

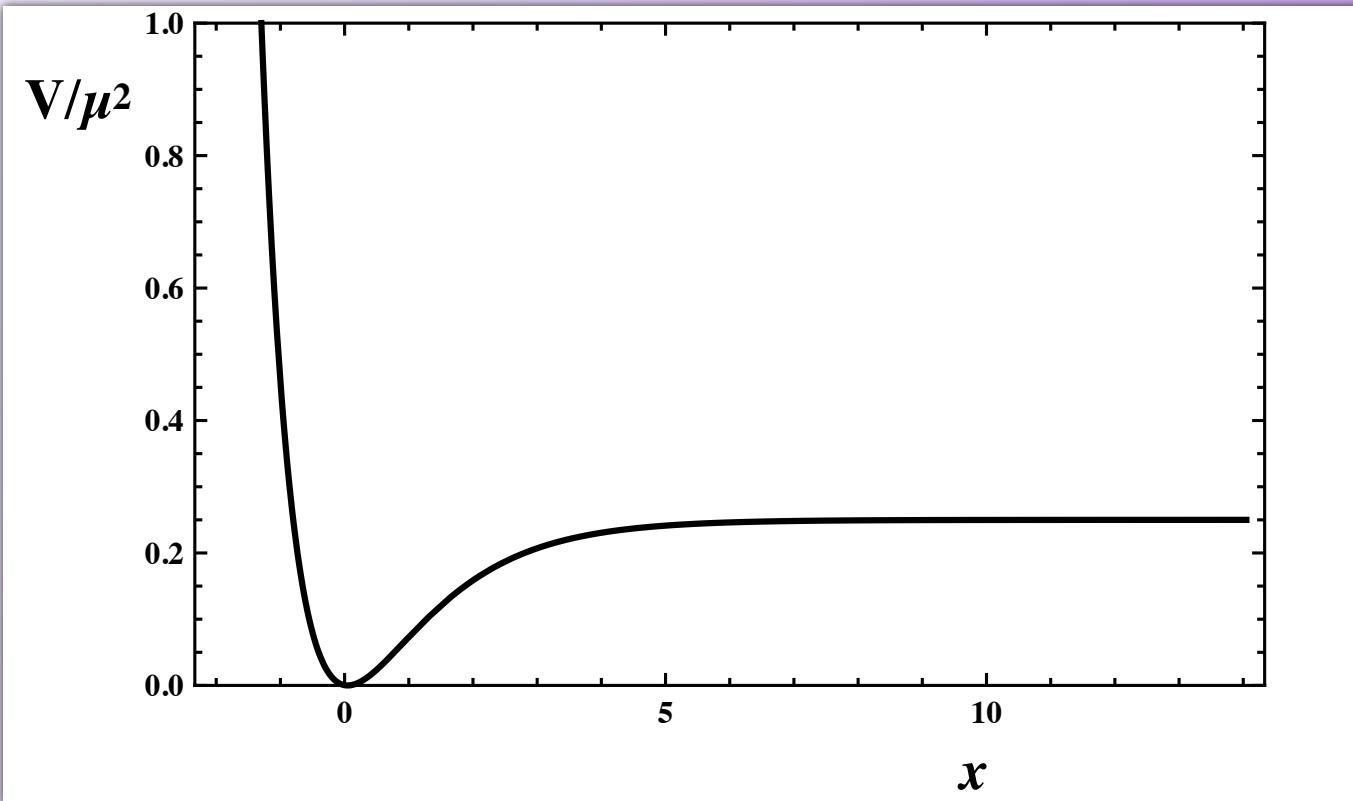
# Gravitational Portals and Particle Production during Reheating

