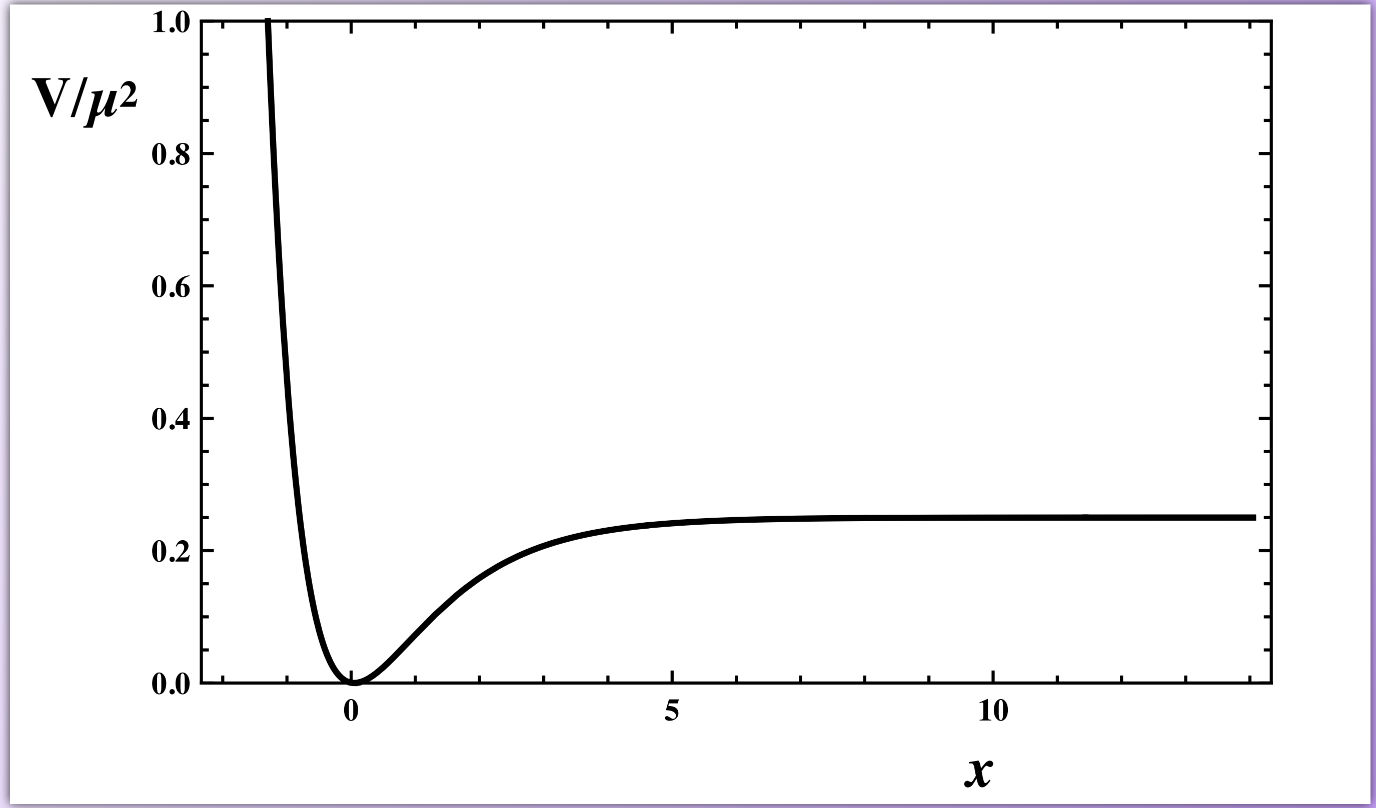
Gravitational Portals

- Examples of Inflation:Starobinsky and T-models
- Instantaneous vs non-instantaneous reheating
- Particle Production
- Gravitational Portals

Key Steps as Inflation ends

Equations of motion

$$\ddot{\phi} + 3H\dot{\phi} + \frac{\partial V}{\partial \phi} \simeq \ddot{\phi} + 3H\dot{\phi} + m^2(\phi)\phi = 0$$



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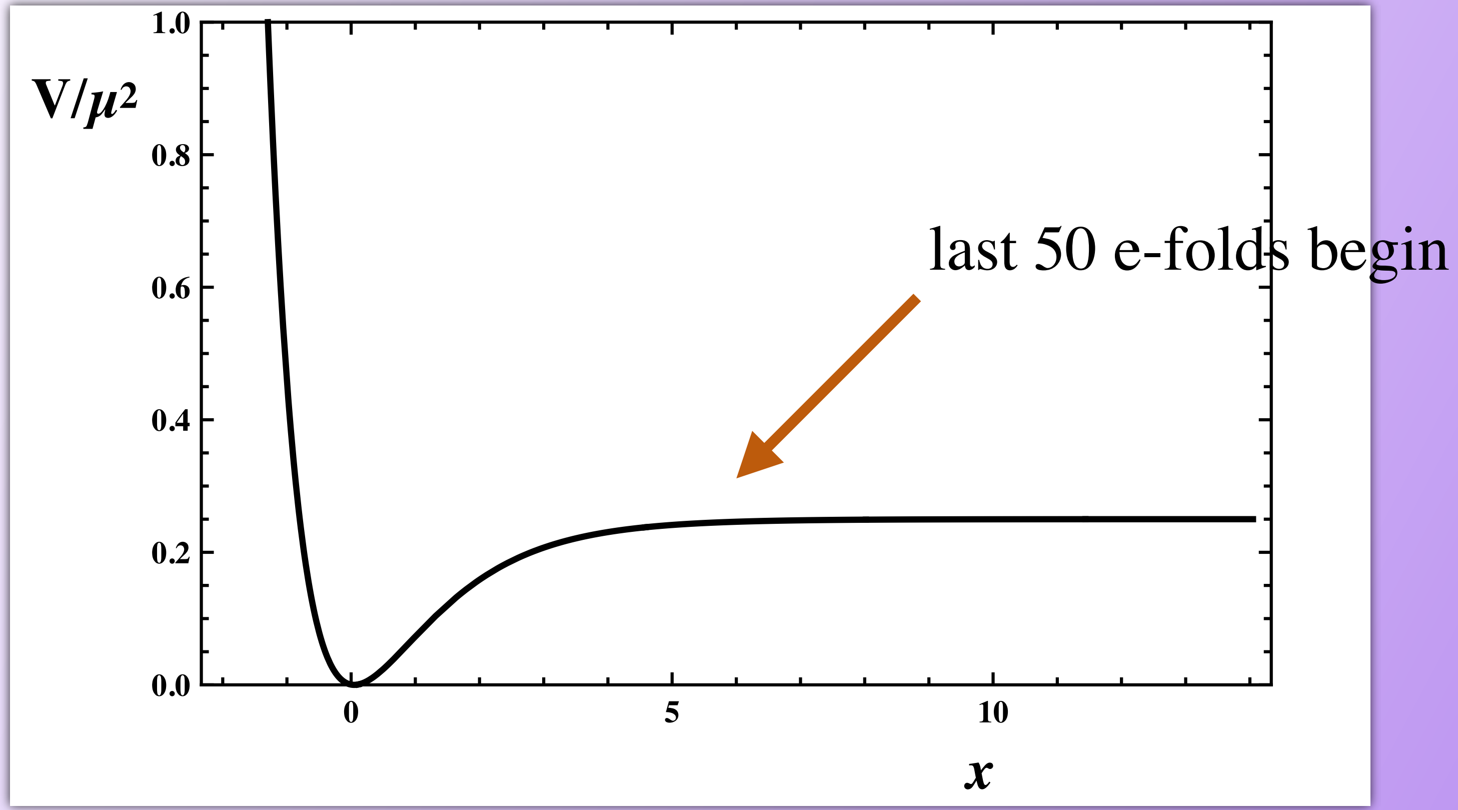

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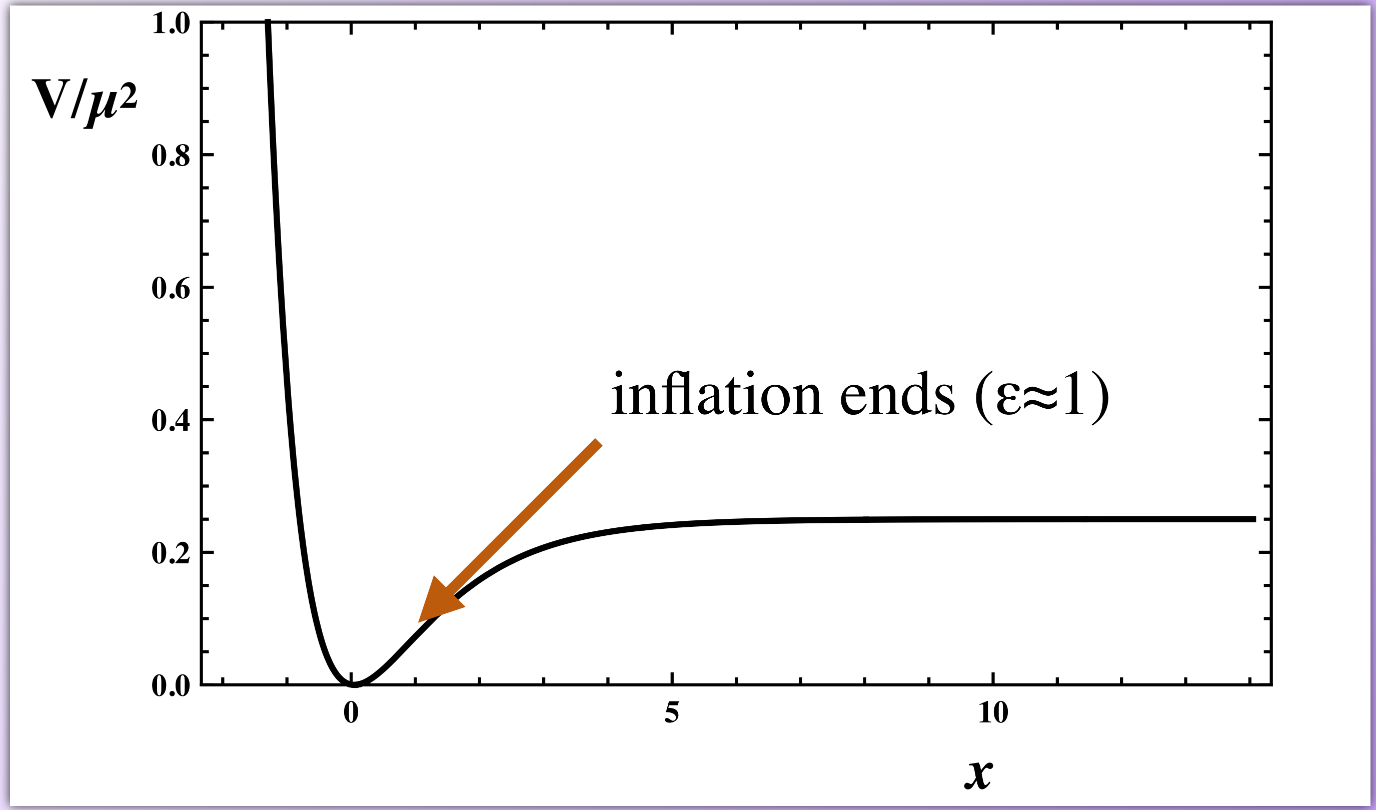

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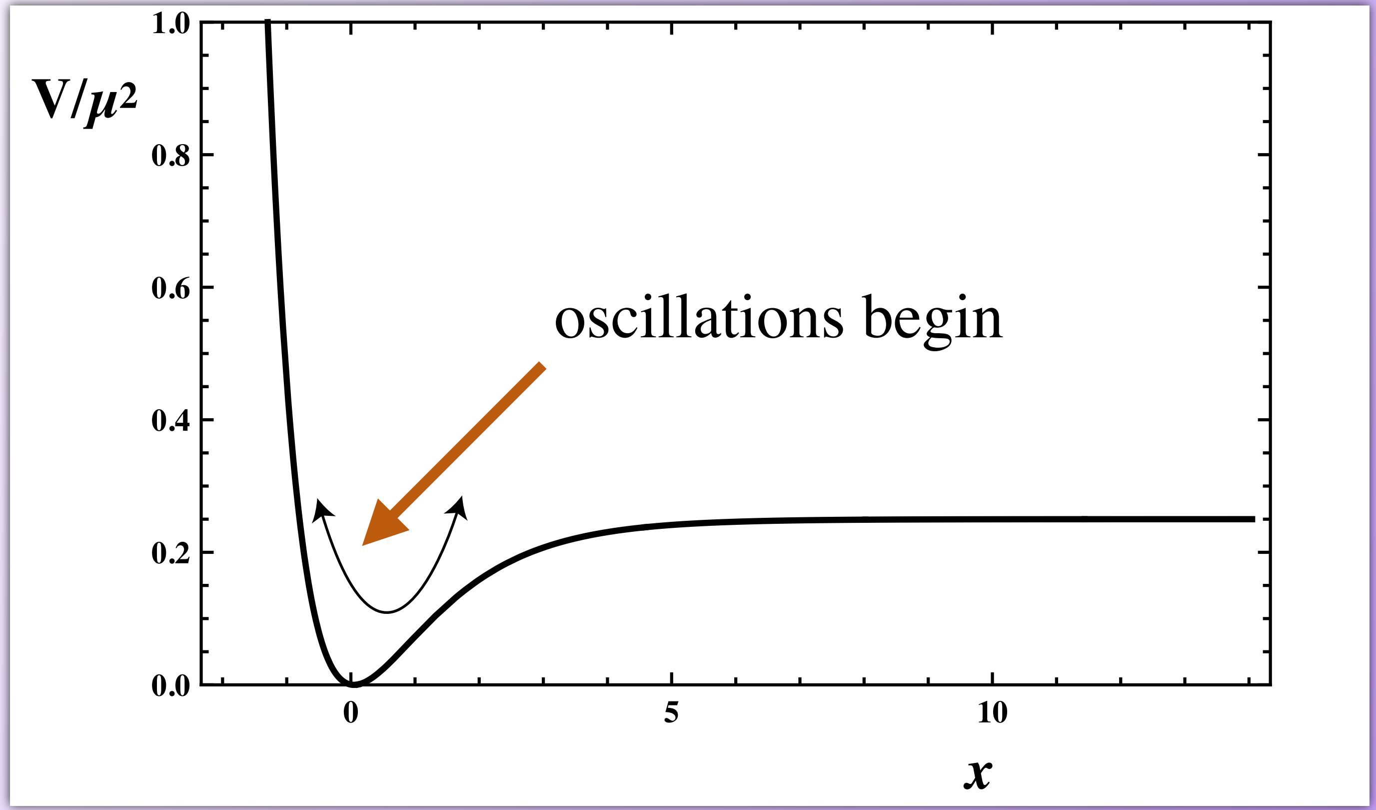


Then what happens?

