Inflation and the Higgs boson

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COSMO 09
CERN
7-11 September 2009

Outline

1. How to inflate with the Higgs boson – tree level
2. What can we say then about the Higgs – radiative corrections

Based on:

- FB, M.Shaposhnikov, Phys. Lett. B **659**, 703 (2008)
- FB, D.Gorbunov, M.Shaposhnikov, JCAP **06**, 029 (2009)
- FB, A.Magnin, M.Shaposhnikov, Phys. Lett. B **675**, 88 (2009)
- FB, M.Shaposhnikov, JHEP **0907** (2009) 089

MAX-PLANCK-GESELLSCHAFT

"Standard" chaotic inflation

Scalar part of the action

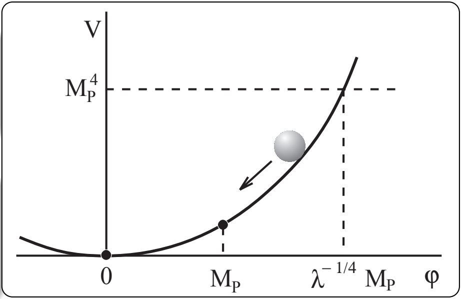
$$S = \int d^4x \sqrt{-g} \left\{ -\frac{M_P^2}{2} R + g_{\mu\nu} \frac{\partial^\mu h \partial^\nu h}{2} - \frac{\lambda}{4} h^4 \right\}$$

Required to get $\delta T / T \sim 10^{-5}$

$$\lambda \sim 10^{-13}$$

The SM Higgs boson

- $\lambda \sim 1$ possible, provided $\xi \sim 50000$



- Rather old idea: [A.Zee'78, L.Smolin'79, B.Spokoiny'84] [D.Salopek J.Bond J.Bardeen'89]
- SM Higgs vev $v \ll M_P/\sqrt{\xi}$, can be neglected in the early Universe

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Non-minimally coupled chaotic inflation

Scalar part of the action

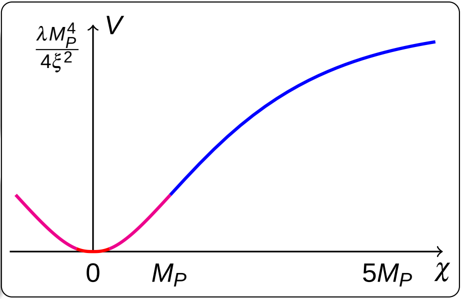
$$S = \int d^4x \sqrt{-g} \left\{ -\frac{M_P^2 + \xi h^2}{2} R + g_{\mu\nu} \frac{\partial^\mu h \partial^\nu h}{2} - \frac{\lambda}{4} h^4 \right\}$$

Required to get $\delta T / T \sim 10^{-5}$

$$\lambda \sim 10^{-10} \xi^2$$

The SM Higgs boson

- $\lambda \sim 1$ possible, provided $\xi \sim 50000$



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- SM Higgs vev $v \ll M_P/\sqrt{\xi}$, can be neglected in the early Universe

Scale invariance at large Higgs field values

For large Higgs field background $h \gg M_P/\sqrt{\xi}$

- "Effective" Planck mass is $M_{P\text{eff}}^2 = M_P^2 + \xi h^2 \propto h^2$
- All other masses $M_h^2, M_W^2, m_t^2 \propto h^2$

No scale (h) dependence—flat potential, scale invariant spectrum, etc.

Exactly what is needed for inflation.

Another way to see that

Conformal transformation

Conformal transformation

It is possible to get rid of the non-minimal coupling by the conformal transformation (change of variables)

$$\hat{g}_{\mu\nu} = \Omega^2 g_{\mu\nu} \,, \qquad \Omega^2 \equiv 1 + \frac{\xi h^2}{M_P^2}$$

Redefinition of the Higgs field to get canonical kinetic term

$$\frac{d\chi}{dh} = \sqrt{\frac{\Omega^2 + 6\xi^2 h^2/M_P^2}{\Omega^4}} \quad \Longrightarrow \begin{cases} h \simeq \chi & \text{for } h < M_P/\xi \\ \Omega^2 \simeq \exp\left(\frac{2\chi}{\sqrt{6}M_P}\right) & \text{for } h > M_P/\xi \end{cases}$$

