Gravitational Portals

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

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

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$$

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

Then what happens? falling as *^T* / *^a*3*/*⁸. The reheating temperature is de-

• Inflaton decays leading to reheating *falling as a falling as T a*² iton decays leading to reheating

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

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

.

 $\mathbf{a} \rightarrow \mathbf{a}$ is a notice of supersymmetric data matter in section of supersymmetric data matter in section of \mathbf{a} $\text{m/s} \Rightarrow \text{partice production}$ • Inflaton oscillations ⇒ particle production

R+R2 Gravity

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

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

Leading to

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

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

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

Starobinsky Planck-friendly Models: R+R² Inflation

1.0

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

= $\mu^2 e^{-\sqrt{2/3}x} \sinh^2(x/\sqrt{6})$

 $x=φ/M_P$, $μ^2 = 3M^2$

0 5 10 0.0 0.2 0.4 0.6 0.8 V/μ^2 *x*

Slow Roll parameters:

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

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

μ is set by the normalization of the quadrupole

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

For N=55, n_s = 0.965; r = .0035
 $x_i = 5.35$

No-Scale realization of Starobinsky

Can we find a model consistent with Planck?

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

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

Ellis, Nanopoulos, Olive

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

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

Assume now that \overline{T} picks up a vev: 2<Re T > = c \mathcal{L}_{eff} $=$ *c* $(c - |\phi|)$ $\frac{2}{\sqrt{3})^2} |\partial_\mu \phi|$ $2 - \frac{\hat{V}}{(c - \delta)^2}$ $(c - |\phi|^2/3)^2$

Redefine inflaton to a canonical field χ

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

No-Scale models revisited

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

(1 *||* ²*/*3)² = ˆ*µ/*^p

3 $\frac{1}{(1 + |z|^2)^{2}} \Rightarrow$ Starobinsky Potential

No-Scale models revisited Then $c = 1$, $\lambda = \hat{\mu}/\sqrt{3}$ (1 *||* ²*/*3)² = ˆ*µ/*^p ⇒ Starobinsky Potential

How well does this do vis a vis Planck?

 n_s

Reheating i 4 Pabasting in a straightforward way, resulting in \mathbf{D}_{14} , \mathbf{L}_{15} 3d²

In the absence of a direct coupling of the inflaton to matter, reheating does NOT occur. 5.1.4 Decays to gauge bosons and gauginos !!
|-
|- \mathcal{L} ence of a direct coupling of the infla 2 \$1999 \$1999 \$1999 \$1999 \$1999 \$1999 \$1999 \$1999 \$1999 \$1999 \$1999 \$1999 \$1999 \$1999 \$1999 \$1999 \$1999 \$1999 \$1
Alternatives, the gauge suppressed by the gauge suppression of the gauge suppression of the gauge suppression e inflaton to ma \mathbf{t}

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

Equating to gauge bosons and gauginos
gauge kinetic function $f_{\alpha\beta} = f(\phi_1)\delta_{\alpha\beta}$

$$
\Gamma(\phi_1) = \Gamma(\phi_1) \Gamma(\phi_2) \Gamma(\phi_3)
$$

$$
\Gamma(\phi_2) = \Gamma(\phi_1) \Gamma(\phi_2) \Gamma(\phi_3) \Gamma(\phi_3)
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\Gamma(\phi_1) = \Gamma(\phi_1) \Gamma(\phi_2) \Gamma(\phi_3)
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\Gamma(\phi_1) = \Gamma(\phi_2) \Gamma(\
$$

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

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

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

 \overline{a}

2 and a post Canada, the gaugino masses of the gaugino masses of the gaugino masses of the gaugino masses, the gaugino masses, the gaugino masses of the gaugino masses of the gaugino masses of the gaugino masses, the gaugi $\langle 12 \rangle$, the rates $\langle 12 \rangle$, the rates $\langle 10 \rangle$ rates $\langle 10 \rangle$ rates $\langle 10 \rangle$ widths into $\mathsf{O}\mathsf{I}$ into $\mathsf{O}\mathsf{I}$ and (91) and (91) and (91) and (91) and (91) and (91) and (91). On the into $\mathsf{O}\mathsf{I}$ In this, date change on the constraint of graviting of graviting production of gravitation of graviting \Box Ellis, Garcia, Nanopoulos, **Olive**

