

# Gravitational portals during reheating

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Based on :

- *Gravitational portals in the early Universe*, SC, Y.Mambrini, K.A. Olive, S. Verner, **2112.15214**
- *Gravitational Portals with Non-Minimal Couplings*, SC, Y. Mambrini, K. A. Olive, A. Shkerin, S. Verner, **2203.02004**
- *Gravity as a Portal to Reheating, Leptogenesis and Dark Matter*, B. Barman, SC, R. Co, Y. Mambrini, K.A. Olive, **2210.05716**

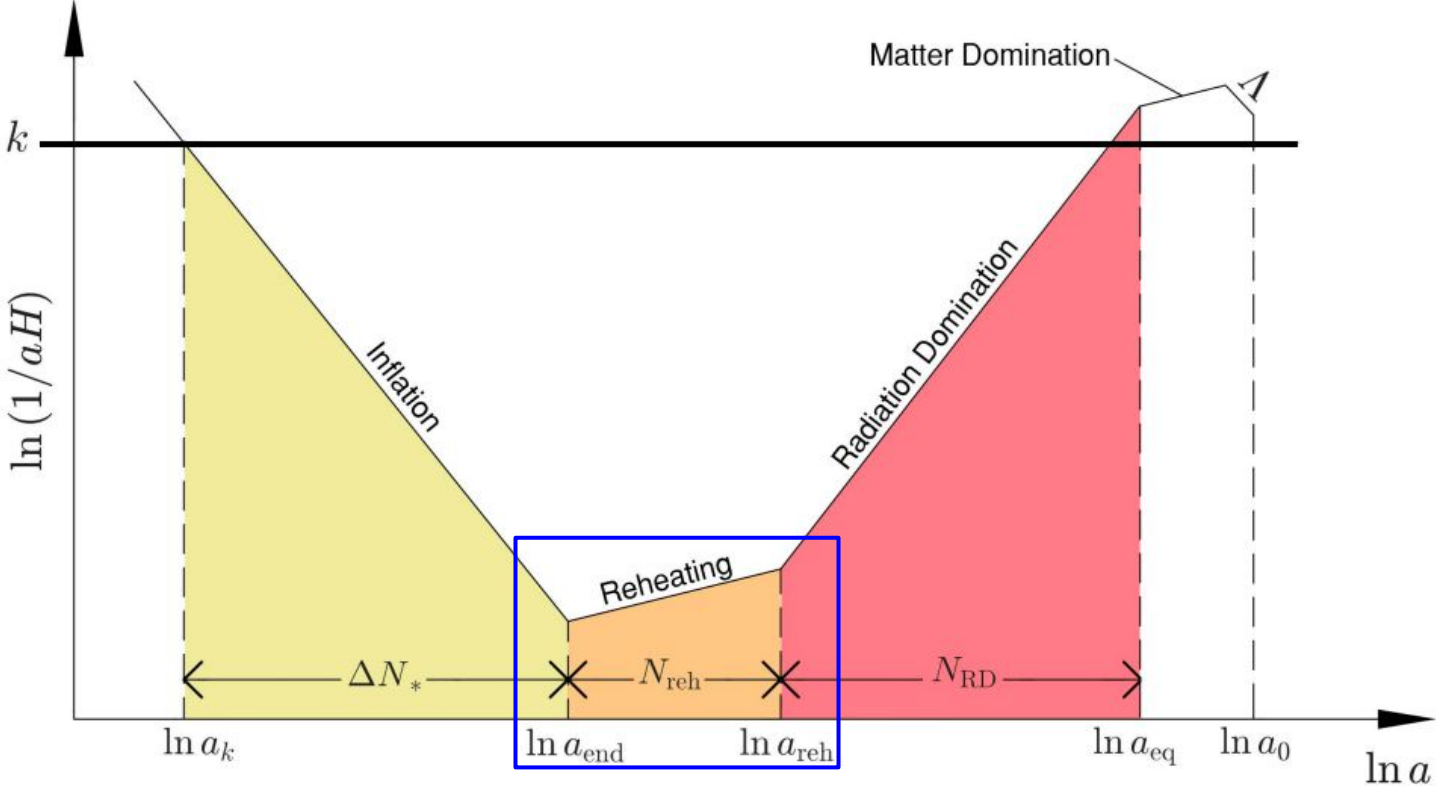


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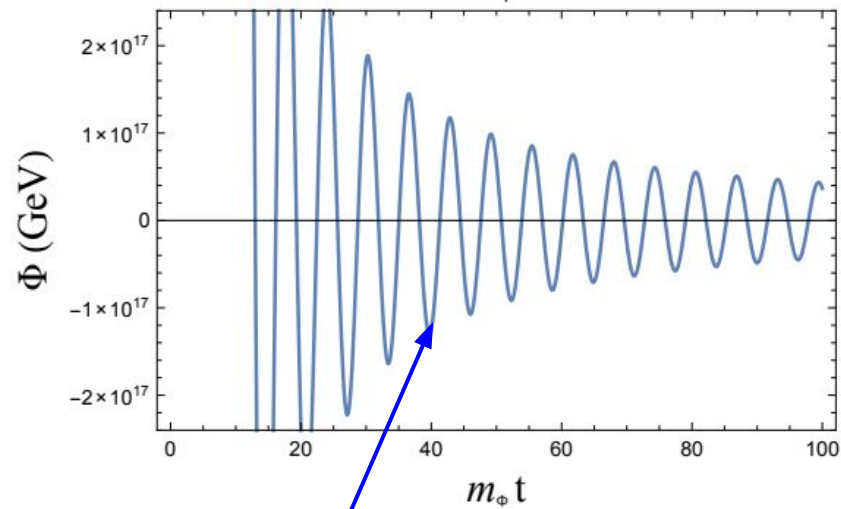
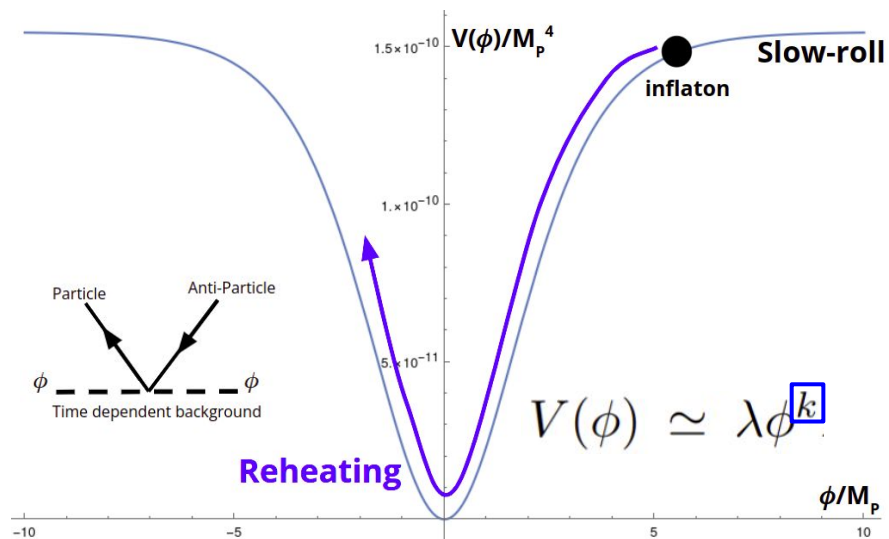
# Focus points

- 1 - Reheating after inflation
- 2 - Gravitational portals to DM and radiation
- 3 - Gravitational reheating and GWs constraints
- 4 - Gravitational portals to leptogenesis

# 1- Reheating after inflation



From (P)reheating Effects of the Kähler Moduli Inflation I Model, Islam Khan, Aaron C. Vincent and Guy Worthey, 2111.11050



EOM:  $\ddot{\phi}(t) + 3H\dot{\phi}(t) + \Gamma\dot{\phi}(t) + V'(\phi(t)) = 0$

Redshifted envelop and frequency of the oscillations depend on the shape of the potential near the minimum

Couplings of the inflaton with the other fields induce transfer of energy during the oscillations : (p)reheating !

$$w = \frac{P_\phi}{\rho_\phi} = \frac{\frac{1}{2}\langle\dot{\phi}^2\rangle - \langle V(\phi)\rangle}{\frac{1}{2}\langle\dot{\phi}^2\rangle + \langle V(\phi)\rangle} = \frac{k-2}{k+2}$$

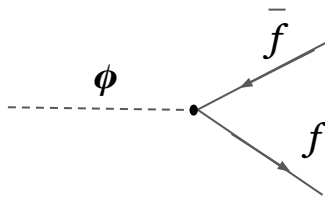
# Particle production

**Perturbative reheating** : considering an oscillating background field with **small couplings** to the other quantum fields  
 → Particle production



Example : Yukawa like interaction

$$\mathcal{L}_{\phi,bath} = y_{\phi} \phi \bar{f} f \Rightarrow \Gamma_{\phi} = \frac{y_{\phi}^2}{8\pi} m_{\phi}$$



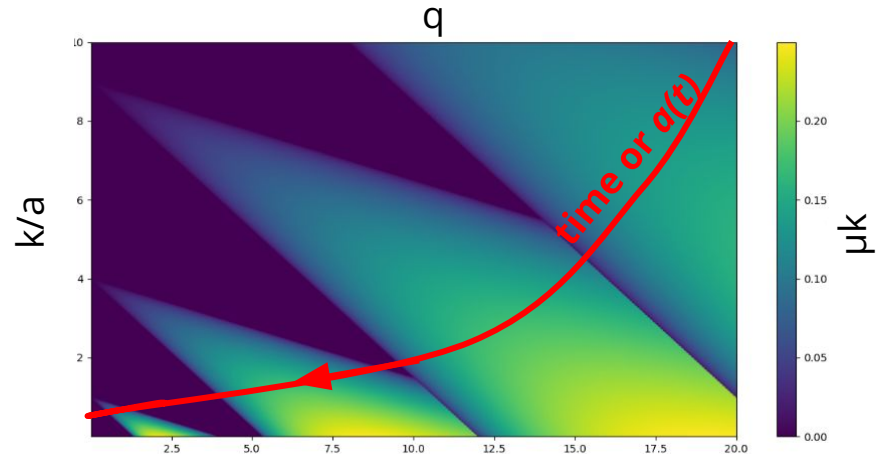
Constitute the **primordial bath** that will thermalize

See Freeze-in from preheating, Garcia, Kaneta, Mambrini, Olive, Verner, 2109.13280

Classical **non-perturbative** approach : **preheating**  
 Time dependent background coupled to **fields**  
 leads to **parametric resonance, tachyonic instabilities** etc...

$$\chi_k'' + \left( \frac{k^2}{m_{\phi}^2 a^2} + 2q - 2q \cos(2z) \right) \chi_k = 0$$