- Inflaton decays leading to reheating

$$\frac{\pi^2 g_{\rm reh} T_{\rm reh}^4}{30} = \frac{12}{25} \left(\Gamma_\varphi M_P\right)^2 \qquad \rho_R(a_{\rm RH}) = \rho_\phi(a_{\rm RH})$$

For $\Gamma_\phi = \frac{y^2}{8\pi} m_\phi(\phi)$

$$T_{\rm reh} \simeq 1.9 \times 10^{15}\,{\rm GeV} \cdot y \cdot g_{\rm reh}^{-1/4} \left(\frac{m_\varphi}{3 \times 10^{13}\,{\rm GeV}}\right)^{1/2} .$$

- Inflaton oscillations ⇒ particle production

R+R² Gravity

$$\mathcal{A} = \frac{1}{2\kappa^2}\int d^4x\sqrt{-g}\left(R+\tilde{\alpha}R^2\right)$$

Starobinsky

transform to Einstein frame $\tilde{g}_{\mu\nu} = e^{2\Omega}g_{\mu\nu} = \left(1+2\tilde{\alpha}\Phi\right)g_{\mu\nu}$

Leading to

$$\mathcal{A} = \frac{1}{2\kappa^2}\int d^4x\sqrt{-\tilde{g}}\left[\tilde{R}-\kappa^2\partial^\mu\phi\partial_\mu\phi-\frac{1}{4\tilde{\alpha}}\left(1-e^{-\sqrt{\frac{2}{3}}\kappa\phi}\right)^2\right]$$

$$\tilde{\alpha} = 1/6M^2$$

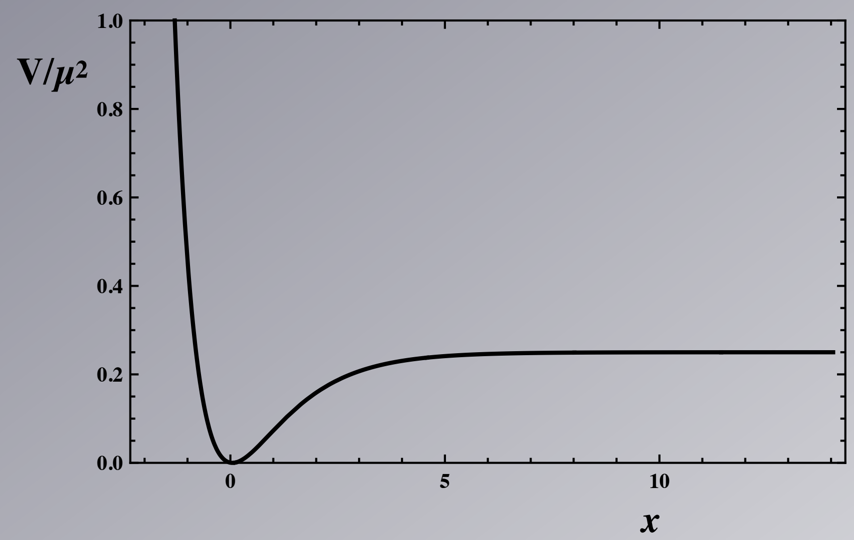
$$V = \frac{3}{4}M^2(1-e^{-\sqrt{2/3}\varphi'})^2$$

Starobinsky

Planck-friendly Models: R+R^2 Inflation

$$V = \frac{3}{4}M^2(1 - e^{-\sqrt{2/3}\varphi'})^2$$
$$= \mu^2 e^{-\sqrt{2/3}x}\sinh^2(x/\sqrt{6})$$

x=ϕ/M_P, $\mu^2 = 3M^2$



Slow Roll parameters:

$$\epsilon = \frac{1}{3}\mathrm{csch}^2(x/\sqrt{6})e^{-\sqrt{2/3}x},$$
$$\eta = \frac{1}{3}\mathrm{csch}^2(x/\sqrt{6})\left(2e^{-\sqrt{2/3}x} - 1\right)$$

μ is set by the normalization of the quadrupole

$$A_s = \frac{V}{24\pi^2\epsilon} = \frac{\mu^2}{8\pi^2}\sinh^4(x/\sqrt{6})$$

$\Longrightarrow$ μ = 2.2 x 10^{-5} for N = 55

$x_i = 5.35$

For N=55, n_s = 0.965; r = .0035

No-Scale realization of Starobinsky

Can we find a model consistent with Planck?

Ellis, Nanopoulos, Olive

Cremmer, Ferrara, Kounnas, Nanopoulos; Ellis, Kounnas, Nanopoulos; Lahanas, Nanopoulos

Start with NS: $K = -3\ln(T + T^* - \phi^i \phi_i{}^*/3)$

and a WZ model: $W = \frac{\hat{\mu}}{2}\Phi^2 - \frac{\lambda}{3}\Phi^3$

Assume now that T picks up a vev: 2<Re T> = c

$$\mathcal{L}_{eff} = \frac{c}{(c - |\phi|^2/3)^2}|\partial_\mu \phi|^2 - \frac{\hat{V}}{(c - |\phi|^2/3)^2}$$

Redefine inflaton to a canonical field χ

$$\hat{V} = |W_\Phi|^2$$

$$\phi = \sqrt{3c}\tanh\left(\frac{\chi}{\sqrt{3}}\right)$$

No-Scale models revisited

Then c = 1, $\lambda = \hat{\mu}/\sqrt{3}$ $\quad \dfrac{\hat{V}}{(1 - |\phi|^2/3)^2}$ $\Rightarrow$ Starobinsky Potential

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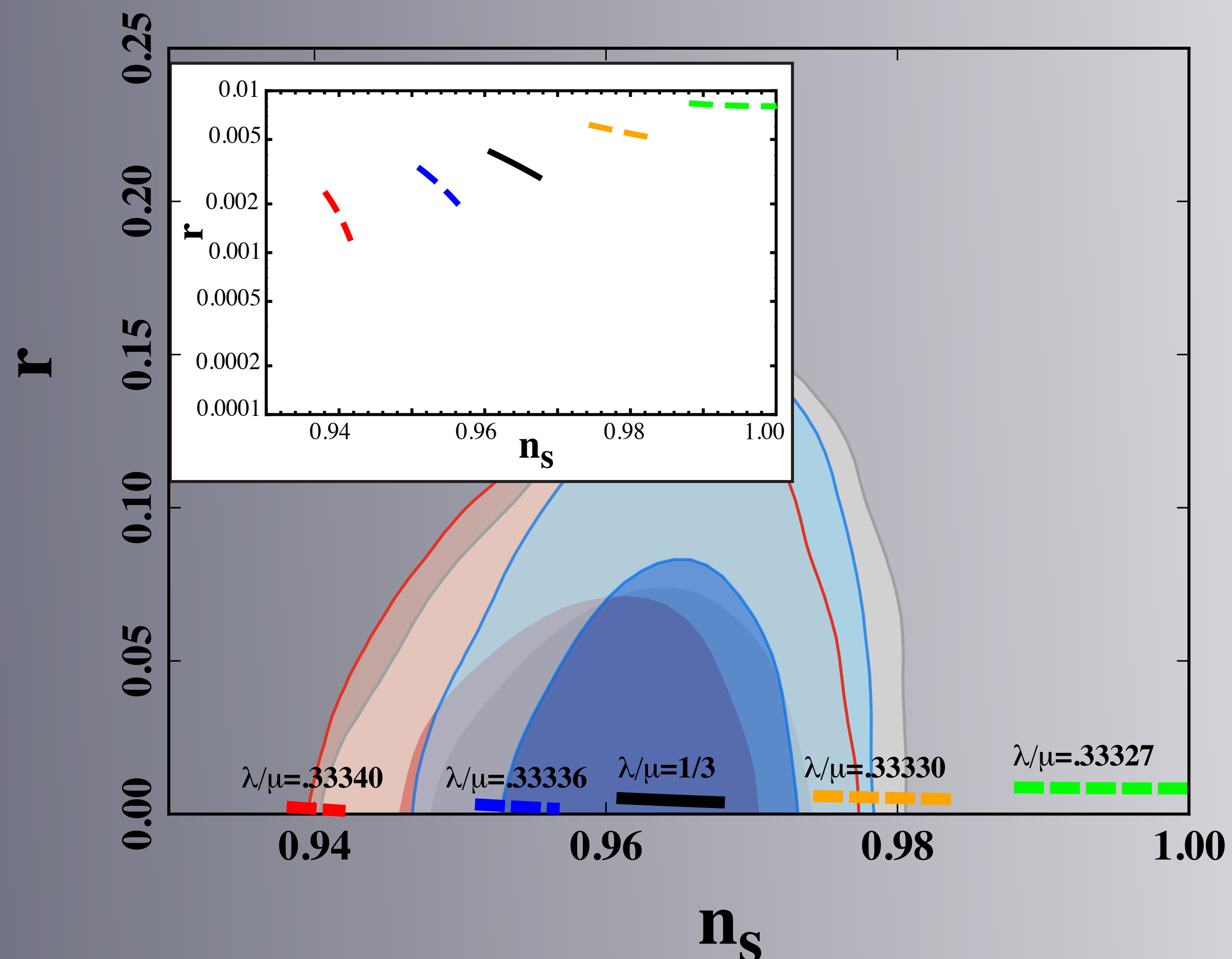
How well does this do vis a vis Planck?



Reheating

In the absence of a direct coupling of the inflaton to matter, reheating does NOT occur.

$$\Gamma_{\phi_1} = 0$$

Endo, Kadota, Olive, Takahashi, Yanagida

coupling to gauge bosons and gauginos

Kallosh, Linde, Olive, Rube

gauge kinetic function $f_{\alpha\beta} = f(\phi_1)\delta_{\alpha\beta}$

$$\Gamma(\phi_1 \to gg) = \Gamma(\phi_1 \to \tilde{g}\tilde{g}) = \frac{3 d_{g,1}^2}{32\pi} \left(\frac{N_G}{12} \right) \frac{m^3}{M_P^2}$$

$$d_{g,1} \equiv \langle \mathrm{Re}\, f \rangle^{-1} \left| \left\langle \frac{\partial f}{\partial \phi_1} \right\rangle \right|$$

$$T_R = (2 \times 10^{10}~\mathrm{GeV})\, d_{g,1}\, g^{-1/4} \left(\frac{N_G}{12} \right)^{1/2} \left(\frac{m}{10^{-5} M_P} \right)^{3/2}$$

Ellis, Garcia, Nanopoulos, Olive

Reheating

Ellis, Garcia, Nanopoulos, Olive

Significant reheating if the inflation (Φ) is directly coupled to matter

$$\Delta W = y_\nu H_u L \phi_1$$

and ϕ_1 can be associated with a heavy singlet sneutrino

$$\Gamma(\phi_1 \to H_u^0 \tilde{\nu}, H_u^+ \tilde{f}_L) = m \frac{|y_\nu|^2}{16\pi} \, ,$$

or

$$\Gamma(\phi_1 \to \tilde{H}_u^0 \nu, \, \tilde{H}_u^+ f_L) = m \frac{|y_\nu|^2}{16\pi} \, ,$$

$\Rightarrow$ $y_\nu \lesssim 10^{-5}$

$$T_R = (5.6 \times 10^{14}\,\mathrm{GeV}) |y_\nu| \left(\frac{g}{915/4} \right)^{-1/4} \left(\frac{m}{10^{-5} M_P} \right)^{1/2}$$

Inflationary Context

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No-scale supergravity: $$K = -3\ln\left(T + \bar{T} - \frac{|\phi|^2}{3}\right)$$

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$$W = M\left(\frac{\phi^2}{2} - \frac{\phi^3}{3\sqrt{3}}\right)$$

Starobinsky $$V = \frac{3}{4}M^2(1 - e^{-\sqrt{2/3}\varphi'})^2$$

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$$W = 2^{\frac{k}{4}+1}\sqrt{\lambda}\left(\frac{\phi^{\frac{k}{2}+1}}{k+2} - \frac{\phi^{\frac{k}{2}+3}}{3(k+6)}\right)$$ T-models $$V = \lambda\left[\sqrt{6}\tanh(\varphi'/\sqrt{6})\right]^k$$

