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

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Outline

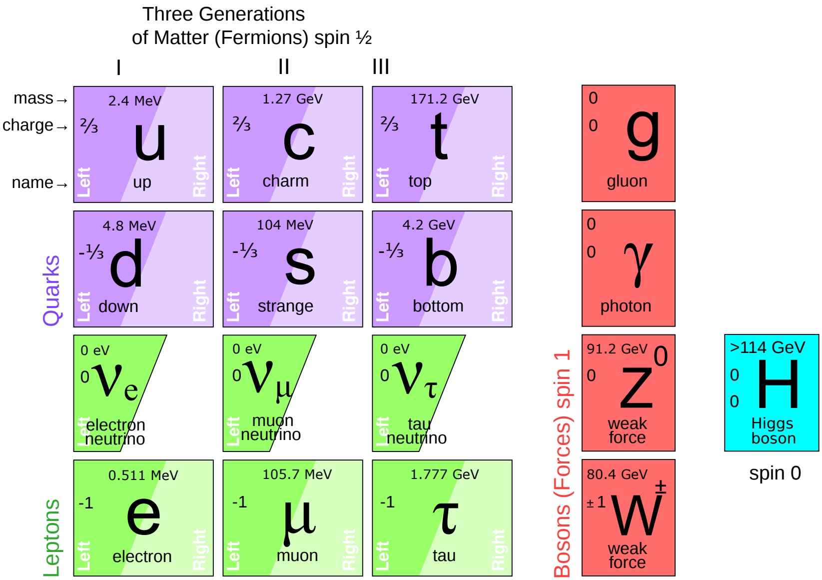
1. Minimally extending the Standard Model

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



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!

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"Standard" chaotic inflation

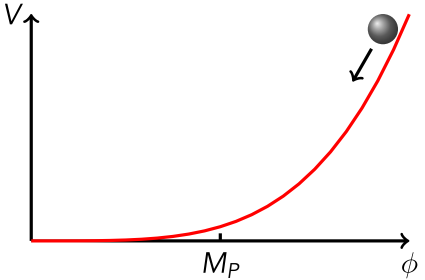
Scalar part of the action

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

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

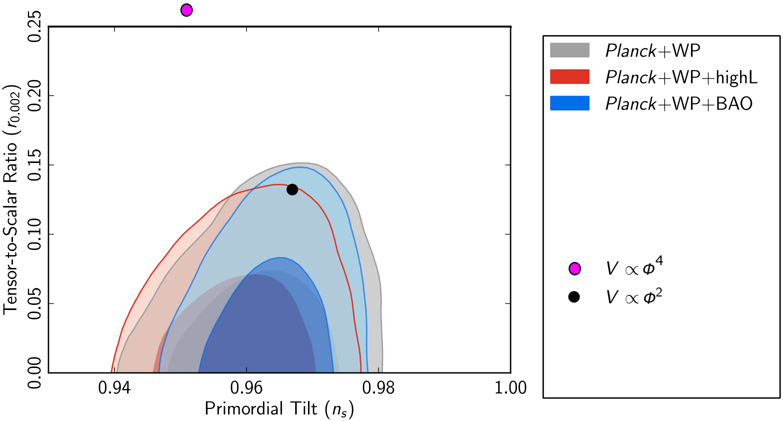
$$\beta \sim 10^{-13}$$

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



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

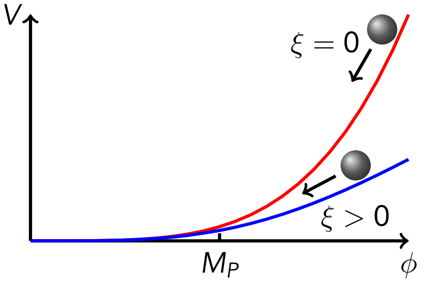
$$S = \int d^4x\sqrt{-g}\left\{ -\frac{M_P^2}{2}R - \frac{\xi}{2}\phi^2 R + \frac{\partial_\mu\phi\partial^\mu\phi}{2} - \frac{\lambda}{4}\phi^4 \right\}$$