Resulting action (Einstein frame action)

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

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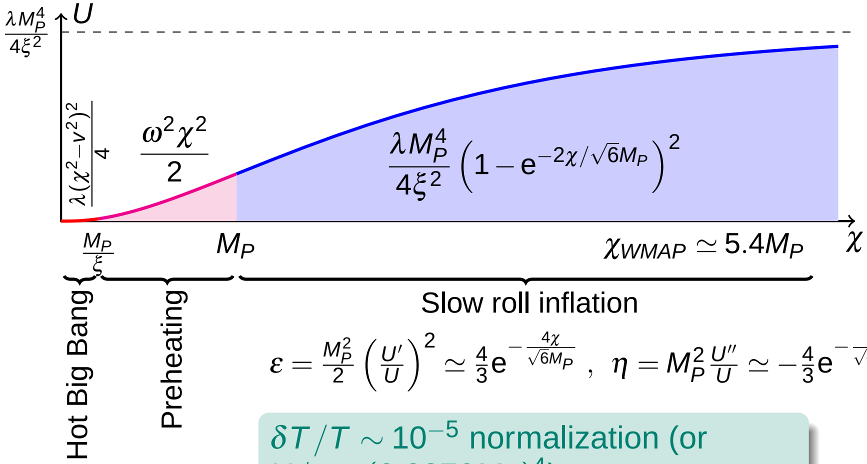
Potential—different stages of the Universe



$$\varepsilon = \frac{M_P^2}{2}\left(\frac{U'}{U}\right)^2 \simeq \frac{4}{3}e^{-\frac{4\chi}{\sqrt{6}M_P}}\ , \quad \eta = M_P^2\frac{U''}{U} \simeq -\frac{4}{3}e^{-\frac{2\chi}{\sqrt{6}M_P}}$$

$\delta T/T \sim 10^{-5}$ normalization (or $U/\varepsilon = (0.0276 M_P)^4$)

$$\frac{\xi}{\sqrt{\lambda}} \simeq 47000$$

$$\omega = \sqrt{\frac{\lambda}{3}}\frac{M_P}{\xi}$$

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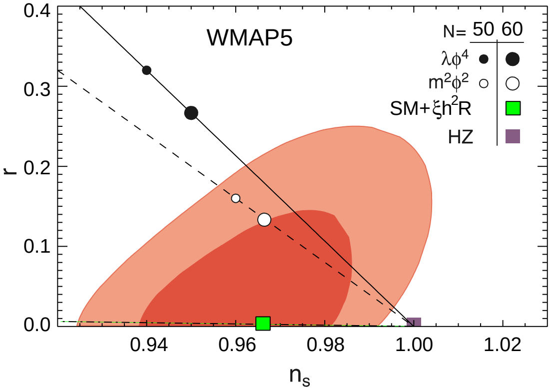
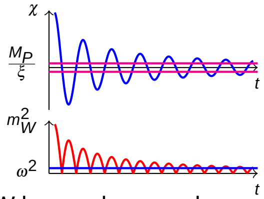
CMB parameters—spectrum and tensor modes



spectral index	$n = 1 - 6\varepsilon + 2\eta \simeq 1 - \frac{8(4N+9)}{(4N+3)^2} \simeq 0.97$
tensor/scalar ratio	$r = 16\varepsilon \simeq \frac{192}{(4N+3)^2} \simeq 0.0033$

Preheating

- Background evolution after inflation $\chi < M_P$ ($h < M_P/\sqrt{\xi}$)
  - Quadratic potential $U \simeq \frac{\omega^2}{2}\chi^2$ with $\omega = \sqrt{\frac{\lambda}{3}}\frac{M_P}{\xi}$
  - Matter dominated stage $a \propto t^{2/3}$



