delta\varphi_\lambda \propto 1/\lambda \propto 1/a$

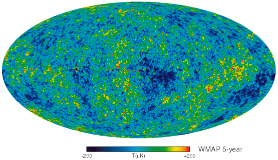
- outside horison: $\lambda > l_H$
  $\lambda \propto a \Rightarrow$ $\delta\varphi_\lambda = \text{const} = H_{infl}$!!!

- got "classical" fluctuations:
  $\delta\varphi_\lambda = \delta\varphi_\lambda^{quantum} \times e^{N_e}$

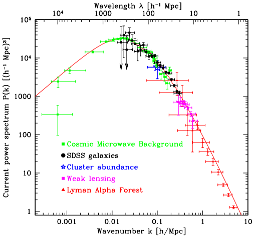


Inflationary solution of Hot Big Bang problems

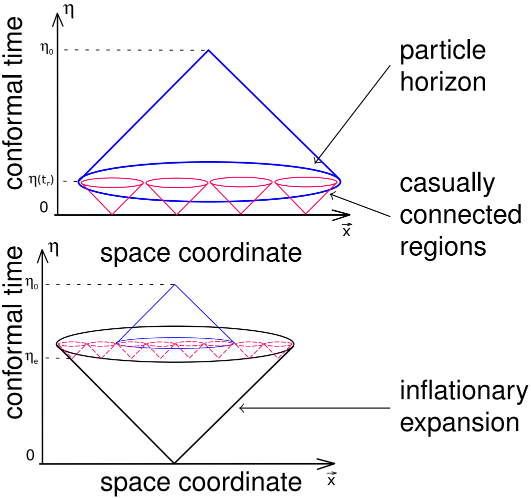
Temperature fluctuations $\delta T/T \sim 10^{-5}$



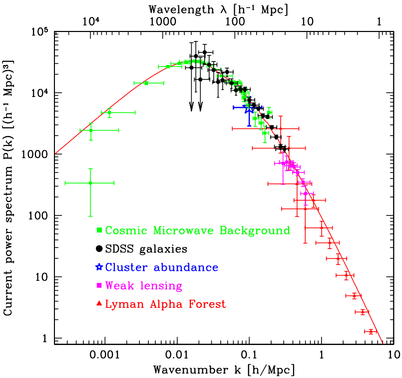
Universe is uniform!

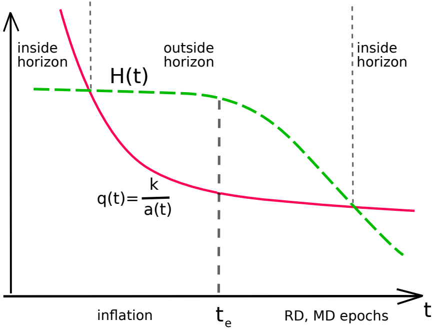


$\delta\rho/\rho \sim 10^{-5}$



Probing the matter power spectrum





$$\delta\phi \to \frac{\delta\rho}{\rho} \sim \frac{H^2}{\dot{\phi}} \propto \frac{V^{3/2}}{V'}, \qquad h \sim \frac{H}{M_{Pl}} \propto V^{1/2}$$

$$A_S \to \frac{V^{3/2}}{V'}, \qquad n_S \to \frac{V''}{V}, \left(\frac{V'}{V}\right)^2, \qquad r \equiv \frac{A_T}{A_S} \to \left(\frac{V'}{V}\right)^2$$

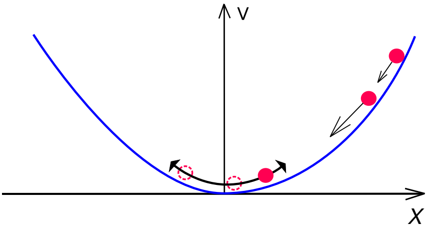
Chaotic inflation: simple realization

$$S = \int d^4x\sqrt{-g}\left(-\frac{M_P^2}{2}R + \frac{(\partial_\mu X)^2}{2} - \beta X^4\right)$$

$$\ddot{X} + 3H\dot{X} + V'(X) = 0$$

$$H^2 = \frac{1}{M_P^2}V(X)\,, \qquad a(t) \propto e^{Ht}$$

Chaotic inflation, A.Linde (1983)



slow roll conditions get satisfied at

$X_e > M_{Pl}$ $\qquad M_P^2 = M_{Pl}^2/(8\pi)$

generation of scale-invariant scalar (and tensor) perturbations from exponentially stretched quantum fluctuations of X $\Longrightarrow$

$\delta\rho/\rho \sim 10^{-5}$ requires

$V = \beta X^4 : \beta \sim 10^{-13}$

We have scalar in the SM! The Higgs field!

In a unitary gauge $H^T = \left(0, (h+v)/\sqrt{2}\right)$ (and neglecting $v = 246\,\text{GeV}$) $\lambda \sim 0.01 - 1$

$$S = \int d^4x\sqrt{-g}\left(-\frac{M_P^2}{2}R + \frac{(\partial_\mu h)^2}{2} - \frac{\lambda h^4}{4}\right)$$

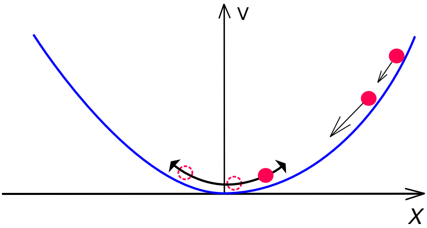
Chaotic inflation: simple realization

$$S = \int d^4x\sqrt{-g}\left(-\frac{M_P^2}{2}R + \frac{(\partial_\mu X)^2}{2} - \beta X^4\right)$$

$$\ddot{X} + 3H\dot{X} + V'(X) = 0$$

$$H^2 = \frac{1}{M_P^2}V(X)\,, \qquad a(t) \propto e^{Ht}$$

Chaotic inflation, A.Linde (1983)



slow roll conditions get satisfied at
$X_e > M_{Pl}$ $\qquad M_P^2 = M_{Pl}^2/(8\pi)$

generation of scale-invariant scalar (and tensor) perturbations from exponentially stretched quantum fluctuations of X $\Longrightarrow$

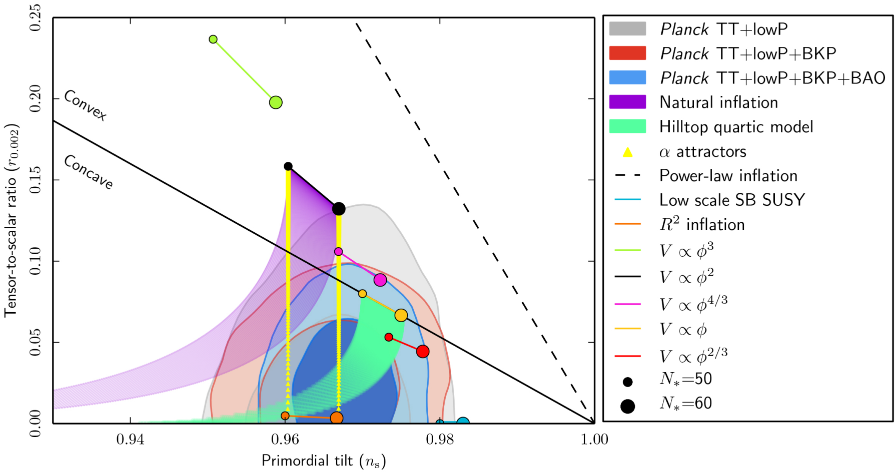
$\delta\rho/\rho \sim 10^{-5}$ requires
$V = \beta X^4 : \beta \sim 10^{-13}$

We have scalar in the SM! The Higgs field!

