

Light Inflation – Reconciling ϕ^4 Inflation with Planck and Experimental Prospects

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Outline

- 1 Minimally extending the Standard Model
- 2 ϕ^4 inflation after Planck
 - Minimally coupled inflation
 - Non-minimally coupled inflation
- 3 Coupling to the SM and cosmological constraints
 - The full model
 - Constraints from reheating and radiative corrections
- 4 Anything interesting in the laboratory?
 - Direct inflaton search
 - Is the Higgs compatible?

Standard Model of particle physics

Three Generations
of Matter (Fermions) spin $\frac{1}{2}$

	I	II	III		
mass →	2.4 MeV	1.27 GeV	171.2 GeV	0	
charge →	$\frac{2}{3}$	$\frac{2}{3}$	$\frac{2}{3}$	0	
name →	u Left up Right	c Left charm Right	t Left top Right	g gluon	
	4.8 MeV	104 MeV	4.2 GeV	0	
	$-\frac{1}{3}$	$-\frac{1}{3}$	$-\frac{1}{3}$	0	
Quarks	d Left down Right	s Left strange Right	b Left bottom Right	γ photon	
	0 eV	0 eV	0 eV	91.2 GeV	>114 GeV
	0	0	0	0	0
	ν_e Left electron neutrino Right	ν_μ Left muon neutrino Right	ν_τ Left tau neutrino Right	Z⁰ weak force	H Higgs boson
	0.511 MeV	105.7 MeV	1.777 GeV	80.4 GeV	
	-1	-1	-1	± 1	
Leptons	e Left electron Right	μ Left muon Right	τ Left tau Right	W[±] weak force	spin 0

Bosons (Forces) spin 1

Standard Model and nothing else above up to Planck scale?

- No heavy particles/scales
 - no physical high scale quadratic contributions to the Higgs boson mass
 - hierarchy problem is not that scary (however, the gravity should be generous enough not to give quadratically divergent contributions)
 - Processes at the highest energy (inflation) may be directly related to the low energy properties

Standard Model – extended for inflation

Some models that minimally expand the SM and have inflation

- Higgs inflation
 - very direct relation of inflation and SM, some subtleties with the UV properties
- R^2 inflation
 - purely gravitational solution, nothing interesting for the particle physics
- Light inflaton with non-minimal coupling
 - this talk, solution on the particle physics side

Note – the whole Universe evolution should be fully described within the model!

Standard Model – extended for inflation

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“Standard” chaotic inflation

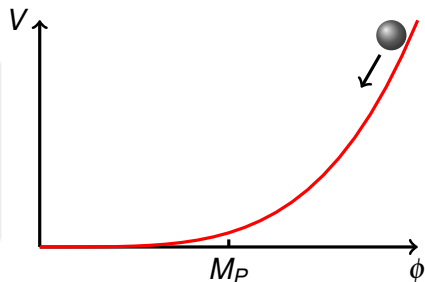
Scalar part of the action

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

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

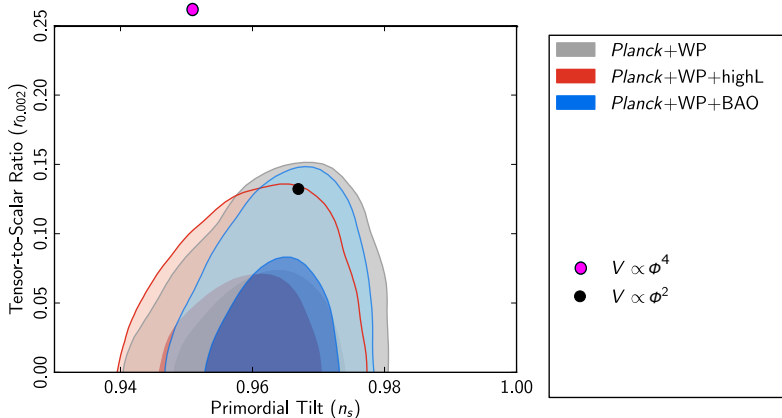
$$\beta \sim 10^{-13}$$

$$m \sim 10^{13} \text{ GeV}$$



Fields $\gtrsim M_P$, energy $\sim \lambda^{1/4} M_P$.

