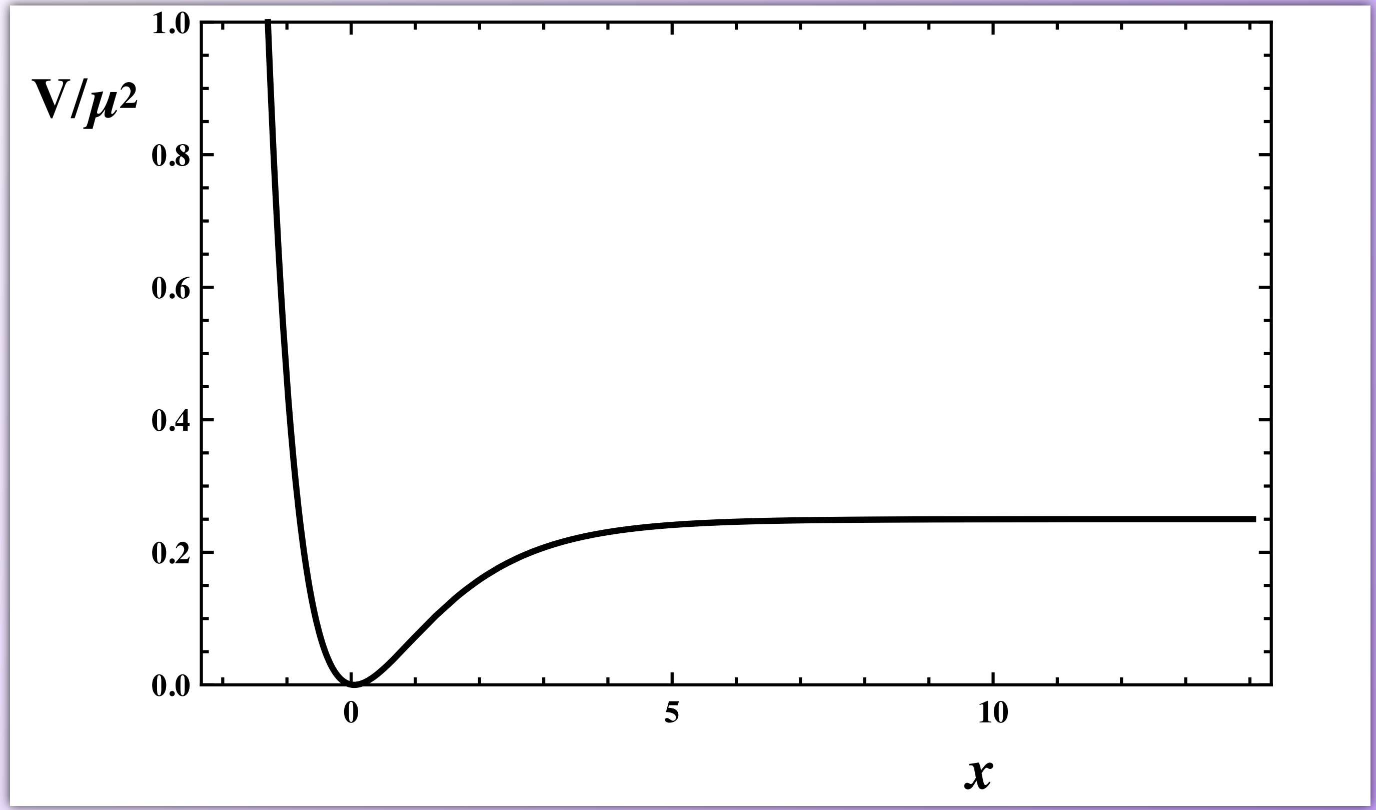
Gravitational Portals

- 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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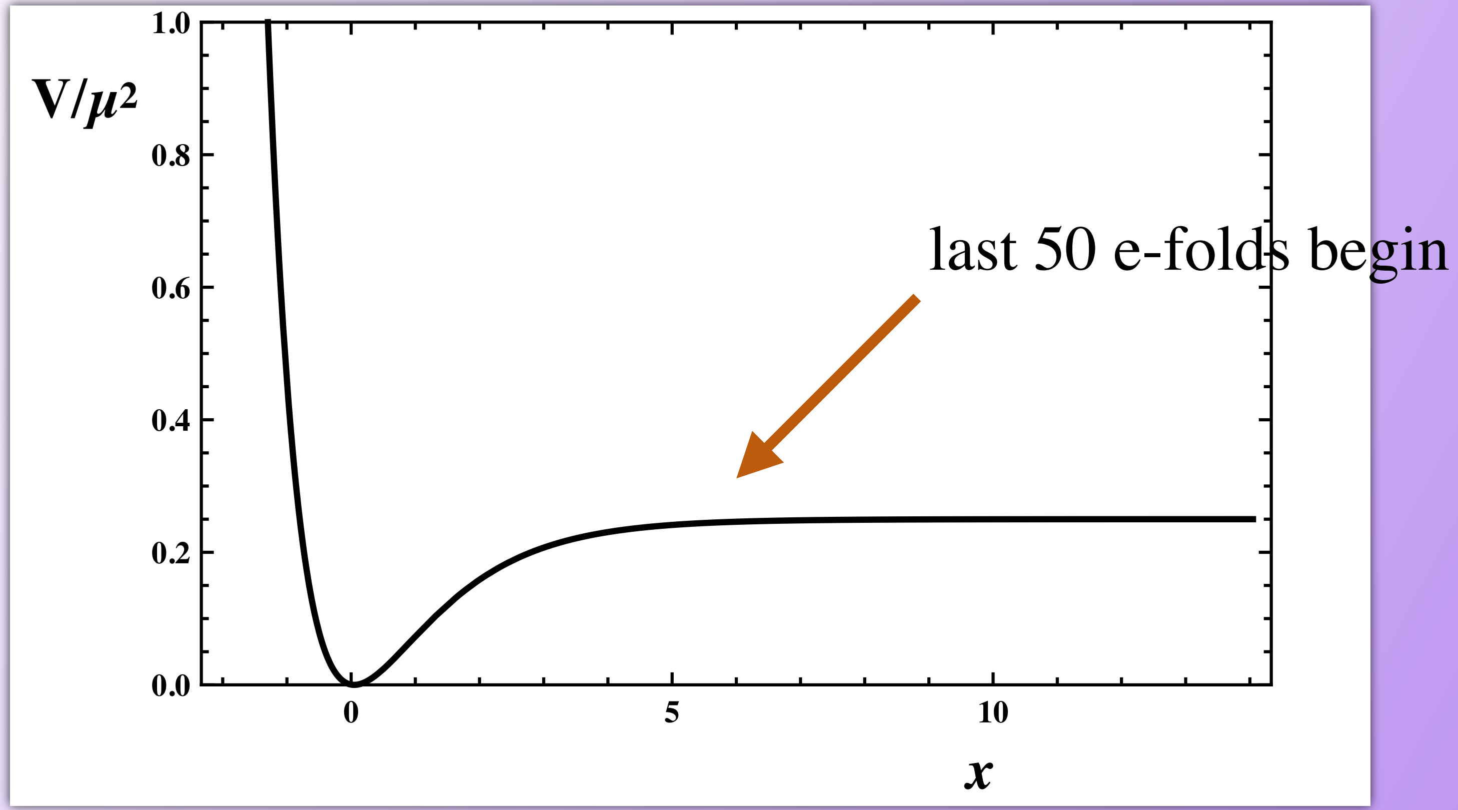