In a unitary gauge $H^T = \left(0, (h+v)/\sqrt{2}\right)$ (and neglecting $v = 246\,\text{GeV}$) $\quad \lambda \sim 0.01 - 1$

$$S = \int d^4x\sqrt{-g}\left(-\frac{M_P^2}{2}R + \frac{(\partial_\mu h)^2}{2} - \frac{\lambda h^4}{4}\right)$$

Planck 2015 favors flat inflaton potentials



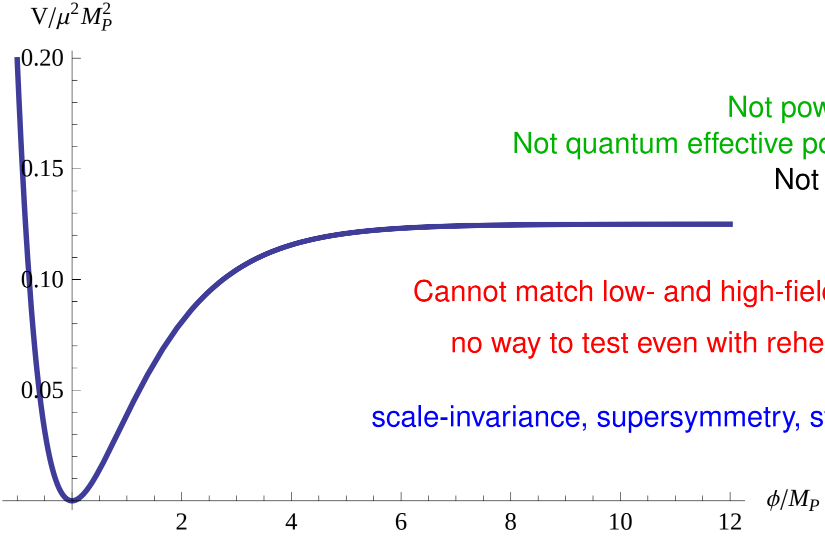
$$r = \frac{A_T}{A_S} \propto \frac{\dot{\phi}^2}{H^2 M_{Pl}^2} \propto \left(\frac{V'}{V}\right)^2 \ll 1$$

Other ways of testing inflation

- Curvature: the World is flat
  not convincing for many
- Relic tensor modes (gravitational waves)
  low-l *B*-mode: well below Galactic foreground
- preheating: $T_{reh} \to N_e$, GW ?
  tiny effects, $n_s, r = f(log(N_e))$, GW from clumps
- Direct tests: inflaton potential
  only in specific models with light inflaton
- Generic for many-field inflation are
  isocurvature modes, non-Gaussianity
- Exotic signatures
  primordial black holes, GW from oscillons, etc

and the calculations must be reliable

Inflaton potential is apparently nonrenormalizable



Not power-law

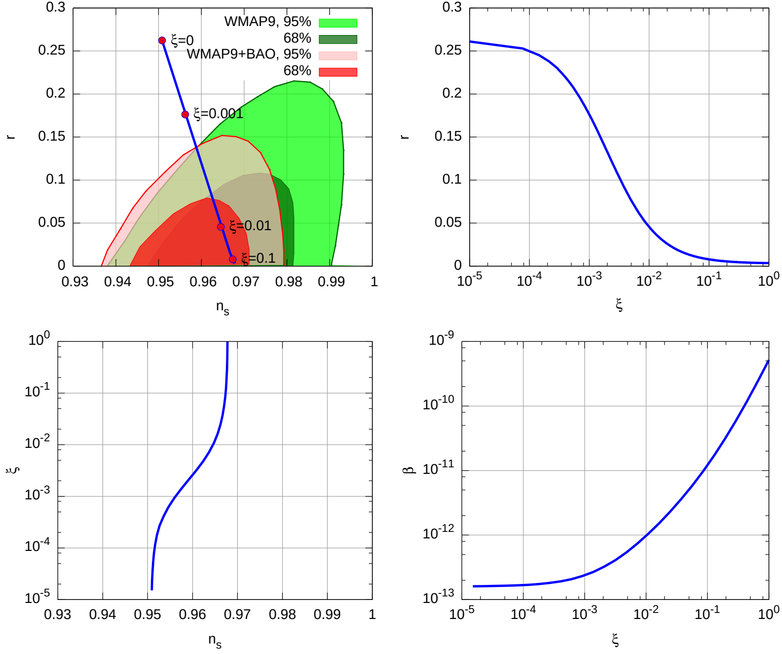
Not quantum effective potential

Not $\log\phi$

Cannot match low- and high-field parts

no way to test even with reheating !!

scale-invariance, supersymmetry, strings?



F.Bezrukov, D.G. (2013)

How it works…

$V = \beta\phi^4$

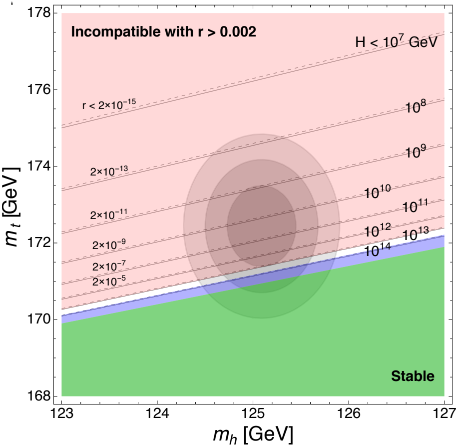
$\xi\phi^2 R$

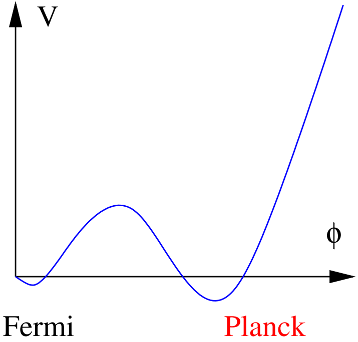
it changes GR-scale

it changes kinetic term

hence changes scalar and tensor spectra

Wrong EW vacuum: $\Phi \sim H/(2\pi)$





1607.00381

Thus we

either constrain inflation, $H \lesssim \ldots 10^{10}\,\text{GeV}\ldots$ and hence GW, that is r

or just assume we are 2σ-off and $\lambda > 0$

Higgs-driven inflation

F.Bezrukov, M.Shaposhnikov (2007)

$$S^{JF} = \int d^4x \sqrt{-g} \left(-\frac{M_P^2}{2} R - \xi H^\dagger H R + \mathscr{L}_{SM} \right)$$