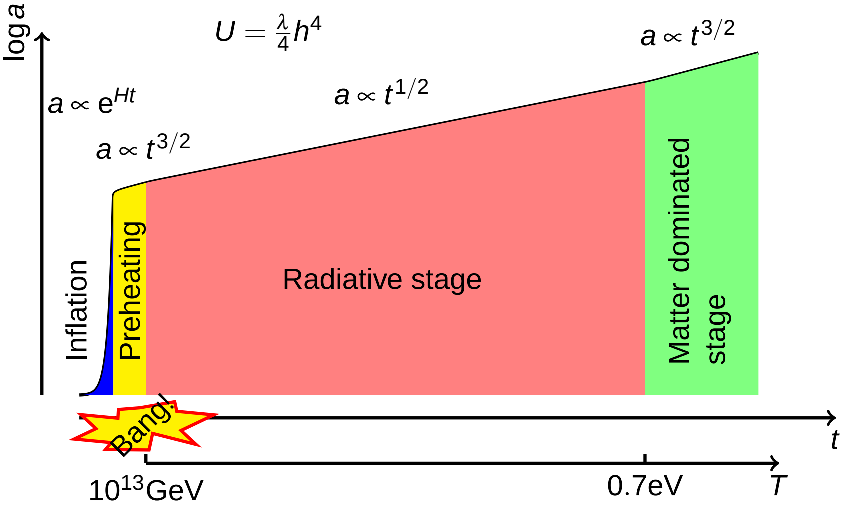
- Stohastic resonance
  - Particle masses $m_W^2(\chi) \sim g^2 \frac{M_P|\chi|}{\xi}$
  - W bosons are created (non-relativistic)
    - ★ $\sqrt{\langle\chi^2\rangle} \gtrsim 23\left(\frac{\lambda}{0.25}\right)\frac{M_P}{\xi}$: non-resonant creation/W boson decay – slow
    - ★ $\sqrt{\langle\chi^2\rangle} \lesssim 23\left(\frac{\lambda}{0.25}\right)\frac{M_P}{\xi}$: resonant creation/W boson annihilation – fast
  - Higgs creation – relativistic, less efficient $\sqrt{\langle\chi^2\rangle} \sim 2.6\left(\frac{\lambda}{0.25}\right)^{1/2}\frac{M_P}{\xi}$
- Radiation dominated stage starts

$$3.4 \times 10^{13}\,\text{GeV} < T_r < \left(\frac{\lambda}{0.25}\right)^{1/4} 1.1 \times 10^{14}\,\text{GeV}$$

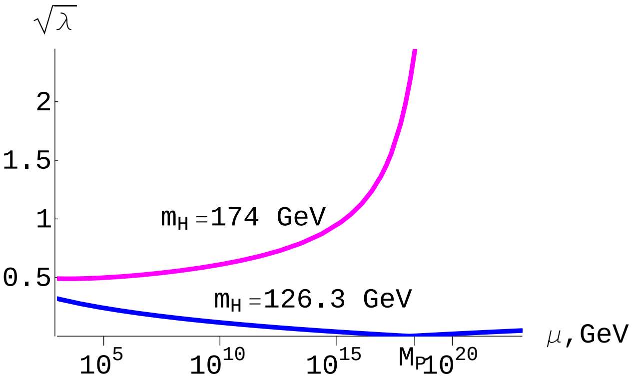
- At Higgs amplitude $\sqrt{\langle\chi^2\rangle} \lesssim \frac{M_P}{\xi}$ – exact SM. $T_{reh} > 1.5 \times 10^{13}$ GeV

[FB, Gorbunov, Shaposhnikov'09], [J.García-Bellido, D.Figueroa, J.Rubio'09]

History of the Universe



Validity of SM up to Planck scale



Usual SM result

$$126.3\,\text{GeV} < m_H < 174\,\text{GeV}$$

Corrections to the potential

1-loop effective potential

$$\Delta U(\chi) \sim \sum_{\text{particles}} \frac{m^4(\chi)}{64\pi^2} \log \frac{m^2(\chi)}{\mu^2} \quad \Big| \quad \frac{m^4(\chi)}{64\pi^2} \log \frac{m^2(\chi)}{\mu^2/\Omega^2(\chi)}$$