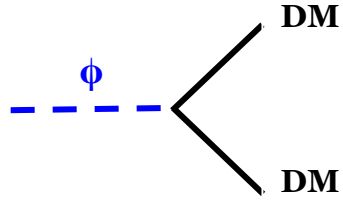
*EOM for Fourier modes in the oscillating background*



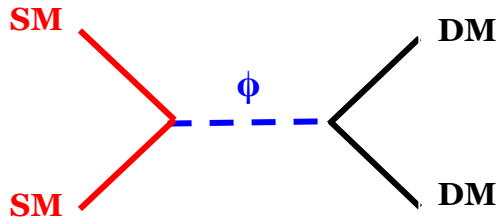
**Instabilities** in the colored regions  
 => increasing occupation number of the modes

# Perturbative processes

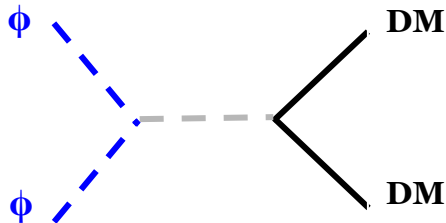
Inflaton sector can also handle non-thermal **Dark Matter (DM) production** through **perturbative processes**



→ From **inflaton background direct decay** to DM, see for example *Reheating and Post-inflationary Production of Dark Matter*, Garcia, Kaneta, Mambrini, Olive, **2004.08404**



→ From **inflaton portal**, in which the inflaton mediates between SM and DM sectors, see *The Inflaton Portal to Dark Matter*, Heurtier, **1707.08999**



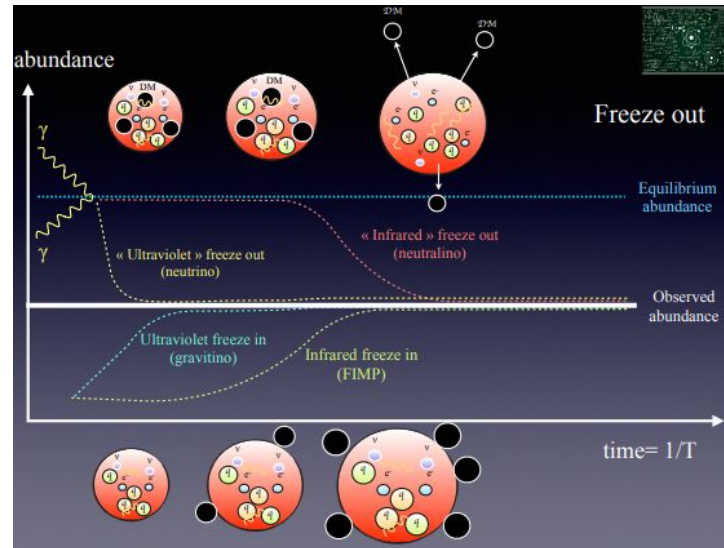
→ From **inflaton scattering mediated by a (massive) particle**, see for example, *Gravitational Production of Dark Matter during Reheating*, Mambrini, Olive, **2102.06214**

→ No results of DM detection raised a fundamental question → What is the scale of interaction between DM and other sectors ?

→ Beyond the WIMPs, the FIMPs ? Phenomenological approach with a wide range of mass and couplings to explore

→ The energy scales providing the right relic density could link the DM puzzle to open questions of particle physics and cosmology :

- Neutrino masses
- Hierarchy problem
- Leptogenesis and Baryogenesis
- GUT
- Inflation



Credit : Yam Mambrini

# 2 - Gravitational portals to DM and radiation

→ Graviton portal arises from metric perturbation around its locally flat form

$$g_{\mu\nu} \simeq \eta_{\mu\nu} + 2h_{\mu\nu}/M_P$$

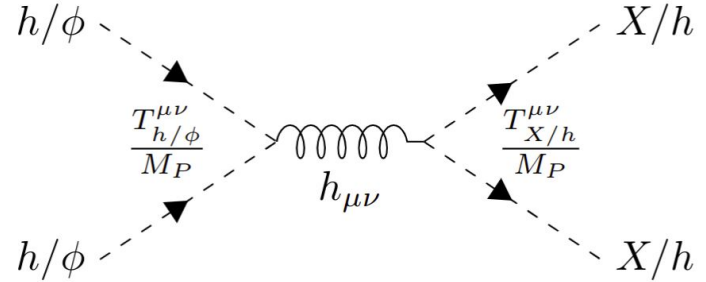


$$\mathcal{L}_{\text{min.}} = -\frac{1}{M_P} h_{\mu\nu} \left( T_h^{\mu\nu} + T_\phi^{\mu\nu} + T_X^{\mu\nu} \right)$$

→ Consider massless gravitons and from the stress-energy of spin 0, 1, ½ fields we can compute the amplitudes for the processes

*Spin-2 Portal Dark Matter*, Bernal, Dutra, Mambrini, Olive, Peloso, **1803.01866**

*Gravitational Production of Dark Matter during Reheating*, Mambrini, Olive, **2102.06214**



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

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


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



The **natural generalization** of this minimal interaction is to introduce **non-minimal couplings** to gravity of the form :

$$\mathcal{L}_{\text{non-min.}} = -\frac{M_P^2}{2}\Omega^2\tilde{R} + \mathcal{L}_\phi + \mathcal{L}_h + \mathcal{L}_X \quad \text{with} \quad \Omega^2 \equiv 1 + \underbrace{\frac{\xi_\phi\phi^2}{M_P^2}}_{\text{inflaton}} + \underbrace{\frac{\xi_h h^2}{M_P^2}}_{\text{SM}} + \underbrace{\frac{\xi_X X^2}{M_P^2}}_{\text{DM}}$$

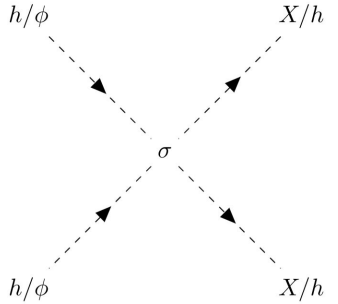
in the **Jordan frame**

$$g_{\mu\nu} = \Omega^2 \tilde{g}_{\mu\nu}$$


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

in the **Einstein frame**

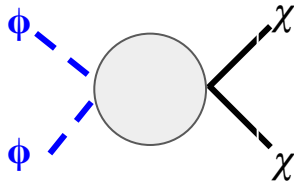
This non-minimal couplings induce **leading-order interactions** in the small fields limit, involved in **radiation and DM production**.



*Reheating and Dark Matter Freeze-in in the Higgs-R<sup>2</sup> Inflation Model*, Aoki, Lee, Menkara, Yamashita, **2202.13063**  
*Gravitational Portals with Non-Minimal Couplings*, SC, Mambrini, Olive, Shkerin, Verner, **2203.02004**

# Boltzmann approach

Assuming that the local background geometry is Minkowskian, we compute transition probability



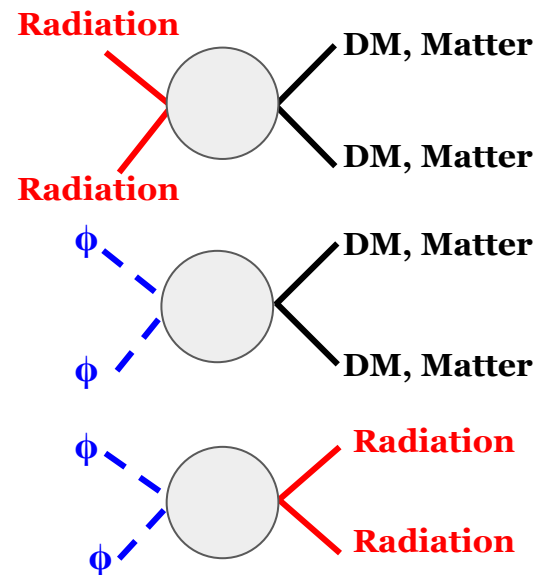
Initial state inflaton  $\phi$  as a coherently oscillating homogeneous condensate with no momentum

From this, production rate can be computed which is the right hand side of the Boltzmann equations

$$\dot{n}_\chi + 3Hn_\chi = R_{\phi\phi\rightarrow\chi\chi}^{(N)}$$
$$\frac{d\rho_\phi}{dt} + 3H(1 + w_\phi)\rho_\phi \simeq -(1 + w_\phi)\Gamma_{\phi\phi}$$
$$\frac{d\rho_R}{dt} + 4H\rho_R \simeq (1 + w_\phi)\Gamma_{\phi\phi}.$$

Gravitational portals can connect different sectors :

- Thermal bath and DM through the FIMP scenario
- Inflaton and DM to directly produce DM from the condensate
- Inflaton and the thermal bath to initiate the reheating process



But inflaton scattering cannot reheat entirely ( $\rho_\phi = \rho_{\text{Radiation}}$ ) in a quadratic potential ( $\propto \phi^2$ ) as the radiation produced is more "redshifted" than the inflaton energy density

*Gravitational portals in the early Universe, SC, Mambrini, Olive, Verner, 2112.15214*

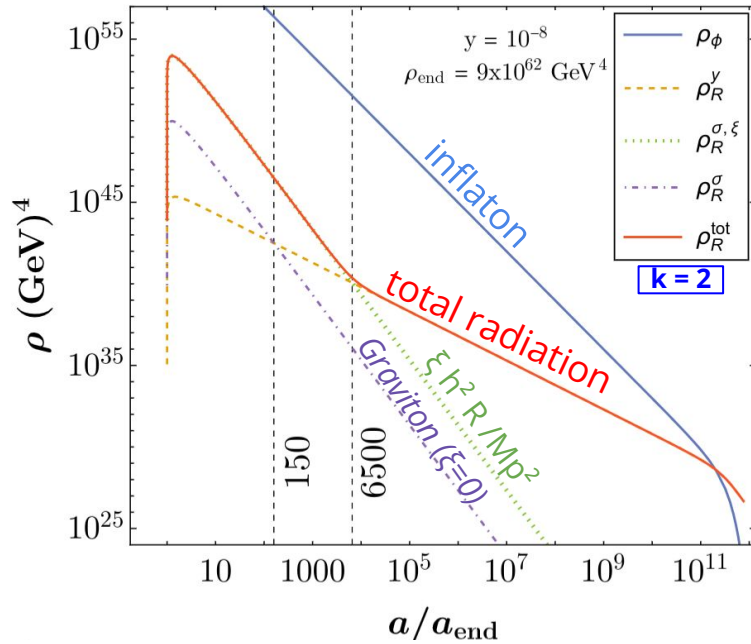
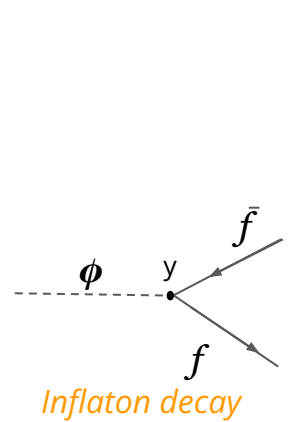
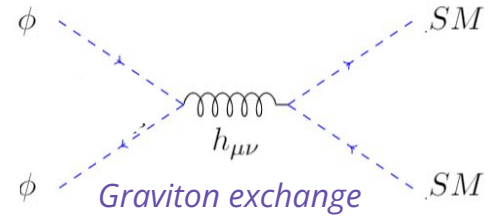