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

# Key Steps as Inflation ends

Equations of motion

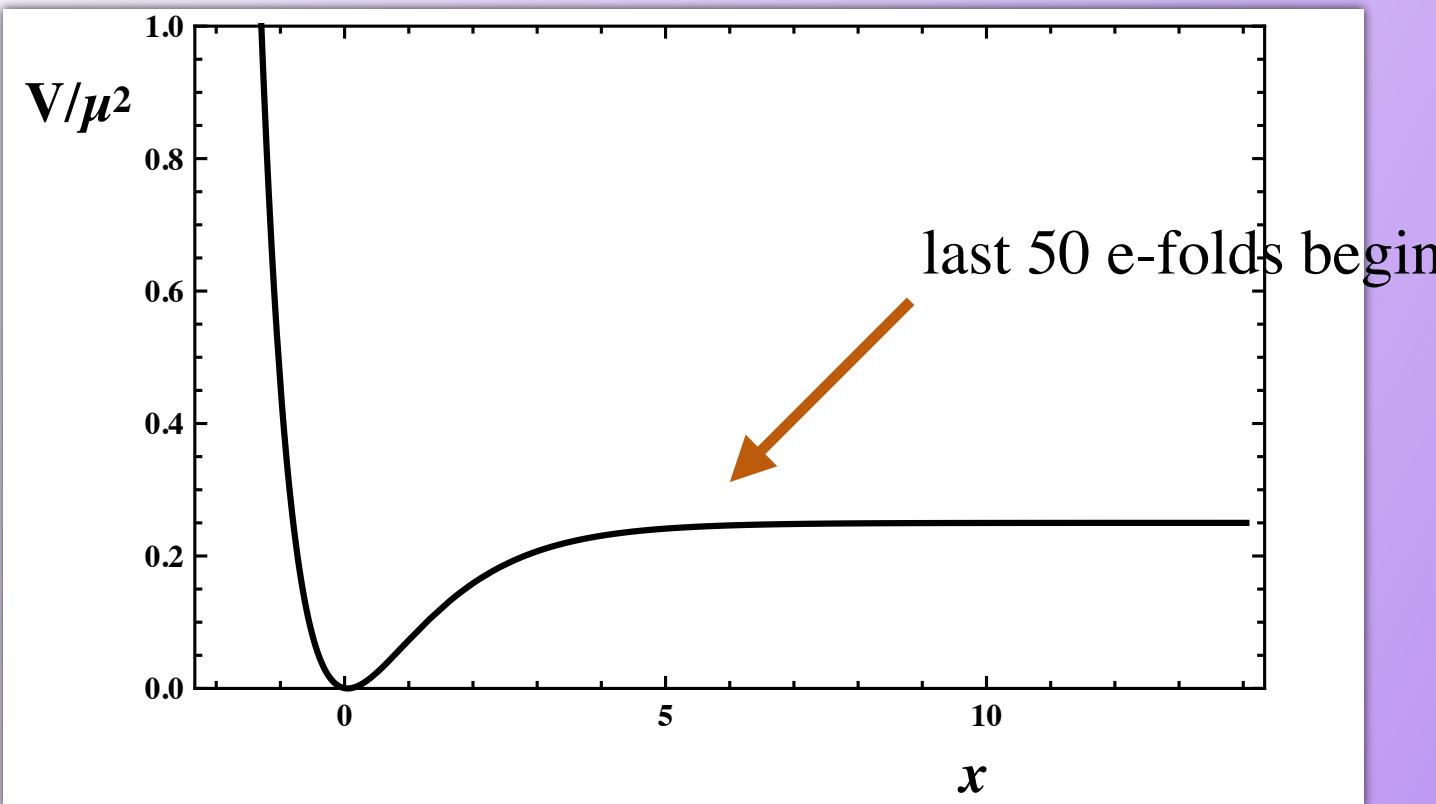
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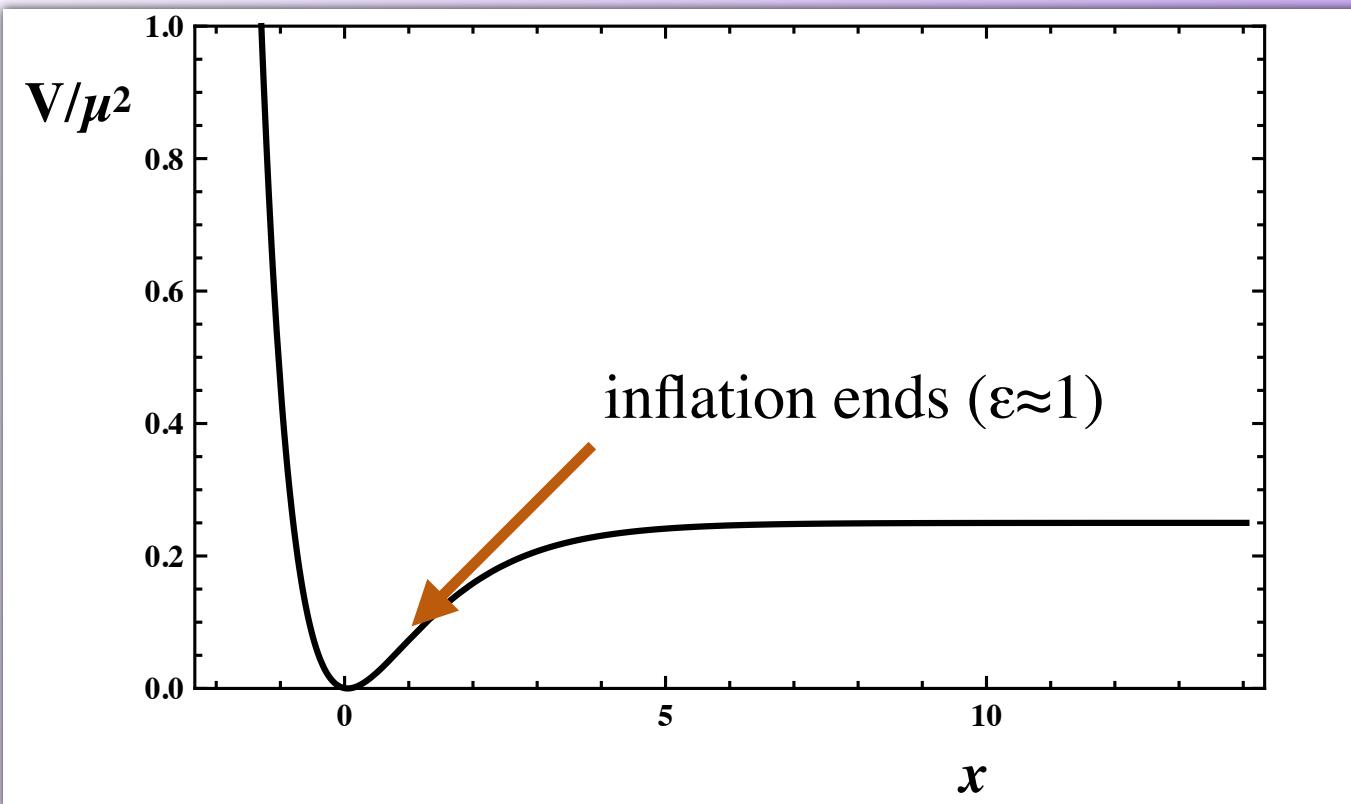
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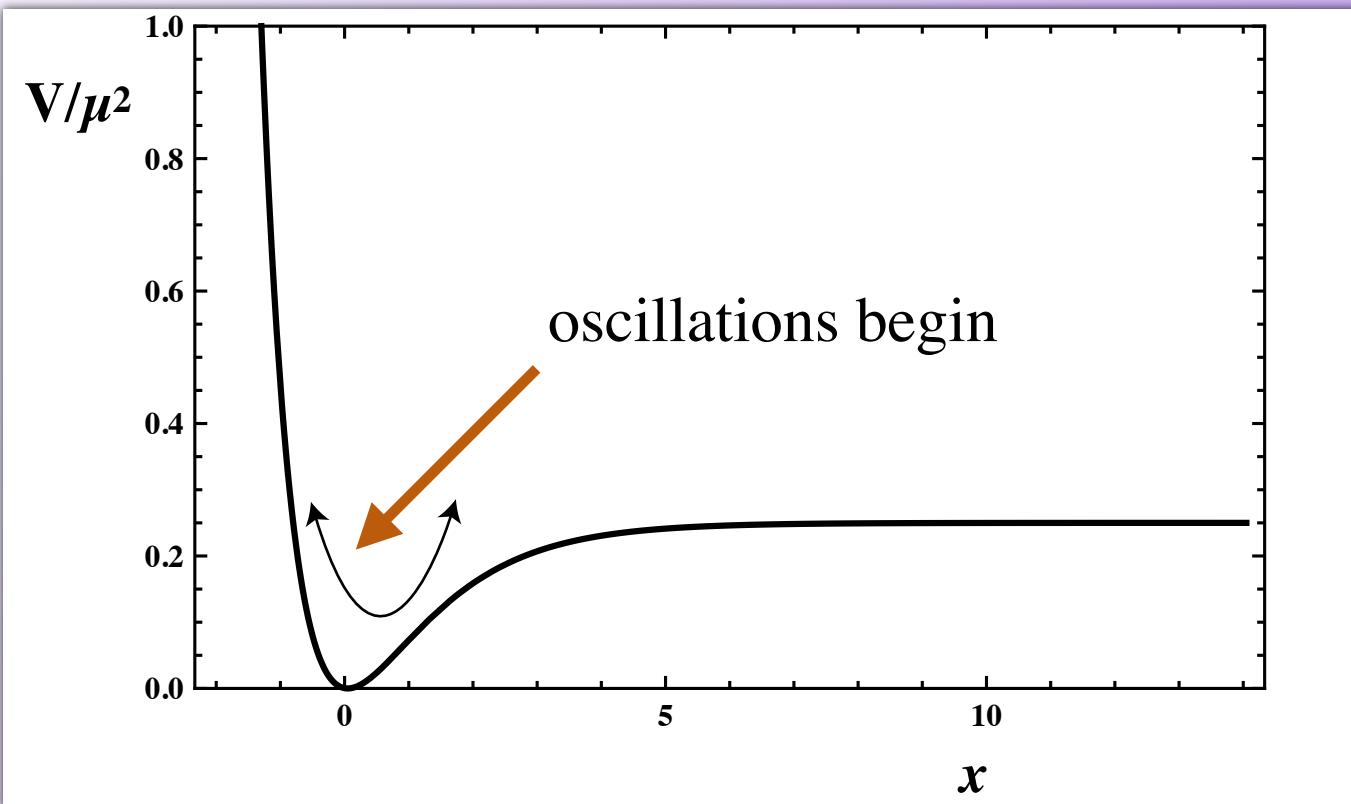
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# Key Steps as Inflation ends

Equations of motion

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



Then what happens?

- Inflaton decays leading to reheating

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

For  $\Gamma_\phi = \frac{y^2}{8\pi} m_\phi(\phi)$   $T_{\text{reh}} \simeq 1.9 \times 10^{15} \text{ GeV} \cdot y \cdot g_{\text{reh}}^{-1/4} \left( \frac{m_\varphi}{3 \times 10^{13} \text{ GeV}} \right)^{1/2}$ .

- Inflaton oscillations  $\Rightarrow$  particle production

# R+R<sup>2</sup> Gravity

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

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

Leading to

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

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

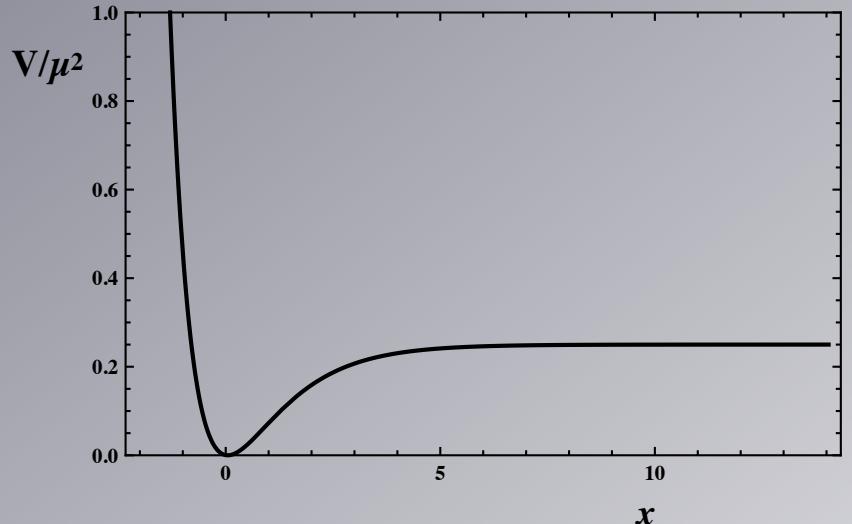
$$V = \frac{3}{4} M^2 (1 - e^{-\sqrt{2/3}\varphi'})^2$$

