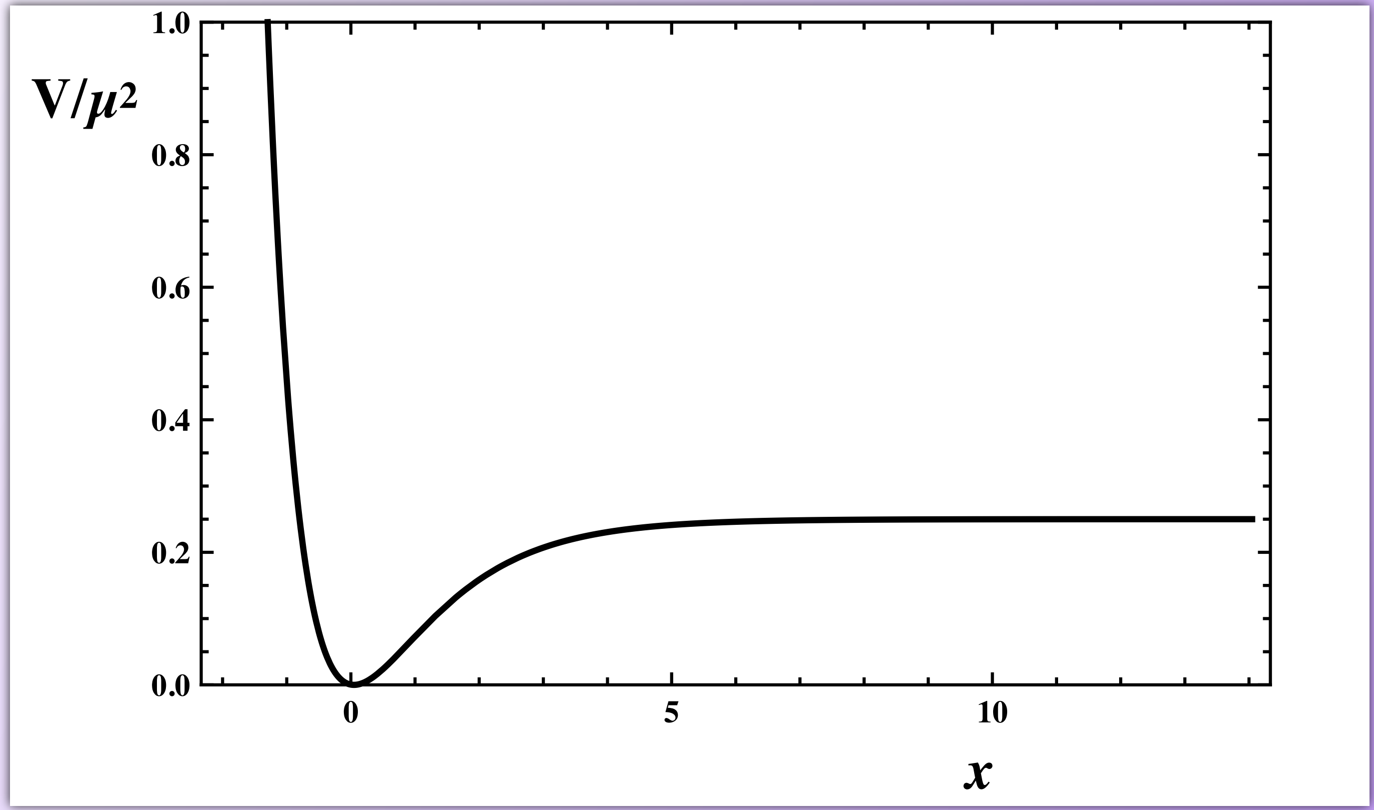
Gravitational Production of Dark Matter after Inflation

- Instantaneous vs non-instantaneous reheating
- Freeze-in Production of DM
- Gravitational Portals
- Scalar DM from large scale fluctuations

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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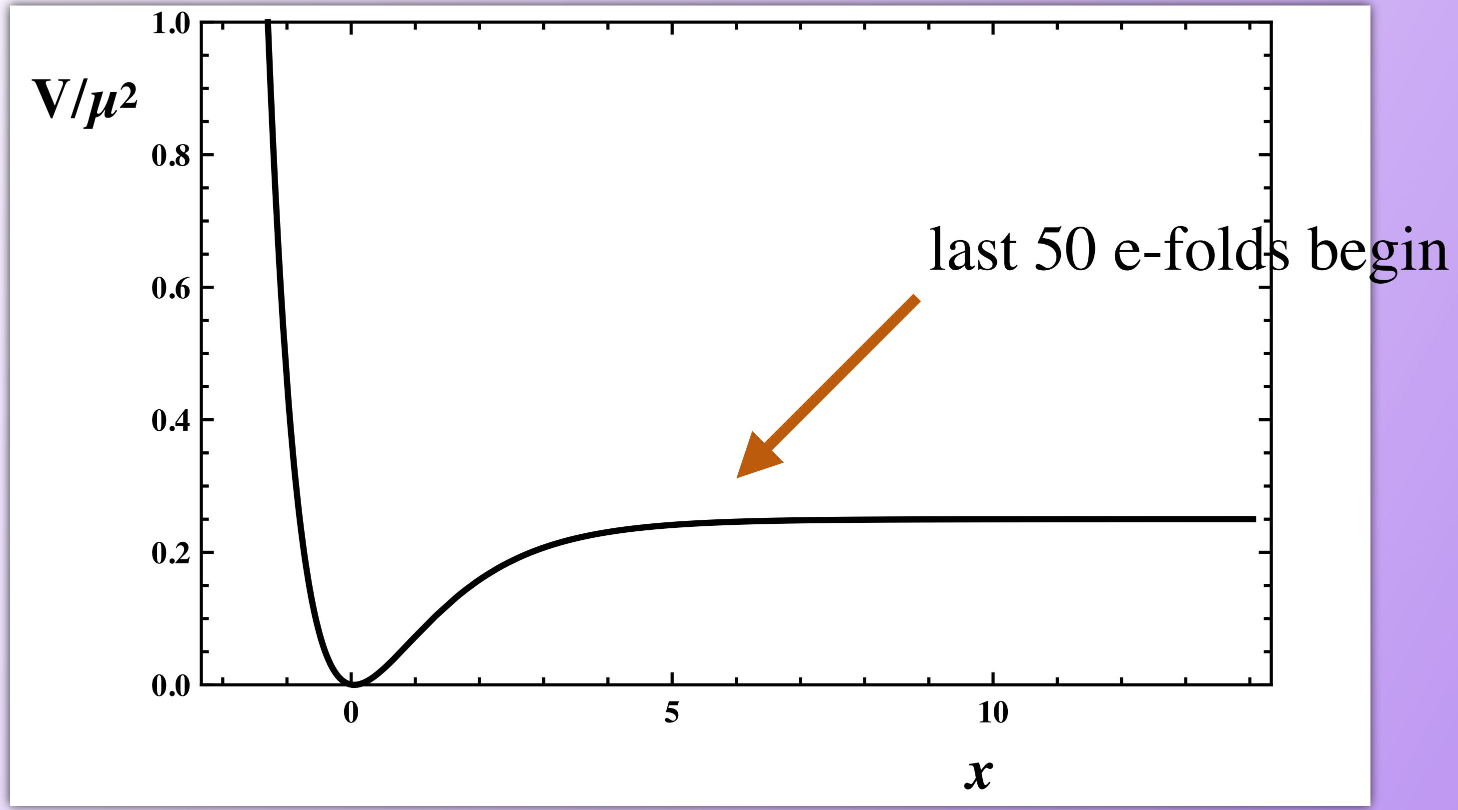