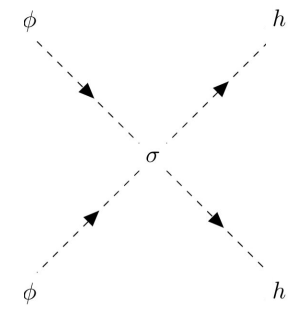
Figure 1 : Energy densities of *inflaton* (blue), *total radiation* (red), radiation from *inflaton decay* (orange), from *scattering mediated by graviton* (purple) and from *non-minimal coupling* (green), with  $\xi_h = \xi = 2$



+



+



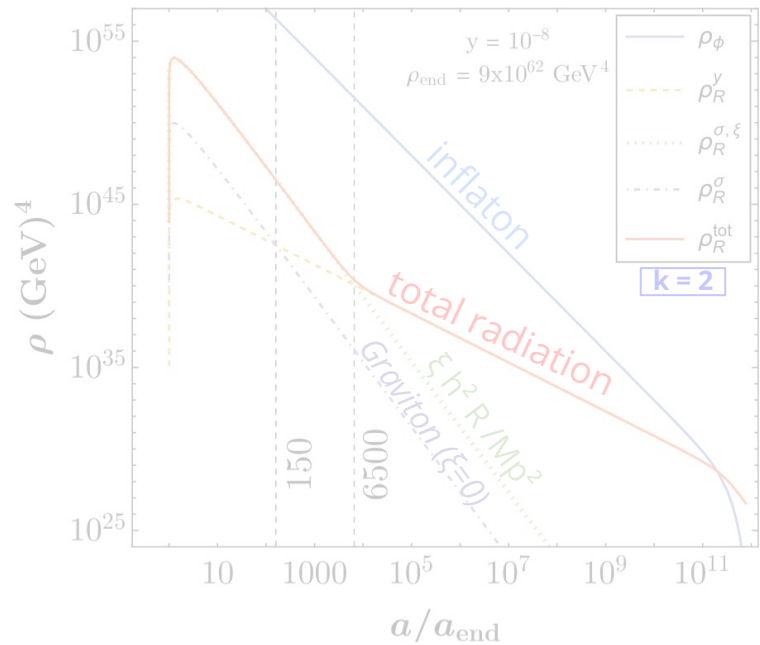


Figure 1 : Energy densities of *inflaton* (blue), *total radiation* (red), radiation from *inflaton decay* (orange), from scattering mediated by graviton (purple) and from *non-minimal coupling* (green), with  $\xi_h = \xi = 2$

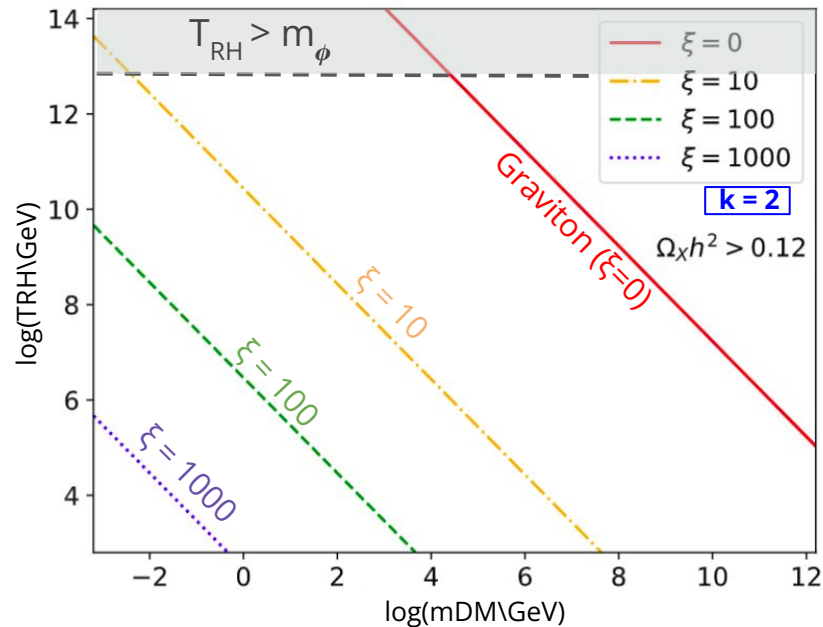
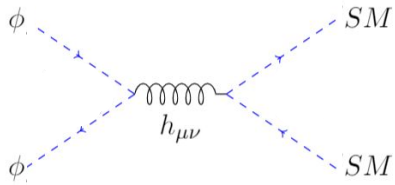


Figure 2 : Contours respecting  $\Omega_\chi h^2 = 0.12$  for *spin 0 DM*, for different values of  $\xi_h = \xi_x = \xi$ . Both *minimal and non-minimal contributions* are added.

→ **Non-minimal couplings** alleviate difficulties to produce DM and radiation through gravitational portals

# 3 - Gravitational reheating and GWs constraints

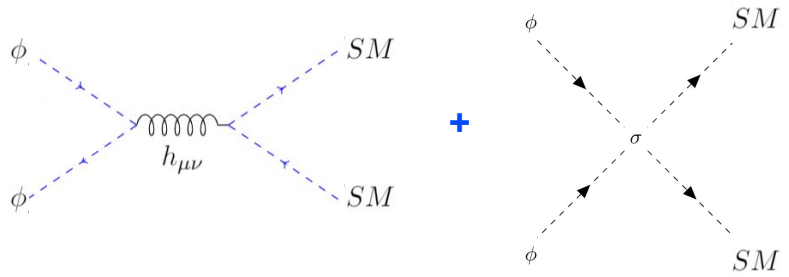


→ Graviton exchange processes can be sufficient to reheat entirely, for sufficiently steep inflaton potential :  $k > 9$

*Gravitational Reheating*, Haque, Maity, **2201.02348**

*Inflationary Gravitational Leptogenesis*, Co, Mambrini, Olive, **2205.01689**

$$\rho_\phi(a) \propto \left(\frac{a_{\text{end}}}{a}\right)^{\frac{6k}{k+2}} \quad \rho_R(a) \propto \left(\frac{a_{\text{end}}}{a}\right)^4$$



→ The requirement of large  $k$  can be relaxed if we add the non-minimal contribution to radiation production, (but still need  $k > 4$ ).

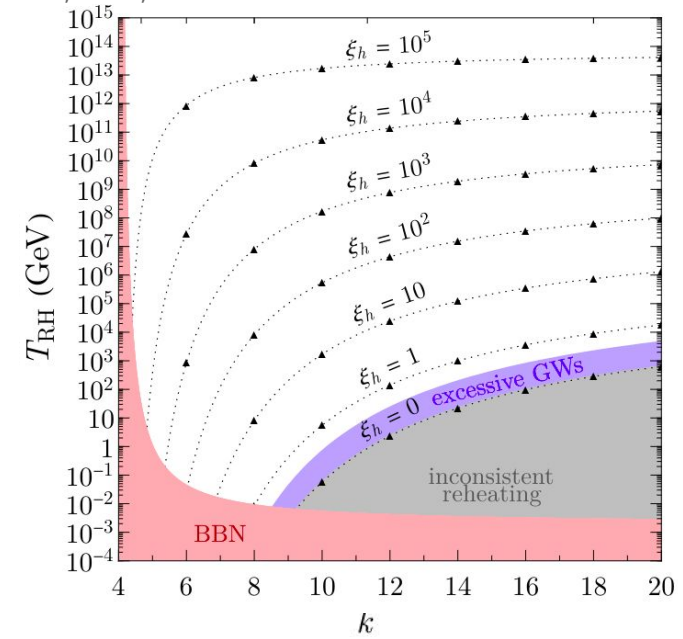
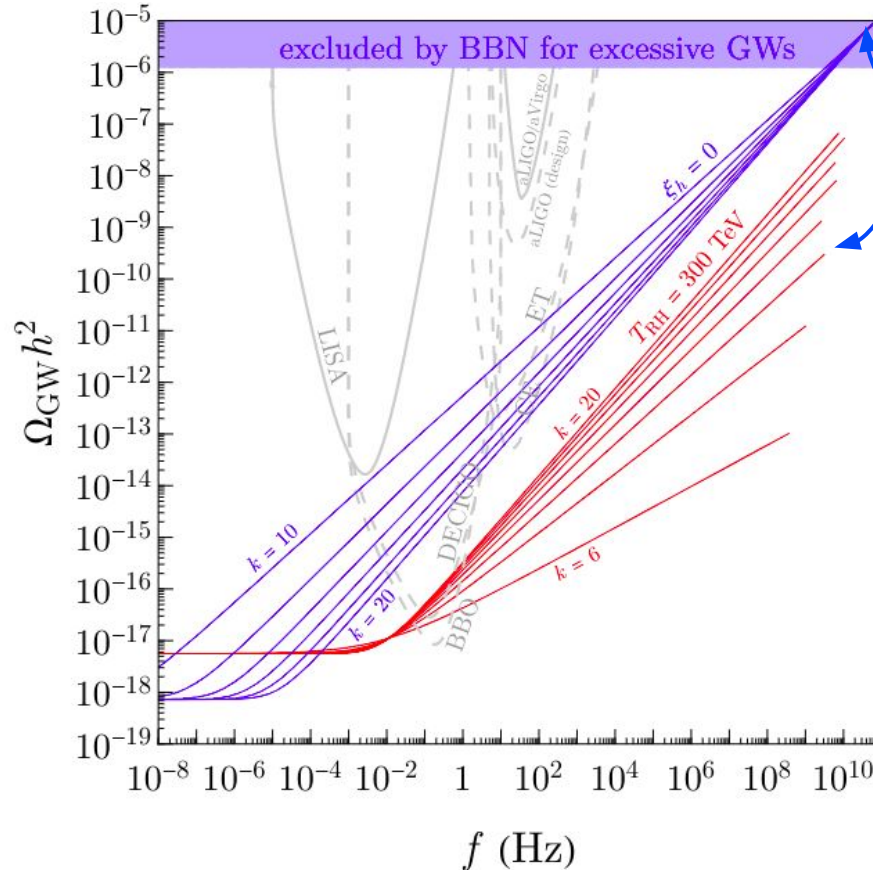


Figure 3 : Reheating temperature from gravitational portals as function of  $k$ , for different  $\xi_h$

→ Primordial GWs re-entering the horizon during reheating, if inflaton redshifts faster than radiation, are enhanced.