Kallosh, Linde

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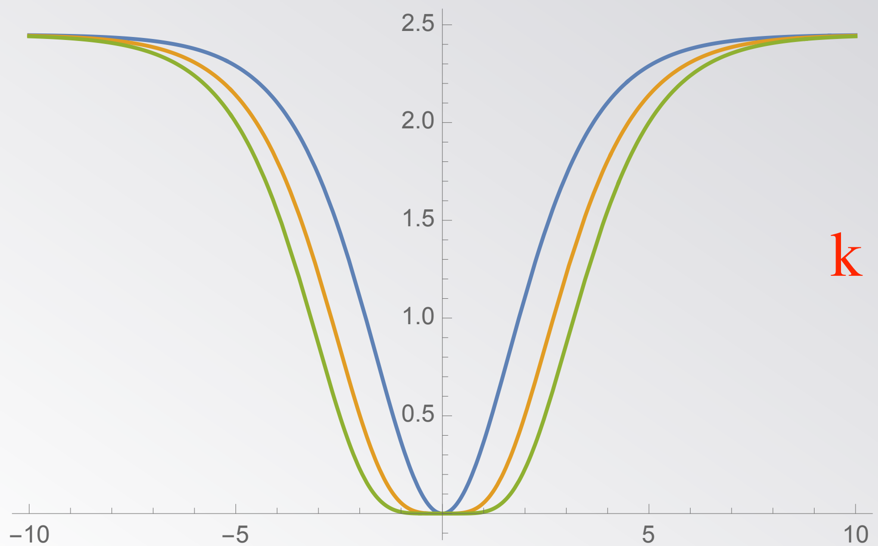

k = 2,4,6

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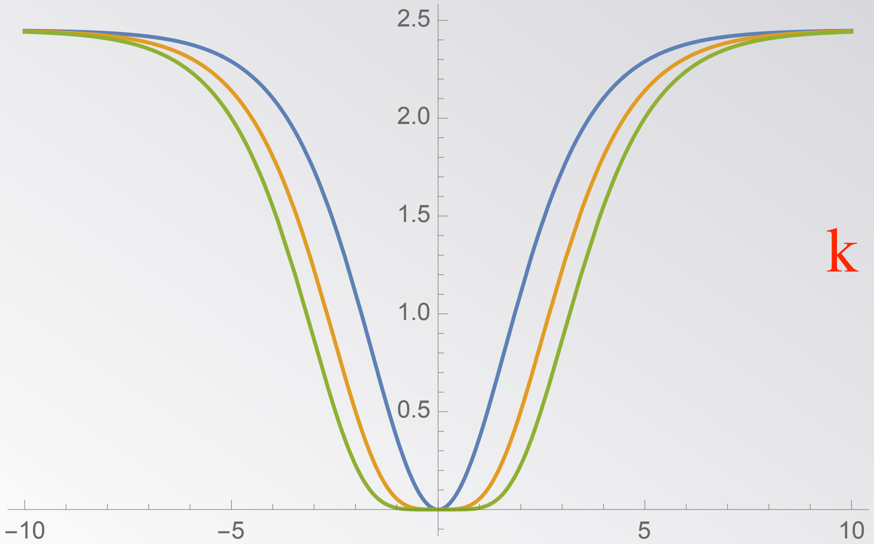
Kallosh, Linde

$$V = \lambda\varphi'^k$$

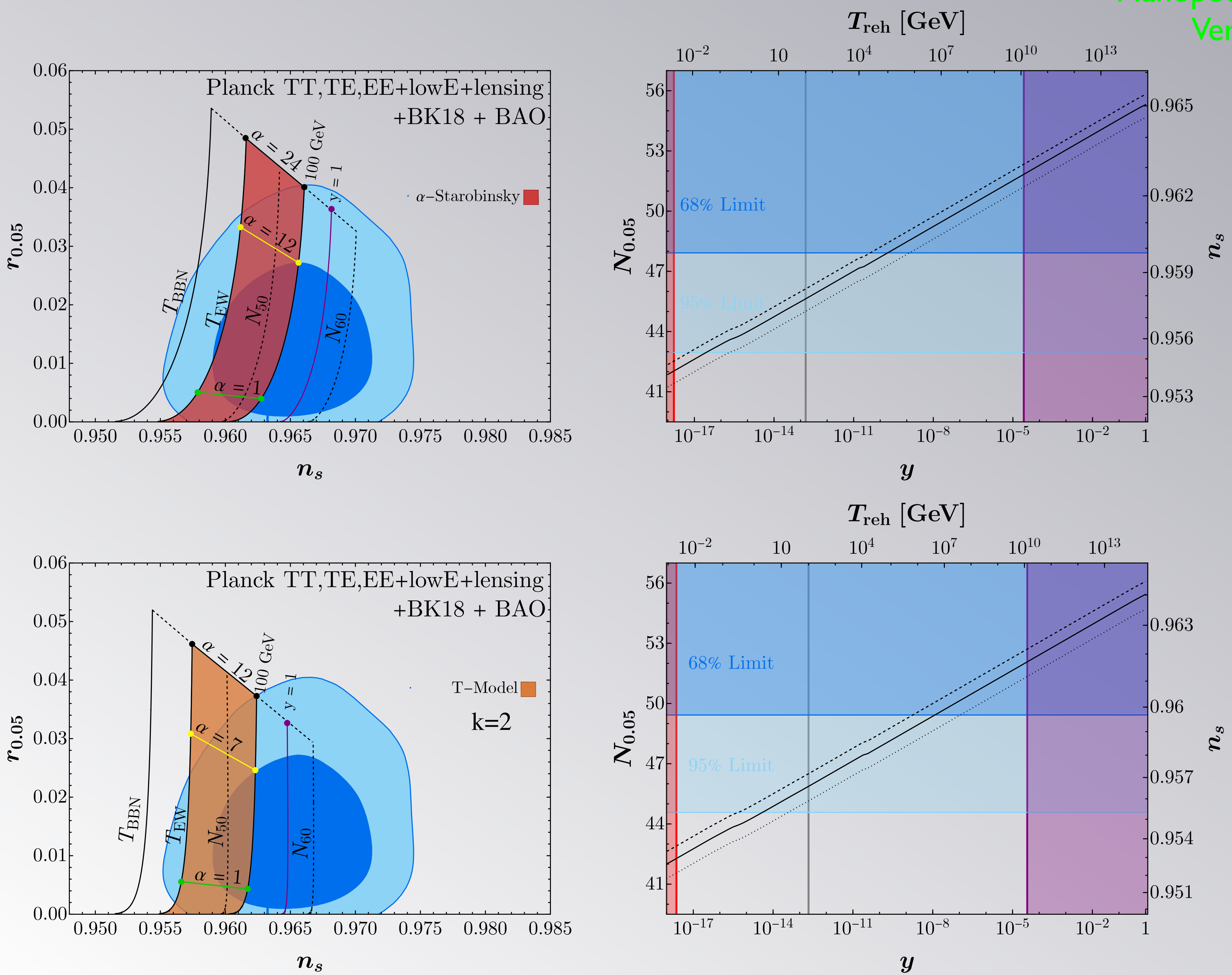
$$\varphi' \ll 1$$



k = 2,4,6

Results for α-Starobuinsky and α-T-models -3ln →-3α ln

Ellis, Garcia, Nanopoulis, Olive, Verner



Post-Inflation

$$\rho_\Phi = \frac{1}{2}\dot{\Phi}^2 + V(\Phi); \qquad P_\Phi = \frac{1}{2}\dot{\Phi}^2 - V(\Phi),$$

$$\dot{\rho}_\Phi + 3H(\rho_\Phi + P_\Phi) = 0,$$

$$\ddot{\Phi} + 3H\dot{\Phi} + V'(\Phi) = 0,$$

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$$\frac{d\rho_\phi}{dt} + 3H(1+w_\phi)\rho_\phi \simeq -(1+w_\phi)\Gamma_\phi\rho_\phi$$

$$\frac{d\rho_R}{dt} + 4H\rho_R \simeq (1+w_\phi)\Gamma_\phi\rho_\phi$$

$$H^2 = \frac{\rho_\phi + \rho_R}{3M_P^2} \simeq \frac{\rho_\phi}{3M_P^2}$$

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$$w_\phi = \frac{p_\phi}{\rho_\phi} = \frac{k-2}{k+2}$$

$$H^2 = \frac{\rho_\phi + \rho_R}{3M_P^2} \simeq \frac{\rho_\phi}{3M_P^2}$$

Inflaton Oscillations

Ichikawa, Suyama, Takahashi, Yamaguchi; Kainulainen, Nurmi, Tenkanen, Tuominen; Garcia, Kaneta, Mambrini, Olive

$$\phi(t) \;=\; \phi_0(t) \cdot \mathcal{P}(t)$$

$$\phi_0 = \left(\frac{\rho_{\rm end}}{\lambda}\right)^{\frac{1}{k}} \left(\frac{a_{\rm end}}{a}\right)^{\frac{6}{k+2}}$$

Periodicity

$$V(\phi) = V(\phi_0) \sum_{n=-\infty}^{\infty} \mathcal{P}_n^k e^{-in\omega t} = \rho_\phi \sum_{n=-\infty}^{\infty} \mathcal{P}_n^k e^{-in\omega t} \,,$$

$$\omega = m_\phi \sqrt{\frac{\pi k}{2(k-1)}} \frac{\Gamma(\frac{1}{2}+\frac{1}{k})}{\Gamma(\frac{1}{k})} .$$

Reheating: Generation of the Radiation bath

Garcia, Kaneta, Mambrini, Olive

For $\Gamma_\Phi \ll H$ $\quad \rho_\Phi(a) = \rho_{\rm end}\left(\frac{a_{\rm end}}{a}\right)^{\frac{6k}{k+2}}$

as matter for k=2

End of Inflation: Inflation ends when

$$\epsilon_H(\phi) \equiv 2M_P^2\left(\frac{H'(\phi)}{H(\phi)}\right)^2 = 1$$

$$(\ddot{a} = 0)$$

In terms of conventional slow-roll parameters

$$\epsilon_V \simeq (1 + \sqrt{1 - \eta_V/2})^2$$

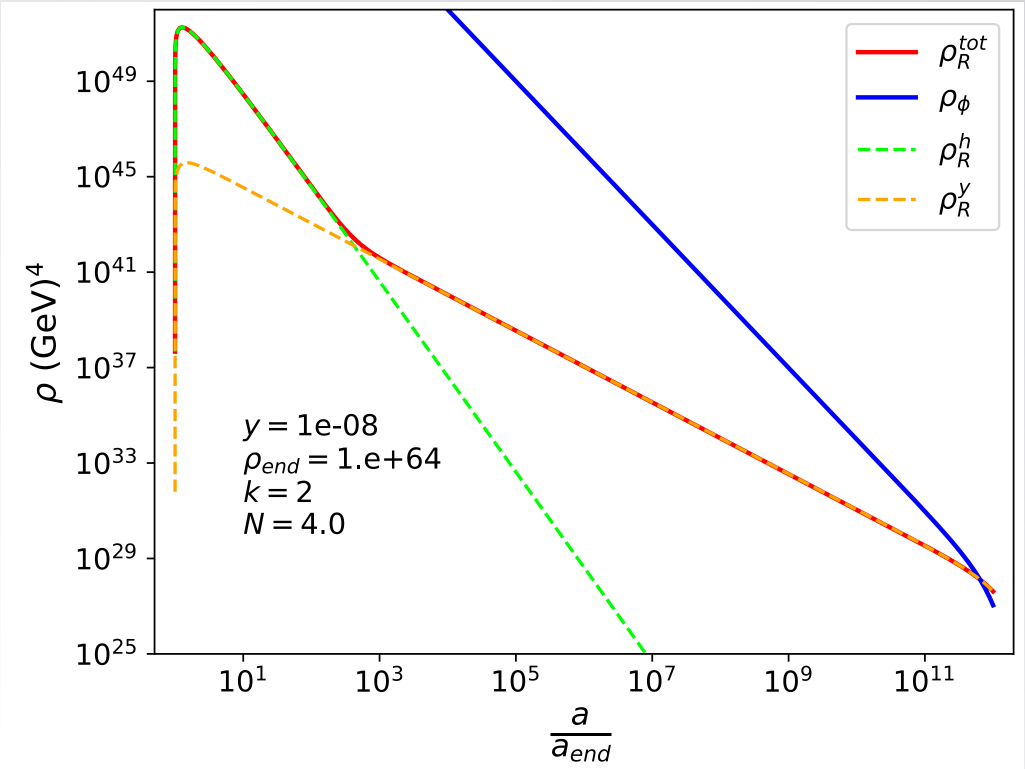
Reheating: Generation of the Radiation bath

Giudice, Kolb, Riotto; Chung, Kolb, Riotto; Garcia, Kaneta, Mambrini, Olive; Bernal; Clery, Mambrini, Olive Verner

For $\Gamma_\Phi \ll H$

$$\rho_\Phi(a) = \rho_{\rm end}\left(\frac{a_{\rm end}}{a}\right)^{\frac{6k}{k+2}}$$

$$\rho_R(a) = \rho_{\rm RH}\left(\frac{a_{\rm RH}}{a}\right)^{\frac{6k-6}{k+2}} \frac{1-\left(\frac{a_{\rm e}}{a}\right)^{\frac{14-2k}{k+2}}}{1-\left(\frac{a_{\rm e}}{a_{\rm RH}}\right)^{\frac{14-2k}{k+2}}}$$