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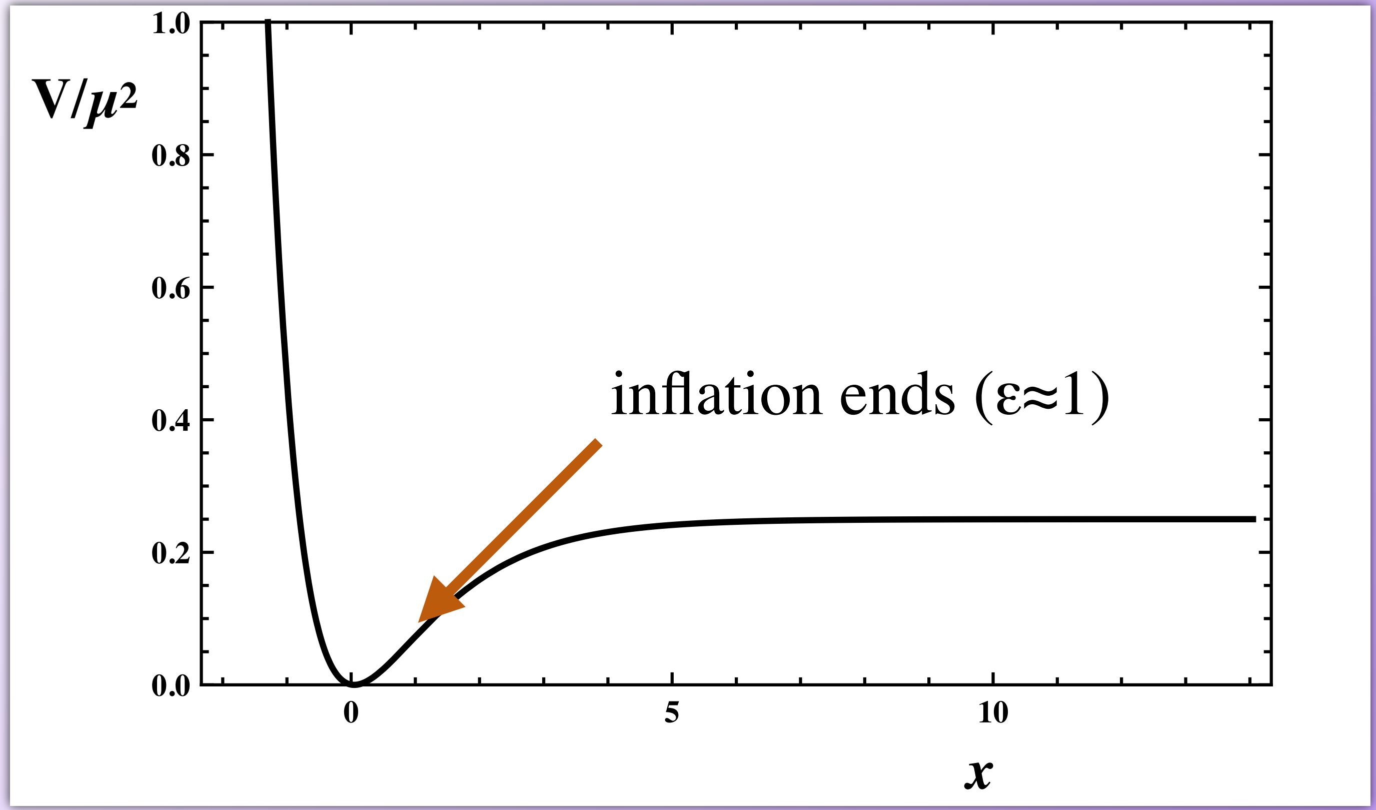

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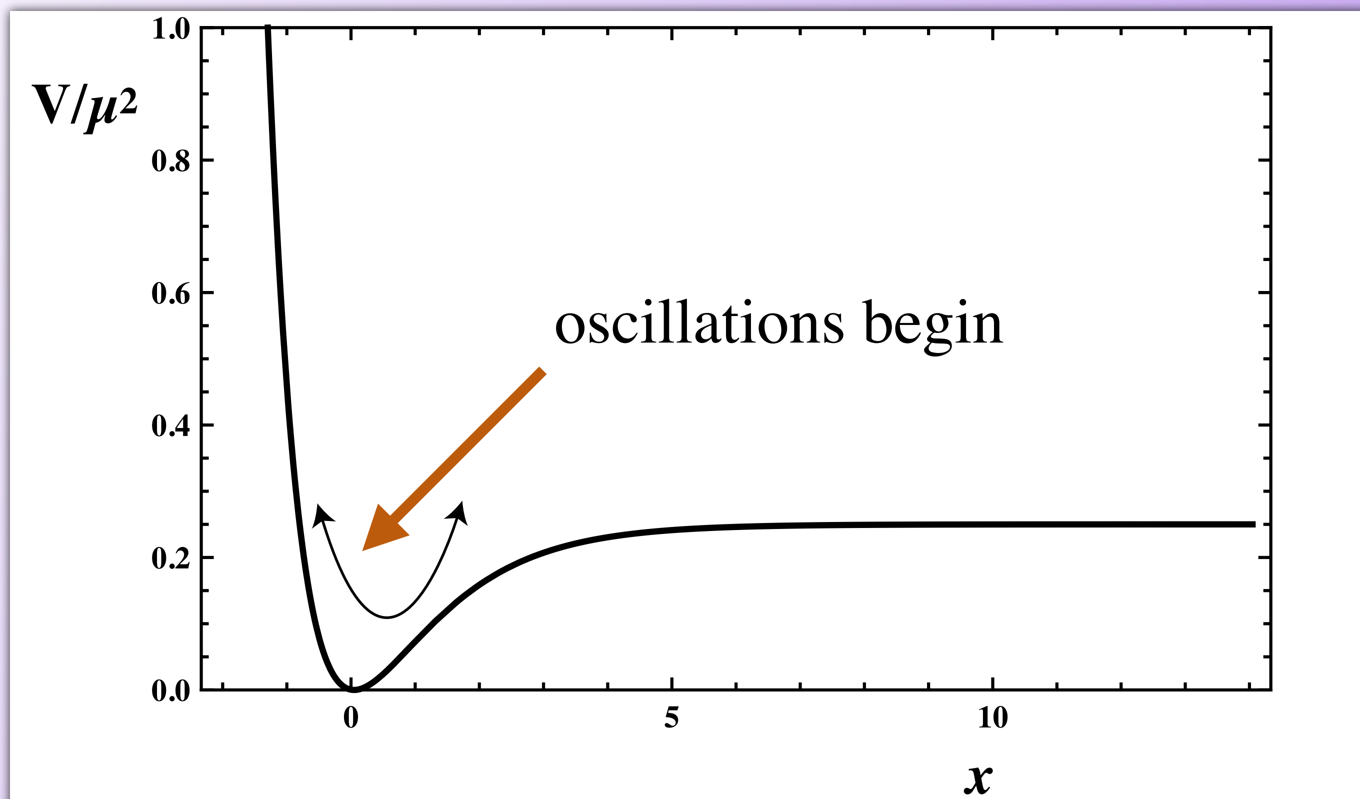

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during which:

$$H\tau \sim \frac{H^2}{|m^2|} \sim \frac{v^4}{M_P^2|m^2|}$$

Plenty of inflation possible!

Then what happens?

Late time evolution

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Then decays occur when $\Gamma_\phi \sim H \sim T_R^2/M_P$

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

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

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- Inflaton oscillations $\Rightarrow$ particle production

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$$\rho_\phi = \frac{1}{2}\dot{\phi}^2 + V(\phi); \qquad p_\phi = \frac{1}{2}\dot{\phi}^2 - V(\phi)$$

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about the minimum of V $\qquad V(\phi) \sim \phi^k$

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

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

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

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

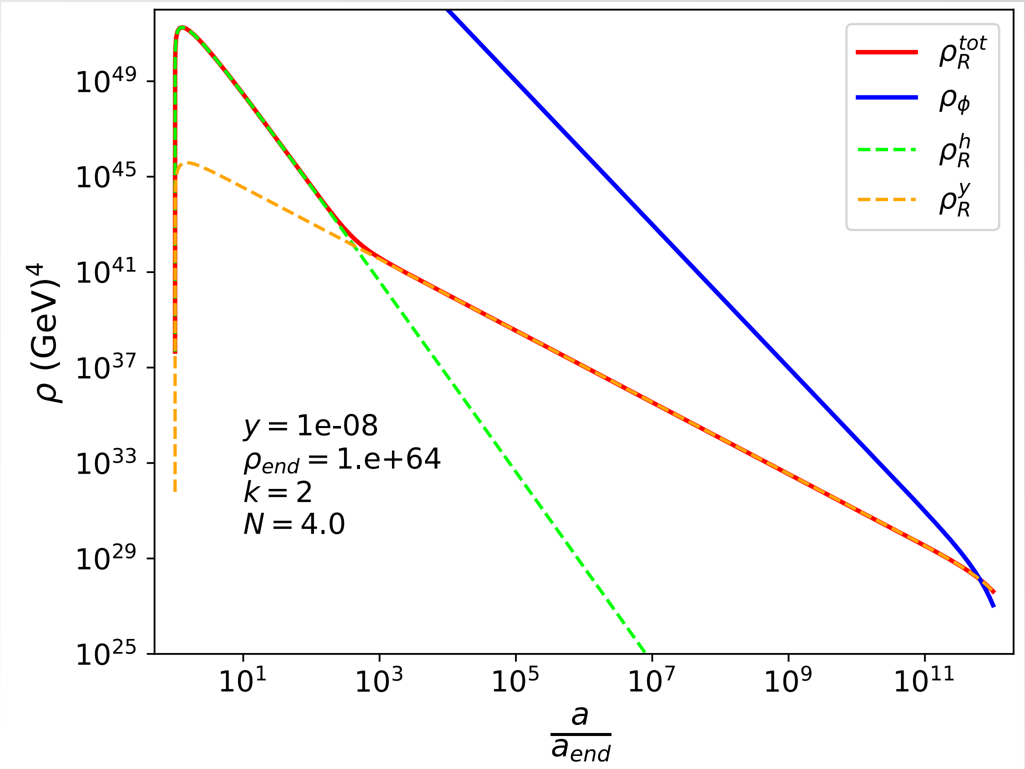
Reheating: Generation of the Radiation bath