In Einstein frame: $m^2(\chi) \sim g^2 h^2(\chi)/\Omega^2(\chi)$

- Correct by RG running
- Ambiguity in the theory definition in UV

Cutoff frame dependence and choice

	choice I	choice II
Jordan frame	$M_P^2 + \xi h^2$	M_P^2
Einstein frame	M_P^2	$\frac{M_P^4}{M_P^2 + \xi h^2}$

[FB, Magnin, Shapshnikov'08]

Higgs mass bounds

- Prescription I ($\Lambda \propto M_P$ in Einstein frame)

$$m^{I}_{\text{min}} = \left[126.1 + \frac{m_t - 171.2}{2.1} \times 4.1 - \frac{\alpha_s - 0.1176}{0.002} \times 1.5\right] \text{GeV}$$

$$m_{\text{max}} = \left[193.9 + \frac{m_t - 171.2}{2.1} \times 0.6 - \frac{\alpha_s - 0.1176}{0.002} \times 0.1\right] \text{GeV}$$

- Prescription II ($\Lambda \propto M_P$ in Jordan frame)

$$m^{II}_{\text{min}} = \left[126.7 + \frac{m_t - 171.2}{2.1} \times 4.5 - \frac{\alpha_s - 0.1176}{0.002} \times 1.7\right] \text{GeV}$$

- overall error $\delta m \sim 2\,\text{GeV}$

[FB, Shaposhnikov'09]. See also [A.De Simone, M.Hertzberg, F.Wilczek'09, A.Barvinsky, A.Kamenshchik, C.Kiefer, A.Starobinsky, C.Steinwachs'09]

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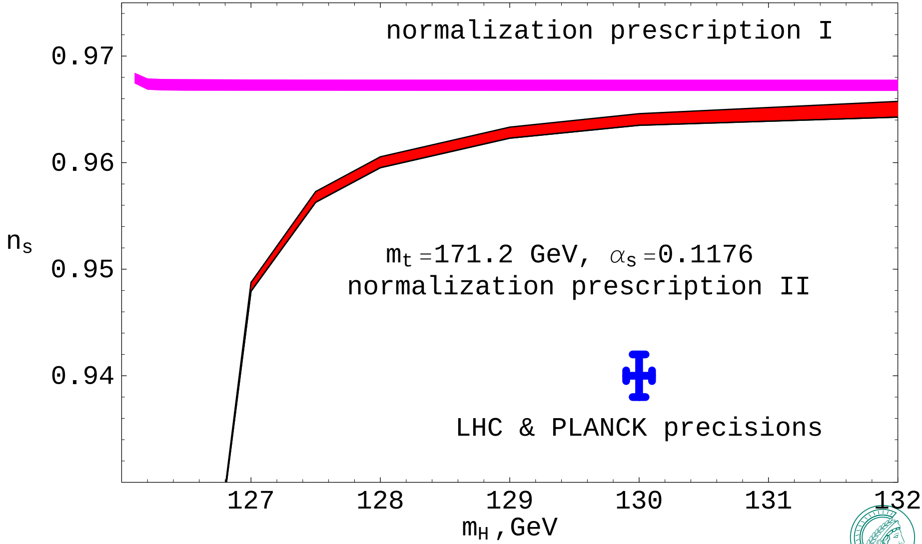
Future experiments—clue on Planck scale physics?



Assumptions and future work

- No new physics (except for νMSM, i.e. 3 sterile neutrinos) up to the Planck scale
- UV completion leading to higher dimensional operators suppressed at least by M_P
  - [S.Sibiryakov'08, private communications]
  - [C.Burgess, H.Lee, M.Trott'09]
  - [J.Barbon, J.Espinose'09]
- Specific substraction rules (c.f. difference between prescriptions I and II)
- Proper $1/\xi$ corrections to the calculation of the radiative corrections during inflationary stage

Conclusions

- Adding non-minimal coupling $\xi H^\dagger H R$ of the Higgs field to the gravity makes inflation possible without introduction of new fields
- Predicted for CMB
  - spectral index $n_s \simeq 0.97$
  - tiny tensor perturbations $r \simeq 0.0033$
- Successful inflation requires
  - Higgs mass in the interval $126\,\text{GeV} < m_H < 194\,\text{GeV}$
  - No new physics up to the Planck scale, except for νMSM (three singlet neutrinos allowing for oscillations, DM&baryosynthesis)
- Precision measurements of PLANCK and LHC may shed light on the Planck scale physics

Thank you!