Reheating Ellis, Garcia, Nanopoulos, **A direct coupling between** \blacksquare **and the matter sector matter sector matter sector matter sector matter sector may be allowed.** Filis, García, Nanopoulos, example, this field can be associated with a heavy singlet sneutrino in such case, the $\mathsf{R}\mathsf{a}\mathsf{h}\mathsf{a}\mathsf{a}\mathsf{f}\mathsf{in}\mathsf{o}$ are liable to yield a relic neutralino density that is far too large. Thus we can not afford a relic neutralin
Thus we can not afford a relic neutralino density that is far too large. Thus we can not afford a relic neutra $+$ four-fermion terms terms to K

Olive

Significant reheating if the inflation (Φ) is directly coupled to matter decays to moduli can be the setter to be the setter of the inflation (Φ) is directly contained to be the setter after |
|-
| Internative of the set i≀ ڊ \mathbf{F} $\ddot{\theta}$ \mathbf{H} Wikipedia Wikaya 2

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

and ϕ_1 can be associated with a heavy singlet sneutrino if Wij Wij de De Onamely −1IJ φ1Φ το particular case of sneutrino inflation, the particular case of sneutrino i
2011 - Liste of sneutrino inflation, this particular case of sneutrino inflation, this particular case of sne and ϕ_1 can be associated with a heavy singlet sneutrino α can he associated with a heavy su

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

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

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

Inflationary Context

Inflationary Context scale supergravity [60–62] defined by a Kähler potential of Im

No-scale supergravity:

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

Inflationary Context scale supergravity [60–62] defined by a Kähler potential of where \blacksquare is a volume modulus and \blacksquare we have worked in units of MP. In the remainder of MP. In the remainder of the remainder of the remainder of th **Appendix restormed in the MP.** The most of MP. Th

No-scale supergravity: $K = -$

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

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

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

Inflationary Context scale supergravity [60–62] defined by a Kähler potential of where \blacksquare is a volume modulus and \blacksquare we have worked in units of MP. In the remainder of MP. In the remainder of the remainder of the remainder of th **Appendix restormed in the MP.** The most of MP. Th Inf l, " art N ≅ τ

No-scale supergravity: $K = -$ 1

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

$$
W = M\left(\frac{\phi^2}{2} - \frac{\phi^3}{3\sqrt{3}}\right) \qquad \text{Starobinsky} \qquad V = \frac{3}{4}M^2(1 - e^{-\sqrt{2/3}\varphi'})^2
$$

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

Inflationary Context scale supergravity [60–62] defined by a Kähler potential of where \blacksquare is a volume modulus and \blacksquare we have worked in units of MP. In the remainder of MP. In the remainder of the remainder of the remainder of th **Appendix restormed in the MP.** The most of MP. Th Inf l, " art N ≅ τ

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$$
\nKallosh, Linde

 $\overline{}$ \mathbb{N} ^{1.5} /// $k = 2,4,6$ \bigcup \bigcup 1.0 $\frac{1}{10}$ $\frac{1}{2}$ 2.5 \vdash $\sqrt{2}$ 4 $\sqrt{2}$ 1.0 $\frac{1}{2}$ /// $\sqrt{ }$ when hti $\mathcal{L} = 2.1$ Here the inflaton mass, $\mathcal{L} = 2.1$ \overline{C} inflationary potential allows us to relate the number of \mathcal{L} -10 -5 $+$ 5 10 0.5 1.5 2.0 2.5 The resulting scalar potential is then 2.5

Inflationary Context scale supergravity [60–62] defined by a Kähler potential of where \blacksquare is a volume modulus and \blacksquare we have worked in units of MP. In the remainder of MP. In the remainder of the remainder of the remainder of th **Appendix restormed in the MP.** The most of MP. Th Inf l, " art N ≅ τ

No-scale supergravity: $K = -$ 1

 λ λ Ω

when hti $\mathcal{L} = 2.1$ Here the inflaton mass, $\mathcal{L} = 2.1$

 -10 -5 $+$ 5 10

0.5

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

$$
W = M\left(\frac{\phi^2}{2} - \frac{\phi^3}{3\sqrt{3}}\right) \qquad \text{Starobinsky} \qquad V = \frac{3}{4}M^2(1 - e^{-\sqrt{2/3}\varphi'})^2
$$