Reheating: Generation of the Radiation bath

Garcia, Kaneta, Mambrini, Olive; Clery, Mambrini, Olive, Verner

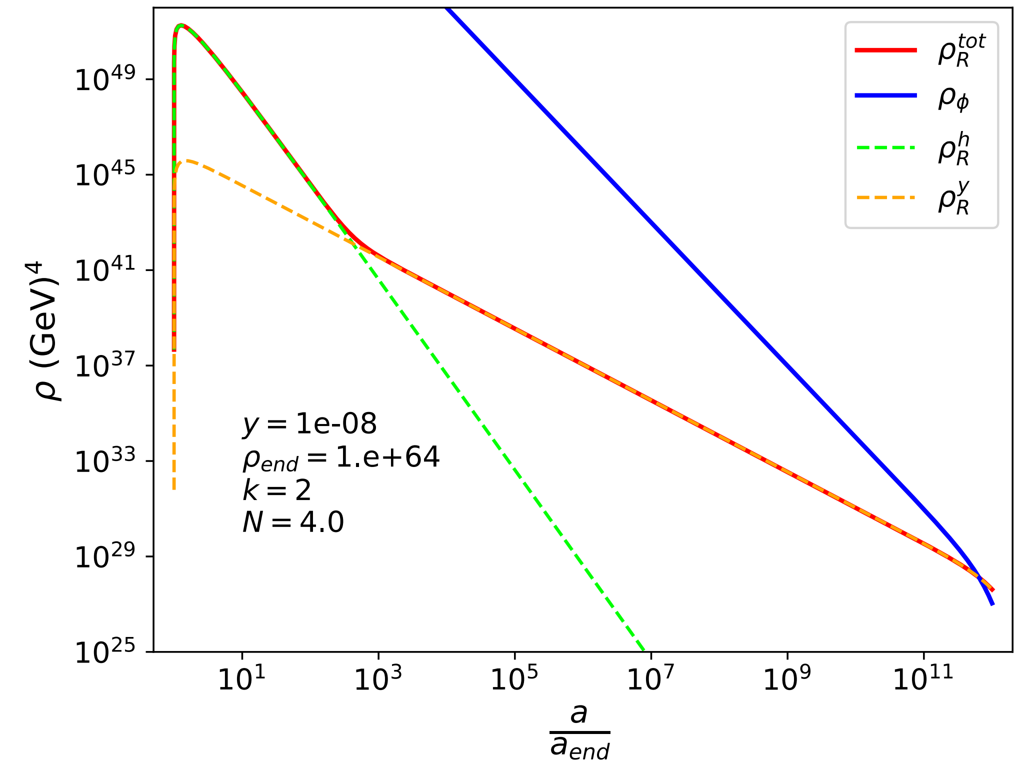
$$\rho_R = \frac{g_T \pi^2}{30} T^4$$

$$\frac{a_{\max}}{a_{\text{end}}} = \left(\frac{2k+4}{3k-3}\right)^{\frac{k+2}{14-2k}}$$

for k=2:

$$\rho_R \sim a^{-3/2}$$

$$T \sim a^{-3/8}$$



$$\frac{\pi^2 g_{\text{reh}} T_{\text{reh}}^4}{30} = \frac{12}{25}(\Gamma_\varphi M_P)^2$$

$$T_{\text{reh}} \simeq 1.9 \times 10^{15}\,\text{GeV} \cdot y \cdot g_{\text{reh}}^{-1/4} \left(\frac{m_\varphi}{3 \times 10^{13}\,\text{GeV}}\right)^{1/2}$$

Reheating: Generation of the Radiation bath

Garcia, Kaneta, Mambrini, Olive

More generally, $$\mathcal{L} \supset \begin{cases} y\phi\bar{f}f & \phi \to \bar{f}f \\ \mu\phi bb & \phi \to bb \\ \sigma\phi^2 b^2 & \phi\phi \to bb, \end{cases}$$

channel	generic	$k=2$	$k=4$	$k=6$	$m_{\rm eff}^2 \gg m_\phi^2$
$\phi \to \bar{f}f$	$T \propto a^{-\frac{3k-3}{2k+4}}$	$T \propto a^{-3/8}$	$T \propto a^{-3/4}$	$T \propto a^{-15/16}$	$T \propto a^{-\frac{9(k-2)}{4(k+2)}}$
$\phi \to bb$	$T \propto a^{-\frac{3}{2k+4}}$	$T \propto a^{-3/8}$	$T \propto a^{-1/4}$	$T \propto a^{-3/16}$	$T \propto a^{-\frac{3(5-k)}{4(k+2)}}$
$\phi\phi \to bb$	$T \propto a^{-\frac{9}{2k+4}}$	$T \propto a^{-1}$	$T \propto a^{-3/4}$	$T \propto a^{-9/16}$	$T \propto a^{-3/4}$

↖ will not reheat

Particle Production

(Freeze-in)

Kaneta, Mambrini, Olive

Suppose some coupling to the Standard Model with cross section

$$\langle \sigma v \rangle = \frac{T^n}{\tilde{\Lambda}^{n+2}} \,,$$

Boltzmann Eq.

$$\dot{n}_\chi + 3H n_\chi \;=\; g_\chi^2 \langle \sigma v \rangle n_R^2 \;\equiv\; R(T) \;=\frac{T^{n+6}}{\Lambda^{n+2}} \,.$$

$$n_R = \frac{\zeta(3)}{\pi^2} T^3 \,.$$

Define $\quad Y_\chi = n_\chi a^3$

$$\frac{dY_\chi}{da} = \frac{a^2 R_\chi^i(a)}{H}$$

Particle Production

Garcia, Kaneta, Mambrini, Olive

(i) For $n < \frac{10-2k}{k-1}$,

$$n^s(T_{\rm reh}) = \sqrt{\frac{10}{g_*}}\frac{M_P}{\pi}\frac{2k+4}{n-nk+10-2k}\frac{T_{\rm reh}^{n+4}}{\Lambda^{n+2}}.$$

(ii) For $n = \frac{10-2k}{k-1}$,

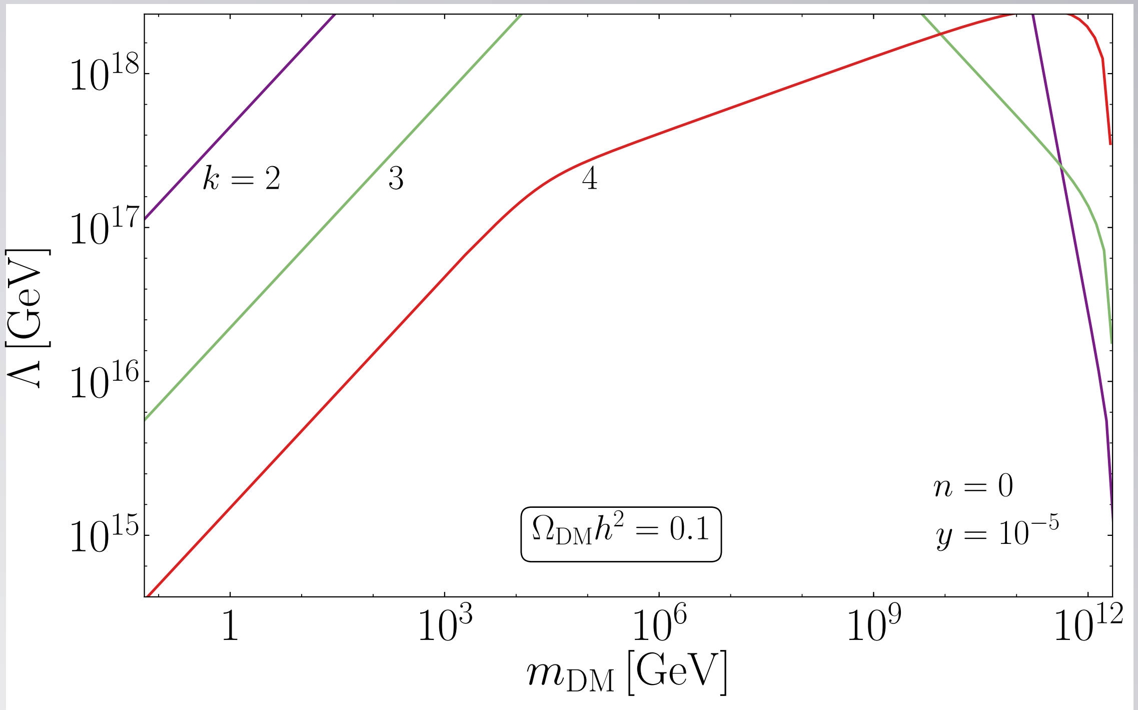
$$n^s(T_{\rm reh}) = \sqrt{\frac{10}{g_*}}\frac{M_P}{\pi}\left(\frac{2k+4}{k-1}\right)\frac{T_{\rm reh}^{n+4}}{\Lambda^{n+2}}\ln\left(\frac{T_{\rm max}}{T_{\rm reh}}\right).$$

(iii) For $n > \frac{10-2k}{k-1}$,

$$n^s(T_{\rm reh}) = \sqrt{\frac{10}{g_*}}\frac{M_P}{\pi}\frac{2k+4}{kn-n-10+2k} \times \left(\frac{T_{\rm reh}}{T_{\rm max}}\right)^{\frac{2k+6}{k-1}}\frac{T_{\rm max}^{n+4}}{\Lambda^{n+2}}.$$

$n_{\rm crit} = 6$ for k=2

Particle Production



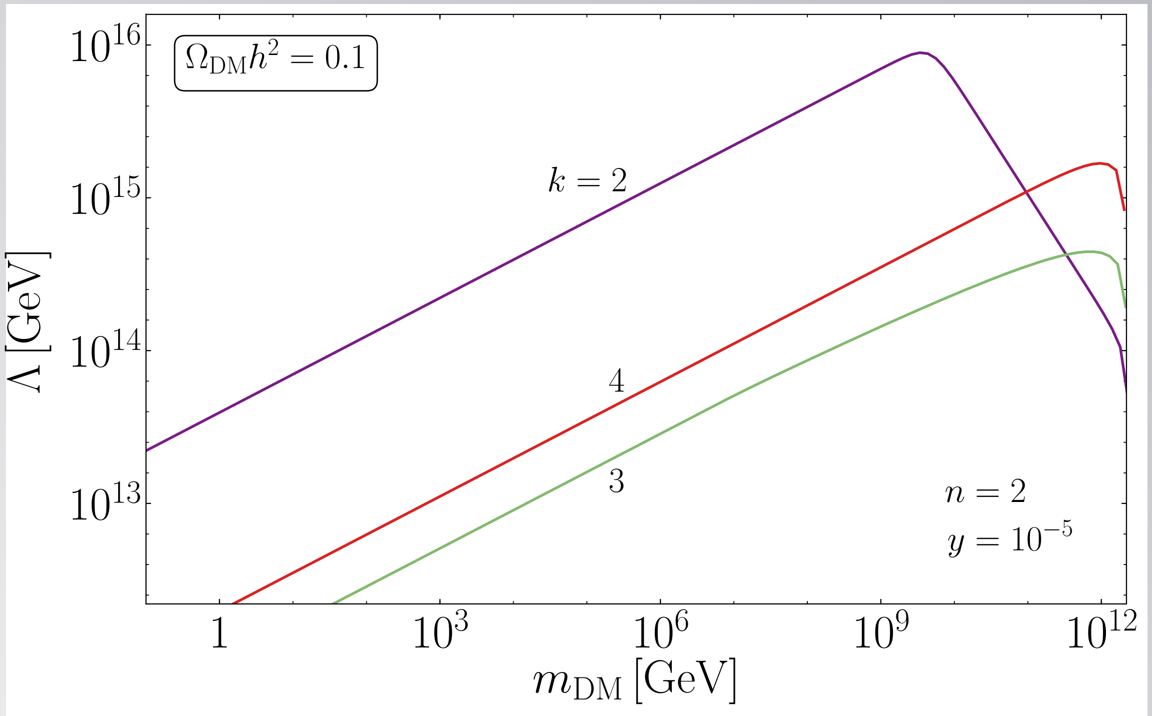
Garcia, Kaneta, Mambrini, Olive

k=2 $\quad T_{\rm max} \sim 10^{12}$ GeV and $T_{\rm reh} \sim 10^{10}$ GeV

ex: gravitino - n=0, $\Lambda = M_P$, and for k=2, $\Omega h^2 \sim .1$ when $m_{3/2} \sim 100$ GeV

slope changes when $m_\chi \sim T_{\rm reh}$

Particle Production



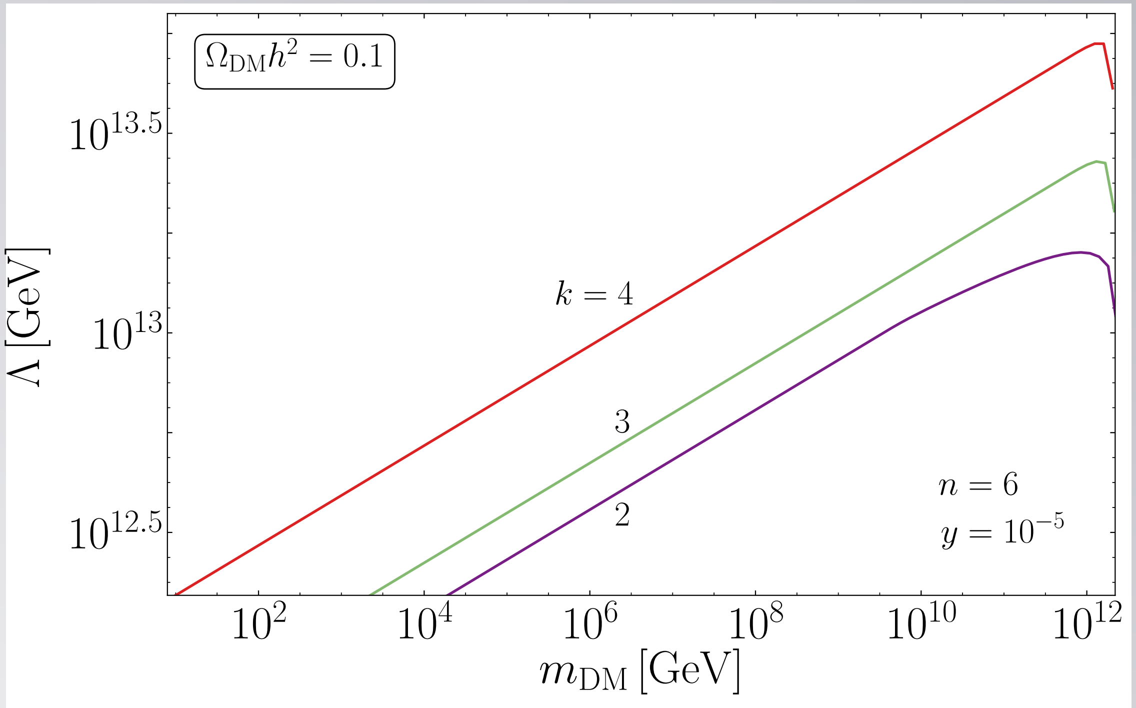
Garcia, Kaneta, Mambrini, Olive

k=2 $T_{\rm max} \sim 10^{12}$ GeV and $T_{\rm reh} \sim 10^{10}$ GeV

ex: mediator with mass Λ

slope changes when $m_\chi \sim T_{\rm reh}$

Particle Production



(c)