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

For $\Gamma_\Phi \ll H$

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

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



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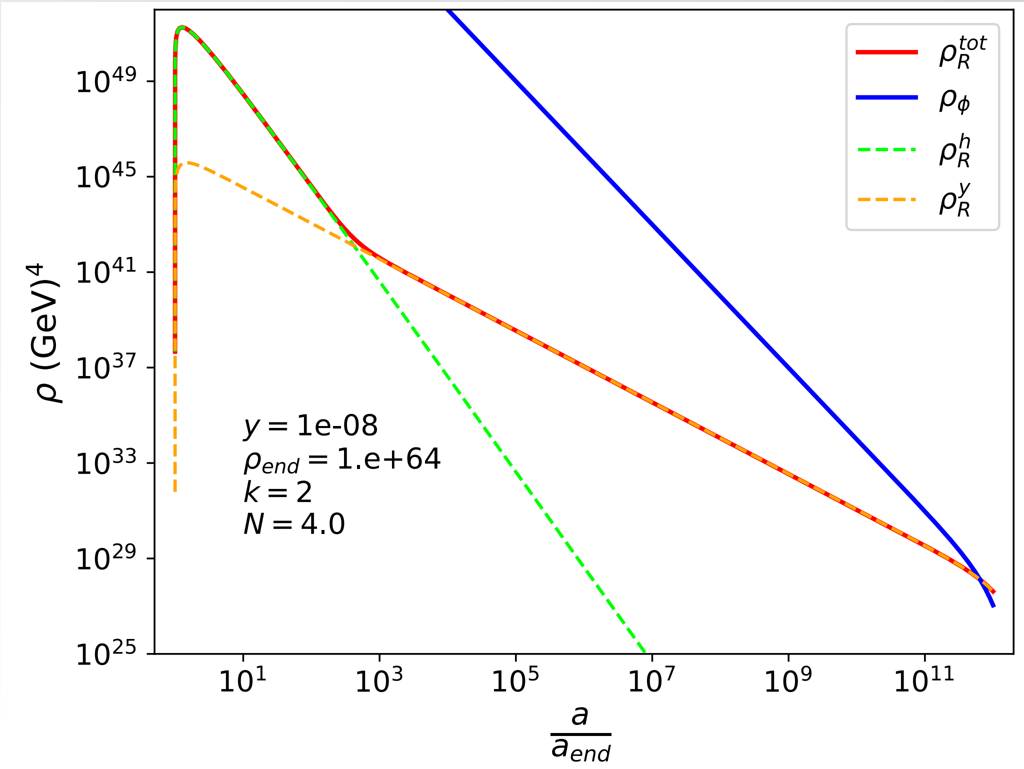


For k=2

$$\rho_\phi \propto a^{-3}$$

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

Reheating: Generation of the Radiation bath

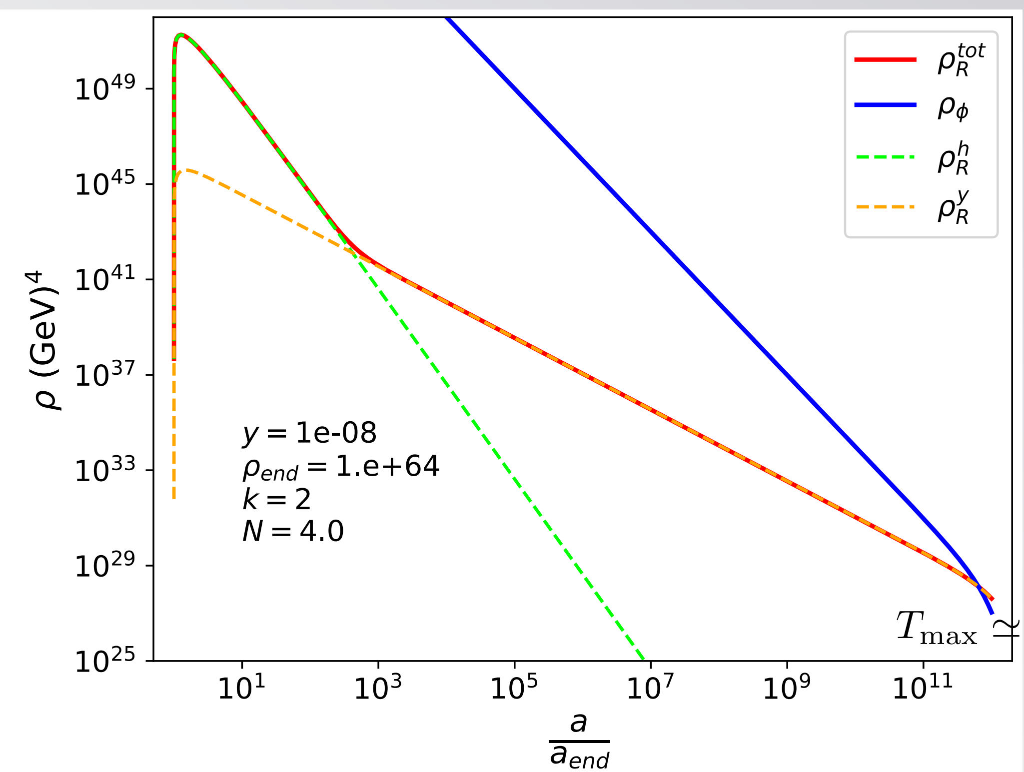
$$\rho_R = \frac{g_T \pi^2}{30} T^4$$

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

for k=2:

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

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



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

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

$$T_{\rm max} \simeq 2.8 \times 10^{15} y^{1/2} g_{\rm reh}^{-1/4} \left(\frac{\rho_{\rm end}^{1/4}}{5.5 \times 10^{15}{\rm GeV}}\right)^{1/2} \left(\frac{m_\phi}{3 \times 10^{13}{\rm GeV}}\right)^{1/8}$$

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

will not reheat

recall,

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

Particle Production

(Freeze-in)

Suppose some coupling to the Standard Model with cross section

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

Boltzmann Eq.

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

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

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

To get Ω from n: $\rho_{\rm RH} = \rho(a_{\rm RH}) = mn(a_{\rm RH})$

$$\Omega h^2 = \frac{\rho_{\rm RH}}{\rho_c}\left(\frac{a_{\rm RH}}{a_0}\right)^3$$

$$= \frac{\rho_{\rm RH}}{\rho_c}\left(\frac{T_0}{T_{\rm RH}}\right)^3 \frac{g_0}{g_{\rm RH}}$$

$$= 5.88 \times 10^6 \frac{\rho_{\rm RH}}{T_{\rm RH}^3}$$

$g_0 = 43/11; \qquad g_{\rm RH} = 427/4$

Particle Production

Garcia, Kaneta, Mambrini, Olive

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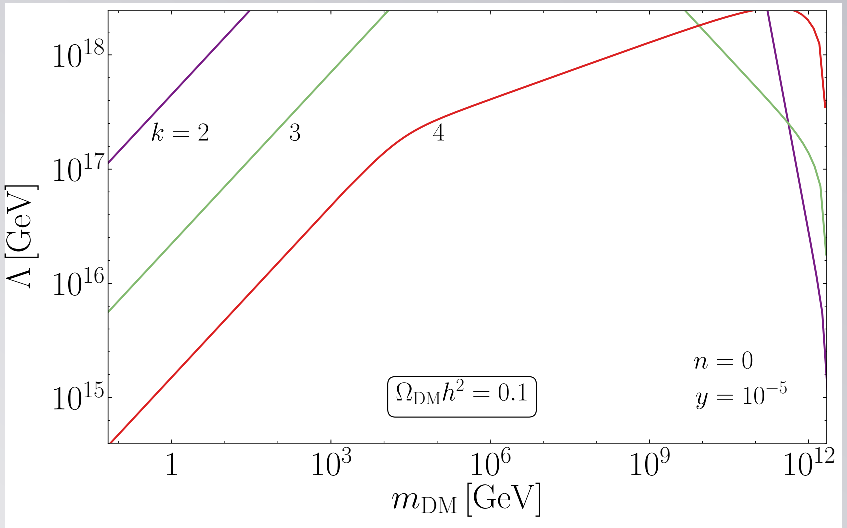
ex: gravitino - n=0, $\Lambda = M_P$, and for k=2,

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

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



Particle Production

Garcia, Kaneta, Mambrini, Olive

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

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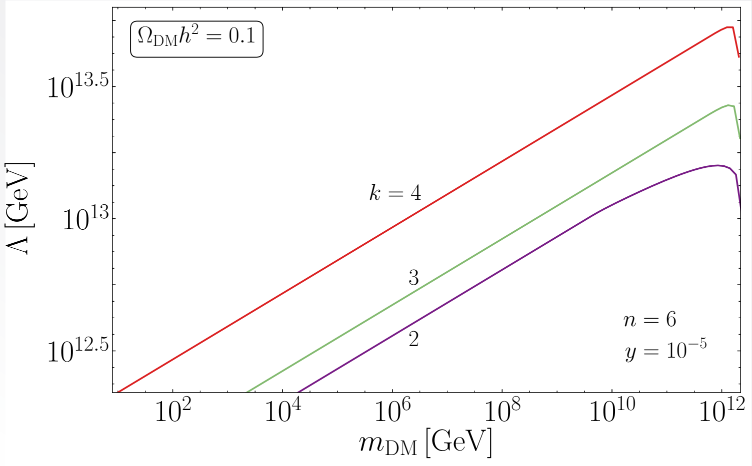
ex: gravitino production in high scale supersymmetry

