Light Inflation – ϕ^4 Inflation After Planck and Possible Search on Colliders

based on F.B., D.Gorbunov arXiv:1303.4395
F.B., D.Gorbunov JHEP 1005 (2010) 010
A.Anisimov, Y.Bartocci, F.B. Phys.Lett.B671(2009)211

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Outline

Minimal models are good

No new *physical* scales (massive particles) above electroweak scale – no problems with "quadratic divergences"

Minimal models:

- No new scales
- Minimal number of new particles
- Should explain all experimental data
  - Neutrino masses
  - Dark Matter
  - Baryon Asymmetry
  - Inflation
  - Dark Energy

(Neutrino masses, Dark Matter, Baryon Asymmetry) } sterile neutrinos (νMSM)

- May link particle physics directly to inflation

"Standard" chaotic inflation

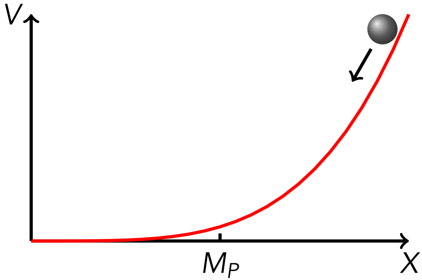
Scalar part of the action

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

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

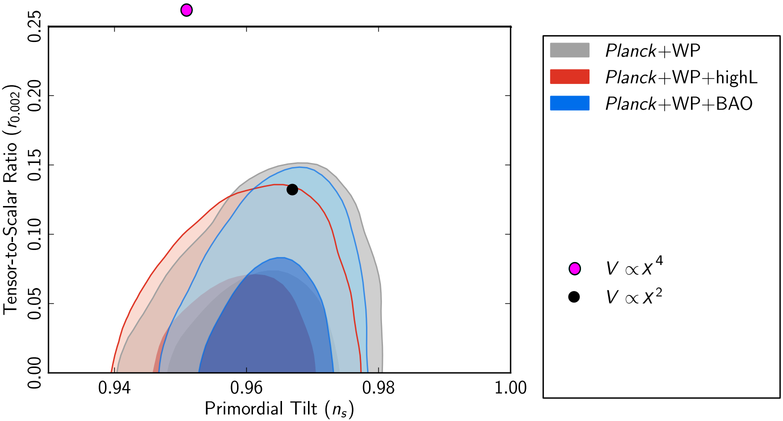
$$\beta \sim 10^{-13}$$

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



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

Planck results disfavor plain X^4



Non-minimal coupling to gravity leads to good inflation

Scalar action with non-minimal coupling

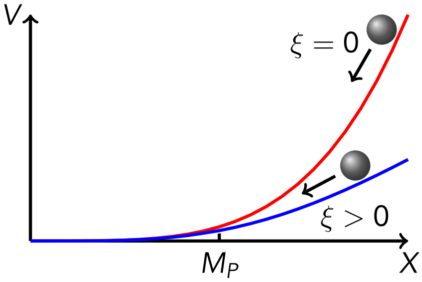
$$S = \int d^4x\sqrt{-g}\left\{ -\frac{M_P^2}{2}R - \frac{\xi}{2}X^2 R + \frac{\partial_\mu X \partial^\mu X}{2} - \frac{\lambda}{4}X^4 \right\}$$

Conformal transformation to the Einstein frame

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

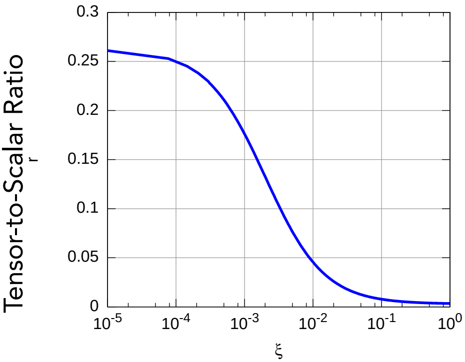
flattens the potential

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

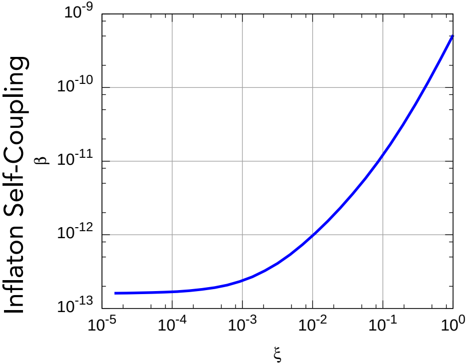


(Change of the field $\frac{d\chi}{dX} = \sqrt{\frac{1+(\xi+6\xi^2)X^2/M_P^2}{(1+\xi X^2/M_P^2)^2}}$ is also needed)