In a unitary gauge $H^T = \left(0, (h+v)/\sqrt{2}\right)$ (and neglecting $v = 246\,\text{GeV}$)

$$S = \int d^4x \sqrt{-g} \left(-\frac{M_P^2 + \xi h^2}{2} R + \frac{(\partial_\mu h)^2}{2} - \frac{\lambda h^4}{4} \right)$$

slow roll behavior due to modified kinetic term even for $\lambda \sim 1$

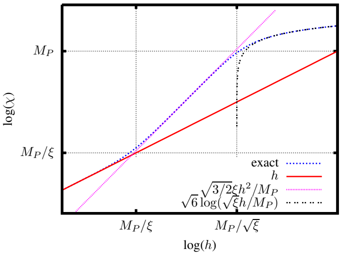
Go to the Einstein frame: $(M_P^2 + \xi h^2)\, R^{JR} \to M_P^2\, R^{EF}$

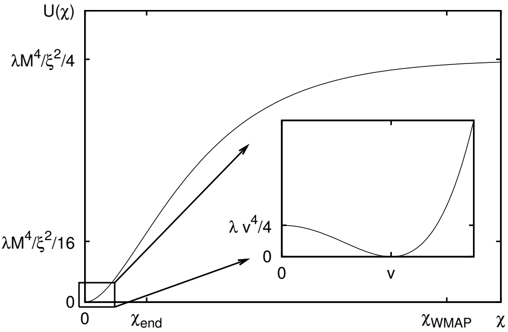
$$g_{\mu\nu}^{JF} = \Omega^{-2} \tilde{g}_{\mu\nu}^{EF} , \qquad \Omega^2 = 1 + \frac{\xi h^2}{M_P^2}$$

with canonically normalized χ: interval ds^2 changes !

$$\frac{d\chi}{dh} = \frac{M_P \sqrt{M_P^2 + (6\xi + 1)\xi h^2}}{M_P^2 + \xi h^2} , \; U(\chi) = \frac{\lambda M_P^4 h^4(\chi)}{4(M_P^2 + \xi h^2(\chi))^2} .$$

we have a flat potential at large fields: $U(\chi) \to \text{const}$ @ $h \gg M_P/\sqrt{\xi}$





Reheating by Higgs field

after inflation: $M_P/\xi < h < M_P/\sqrt{\xi}$

effective dynamics : $h^2 \to \chi$

$$\mathscr{L} = \frac{1}{2}\partial_\mu\chi\partial^\mu\chi - \frac{\lambda}{6}\frac{M_P^2}{\xi^2}\chi^2$$

Advantage: NO NEW interactions to reheat the Universe
inflaton couples to all SM fields!

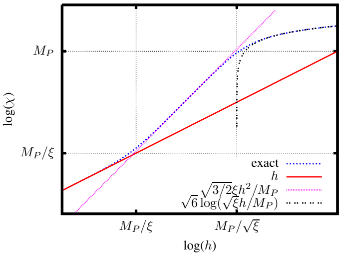
exponentially flat potential! @ $h \gg M_P/\sqrt{\xi}$:

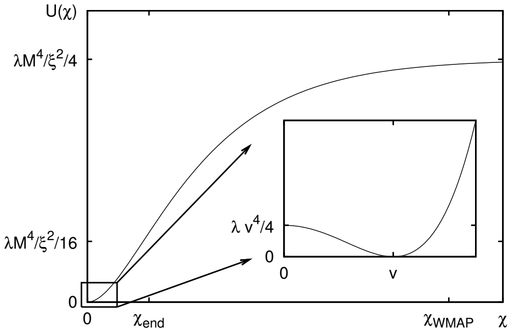
$$U(\chi) = \frac{\lambda M_P^4}{4\xi^2}\left(1 - \exp\left(-\frac{\sqrt{2}\chi}{\sqrt{3}M_P}\right)\right)^2$$

NO NEW d.o.f.
Different reheating temperature...

0812.3622, 1111.4397

from WMAP-normalization: $\xi \approx 47000 \times \sqrt{\lambda}$





Reheating by Higgs field

after inflation: $M_P/\xi < h < M_P/\sqrt{\xi}$

exponentially flat potential! @ $h \gg M_P/\sqrt{\xi}$:

effective dynamics : $h^2 \to \chi$

$$U(\chi) = \frac{\lambda M_P^4}{4\xi^2}\left(1 - \exp\left(-\frac{\sqrt{2}\chi}{\sqrt{3}M_P}\right)\right)^2$$

$$\mathscr{L} = \frac{1}{2}\partial_\mu\chi\partial^\mu\chi - \frac{\lambda}{6}\frac{M_P^2}{\xi^2}\chi^2$$

Advantage: NO NEW interactions
to reheat the Universe
inflaton couples to all SM fields!

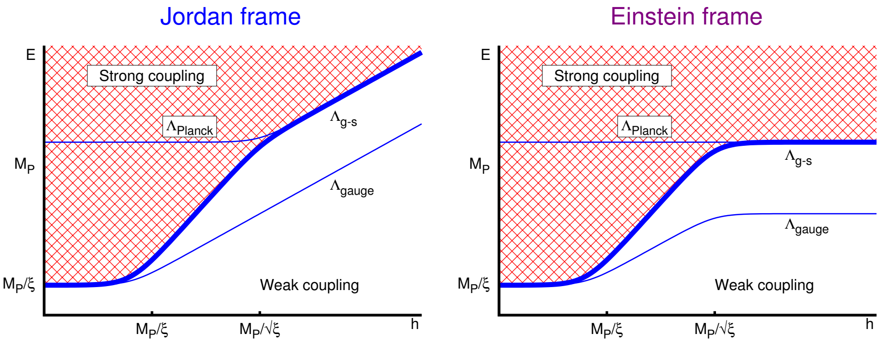
NO NEW d.o.f.