Conformal transformation to the Einstein frame

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

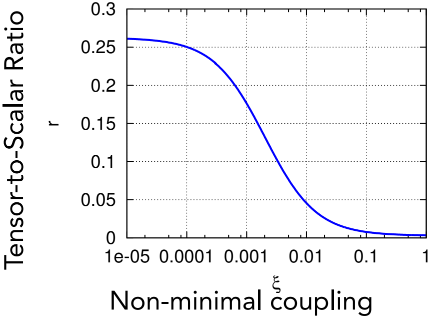
flattens the potential

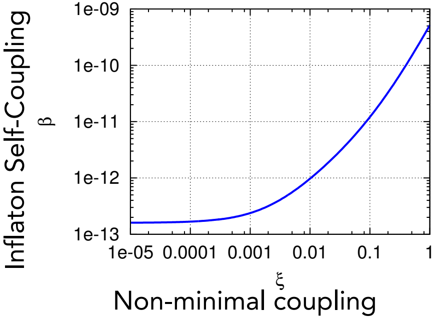
$$V(\phi) \to \hat{V}(\phi) = \frac{V(\phi)}{\left(1 + \xi\phi^2/M_P^2\right)^2}$$



(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)

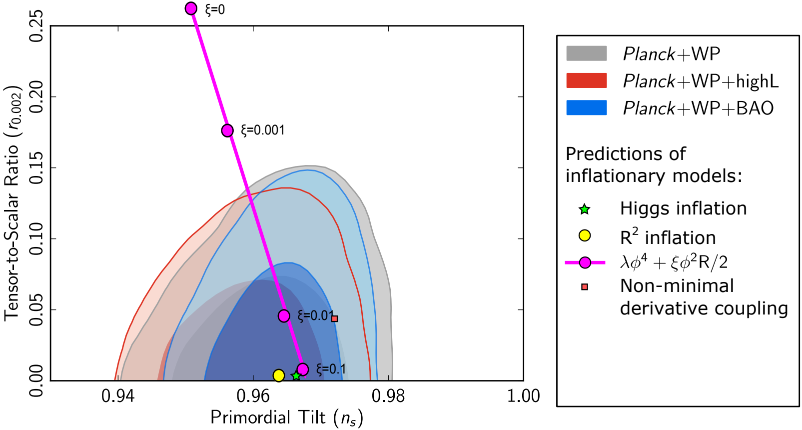
The tensor perturbations are suppressed, inflaton self-coupling β is increased





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

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



SM + Light Inflaton coupled in the Higgs sector only

$$\mathcal{L} = \mathcal{L}_{SM} + \alpha H^\dagger H \phi^2 + \frac{\beta}{4}\phi^4 + \frac{\xi\phi^2}{2}R$$

Standard Model | Interaction | 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 $\beta(\xi)$

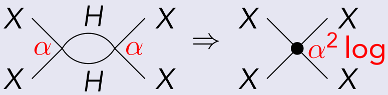
$$\beta = \frac{3\pi^2 \Delta_{\mathcal{R}}^2}{2} \frac{(1+6\xi)(1+6\xi+8(N+1)\xi)}{(1+8(N+1)\xi)(N+1)^3}$$

CMB tensor modes bound ξ

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

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

Inflation is not spoiled by the radiative corrections



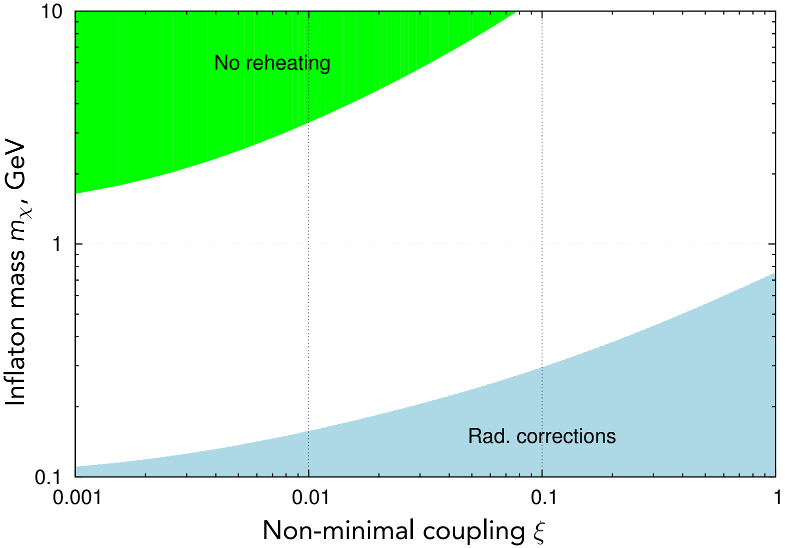
$\alpha > 10^{-7}$ (mass upper bound)