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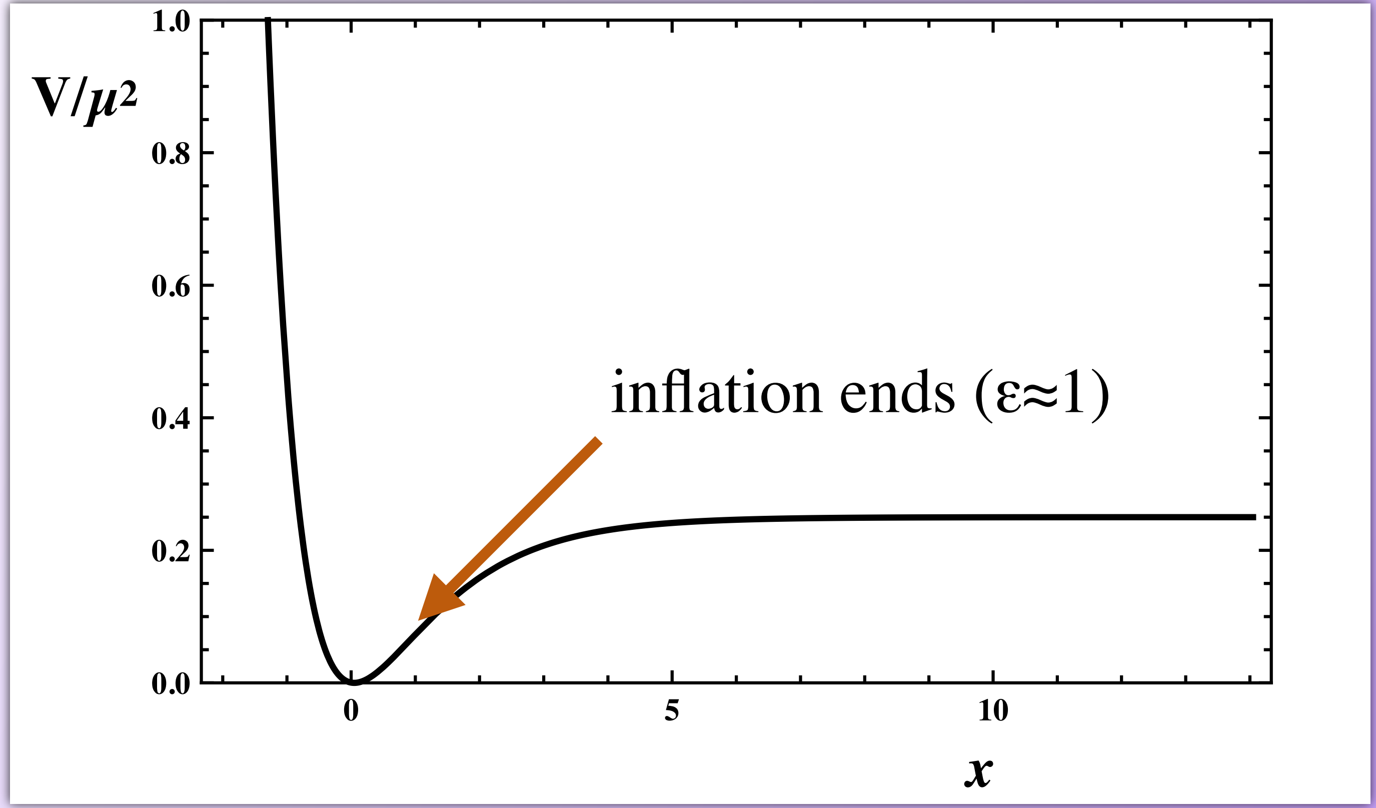

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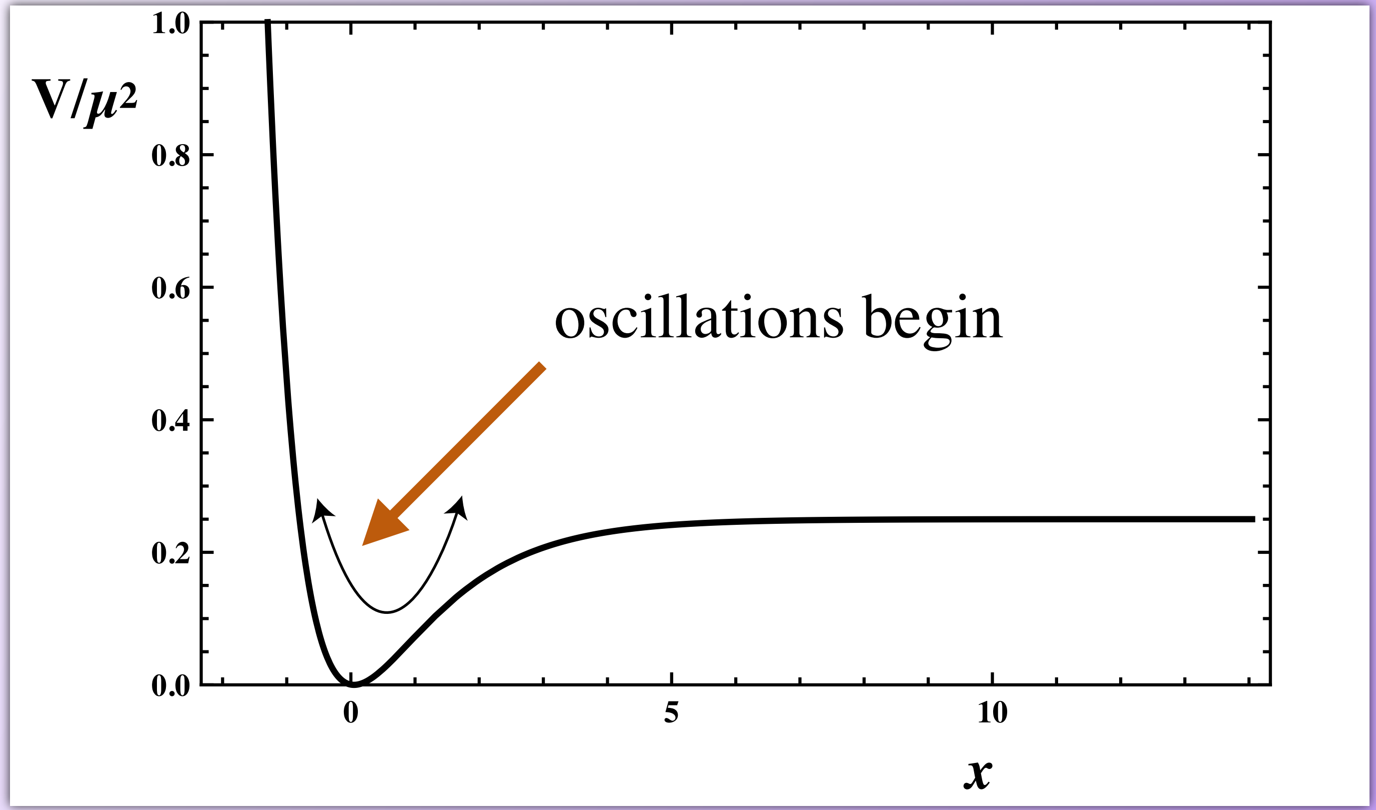


Then what happens?

- 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 $\quad \tilde{g}_{\mu\nu} = e^{2\Omega}g_{\mu\nu} = \left(1 + 2\tilde{\alpha}\Phi\right)g_{\mu\nu}$

Leading to

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

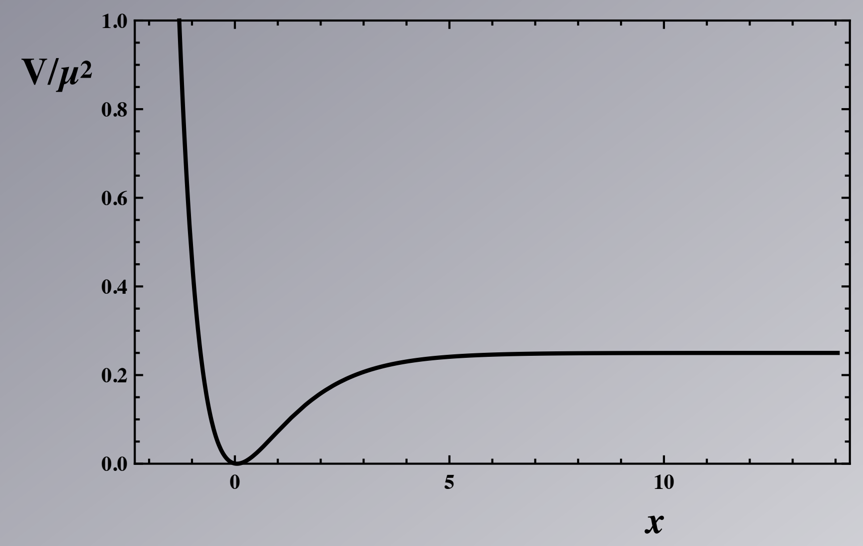
$$\tilde{\alpha} = 1/6M^2$$

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

Starobinsky

Planck-friendly Models: R+R² Inflation

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



$x = \varphi/M_P$, $\mu^2 = 3M^2$

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

$$A_s = \frac{V}{24\pi^2\epsilon} = \frac{\mu^2}{8\pi^2}\sinh^4(x/\sqrt{6}) \implies \mu = 2.2 \times 10^{-5} \text{ for } N = 55$$