0812.3622, 1111.4397

Different reheating temperature...

from WMAP-normalization: $\xi \approx 47000 \times \sqrt{\lambda}$

Strong coupling in Higgs-inflation



gravity-scalar sector:

$$\Lambda_{g-s}(h) \simeq \begin{cases} \frac{M_P}{\xi}, & \text{for } h \lesssim \frac{M_P}{\xi}, \\ \frac{\xi h^2}{M_P}, & \text{for } \frac{M_P}{\xi} \lesssim h \lesssim \frac{M_P}{\sqrt{\xi}}, \\ \sqrt{\xi}\, h, & \text{for } h \gtrsim \frac{M_P}{\sqrt{\xi}}. \end{cases}$$

gravitons: $\Lambda^2_{\text{Planck}} \simeq M_P^2 + \xi h^2$

gauge interactions:

$$\Lambda_{\text{gauge}}(h) \simeq \begin{cases} \frac{M_P}{\xi}, & \text{for } h \lesssim \frac{M_P}{\xi}, \\ h, & \text{for } \frac{M_P}{\xi} \lesssim h, \end{cases}$$

1008.5157

We must modify the model to restore the unitarity

Natural completion with R^2

Y.Ema (2017), D.G., A.Tokareva (2018)

$\xi h^2 R$ induces R^2-term

hep-th/9510140

$$S_0 = \int d^4x \sqrt{-g} \left(-\frac{M_P^2 + \xi h^2}{2} R + \frac{\beta}{4} R^2 + \frac{(\partial_\mu h)^2}{2} - \frac{\lambda}{4}(h^2 - v^2)^2 \right).$$

introduce a Lagrange multiplier L and auxiliary scalar $\mathscr{R}$

$$S = \int d^4x \sqrt{-g} \left(\frac{(\partial_\mu h)^2}{2} - \frac{\lambda}{4}(h^2 - v^2)^2 - \frac{M_P^2 + \xi h^2}{2} \mathscr{R} + \frac{\beta}{4} \mathscr{R}^2 - L\mathscr{R} + LR \right).$$

integrate out $\mathscr{R}$

$$S = \int d^4x \sqrt{-g} \left(\frac{(\partial_\mu h)^2}{2} - \frac{\lambda}{4}(h^2 - v^2)^2 + LR - \frac{1}{\beta}(L + \frac{1}{2}\xi h^2 + \frac{1}{2}M_P^2)^2 \right)$$

$$\xi \to \xi^2/\beta$$

with

$$\beta \gtrsim \frac{\xi^2}{4\pi}$$

everything here look healthy

Further transformations...

Y.Ema (2017)

introducing scalaron ϕ with $m = M_P/\sqrt{3\beta}$

$$g_{\mu\nu} \to \Omega^2 g_{\mu\nu}\,, \quad \Omega^2 \equiv \frac{2L}{M_P^2}\,, \;\; L \to \phi \equiv M_P\sqrt{\frac{2}{3}}\log\Omega^2\,.$$

and setting $M_P = 1/\sqrt{6}$

$$S = \int d^4x\sqrt{-g}\left(-\frac{R}{12} + \frac{1}{2}e^{-2\phi}(\partial h)^2 + \frac{1}{2}(\partial\phi)^2 - \frac{1}{4}e^{-4\phi}\left(\lambda h^4 + \frac{1}{36\beta}(e^{2\phi} - 1 - 6\xi h^2)^2\right)\right)$$

both gravity and scalar sector are weakly coupled up to M_P with $\beta \gtrsim \xi^2/(4\pi)$

And one more. . .

D.G., A.Tokareva (2018)

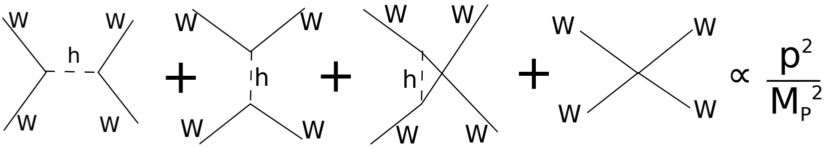
$$h = e^{\Phi} \tanh H,\ \phi = e^{\Phi}/\cosh H,$$

The scalar sector becomes

$$L = \frac{1}{2}\cosh^2 H(\partial\Phi)^2 + \frac{1}{2}(\partial H)^2 - \frac{\lambda}{4}\sinh^4 H - \frac{\lambda}{144\beta}(1 - e^{-2\Phi}\cosh^2 H - 6\xi\sinh^2 H)^2.$$

and the Higgs coupling to gauge bosons, e.g.,

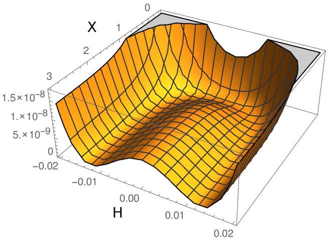
$$L_{gauge} = \frac{g^2 h^2}{4} e^{-2\phi} W^+_\mu W^-_\mu = \frac{g^2}{4}\sinh^2 H\ W^+_\mu W^-_\mu\,.$$

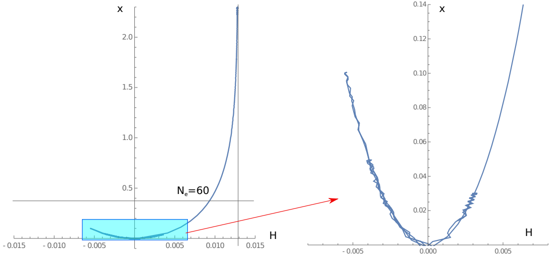


$$\mathscr{A} \sim \frac{g^2 p^2}{m_W^2}\left(\frac{4}{g^2}\left(\frac{dm_W(H)}{dH}\right)^2 - 1\right) \to \mathscr{A} \propto \frac{p^2}{M_P^2}$$

Cosmological spectra

D.G., A.Tokareva 1807.02392





Scalar perturbations: adiabatic

1701.07665

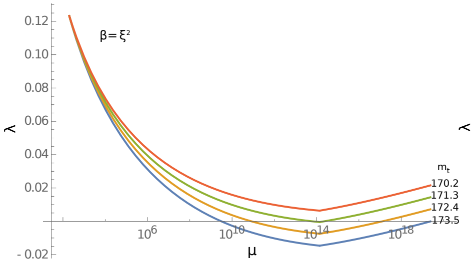
$$\beta + \frac{\xi^2}{\lambda} \simeq 2 \times 10^9$$

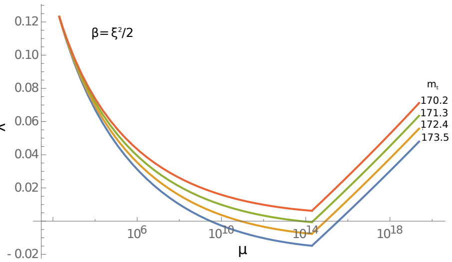
At small β like in the Higgs-inflation

heavy scalaron is integrated out

$$\frac{\xi^2}{4\pi} < \beta < \frac{\xi^2}{\lambda} \quad \rightarrow \quad 5 \times 10^{13}\,\text{GeV} < m < 1.5 \times 10^{15}\,\text{GeV}$$