Garcia, Kaneta, Mambrini, Olive

k=2 $\quad T_{\rm max} \sim 10^{12}$ GeV and $T_{\rm reh} \sim 10^{10}$ GeV

ex: gravitino production in high scale supersymmetry

Expect $\Lambda^2 \sim m_{3/2} M_P$ $\quad$ correct relic density for $m_{3/2} \sim 1$ EeV

Dudas, Mambrini, Olive

Gravitational Portals

Mambrini, Olive;
Clery, Mambrini, Olive, Verner

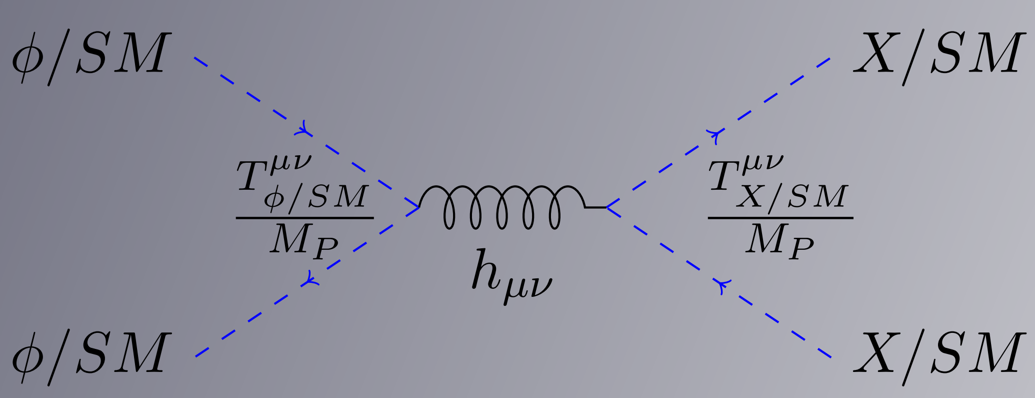
Start with Einstein-Hilbert Lagrangian

$$\mathcal{L} = \frac{M_P^2}{2} R \ni \frac{M_P^2}{8} (\partial^\alpha \tilde{h}^{\mu\nu})(\partial_\alpha \tilde{h}_{\mu\nu}) = \frac{1}{2} (\partial^\alpha h^{\mu\nu})(\partial_\alpha h_{\mu\nu})$$

$$g_{\mu\nu} \simeq \eta_{\mu\nu} + \tilde{h}_{\mu\nu}$$

Graviational interactions

$$\sqrt{-g}\mathcal{L}_{\rm int} = -\frac{1}{M_P} h_{\mu\nu} \left(T^{\mu\nu}_{SM} + T^{\mu\nu}_{\phi} + T^{\mu\nu}_{X} \right)$$



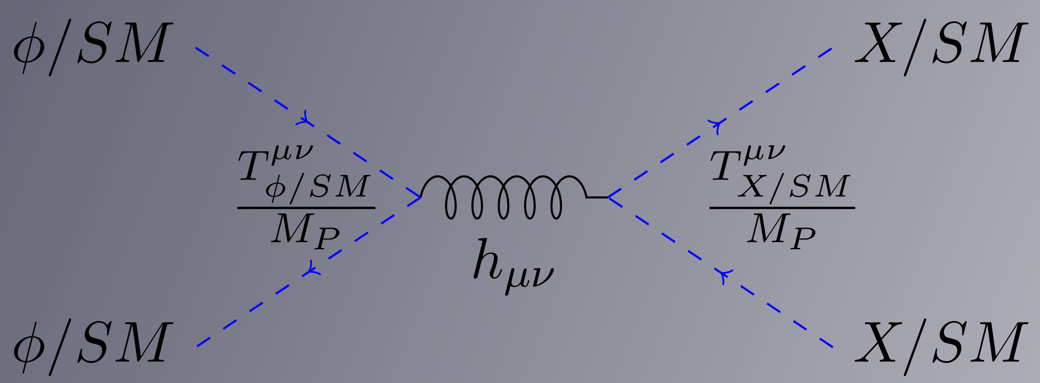
$$T^{\mu\nu}_0 = \partial^\mu S \partial^\nu S - g^{\mu\nu} \left[\frac{1}{2} \partial^\alpha S \partial_\alpha S - V(S) \right],$$

$$T^{\mu\nu}_{1/2} = \frac{i}{4} \left[\bar{\chi} \gamma^\mu \overleftrightarrow{\partial^\nu} \chi + \bar{\chi} \gamma^\nu \overleftrightarrow{\partial^\mu} \chi \right] - g^{\mu\nu} \left[\frac{i}{2} \bar{\chi} \gamma^\alpha \overleftrightarrow{\partial}_\alpha \chi - m_\chi \bar{\chi} \chi \right],$$

$$T^{\mu\nu}_1 = \frac{1}{2} \left[F^\mu_\alpha F^{\nu\alpha} + F^\nu_\alpha F^{\mu\alpha} - \frac{1}{2} g^{\mu\nu} F^{\alpha\beta} F_{\alpha\beta} \right],$$

Gravitational Portals

Mambrini, Olive;
Barman, Bernal;
Haque, Maity;
Clery, Mambrini, Olive, Verner



$$\Pi^{\mu\nu\rho\sigma}(k) = \frac{\eta^{\mu\rho}\eta^{\nu\sigma} + \eta^{\mu\sigma}\eta^{\nu\rho} - \eta^{\mu\nu}\eta^{\rho\sigma}}{2k^2},$$

A. Gravitational Production of DM from the thermal bath

B. Gravitational Production of DM from Inflaton Scattering

C. Gravitational Production of the thermal bath from Inflaton Scattering

Minimal Gravity only - No model dependence!

Gravitational Portals

$$\mathrm{SM}^i(p_1) + \mathrm{SM}^i(p_2) \to X^j(p_3) + X^j(p_4)$$

$$\frac{dY_\chi}{da} = \frac{a^2 R^i_\chi(a)}{H}$$

$$R_j^T = R_j(T) = \beta_j \frac{T^8}{M_P^4}$$

$$n_X^T(a_{\mathrm{RH}}) = \frac{\beta_X \sqrt{3}}{\alpha^2 M_P^3} \frac{\rho_{\mathrm{RH}}^{3/2}}{(1-(a_{\mathrm{end}}/a_{\mathrm{RH}})^{\frac{14-2k}{k+2}})^2} \; \frac{k+2}{6} \left(\frac{1}{3-k} + \; \ldots . \right.$$

$$\Omega_X^T h^2 \simeq 10^8 \frac{g_0}{g_{\mathrm{RH}}} \frac{\beta_X \sqrt{3}}{\sqrt{\alpha}} \frac{m_X}{1\ \mathrm{GeV}} \frac{T_{\mathrm{RH}}^3}{M_P^3}$$

k=2

$$\alpha = g_{\mathrm{RH}} \pi^2/30$$

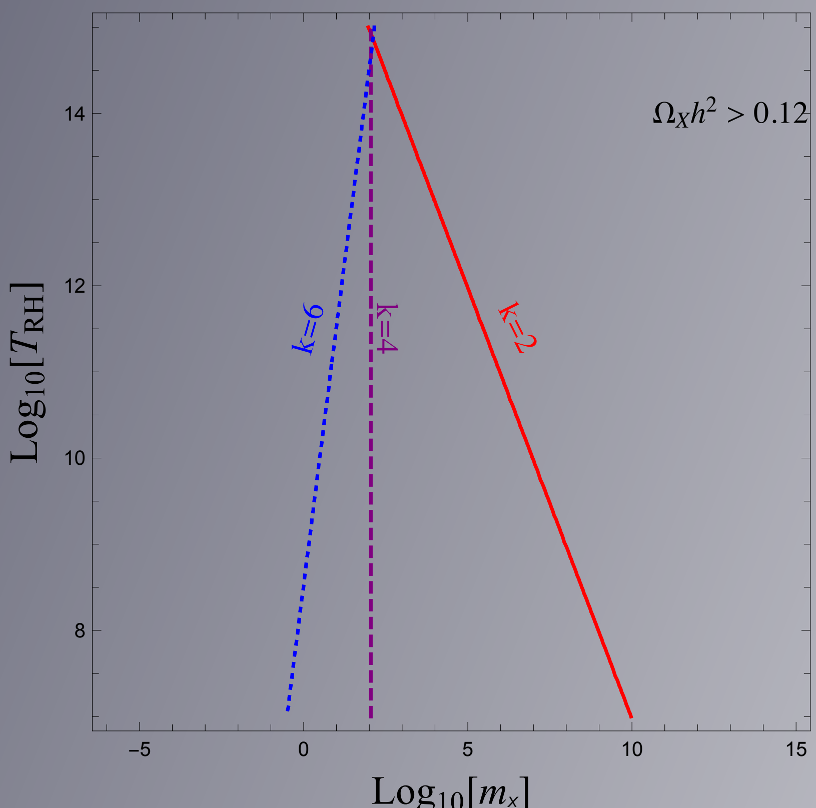
$$\beta_0 = \frac{3997\pi^3}{20736000} \qquad \beta_{1/2} = \frac{11351\pi^3}{10368000}$$

Gravitational Portals

$$\phi(p_1) + \phi(p_2) \to X^j(p_3) + X^j(p_4)$$

$$R_0^{\phi^k} = \frac{2 \times \rho_\phi^2}{16\pi M_P^4} \Sigma_0^k$$

$$\frac{dY_X}{da} = \frac{\sqrt{3} M_P}{\sqrt{\rho_{\rm RH}}} a^2 \left(\frac{a}{a_{\rm RH}}\right)^{\frac{3k}{k+2}} R_X^{\phi^k}(a)$$



$$n_0^\phi(a_{\rm RH}) \simeq \frac{\sqrt{3}\rho_{\rm RH}^{3/2}}{8\pi M_P^3} \frac{k+2}{6k-6} \left(\frac{\rho_{\rm end}}{\rho_{\rm RH}}\right)^{1-\frac{1}{k}} \Sigma_0^k,$$

$$\Sigma_0^k = \sum_{n=1}^{\infty} |\mathcal{P}_n^k|^2 \left[1 + \frac{2m_X^2}{E_n^2}\right]^2 \sqrt{1 - \frac{4m_X^2}{E_n^2}}$$

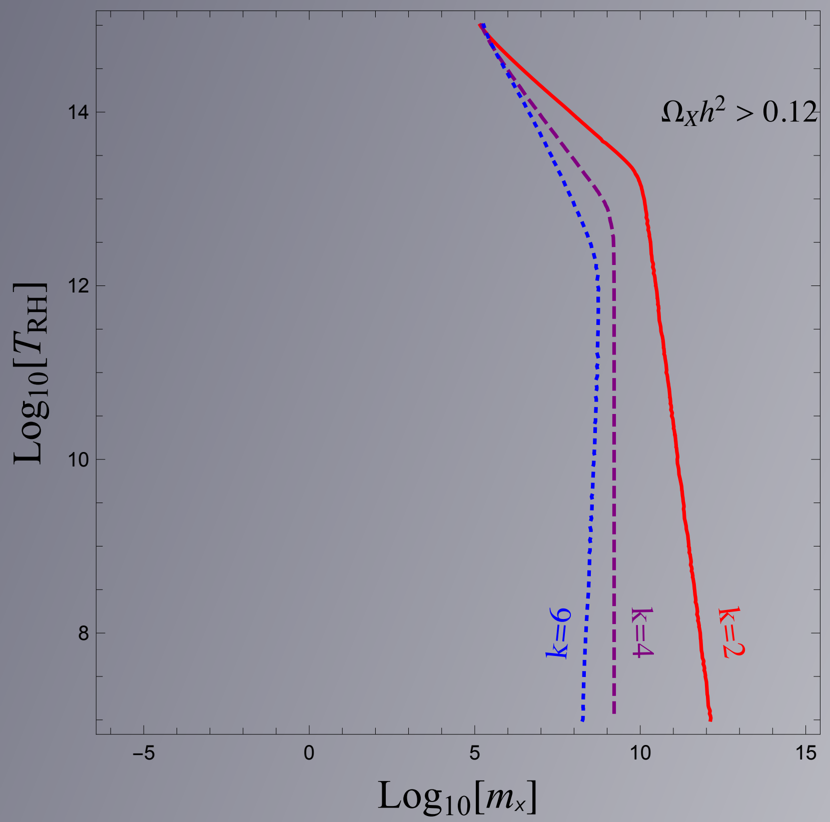
$$\frac{R_0^{\phi^k}(a_{\rm max})}{R_0^T(a_{\rm max})} = g_{\rm max}^2 \frac{5760\Sigma_0^k}{3997} \left(\frac{3k-3}{2k+4}\right)^{\frac{6}{7-k}} \left(\frac{\rho_{\rm end}}{\rho_{\rm RH}}\right)^{\frac{2}{k}} \gg 1$$

