Gravitational portals in the early Universe

Kick-off du GDR CoPhy - 17th January 2023

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

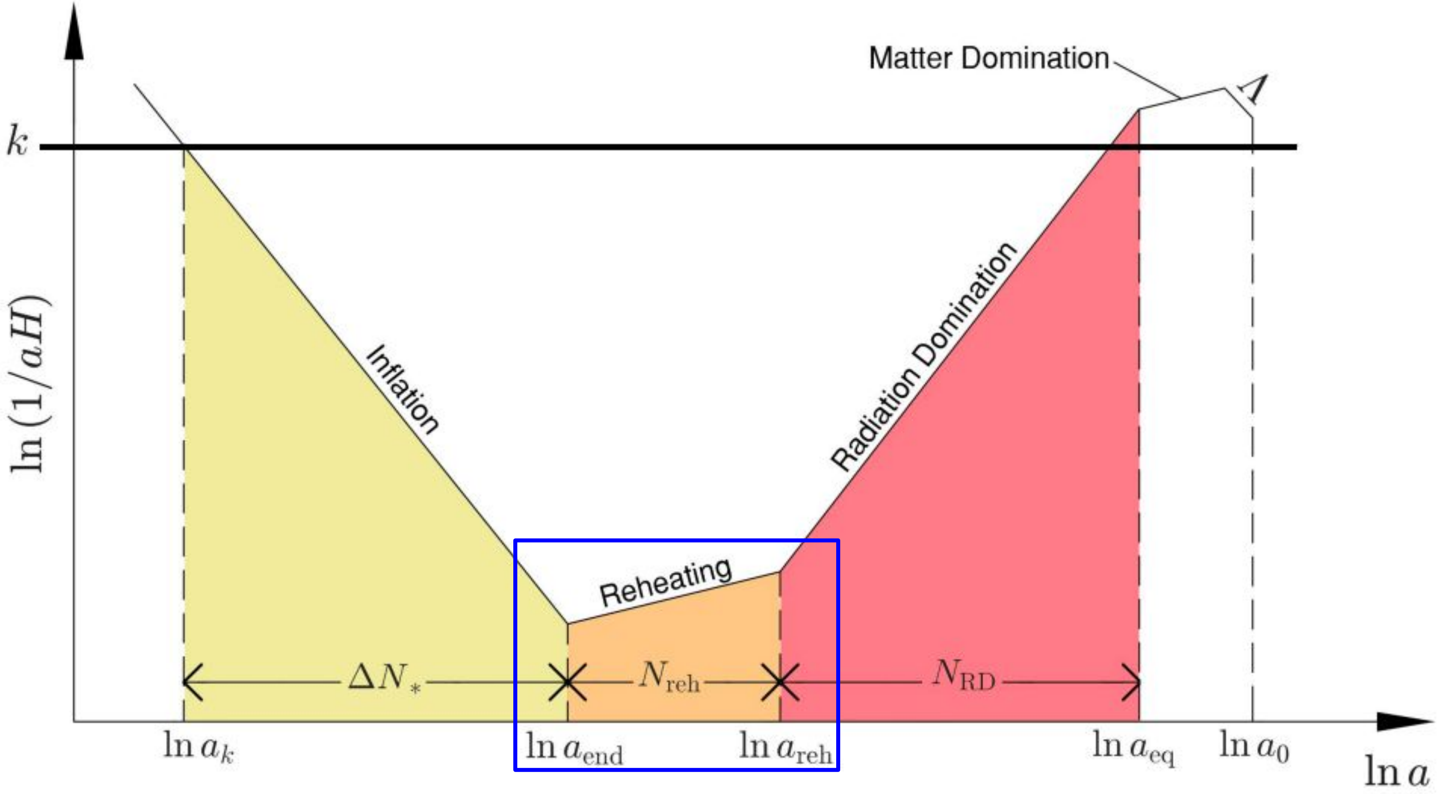
1 - Reheating after inflation

2 - Gravitational portals to DM and radiation

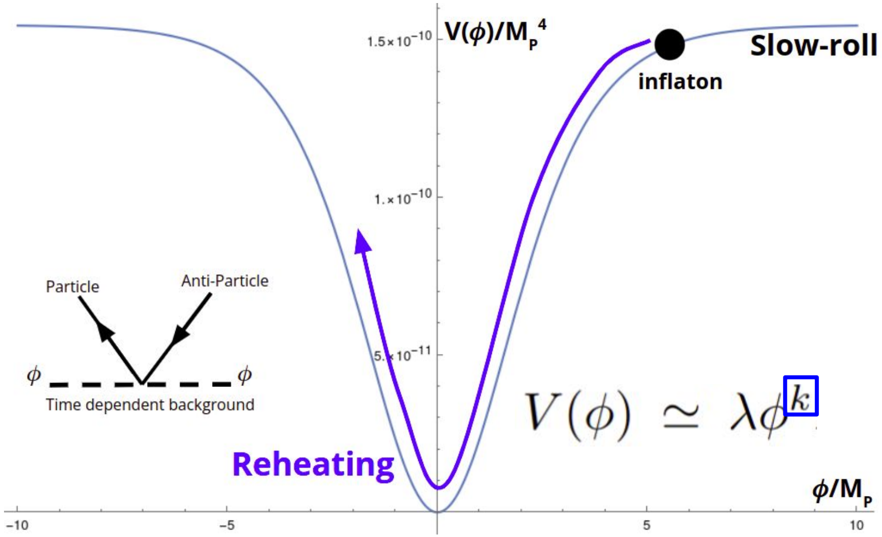
3 - Gravitational reheating and GWs constraints