- FB, M.Shaposhnikov, Phys. Lett. B **659**, 703 (2008)
- FB, D.Gorbunov, M.Shaposhnikov, JCAP **06**, 029 (2009)
- FB, A.Magnin, M.Shaposhnikov, Phys. Lett. B **675**, 88 (2009)
- FB, M.Shaposhnikov, JHEP **0907** (2009) 089
- J.García-Bellido, D.Figueroa, J.Rubio, Phys. Rev. D **79** (2009) 063531
- A.Barvinsky, A.Kamenshchik, C.Kiefer, A.Starobinsky, C.Steinwachs, arXiv:0904.1698 [hep-ph]
- A.De Simone, M.Hertzberg, F.Wilczek, Phys. Lett. B **678** (2009) 1
- J.Barbon, J.Espinosa, Phys. Rev. D **79** (2009) 081302
- C.Burgess, H.Lee, M.Trott, arXiv:0902.4465 [hep-ph]

Possible operators in the SM (+gravity)

- Dimension ≤ 4
- No new degrees of freedom (no higher derivatives)

$$S = \int d^4x \sqrt{-g} \Bigg[$$

SM $\begin{cases} \mathrm{Tr}(F_{\mu\nu}F^{\mu\nu}) + \frac{|D_\mu H|^2}{2} - V(H) + \bar{\Psi}\not{D}\Psi + YH\bar{\Psi}_L\Psi_R + m\bar{N}^c N \\ -\frac{M_P^2}{2}R \end{cases}$

$$-\xi H^\dagger HR$$

$$+R^2 + R_{\mu\nu}R^{\mu\nu} + R_{\mu\nu\lambda\rho}R^{\mu\nu\lambda\rho} + \Box R \Bigg]$$

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Note about R^2 terms

Starobinsky inflation [Starobinsky'80]

$$S = \int d^4x \left\{ \frac{M_P^2}{2} R + aR^2 \right\}$$

is equivalent to the theory with a scalar field

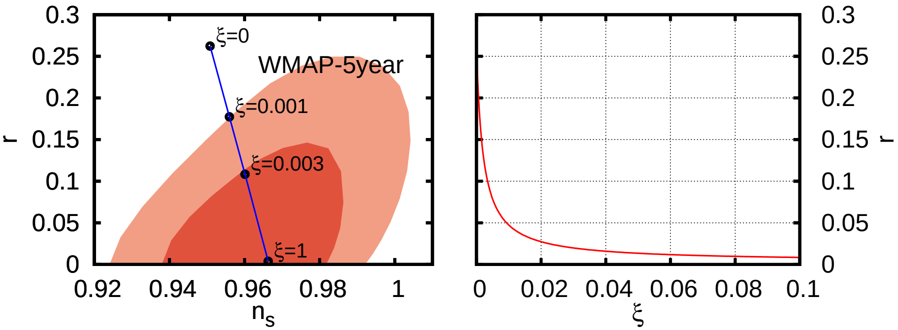
$$S = \int d^4x \left\{ \frac{M_P^2}{2} R + \frac{(\partial\sigma)^2}{2} - \frac{1}{16a} \left(1 - e^{-\frac{2\sigma}{\sqrt{6}M_P}} \right)^2 \right\}$$

Leads to: $n_s \simeq 0.97$, $r \simeq 0.0033$

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

$$a \sim 0.5 \times 10^9$$

Non-minimally coupled $\lambda\phi^4$ and WMAP-5



Message

With non-minimal coupling it is very natural for $\lambda\phi^4$ inflation to be compatible with observations!