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

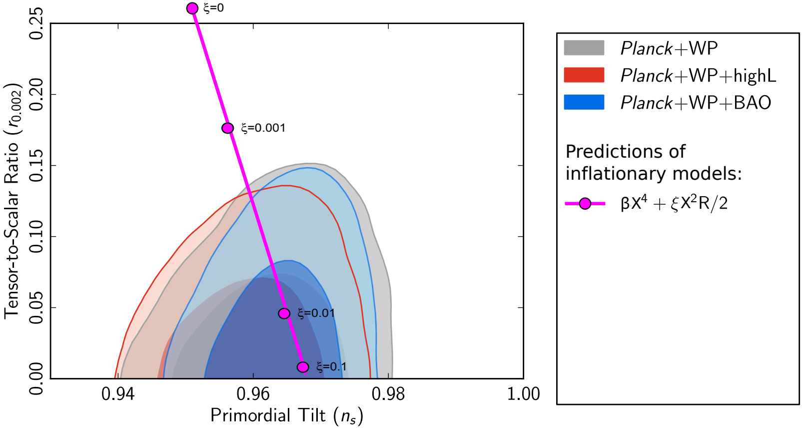


Non-minimal coupling



Non-minimal coupling

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



SM + Light Inflaton coupled in the Higgs sector only

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

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

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

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

[Anisimov, Bartocci, FB'09, FB, Gorbunov'10, FB, Gorbunov'13]

Inflaton is in the experimentally explorable range

CMB normalization sets $\beta(\xi)$

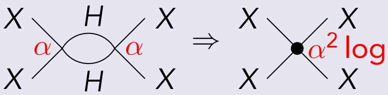
$$\beta = \frac{3\pi^2\,\Delta_{\mathcal{R}}^2}{2}\,\frac{(1+6\xi)(1+6\xi+8(N+1)\xi)}{(1+8(N+1)\xi)(N+1)^3}$$

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



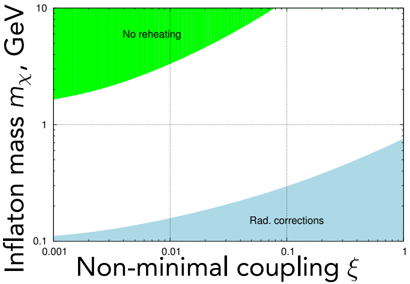
$\alpha > 10^{-7}$ (mass upper bound)

Sufficient reheating

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

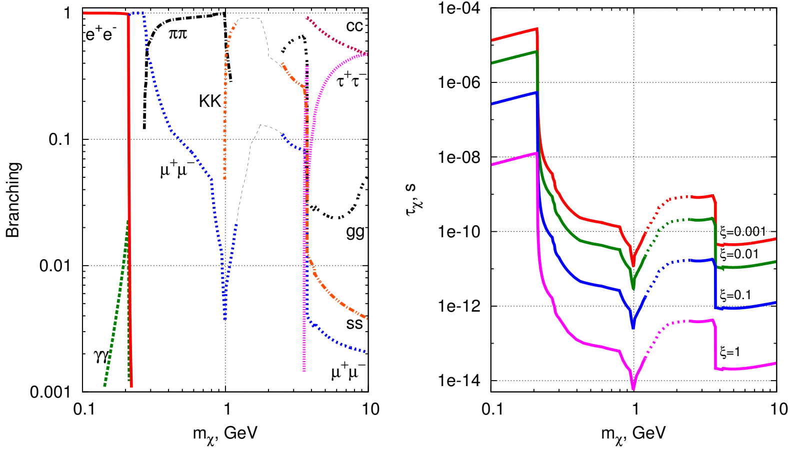
[Anisimov, Bartocci, FB'09]

The Inflaton mass is bounded from cosmology



Inflaton decays and lifetime

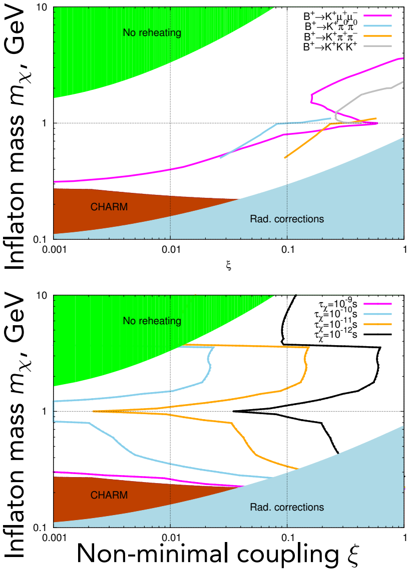
Coupled to everything proportional particle mass