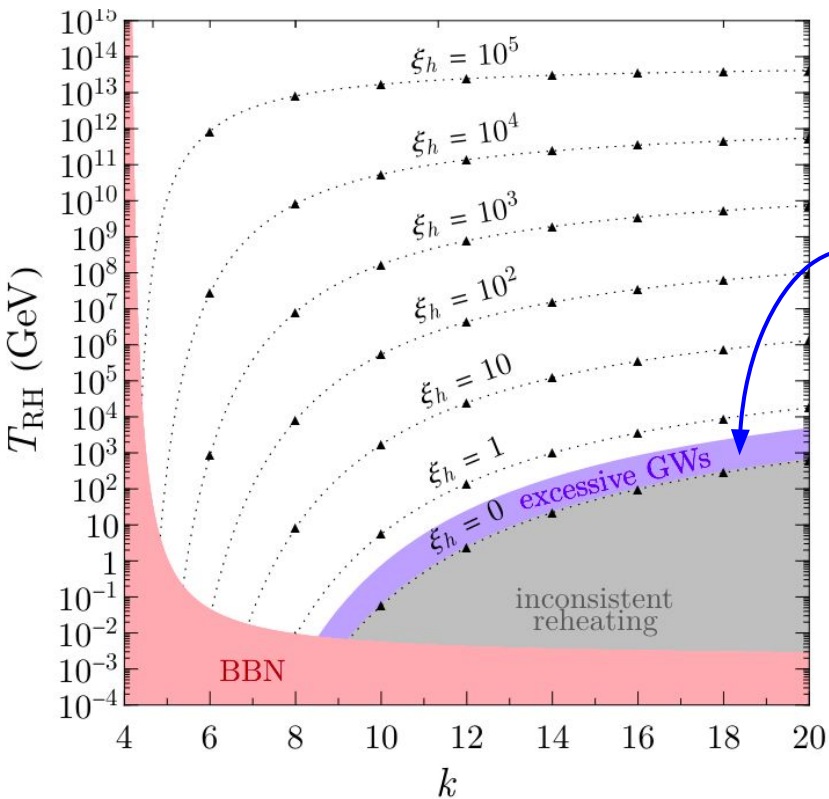
→ GWs spectrum scales with the frequency as  $\Omega_{\text{GW}}^0 h^2 \propto f^{k-4/k-1}$

→ The slope of this spectrum can probe the shape of the inflaton potential near the minimum



The largest enhancement is for the mode that re-enters the horizon right after inflation

Figure 4 : Primordial GWs strength as function of its frequency  $f$ . Blue curves fix  $\xi_h = 0$  and Red curves fix  $T_{RH} = 300 \text{ TeV}$ , for  $k$  in  $[6, 20]$ . The sensitivity of several future GWs experiments are shown.



→ GWs leave the same imprint as free-streaming dark radiation on CMB

→ The case of minimal gravitational reheating is excluded by the CMB + BBN bound of  $\Omega_{\text{GW}}^0 h^2 \lesssim 10^{-6}$ , from excessive GWs as dark radiation.

→ The constraint is relaxed when radiation production is increased by non-minimal gravitational interactions  $\xi_h > 0$

Figure 3 : Reheating temperature from gravitational portals as function of  $k$ , for different  $\xi_h$



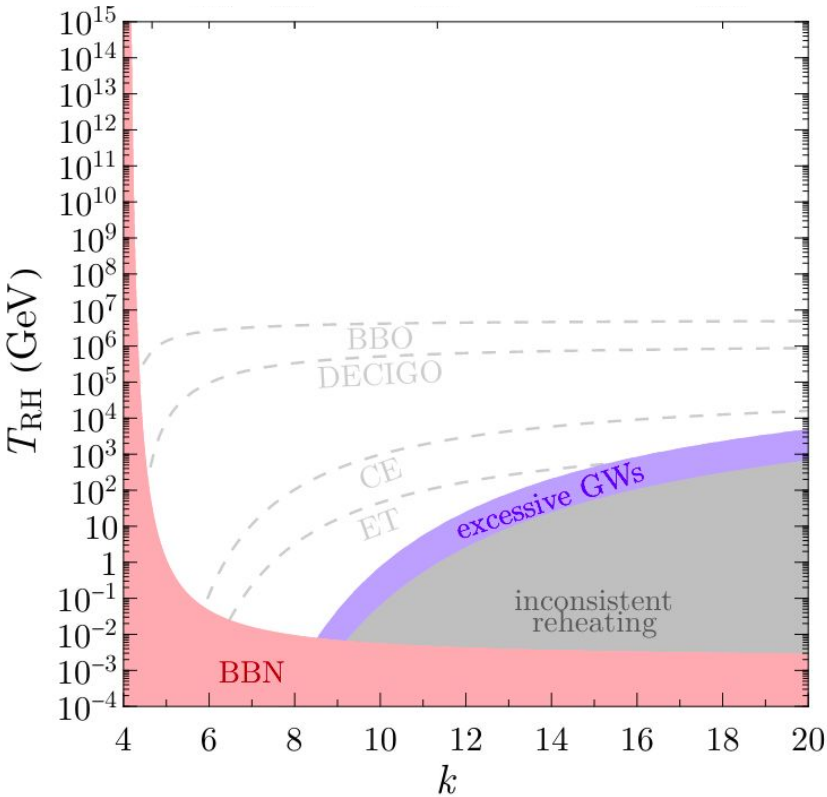


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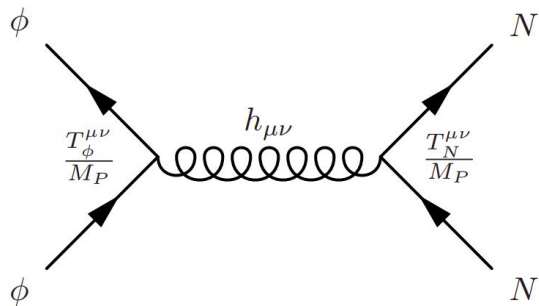
→ GWs leave the same imprint on the CMB as free-streaming dark radiation

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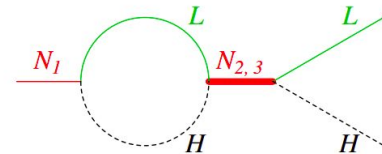
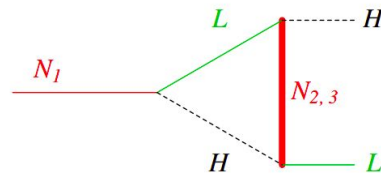
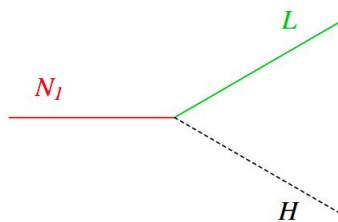
→ The constraint is relaxed when radiation production is increased by non-minimal gravitational interactions  $\xi_h > 0$

→ An important part of the parameter space for reheating could be probed by future GWs experiments !

# 4 - Gravitational portals to Leptogenesis



Graviton portal can handle the production of Right Handed Neutrinos (RHN)



Baryogenesis via leptogenesis, Strumia, **0608347**

Interference between tree level decay and vertex + self energy 1-loop order corrections provides a CP violation in the decay of the sterile neutrino.

$$\epsilon \equiv \frac{\Gamma_{N \rightarrow L_\alpha H} - \Gamma_{N \rightarrow \bar{L}_\alpha \bar{H}}}{\Gamma_{N \rightarrow L_\alpha H} + \Gamma_{N \rightarrow \bar{L}_\alpha \bar{H}}} \simeq -\frac{3 \delta_{\text{eff}}}{16\pi} \cdot \frac{m_{\nu_i} m_N}{v^2}$$

$$Y_L \equiv \frac{n_L}{s} = \epsilon \frac{n_N}{s}$$

Considering type I see-saw mechanism with,  $v = 174$  GeV (Higgs VEV) and the effective CP violation phase  $\delta_{\text{eff}}$

Lepton asymmetry, which stays out-of equilibrium

Finally, gathering all these results in one “purely” gravitational framework :

$$\mathcal{L} \supset \sqrt{-\tilde{g}} \left[ -\frac{M_P^2}{2} \Omega^2 \tilde{\mathcal{R}} + \underbrace{\tilde{\mathcal{L}}_\phi}_{\text{inflaton}} + \tilde{\mathcal{L}}_h + \underbrace{\tilde{\mathcal{L}}_{N_i}}_{\text{RHNS}} \right] \text{ with } (N_1, N_2, N_3)$$

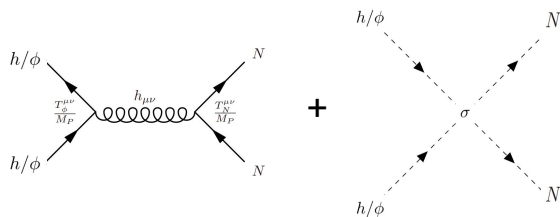
$$\Omega^2 \equiv 1 + \frac{\xi_\phi \phi^2}{M_P^2} + \frac{\xi_h h^2}{M_P^2}$$

Non-minimal couplings to gravity

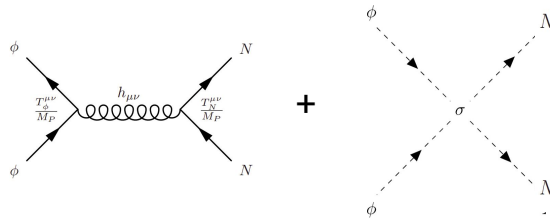
$$\tilde{\mathcal{L}}_{N_i} = -\frac{1}{2} M_{N_i} \bar{N}_i^c N_i - (y_N)_{ij} \bar{N}_i \tilde{H}^\dagger L_j + \text{h.c.}$$

$N_1$  is the lightest right handed neutrino (RHN) and the DM candidate, assumed to be decoupled from  $N_2, N_3$

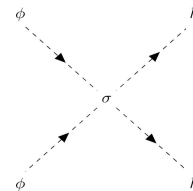
$N_2, N_3$  are much heavier and generate the lepton asymmetry through their gravitational production and out-of equilibrium decay



$\phi\phi \rightarrow N_1 N_1$  and  $\text{SM SM} \rightarrow N_1 N_1$   
from gravitational portals