[S.Tsujikawa, B.Gumjudpai'04], [FB'08]

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RG improvement

$$U_{\text{eff}}(\chi,\mu) = \frac{\lambda(\mu)}{4\xi^2(\mu)} f(\chi) + s(g,g',g_3,y_t) f(\chi) \log\left(\frac{m_t^2}{\mu^2}\right) + \mu\text{-independent}$$

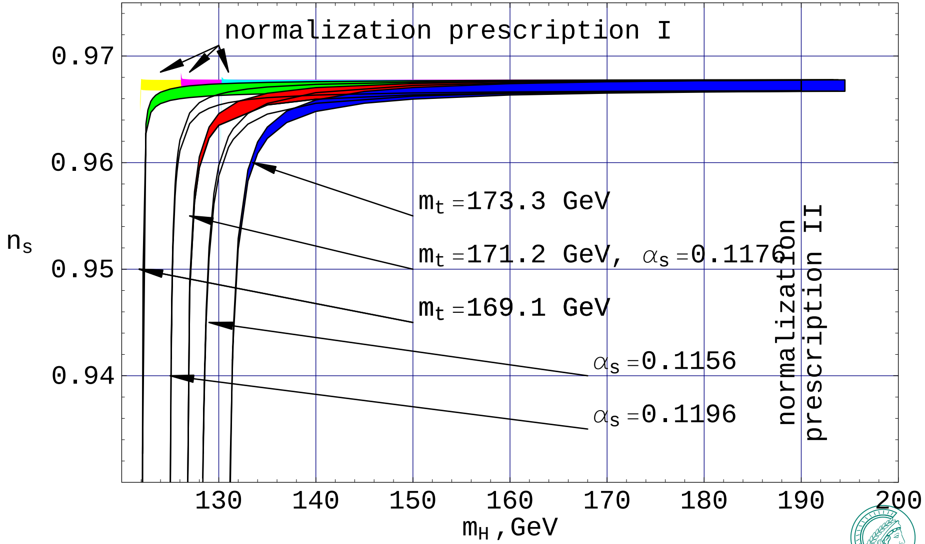
$$f(\chi) = M_P^4 \left(1 - e^{-\frac{2\chi}{\sqrt{6}M_P}}\right)^2$$

$$16\pi^2 \mu \frac{\partial}{\partial\mu}\left(\frac{\lambda}{\xi^2}\right) = \frac{1}{\xi^2}\left(-6y_t^4 + \frac{3}{8}\left(2g^2 + (g'^2 + g^2)^2\right)\right)$$