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

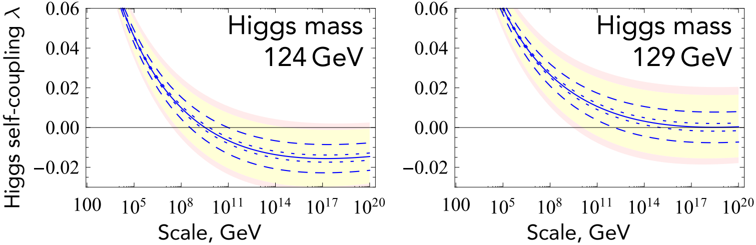
Search (LHCb, Belle)

- 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: positive up to inflationary scales



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

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

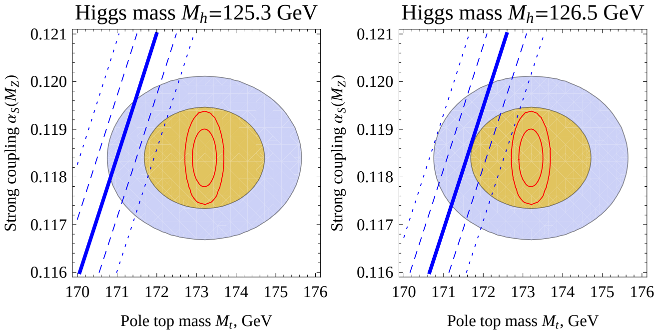
$$M_{\text{min}} = \left[129.5 + \frac{M_t - 173.2\text{GeV}}{0.9\text{GeV}} \times 1.8 - \frac{\alpha_s - 0.1184}{0.0007} \times 0.6 \pm 2\right] \text{GeV}$$

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

Critical Higgs mass is compatible with M_t and α_s

Tevatron value: $M_t = 173.2 \pm 0.6(\text{stat}) \pm 0.8(\text{syst})\text{GeV}$

$\alpha_s(M_Z) = 0.1184 \pm 0.0007$



- Coincidence? Given parameters at EW scale: M_h, M_t, α_s, G_F, α, $\sin\theta_W$ you get: $\lambda = \beta_\lambda = 0$ at exactly Planck scale.

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[FB, Kalmykov, Kniehl, Shaposhnikov'12]

Conclusions

- There is a good model with light inflaton and no scales up to inflation
- Cosmological observations constrain the inflaton mass to be light (in GeV range)
- 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

- Minimal models without new scales give interesting predictions relating cosmology and particle physics.

Dark matter – add νMSM and stir

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

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

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

DM sterile neutrino mass bound

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

How to reheat universe after inflation?

State of the Universe after inflation

- Empty! Cold!
- Only the uniform (oscillating) inflaton field.

Needed for the Hot Big Bang cosmology

- All the known and unknown particles and HOT!

HOT – means at least above electroweak transition,
$T_r > 150$ GeV – for baryogenesis (via leptogenesis)

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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

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

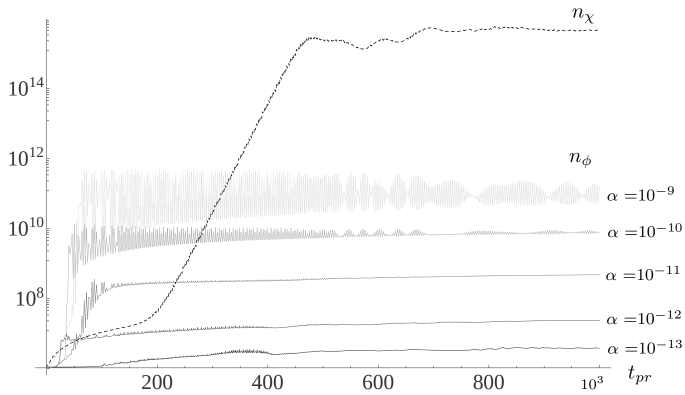
- Important – $X(t)$ oscillates
- Let us neglect the Universe expansion, and say that $X(t) = A\sin(\omega t)$, then