Planck results disfavor plain ϕ^4



Non-minimal coupling to gravity leads to good inflation

Scalar action with non-minimal coupling

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

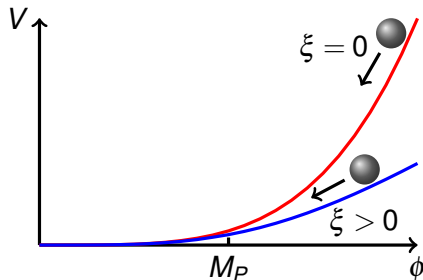
Conformal transformation to the Einstein frame

$$\hat{g}_{\mu\nu} = \sqrt{1 + \frac{\xi \phi^2}{M_P^2}} g_{\mu\nu},$$

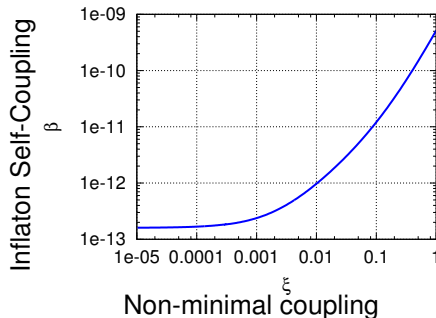
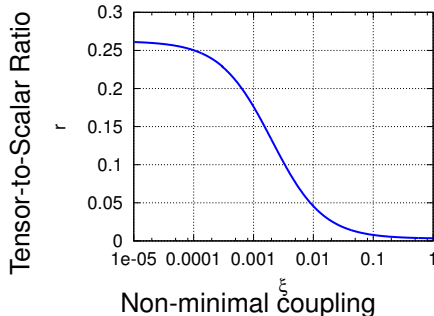
flattens the potential

$$V(\phi) \rightarrow \hat{V}(\phi) = \frac{V(\phi)}{(1 + \xi \phi^2 / M_P^2)^2}$$

(Change of the field $\frac{d\chi}{d\phi} = \sqrt{\frac{1 + (\xi + 6\xi^2)\phi^2 / M_P^2}{(1 + \xi \phi^2 / M_P^2)^2}}$ is also needed)

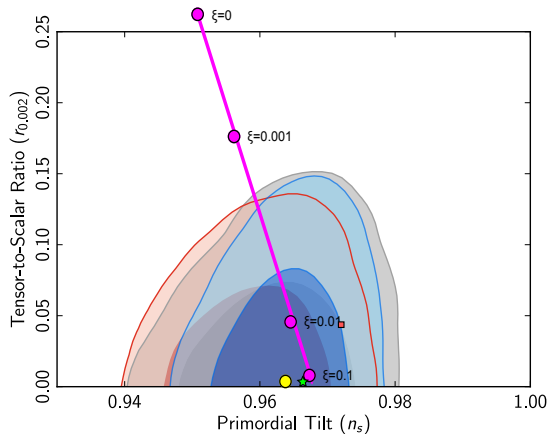


The tensor perturbations are suppressed,
inflaton self-coupling β is increased



[TsujiKawa, Gumjudpai'04, FB'08, Okada, Rehman, Shafi'10]

Inflationary predictions are ok for $\xi \gtrsim 0.003$



- Planck*+WP
- Planck*+WP+highL
- Planck*+WP+BAO

Predictions of
inflationary models:

- ★ Higgs inflation
- R^2 inflation
- $\lambda\phi^4 + \xi\phi^2 R/2$
- Non-minimal
derivative coupling

SM + Light Inflaton coupled in the Higgs sector only

$$\mathcal{L} = \underbrace{\mathcal{L}_{\text{SM}}}_{\text{Standard Model}} + \underbrace{\alpha H^\dagger H \phi^2}_{\text{Interaction}} + \underbrace{\frac{\beta}{4} \phi^4 + \frac{\xi \phi^2}{2} R}_{\text{Inflationary sector}}$$

Inflaton mass depends on interaction strength: $m_\chi = m_h \sqrt{\beta/2\alpha}$

Specifically: the Higgs-inflaton scalar potential is

$$V(H, \phi) = \lambda \left(H^\dagger H - \frac{\alpha}{\lambda} \phi^2 \right)^2 + \frac{\beta}{4} \phi^4 - \frac{1}{2} \mu^2 \phi^2 + V_0$$

We assumed here, that the scale invariance is broken *in the inflaton sector only*

[Shaposhnikov, Tkachev'06, Anisimov, Bartocci, FB'09, FB, Gorbunov'10,13]

