Light inflaton – cosmology and experiments

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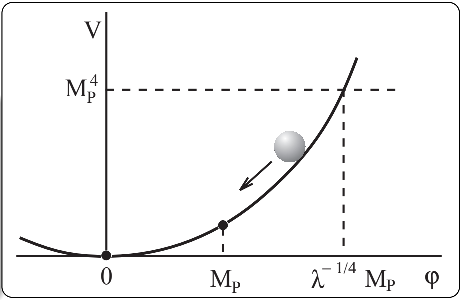
A.Anisimov, Y.Bartocci, F.B. Phys.Lett.B671(2009)211

Outline

1. Inflationary model
2. Bounds from cosmology
   - How not to spoil inflation – radiative corrections
   - How to reheat the Universe
3. How to detect the inflaton
   - Inflaton particle properties
   - Production in meson decays
   - Decays of the inflaton
4. Conclusions

"Standard" chaotic inflation



Scalar field

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

quartic coupling: $\lambda \sim 10^{-13}$

mass: $m \sim 10^{13}$ GeV

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

- Inflaton/inflationary scale – heavy/large, 10^{13} GeV
  - Effects suppressed at low scale
- Inflationary scale low
  - Potential should be *very* flat
  - Either radiative corrections spoil flatness
  - Either no coupling with SM (no signatures, and no reheating)

Good theory with light inflaton?

- Can we construct a theory with the following properties:
  - Renormalisable
  - Explains usual chaotic inflation
  - Has only particles at or below electroweak scale
  - Leads to good Hot Big Bang afterwards
- Ideally, it should also explain everything else
  - Neutrino masses
  - Baryon asymmetry of the Universe
  - Dark Matter

Yes!

- And it can be searched for in experiments

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  } Will not have time today

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Light inflaton model

Add a singlet scalar X to SM, mixed with the Higgs H via the scalar potential

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

$$\langle H\rangle = \frac{v}{\sqrt{2}}\,, \quad \langle X\rangle = \sqrt{\frac{\lambda}{2\alpha}}v = \frac{m_\chi}{\sqrt{2\beta}}$$

Mass spectrum: $m_h = \sqrt{2\lambda}\,v\,, \quad m_\chi = m_h\sqrt{\frac{\beta}{2\alpha}}$

Excitations are rotated with respect to the gauge basis $(\sqrt{2}H - v, X)$ by the angle

$$\theta = \sqrt{\frac{2\alpha}{\lambda}} = \frac{\sqrt{2\beta}\,v}{m_\chi}$$

$\beta \simeq \beta_0 = 1.5\times 10^{-13}$ – inflationary requirement

Note Add three sterile neutrinos to explain DM, BAU, ν masses...

Radiative corrections to the inflationary potential

For each species of mass $m(X)$ in the inflaton background X

$$\delta V = \frac{m^4(X)}{64\pi^2} \log \frac{m^2(X)}{\mu^2}$$

We need all this to be smaller, than

$$V_{\text{inflaton}} = \frac{\beta}{4} X^4$$

For example, for the Higgs boson $m^2(X) = 4\alpha X^2$, thus

$$\alpha \lesssim 10^{-7} \qquad \text{(roughly: } \alpha < \sqrt{\beta}\text{)}$$

Lower bound for the inflaton mass

$$m_\chi > 120 \left(\frac{m_h}{150\ \text{GeV}}\right) \left(\frac{\beta}{1.5\times 10^{-13}}\right)^{\frac{1}{2}} \text{ MeV}$$

How to reheat the Universe after inflation?

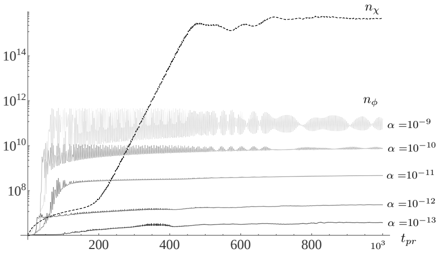
- After inflation: empty & cold
- Needed: hot, $T_r > 150$ GeV (to get baryogenesis, eg. via leptogenesis)

The estimate:

- Require, that at $T_r \sim 150$ GeV $\chi\chi \to HH$ process enters thermal equilibrium

$$\alpha \gtrsim 7 \times 10^{-10}$$

Parametric resonance?
Not so easy to create the Higgs



The large Higgs self interaction destroys coherence and spoils parametric resonance.