Sufficient reheating

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

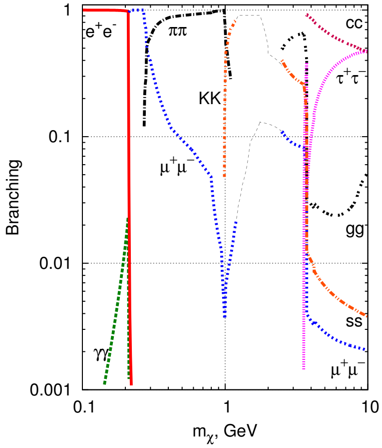
[Anisimov, Bartocci, FB'09]

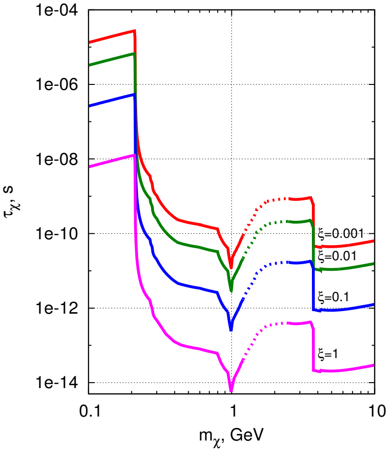
The Inflaton mass is bounded from cosmology



Inflaton decays and lifetime

Coupled to everything proportional particle mass

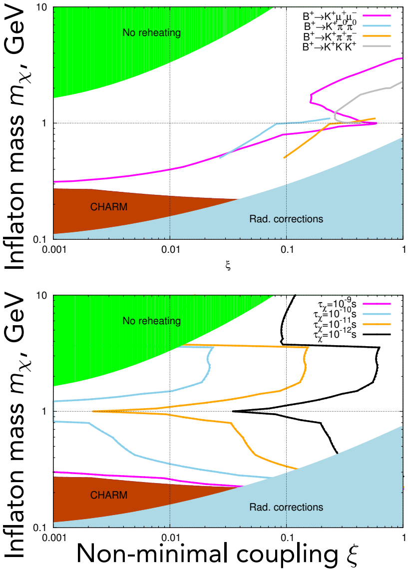




Created in meson decays:

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

Experimental searches are possible



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

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

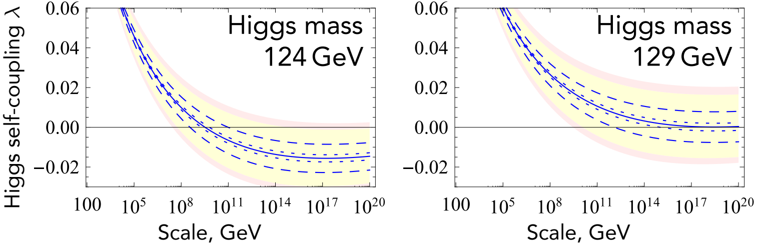
Search (LHCb, Belle)

- 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



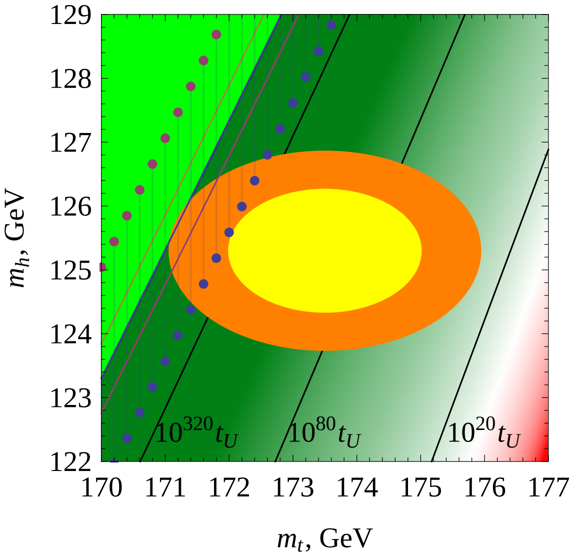
Current experimental value: $m_H = 125.7 \pm 0.4\,\text{GeV}$ (CMS)