# Planck-friendly Models: R+R<sup>2</sup> Inflation

Starobinsky

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

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



Slow Roll parameters:

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

$\mu$  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:  $2\langle \text{Re } T \rangle = c$

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

Redefine inflaton to a canonical field  $\chi$

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

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

# No-Scale models revisited

Then  $c = 1$ ,  $\lambda = \hat{\mu}/\sqrt{3}$

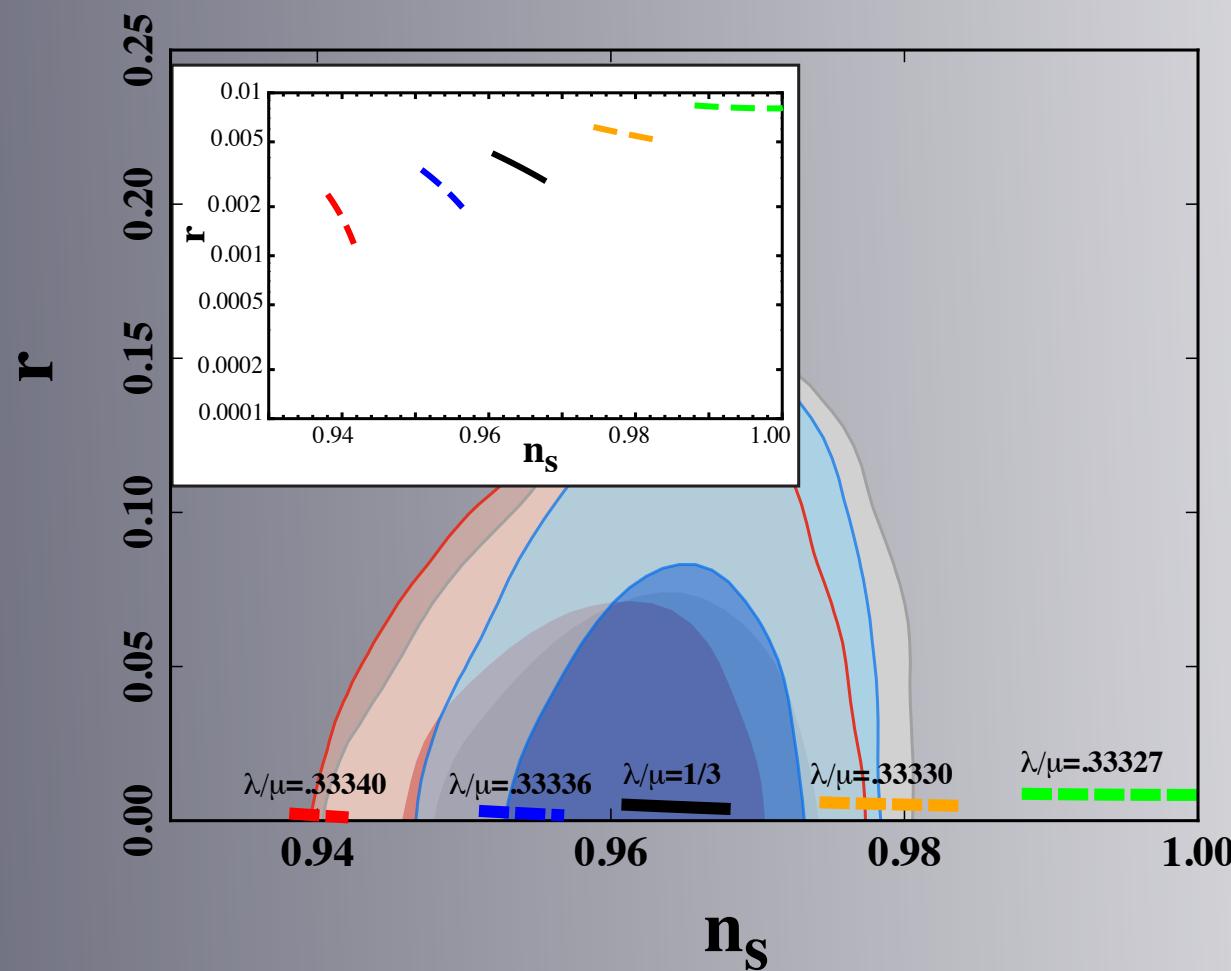
$$\frac{\hat{V}}{(1 - |\phi|^2/3)^2} \Rightarrow \text{Starobinsky Potential}$$

# No-Scale models revisited

Then  $c = 1$ ,  $\lambda = \hat{\mu}/\sqrt{3}$

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How well does this do vis a vis Planck?



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$$K = -3 \ln \left( T + \bar{T} - \frac{|\phi|^2}{3} \right)$$

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Starobinsky

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

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

Kallosch, Linde

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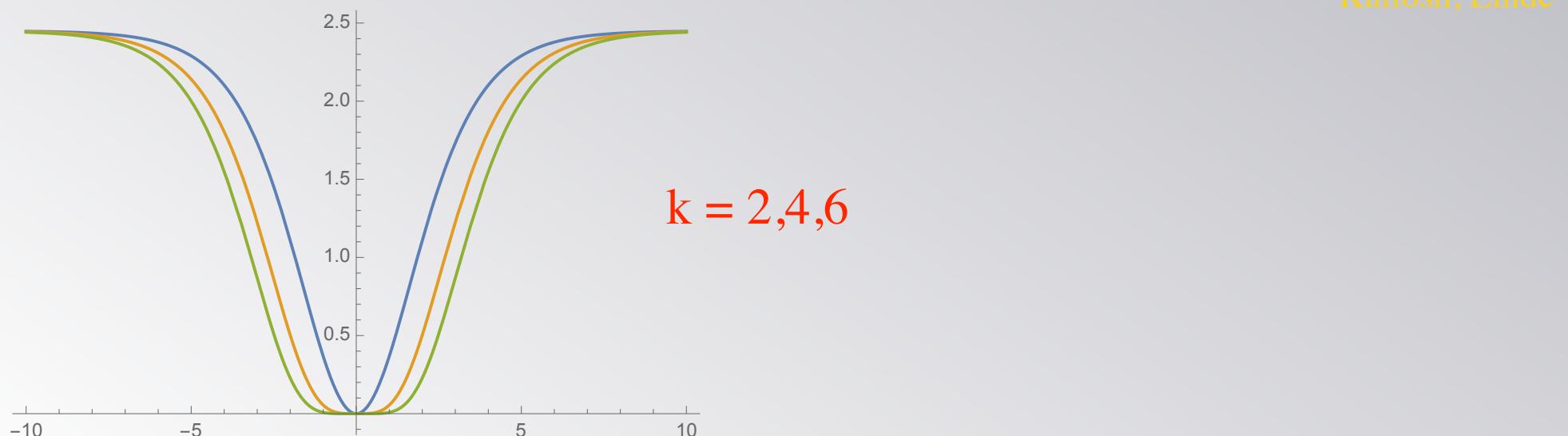
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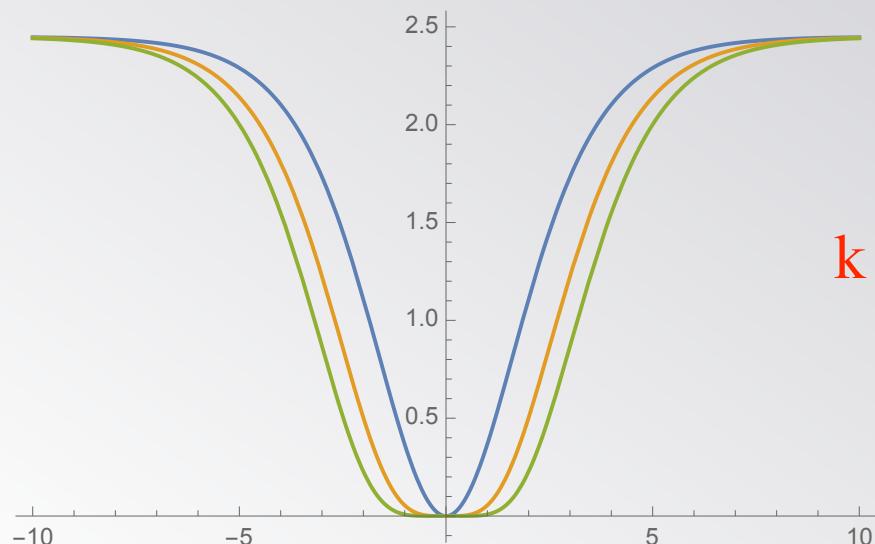
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$k = 2, 4, 6$