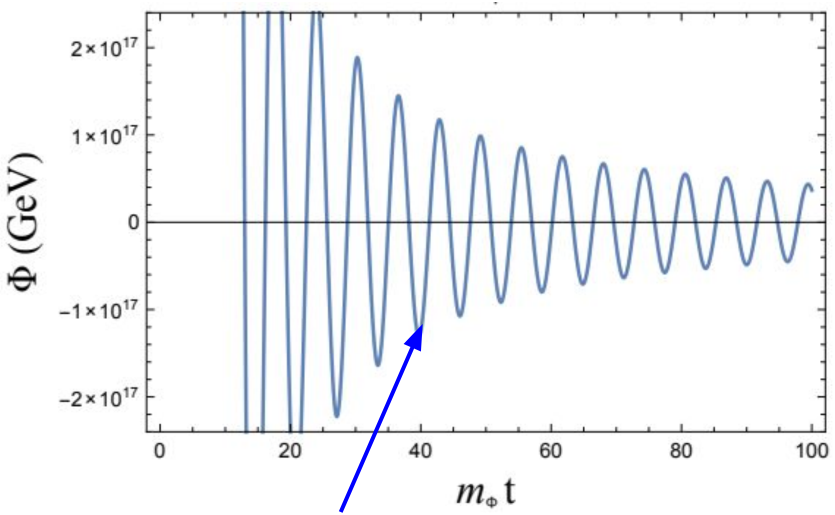
4 - Gravitational portals to leptogenesis

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**





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

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

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

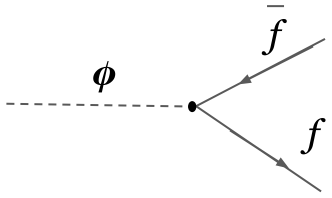
$$w = \frac{P_\phi}{\rho_\phi} = \frac{\frac{1}{2}\langle\dot{\phi}^2\rangle - \langle V(\phi)\rangle}{\frac{1}{2}\langle\dot{\phi}^2\rangle + \langle V(\phi)\rangle} = \boxed{\frac{k-2}{k+2}}$$

Particle production

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

<u>Example :</u> Yukawa like interaction

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



Constitute the primordial bath that will thermalize

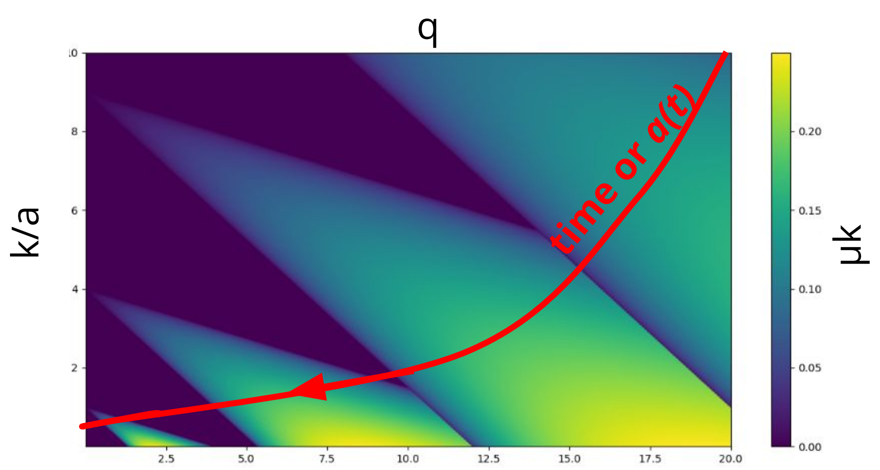
See Freeze-in from preheating, Garcia , Kaneta, Mambrini, Olive, Verner, **2109.13280**

Classical non-perturbative approach : **p**reheating

Time dependent background coupled to fields leads to parametric resonance, tachyonic instabilities etc...

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

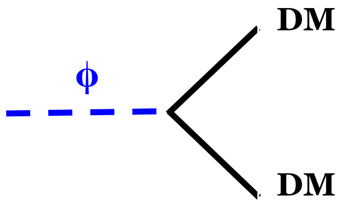
EOM for Fourier modes in the oscillating background



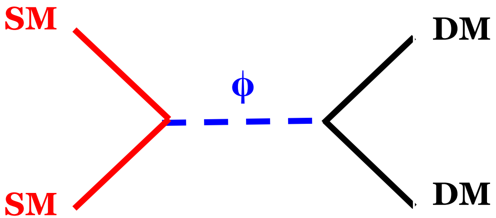
Instabilities in the colored regions
=> increasing occupation number of the modes

Perturbative processes

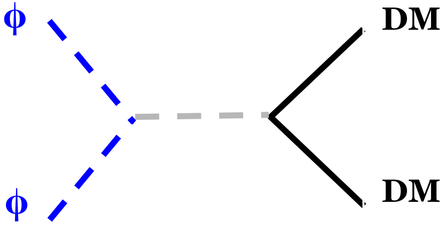
Inflaton sector can also handle non-thermal Dark Matter (DM) production through perturbative processes



➜ 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**



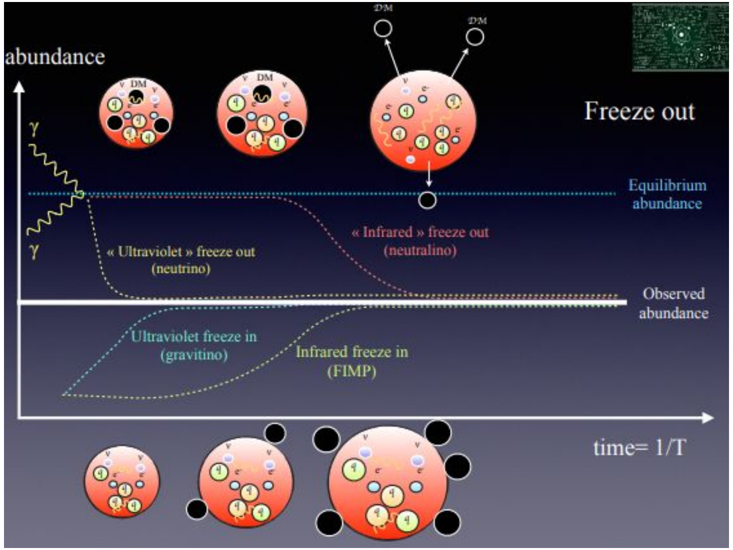
➜ From inflaton scattering mediated by a (massive) particle, see for example, *Gravitational Production of Dark Matter during Reheating*, Mambrini, Olive, **2102.06214**