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

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

$$
k = 2,4,6
$$

 $\frac{1}{2}$

 $\frac{1}{10}$

 $\boldsymbol{n_s}$

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

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

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

 $=$ $\sqrt{2}$, we obtain the equation of $\sqrt{2}$

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Den einingu þess að þ

$$
\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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expediately allows $\frac{1}{2}$ when $\frac{1}{2}$ $\mathbf{1}$ is the Hubble parameter. Inserting Eq. (1) is the \mathcal{P} allowin mDM > Treh, production ends at T ≃ mDM and the dark \therefore $\mathcal{L}_{\phi-SM} = -y$ ϕ , \boldsymbol{J} , $\boldsymbol{$ allo allowing for decay coupling: $\mathcal{L}^y_{\phi-SM} = -y\phi\bar{f}f$

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

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

$$
\ddot{\Phi} + 3H\dot{\Phi} + V'(\Phi) = 0,
$$
or decay coupling: $\mathcal{L}_{\phi}^{y} = -u\phi\bar{f}f$
$$
\Gamma_{\phi} = \frac{y^{2}}{-m_{\phi}(\phi)}
$$

expediately allows $\frac{1}{2}$ when $\frac{1}{2}$ a is the Hubble parameter. In the Hubble parameter $\delta \pi$ is the $\delta \pi$ allowin mDM > Treh, production ends at T ≃ mDM and the dark \therefore $\mathcal{L}_{\phi-SM} = -y$ ðΦÞ ¼ 0; ð3Þ 8⇡ allo allowing for decay coupling: $\mathcal{L}^y_{\phi-S}$ $\Delta u = \Delta u$ $\mathbf{I} = -y\phi f f$ **l** ϕ $\nonumber\varphi\,\backslash\,\varphi$

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

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

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

expediately allows $\frac{d}{dx}$ is the Hubble parameter $\frac{d}{dx}$, $\frac{d}{dx}$ is the $\frac{d}{dx}$ into $\frac{d}{dx}$ allowin mDM > Treh, production ends at T ≃ mDM and the dark $\mathbf{L}_{\phi-SM} = -y\varphi JJ$ $\mathbf{L}_{\phi} = \frac{\partial \mathbf{L}_{\phi-SM}}{\partial \pi} \mathbf{L}_{\phi}(\mathbf{G})$ allo g for decay coupling: $\mathcal{L}^y_{\phi-S}$ $\Delta u = \Delta u$ allowing for decay coupling: $\mathcal{L}^y_{\phi-SM} = -y\phi \bar{f}f$ $\Gamma_\phi =$ 8π $m_\phi(\phi)$

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

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

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

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

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

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

expediately allows $\frac{d}{dx}$ is the Hubble parameter $\frac{d}{dx}$, $\frac{d}{dx}$ is the $\frac{d}{dx}$ into $\frac{d}{dx}$ allowin mDM > Treh, production ends at T ≃ mDM and the dark $\mathbf{L}_{\phi-SM} = -y\varphi JJ$ $\mathbf{L}_{\phi} = \frac{\partial \mathbf{L}_{\phi-SM}}{\partial \pi} \mathbf{L}_{\phi}(\mathbf{G})$ allo g for decay coupling: $\mathcal{L}^y_{\phi-S}$ $\Delta u = \Delta u$ allowing for decay coupling: $\mathcal{L}^y_{\phi-SM} = -y\phi \bar{f}f$ $\Gamma_\phi =$ 8π $m_\phi(\phi)$

$$
\frac{d\rho_{\phi}}{dt} + 3H(1 + w_{\phi})\rho_{\phi} \simeq -(1 + w_{\phi})\Gamma_{\phi}\rho_{\phi}
$$
\n
$$
\frac{d\rho_R}{dt} + 4H\rho_R \simeq (1 + w_{\phi})\Gamma_{\phi}\rho_{\phi}
$$
\n
$$
H^2 = \frac{\rho_{\phi} + \rho_R}{3M_P^2} \simeq \frac{\rho_{\phi}}{3M_P^2}
$$
\n
$$
w_{\phi} = \frac{p_{\phi}}{\rho_{\phi}} = \frac{k - 2}{k + 2}
$$

 Γ the potential can be the potential can be the small can be thought of as the small can be thought of as the small can be the small