Inflaton mass window

Flatness from radiative corrections

$$m_\chi > 120 \left(\frac{m_h}{150\ \ \mathrm{GeV}}\right) \left(\frac{\beta}{1.5\times 10^{-13}}\right)^{\frac{1}{2}}\ \mathrm{MeV}$$

Sufficient reheating

$$m_\chi \leq 1.5 \left(\frac{m_H}{150\,\mathrm{GeV}}\right) \left(\frac{\beta}{1.5\times 10^{-13}}\right)^{\frac{1}{2}}\ \mathrm{GeV}$$

To be precise, the window also exists

$$2m_H < m_\chi \lesssim 460 \cdot \left(\frac{m_h}{150\ \ \mathrm{GeV}}\right)^{4/3} \cdot \left(\frac{\beta}{1.5\times 10^{-13}}\right)^{1/3}\ \mathrm{GeV}$$

Inflaton-SM Interactions

Just like the Higgs boson, but light and suppressed by $\theta = \sqrt{2\beta} v / m_\chi$

- Created: in meson decays
- Decays: into the heaviest particles allowed (ee, $\pi\pi$, $\mu\mu$, KK)
- Interacts with media: extremely weakly

$$\mathscr{L}_{\chi\bar{f}f} = \theta \frac{m_f}{v} \chi \bar{f} f = \sqrt{2\beta} \frac{m_f}{m_\chi} \chi \bar{f} f$$

details

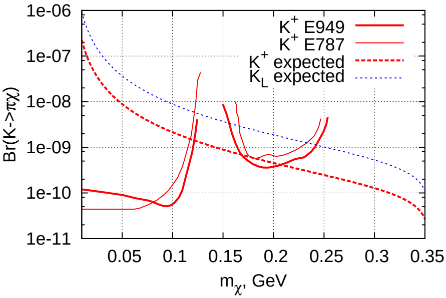
$$\mathscr{L}_{\chi\pi\pi} = 2\kappa\sqrt{2\beta} \cdot \frac{\chi}{m_\chi} \cdot \left(\frac{1}{2} \partial_\mu \pi^0 \partial^\mu \pi^0 + \partial_\mu \pi^+ \partial^\mu \pi^- \right)$$

$$- (3\kappa + 1)\sqrt{2\beta} \cdot \frac{\chi}{m_\chi} \cdot m_\pi^2 \cdot \left(\frac{1}{2} \pi^0 \pi^0 + \pi^+ \pi^- \right) \qquad (\kappa = 2/9)$$

$$\mathscr{L}_{\chi\gamma\gamma} \approx \frac{F_{\gamma\gamma}\alpha}{4\pi} \frac{\sqrt{2\beta}}{m_\chi} \chi F_{\mu\nu} F^{\mu\nu} \qquad \mathscr{L}_{\chi gg} \approx \frac{F_{gg}\alpha_s}{4\sqrt{8}\pi} \frac{\sqrt{2\beta}}{m_\chi} \chi G^a_{\mu\nu} G^{a\mu\nu}$$

Production: hadron decays

$$\left.\begin{aligned} \mathrm{Br}\,(K^+ \to \pi^+\chi) &\approx 2.3\times 10^{-9} \\ \mathrm{Br}\,(K_L \to \pi^0\chi) &\approx 1.0\times 10^{-8} \\ \mathrm{Br}\,(\eta \to \pi^0\chi) &\approx 1.8\times 10^{-12} \\ \mathrm{Br}\,(B \to X_s\chi) &\approx 10^{-5} \end{aligned}\right\} \times \left(\frac{\beta}{\beta_0}\right)\cdot\left(\frac{100\text{ MeV}}{m_\chi}\right)^2\cdot k\left(\frac{m_\chi}{m_{hadron}}\right)$$



Bound from $K^+ \to \pi^+ + \text{nothing}$

Excluded: $m_\chi \lesssim 120$ MeV

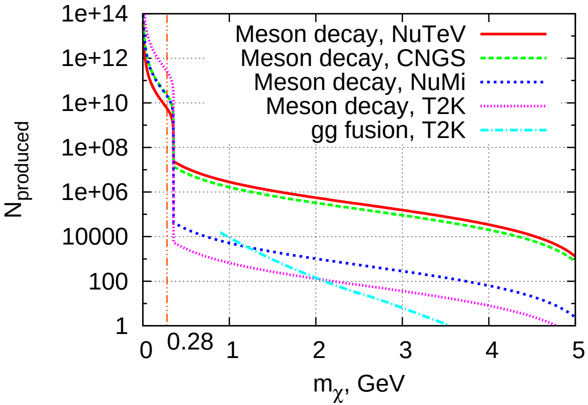
Disfavoured:

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

Next bound – NA62?