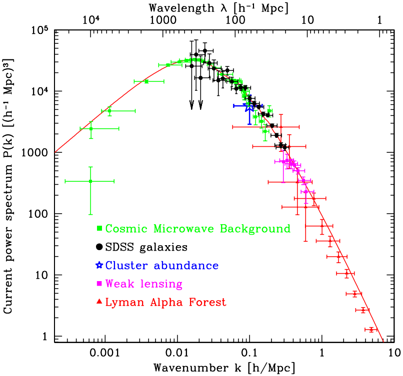
Bonus: stable for a bit heavier top-quark

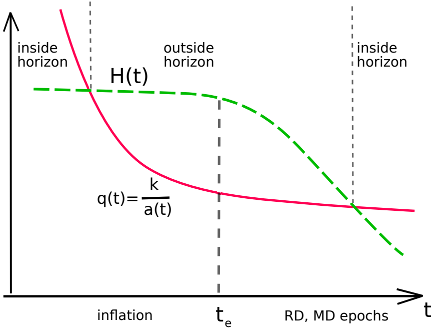




We can calculate observables at any energy scale up to Planck

Probing the spectrum at energy scale $\mu = \mu(T_{reh})$





$$\delta\phi \to \frac{\delta\rho}{\rho} \sim \frac{H^2}{\dot{\phi}} \propto \frac{V^{3/2}}{V'}\,, \qquad h \sim \frac{H}{M_{Pl}} \propto V^{1/2}$$

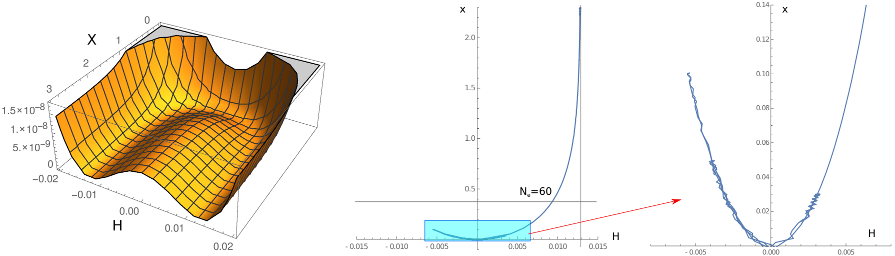
$$A_S \to \frac{V^{3/2}}{V'}\,, \qquad n_S \to \frac{V''}{V}\,, \left(\frac{V'}{V}\right)^2\,, \qquad r \equiv \frac{A_T}{A_S} \to \left(\frac{V'}{V}\right)^2$$

Reheating. . . all masses depend on oscillating Higgs

- Huge spikes do not reheat !! 1812.10099
- it is a highly nonlinear system
- ω^2 for W_L and Z_L rapidly oscillates and becomes negative for some time
- similar for one of the scalars (a mixture of Higgs and scalaron)
- we expect instant preheating, at least for a region in model parameter space F.Bezrukov, D.G., Ch.Shepherd, A.Tokareva (2019)
- but for precise number the backreaction must be taken into account

Cosmological spectra

D.G., A.Tokareva 1807.02392



Scalar perturbations:

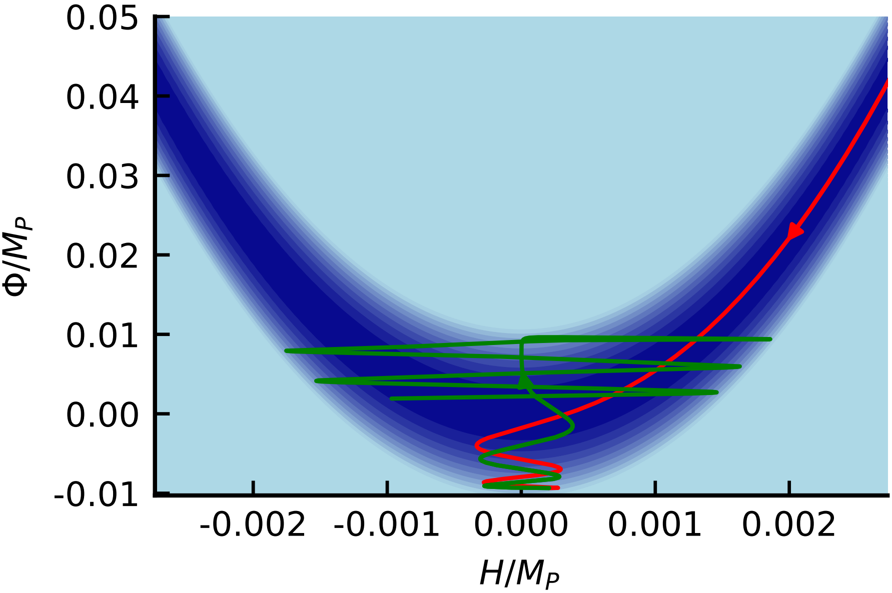
1701.07665

$$\beta + \frac{\xi^2}{\lambda} \simeq 2 \times 10^9$$

At small β like in the Higgs-inflation

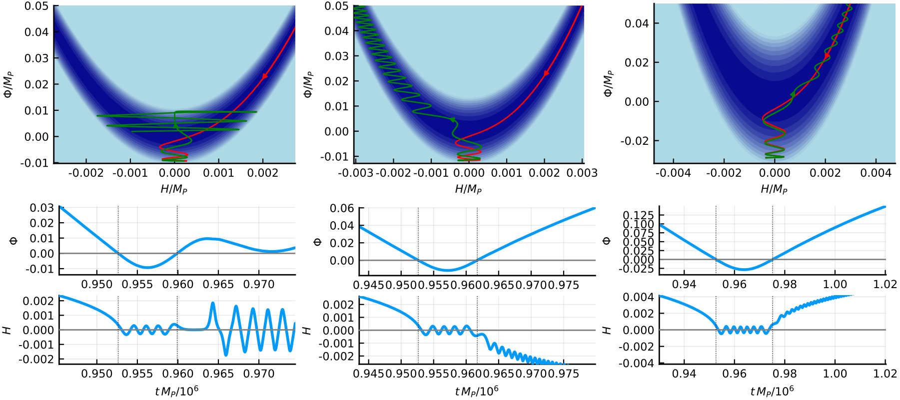
heavy scalaron is integrated out

$$\frac{\xi^2}{4\pi} < \beta < \frac{\xi^2}{\lambda} \quad \rightarrow \quad 5 \times 10^{13}\,\text{GeV} < m < 1.5 \times 10^{15}\,\text{GeV}$$