$x_i = 5.35$

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

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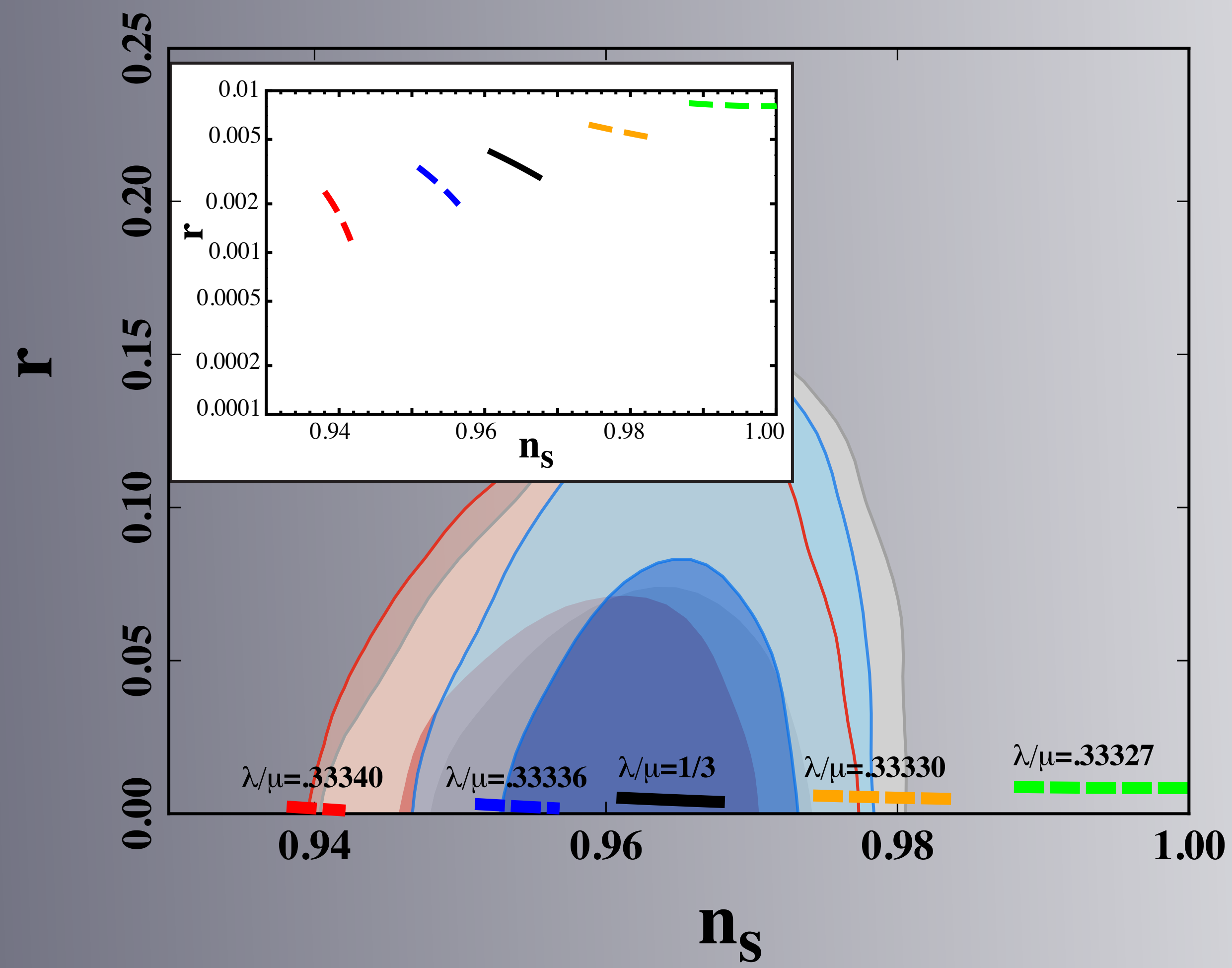
How well does this do vis a vis Planck?



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

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

Endo, Kadota, Olive, Takahashi, Yanagida

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

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

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

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

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

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

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

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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 $$V = \lambda\left[\sqrt{6}\tanh(\varphi'/\sqrt{6})\right]^k$$

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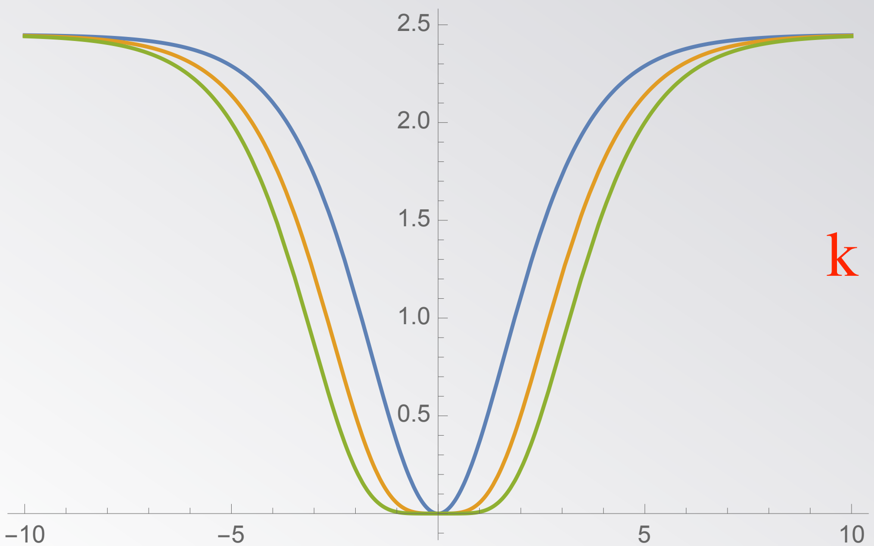

k = 2,4,6

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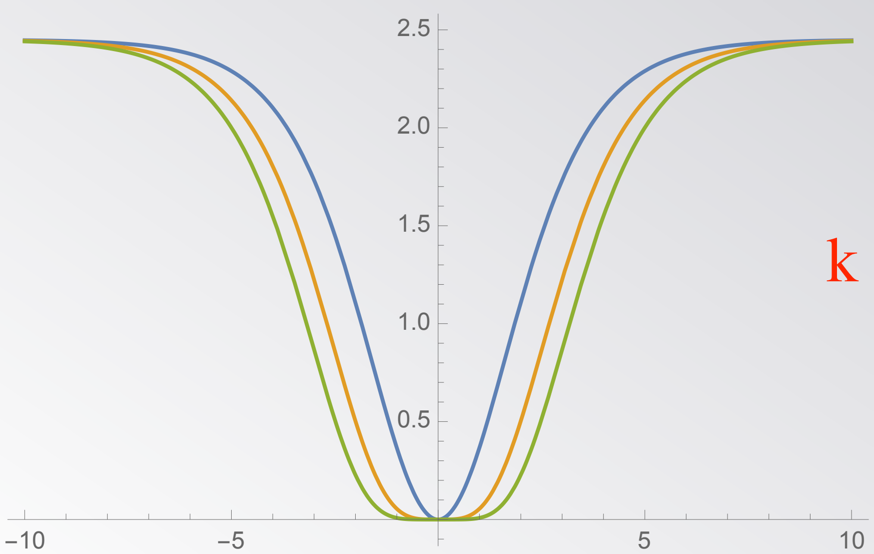