Kallosh, Linde

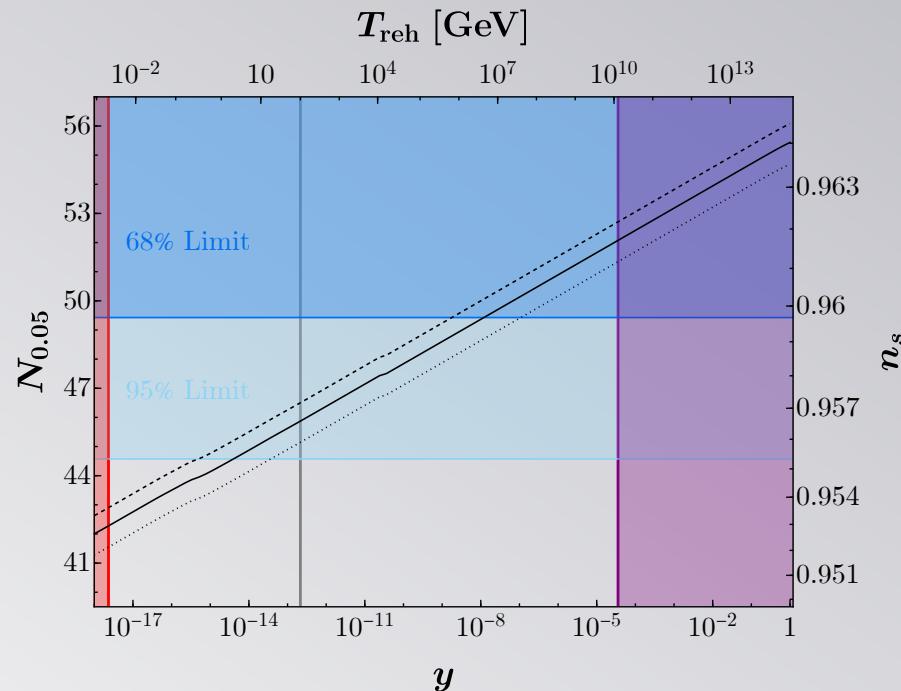
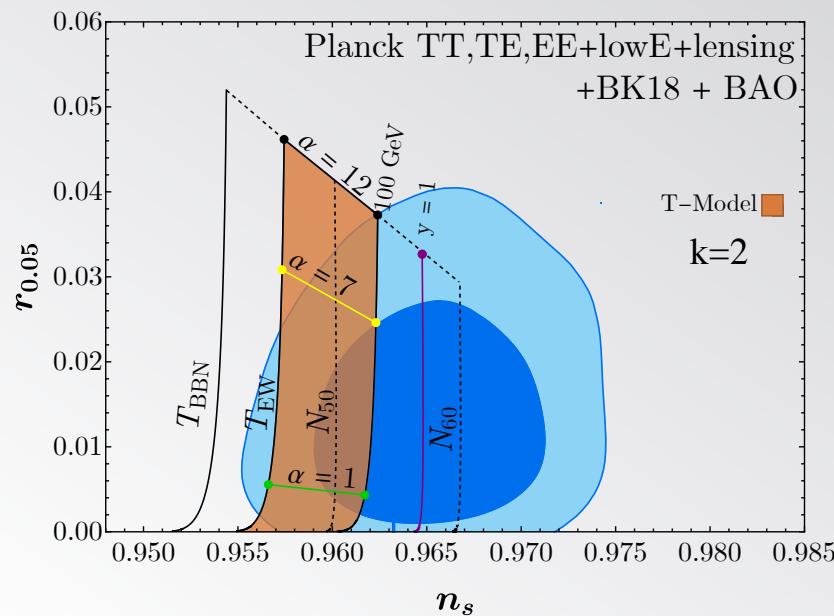
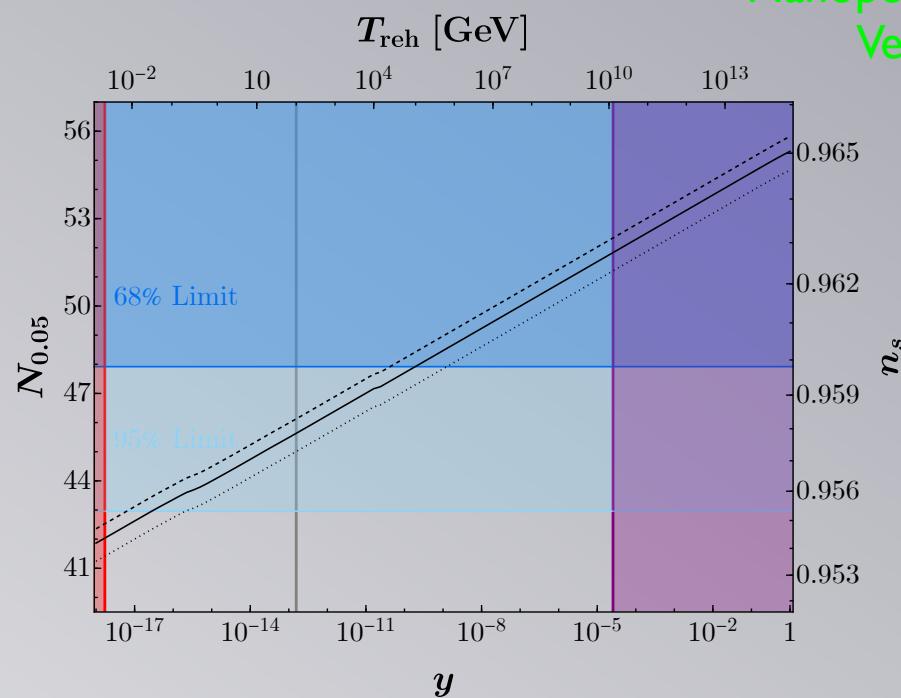
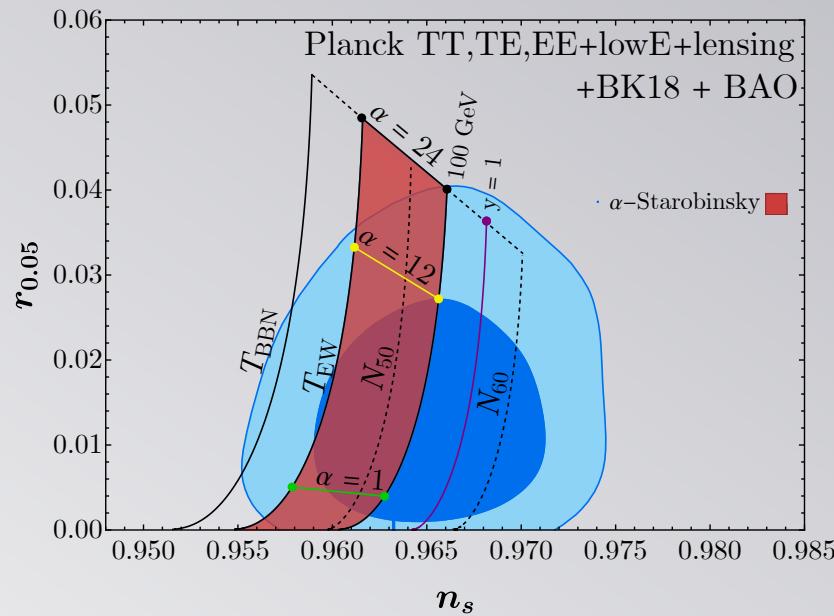
$$V = \lambda \varphi'^k$$