➜ 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 : Yann Mambrini

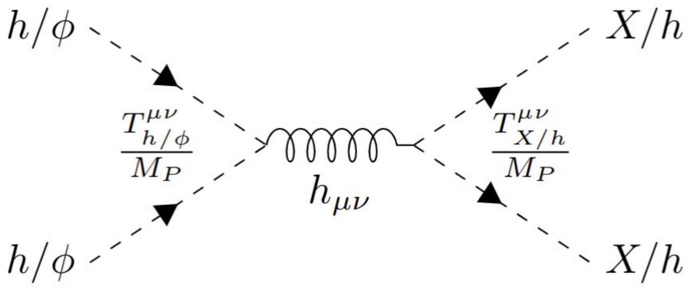
2 - Gravitational portals to DM and radiation

➜ 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



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

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

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

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

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

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

$$\mathcal{L}_{\rm non-min.} = -\frac{M_P^2}{2}\Omega^2\tilde{R} + \mathcal{L}_\phi + \mathcal{L}_h + \mathcal{L}_X$$

in the Jordan frame

with

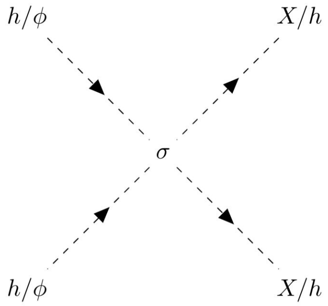
$$\Omega^2 \equiv 1 + \underbrace{\frac{\xi_\phi \phi^2}{M_P^2}}_{\text{inflaton}} + \underbrace{\frac{\xi_h h^2}{M_P^2}}_{\text{SM}} + \underbrace{\frac{\xi_X X^2}{M_P^2}}_{\text{DM}}$$

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

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

in the Einstein frame

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

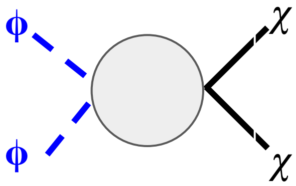


Gravitational Portals with Non-Minimal Couplings, SC, Mambrini, Olive, Shkerin, Verner, **2203.02004**

Reheating and Dark Matter Freeze-in in the Higgs-R^2 Inflation Model, Aoki, Lee, Menkara, Yamashita, **2202.13063**

Boltzmann approach

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



Initial state inflaton ϕ 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

$$\dot{n}_\chi + 3Hn_\chi = R^{(\mathrm{N})}_{\phi\phi\to\chi\chi}$$

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

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

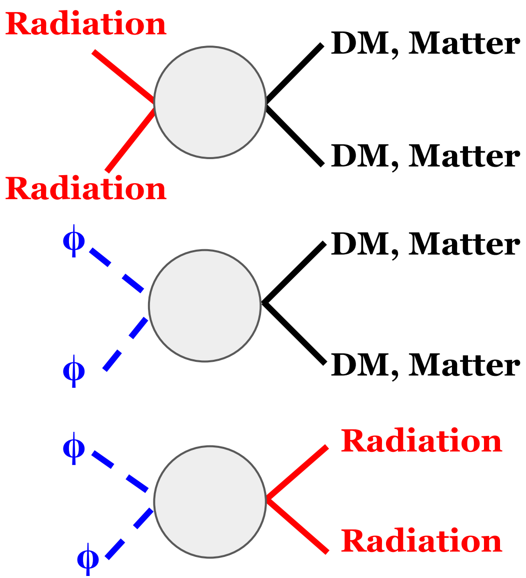
See Boltzmann or Bogoliubov? Approaches Compared in Gravitational Particle Production, Kunio Kaneta, Sung Mook Lee, Kin-ya Oda, **2206.10929**

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 ($\rho_{\phi} = \rho_{Radiation}$) 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**

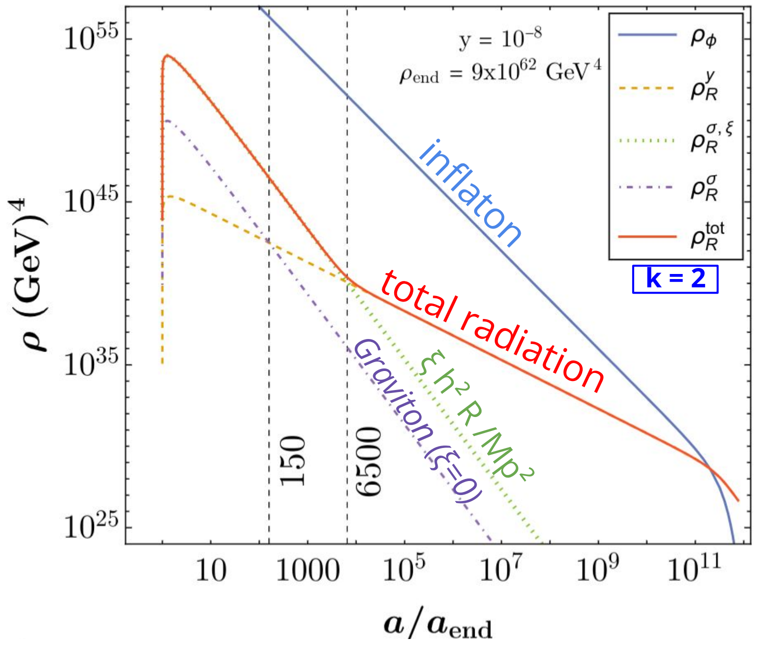
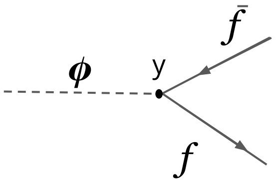
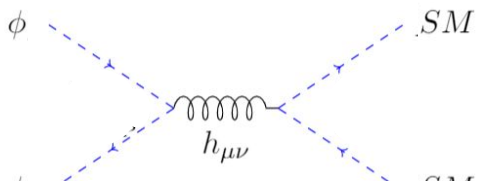


Figure 1 : Energy densities of inflaton (blue), total radiation (red), radiation from inflaton decay (orange), from scattering mediated by graviton (purple) and from non-minimal coupling (green), with $\xi_h = \xi = 2$