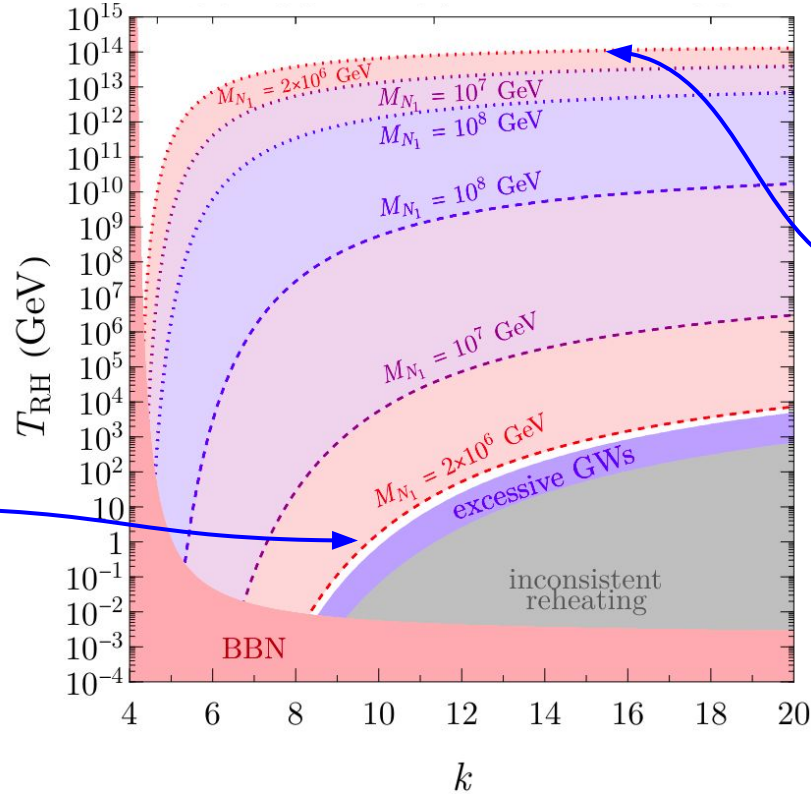
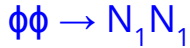
$\phi\phi \rightarrow N_2 N_2$  ( $N_3 N_3$ )  
from gravitational portals



$\phi\phi \rightarrow \text{SM SM}$   
from gravitational portals  
(non-minimal)

# DM ( $N_1$ ) production

Lower limits are coming from inflaton contribution



Upper limits are coming from thermal contribution



Figure 5 : Lines corresponding to the *observed DM relic abundance, all gravitational contributions added, for different  $M_{N_1}$* . Shaded regions correspond to under abundance of DM.

# Baryon asymmetry from leptogenesis ( $N_2$ )

Lepton asymmetry is converted into a **baryon asymmetry** :

$$Y_B = \frac{28}{79} Y_L \simeq 3.5 \times 10^{-4} \delta_{\text{eff}} \frac{n_N}{s} \left( \frac{m_{\nu_i}}{0.05 \text{ eV}} \right) \left( \frac{M_{N_2}}{10^{13} \text{ GeV}} \right)$$

*Gravity as a Portal to Reheating, Leptogenesis and Dark Matter, B. Barman, SC, R. Co, Y. Mambrini, K.A. Olive, 2210.05716*

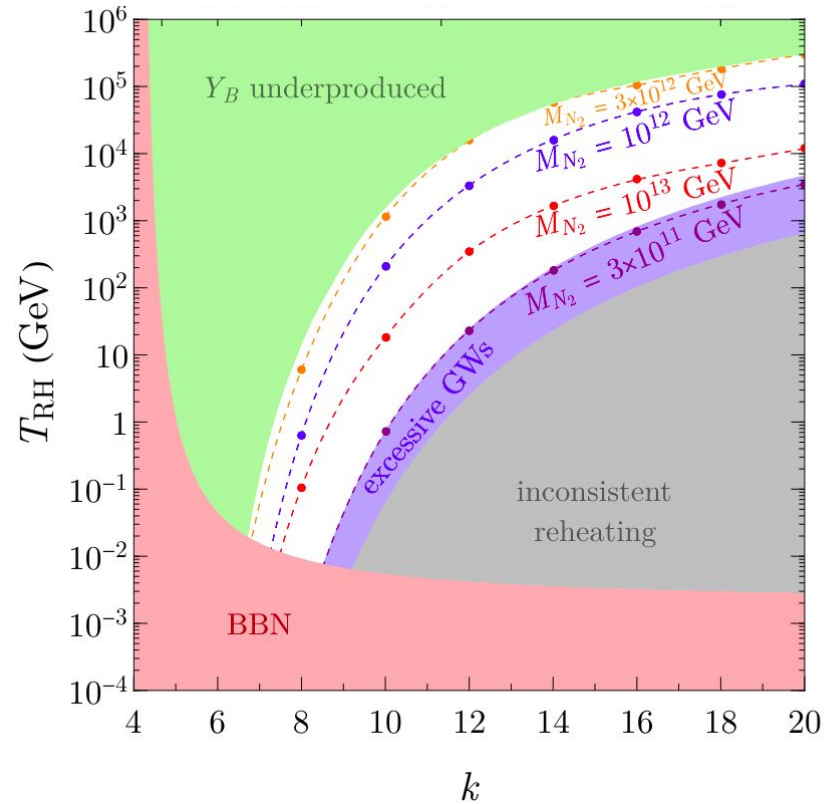
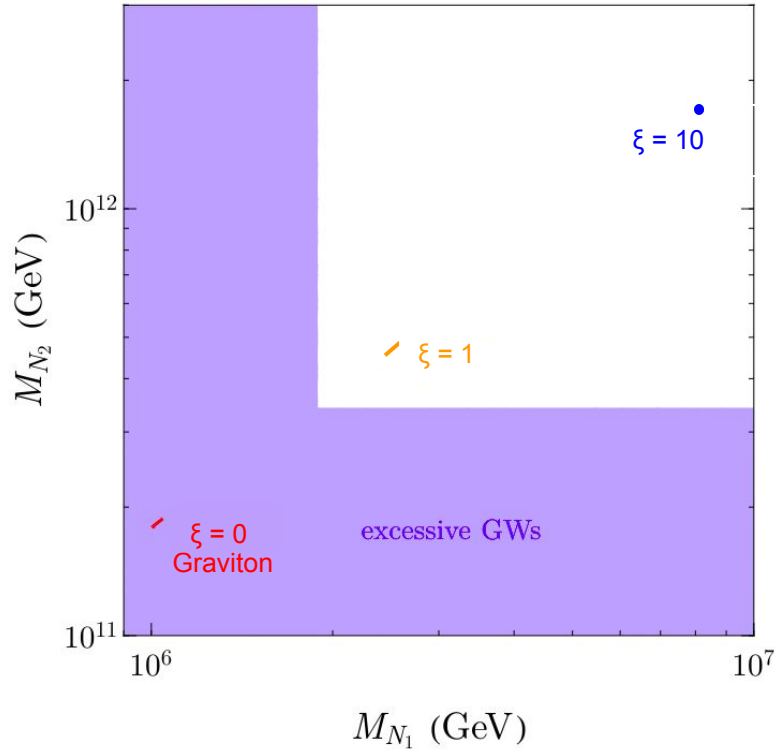


Figure 6 : Lines corresponding to the **observed baryon asymmetry**  $Y_B \simeq 8.7 \times 10^{-11}$  for different  $M_{N_2}$

# Gravitational leptogenesis, reheating and DM production simultaneously



$M_{N_1}$ [PeV]	$M_{N_2}$ [GeV]	$\xi_h$
1.1	$1.6 \times 10^{11}$	0
2.8	$4.0 \times 10^{11}$	1
8.7	$1.3 \times 10^{12}$	10

We choose in this table  $k = 6$  as a benchmark. For each  $\xi$  on the plot, the range runs over  $k \in [6, 20]$  without a significant change.

*Gravity as a Portal to Reheating, Leptogenesis and Dark Matter, B. Barman, SC, R. Co, Y. Mambrini, K.A. Olive, 2210.05716*

Figure 7 :  $(M_{N_1}, M_{N_2})$  parameter space satisfying simultaneously the observed DM relic abundance ( $N_1$ ) and the baryon asymmetry ( $N_2$ ) via gravitational production, asking also for a gravitational reheating.

# Conclusion

- Gravitational production puts unavoidable lower limits on particle production during reheating
- Gravitational portals can complete the reheating for steep inflaton potential near the minimum (large  $k$ )
- Primordial GWs are enhanced during reheating when inflaton redshifts faster than radiation (large  $k$ )
- GWs enhancement constrain gravitational reheating from excessive dark radiation
- GWs have a distinctive spectrum for different inflation potential near the minimum (different  $k$ )
- It provides a minimal framework to produce RHN that handle leptogenesis

There is a way to explain DM relic abundance, baryon asymmetry and reheating in a framework which involves only gravitational interactions, with non-minimal couplings to gravity !

**Thank you for your attention !**



# APPENDIX

Can arise from **superpotential in no-scale supergravity** :

$$W = 2^{\frac{k}{4}+1} \sqrt{\lambda} M_P^3 \left( \frac{(\phi/M_P)^{\frac{k}{2}+1}}{k+2} - \frac{(\phi/M_P)^{\frac{k}{2}+3}}{3(k+6)} \right)$$



$$V(\phi) = \lambda M_P^4 \left[ \sqrt{6} \tanh \left( \frac{\phi}{\sqrt{6} M_P} \right) \right]^k$$

$$A_{S^*} \simeq \frac{V_*}{24\pi^2 \epsilon_* M_P^4} \simeq \frac{6^{\frac{k}{2}}}{8k^2 \pi^2} \lambda \sinh^2 \left( \sqrt{\frac{2}{3}} \frac{\phi_*}{M_P} \right) \tanh^k \left( \frac{\phi_*}{\sqrt{6} M_P} \right)$$