Gravitational Portals

$$\phi(p_1) + \phi(p_2) \to X^j(p_3) + X^j(p_4)$$

$$R_{1/2}^{\phi^k} = \frac{2 \times \rho_\phi^2}{4\pi M_P^4} \frac{m_X^2}{m_\phi^2} \Sigma_{1/2}^k$$

$$\frac{dY_X}{da} = \frac{\sqrt{3} M_P}{\sqrt{\rho_{\rm RH}}} a^2 \left(\frac{a}{a_{\rm RH}}\right)^{\frac{3k}{k+2}} R_X^{\phi^k}(a)$$

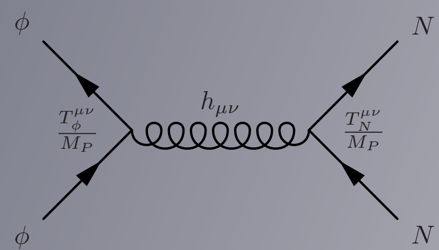


$$n_{1/2}^{\phi}(a_{\rm RH}) \simeq \frac{m_X^2 \sqrt{3}(k+2)\rho_{\rm RH}^{\frac{1}{2}+\frac{2}{k}}}{12\pi k(k-1)\lambda^{\frac{2}{k}} M_P^{1+\frac{8}{k}}} \left(\frac{\rho_{\rm end}}{\rho_{\rm RH}}\right)^{\frac{1}{k}} \Sigma_{\frac{1}{2}}^k$$

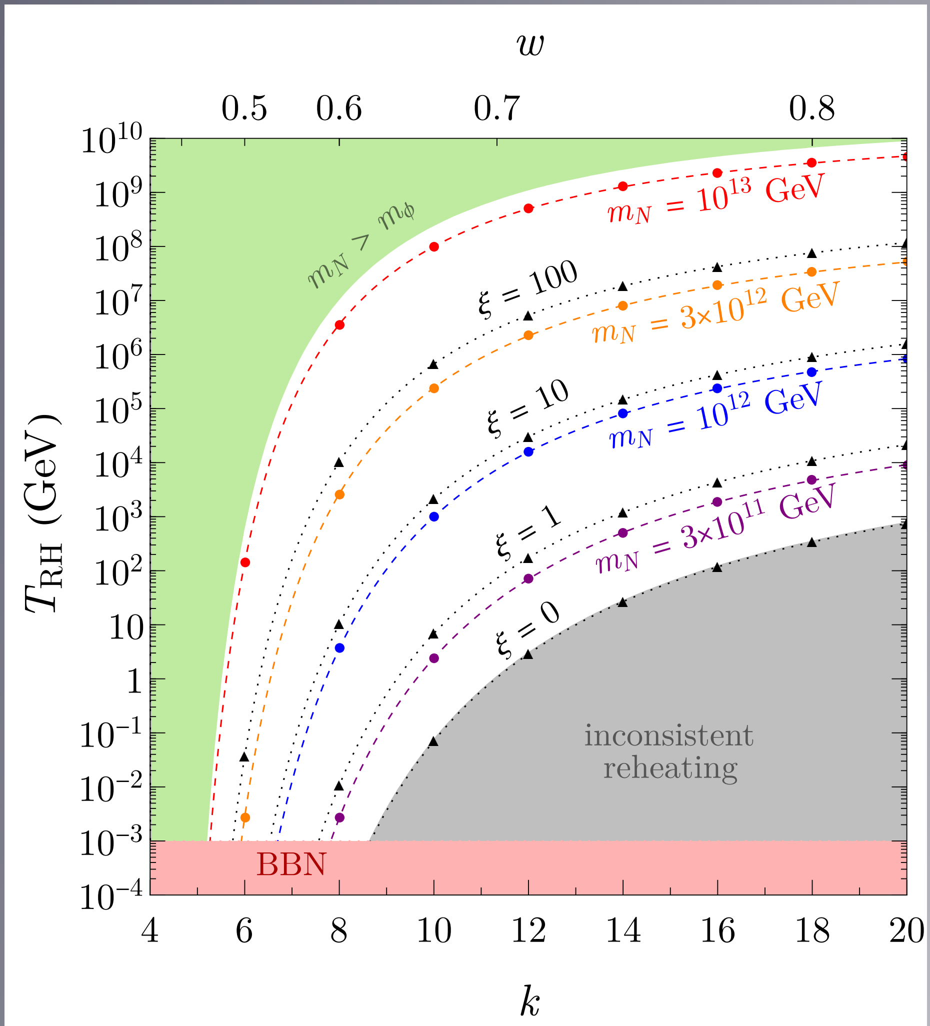
$$\frac{R_{1/2}^{\phi^k}(a_{\rm max})}{R_{1/2}^T(a_{\rm max})} = g_{\rm RH}^2 \frac{11520\ \Sigma_{1/2}^k}{11351} \frac{m_X^2}{m_\phi^2} \left(\frac{3k-3}{2k+4}\right)^{\frac{6}{7-k}} \left(\frac{\rho_{\rm end}}{\rho_{\rm RH}}\right)^{\frac{2}{k}} \gg 1$$

Inflationary Gravitational Leptogenesis

X = N_R



Co, Mambrini, Olive; Bernal, Fong



$$n_N(a_{\rm RH}) \simeq \frac{m_N^2\sqrt{3}(k+2)\rho_{\rm RH}^{\frac{1}{2}+\frac{2}{k}}}{12\pi k(k-1)\lambda^{\frac{2}{k}}M_P^{1+\frac{8}{k}}}\left(\frac{\rho_{\rm end}}{\rho_{\rm RH}}\right)^{\frac{1}{k}}\Sigma^k_{1/2}$$

$$Y_B \simeq 3.5\times10^{-4}\delta_{\rm eff}\frac{n_N}{s}\left(\frac{m_{\nu_i}}{0.05\ {\rm eV}}\right)\left(\frac{m_N}{10^{13}\ {\rm GeV}}\right)$$

$$\propto m_N^3 T_{\rm RH}^{\frac{4}{k}-1}$$

Gravitational Portals

Clery, Mambrini, Olive, Verner;
Haque, Maity

$$\phi(p_1) + \phi(p_2) \to \mathrm{SM}^i(p_3) + \mathrm{SM}^i$$

$$(\phi\phi \to h_{\mu\nu} \to HH)$$

effective quartic coupling $\mathcal{L}_h = \sigma_h \phi^2 H^2 \,.$

$$\sigma_h = \frac{\rho_\phi}{2M_P^2\phi_0^2},$$

$$\sigma_h = \frac{m_\phi^2}{4M_P^2} \simeq 3.9 \times 10^{-11} \left(\frac{m_\phi}{3 \times 10^{13}\ \mathrm{GeV}}\right)^2 .$$

k=2

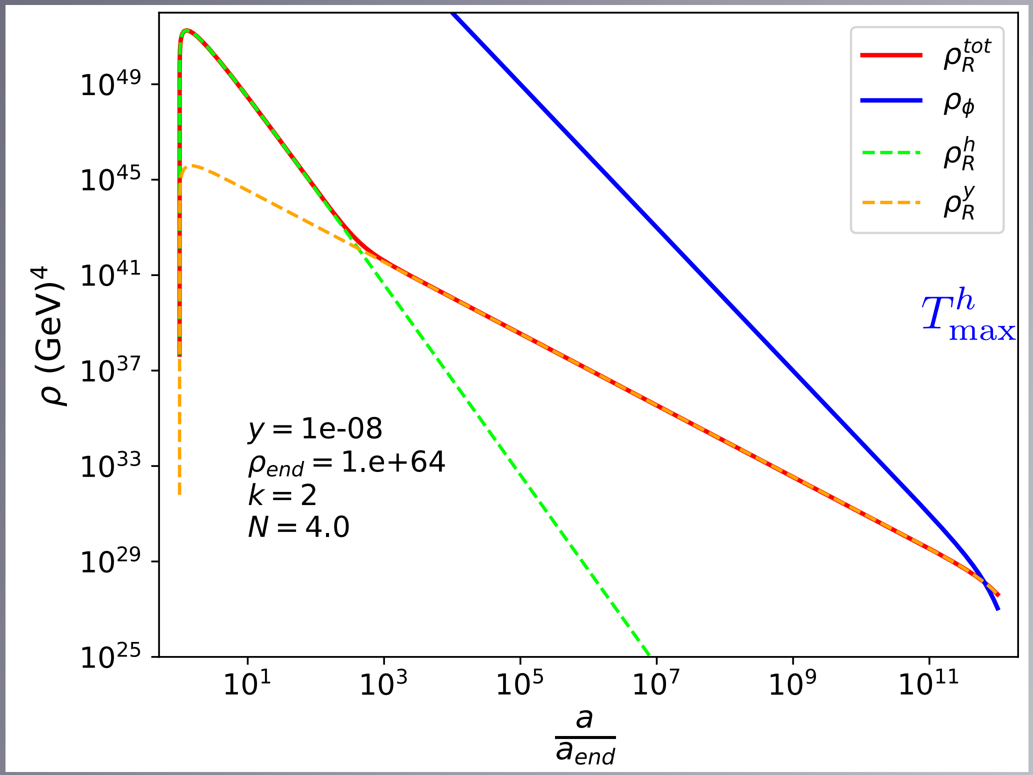
$$\frac{d\rho_R^h}{dt} + 4H\rho_R^h = N\frac{\rho_\phi^2\omega}{16\pi M_P^4}\sum_{n=1}^{\infty} n|\mathcal{P}_n^k|^2 \,.$$

Gravitational Portals

$$\phi(p_1) + \phi(p_2) \to \mathrm{SM}^i(p_3) + \mathrm{SM}^i$$
$$(\phi\phi \to h_{\mu\nu} \to HH)$$

Solution:

$$\rho_R^h = N \frac{\sqrt{3} M_P^4 \gamma_k \Sigma_k^h}{16\pi} \left(\frac{\rho_e}{M_P^4}\right)^{\frac{2k-1}{k}} \frac{k+2}{8k-14} \left[\left(\frac{a_e}{a}\right)^4 - \left(\frac{a_e}{a}\right)^{\frac{12k-6}{k+2}} \right]$$



$$\gamma_k = \sqrt{\frac{\pi}{2}} k \frac{\Gamma(\frac{1}{2} + \frac{1}{k})}{\Gamma(\frac{1}{k})} \lambda^{\frac{1}{k}} \qquad \Sigma_k^h = \sum_{n=1}^{\infty} n |\mathcal{P}_n^k|^2 .$$

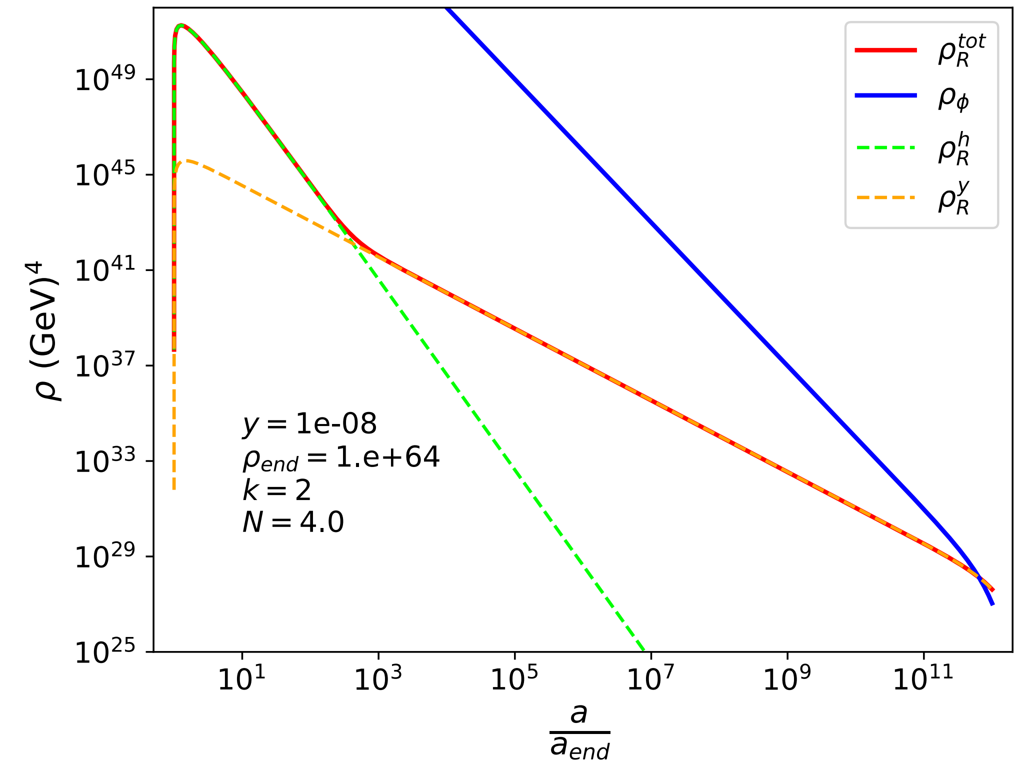
$$T_{\max}^h \simeq 3.1 \times 10^{12} \left(\frac{\rho_{\mathrm{end}}}{10^{64}\ \mathrm{GeV}^4}\right)^{\frac{3}{8}} \left(\frac{m_\phi}{3 \times 10^{13}\ \mathrm{GeV}}\right)^{\frac{1}{4}} \mathrm{GeV},$$

Absolute lower bound on T_{max}

Gravitational Portals

$$\phi(p_1) + \phi(p_2) \to \mathrm{SM}^i(p_3) + \mathrm{SM}^i$$
$$(\phi\phi \to h_{\mu\nu} \to HH)$$