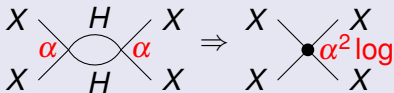
All constants of the model are bound from cosmology

CMB normalization sets
 $\beta(\xi)$

$$\beta = \frac{3\pi^2 \Delta_{\mathcal{R}}^2}{2} \frac{(1+6\xi)(1+6\xi+8(N+1)\xi)}{(1+8(N+1)\xi)(N+1)^3}$$

$\alpha \lesssim \beta^2$ (mass lower bound)

Inflation is not spoiled by the radiative corrections



CMB tensor modes bound ξ

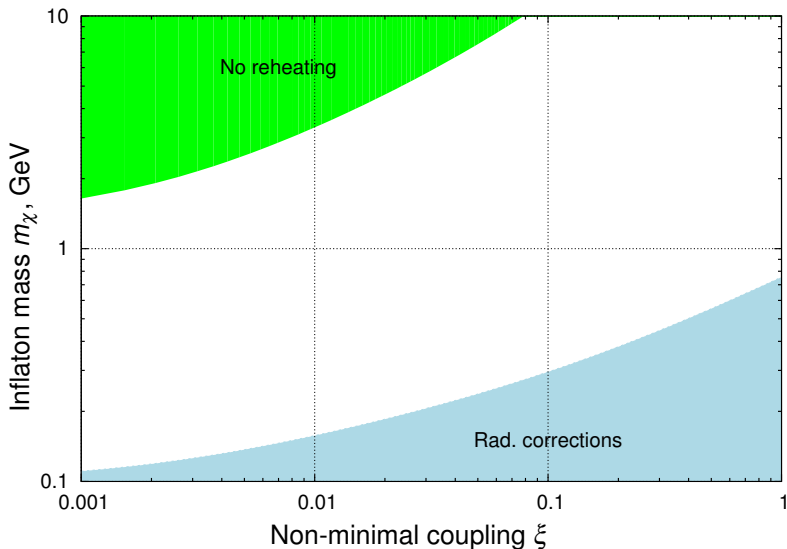
$$r = \frac{16(1+6\xi)}{(N+1)(1+8(N+1)\xi)} \lesssim 0.15$$

$\alpha > 10^{-7}$ (mass upper bound)

Sufficient reheating

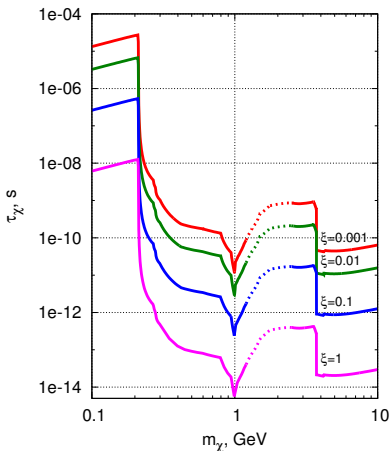
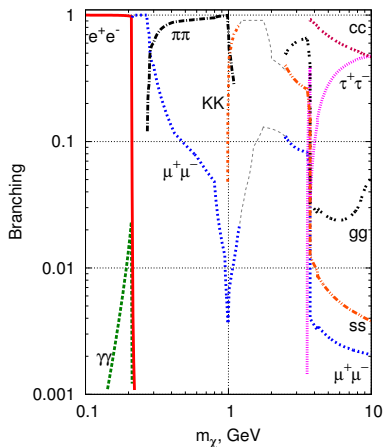
- After inflation: empty & cold
- Needed: hot,
 $T_r \gtrsim 150 \text{ GeV}$ (to get baryogenesis)

The Inflaton mass is bounded from cosmology



Inflaton decays and lifetime

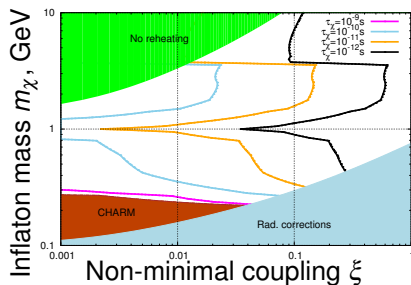
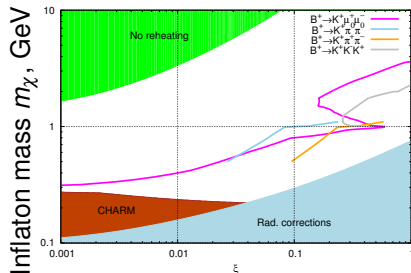
Coupled to everything proportional particle mass