$\lambda$  determined by the **power spectrum amplitude of the CMB "As"**

→ Planck measurements give for  $k=2$  :  $\lambda \sim 10^{-11}$  for  $N \sim 50$  e-folds

$$\lambda \simeq \frac{18\pi^2 A_{S^*}}{6^{k/2} N_*^2}$$

Class of models :  **$\alpha$ -attractor T-model inflation**

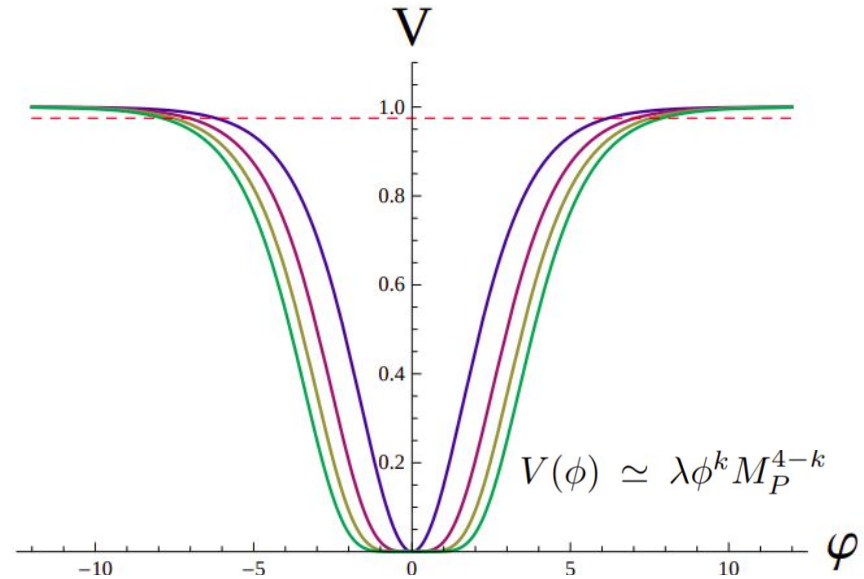
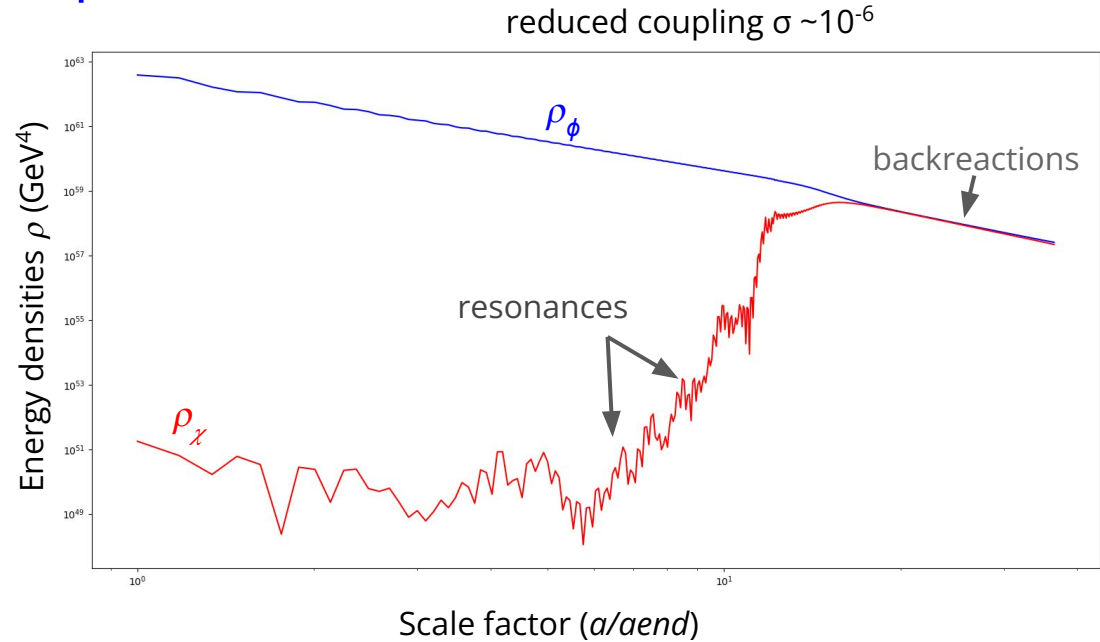
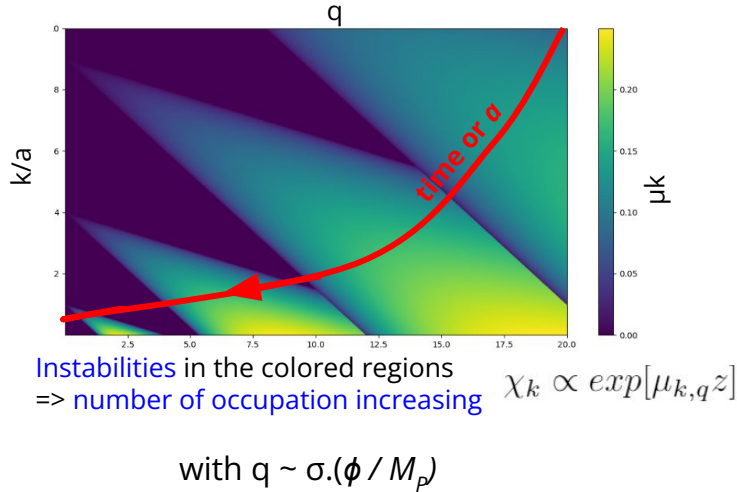


Figure 1: Potentials for the T-Model inflation  $\tanh^{2n}(\varphi/\sqrt{6})$  for  $n = 1, 2, 3, 4$

From *Universality Class in Conformal Inflation*, Kallosh and Linde, **1306.5220**

# Preheating : non-perturbative processes



Preheating corresponds to the first oscillations of the background => resonances and exponential production

For large couplings, reach a regime of large backreactions of the fields on the background

# Bogoliubov approach

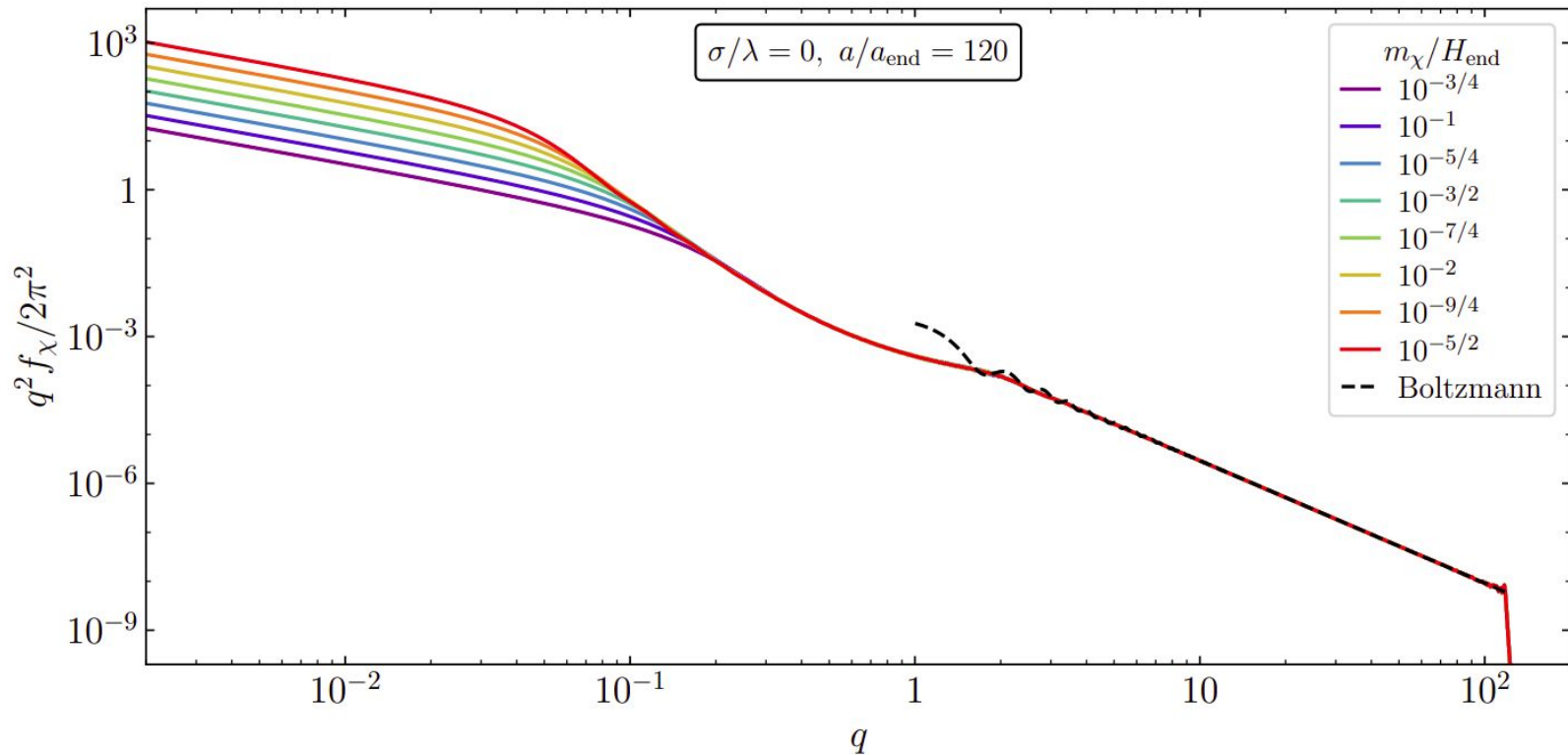
Instead of transition probability, consider the **time evolution of the wave function in the vacuum** while keeping the **effect of curved spacetime**

$$S_\chi = \int d^4x \left[ \frac{1}{2} (\tilde{\chi}')^2 - \frac{1}{2} \tilde{\chi} \omega^2 \tilde{\chi} \right] \quad \text{Consider simply a single field in the vacuum}$$

EOM:  $\tilde{\chi}'' + \omega^2 \tilde{\chi} = 0$  with  $\omega^2 \equiv -\nabla^2 + \boxed{a^2} m_\chi^2 + \boxed{\Delta}$  time dependent frequency!

Then, it is clear that the **Hamiltonian is changing with time through the time dependence in  $\omega$** .  
 => cannot decompose  $\chi$  based on the positive/negative frequency in the Fourier space

$$\tilde{\chi}(x) \equiv \int \frac{d^3k}{(2\pi)^{3/2}} e^{i\vec{k}\cdot\vec{x}} \tilde{\chi}_k \quad \xrightarrow{\text{Bogoliubov coefficients}} \quad \begin{cases} u_k = \frac{\boxed{A_k}}{\sqrt{2\omega_k}} e^{-i \int \omega_k d\eta} + \frac{\boxed{B_k}}{\sqrt{2\omega_k}} e^{i \int \omega_k d\eta} \\ \alpha_k \equiv A_k e^{-i \int \omega_k d\eta}, \quad \beta_k \equiv B_k e^{i \int \omega_k d\eta} \end{cases} \quad \xrightarrow{\text{the occupation number is given by}} \quad |\beta_k|^2$$



*Phase space distribution of a gravitationally excited scalar field for a range of DM masses, coded by color. The dashed black curve corresponds to the numerical integration of the Boltzmann equation, which is valid for  $q > 1$*

# Inflaton scattering

Potential near the minimum is a **power k-dependent monomial**

$$V(\phi) = \lambda \frac{\phi^k}{M_P^{k-4}}, \quad \phi \ll M_P$$

Treat the time dependent condensate as a time dependent coupling with an **amplitude and quasi-periodic function which is k-dependent**

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

→ An homogeneous classical field, not a quantum field !