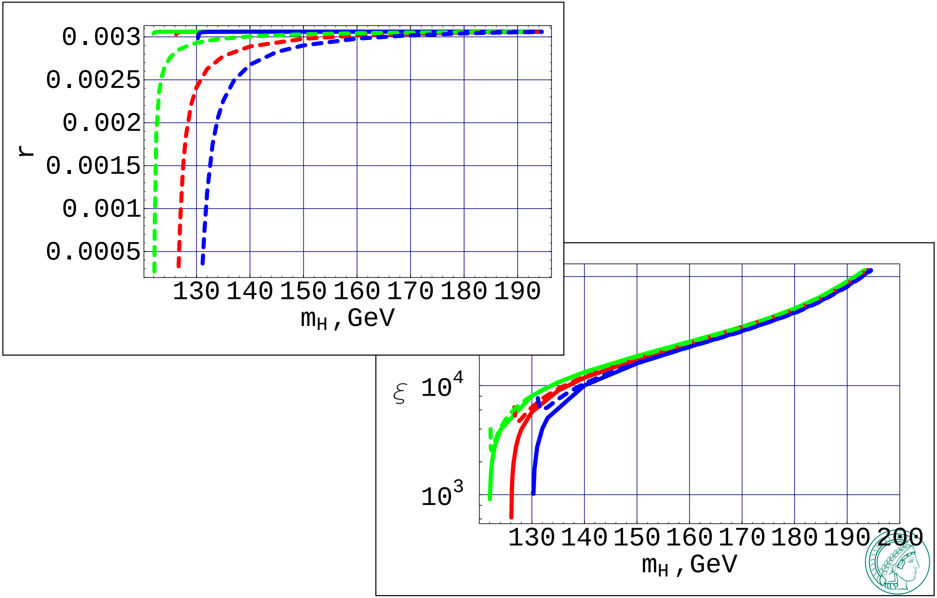
μ is a function of χ defined by

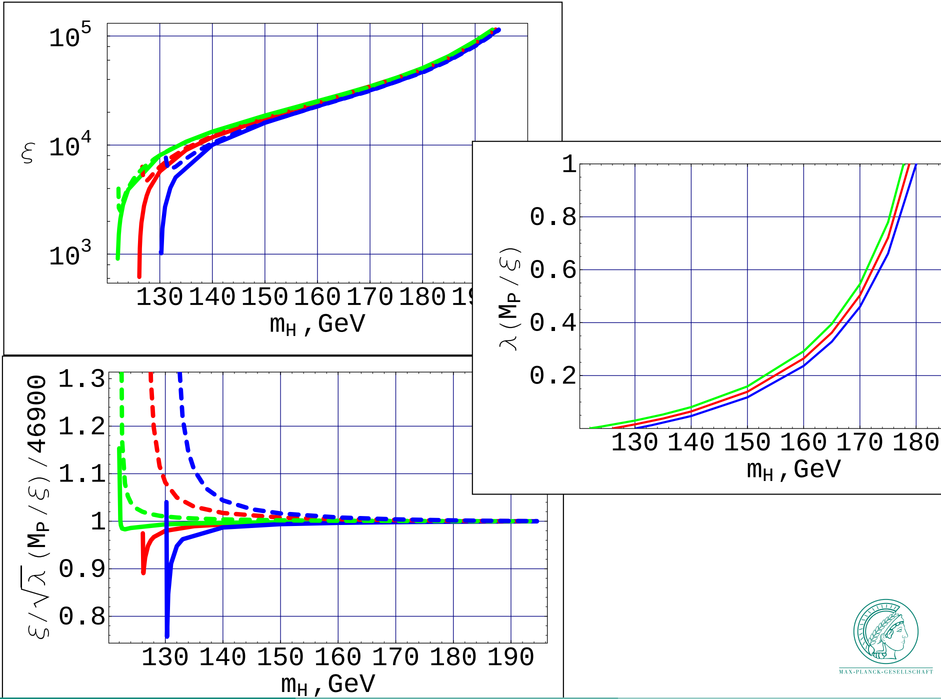
$$\mu^2 = m_t^2(\chi)$$

Spectral index–Higgs mass relation

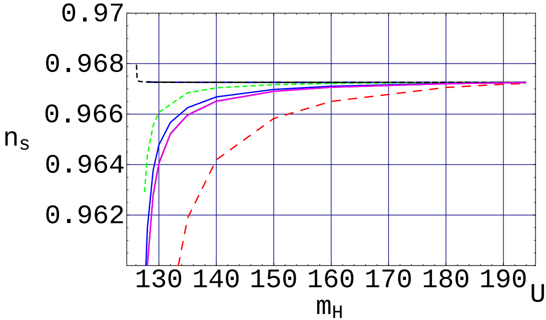


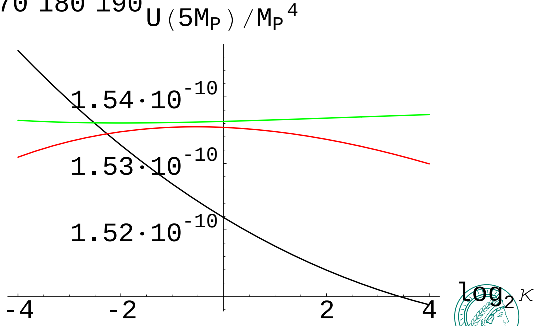
Tensor perturbations r and non minimal coupling ξ





10^5
10^4
10^3
ξ
130 140 150 160 170 180
m_H, GeV
1
0.8
0.6
0.4
0.2
$\lambda(M_P/\xi)$
130 140 150 160 170 180
m_H, GeV
1.3
1.2
1.1
1
0.9
0.8
$\xi/\sqrt{\lambda}(M_P/\xi)/46900$
130 140 150 160 170 180 190
m_H, GeV