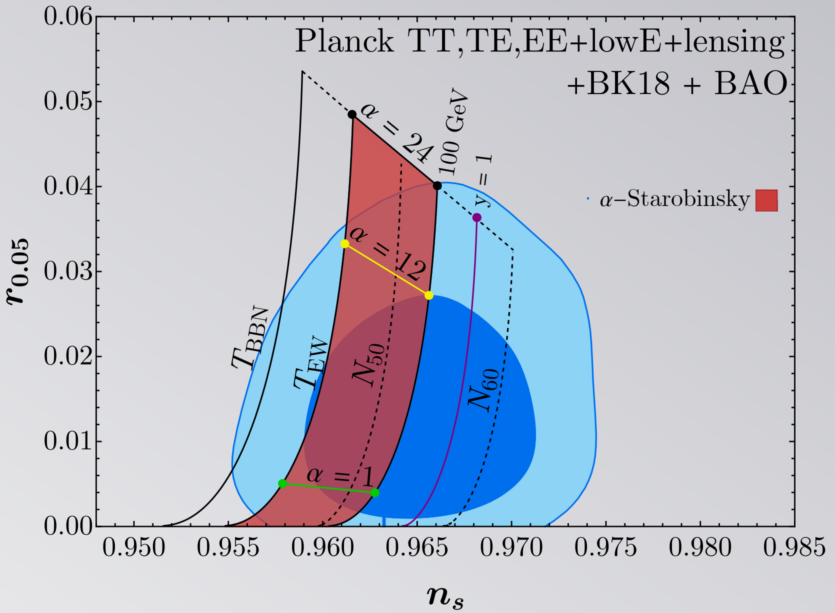
k = 2,4,6

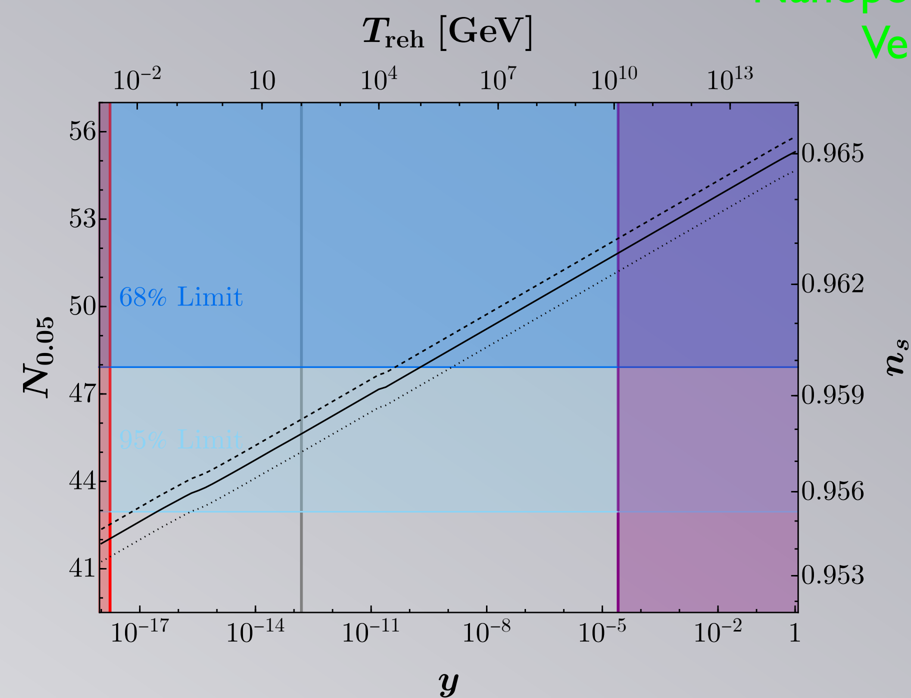
$$V = \lambda\varphi'^k$$

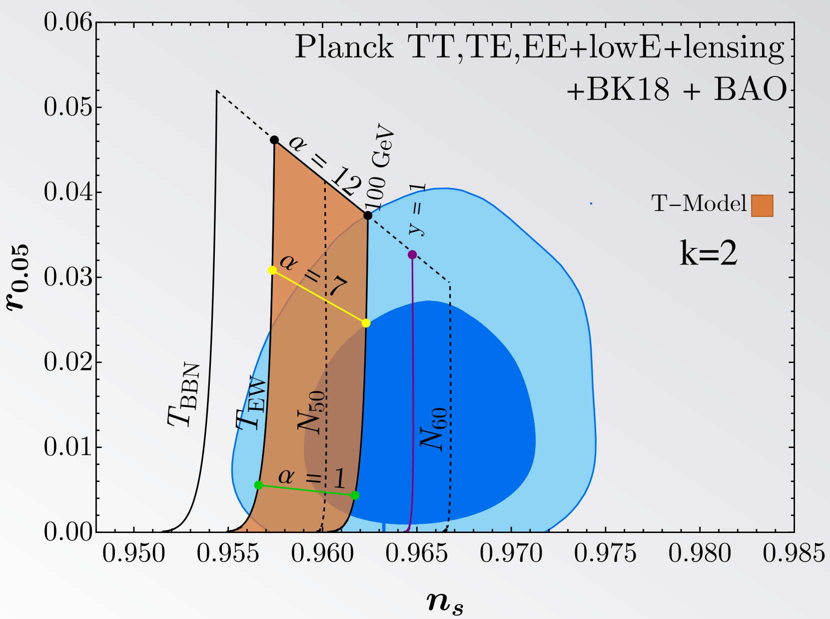
$$\varphi' \ll 1$$

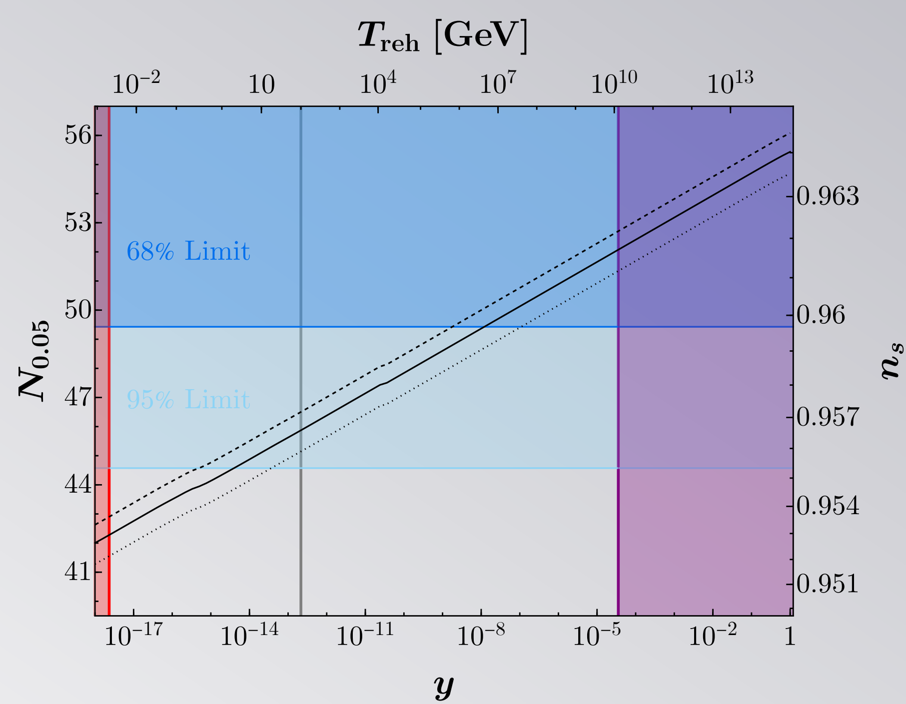
Results for α-Starobuinsky and α-T-models   -3ln →-3α ln