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

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

[FB, Kalmykov, Kniehl, Shaposhnikov'12, Degrassi et.al'12]

Critical Higgs mass is compatible with M_t and α_s



Vacuum stability

Conclusions 1: Cosmology

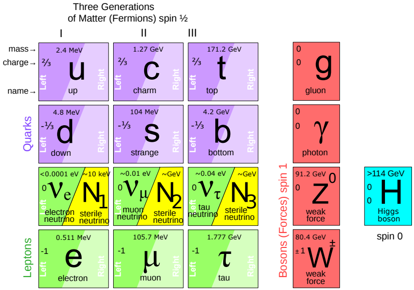
- Single filed quartic inflation with *small* non-minimal coupling is perfectly ok with the current CMB observations

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

Dark matter – add νMSM and stir



Role of sterile neutrinos

N_1 (Warm) Dark Matter, $M_1 \sim$ 1–50 keV

$N_{2,3}$ Baryogenesys, $M_{2,3} \sim \ldots$GeV

http://arxiv.org/abs/hep-ph/0505013

Dark matter – add νMSM and stir

A νMSM inspired model with inflation χ

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

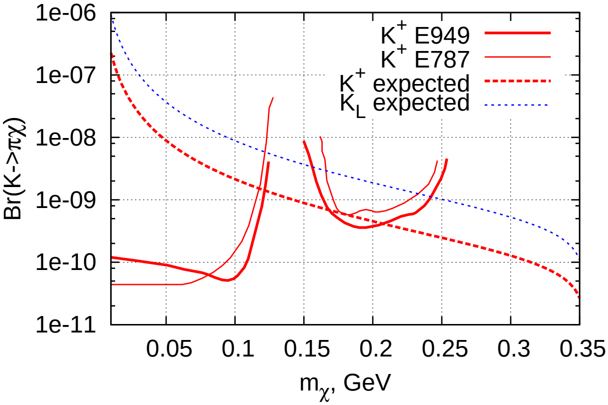
$$\Omega_N = \frac{1.6 f(m_\chi)}{S} \cdot \frac{\beta}{1.5\times 10^{-13}} \cdot \left(\frac{M_1}{10\text{keV}}\right)^3 \cdot \left(\frac{100\text{ MeV}}{m_\chi}\right)^3 ,$$

DM sterile neutrino mass bound

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

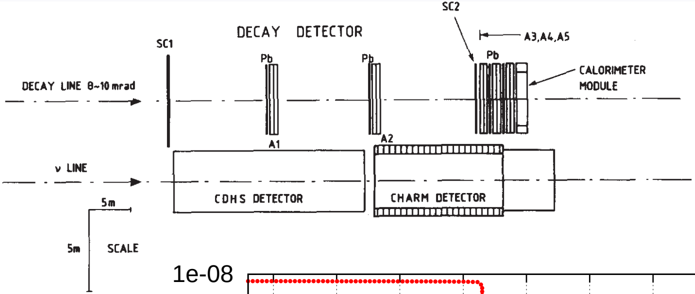
[Shaposhnikov, Tkachev'06, FB, Gorbunov'10,13]

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

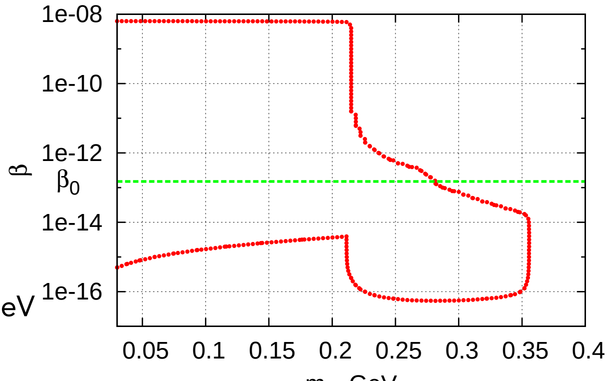


Excluded: $m_\chi \lesssim 120$ MeV
Disfavoured: $170 \text{ MeV} \lesssim m_\chi \lesssim 205$ MeV

CHARM – bound



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



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