Inflator	Scillations	Ichikawa, Suyama, Takahashi, Yamaguchi; Kanaguchi; Kanudainen, Nurmi, Tarkanen, Tuominen;
$\phi(t) = \phi_0(t) \cdot \mathcal{P}(t)$	Garcia, Kaneta, Garcia, Kaneta, Gareta, Olive	
$\phi_0 = \left(\frac{\rho_{\text{end}}}{\lambda}\right)^{\frac{1}{k}} \left(\frac{a_{\text{end}}}{a}\right)^{\frac{6}{k+2}}$	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** $\overline{ }$ 6*k k*+2 2 V $\overline{}$ g: Ger , (20) $6h$ For $\Gamma_t \times H$ of $(\alpha) = \alpha$ Garcia, Kaneta, Mambrini, Olive

For $\Gamma_{\Phi} \ll H \quad \rho_{\Phi}(a) = \rho_{\text{end}} \left(\frac{a_{\text{end}}}{a}\right)$ *a*

as matter for k=2 α as matter for $k=2$

End of Inflation: Inflation ends when $\frac{1}{2}$ = (2M2) \mathbf{P} flation ends when

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

In terms of conventional slow-roll parameters $(\ddot{a}=0)$ In terms of conventional slow-roll parameters \mathbb{R}^2

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

Reheating: Generation of the Radiation bath Garcia, Kaneta, Mambrini, Olive; Clery, Mambrini, Olive,

Reheating: Generation of the **Padiation bath 3 Inflaton decay and annungation** damped by decays. To stay as possible, we consider the following possible, we consider the following possible c butions to the Lagrangian leading to decay or annihilation: Garcia, Kaneta, Mambrini, Olive

More generally, *∠* ⊃ $\sqrt{ }$ \int $\overline{\mathcal{L}}$ $y \phi \bar{f} f \quad \phi \to \bar{f} f$ $\mu \phi bb \quad \phi \to bb$ $\sigma\phi^2b^2$ $\phi\phi \rightarrow bb,$

Table 1. Dependence of the temperature *T* as function of the scale factor *a* for the dierent cases will not reheat.

1 Darticle Production in the following way, REHEATING AND POST-INFLATIONARY PRODUCTION OF … PHYS. REV. D 101, 123507 (2020)

 $(Freeze-in)$ where $(Freeze-in)$ is a heavy related to the mass of a heavy relation $Kaneza$, Mambrini,

valid for the duration of reheating provided that Λ ≳ Tmax.

 α didates during the reflection α abundance of the relic abundance of α mediator in the UV theory. For *n >* ≠1, DM production after reheating is subdominant [15, **Olive**

Suppose some coupling to the Standard Model with cross section in the following way, Suppose some coupling to the Standard Model with cross section that this eective description is valid as long as ˜ is above *T*max. The amount of DM produced .
∙d M odel with cross $\frac{1}{2}$

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

Where the mass scale q .

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

Define
$$
Y_{\chi} = n_{\chi} a^{3}
$$

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

Particle Production valid for the duration of reduced that Λ \mathbf{p} **The suppression by the UV settion by the UV scale ensures** the UV scale ensures that DM annihilation can be neglected. Integration of (29) after

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

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

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

$$
n^{s}(T_{\text{reh}}) = \sqrt{\frac{10}{g_{*}} \frac{M_{P}}{\pi} \frac{2k+4}{kn-n-10+2k}}
$$

$$
\times \left(\frac{T_{\text{reh}}}{T_{\text{max}}}\right)^{\frac{2k+6}{k-1}} \frac{T_{\text{max}}^{n+4}}{\Lambda^{n+2}}.
$$

 $-\frac{1}{2}$ \int K=2 $n_{\text{crit}} = 6$ for k=2

Garcia, Karleta,
Mambrini, Olive Garcia, Kaneta,

Particle Production

Particle Production BR, and the DM mass. In the DM mass. In the case of scattering \mathbf{r}

Kaneta,
sidolise $t_{\rm t}$ the required value of θ Garcia, Kaneta, Mambrini, Olive

Particle Production **the inflaton-band inflaton-band inflaton-strategies in the inflaton-strategies of the intervalse in the intervalse intervalse in the intervalse inter**

ture. It depends on the square of the ratio of the ratio of the ratio of the ratio of the square of the ratio of the square of the square of the ratio of the ratio o

ex: gravitino production in high scale supersymmetry $T_{\rm max} \sim 10^{12}$ GeV and $T_{\rm reh} \sim 10^{10}$ GeV k=2 $T_{\text{max}} \sim 10^{12}$ GeV and $T_{\text{reh}} \sim 10^{10}$ GeV