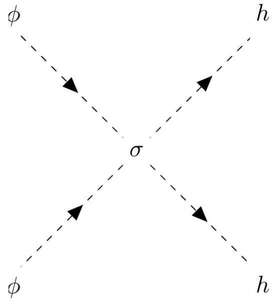
Inflaton decay

+



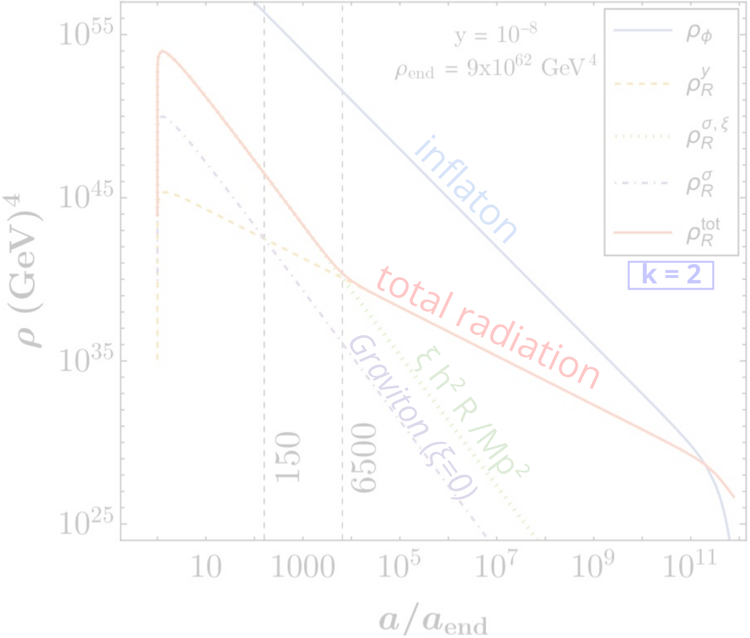
Graviton exchange

+



Non-minimal coupling

Gravitational Portals with Non-Minimal Couplings, SC, Mambrini, Olive, Shkerin, Verner, **2203.02004**



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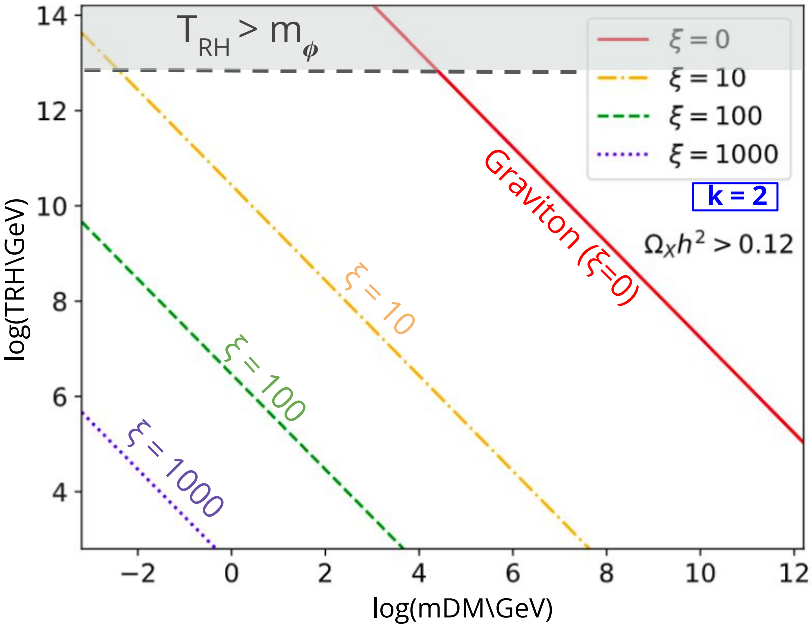
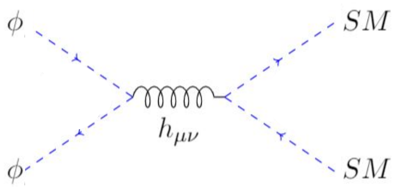


Figure 2 : Contours respecting $\Omega_X h^2 = 0.12$ for spin 0 DM, for different values of $\xi_h = \xi_X = \xi$. Both minimal and non-minimal contributions are added.

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

Gravitational Portals with Non-Minimal Couplings, SC, Mambrini, Olive, Shkerin, Verner, **2203.02004**

3 - Gravitational reheating and GWs constraints

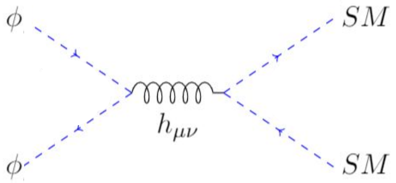


➜ Graviton exchange processes can be sufficient to reheat entirely, for sufficiently steep inflaton potential : $k > 9$

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

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

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



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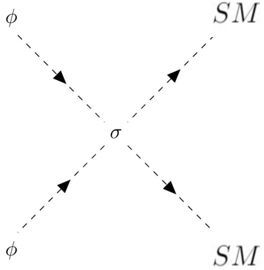


➜ The requirement of large k can be relaxed if we add the non-minimal contribution to radiation production, (but still need k>4).