Gravitationally produced radiation density exceeds that produced by decays when:



$$y \lesssim 0.4\sqrt{\frac{\rho_{\rm end}}{M_P^4}} \simeq 6.9 \times 10^{-6} \left(\frac{\rho_{\rm end}}{10^{64}\mathrm{GeV}^4}\right)^{\frac{1}{2}}$$

or

$$T_{\rm RH} \lesssim 3.0 \times 10^9 \left(\frac{\rho_{\rm end}}{10^{64}\mathrm{GeV}^4}\right)^{1/2} \left(\frac{\lambda}{2.5 \times 10^{-11}}\right)^{1/4} \mathrm{GeV}$$

Non-minimal Gravitational Portals

Clery, Mambrini, Olive,
Shkerin, Verner

Consider a non-minimal coupling to curvature:

$$\mathcal{S} = \int d^4x\sqrt{-\tilde{g}}\left[-\frac{M_P^2}{2}\Omega^2\tilde{R} + \mathcal{L}_\phi + \mathcal{L}_h + \mathcal{L}_X\right]$$

$$\Omega^2 \equiv 1 + \frac{\xi_\phi \phi^2}{M_P^2} + \frac{\xi_h h^2}{M_P^2} + \frac{\xi_X X^2}{M_P^2}$$

$$\frac{|\xi_\phi|\phi^2}{M_P^2}\,, \quad \frac{|\xi_h|h^2}{M_P^2}\,, \quad \frac{|\xi_X|X^2}{M_P^2} \ll 1\,.$$

Rewrite in the Einstein frame

$$\mathcal{S} = \int d^4x\sqrt{-g}\left[-\frac{M_P^2}{2}R + \frac{1}{2}K^{ij}g^{\mu\nu}\partial_\mu S_i \partial_\nu S_j - \frac{V_\phi + V_h + V_X}{\Omega^4}\right]\,.$$

$$K^{ij} = 6\frac{\partial \log\Omega}{\partial S_i}\frac{\partial \log\Omega}{\partial S_j} + \frac{\delta^{ij}}{\Omega^2}\,.$$

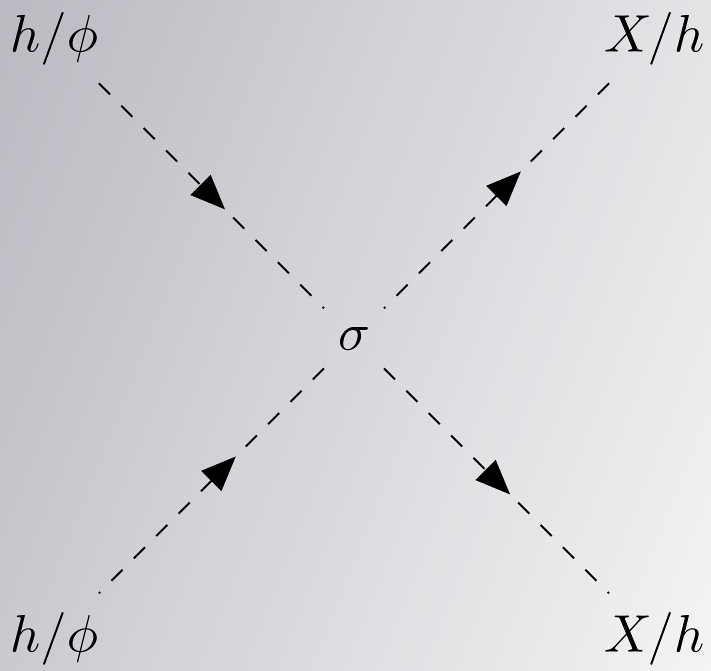
Non-minimal Gravitational Portals

In the limit, $\frac{|\xi_\phi|\phi^2}{M_P^2}\,, \quad \frac{|\xi_h|h^2}{M_P^2}\,, \quad \frac{|\xi_X|X^2}{M_P^2} \ll 1\,.$

Generate $$\mathcal{L}_{\rm non-min.} = -\sigma^{\xi}_{hX} h^2 X^2 - \sigma^{\xi}_{\phi X}\phi^2 X^2 - \sigma^{\xi}_{\phi h}\phi^2 h^2\,,$$

For example,

$$\sigma^{\xi}_{hX} = \frac{1}{4M_P^2}\left[\xi_h(2m_X^2+s)+\xi_X(2m_h^2+s)\right.$$
$$\left.+\left(12\xi_X\xi_h(m_h^2+m_X^2-t)\right)\right]\,,$$



Non-minimal Gravitational Portals

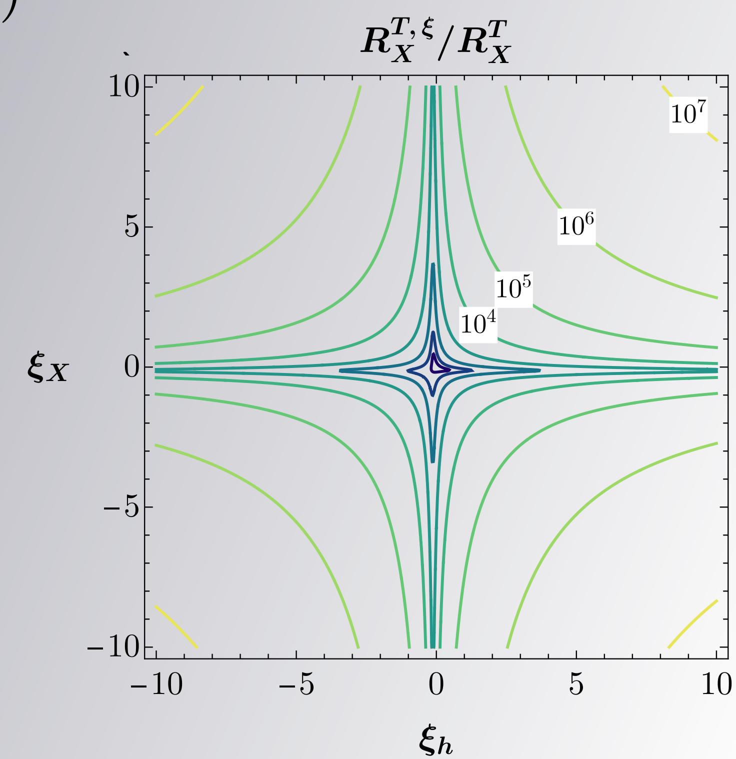
$$\mathrm{SM}^i(p_1) + \mathrm{SM}^i(p_2) \to X^j(p_3) + X^j(p_4)$$

$$\frac{dY_X^\xi}{da} = \frac{\sqrt{3}M_P}{\sqrt{\rho_{\mathrm{RH}}}} a^2 \left(\frac{a}{a_{\mathrm{RH}}}\right)^{\frac{3}{2}} R_X^{T,\,(\xi)}(a)$$

$$R_X^{T,\,(\xi)}(T) = \quad \beta_1^{(\xi)} \frac{T^8}{M_P^4} + \quad \cdots.$$

$$n_X^{T,\,\xi}(a_{\mathrm{RH}}) = \frac{2\beta_1^\xi}{\sqrt{3}\alpha^2 M_P^3} \frac{\rho_{\mathrm{RH}}^{3/2}}{(1-(a_{\mathrm{end}}/a_{\mathrm{RH}})^{\frac{5}{2}})^2} \times \ (1 + \ldots$$

$$\beta_1^\xi = \frac{\pi^3}{81000} \left[30\xi_h^2 (12\xi_X(4\xi_X + 1) + 1) + 10\xi_h(6\xi_X+1)^2 + 10\xi_X(3\xi_X+1) + 1\right],$$



$$\alpha = g_{\mathrm{RH}}\pi^2/30$$

Non-minimal Gravitational Portals

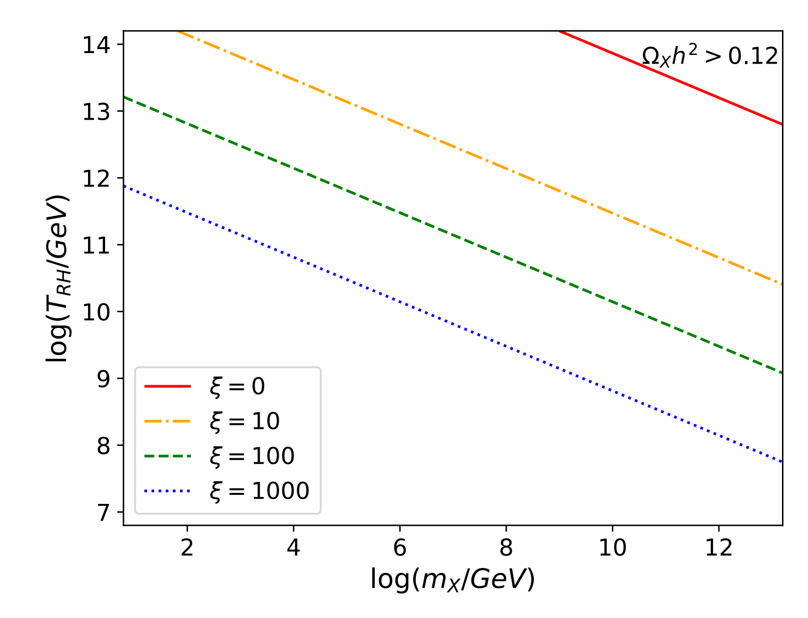
$$\mathrm{SM}^i(p_1) + \mathrm{SM}^i(p_2) \to X^j(p_3) + X^j(p_4)$$

$$\frac{dY_X^\xi}{da} = \frac{\sqrt{3}M_P}{\sqrt{\rho_{\mathrm{RH}}}} a^2 \left(\frac{a}{a_{\mathrm{RH}}}\right)^{\frac{3}{2}} R_X^{T,(\xi)}(a)$$

$$R_X^{T,(\xi)}(T) = \beta_1^{(\xi)} \frac{T^8}{M_P^4} + \quad \cdots$$

$$n_X^{T,\xi}(a_{\mathrm{RH}}) = \frac{2\beta_1^\xi}{\sqrt{3}\alpha^2 M_P^3} \frac{\rho_{\mathrm{RH}}^{3/2}}{(1-(a_{\mathrm{end}}/a_{\mathrm{RH}})^{\frac{5}{2}})^2} \times \ (1 + \ldots$$

$$\beta_1^\xi = \frac{\pi^3}{81000}\left[30\xi_h^2\left(12\xi_X(4\xi_X+1)+1\right) + 10\xi_h(6\xi_X+1)^2 + 10\xi_X(3\xi_X+1)+1\right],$$



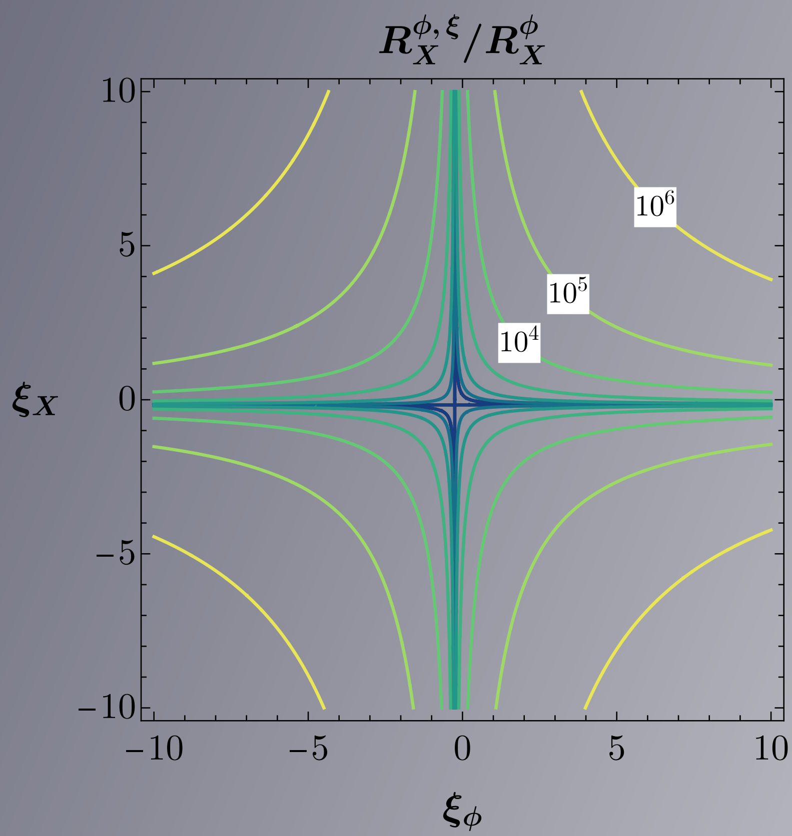
$$\alpha = g_{\mathrm{RH}}\pi^2/30$$

Non-minimal Gravitational Portals

$$\phi(p_1) + \phi(p_2) \to X^j(p_3) + X^j(p_4)$$

$$\frac{dY_X^{\xi}}{da} = \frac{\sqrt{3}M_P}{\sqrt{\rho_{\rm RH}}} a^2 \left(\frac{a}{a_{\rm RH}}\right)^{\frac{3}{2}} R_X^{\phi,\,\xi}(a)$$

$$R_X^{\phi,\,\xi} = \frac{2 \times \sigma_{\phi X}^{\xi\;2}}{16\pi} \frac{\rho_\phi^2}{m_\phi^4} \sqrt{1 - \frac{m_X^2}{m_\phi^2}}$$



$$n_X^{\phi,\,\xi}(a_{\rm RH}) \simeq \frac{\sigma_{\phi X}^{\xi\;2} \rho_{\rm RH} \sqrt{\rho_{\rm end}} M_P}{4\sqrt{3}\pi m_\phi^4} \sqrt{1 - \frac{m_X^2}{m_\phi^2}}\,,$$

$$\frac{\Omega_X^{\phi,\,\xi} h^2}{0.12} \simeq \frac{1.3 \times 10^7 \sigma_{\phi X}^{\xi\;2} \rho_{\rm RH}^{1/4} M_P^2}{m_\phi^3} \frac{m_X}{1\,{\rm GeV}} \sqrt{1 - \frac{m_X^2}{m_\phi^2}}\,,$$