Ellis, Garcia, Nanopoulis, Olive, Verner









Post-Inflation

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

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

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

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

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

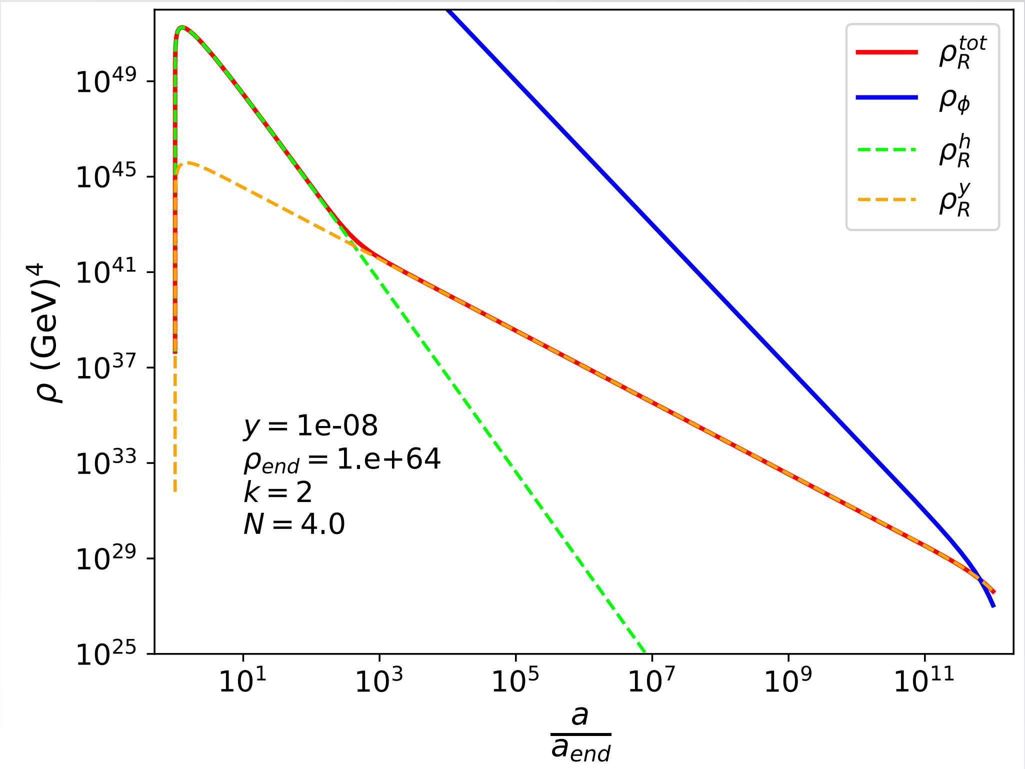
Reheating: Generation of the Radiation bath

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

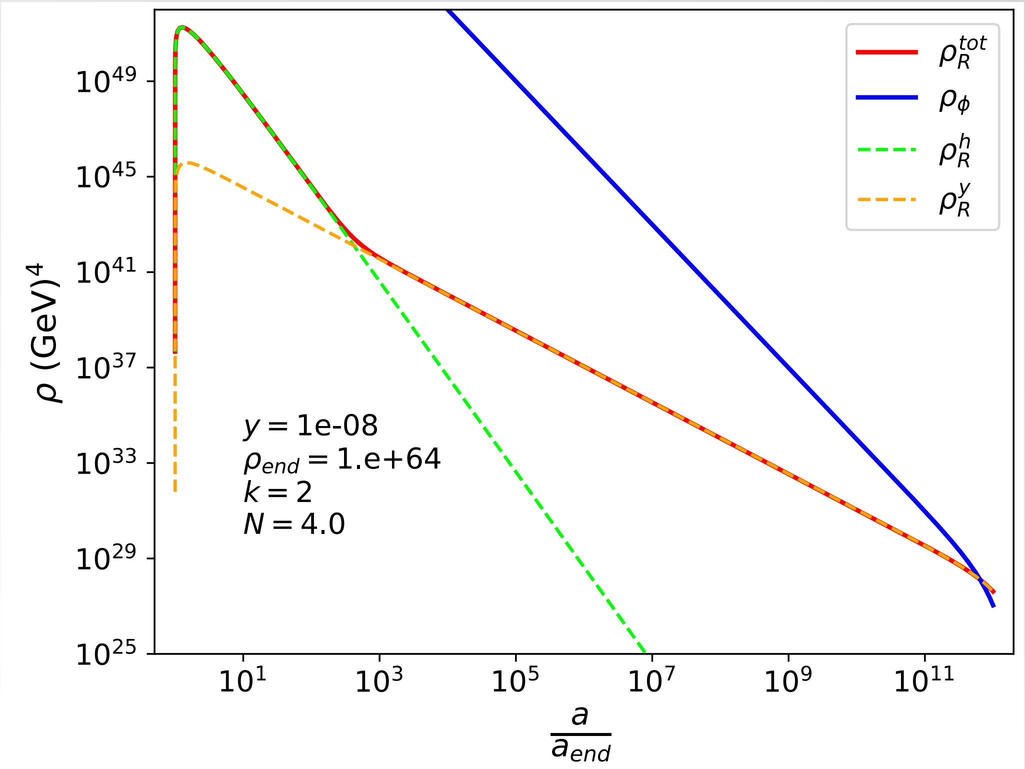
$$\rho_R = \frac{g_T \pi^2}{30} T^4$$

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

for k=2:

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

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



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

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

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.

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

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

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 $n = \frac{10-2k}{k-1}$,

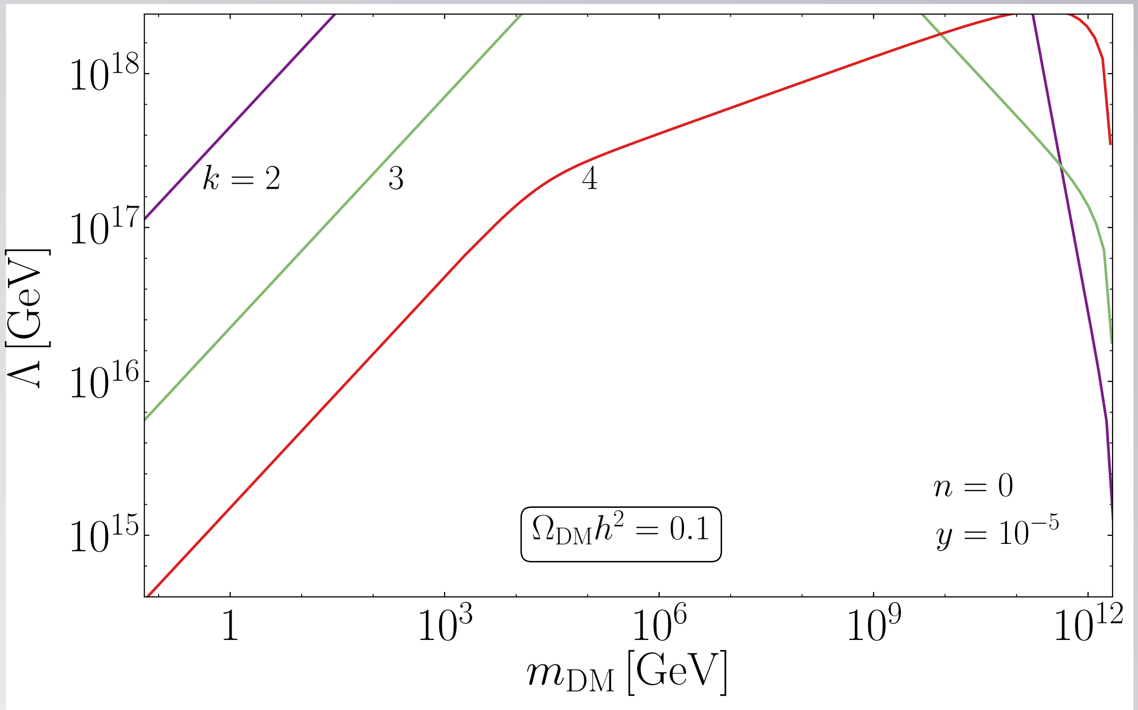
$$n^s(T_{\rm reh}) = \sqrt{\frac{10}{g_*}}\frac{M_P}{\pi}\left(\frac{2k+4}{k-1}\right)\frac{T_{\rm reh}^{n+4}}{\Lambda^{n+2}}\ln\left(\frac{T_{\rm max}}{T_{\rm reh}}\right).$$