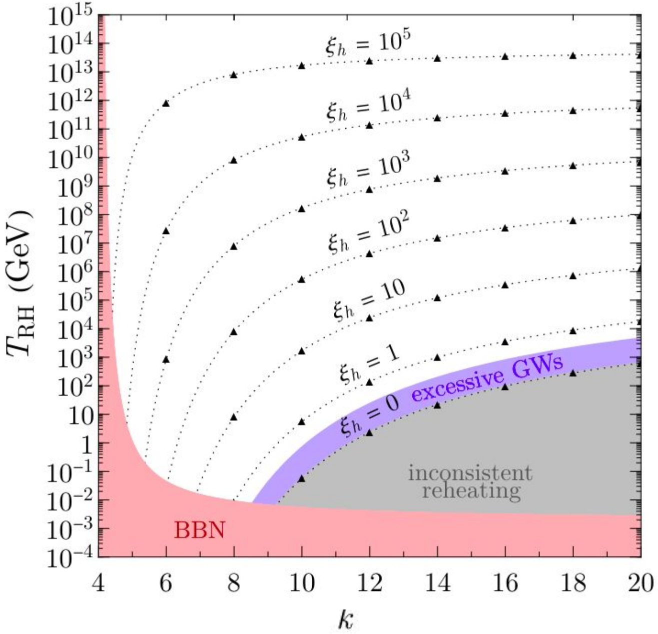
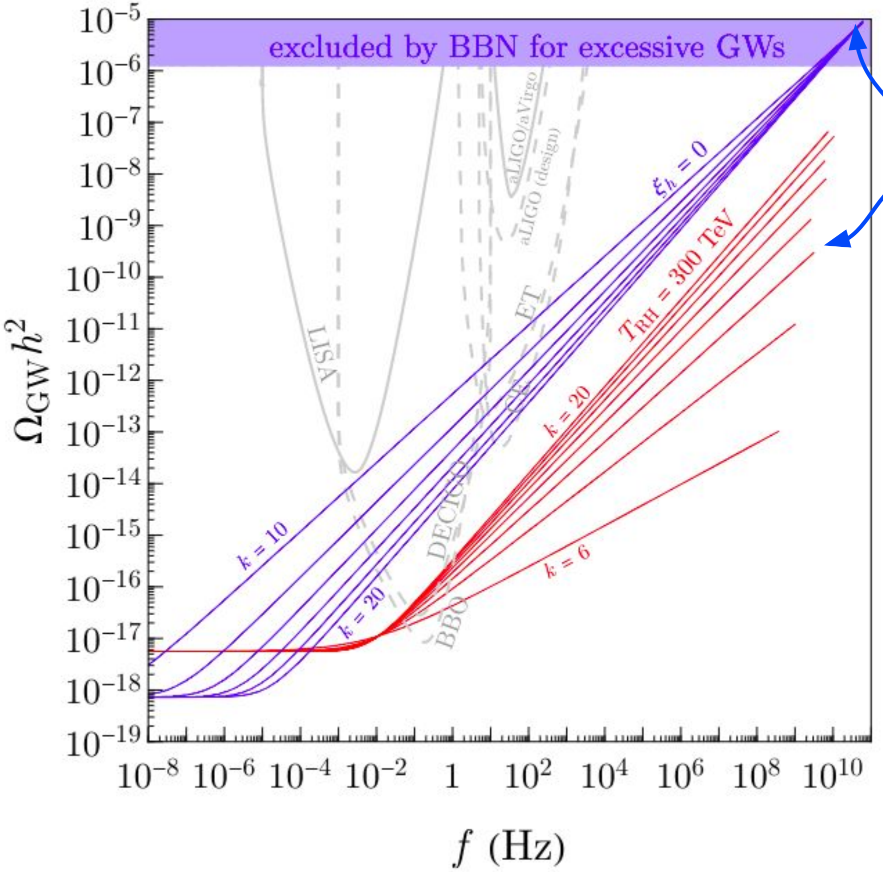


Figure 3 : Reheating temperature from gravitational portals as function of k, for different ξ_h

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

➜ GWs spectrum scales with the frequency as $\Omega^0_{GW}h^2 \propto f^{\,k-4/k-1}$

➜ 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 TeV, for k in [6,20]. The sensitivity of several future GWs experiments are shown.

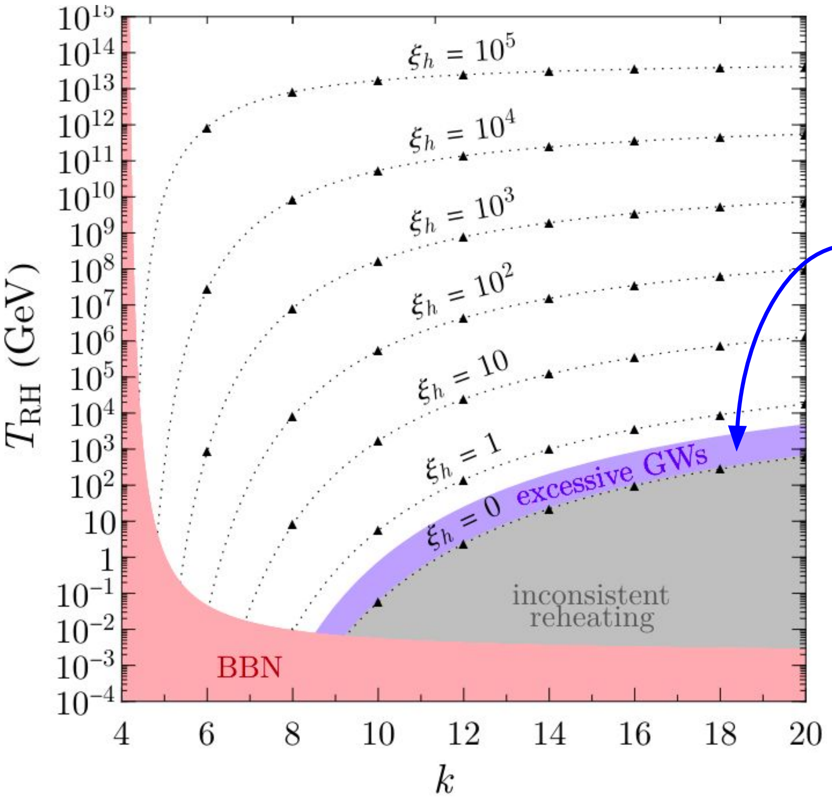
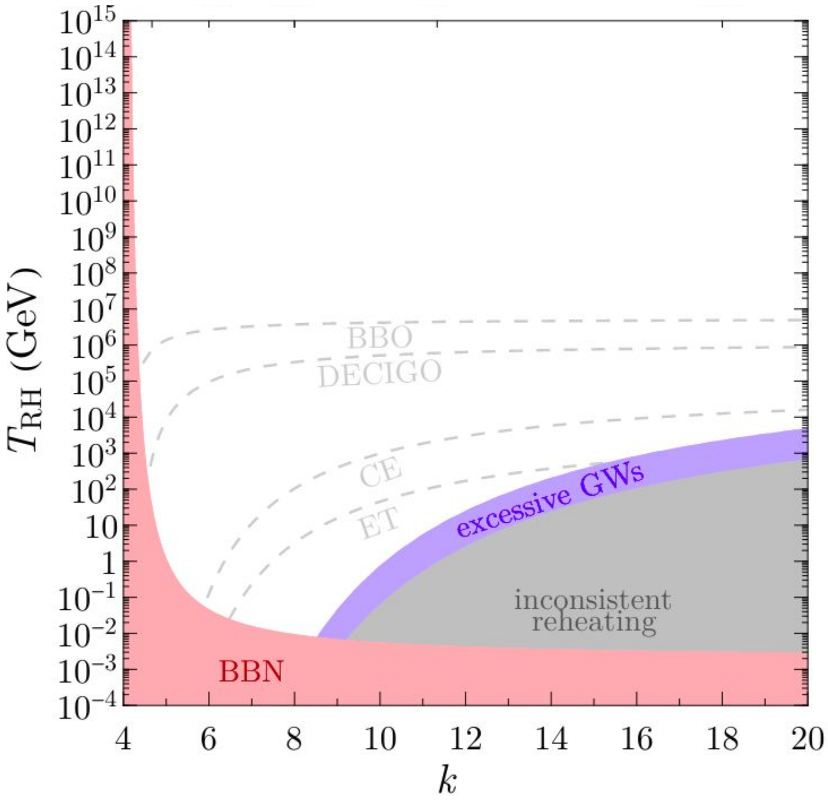