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

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



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

Dudas, Mambrini, Olive

Particle Production

Garcia, Kaneta, Mambrini, Olive

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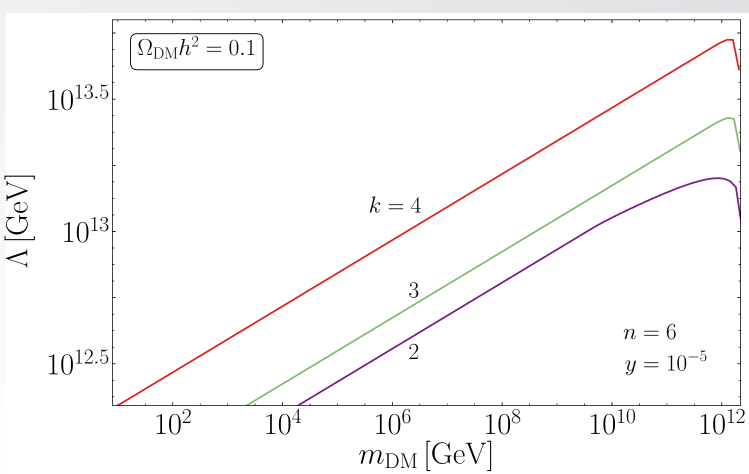

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Dudas, Mambrini, Olive

Also possible through direct decays

Gravitational Portals

Mambrini, Olive;
Clery, Mambrini, Olive, Verner

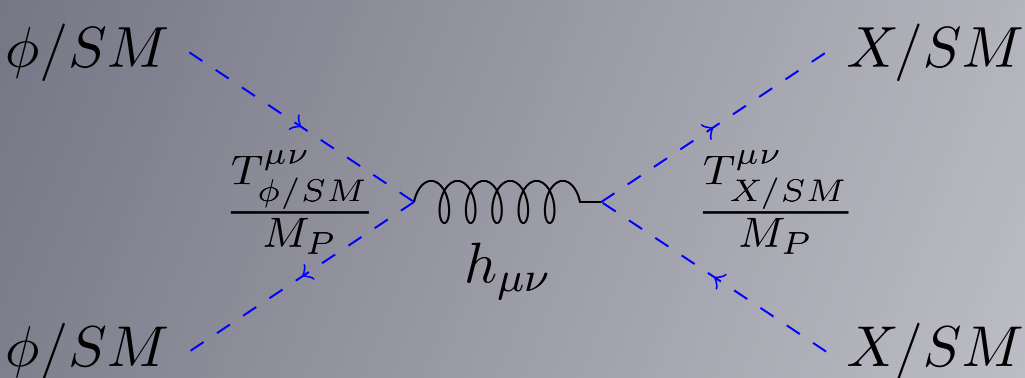
Start with Einstein-Hilbert Lagrangian

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

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

Graviational interactions

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



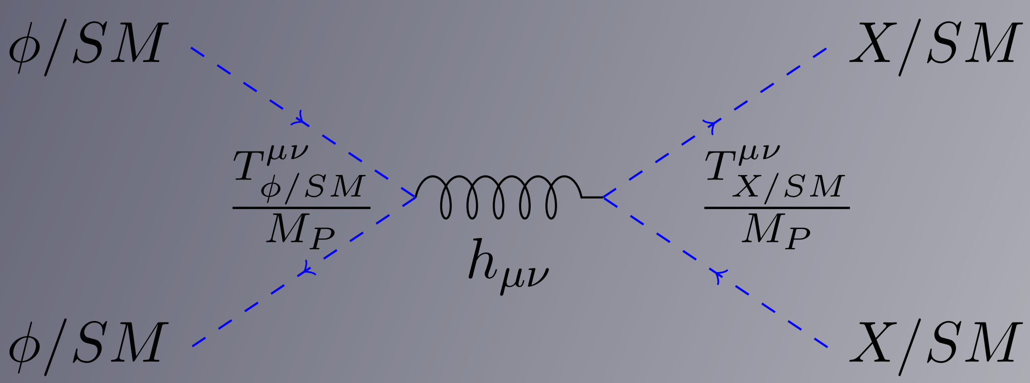
$$T_0^{\mu\nu} = \partial^\mu S \partial^\nu S - g^{\mu\nu} \left[\frac{1}{2} \partial^\alpha S \partial_\alpha S - V(S) \right],$$

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

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

Gravitational Portals

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



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

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

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

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

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

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

from $\quad Y = na^3$

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

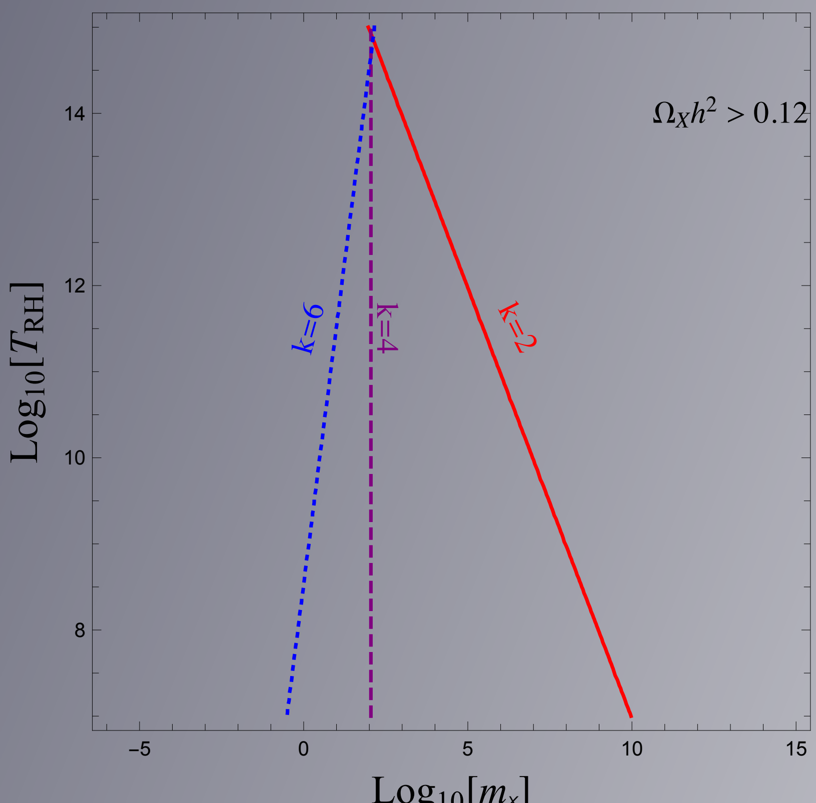
$$\alpha = g_{\rm RH}\pi^2/30$$

Gravitational Portals

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

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

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



$$\frac{\Omega_0^\phi h^2}{0.1} \simeq \left(\frac{\rho_{\rm end}}{10^{64}\ \mathrm{GeV}^4}\right)^{1-\frac{1}{k}} \left(\frac{10^{40}\ \mathrm{GeV}^4}{\rho_{\rm RH}}\right)^{\frac{1}{4}-\frac{1}{k}} \left(\frac{k+2}{6k-6}\right) \times \Sigma_0^k \times \frac{m_X}{2.4 \times 10^{\frac{24}{k}-7}\ \mathrm{GeV}},$$

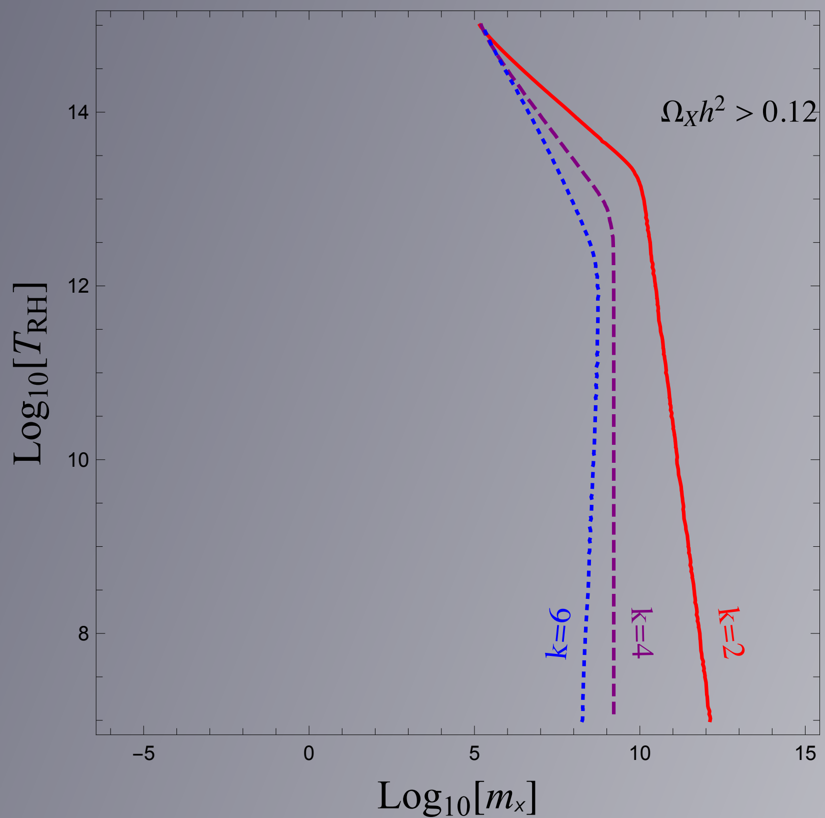
$$\simeq 1.3 \frac{m_\chi}{10^7\ \mathrm{GeV}} \frac{T_{\rm RH}}{10^{10}\ \mathrm{GeV}} \qquad \text{k=2}$$