Created in meson decays:

$$\text{Br}(B \rightarrow \chi X_s) \simeq 10^{-6} \frac{\beta(\xi)}{1.5 \times 10^{-13}} \frac{300 \text{ MeV}^2}{m_\chi}$$

Experimental searches are possible



Behaves as light “Higgs” boson, suppressed by $\theta = \sqrt{2\beta} v / m_\chi$

- Created in meson decays
- Decays: KK , $\pi\pi$, $\mu\mu$, ee , ...
- Interacts with media: extremely weakly

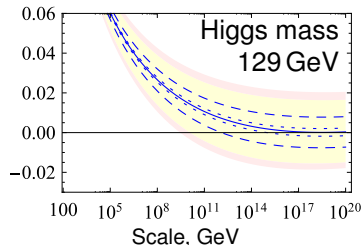
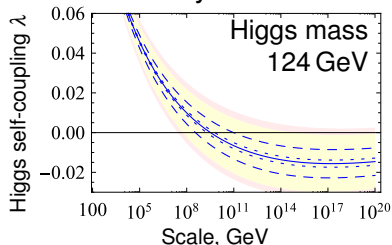
Search (LHCb, Belle)

- Events with offset vertices in B decays
- Peaks in Daltiz plot of three body B decays

Another prediction: The Higgs boson can not be light

Inflation proceeds along $H^\dagger H = \frac{\alpha}{\lambda} X^2$

- The Higgs self-coupling λ : must be positive up to inflationary scales

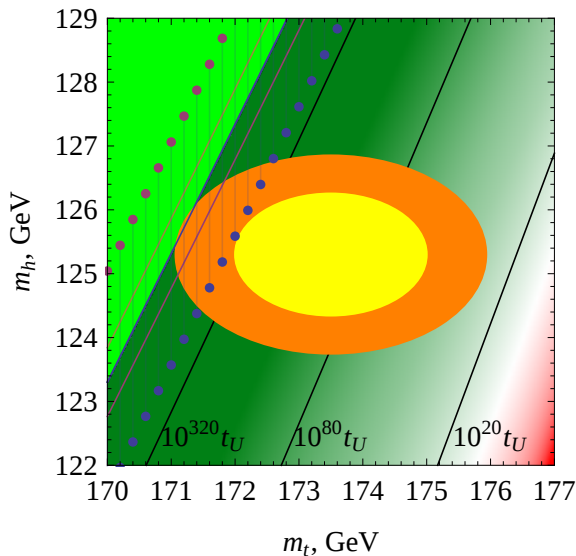


Current experimental value: $m_H = 125.7 \pm 0.4$ GeV (CMS)

Mass for $\lambda(\mu) = \beta_\lambda(\mu) = 0$

$$M_{\min} = \left[129.5 + \frac{M_t - 173.2 \text{ GeV}}{0.9 \text{ GeV}} \times 1.8 - \frac{\alpha_s - 0.1184}{0.0007} \times 0.6 \pm 2 \right] \text{ GeV}$$

Critical Higgs mass is compatible with M_t and α_s



Vacuum stability

Conclusions 1: Cosmology

- Single field quartic inflation with *small* non-minimal coupling is perfectly ok with the current CMB observations

Conclusions 2: Cosmology and Particle Physics

- An example of a model minimally extending SM without any heavy scales: a singlet scalar field with non-minimal coupling
- Cosmological observations constrain the inflaton mass to be light (in GeV range) – interesting for particle physics!
- Further study
 - Detection of tensor modes is especially interesting to constrain the theory
 - The inflaton can be searched in low energy experiments – rare B decays
 - Offset vertices in B decays
 - Peaks in B three body decay Dalitz plot
 - Higgs mass bounds – top quark mass measurement is needed!