Figure 3 : Reheating temperature from gravitational portals as function of k, for different ξ_h

➜ 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 $\Omega^0_{GW}h^2 \lesssim 10^{-6}$, from excessive GWs as dark radiation.

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



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

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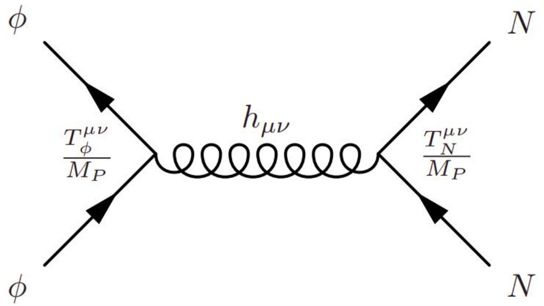
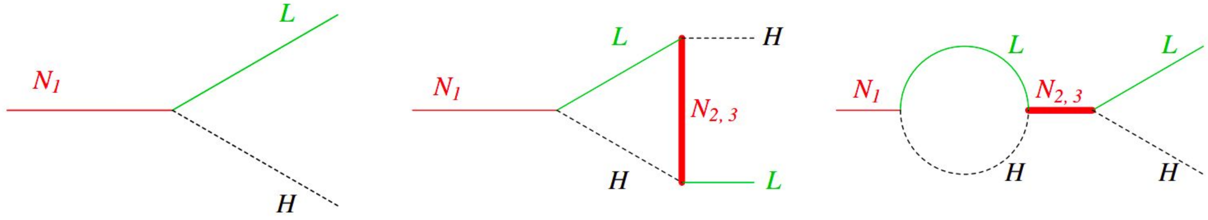
➜ The constraint is relaxed when radiation production is increased by non-minimal gravitational interactions $\xi_h > 0$

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

4 - Gravitational portals to Leptogenesis





Baryogenesis via leptogenesis, Strumia, **0608347**

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

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

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

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

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

Lepton asymmetry, which stays out-of equilibrium

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

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

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

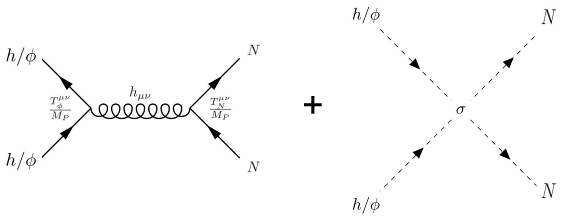
$$\Omega^2 \equiv 1 + \frac{\xi_\phi\,\phi^2}{M_P^2} + \frac{\xi_h\,h^2}{M_P^2}$$

Non-minimal couplings to gravity

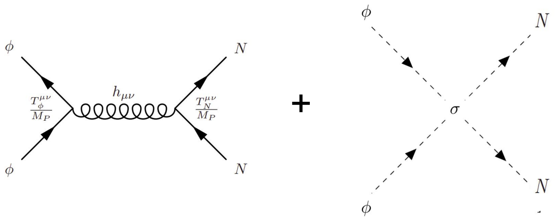
$$\widetilde{\mathcal{L}}_{N_i} = -\frac{1}{2}\,M_{N_i}\,\overline{N_i^c}N_i - (y_N)_{ij}\,\overline{N}_i\,\widetilde{H}^\dagger\,L_j + \text{h.c.}\,.$$

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

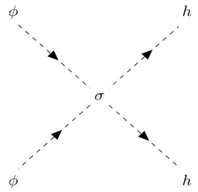
N_2, N_3 are much heavier and generate the lepton asymmetry through their gravitational production and out-of equilibrium decay



$\phi\phi \to N_1N_1$ and SM SM $\to N_1N_1$
from gravitational portals

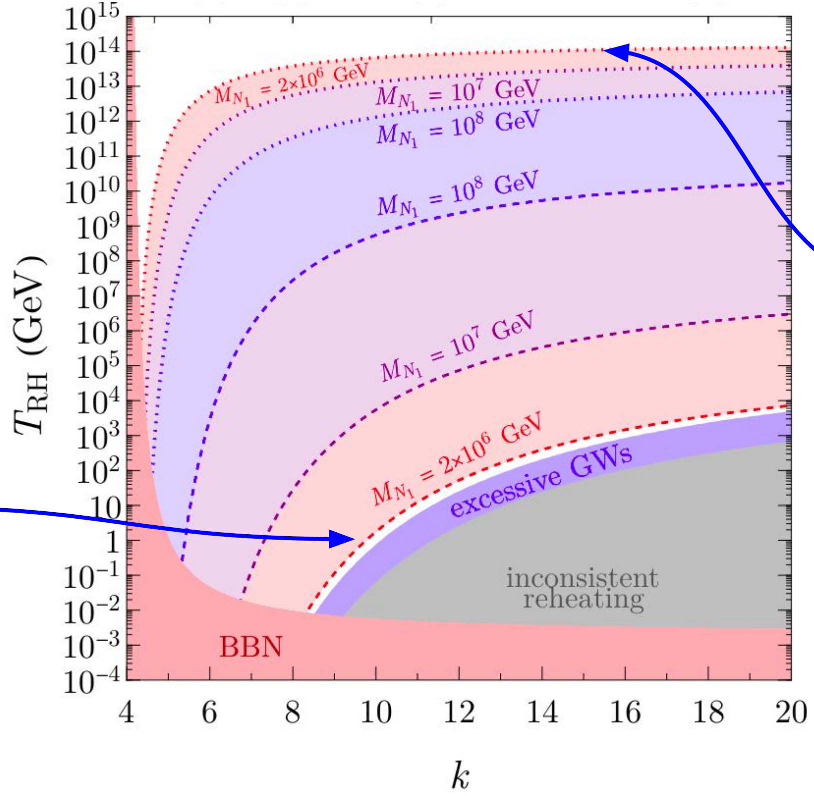


$\phi\phi \to N_2N_2$ (N_3 N_3)
from gravitational portals



$\phi\phi \to$ SM SM
from gravitational portals
(non-minimal)