0.05
0.04
0.03
0.02
0.01
0.00
-0.01
Φ/M_P
-0.002
-0.001
0.000
0.001
0.002
H/M_P

Scalaron Φ and Higgs H evolution after inflation

Homogeneous modes (mixing in kinetic sector), $\dot{\Phi} < 0$, $\dot{\Phi} > 0$



$\beta = 1.869 \times 10^6$ $\beta = 2.9 \times 10^6$ $\beta = 18 \times 10^6$

$$V(H,\Phi) = \frac{1}{4}\left(\lambda + \frac{\xi^2}{\beta}\right)H^4 + \frac{M_P^2}{6\beta}\Phi^2 - \frac{\xi M_P}{\sqrt{6}\beta}\Phi H^2 + \frac{7}{108\beta}\Phi^4 + \frac{\xi}{6\beta}\Phi^2 H^2 - \frac{M_P}{3\sqrt{6}\beta}\Phi^3$$

Linear equations for gauge bosons

Gauge bosons (e.g. $W^{\pm}$)

$$L_g^{(2)} = -\frac{1}{2}\left(\partial_\mu W_\nu^+ - \partial_\nu W_\mu^+\right)\left(\partial_\lambda W_\rho^- - \partial_\rho W_\lambda^-\right) g^{\mu\lambda} g^{\nu\rho} + \frac{g^2 H_0^2}{4} W_\mu^+ W_\nu^- g^{\mu\nu},$$

transverse modes

$$\ddot{W}_k^T + 3\mathscr{H}\dot{W}_k^T + \frac{k^2}{a^2} W_k^T + m_T^2 W_k^T = 0, \qquad m_T \equiv \frac{g}{2} H_0$$

longitudinal modes

$$\ddot{W}_k^L + 3\mathscr{H}\dot{W}_k^L + \omega_W^2(\mathbf{k}) W_k^L = 0.$$

$$\omega_W^2(\mathbf{k}) = \frac{k^2}{a^2} + m_T^2 - \frac{k^2}{k^2 + a^2 m_T^2}\left(\dot{\mathscr{H}} + 2\mathscr{H}^2 + 3\mathscr{H}\frac{\dot{m}_T}{m_T} + \frac{\ddot{m}_T}{m_T} - \frac{3(\dot{m}_T + \mathscr{H} m_T)^2}{k^2/a^2 + m_T^2}\right).$$

for $k/a \gg m_T$ after inflation

$$\omega_W^2 = \frac{k^2}{a^2} + \frac{g^2}{4} H_0^2 + \frac{\xi}{3\beta}\Phi_0^2 + \left(\lambda + \frac{\xi^2}{\beta}\right) H_0^2 - \frac{\xi\sqrt{2}}{\beta\sqrt{3}} M_P \Phi_0,$$

Linear equations for scalaron and Higgs

A mixutre of the two scalars

$$m^2_{L,H} = \frac{1}{2}\left(V_{H_0H_0} + V_{\Phi_0\Phi_0}\right) \times \left(1 \pm \sqrt{1 - 4\frac{V_{\Phi_0\Phi_0}V_{H_0H_0} - V^2_{\Phi_0 H_0}}{\left(V_{H_0H_0} + V_{\Phi_0\Phi_0}\right)^2}}\right).$$

after inflation can be approximated as

$$m^2_{H,L} \approx V_{H_0H_0} \approx 2\left(\lambda + \frac{\xi^2}{\beta}\right)H_0^2 + \left(\lambda + \frac{\xi^2}{\beta}\right)H_0^2 - \frac{\sqrt{2}\xi}{\sqrt{3}\beta}M_P\Phi_0$$

Then we calculate the Bogolubov coefficients from the field solutions $f_{\mathbf{k}}(t) = e^{-i\omega t}/\sqrt{2\omega(\mathbf{k})}$ at $t \to 0$, which gives for the number density

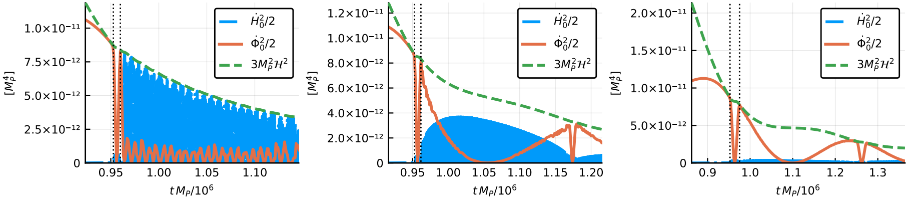
$$n_{\mathbf{k}} = \frac{1}{2}\left|\sqrt{\omega(\mathbf{k})}f_{\mathbf{k}} - \frac{i}{\sqrt{\omega(\mathbf{k})}}\dot{f}_{\mathbf{k}}\right|^2$$

and the physical energy

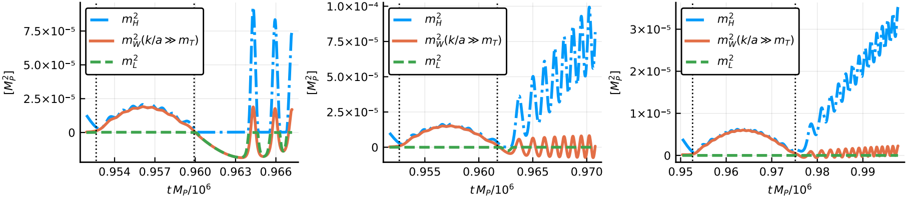
$$\rho = \int \frac{d^3\mathbf{k}}{(2\pi)^3 a^3(t)}\omega(\mathbf{k})n_{\mathbf{k}}.$$