Production: beam dump, ideal luminosity

Number of inflatons produced (via meson decays) during one year of operation[1]

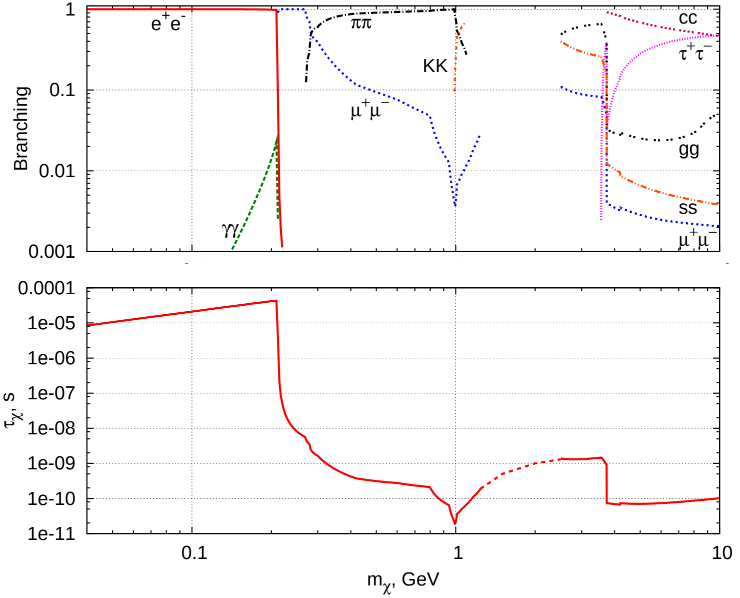


	E, GeV
NuTeV	800
CNGS	400
NuMi	120
T2K	50

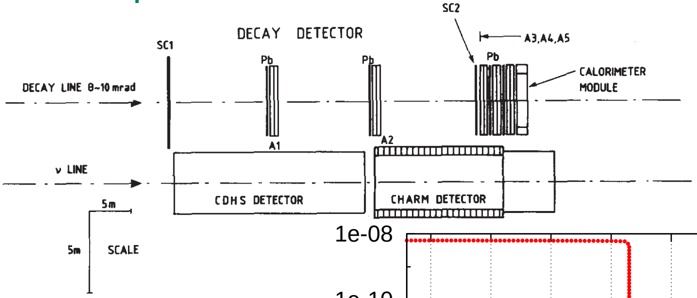
	N_{POT}, 10^{19}
NuTeV	1
CNGS	4.5
NuMi	5
T2K	100

[1] no geometric factors, particle separation, etc.

Inflaton decays and lifetime

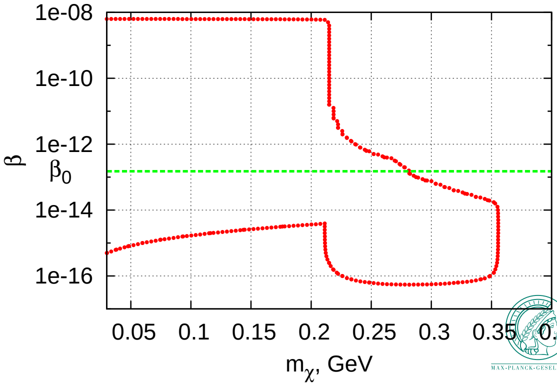


Beam dump: CHARM bound



Search for decays of something into $\gamma\gamma$, e^+e^-, $\mu^+\mu^- \Longrightarrow$

$m_\chi < 270$ MeV



Production: search in B decays

$$\left.\begin{aligned} \mathrm{Br}(K^+ \to \pi^+\chi) &\approx 2.3\times 10^{-9} \\ \mathrm{Br}(K_L \to \pi^0\chi) &\approx 1.0\times 10^{-8} \\ \mathrm{Br}(\eta \to \pi^0\chi) &\approx 1.8\times 10^{-12} \\ \mathrm{Br}(B \to X_s\chi) &\approx 10^{-5} \end{aligned}\right\} \times \left(\frac{\beta}{\beta_0}\right)\cdot\left(\frac{100\text{ MeV}}{m_\chi}\right)^2 \cdot k\left(\frac{m_\chi}{m_{hadron}}\right)$$

- Inflaton is produced quite abundant in *B* decays
- With typical lifetime of 10^{-9} s it decays at some distance but inside the detector
- Search for events with offset vertex in b-factories – BaBar, Belle
- LHCb !