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

Dudas, Mambrini, **Olive**

 $\mathcal{S}(\mathcal{S})$

Gravitational Portals must exist between the inflationary and dark sectors. If **discussional Portal space-time metric is expanded and space-time metric is expanded and space users are detailed and space users of the space use** ing *gµ*⌫ ' ⌘*µ*⌫ + *h*˜*µ*⌫ the gravitational Lagrangian in the **Gravitational Porc**
 Property ton to the Standard Model (as will see gravitation interaction alone will not lead to radiational $\boldsymbol{\mathsf{F}}$ the mechanism for producing dark matter may in fact be *P* \overline{O} *M*² *P* ⁸ (@↵*h*˜*µ*⌫)(@↵*h*˜*µ*⌫) = ¹

(@↵*h^µ*⌫)(@↵*hµ*⌫) (1) where *hµ*⌫ = (*M^P /*2)*h*˜*µ*⌫ is the canonically normalized Clery, Mambrini, Olive, Mambrini, Olive; **perturbation and** *M*_P $\frac{1}{2}$ /² Verner

,

Start with Einstein-Hilbert Lagrangian \mathbb{R}^n St transverse-traceless gauge at second order can be written reflexion to the *h p <i><i>n <i>n*² *<i><i>n**<i>n <i><i>n <i>n <i><i>n <i>n <i>n* processes involving a gravitational interactions, comparstart with Einstein-Hilbert Lagrang

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

Gravitional interactions

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

processes involving a gravitational interactions, comparconsidered as *derivational interactions* as α 2*M^P* $\frac{1}{2}$

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

$$
\phi/SM
$$

$$
\frac{T_{\phi/SM}^{\mu\nu}}{M_{P}} \sim N/SM
$$

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

$$
\phi/SM
$$

$$
\phi/SM
$$

$$
\gamma^{\mu\nu} = \frac{i}{2} \left[\bar{\chi} \gamma^{\mu} \dot{\partial}^{\nu} \chi + \bar{\chi} \gamma^{\nu} \dot{\partial}^{\mu} \chi \right],
$$

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

Gravitational Portals Mambrini, Olive; matter, A) SM + SM ! *X*+*X*; B) + ! *X*+*X*, where Haque, Maity; *Hatter inflaton condensate (2002)* α mode), α and β *n* in the initial state rather than α in the initial state particle particle particle particle particle particle Mambrini, Olive; **Barman, Bernal;** Verner where the graviton propagator for the canonicallycesses */h*(*p*1) + */h*(*p*2) ! *h/X*(*p*3) + *h/X*(*p*4) can be

X the Standard Model is straightforward, and we have the Standard Model is straightforward, and we have the straightforward, and we have the straightforward of the straight \mathbf{X}

leave it for future work.

- A. Gravitational Production of DM from the thermal bath the fact that the energy associated with the momenta, $\sum_{i=1}^n$ $\sum_{i=1}^n$ for the production $\sum_{i=1}^n$ for the pro
	- $\overline{0}$ B. Gravitational Production of DM from Inflaton Scattering ! *^X* ⁺ *^X* process with amplitude *^M*³ is
- **Standard C.** Gravitational Production of the thermal the inflaton condensate in the initial state. *R* R **Ext** 1111aw₁ C. Gravitational Production of the thermal bath from Inflaton Scattering

of reduced is a matter endurance in the gravity only - No model dependence! momenta p1*,*³ and p1*,*2, respectively, and Minimal Gravity only - No model dependence! B. The production of dark matter from direct excitations

Gravitational Portals ↵²*M*⁴ *P a* 4 ori iravitational Portals ر
12 \mathbb{P} brtals

$$
SM^{i}(p_{1}) + SM^{i}(p_{2}) \rightarrow X^{j}(p_{3}) + X^{j}(p_{4}) \qquad \frac{dY_{\chi}}{da} = \frac{a^{2}R_{\chi}^{i}(a)}{H}
$$

$$
R_{j}^{T} = R_{j}(T) = \beta_{j}\frac{T^{8}}{M_{P}^{4}}
$$

$$
n_{X}^{T}(a_{RH}) = \frac{\beta_{X}\sqrt{3}}{\alpha^{2}M_{P}^{3}}\frac{\beta_{RH}^{3/2}}{(1 - (a_{end}/a_{RH})^{\frac{14 - 2k}{k + 2}})^{2}} \frac{k+2}{6} \left(\frac{1}{3-k} + \dots\right)
$$