Mathieu equation

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

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

Not so easy to create the Higgs



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

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

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

Temperature estimate for the reheating II

However, $p_{avg} \not\propto T$, the cross-section is enhanced, so

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

For this estimate the bound is *weaker*

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

Upper bound for the inflaton mass

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

Inflaton mass window

Flatness from radiative corrections

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

Sufficient reheating

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

To be precise, the window also exists

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

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Inflaton-SM Interactions

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

$$\mathcal{L}_{\chi\pi\pi} = 2\kappa\sqrt{2\beta}\cdot\frac{\chi}{m_\chi}\cdot\left(\frac{1}{2}\partial_\mu\pi^0\partial^\mu\pi^0 + \partial_\mu\pi^+\partial^\mu\pi^-\right) - (3\kappa+1)\sqrt{2\beta}\cdot\frac{\chi}{m_\chi}\cdot m_\pi^2\cdot\left(\frac{1}{2}\pi^0\pi^0 + \pi^+\pi^-\right)$$

$$\kappa = 2/9$$

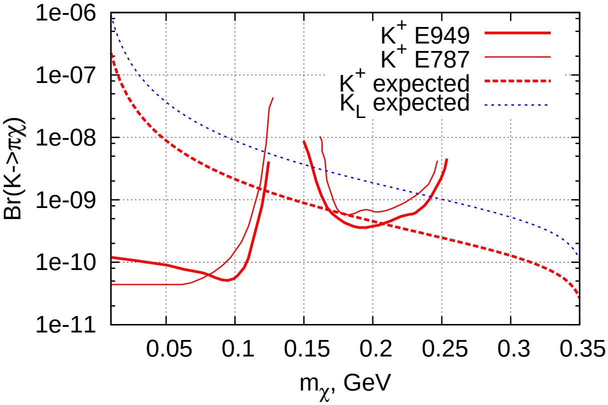
$$\mathcal{L}_{\chi\gamma\gamma} \approx \frac{F_{\gamma\gamma}\alpha}{4\pi}\,\frac{\sqrt{2\beta}}{m_\chi}\,\chi\,F_{\mu\nu}F^{\mu\nu}$$

$$\mathcal{L}_{\chi gg} \approx \frac{F_{gg}\alpha_s}{4\sqrt{8}\,\pi}\,\frac{\sqrt{2\beta}}{m_\chi}\,\chi\,G^a_{\mu\nu}G^{a\,\mu\nu}$$

Production: hadron decays

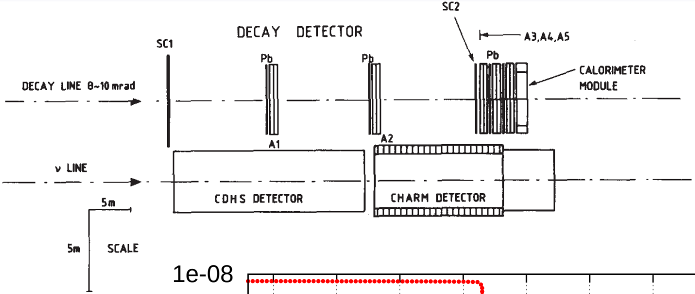
$$\left.\begin{array}{r} \mathrm{Br}\left(K^+ \to \pi^+ \chi\right) \approx \; 2.3 \times 10^{-9} \\ \mathrm{Br}\left(K_L \to \pi^0 \chi\right) \approx \; 1.0 \times 10^{-8} \\ \mathrm{Br}\left(\eta \to \pi^0 \chi\right) \approx 1.8 \times 10^{-12} \\ \mathrm{Br}\left(B \to X_s \chi\right) \approx \qquad\quad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

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

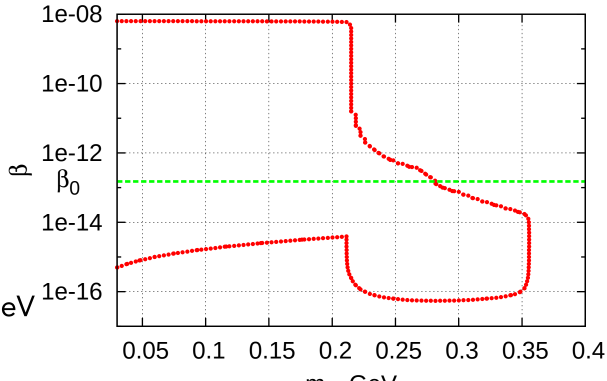


Excluded: $m_\chi \lesssim 120$ MeV
Disfavoured: 170 MeV $\lesssim m_\chi \lesssim 205$ MeV

CHARM – bound



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



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