DM (N_1) production



Upper limits are coming from thermal contribution

SM SM $\rightarrow N_1 N_1$

Lower limits are coming from inflaton contribution

$\phi\phi \rightarrow N_1 N_1$

Figure 5 : Lines corresponding to the observed DM relic abundance, all gravitational contributions added, for different M_{N1}. Shaded regions correspond to under abundance of DM.

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

Baryon asymmetry from leptogenesis (N_2)

Lepton asymmetry is converted into a baryon asymmetry :

$$Y_B = \frac{28}{79} Y_L \simeq 3.5 \times 10^{-4} \delta_{\rm eff} \frac{n_N}{s} \left(\frac{m_{\nu_i}}{0.05 \text{ eV}}\right) \left(\frac{M_{N2}}{10^{13} \text{ GeV}}\right)$$

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

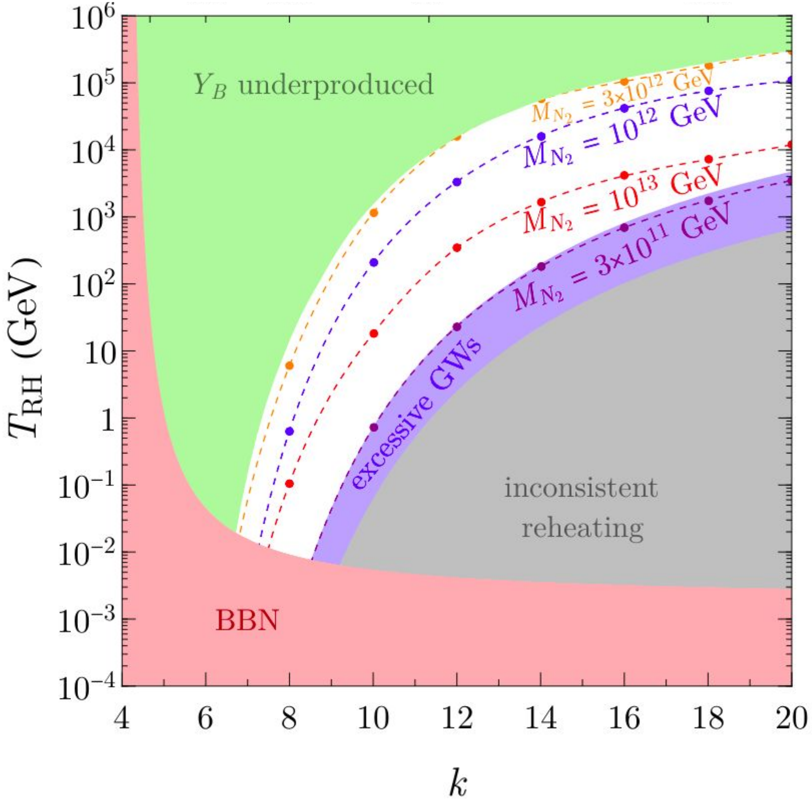
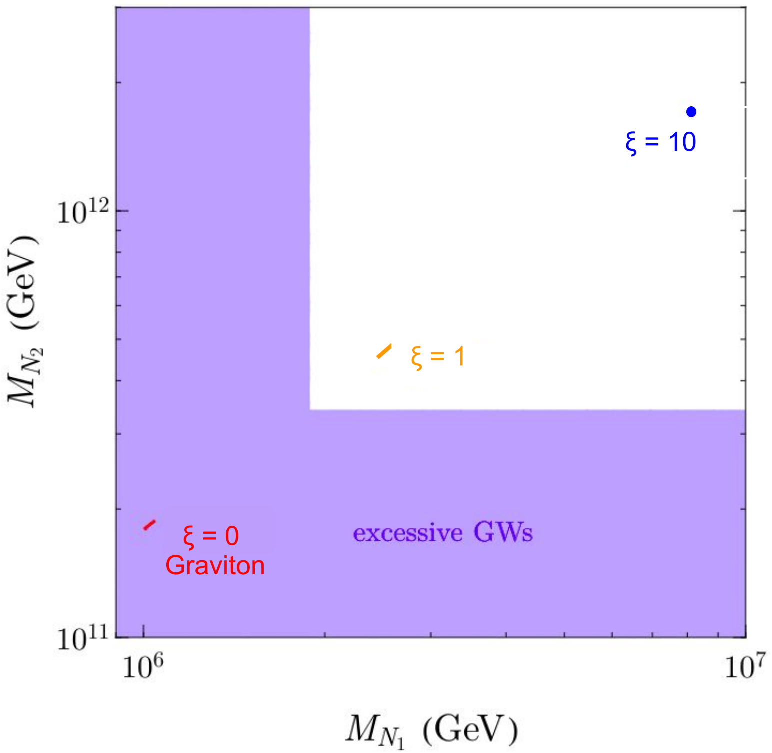


Figure 6 : Lines corresponding to the observed baryon asymmetry $\boxed{Y_B \simeq 8.7 \times 10^{-11}}$ *for different* M_{N2}

Gravitational leptogenesis, reheating and DM production simultaneously



M_{N_1} [PeV]	M_{N_2} [GeV]	ξ_h
1.1	1.6×10^{11}	0
2.8	4.0×10^{11}	1
8.7	1.3×10^{12}	10