Gravitational Portals

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

$$R^{\phi^k}_{1/2} = \frac{2 \times \rho_\phi^2}{4\pi M_P^4} \frac{m_X^2}{m_\phi^2} \Sigma^k_{1/2}$$

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



$$\frac{\Omega^\phi_{1/2} h^2}{0.1} = \frac{\Sigma^k_{1/2}}{2.4^{\frac{8}{k}}} \frac{k+2}{k(k-1)} \left(\frac{10^{-11}}{\lambda}\right)^{\frac{2}{k}} \left(\frac{10^{40}\ \text{GeV}^4}{\rho_{\rm RH}}\right)^{\frac{1}{4}-\frac{1}{k}} \times \left(\frac{\rho_{\rm end}}{10^{64}\ \text{GeV}^4}\right)^{\frac{1}{k}} \left(\frac{m_X}{8.3 \times 10^{6+\frac{6}{k}}\ \text{GeV}}\right)^3.$$

$$\simeq 5 \left(\frac{m_\chi}{10^{11}\ \text{GeV}}\right)^3 \frac{T_{\rm RH}}{10^{10}\ \text{GeV}}$$

k=2

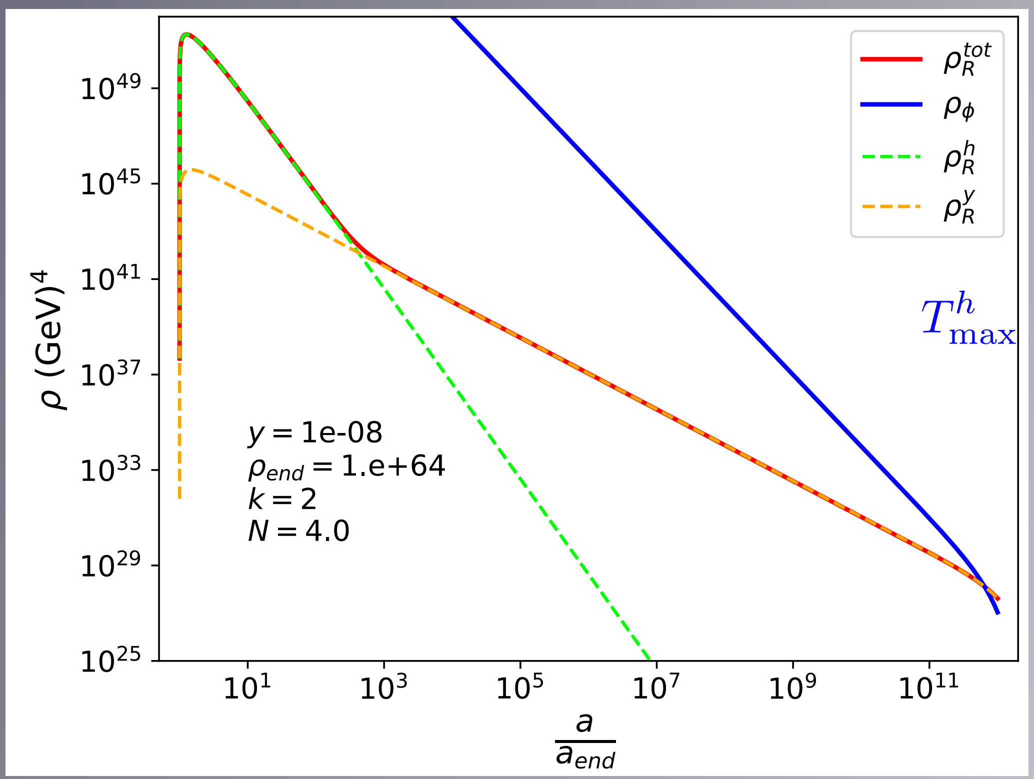
Gravitational Portals

$$\phi(p_1) + \phi(p_2) \to \mathrm{SM}^i(p_3) + \mathrm{SM}^i(p_4)$$
$$(\phi\phi \to h_{\mu\nu} \to HH)$$

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}

Scalar Dark Matter through fluctuations

$$\mathcal{S} = \int d^4x\sqrt{-g}\Big[\frac{1}{2}\partial^\mu\phi\partial_\mu\phi - V(\phi) + \frac{1}{2}\partial_\mu\chi\partial^\mu\chi - \frac{1}{2}m_\chi^2\chi^2 - \frac{1}{2}\sigma\phi^2\chi^2\Big],$$

Markkanen, Rajantie, Tenkanen; Cosme, Tenkanen; Lebedev; Choi, Garcia, Ke, Mambrini, Olive, Verner

effective mass $m_{\chi,\text{eff}}^2 = m_\chi^2 + \sigma\langle\phi^2\rangle$

equations of motion $\ddot{\chi} + 3H\dot{\chi} + m_{\chi,\text{eff}}^2\chi = 0$

critical events:

end of inflation: a_{end}
start of χ oscillations: a_{osc}
effective mass dominated by m_χ : a_χ
reheating: a_{RH}

Scalar Dark Matter through fluctuations

During inflation $\langle\chi^2\rangle$ grow linearly in time: $H^3\, t$, up to

Bunch, Davies;
Vilenkin;
Vilenkin, Ford;
Linde;
Enqvist, Ng, Olive

$$\langle\chi^2\rangle_{\rm end} \simeq \frac{3H_{\rm end}^4}{8\pi^2 m_{\chi,\rm eff}^2(a_{\rm end})} \,.$$

$\gg H^2$, for $m_\chi \ll H$

$\langle\chi^2\rangle$ satisfies same equations of motion as a scalar field. Linde

and $$\rho_\chi(a) = \frac{1}{2} m_{\chi,\rm eff}^2 \chi^2(a)$$

for $\sigma\phi^2(a) \gg m_\chi^2$ $\quad a_{\rm osc} < a < a_\chi ,$

Choi, Garcia, Ke,
Mambrini, Olive,
Verner

$$\rho_\chi(a) \simeq \frac{3H_{\rm end}^4}{16\pi^2}\left(\frac{\phi(a)}{\phi_{\rm end}}\right)^2\left(\frac{a_{\rm end}}{a}\right)^{\frac{3}{2}} \propto a^{-\frac{9}{2}}$$

Evolution

$$\left(\frac{a_{\rm osc}}{a_{\rm end}}\right)^3 = {\rm Max}\left(\frac{9H_{\rm end}^2}{4m_\chi^2}\left(1-\frac{16}{9}\tilde{\sigma}\right),1\right),$$

$$\left(\frac{a_\chi}{a_{\rm end}}\right)^3 = {\rm Max}\left(\frac{\sigma\phi_{\rm end}^2}{m_\chi^2},1\right) = {\rm Max}\left(\frac{4\tilde{\sigma}H_{\rm end}^2}{m_\chi^2},1\right)$$

$$\sigma \equiv \tilde{\sigma}\frac{m_\phi^2}{M_P^2}$$

$$\left(\frac{a_{\rm RH}}{a_{\rm end}}\right)^3 = \frac{3H_{\rm end}^2 M_P^2}{\alpha T_{\rm RH}^4}.$$

Choi, Garcia, Ke, Mambrini, Olive, Verner

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$$\left(\frac{a_\chi}{a_{\rm end}}\right)^3 = {\rm Max}\left(\frac{\sigma\phi_{\rm end}^2}{m_\chi^2},1\right) = {\rm Max}\left(\frac{4\tilde\sigma H_{\rm end}^2}{m_\chi^2},1\right)$$

$$\sigma \equiv \tilde\sigma\frac{m_\phi^2}{M_P^2}$$

$$\left(\frac{a_{\rm RH}}{a_{\rm end}}\right)^3 = \frac{3H_{\rm end}^2 M_P^2}{\alpha T_{\rm RH}^4}.$$

$$\tilde\sigma < \frac{9}{32}, \qquad a_\chi < a_{\rm osc},$$

$$\tilde\sigma < \frac{3}{4}\frac{m_\chi^2 M_P^2}{\alpha T_{\rm RH}^4}, \qquad a_\chi < a_{\rm RH},$$

$$\tilde\sigma < \frac{9}{16}\left(1-\frac{4M_P^2 m_\chi^2}{3\alpha T_{\rm RH}^4}\right), \qquad a_{\rm RH} < a_{\rm osc}.$$