Conclusions

- A model with light inflaton and no scales above electroweak scale up to inflation can explain cosmology and searched for in experiments
- It has light particle (inflaton) 0.12 GeV $< m_\chi <$ 1.8 GeV
- The inflaton can be searched in low energy experiments
  - Meson rare decays (Kaon or B-meson)
  - Inflaton decays if created in beam dump
- It is already bound by existing experiments (CHARM) with $m_\chi >$ 270 MeV
- Search for it! (NA62, LHCb)

Dark matter – add νMSM and stir

A νMSM inspired model with inflation χ (Shaposhnikov&Tkachev'06)

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

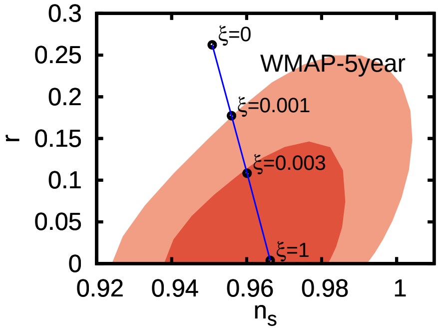
$$\Omega_N = \frac{1.6 f(m_\chi)}{S} \cdot \frac{\beta}{1.5\times 10^{-13}} \cdot \left(\frac{M_1}{10\text{keV}}\right)^3 \cdot \left(\frac{100\text{ MeV}}{m_\chi}\right)^3 ,$$

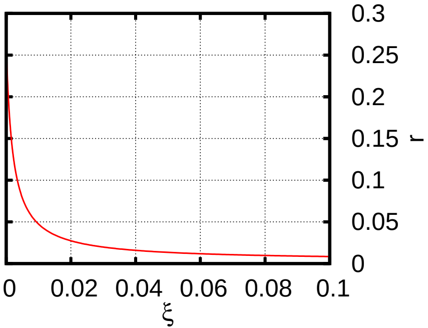
DM sterile neutrino mass bound

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

Return

WMAP-5 bounds





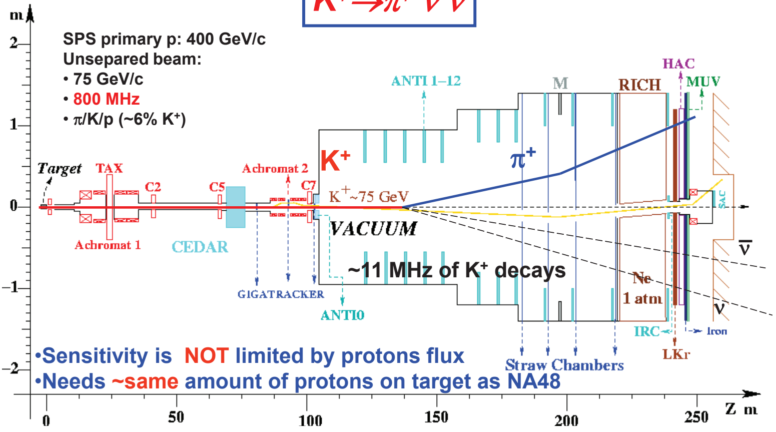
Message

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

Return

Proposed Detector Layout

$K^+ \to \pi^+ \nu \bar{\nu}$



•Sensitivity is **NOT** limited by protons flux

•Needs ~same amount of protons on target as NA48

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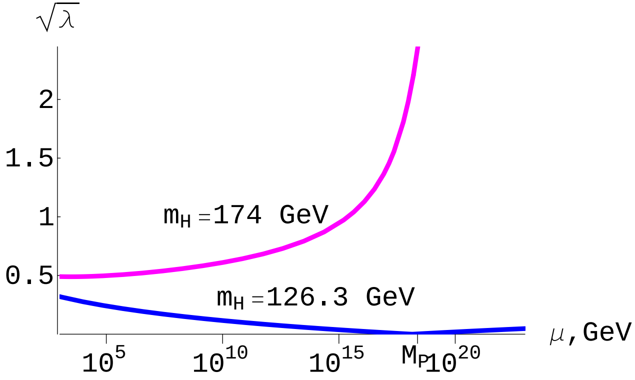
Side note – Higgs mass