$$\varphi' \ll 1$$

# Results for $\alpha$ -Starobinsky and $\alpha$ -T-models

$-3\ln \rightarrow -3\alpha \ln$

Ellis, Garcia,  
Nanopoulos, Olive,  
Verner



# Post-Inflation

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

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

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

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

# Inflaton Oscillations

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

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

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

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

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

# Reheating: Generation of the Radiation bath

Garcia, Kaneta,  
Mambrini, Olive

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

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

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

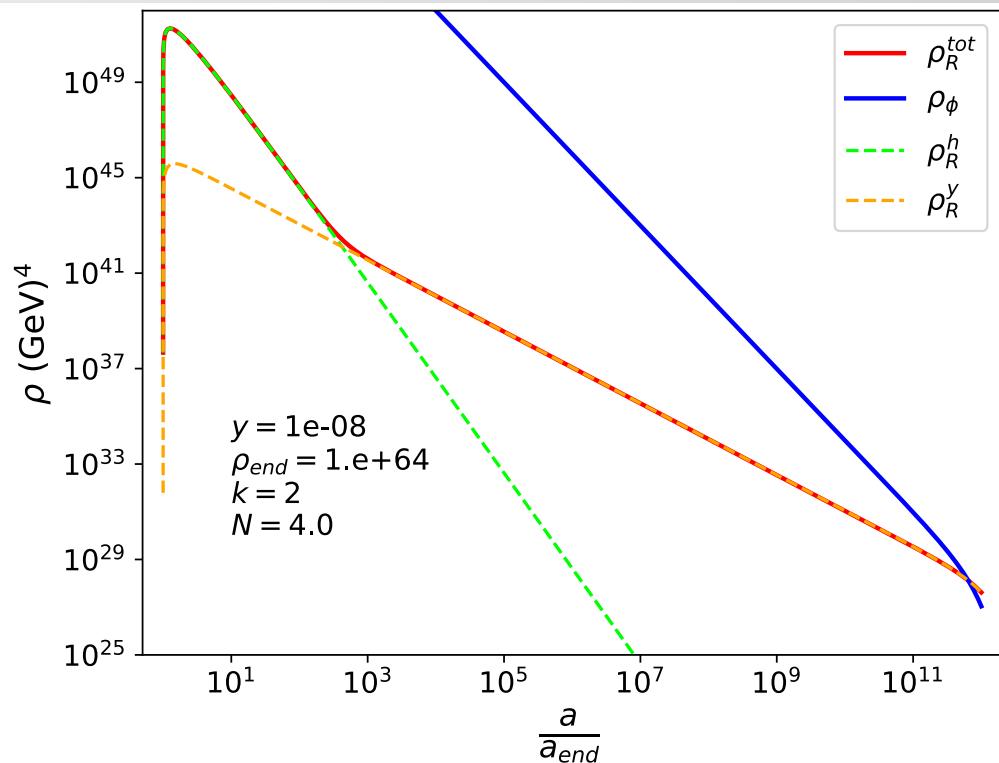
# Reheating: Generation of the Radiation bath

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

For  $\Gamma_\Phi \ll H$

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

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



# Reheating: Generation of the Radiation bath

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

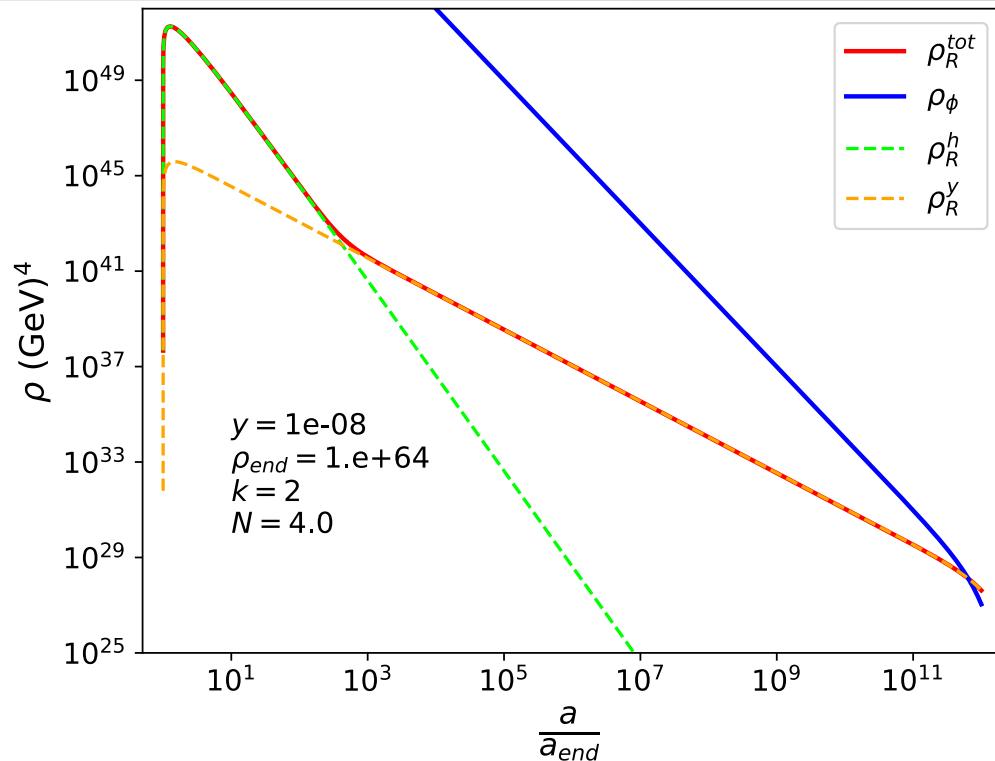
$$\rho_R = \frac{g_T \pi^2}{30} T^4$$

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

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

for k=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,  $\mathcal{L} \supset \begin{cases} y\phi\bar{f}f & \phi \rightarrow \bar{f}f \\ \mu\phi bb & \phi \rightarrow bb \\ \sigma\phi^2 b^2 & \phi\phi \rightarrow bb, \end{cases}$

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



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.

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

Define  $Y_\chi = n_\chi a^3$   $n_R = \frac{\zeta(3)}{\pi^2} T^3$

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

# Particle Production

Garcia, Kaneta,  
Mambrini, Olive

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

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

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

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

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

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

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

# Particle Production

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Garcia, Kaneta,  
Mambrini, Olive

ex: gravitino - n=0,  $\Lambda=M_P$ , and for k=2,

$$n^s/n_\gamma \sim T_{\text{reh}}/M_P$$

$\Omega h^2 \sim .1$  when  $m_{3/2} \sim 100$  GeV, for  $y=10^{-5}$  and  $T_{\text{reh}} \sim 10^{10}$  GeV

# Particle Production

Garcia, Kaneta,  
Mambrini, Olive

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ex: gravitino production in high scale supersymmetry

$n=6$ , Expect  $\Lambda^2 \sim m_{3/2} M_P$ , and for  $k=2$ ,

$$T_{\text{max}} \sim 10^{12} \text{ GeV} \text{ and } T_{\text{reh}} \sim 10^{10} \text{ GeV}$$