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

 $3997\pi^3$ $\frac{36864n}{20736000}$ $\beta_{1/2} =$ $11351\pi^3$ 10368000 scale factor corresponding to the end of inflation, *a*end, $a_{\rm H} \pi^2 / 30$ and $a_{\rm O} = \frac{3997 \pi^3}{\sqrt{3}}$

Gravitational Portals **Canadia Construction** To calculate the dark matter production rate, we com-*^V* () = *^V* (0) *· P*(*t*)*^k*. We next expand the potential

 $\phi(p_1) + \phi(p_2) \rightarrow X^j(p_3) + X^j(p_4)$ between *a*end and *a*RH gives for scalar dark matter

$$
R_0^{\phi^k} = \frac{2 \times \rho_{\phi}^2}{16\pi M_P^4} \Sigma_0^k \qquad \qquad \frac{dY_X}{da} = \frac{\sqrt{3}M_P}{\sqrt{\rho_{\rm RH}}} a^2 \left(\frac{a}{a_{\rm RH}}\right)^{\frac{3k}{k+2}} R_X^{\phi^k}(a)
$$

Gravitational Portals

Inflationary Gravitational Leptogenesis $\frac{1}{2}$ antecess *a ,* (12) *^s* ⁼ ✏ *^s* (15) **is produced.** Here α ² α ¹ α ³ where y is a Yukawa coupling, and y is a Yukawa coupling, and y

^N!*L*↵*^H ^N*!*L*¯↵*^H*

 \mathbb{R}^N Co, Mambrini, Olive; w*here a*end is the scale factor of scale factor when inflation ends (de- $Bernal, Fong$

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

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

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

Gravitational Portals imum temperature is not given by the inflaton width, **but by the scattering process, whereat**ing (and thus *T*RH) is still dominated by the decay. This *k* 7GeV (47) **C**even Construction Con (1 + *^w*)⇢ ⁼ *^N* ² 0! *n*=1 *ⁿ|P^k n|*

 $\phi(p_1) + \phi(p_2) \rightarrow \text{SM}^i(p_3) + \text{SM}^i$ $(\phi \phi \rightarrow h_{\mu\nu} \rightarrow HH)$ is illustrated in Fig. 2 below. In fact, the gravitation \mathbf{r} is the gravitational term in fact, the gravitational term is the gravitation of \mathbf{r} $+\varphi(p_2) \rightarrow SM^{\circ}(p_3) + SM^{\circ}$ where we assumed *a*RH *a*end. Note that the depen- $\phi(p_1) + \phi(p_2) \rightarrow \text{SM}^i(p_1)$ $+$ SM^i $+$ $\text{Haque},$ Maity rate with that in Eq. (20), and (1 + *^w*)⇢ ⁼ !*R^k* $\phi(n_1) + \phi(n_2) \rightarrow SM^{i}(n_2) + SM^{i}$ φ (P₁), φ (P₂), and (P₃), sind
(dd $\rightarrow h_{\mu\nu} \rightarrow HH$)

 \overline{a} Clery, Mambrini, Olive, Verner;

effective quartic coupling $\mathcal{L}_h = \sigma_h \phi^2 H^2$. \sim 2 \sim ϵ cenve quarue coupir *^a*end ◆ upling $\mathcal{L}_h = \sigma_h \phi^2 H^2$. ⇢ λ_h = $=\sigma_b\phi^2H^2$.

 $\sigma_h = \frac{P}{2M}$ ρ_{ϕ} $2M_P^2\phi_0^2$ *,* (53) for each real scalar. Thus for the Standard Model Higgs,

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

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

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

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

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

⌃*^h ^k* ⁼ ^X *n*=1 *n*² $\frac{3}{8}$ / **100** $\begin{pmatrix} 10 & \text{GeV} \end{pmatrix}$ point during the reheating process. This gives us the re- $\sqrt{\frac{1}{4}}$ $\frac{1}{\tau}$ is GeV, couplings beyond gravity between the inflaton and the $\frac{3}{8}$ $\chi^3\times$ = $\frac{13}{4}$ GeV $\frac{12}{4}$ $\left|T^h_{\text{max}}\right| \simeq 3.1 \times 10^{12} \left(\frac{\rho_{\text{end}}}{10^{64} \text{ GeV}^4}\right)^{\frac{3}{8}} \left(\frac{m_\phi}{3 \times 10^{13} \text{ GeV}}\right)^{\frac{1}{4}} \text{GeV}$ 10^{64} GeV⁴ $\bigg)^{\frac{3}{8}}\left(\frac{m_\phi}{3\times10^{13}\text{ GeV}}\right)^{\frac{1}{4}}$ 4 GeV *,*