SM should be good at least up to $H|_{\text{during inflation}} \sim \sqrt{\frac{\alpha}{\lambda}} M_P$



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

(or a bit wider, but be careful at the boundaries, as always)

Parametric enchancement

Let us suppose again that there is an inflaton X coupled to some particle ϕ. Then, during inflaton oscillations, for the ϕ modes with momentum k we have

$$\ddot{\phi}_k + 3H\dot{\phi}_k + \left(\frac{k^2}{a^2(t)} + g^2 X(t)^2\right)\phi_k = 0$$

- Important – $X(t)$ oscillates
- Let us neglect the Universe expansion, and say that $X(t) = A\sin(\omega t)$, then

Mathieu equation

$$\frac{d^2\phi_k}{d\eta^2} + (A_k - 2q\cos 2\eta) = 0$$

where $A_k = k^2/\omega^2 + 2q$, $q = g^2 X_0^2/4\omega^2$, $\eta = \omega t$.

Return

Temperature estimate for the reheating

Equating mean free path $n\sigma_{2l\to 2H}v \sim n\frac{\alpha^2}{\pi p_{\text{avg}}^2}$ with the Hubble rate $H = \frac{T^2}{m_{\text{Pl}}}\sqrt{\frac{\pi^2 g_*}{90}}$ we get

$$T_R \approx \frac{\zeta(3)\alpha^2}{\pi^4}\sqrt{\frac{90}{g_*}}m_{\text{Pl}}$$

Requiring $T_R > 150\,\text{GeV}$ we can obtain the lower bound on α

$$\alpha \geq 7.3 \times 10^{-8}\,,$$

Return

Temperature estimate for the reheating II

However, $p_{\rm avg} \propto T$, the cross-section is enhanced, so

$$\frac{\zeta(3)\alpha^2}{\pi^3}\frac{T^4}{p_{\rm avg}^3} \sim \frac{T^2}{\sqrt{\frac{90}{8\pi^3 g^*}}M_{Pl}}$$

For this estimate the bound is *weaker*

$$\alpha \geq 7\times 10^{-10}$$

Upper bound for the inflaton mass

$$m_\chi \leq 1.5\left(\frac{m_H}{150\,\mathrm{GeV}}\right)\sqrt{\frac{\beta}{1.5\times 10^{-13}}}\,\mathrm{GeV}$$

Return

MAX-PLANCK-GESELLSCHAFT

$\kappa = 2N_h/3b = 2/9$ where $N_h = 3$ is the number of heavy flavours, $b = 9$ is the first coefficient in the QCD beta function without heavy quarks

$$F_{\gamma\gamma} = F_W + \sum_{f,\text{colors}} q_f^2 F_f \tag{1}$$

$$F_W = 2 + 3y\left[1 + (2-y)x^2\right] \tag{2}$$

$$F_f = -2y\left[1 + (1-y)x^2\right]$$

and $y = 4m^2/m_\chi^2$, m – mass of the contributing particle

$$x = \text{Arctan}\frac{1}{\sqrt{y-1}}\,,\ \text{for } y > 1$$

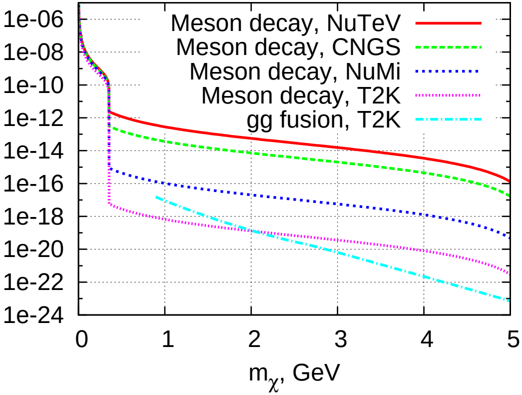
$$x = \frac{1}{2}\left(\pi + i\log\frac{1+\sqrt{1-y}}{1-\sqrt{1-y}}\right)\,,\ \text{for } y < 1$$

$F_{gg} = \sum_f F_f$, with sum only over quarks

Return

Production: beam dump

$$\frac{\sigma}{\sigma_{pp,\text{total}}} = M_{pp}\Big(\chi_s(0.5\,\text{Br}(K^+ \to \pi^+\chi) + 0.25\,\text{Br}(K_L \to \pi^0\chi)) + \chi_c\,\text{Br}(B \to \chi X_s)\Big)$$



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