correct relic density for  $m_{3/2} \sim 1 \text{ EeV}$

Dudas, Mambrini,  
Olive

# Gravitational Portals

Mambrini, Olive;  
 Clery, Mambrini, Olive,  
 Verner

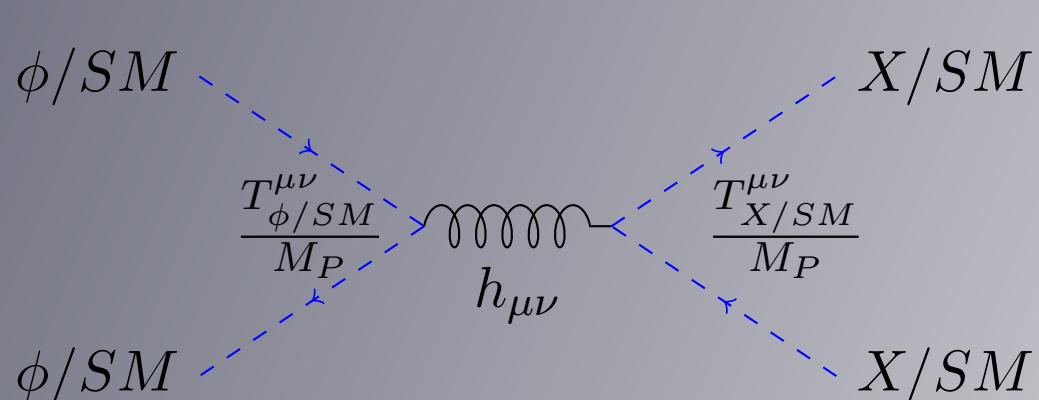
Start with Einstein-Hilbert Lagrangian

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

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

Gravitaional interactions

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



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

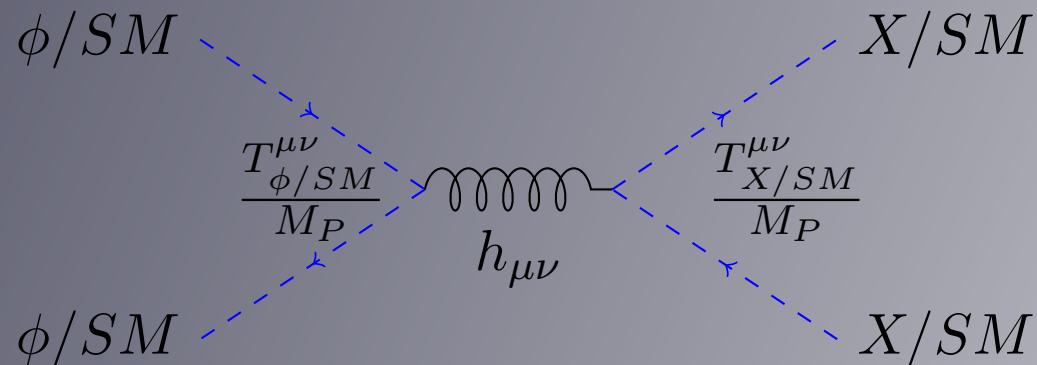
$$T_{1/2}^{\mu\nu} = \frac{i}{4} \left[ \bar{\chi} \gamma^\mu \overleftrightarrow{\partial}^\nu \chi + \bar{\chi} \gamma^\nu \overleftrightarrow{\partial}^\mu \chi \right]$$

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

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

# 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

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

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

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

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

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

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

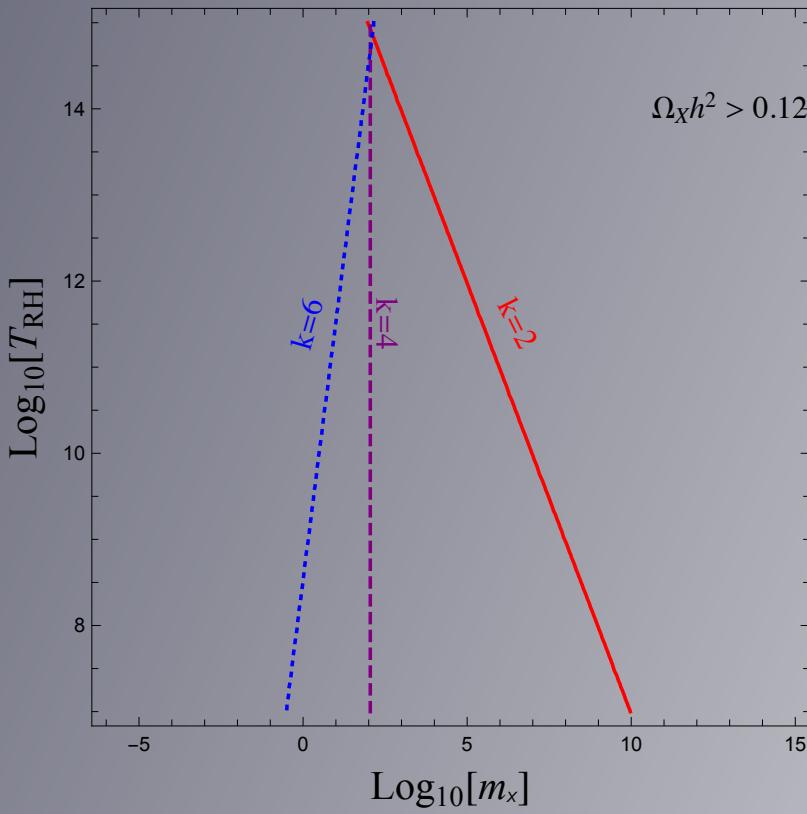
$$\beta_0=\frac{3997\pi^3}{20736000} \qquad \beta_{1/2}=\frac{11351\pi^3}{10368000}$$

# Gravitational Portals

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

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

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



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

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

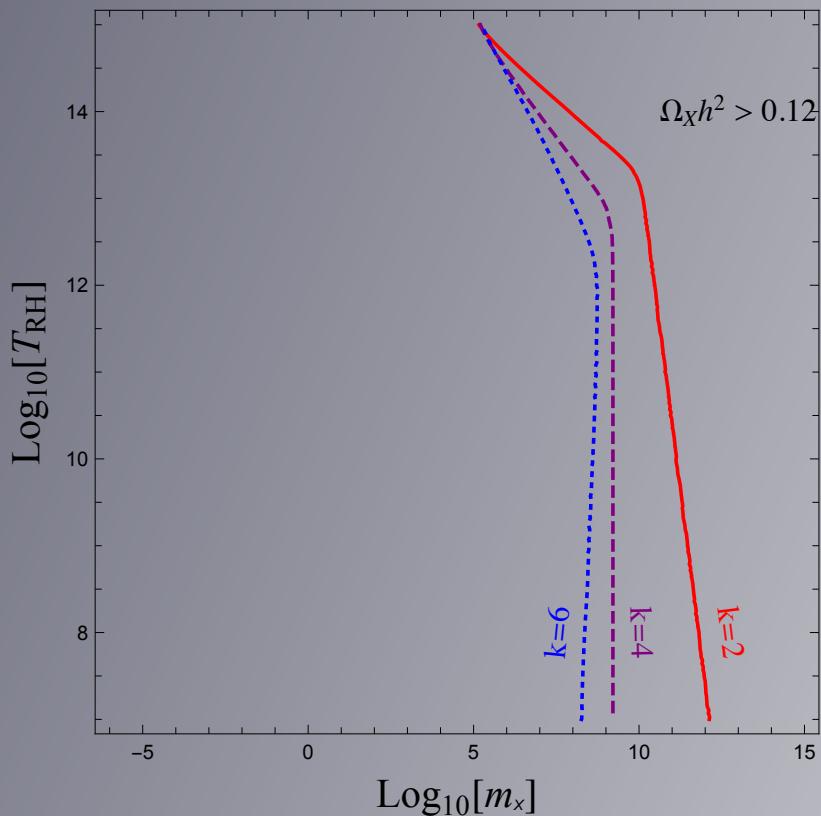
$$\frac{R_0^{\phi^k}(a_{\text{max}})}{R_0^T(a_{\text{max}})} = g_{\text{max}}^2 \frac{5760\Sigma_0^k}{3997} \left(\frac{3k-3}{2k+4}\right)^{\frac{6}{7-k}} \left(\frac{\rho_{\text{end}}}{\rho_{\text{RH}}}\right)^{\frac{2}{k}} \gg 1$$

# Gravitational Portals

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

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

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

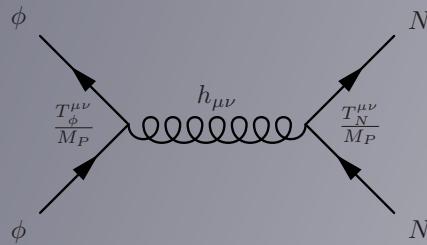


$$n_{1/2}^{\phi}(a_{\text{RH}}) \simeq \frac{m_X^2 \sqrt{3}(k+2) \rho_{\text{RH}}^{\frac{1}{2} + \frac{2}{k}}}{12\pi k(k-1) \lambda^{\frac{2}{k}} M_P^{1+\frac{8}{k}}} \left( \frac{\rho_{\text{end}}}{\rho_{\text{RH}}} \right)^{\frac{1}{k}} \Sigma_{\frac{1}{2}}^k$$