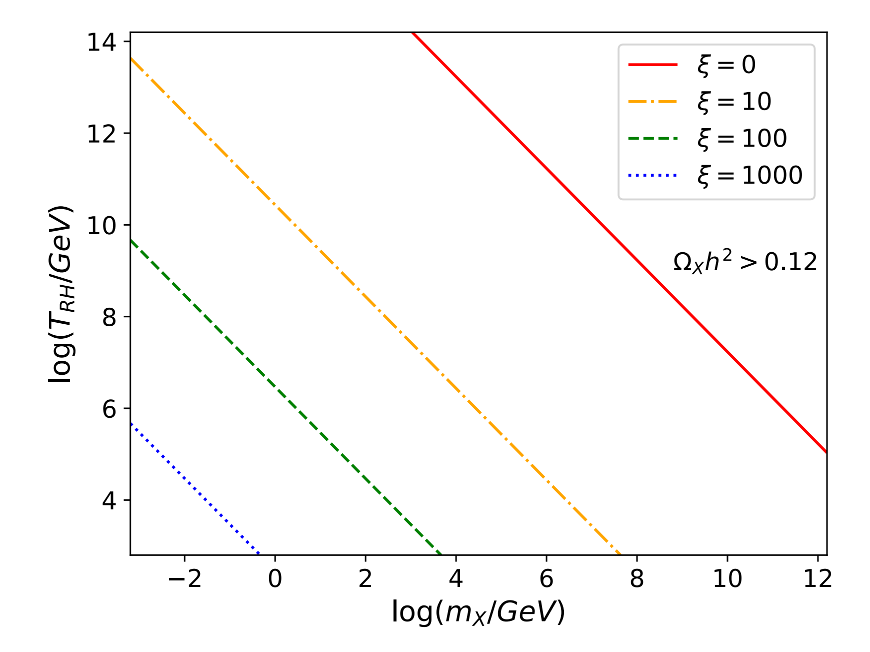
$$\frac{\Omega_X^{\phi,\,\xi}}{\Omega_X^{\phi}} = \frac{\sigma_{\phi X}^{\xi\;2}}{\sigma_{\phi X}^2} \simeq 4\xi^2(5 + 12\xi)^2\,,$$

Non-minimal Gravitational Portals

$$\phi(p_1) + \phi(p_2) \to X^j(p_3) + X^j(p_4)$$

$$\frac{dY_X^\xi}{da} = \frac{\sqrt{3}M_P}{\sqrt{\rho_{\rm RH}}} a^2 \left(\frac{a}{a_{\rm RH}}\right)^{\frac{3}{2}} R_X^{\phi,\,\xi}(a)$$

$$R_X^{\phi,\,\xi} = \frac{2 \times \sigma_{\phi X}^{\xi\ 2}}{16\pi} \frac{\rho_\phi^2}{m_\phi^4} \sqrt{1 - \frac{m_X^2}{m_\phi^2}}$$



$$n_X^{\phi,\,\xi}(a_{\rm RH}) \simeq \frac{\sigma_{\phi X}^{\xi\ 2} \rho_{\rm RH} \sqrt{\rho_{\rm end}} M_P}{4\sqrt{3}\pi m_\phi^4} \sqrt{1 - \frac{m_X^2}{m_\phi^2}}\,,$$

$$\frac{\Omega_X^{\phi,\,\xi} h^2}{0.12} \simeq \frac{1.3 \times 10^7 \sigma_{\phi X}^{\xi\ 2} \rho_{\rm RH}^{1/4} M_P^2}{m_\phi^3} \frac{m_X}{1\,{\rm GeV}} \sqrt{1 - \frac{m_X^2}{m_\phi^2}}\,,$$

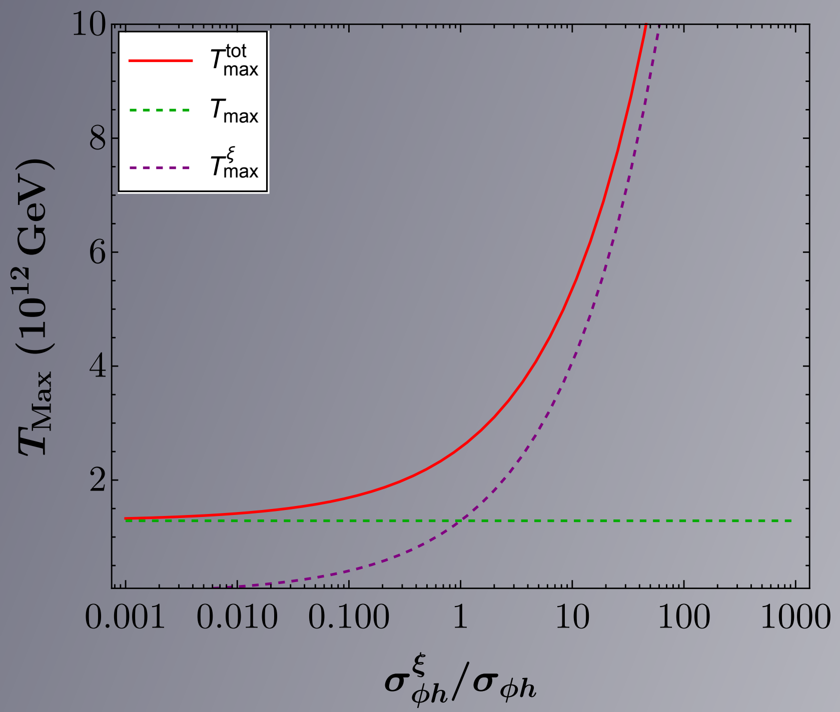
$$\frac{\Omega_X^{\phi,\,\xi}}{\Omega_X^\phi} = \frac{\sigma_{\phi X}^{\xi\ 2}}{\sigma_{\phi X}^2} \simeq 4\xi^2(5 + 12\xi)^2\,,$$

Non-minimal Gravitational Portals

$$\phi(p_1) + \phi(p_2) \to \mathrm{SM}^i(p_3) + \mathrm{SM}^i$$

$$(\phi\phi \to h_{\mu\nu} \to HH)$$

$$\frac{d\rho_R}{dt} + 4H\rho_R \simeq N_h \frac{\sigma^{\xi\ 2}_{\phi h}}{8\pi} \frac{\rho_\phi^2}{m_\phi^3}$$



$$T^{\xi}_{\rm max} \simeq 1.8 \times 10^{12} \sqrt{|\xi|}\,(|5+12\xi|)^{\frac{1}{2}} \left(\frac{m_\phi}{3\times 10^{13}\,\mathrm{GeV}}\right) \mathrm{GeV}$$

dominates when

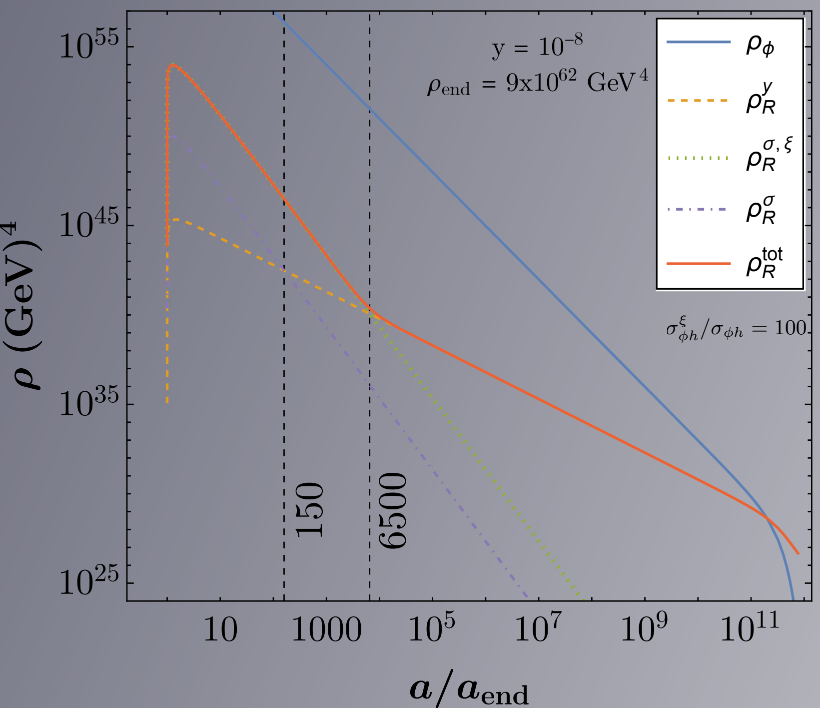
$$T_{\rm RH} \lesssim 2.4 \times 10^9 \left(\frac{m_\phi}{3\times 10^{13}}\right)^{\frac{3}{2}} \xi(5+12\xi)\ \mathrm{GeV}$$

Non-minimal Gravitational Portals

$$\phi(p_1) + \phi(p_2) \to \mathrm{SM}^i(p_3) + \mathrm{SM}^i$$

$$(\phi\phi \to h_{\mu\nu} \to HH)$$

$$\frac{d\rho_R}{dt} + 4H\rho_R \simeq N_h \frac{{\sigma^{\xi}_{\phi h}}^2}{8\pi} \frac{\rho_\phi^2}{m_\phi^3}$$



$$T^{\xi}_{\max} \simeq 1.8 \times 10^{12} \sqrt{|\xi|}\,(|5 + 12\xi|)^{\frac{1}{2}} \left(\frac{m_\phi}{3 \times 10^{13}\,\mathrm{GeV}}\right) \mathrm{GeV}$$

dominates when

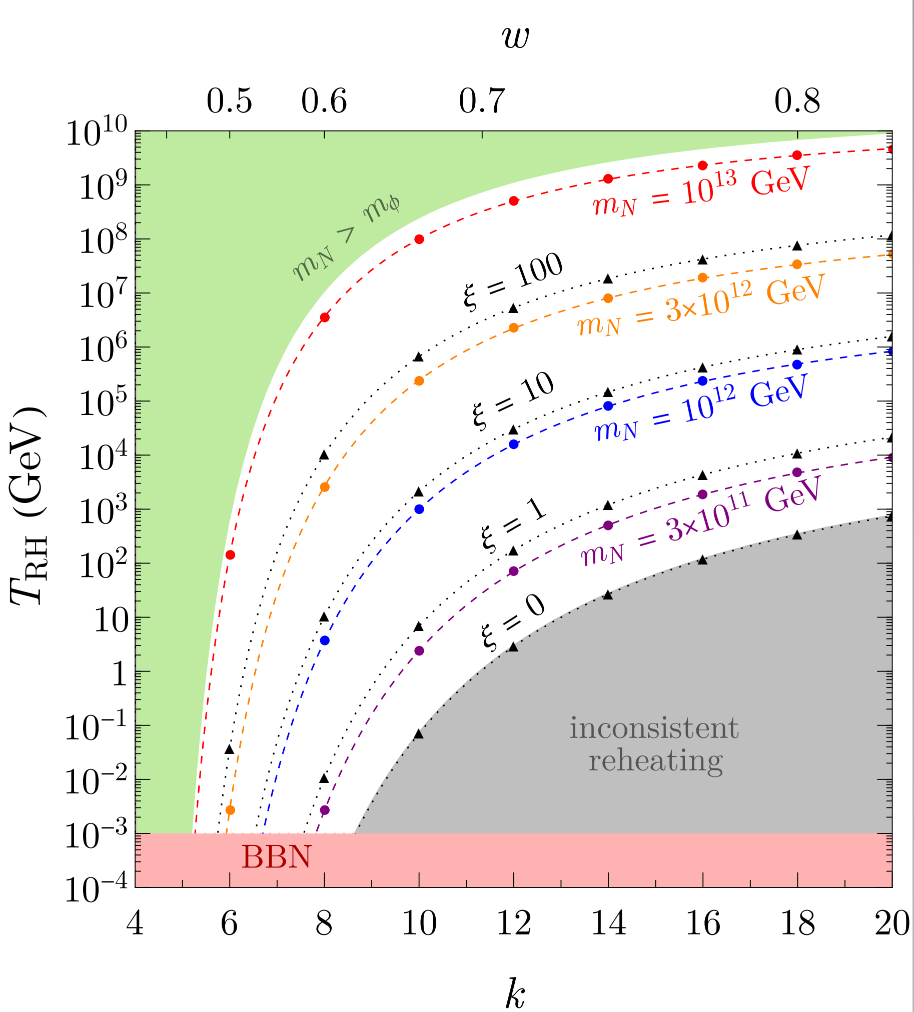
$$T_{\mathrm{RH}} \lesssim 2.4 \times 10^9 \left(\frac{m_\phi}{3 \times 10^{13}}\right)^{\frac{3}{2}} \xi(5 + 12\xi)\ \mathrm{GeV}$$

Non-minimal Gravitational Portals

Co, Mambrini, Olive

$$\phi(p_1) + \phi(p_2) \to \text{SM}^i(p_3) + \text{SM}^i$$

$$(\phi\phi \to h_{\mu\nu} \to HH)$$



For k>6, entire radiation bath can be produced when $\xi > 0$

Summary

- Reheating- an essential component of all inflation models
- In many cases, the instantaneous reheating approximation is too crude.
- Particle Production enhanced in the early phases of reheating when rates are proportional to T^{n+6} with $n > 6$ (expected for gravitino production in high scale susy models).
- Gravitational portals determine a minimal particle production rate and a minimal maximum temperature during reheating.
- Can be an important (and minimal) component for leptogenesis.