> $\mathbf x$ Absolute lower bound on T_{max}

Gravitational Portals

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

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

exceeds that produced by decays when: Gravitationally produced radiation density

Mon-minimal Gravitational Portals field³ *H*, for which we adopt the Unitary gauge, *H* = ^p2, and the dark matter candidate *^X*. The relnient, Olive, verner
I field³ *H*, for which we adopt the Unitary gauge, *H* = **2. The Mon-minimal Gravitational Portals he definition field. In the data metric field.** Leaving the data metric field. Cleavy, Mambrini, Olive, to Appendix A, we write the action (2) in the Einstein Shkerin, Verner*V^h* = **1** 2 *m*² *^hh*² + 1 4 *ll Gravitation* II. The Framework \mathbf{r} is a weak scale mass, which is a good approximation in \mathbf{r} witational Portals and our *^XX*² *.* (8) definite. Computing the eigenvalues, one arrives at the

Consider a non-minimal coupling to curvature: ^p*g*˜ non-minimal coupling to curvatu Consider a non-minimal coupling to curvature: Consider a non-infilming coupling to curvature.

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

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

Here *^M^P* = 2*.*⁴ ⇥ ¹⁰¹⁸ GeV is the reduced Planck mass, **Exercise in the Einstein frame** the Appendix A, we write the action of the action (2) in the action (2) in the Appendix A, we write the action (2) in Rewrite in the Einstein frame *M*² *M*² *M*²

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

$$
- \frac{V_\phi + V_h + V_X}{\Omega^4} \right].
$$

Non-minimal Gravitational Portals lowed in scalar field water for certain scalar field was a set of the scalar field magnitude \sim P ri-milimial diavitational Portais *^L*e↵ ⁼ ¹ 2 *M*² *P M*² *P* @*^µh*@*µ^h* ¹ 2 *M*² *P M*² *P* @*^µ*@*µ* ¹ 6⇠*h*⇠*XhX* 6⇠*h*⇠*h* 6⇠⇠*XX*

kinetic term for the scalar fields and deduce the scalar fields and deduce the leading-

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

The latter can be brought to the form of the form of the form of the form of the form **L**_n \mathbf{E}_{new} are positive-function (10) must be positive-function definite the eigenvalues, \mathbf{C} For example,

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

@*^µ*@*µX* + *m*²

*M*²

*XX*²

Non-minimal Gravitational Portals \mathbf{r} the coefficients: the terms (⇠) ²*,* ³. If we use *H* ' ravitational Porta \overline{a} \overline{b} \overline{c} $\overline{$ allows us to consider all $\bigcap_{x\in A}$ the there all $\bigcap_{x\in A}$ indi-filminial diavitationa

$$
SM^{i}(p_1) + SM^{i}(p_2) \rightarrow X^{j}(p_3) + X^{j}(p_4) \qquad \frac{dY_{X}^{\xi}}{da} = \frac{\sqrt{3}M_H}{\sqrt{\rho_{RH}}}
$$

p⇢RH

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

$$
R_{X}^{T, (\xi)}(T) = \beta_{1}^{(\xi)} \frac{T^{8}}{M_{P}^{4}} + \cdots
$$
\n
$$
n_{X}^{T, \xi}(a_{\text{RH}}) = \frac{2\beta_{1}^{\xi}}{\sqrt{3}\alpha^{2}M_{P}^{3}} \frac{\beta_{\text{RH}}^{3/2}}{(1 - (a_{\text{end}}/a_{\text{RH}})^{\frac{5}{2}})^{2}} \times (1 + \cdots
$$
\n
$$
\beta_{1}^{\xi} = \frac{\pi^{3}}{81000} \left[30\xi_{h}^{2}(12\xi_{X}(4\xi_{X} + 1) + 1)\right]
$$
\n
$$
+10\xi_{h}(6\xi_{X} + 1)^{2} + 10\xi_{X}(3\xi_{X} + 1) + 1], \quad \xi_{X} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}
$$
\n
$$
\alpha = g_{\text{RH}}\pi^{2}/30
$$

[2 + 5⇠*^h* (32⇠*^h* 2)] *.* (89)

 $t = \frac{10}{3}$ and $t = \frac{10}{3}$.