Choi, Garcia, Ke, Mambrini, Olive, Verner

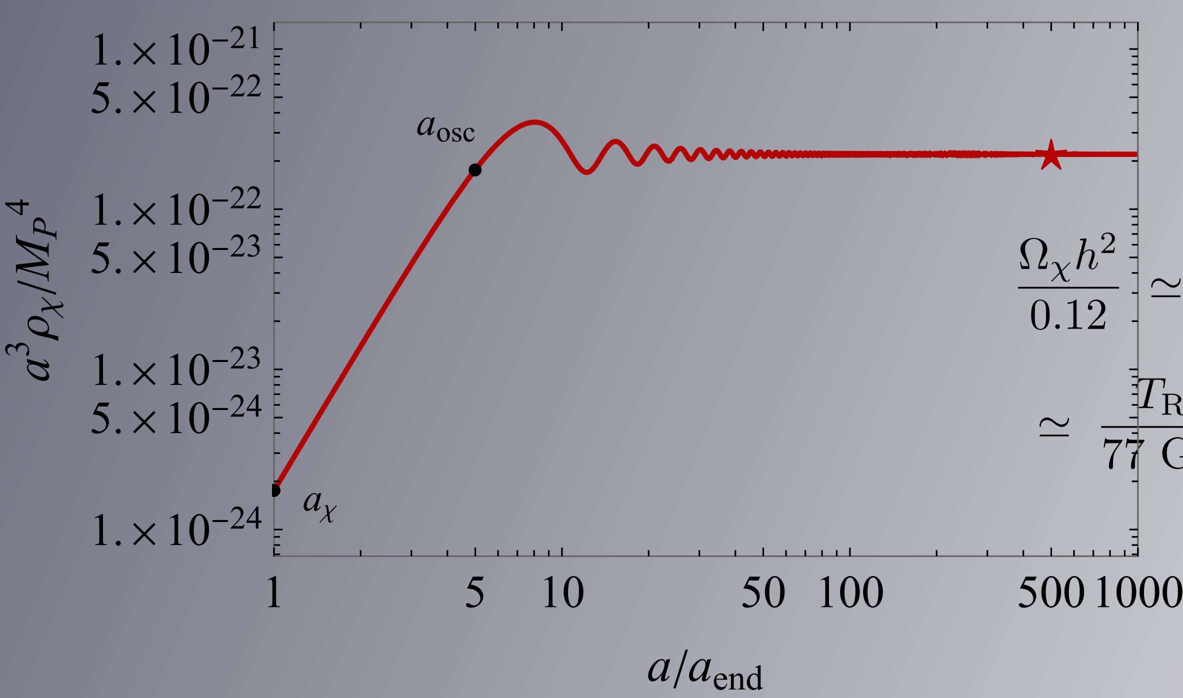
Evolution for small σ

$$\rho_\chi(a_{\rm RH}) = \frac{1}{2} m_\chi^2 \langle \chi^2 \rangle_{\rm end} \left(\frac{a_{\rm osc}}{a_{\rm end}}\right)^3 \left(\frac{a_{\rm end}}{a_{\rm RH}}\right)^3$$

$$= \frac{9}{64\pi^2} H_{\rm end}^4 \frac{\alpha T_{\rm RH}^4}{M_P^2 (m_\chi^2 + \sigma \phi_{\rm end}^2)} \left(1 - \frac{16}{9}\tilde{\sigma}\right)$$

$$= \frac{9 \alpha H_{\rm end}^4 T_{\rm RH}^4}{64 \pi^2 m_\chi^2 M_P^2}\,, \qquad \sigma \phi_{\rm end} \ll m_\chi^2;\ \tilde{\sigma} \ll 1\,.$$

Choi, Garcia, Ke, Mambrini, Olive, Verner



$$\frac{\Omega_\chi h^2}{0.12} \simeq 2.5 \times 10^7\,{\rm GeV}^{-1} \frac{H_{\rm end}^4 T_{\rm RH}}{M_P^2 (m_\chi^2 + \sigma \phi_{\rm end}^2)} \left(1 - \frac{16}{9}\tilde{\sigma}\right)$$

$$\simeq \frac{T_{\rm RH}}{77\ {\rm GeV}} \left(\frac{10^{12}\ {\rm GeV}}{m_\chi}\right)^2, \qquad \sigma \phi_{\rm end} \ll m_\chi^2;\ \tilde{\sigma} \ll 1\,.$$

Constraints

$$\frac{\Omega_\chi h^2}{0.12} \simeq \frac{T_{\rm RH}}{77\ \rm GeV}\left(\frac{10^{12}\ \rm GeV}{m_\chi}\right)^2, \qquad \sigma\phi_{\rm end} \ll m_\chi^2;\ \tilde{\sigma} \ll 1$$

fluctuations

$$\frac{\Omega h^2}{0.12} \simeq 1.1 \frac{m_\chi}{10^7\ \rm GeV}\frac{T_{\rm RH}}{10^{10}\ \rm GeV}$$

Gravitational scattering

$$.004 < \frac{T_{\rm RH}}{\rm GeV} < 4300$$

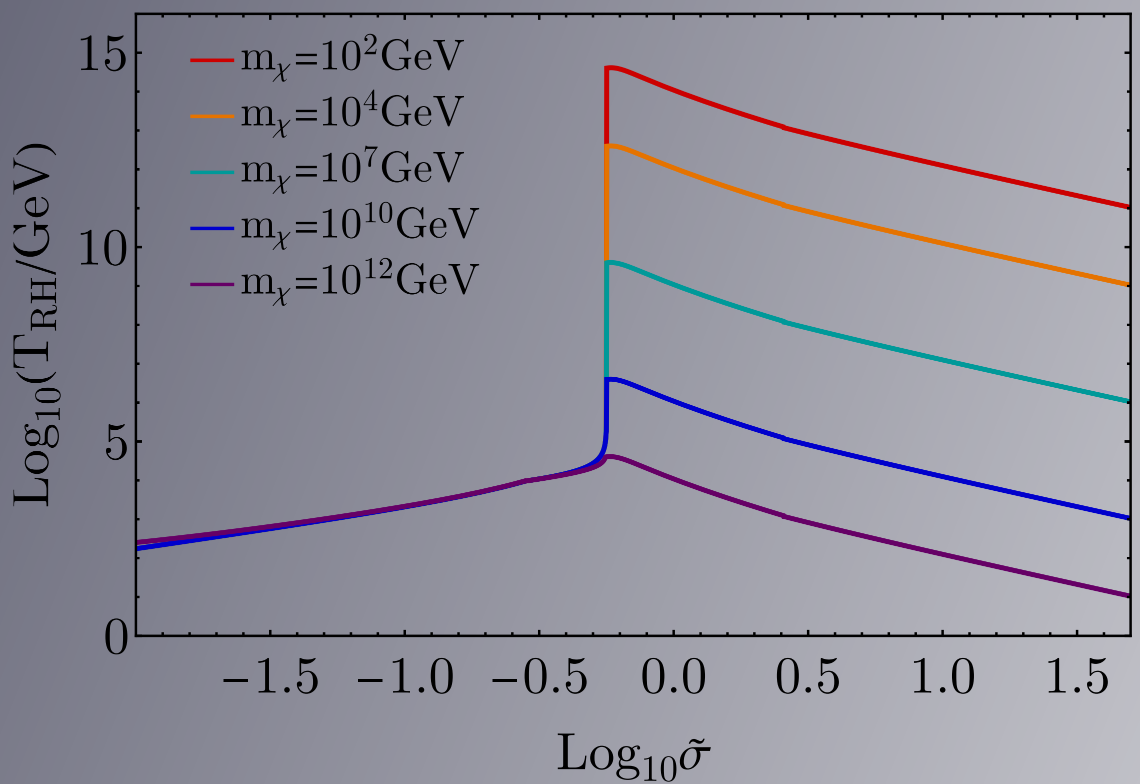
$$7 \times 10^9 < \frac{m_\chi}{\rm GeV} < 3 \times 10^{13}$$