(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



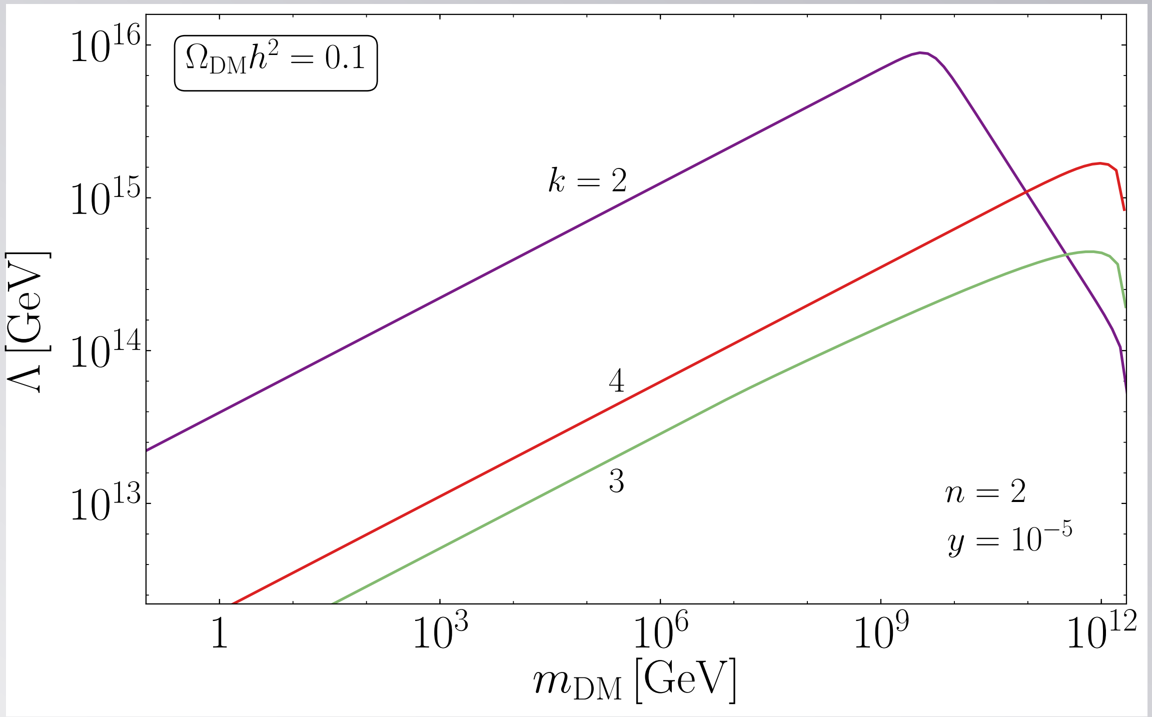
Garcia, Kaneta, Mambrini, Olive

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



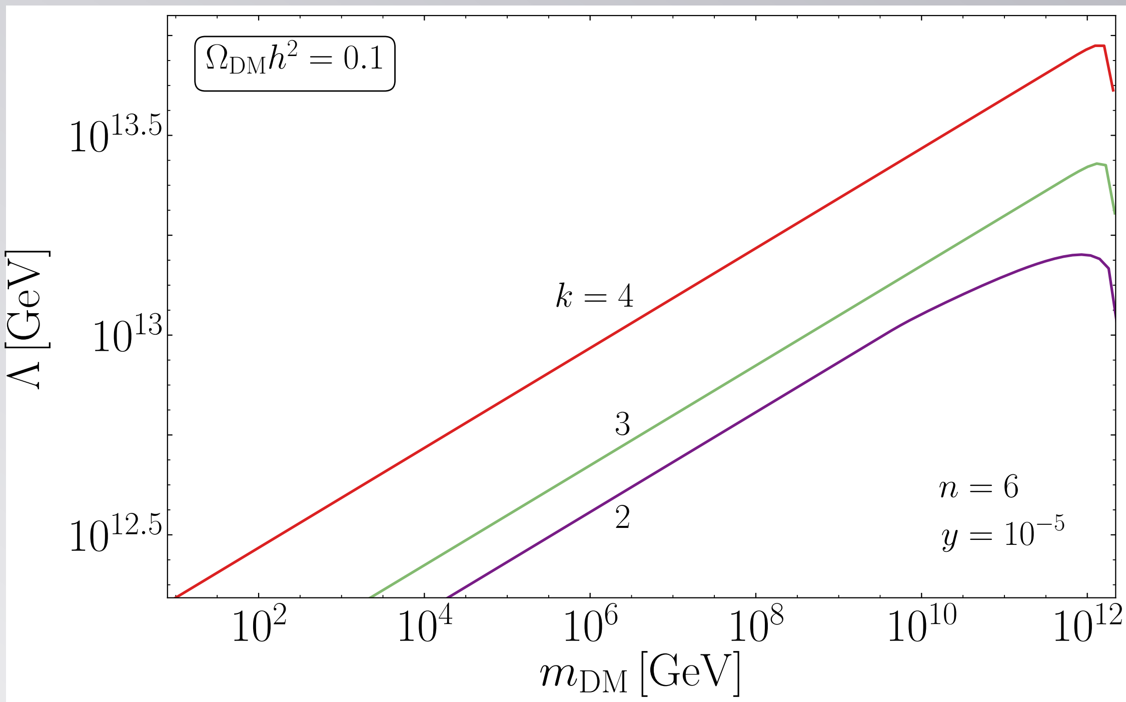
Garcia, Kaneta, Mambrini, Olive

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

ex: mediator with mass Λ

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

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

Dudas, Mambrini, Olive

Gravitational Portals

Mambrini, Olive;
Clery, Mambrini, Olive, Verner

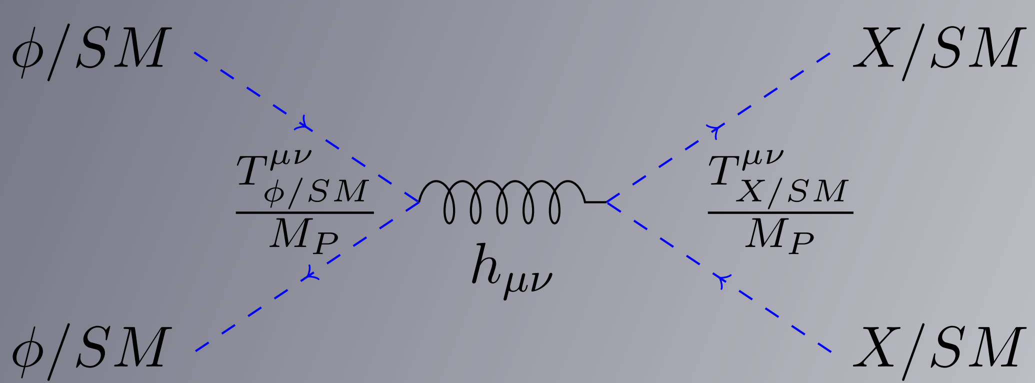
Start with Einstein-Hilbert Lagrangian

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

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

Graviational interactions

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



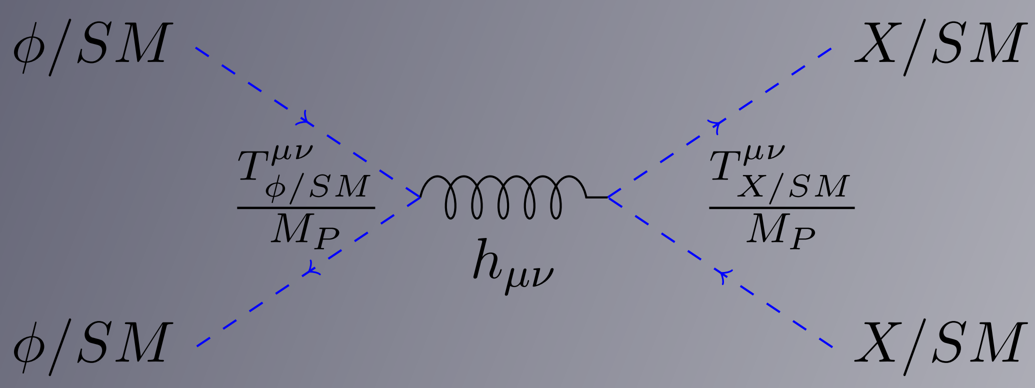
$$T_0^{\mu\nu} = \partial^\mu S \partial^\nu S - g^{\mu\nu} \left[\frac{1}{2} \partial^\alpha S \partial_\alpha S - V(S) \right],$$