Numerical results for perturbations

energy distribution over homogeneous modes

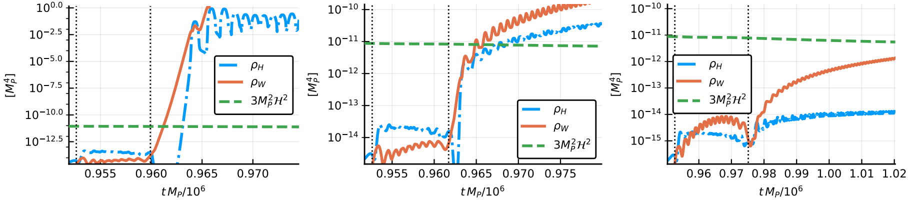


mass squared for the relevant perturbations

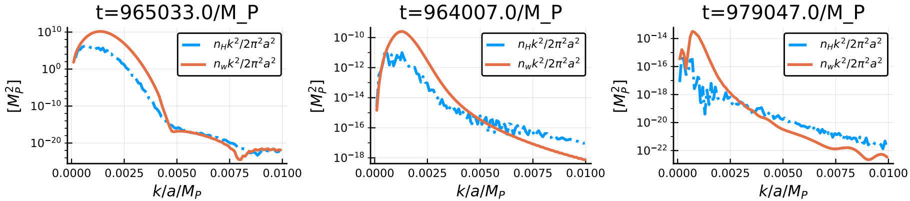


Spectra and energy density of produced particles

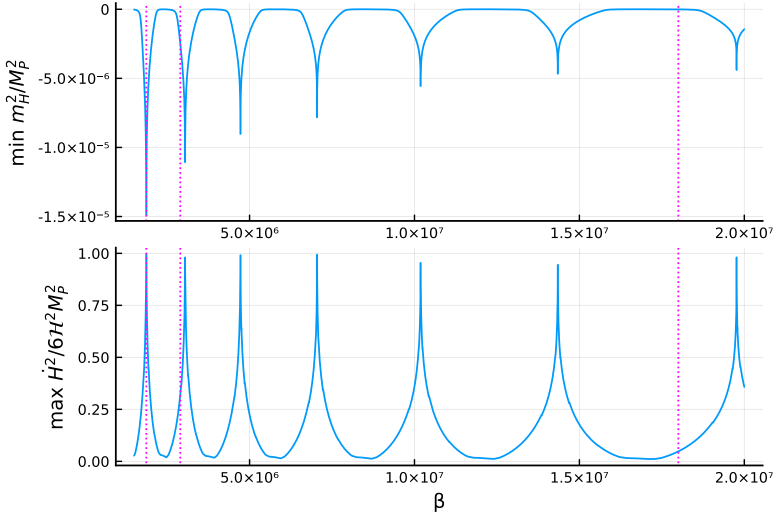
neglecting the adiabaticity conditions... and backreaction



spectra at a reference moment



The resonance positions and energy in Higgs between two zero crossings are correlated



Direct check of the inflation potential

– Higgs frequency is much and scalaron frequency is significantly higher than the expansion rate:
It seems that the reheating is instant

$$N_e = 59, \quad n_s = 0.97, \quad r = 0.0034.$$

– Higgs selfcoupling becomes canonical λ below the scalaron scale $\mu = M_P/\sqrt{3\beta}$

$$V(H,\Phi) = \frac{1}{4}\left(\lambda + \frac{\xi^2}{\beta}\right)H^4 + \frac{M_P^2}{6\beta}\Phi^2 - \frac{\xi M_P}{\sqrt{6}\beta}\Phi H^2 + \frac{7}{108\beta}\Phi^4 + \frac{\xi}{6\beta}\Phi^2 H^2 - \frac{M_P}{3\sqrt{6}\beta}\Phi^3$$

cancellation: $\xi M_P/\beta \times 1/\mu^2 \times \xi M_P/\beta \to \xi^2/\beta$

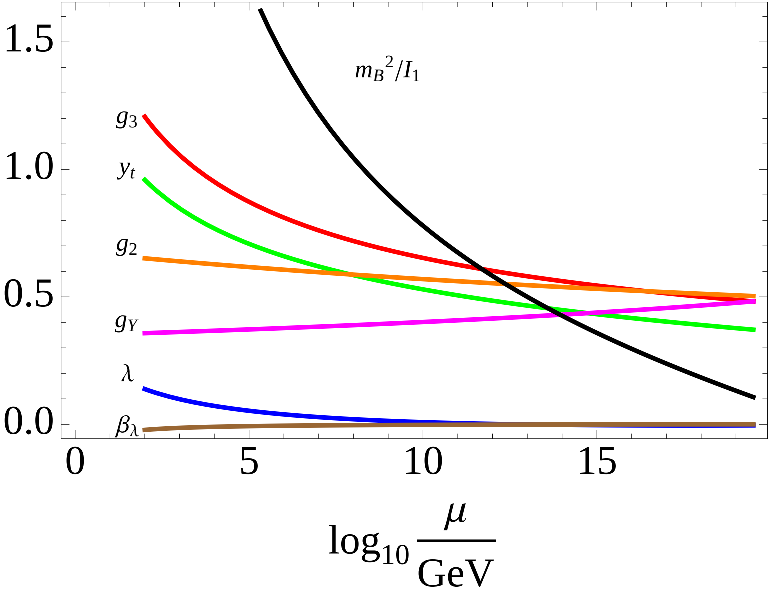
Conclusions

- Higgs inflation is a viable cosmological model unique in minimality:
  no new d.o.f., no new interactions to reheat the Universe
- however it suffers from the stong coupling problem:
  predictivity $\delta\rho/\rho \leftrightarrow \lambda$ is lost
- R^2-term with heavy scalaron cures the model:
  it seems minimal, natural, Higgs-inflation predictions remain intact
- cosmological and particle physics observables are pertrurbatively related
- to refine predictions we must study the backreaction at reheating
  and improve the accuracy of Y_t, (m_h, α_s, etc) to convince it works indeed
  ... ILC, FCC, etc

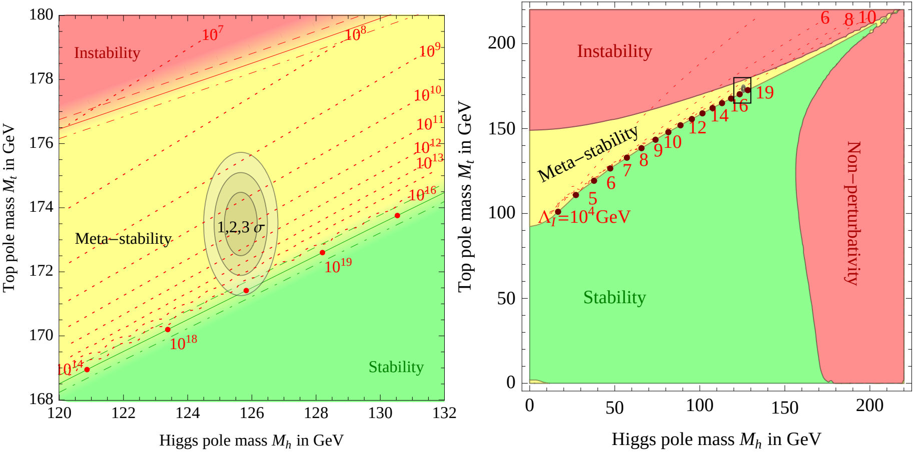
Backup slides

Running of the SM couplings

1305.7055



How weird to live with 125 GeV Higgs. . .



1307.7879

Power spectrum of perturbations

In the Minkowski space-time:

- fluctuations of a free quantum field φ are gaussian its power spectrum is defined as

$$\int_0^\infty \frac{dq}{q}\,\mathscr{P}_\varphi(q) \equiv \langle \varphi^2(x) \rangle = \int_0^\infty \frac{dq}{q}\,\frac{q^2}{(2\pi)^2}$$

We define amplitude as $\delta\varphi(q) \equiv \sqrt{\mathscr{P}_\varphi} = q/(2\pi)$

- In the expanding Universe momenta $q = k/a$ gets redshifted
- Cast the solution in terms $\phi(\mathbf{x},t) = \phi_c(t) + \varphi(\mathbf{x},t)\,, \quad \varphi(\mathbf{x},t) \propto e^{\pm i\mathbf{kx}}\,\varphi(\mathbf{k},t)$
  φ solves the equation

$$\ddot{\varphi} + 3H\dot{\varphi} + \frac{k^2}{a^2}\,\varphi + V''(\phi_c)\varphi = 0$$

- $q = k/a \gg H \;\Rightarrow$ as in Minkowski space-time
- $q = k/a \ll H \;\Rightarrow$ for inflaton $\varphi = \text{const}$
- Matching at t_k: $q(t_k) = k/a(t_k) = H(t_k) \equiv H_k$ gives

$$\delta\varphi(q) = \frac{H_k}{2\pi} \;\Rightarrow\; \mathscr{P}_\varphi(q) = \frac{H_k^2}{(2\pi)^2}$$

amplification $H_k/q = e^{N_e(k)}$!!!