Backup slides

Three Generations of Matter (Fermions) spin $\frac{1}{2}$

	I	II	III	
mass --	2.4 MeV	1.27 GeV	171.2 GeV	
charge -- $\frac{2}{3}$	u	c	t	g
name --	up	charm	top	gluon
	d	s	b	γ
	down	strange	bottom	photon
	ν_e	ν_μ	ν_τ	Z⁰
	electron neutrino	muon neutrino	tau neutrino	weak force
	N₁	N₂	N₃	H
	sterile neutrino	sterile neutrino	sterile neutrino	Higgs boson
	e	μ	τ	W[±]
	electron	muon	tau	weak force

Quarks

Leptons

Bosons (Forces) spin 1

spin 0

$N_{2,3}$ Baryogenesis, $M_{2,3} \sim \dots \text{GeV}$

Dark matter – add ν MSM and stir

A ν MSM inspired model with inflation χ

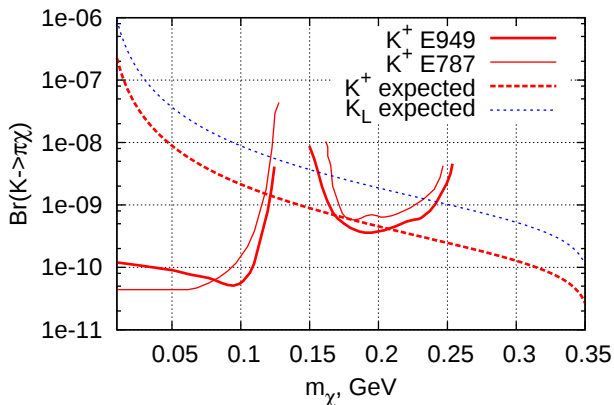
$$\mathcal{L} = (\mathcal{L}_{SM} + \bar{N}_I i \partial_\mu \gamma^\mu N_I - F_{\alpha I} \bar{L}_\alpha N_I \Phi - \frac{f_I}{2} \bar{N}_I^c N_I X + \text{h.c.}) + \frac{1}{2} (\partial_\mu X)^2 - V(\Phi, X)$$

$$\Omega_N = \frac{1.6 f(m_\chi)}{S} \cdot \frac{\beta}{1.5 \times 10^{-13}} \cdot \left(\frac{M_1}{10 \text{keV}} \right)^3 \cdot \left(\frac{100 \text{ MeV}}{m_\chi} \right)^3 ,$$

DM sterile neutrino mass bound

$$M_1 \lesssim 13 \cdot \left(\frac{m_\chi}{300 \text{ MeV}} \right) \left(\frac{S}{4} \right)^{1/3} \cdot \left(\frac{0.9}{f(m_\chi)} \right)^{1/3} \text{ keV} .$$

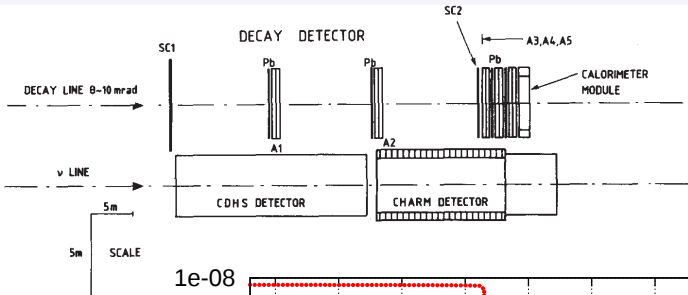
Production: bound from $K^+ \rightarrow \pi^+ + \text{nothing}$



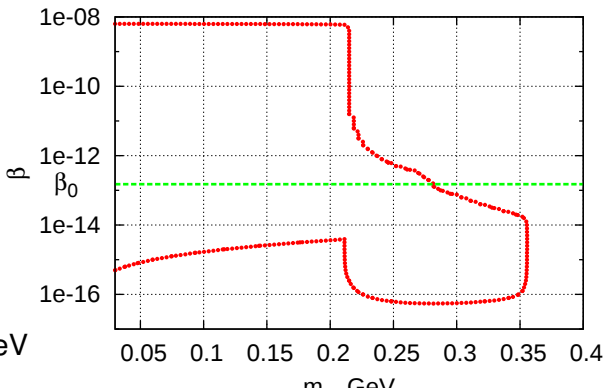
Excluded: $m_\chi \lesssim 120 \text{ MeV}$

Disfavoured: $170 \text{ MeV} \lesssim m_\chi \lesssim 205 \text{ MeV}$

CHARM – bound



Search
for
decays of
some-
thing into
 $\gamma\gamma, e^+e^-,$
 $\mu^+\mu^- \Rightarrow$
 $m_\chi < 270 \text{ MeV}$





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