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

$$T_1^{\mu\nu} = \frac{1}{2} \left[F^\mu_\alpha F^{\nu\alpha} + F^\nu_\alpha F^{\mu\alpha} - \frac{1}{2} g^{\mu\nu} F^{\alpha\beta} F_{\alpha\beta} \right],$$

Gravitational Portals

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



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

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

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

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

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

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

k=2

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

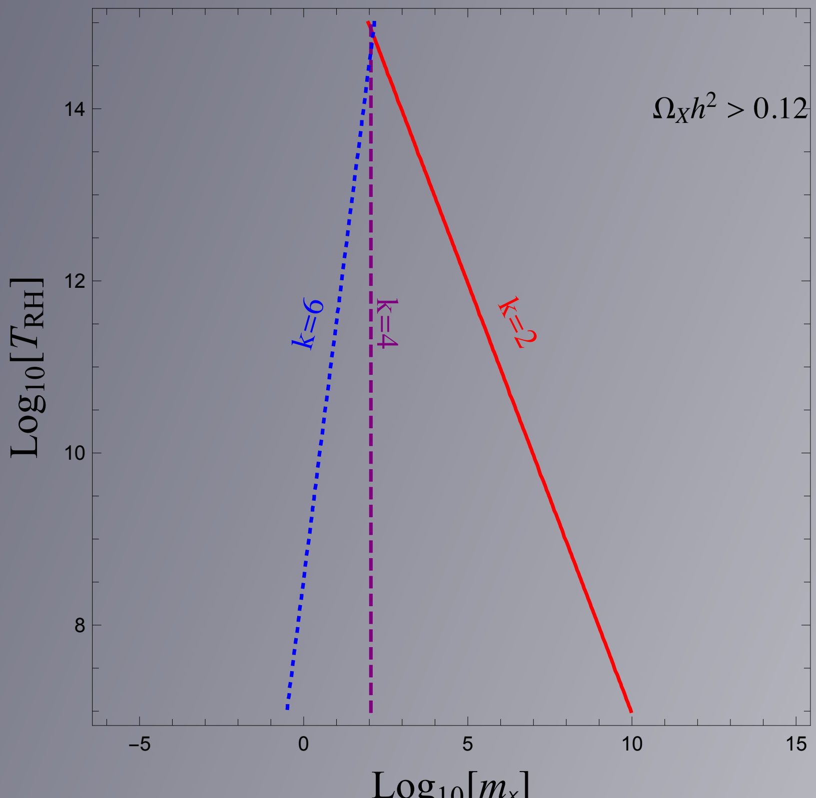
$$\beta_0 = \frac{3997\pi^3}{20736000} \qquad \beta_{1/2} = \frac{11351\pi^3}{10368000}$$

Gravitational Portals

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

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

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



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

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

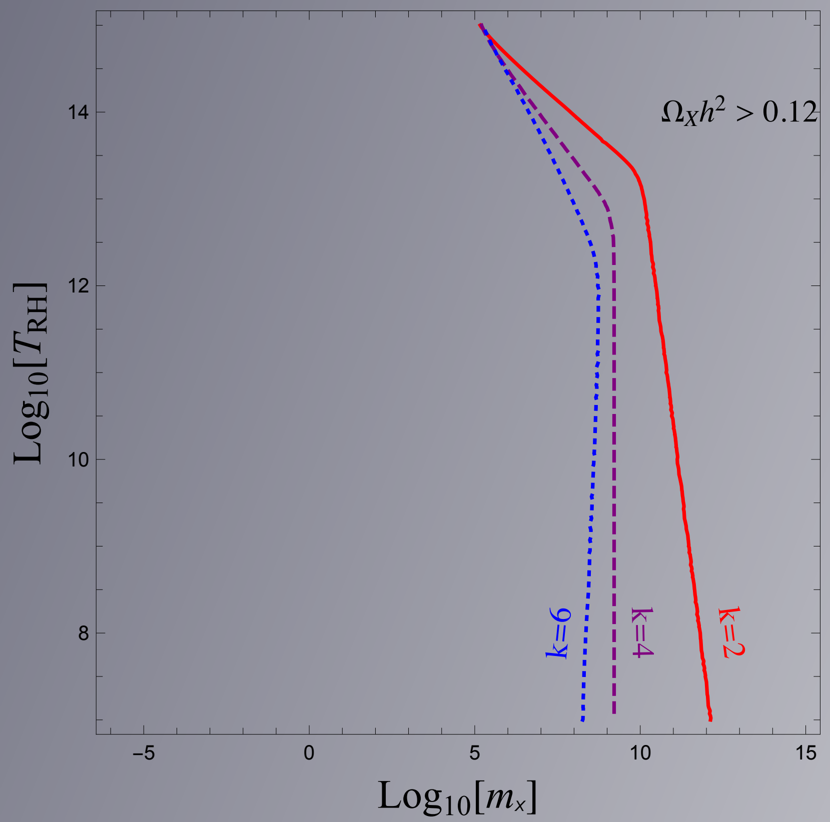
$$\frac{R_0^{\phi^k}(a_{\rm max})}{R_0^T(a_{\rm max})} = g_{\rm max}^2 \frac{5760\Sigma_0^k}{3997} \left(\frac{3k-3}{2k+4}\right)^{\frac{6}{7-k}} \left(\frac{\rho_{\rm end}}{\rho_{\rm RH}}\right)^{\frac{2}{k}} \gg 1$$

Gravitational Portals

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

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

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

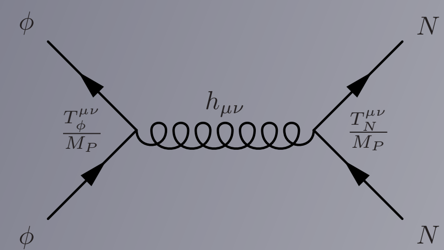


$$n_{1/2}^{\phi}(a_{\rm RH}) \simeq \frac{m_X^2 \sqrt{3}(k+2)\rho_{\rm RH}^{\frac{1}{2}+\frac{2}{k}}}{12\pi k(k-1)\lambda^{\frac{2}{k}} M_P^{1+\frac{8}{k}}} \left(\frac{\rho_{\rm end}}{\rho_{\rm RH}}\right)^{\frac{1}{k}} \Sigma_{\frac{1}{2}}^k$$