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

Expand the quasi-periodic function in **Fourier modes**

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

Each **Fourier mode adds its contribution** to the scattering amplitude **with its energy  $E_n = n \cdot \omega$**

# Thermal bath scattering

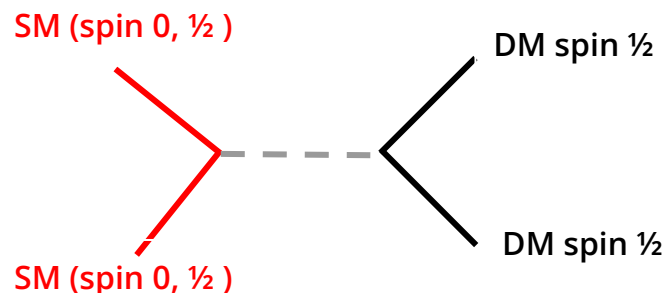
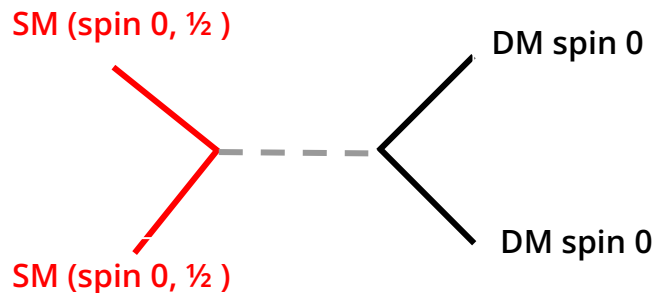
Usual amplitude computation for a  $s$ -channel scattering of (massless) SM particles giving DM particles

$$|\overline{\mathcal{M}}^{00}|^2 = \frac{1}{64M_P^4} \frac{t^2(s+t)^2}{s^2},$$

$$|\overline{\mathcal{M}}^{\frac{1}{2}0}|^2 = \frac{1}{64M_P^4} \frac{(-t(s+t))(s+2t)^2}{s^2}$$

$$|\overline{\mathcal{M}}^{0\frac{1}{2}}|^2 = \frac{(-t(s+t))(s+2t)^2}{64M_P^4 s^2},$$

$$|\overline{\mathcal{M}}^{\frac{1}{2}\frac{1}{2}}|^2 = \frac{s^4 + 10s^3t + 42s^2t^2 + 64st^3 + 32t^4}{128M_P^4 s^2}$$



From amplitudes compute the rate of DM production for each process

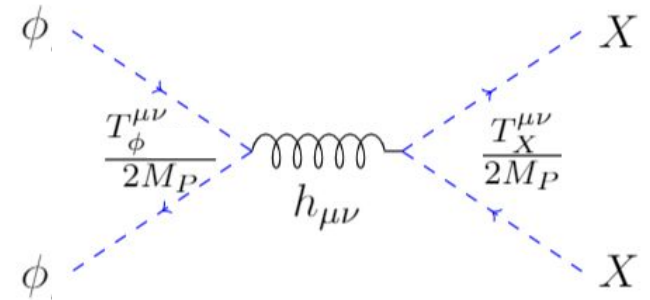
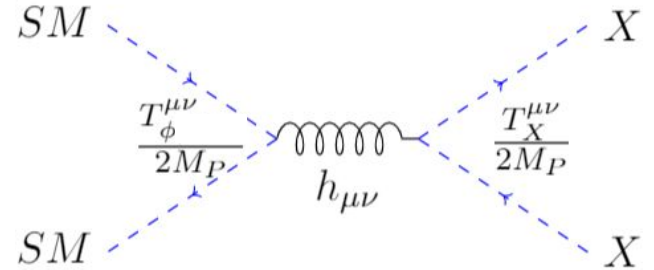
$$R_j^T = \beta_j \frac{T^8}{M_P^4} \text{ for spin } j = 0, \frac{1}{2} \text{ DM final state}$$

See *Spin-2 Portal Dark Matter*, Nicolás Bernal, Maíra Dutra, Yann Mambrini, Keith Olive, Marco Peloso, **1803.01866**

$$R_{\phi^k}^0 = \frac{\rho_\phi^2}{256\pi M_P^4} \sum_{n=1}^{\infty} \left[ 1 + \frac{2m_X^2}{E_n^2} \right]^2 |(\mathcal{P}^k)_n|^2 \sqrt{1 - \frac{4m_X^2}{E_n^2}} \text{ spin 0}$$

$$R_{\phi^k}^{1/2} = \frac{\rho_\phi^2}{64\pi M_P^4} \sum_{n=1}^{\infty} \frac{m_X^2}{E_n^2} |(\mathcal{P}^k)_n|^2 \left( 1 - \frac{4m_X^2}{E_n^2} \right)^{\frac{3}{2}} \text{ spin } \frac{1}{2}$$

See *Gravitational Production of Dark Matter during Reheating*, Yann Mambrini, Keith A. Olive, **2112.15214**





Compute the number density of DM as a function of the scale factor to have the relic abundance

$$\Omega_X^T h^2 = 1.6 \times 10^8 \frac{g_0}{g_{RH}} \frac{\beta_X \sqrt{3}}{\alpha^2 M_P^3} \frac{k+2}{|18-6k|} \frac{m_X}{1 \text{ GeV}} \frac{\rho_{RH}^{3/2}}{T_{RH}^3} \begin{cases} 1 & [k < 3] \\ \left(\frac{2k+4}{3k-3}\right)^{\frac{9-3k}{7-k}} \left(\frac{\rho_{end}}{\rho_{RH}}\right)^{1-\frac{3}{k}} & [k > 3] \end{cases} \quad \text{Thermal case}$$

The relic abundance decreases with k coming from the fact that the Hubble parameter is dominated by inflaton evolution → greater dependence on T<sub>RH</sub> for larger value of k, slowing down the DM production

$$\frac{\Omega_0^\phi h^2}{0.1} \simeq \left(\frac{\rho_{end}}{10^{64} GeV^4}\right)^{1-\frac{1}{k}} \left(\frac{10^{40} GeV^4}{\rho_{RH}}\right)^{\frac{1}{4}-\frac{1}{k}} \left(\frac{k+2}{6k-6}\right) \left(\frac{3k-3}{2k+4}\right)^{\frac{3k-3}{7-k}} \sum_0^k \frac{m_X}{3.8 \times 10^{\frac{24}{k}-6}} \quad \text{Spin 0 inflaton scattering case}$$

$$\frac{\Omega_{1/2}^\phi h^2}{0.1} = \frac{\Sigma_{1/2}^k}{2.4 \frac{8}{k}} \frac{k+2}{k(k-1)} \left(\frac{3k-3}{2k+4}\right)^{\frac{3}{7-k}} \left(\frac{10^{-11}}{\lambda}\right)^{\frac{2}{k}} \left(\frac{10^{40} GeV^4}{\rho_{RH}}\right)^{\frac{1}{4}-\frac{1}{k}} \left(\frac{\rho_{end}}{10^{64} GeV^4}\right)^{\frac{1}{k}} \left(\frac{m_X}{3.2 \times 10^{7+\frac{6}{k}}}\right)^{\frac{1}{k}} \quad \text{Spin } \frac{1}{2} \text{ inflaton scattering case}$$

spin 1/2 helicity suppression !

# DM production in minimal framework

Gravitational portals in the early Universe, SC, Mambrini, Olive, Verner, **2112.15214**

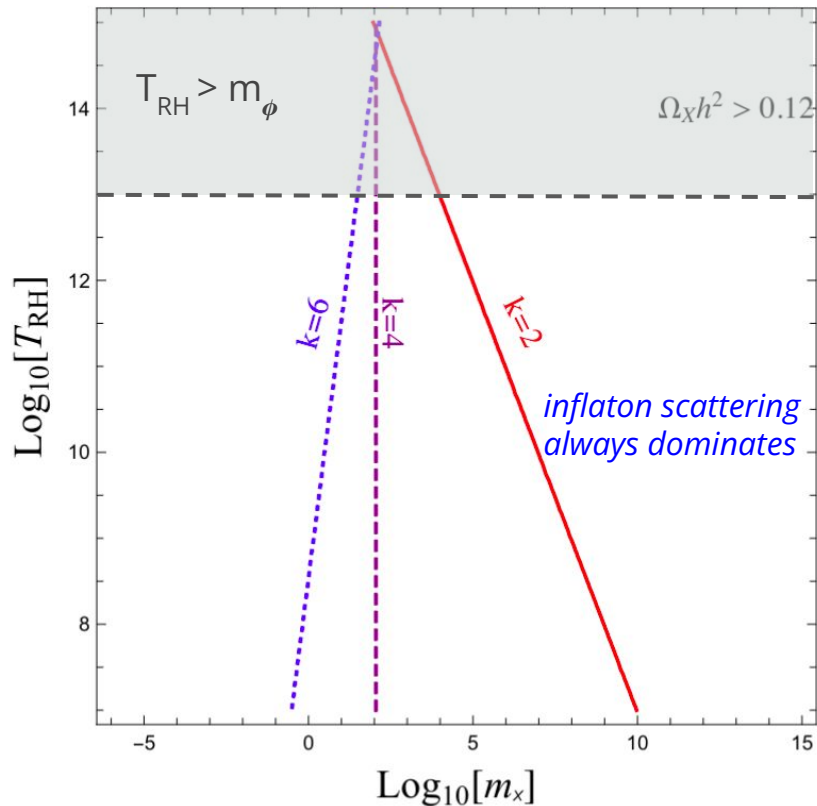


Figure 2 : DM relic,  $\Omega h^2 = 0.12$  in the case of a **spin 0 DM**

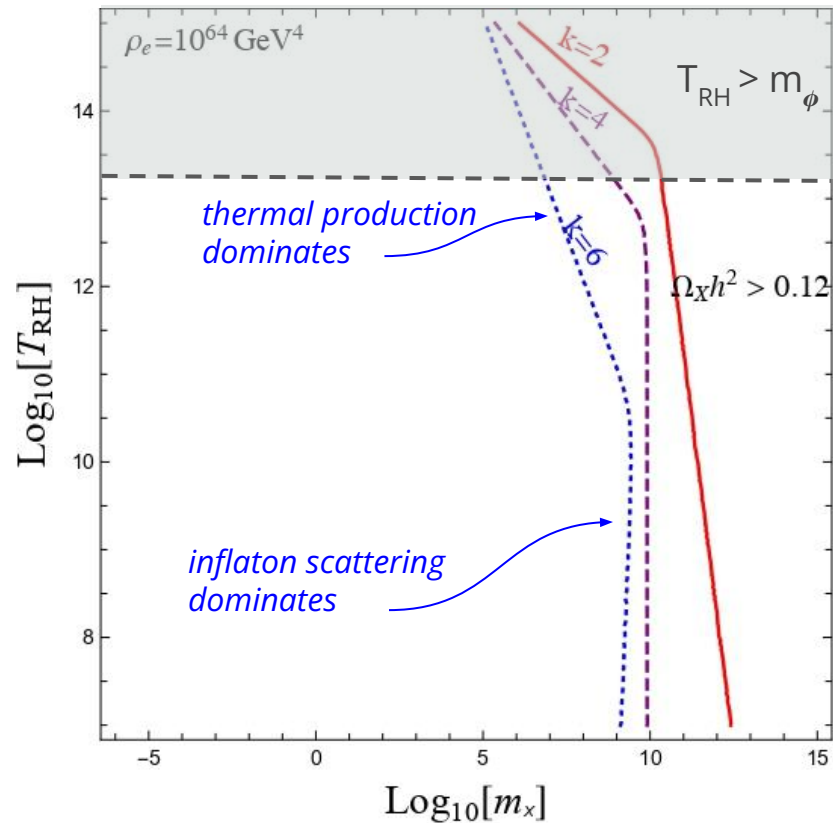
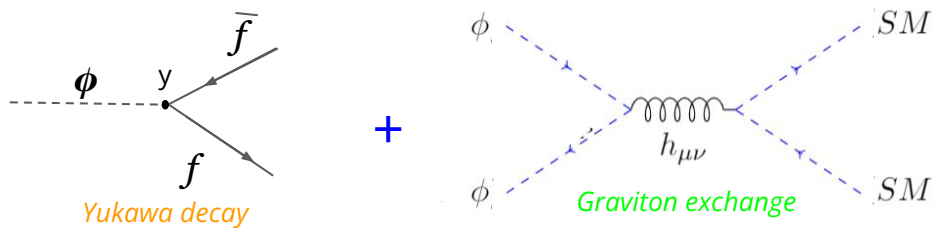