Choi, Garcia, Ke, Mambrini, Olive, Verner

for a stable scalar

but ignores self interactions/gravitational couplings to the inflaton

Evolution for large σ



at larger σ case

$$\frac{\Omega_\chi h^2}{0.12} \simeq \tilde{\sigma}^{-1} \frac{T_{\rm RH}}{25\ \rm TeV}$$

for

$$\tilde{\sigma} < 9/32$$

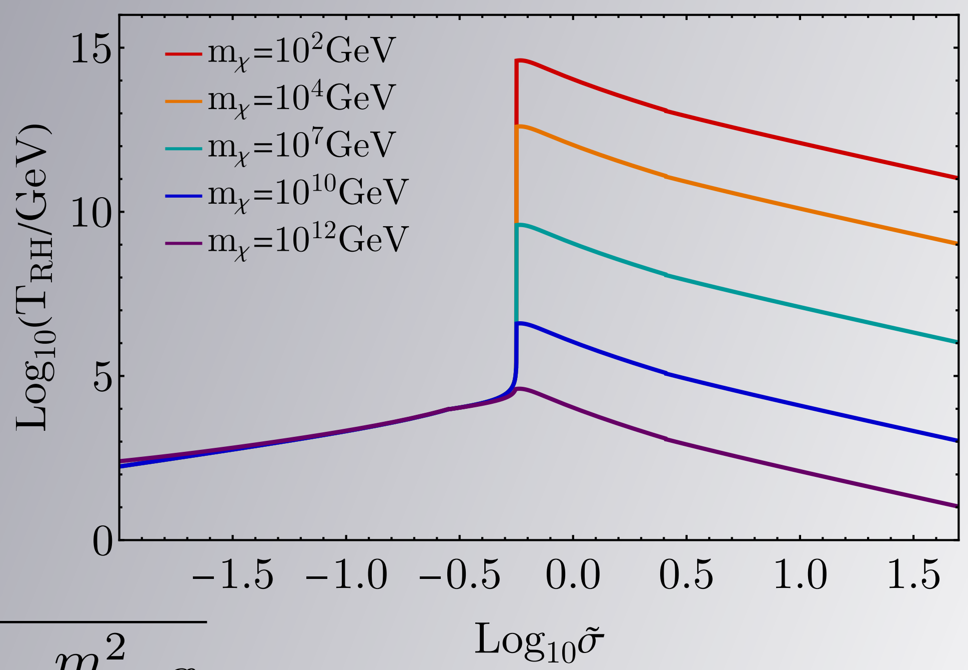
$$(a_\chi < a_{\rm osc})$$

Choi, Garcia, Ke, Mambrini, Olive, Verner

Evolution for large σ

But, at large $\tilde{\sigma}$ $\langle \chi^2 \rangle \propto e^{-1.25\pi(m^2_{\chi,\rm eff}/H^2_{\rm end} - \frac{9}{4})}$

χ production dominated by single graviton exchange and the contact term with the inflaton



Production rate:

$$R_g = \frac{2 \times \rho_\phi^2}{256\pi M_P^4}\left(1 - 4\tilde{\sigma} + \frac{m^2_{\chi,\rm eff}}{2m^2_\phi}\right)^2 \sqrt{1 - \frac{m^2_{\chi,\rm eff}}{m^2_\phi}}\,,$$

$$\frac{dY_\chi}{da} = \frac{\sqrt{3}M_P}{\sqrt{\alpha}T^2_{\rm RH}} a^2 \left(\frac{a}{a_{\rm RH}}\right)^{\frac{3}{2}} R_g(a) \qquad \rho_\chi = m_{\chi,\rm eff} Y_\chi / a^3$$

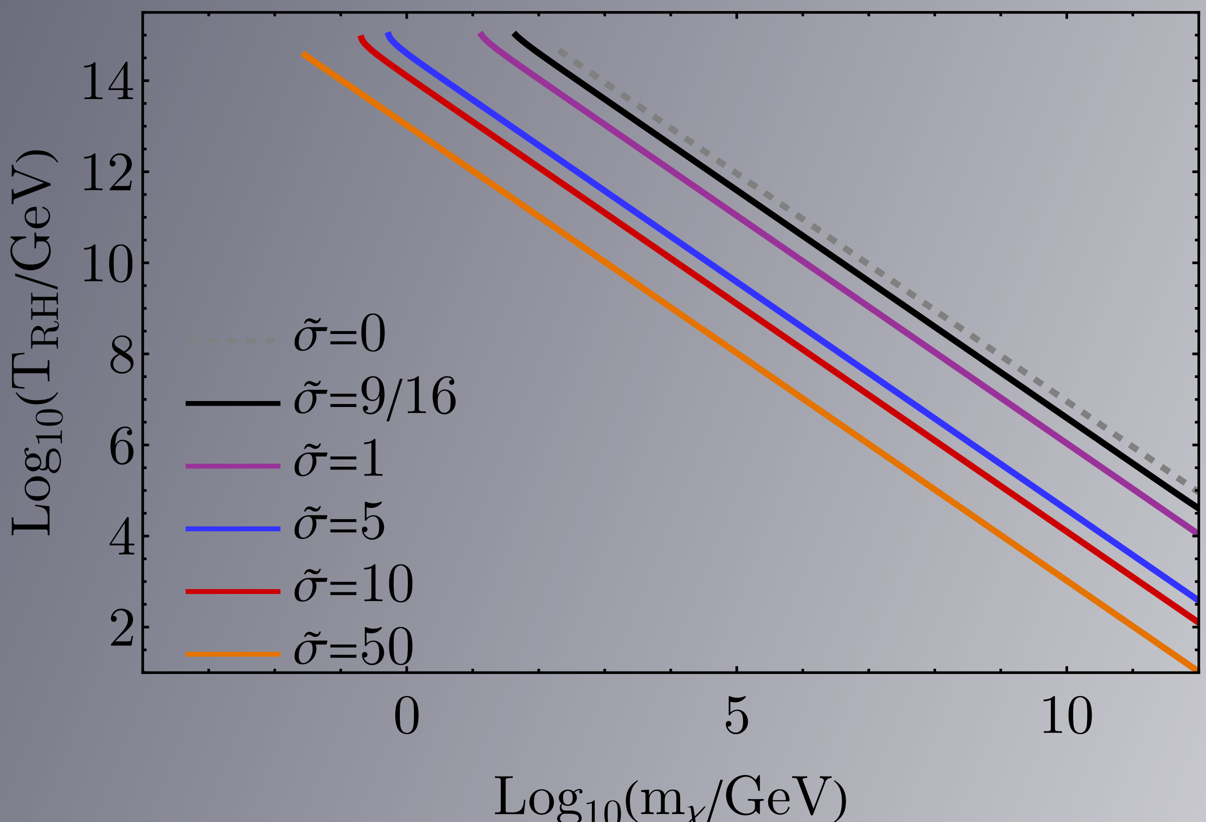
Choi, Garcia, Ke, Mambrini, Olive, Verner

Scalar Dark Matter through scattering

Ranges for m_χ and T_{RH}

$$.004 < \frac{T_{\rm RH}}{\rm GeV} < 2 \times 10^{15}$$

$$0.03 < \frac{m_\chi}{\rm GeV} < 3 \times 10^{13}$$



Scalar Dark Matter through scattering

Ranges for m_χ and T_{RH}

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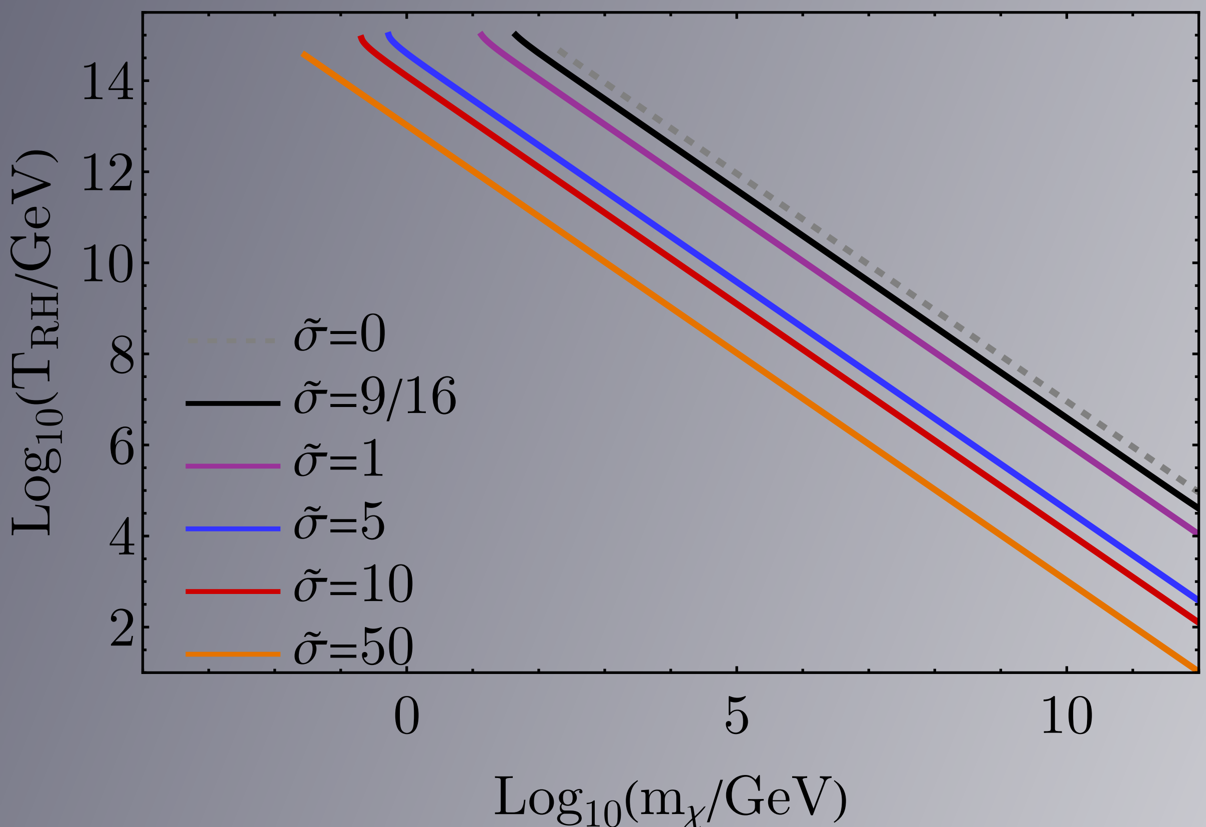