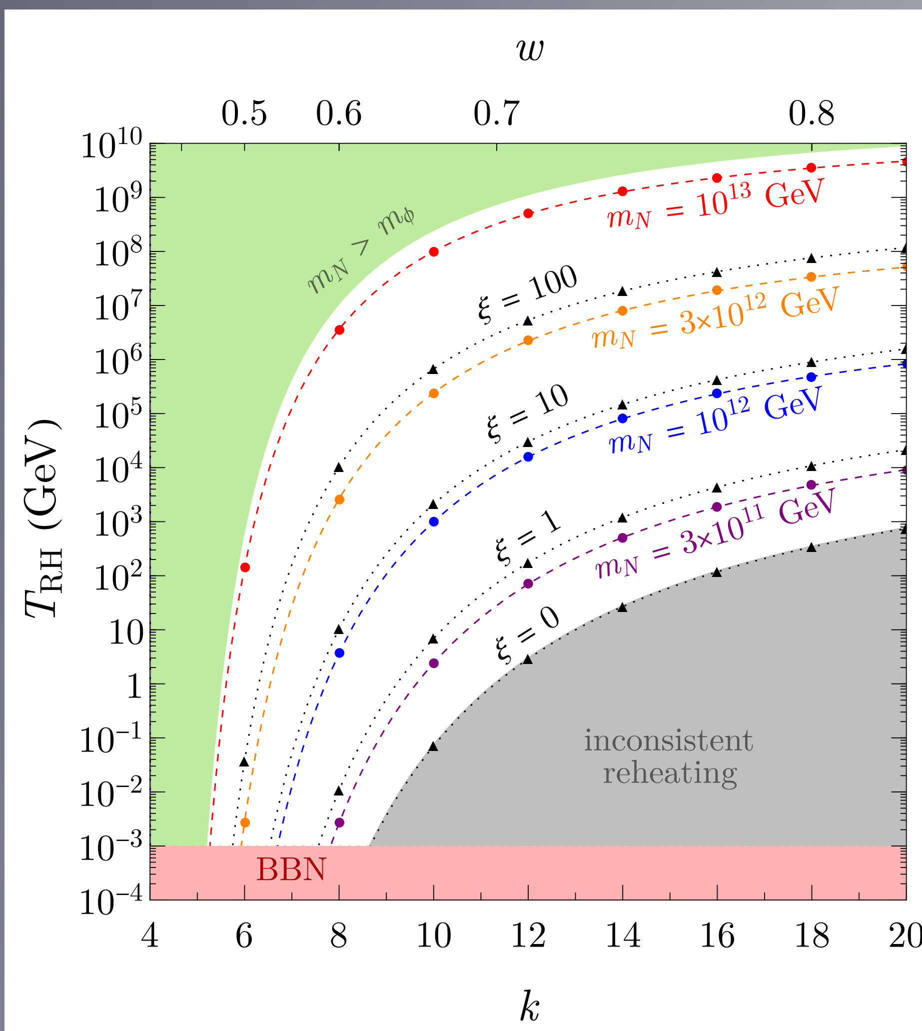
$$\frac{R_{1/2}^{\phi^k}(a_{\max})}{R_{1/2}^{T}(a_{\max})} = g_{\rm RH}^2 \frac{11520\ \Sigma_{1/2}^k}{11351} \frac{m_X^2}{m_\phi^2} \left(\frac{3k-3}{2k+4}\right)^{\frac{6}{7-k}} \left(\frac{\rho_{\rm end}}{\rho_{\rm RH}}\right)^{\frac{2}{k}} \gg 1$$

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

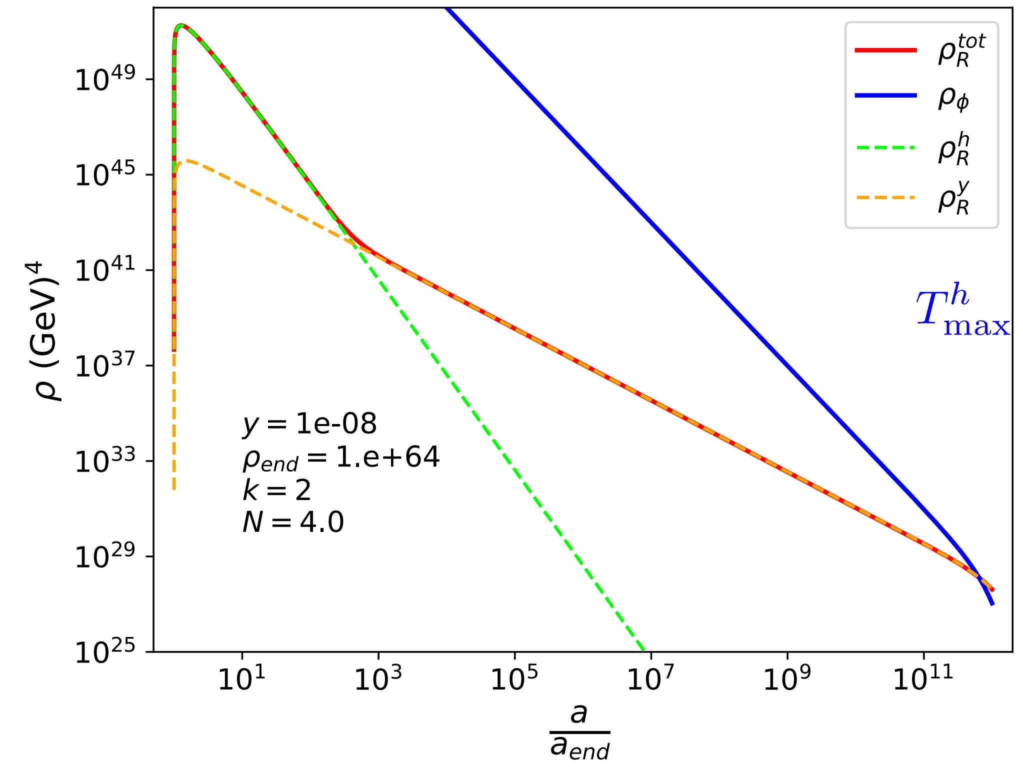
$$\frac{d\rho_R^h}{dt} + 4H\rho_R^h = N\frac{\rho_\phi^2\omega}{16\pi M_P^4}\sum_{n=1}^{\infty} n|\mathcal{P}_n^k|^2\,.$$

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:

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



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

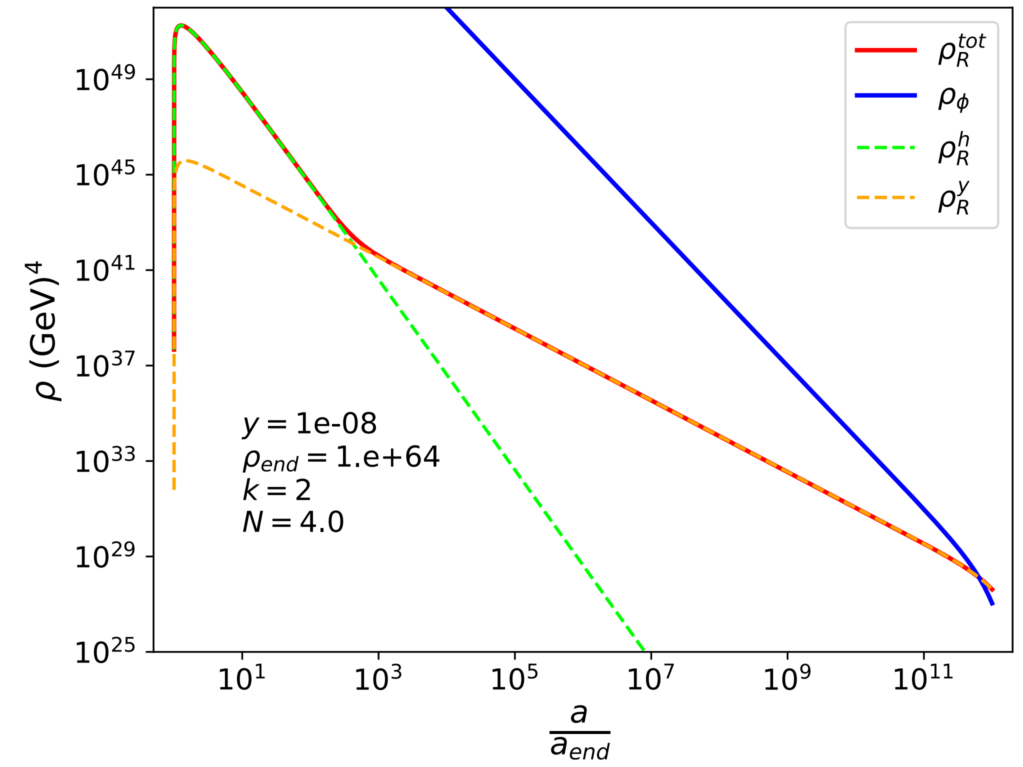
$$T_{\max}^h \simeq 3.1 \times 10^{12} \left(\frac{\rho_{\rm end}}{10^{64}\ \mathrm{GeV}^4}\right)^{\frac{3}{8}} \left(\frac{m_\phi}{3 \times 10^{13}\ \mathrm{GeV}}\right)^{\frac{1}{4}} \mathrm{GeV}\,,$$

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

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

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.