 $\frac{1}{5}$ to $\frac{1}{10}$ -10 -5 0 5 10 ξ_h

 -10 -5

Non-minimal Gravitational Portals \mathbf{r} the coefficients: *Non-minimal Gravitational Porta* \overline{a} \overline{b} \overline{c} $\overline{$ allows us to consider all $\bigcap_{x\in A}$ the there all $\bigcap_{x\in A}$ indi-filminial diavitationa

$$
SM^{i}(p_1) + SM^{i}(p_2) \rightarrow X^{j}(p_3) + X^{j}(p_4) \qquad \frac{dY_{X}^{\xi}}{da} = \frac{\sqrt{3}M_H}{\sqrt{\rho_{RH}}}
$$

 \overline{a}

 \mathcal{T}^8

 $+$ \cdots

….

p⇢RH

*T*8

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

$$
n_X^T \cdot (1) = p_1^T \cdot \frac{M_P^4}{M_P^4} + \cdots
$$

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

 \mathbf{a}

$$
\beta_1^{\xi} = \frac{\pi^3}{81000} \left[30 \xi_h^2 \left(12 \xi_X (4 \xi_X + 1) + 1 \right) + 10 \xi_h (6 \xi_X + 1)^2 + 10 \xi_X (3 \xi_X + 1) + 1 \right], \quad \sum_{\substack{0 \\ \xi = 10}}^{14} \xi_{10}^{\xi}.
$$

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

 $R_X^{T, (\xi)}(T) = \beta_1^{(\xi)}$

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

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

$$
R_X^{\phi,\,\xi}\ =\ {2\times\sigma_{\phi X}^\xi\over16\pi}{\rho_\phi^2\over m_\phi^4}\sqrt{1-{m_X^2\over m_\phi^2}}
$$

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

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

 η/η

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

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

 $\mathcal{Q} \times \sigma^{\xi}$ \mathcal{Q} $\sqrt{2}$ $\sqrt{2}$ $\sqrt{2}$ $t_{\mathbf{p}}\phi,\xi = \frac{2}{\sqrt{2\pi}}\int_{0}^{\infty} \frac{dX}{dx}e^{i\theta}dx + \int_{0}^{\infty} \frac{dM}{dx}dx$ $t_{\rm X} = 16\pi$ m⁴ $\sqrt{t_{\rm w}^2/m^2}$

 ρ_{ϕ}^2

 $\frac{\partial^2 \phi X}{\partial \phi^2} \frac{P \phi}{\partial \phi^2} \sqrt{1 - \frac{m_X}{m_Z^2}}$

 $\sqrt{1-\frac{m_\lambda^2}{m^2}}$

X

 m_ϕ^2

 m_ϕ^4

 $2\times \sigma_{\phi X}^{\xi-2}$

 $\times \sigma_{\phi}^{\xi}$

²*,* ³. If we use *H* ' ^p3*M^P* , which is valid for

 16π

 $R_X^{\phi, \, \xi} =$

 $R_{\mathbf{v}}^{\phi,\,\xi} = -$

^p3*M^P* ✓ *a a*RH ◆ 3

where $\frac{1}{2}$ $\frac{1$

 $a_{\mathcal{D}}\phi, \xi = \frac{2\times\sigma}{\sqrt{2}}$

 $\frac{10\pi}{\pi}$

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

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

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

 η/η

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

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

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

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

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

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 *h* .
3 ∞ 1001 Gev <u>NON-MINIME</u> from Eq. (62) using *^h* from Eq. (32). The evolution of Grovitational Portal *<u>uravitationial i Urtai</u>* pain in a ⇢(*a*RH) = ↵*T*⁴ RH ⁼ ¹² 2 *M*² *^P* ⁼ ³*y*⁴*m*² *M*² *P* ⁴⁰⁰⇡² *,* (64) U universe is determined by the inflaton decay. For a sufficient \mathcal{L} ficiently small coupling *y*, the energy density from the decay dominates the radiation density at *a>a*int, where

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

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

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

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

dominates when Eq. (47), we find for ⇢RH ⌧ ⇢end [1 + 30*f*(⇠*h,* ⇠*X*)] ✓ *^T*RH 101 $\frac{1}{2}$ $\frac{1$ $\mathbf{r}_\mathbf{S}$ when $\mathbf{r}_\mathbf{S}$ p , which is already been raised in $[31]$

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

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

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

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.