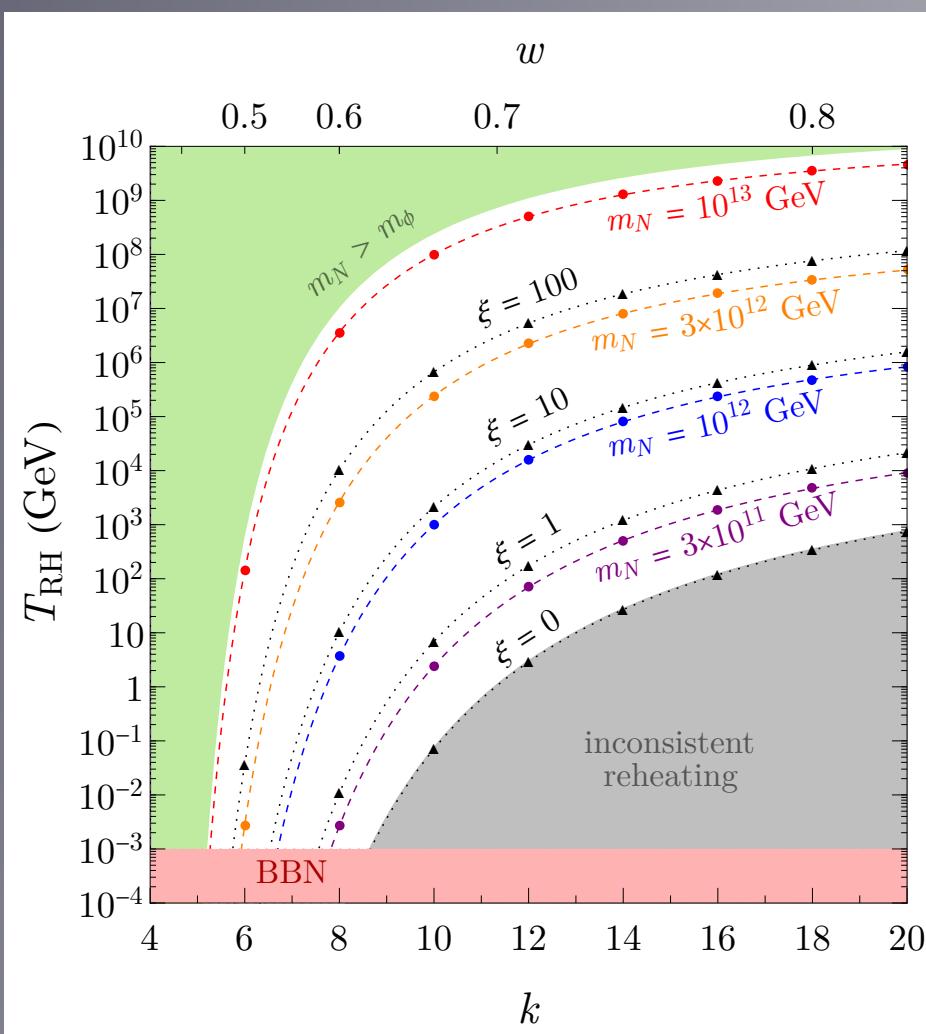
$$\frac{R_{1/2}^{\phi^k}(a_{\text{max}})}{R_{1/2}^T(a_{\text{max}})} = g_{\text{RH}}^2 \frac{11520}{11351} \frac{\Sigma_{1/2}^k}{m_\phi^2} \frac{m_X^2}{\left(\frac{3k-3}{2k+4}\right)^{\frac{6}{7-k}}} \left( \frac{\rho_{\text{end}}}{\rho_{\text{RH}}} \right)^{\frac{2}{k}} \gg 1$$

# Inflationary Gravitational Leptogenesis

$$X = N_R$$



Co, Mambrini, Olive;  
Bernal, Fong



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

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

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

# Gravitational Portals

Clery, Mambrini, Olive,  
Verner;  
Haque, Maity

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

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

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

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

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

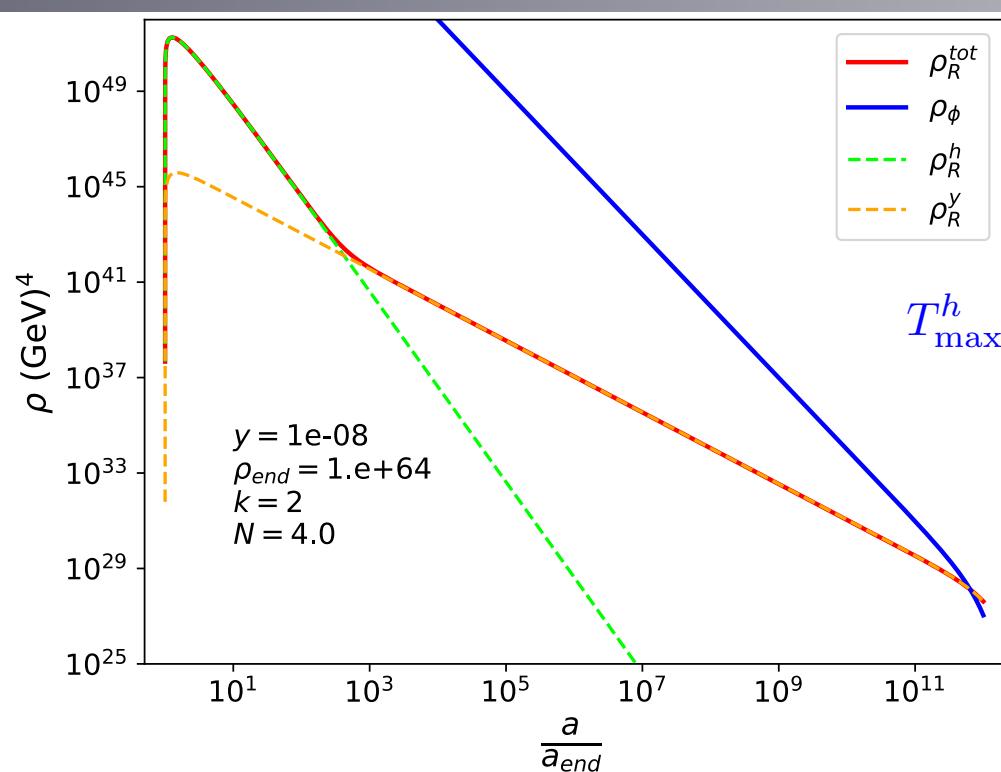
# Gravitational Portals

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

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

Solution:

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



$$\gamma_k = \sqrt{\frac{\pi}{2}} k \frac{\Gamma(\frac{1}{2} + \frac{1}{k})}{\Gamma(\frac{1}{k})} \lambda^{\frac{1}{k}}$$

$$\Sigma_k^h = \sum_{n=1}^{\infty} n |\mathcal{P}_n^k|^2 .$$

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

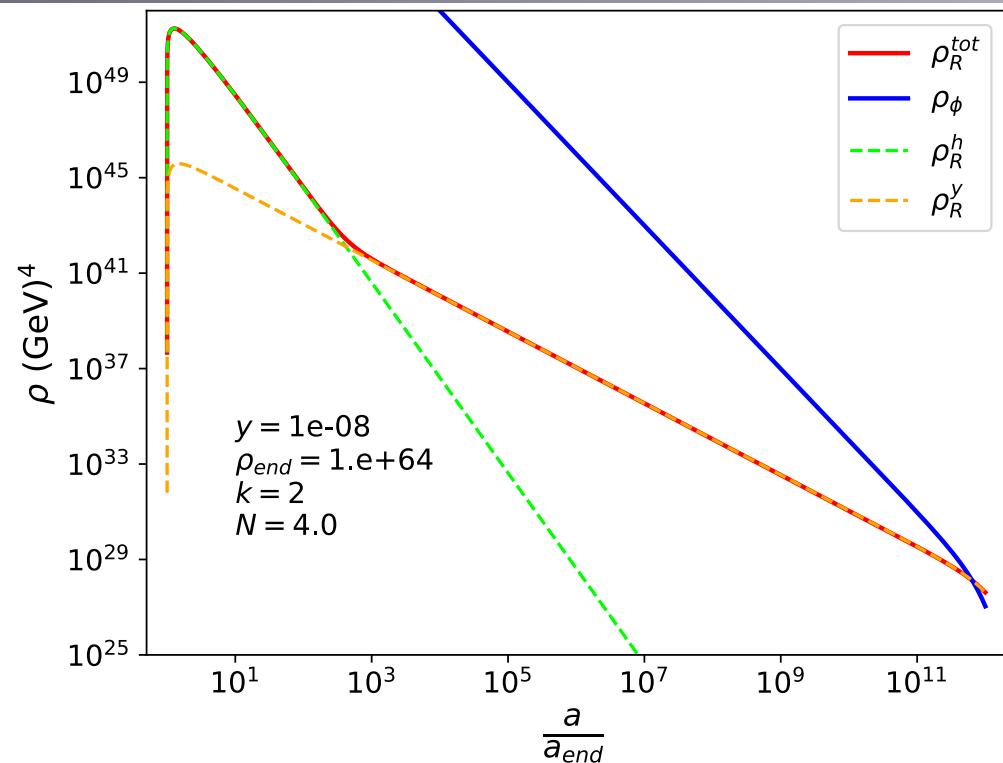
Absolute lower bound on  $T_{\max}$

# Gravitational Portals

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

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

Gravitationally produced radiation density exceeds that produced by decays when:



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

or

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

# Non-minimal Gravitational Portals

Clery, Mambrini, Olive,  
Shkerin, Verner

Consider a non-minimal coupling to curvature:

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

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

Rewrite in the Einstein frame

$$\mathcal{S} = \int d^4x \sqrt{-g} \left[ -\frac{M_P^2}{2} R + \frac{1}{2} K^{ij} g^{\mu\nu} \partial_\mu S_i \partial_\nu S_j - \frac{V_\phi + V_h + V_X}{\Omega^4} \right].$$
$$K^{ij} = 6 \frac{\partial \log \Omega}{\partial S_i} \frac{\partial \log \Omega}{\partial S_j} + \frac{\delta^{ij}}{\Omega^2}.$$

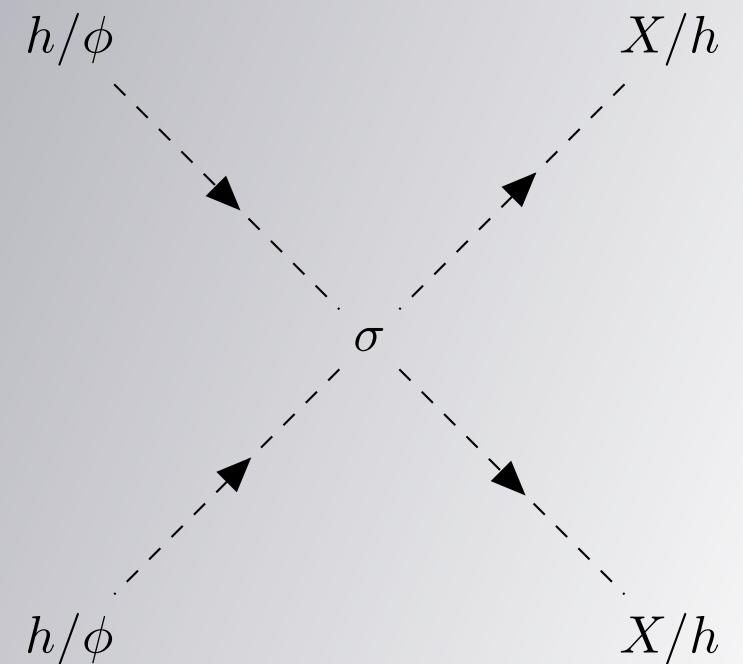
# Non-minimal Gravitational Portals

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

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

For example,

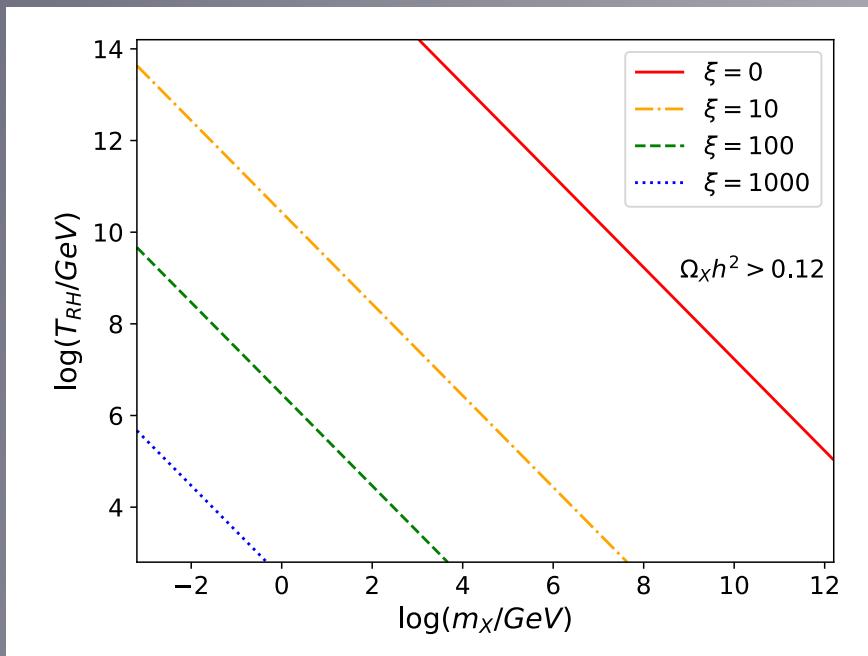
$$\begin{aligned}\sigma_{hX}^\xi &= \frac{1}{4M_P^2} [\xi_h(2m_X^2 + s) + \xi_X(2m_h^2 + s) \\ &+ (12\xi_X\xi_h(m_h^2 + m_X^2 - t))],\end{aligned}$$



# Non-minimal Gravitational Portals

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

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



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

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

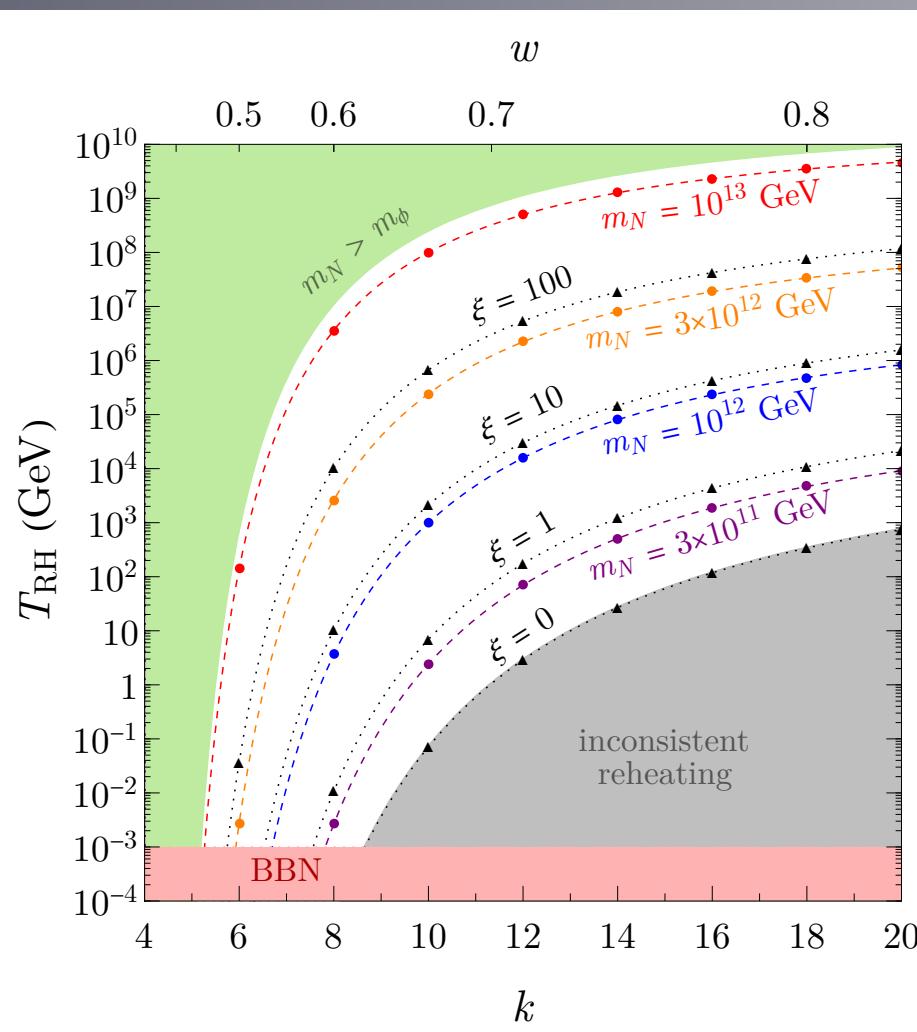
$$\frac{\Omega_X^{\phi, \xi} h^2}{0.12} \simeq \frac{1.3 \times 10^7 \sigma_{\phi X}^{\xi/2} \rho_{\text{RH}}^{1/4} M_P^2}{m_\phi^3} \frac{m_X}{1 \text{ GeV}} \sqrt{1 - \frac{m_X^2}{m_\phi^2}},$$

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

# Non-minimal Gravitational Portals

Co, Mambrini, Olive

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



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.