Figure 3 : DM relic,  $\Omega h^2 = 0.12$  in the case of a **spin 1/2 DM**

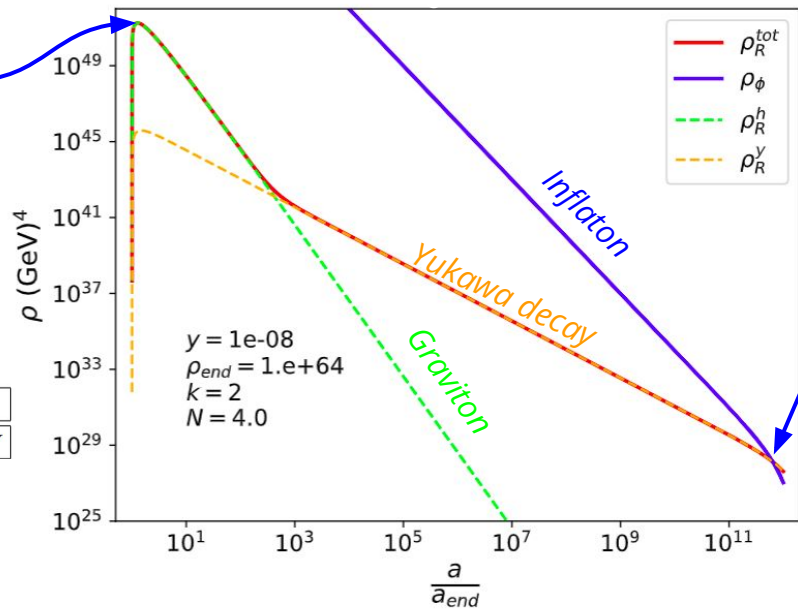
# Radiation production in minimal framework



→ This maximum temperature  $T_{\max} \sim 10^{12}$  GeV reached by the bath is unavoidable !

$T_{\max}$  is almost independent of the potential near the minimum (the power  $k$ )

	$k = 2$	$k = 4$	$k = 6$
$T_{\max}$	$1.0 \times 10^{12}$ GeV	$7.5 \times 10^{11}$ GeV	$6.5 \times 10^{11}$ GeV



Reheating is still given by the decay width of the inflaton

Gravitational portals in the early Universe, SC, Mambrini, Olive, Verner, **2112.15214**

Evolution of energy densities of the inflaton (blue), radiation from Yukawa decay (orange) and graviton exchange (green)

# Leading order interactions

in Einstein frame

$$\begin{aligned}
 \mathcal{L}_{\text{eff}} = & -\frac{1}{2} \left( \frac{\xi_\phi \phi^2}{M_P^2} + \frac{\xi_X X^2}{M_P^2} \right) \partial^\mu h \partial_\mu h - \frac{1}{2} \left( \frac{\xi_h h^2}{M_P^2} + \frac{\xi_X X^2}{M_P^2} \right) \partial^\mu \phi \partial_\mu \phi - \frac{1}{2} \left( \frac{\xi_\phi \phi^2}{M_P^2} + \frac{\xi_h h^2}{M_P^2} \right) \partial^\mu X \partial_\mu X \\
 & + \frac{6\xi_h \xi_X h X}{M_P^2} \partial^\mu h \partial_\mu X + \frac{6\xi_h \xi_\phi h \phi}{M_P^2} \partial^\mu h \partial_\mu \phi + \frac{6\xi_\phi \xi_X \phi X}{M_P^2} \partial^\mu \phi \partial_\mu X + m_X^2 X^2 \left( \frac{\xi_\phi \phi^2}{M_P^2} + \frac{\xi_h h^2}{M_P^2} \right) \\
 & + m_\phi^2 \phi^2 M_P^2 \left( \frac{\xi_X X^2}{M_P^2} + \frac{\xi_h h^2}{M_P^2} \right) + m_h^2 h^2 \left( \frac{\xi_\phi \phi^2}{M_P^2} + \frac{\xi_X X^2}{M_P^2} \right),
 \end{aligned}$$



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

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

$$\sigma_{\phi h}^\xi = \frac{1}{2M_P^2} [\xi_\phi m_h^2 + 12\xi_\phi \xi_h m_\phi^2 + 3\xi_h m_\phi^2 + 2\xi_\phi m_\phi^2]$$

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

$$\mathcal{S}_J = \int d^4x \sqrt{-\tilde{g}} \left[ -\frac{M_P^2}{2} \Omega^2 \tilde{\mathcal{R}} + \tilde{\mathcal{L}}_\phi + \tilde{\mathcal{L}}_h + \tilde{\mathcal{L}}_{N_i} \right] \quad \text{with} \quad \begin{cases} \tilde{\mathcal{L}}_\phi = \frac{1}{2} \partial_\mu \phi \partial^\mu \phi - V(\phi) \\ \tilde{\mathcal{L}}_h = \frac{1}{2} \partial_\mu h \partial^\mu h - V(h) \\ \tilde{\mathcal{L}}_N = \frac{i}{2} \bar{N}_i \overleftrightarrow{\nabla} N_i - \frac{1}{2} M_{N_i} \overline{(\mathcal{N})}^c{}_i N_i + \tilde{\mathcal{L}}_{\text{yuk}} \\ \tilde{\mathcal{L}}_{\text{yuk}} = -y_{N_i} \bar{N}_i \widetilde{H}^\dagger \mathbb{L} + \text{h.c.}, \end{cases}$$

and

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

→  
in the Einstein  
frame

$$\mathcal{S}_E = \int d^4x \sqrt{-g} \left[ -\frac{M_P^2}{2} \mathcal{R} + \frac{K^{ab}}{2} g^{\mu\nu} \partial_\mu S_a \partial_\nu S_b - \frac{1}{\Omega^4} (V_\phi + V_h) + \frac{i}{2} \bar{N}_i \overleftrightarrow{\nabla} N_i - \frac{1}{2\Omega} M_{N_i} \bar{N}_i^c N_i + \frac{1}{\Omega} \mathcal{L}_{\text{yuk}} \right].$$

$$\mathcal{L}_{\text{non-min.}} = -\sigma_{hN_i}^\xi h^2 \bar{N}_i^c N_i - \sigma_{\phi N_i}^\xi \phi^2 \bar{N}_i^c N_i$$

→  
Leading order  
interactions of RHN

$$\sigma_{\phi N_i}^\xi = \frac{M_{N_i}}{2M_P^2} \xi_\phi$$

$$\sigma_{hN_i}^\xi = \frac{M_{N_i}}{2M_P^2} \xi_h.$$

# Non-canonical kinetic term

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

with

$$\Omega^2 \equiv 1 + \frac{\xi_\phi \phi^2}{M_P^2} + \frac{\xi_h h^2}{M_P^2} + \frac{\xi_X X^2}{M_P^2} \quad \text{and} \quad K^{ij} = 6 \frac{\partial \log \Omega}{\partial S_i} \frac{\partial \log \Omega}{\partial S_j} + \frac{\delta^{ij}}{\Omega^2} \quad \text{non-canonical kinetic term}$$

In general, it is impossible to make a field redefinition that would bring it to the canonical form, unless all three non-minimal couplings vanish.

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

In the **small-field limit**, we can expand the action in powers of  $M_P^{-2}$  and **obtain canonical kinetic term and deduce the leading-order interactions** induced by the non-minimal couplings.

# Non-minimal couplings bounds

→ Small field approximation is valid if:  $\sqrt{|\xi_S|} \lesssim M_P / \langle S \rangle$  with  $S = \phi, h, X$

→ Since at the end of inflation we have  $\phi_{\text{end}} \sim M_P$  and that inflaton field is decreasing during the reheating

$$\Rightarrow |\xi_\phi| \lesssim 1$$

→ Since our perturbative computations involve effective couplings in the Einstein frame that depend on all  $\xi$ , the small value of  $\xi_\phi$  can be compensated by  $\xi_h$ . Current constraints on  $\xi_h$  from collider experiments is  $\xi_h < 10^{15}$

See for example *Cosmological Aspects of Higgs Vacuum Metastability*, Tommi Markkanen, Arttu Rajantie, Stephen Stopyra, **1809.06923**

→ On the other hand, to prevent the EW vacuum instability at high energy scale, during inflation, we can invoke stabilization through effective Higgs mass from the non-minimal coupling :  $\xi_h > 10^{-1}$

→ In the case of Higgs inflation,  $\xi_h$  is fixed from CMB (Planck)

See F. L. Bezrukov and M. Shaposhnikov, Phys. Lett. B (2008)

# Sphalerons and baryogenesis

→ Anomalous baryon number violating processes are unsuppressed at high temperatures : the so called non-perturbative sphaleron transitions violate (B+L) but conserve (B-L).

N.S. Manton, Phys. Rev. (1983) , F.R. Klinkhammer and N.S. Manton, Phys. Rev. D (1984), V.A. Kuzmin, V.A. Rubakov and M.E. Shaposhnikov, Phys. Lett. B (1985)

→ Primordial (B-L) asymmetry can be realized as a lepton asymmetry generated by the out-of equilibrium decay of heavy right-handed Majorana neutrinos. L is violated by Majorana masses, while the necessary CP violation comes with complex phases in the Dirac mass matrix of the neutrinos

M. Fukugita and T. Yanagida, Phys. Lett. B (1986)

$$Y_B = \left( \frac{8N_f + 4N_H}{22N_f + 13N_H} \right) Y_{B-L}$$

*Baryogenesis and lepton number violation*, Plümacher M. **9604229**