0.97
0.968
0.966
0.964
0.962
n_s
130 140 150 160 170 180 190
m_H


$U(5M_P)/M_P{}^4$
$1.54\cdot10^{-10}$
$1.53\cdot10^{-10}$
$1.52\cdot10^{-10}$
-4 -2 2 4
$\log_2\kappa$

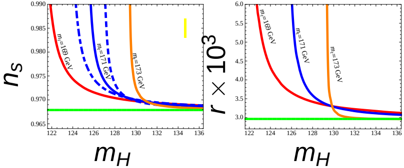
Comparison with other works

This work: $m^{II}_{\min} = \left[126.7 + \frac{m_t - 171.2}{2.1} \times 4.5 - \frac{\alpha_s - 0.1176}{0.002} \times 1.7\right] \text{GeV} \pm \delta$

[A.De Simone, M.Hertzberg, F.Wilczek'09]

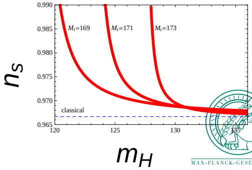
$$m_H > \left[125.7 + 3.8\left(\frac{m_t - 171\,\text{GeV}}{2\,\text{GeV}}\right) - 1.4\left(\frac{\alpha_s - 0.1176}{0.0020}\right)\right] \text{GeV} \pm \delta$$

where $\delta \sim 2\,\text{GeV}$



[A.Barvinsky, A.Kamenshchik, C.Kiefer, A.Starobinsky, C.Steinwachs'09]

$$124\,\text{GeV} < m_H < 180\,\text{GeV}$$



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Comparison with other works

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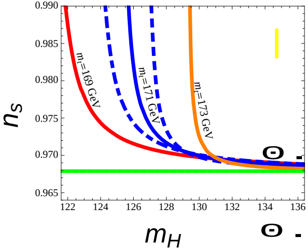
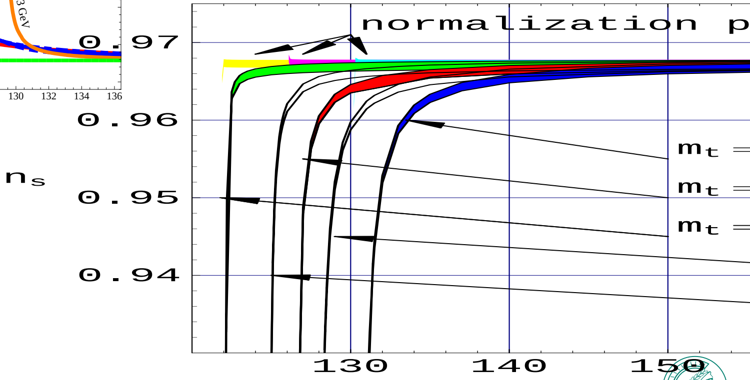
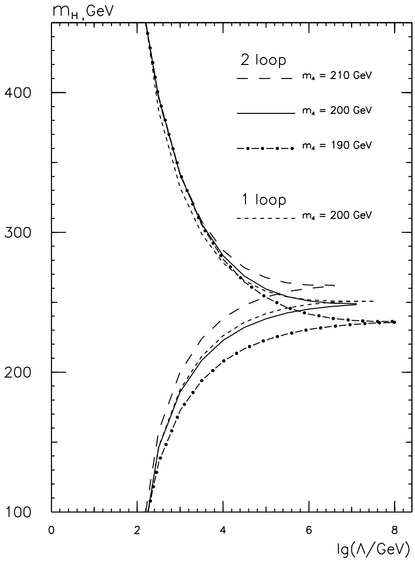


[FB, Shaposhnikov'09]



Note about fourth family



Disallowed by vacuum metastability or strong coupling before M_P.

- With three families – $m_t > 250\,\mathrm{GeV}$ means no inflation.
- PDG bound: $m_t' > 256\,\mathrm{GeV}$
- With 4 families – see picture [Pirogov Zenin'98]