$H_k \approx \text{const} = H_{infl}$ hence (almost) flat spectrum

Inflaton parameters and spectral parameters

- Observation of CMB anisotropy gives $\delta T/T$

$$\frac{\delta T}{T} \sim \frac{\delta\rho}{\rho} \quad \Rightarrow \Delta_{\mathscr{R}} \equiv \sqrt{\mathscr{P}_{\mathscr{R}}} = 5\times 10^{-5}$$

- These are so-called adiabatic perturbations!
  Other possibles (isocurvature) modes (e.g. $\delta T = 0$, but $\delta n_B/n_B \neq 0$) are not found.
- $\Delta_{\mathscr{R}} = 5\times 10^{-5} \Rightarrow$ fixes model paramaters, e.g.:

$$V(\phi) = \frac{\beta}{4}\phi^4 \to \lambda \sim 10^{-13}$$

  With such a tiny coupling perturbations are obviously gaussian
  So far confirmed by observations
- That's why Higgs boson in the SM does not help!

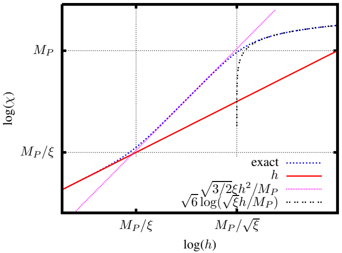
Inflaton parameters and spectral parameters

- In fact, spectra are a bit tilted, as H_{infl} slightly evolves

$$\mathcal{P}_{\mathcal{R}}(k) = A_{\mathcal{R}} \left(\frac{k}{k_*}\right)^{n_s - 1} , \qquad \mathcal{P}_T(k) = A_T \left(\frac{k}{k_*}\right)^{n_T} .$$

- Measure $\Delta_{\mathcal{R}}$ at present scales $q \simeq 0.002/\mathrm{Mpc}$, it fixes the number of e-foldings left N_e
- For tensor perturbations one introduces:

$$r \equiv \frac{\mathcal{P}_T}{\mathcal{P}_{\mathcal{R}}} = \frac{1}{\pi} \frac{M_{Pl}^2 V'^2}{V} = 16\,\varepsilon \;\; \to \;\; \frac{16}{N_e} \;\; \text{for} \;\; \beta\phi^4$$



$$m_W^2(\chi) = \frac{g^2}{2\sqrt{6}} \frac{M_P|\chi(t)|}{\xi}$$

$$m_t(\chi) = y_t \sqrt{\frac{M_P|\chi(t)|}{\sqrt{6}\,\xi}}\,\mathrm{sign}\,\chi(t)$$

reheating via W^+W^-, ZZ production at zero crossings

then nonrelativistic gauge bosons scatter to light fermions

$$\chi \to W^+W^- \to f\bar{f}$$

Reheating by Higgs field

after inflation: $M_P/\xi < h < M_P/\sqrt{\xi}$

effective dynamics : $h^2 \to \chi$

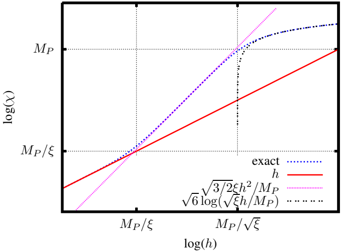
$$\mathscr{L} = \frac{1}{2}\partial_\mu\chi\partial^\mu\chi - \frac{\lambda}{6}\frac{M_P^2}{\xi^2}\chi^2$$

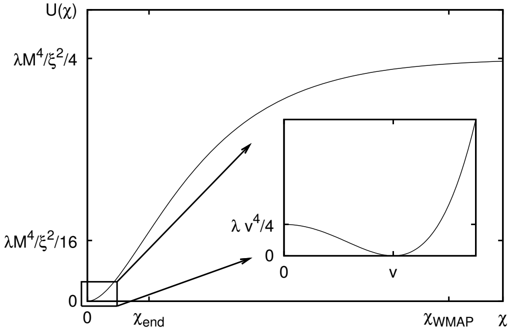
Advantage: NO NEW interactions to reheat the Universe
inflaton couples to all SM fields!

Hot stage starts almost from $T = M_P/\xi \sim 10^{14}$ GeV:

$$3.4\times10^{13}\,\text{GeV} < T_r < 9.2\times10^{13}\left(\frac{\lambda}{0.125}\right)^{1/4}\text{GeV}$$

$n_s = 0.967$, $r = 0.0032$ F.Bezrukov, D.G.,





$$\frac{d\chi}{dh} = \frac{M_P\sqrt{M_P^2+(6\xi+1)\xi\, h^2}}{M_P^2+\xi\, h^2},$$

$$U(\chi) = \frac{\lambda M_P^4 h^4(\chi)}{4(M_P^2+\xi\, h^2(\chi))^2}.$$

exponentially flat potential! @ $h \gg M_P/\sqrt{\xi}$:

$$U(\chi) = \frac{\lambda M_P^4}{4\xi^2}\left(1-\exp\left(-\frac{\sqrt{2}\chi}{\sqrt{3}M_P}\right)\right)^2$$

- renormalizable except gravity
  frame-dependent renormalization scale
- strong coupling (ϕ-dependent)
  save for inflation
  but reheating is questionable

F.Bezrukov et al (2008)

$V_0 \simeq 10^{-12} M_{Pl}^4$

from WMAP-normalization: $\xi \approx 47000 \times \sqrt{\lambda}$

F.Bezrukov, D.G., M.Shaposhnikov (2008,2011)

And the reheating is almost instant

1609.05209, 1810.01304

We made an error, solving

$$\left(m_W^2(h(t)) + \Box\right) W_\nu^\pm = 0$$

while the true equation is

$$W_\nu^\pm m_W^2(h(t)) + \partial_\mu W_{\mu\nu}^\pm = 0$$

the $\partial_\mu W_\mu^\pm = 0$ gauge does not go through the equation...

So, the longitudinal components of vector boson get contributions
$\omega_L^2 \propto \dot{m}_W, \ddot{m}_W$
instant reheating well inside the strong coupling domain...