Contrast with:

$$.004 < \frac{T_{\rm RH}}{\rm GeV} < 4300$$

$$7 \times 10^9 < \frac{m_\chi}{\rm GeV} < 3 \times 10^{13}$$

$$\tilde{\sigma} = 0$$

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

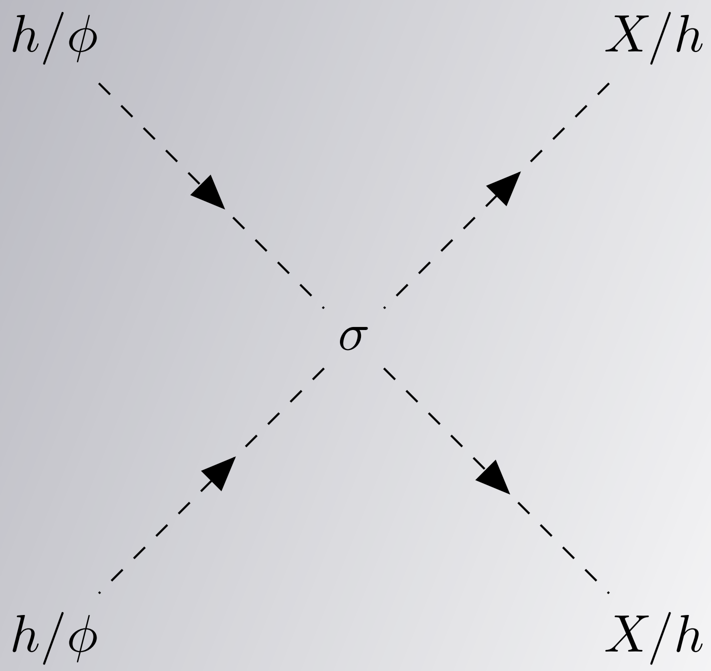
Generate $$\mathcal{L}_{\rm non-min.} = -\sigma^\xi_{hX} h^2 X^2 - \sigma^\xi_{\phi X}\phi^2 X^2 - \sigma^\xi_{\phi h}\phi^2 h^2\,,$$

For example,

$$\sigma^\xi_{\phi X} = \frac{1}{2M_P^2}\left[\xi_\phi m_X^2 + 12\xi_\phi\xi_X m_\phi^2 + 3\xi_X m_\phi^2 + 2\xi_\phi m_\phi^2\right]$$

$$\tilde{\sigma} = -\xi_X$$

For contributions to the effective mass

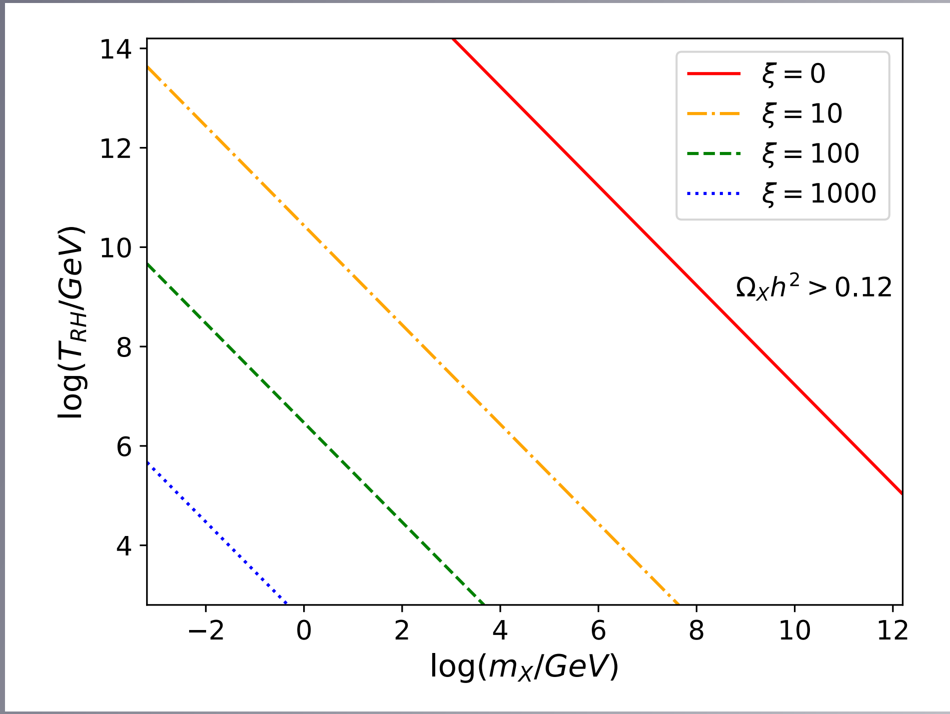


Non-minimal Gravitational Portals

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

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

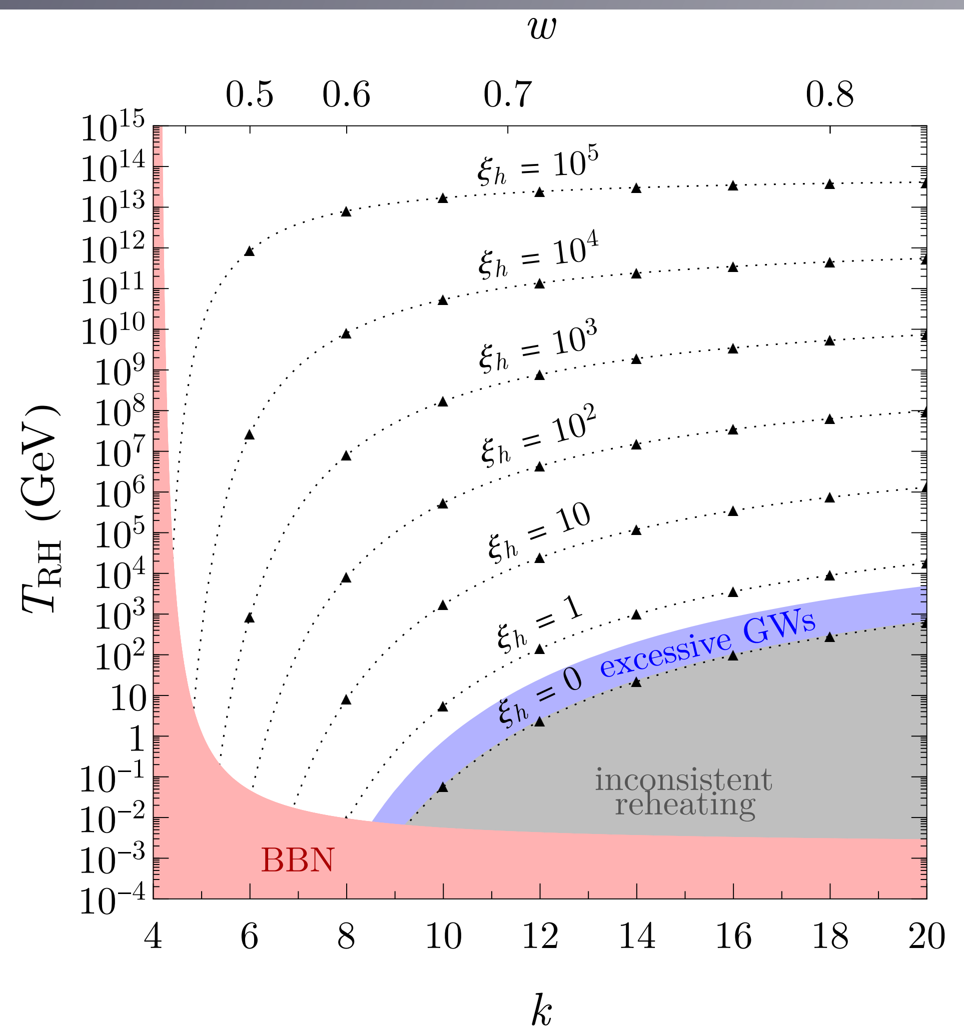
$$\frac{\Omega_X^{\phi,\,\xi} h^2}{0.12} \simeq \frac{1.3 \times 10^7 \sigma_{\phi X}^{\xi\ 2} \rho_{\rm RH}^{1/4} M_P^2}{m_\phi^3} \frac{m_X}{1\,{\rm GeV}} \sqrt{1 - \frac{m_X^2}{m_\phi^2}}\,,$$



Non-minimal Gravitational Portals

Co, Mambrini, Olive
Barman, Clery, Co, Mambrini, Olive

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



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

Summary

- Particle Production enhanced in the early phases of reheating when rates are proportional to T^{n+6} with $n > 6$ (sensitive to $T_{\rm max}$ rather than $T_{\rm RH}$).
- Gravitational portals determine a minimal particle production rate and a minimal maximum temperature during reheating.
- Large Scale fluctuations can provide a huge source for relic density - severely limiting the allowed ranges for m_χ and $T_{\rm RH}$
- Self-interactions or a gravitational coupling to the inflaton restores wide range of allowed masses and reheating temperatures