We choose in this table k = 6 as a benchmark. For each ξ 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_{N1}, M_{N2}) parameter space satisfying simultaneously the observed DM relic abundance (N1) and the baryon asymmetry (N2) 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 :

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

$$\downarrow$$

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

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

λ determined by the power spectrum amplitude of the CMB "*As*"

➞ Planck measurements give for k=2 : $\lambda \sim 10^{-11}$ for N ~ 50 efolds

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

Class of models : α-attractor T-model inflation

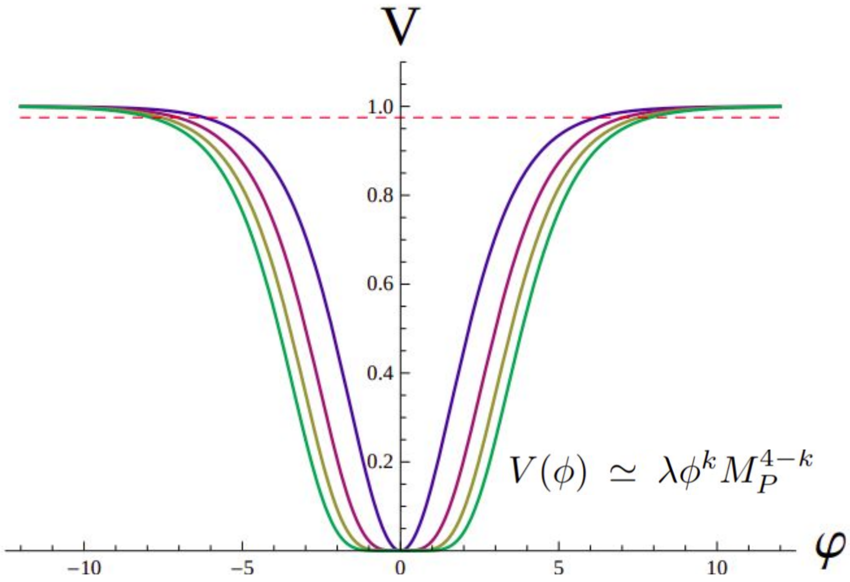
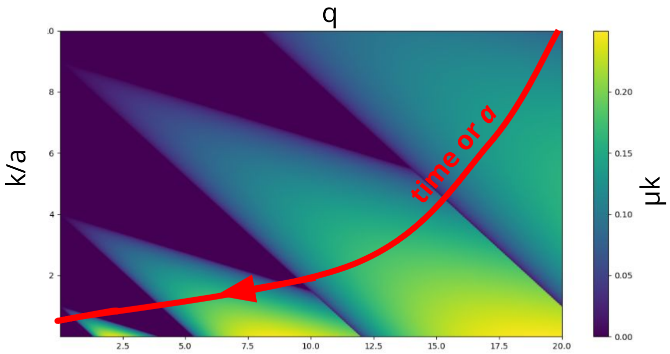


Figure 1: Potentials for the T-Model inflation $\tanh^{2n}(\varphi/\sqrt{6})$ for $n = 1, 2, 3, 4$

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

Reheating and Post-inflationary Production of Dark Matter, Marcos A.G. Garcia, Kunio Kaneta, Yann Mambrini, Keith A. Olive, **2004.08404**

Preheating : non-perturbative processes

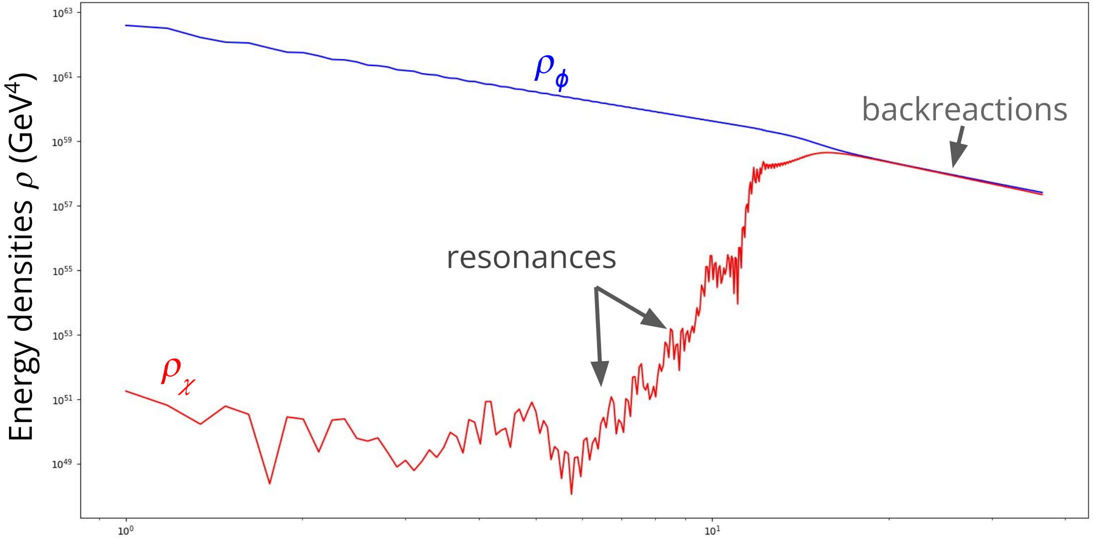


Instabilities in the colored regions
=> number of occupation increasing

$$\chi_k \propto exp[\mu_{k,q} z]$$

with q ~ σ.(ϕ / M_P)

reduced coupling σ ~10^{-6}



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

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

Bogoliubov approach

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

$$S_\chi = \int d^4x \left[\frac{1}{2}(\widetilde{\chi}')^2 - \frac{1}{2}\widetilde{\chi}\omega^2\widetilde{\chi}\right]$$

Consider simply a single field in the vacuum

EOM : $\widetilde{\chi}'' + \omega^2\widetilde{\chi} = 0$ 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 ω.
=> cannot decompose χ based on the positive/negative frequency in the Fourier space

$$\widetilde{\chi}(x) \equiv \int \frac{d^3k}{(2\pi)^{3/2}} e^{i\vec{k}\cdot\vec{x}}\widetilde{\chi}_k$$
$$\widetilde{\chi}_k \equiv a_{\vec{k}} u_k + a^\dagger_{-\vec{k}} u_k^*$$

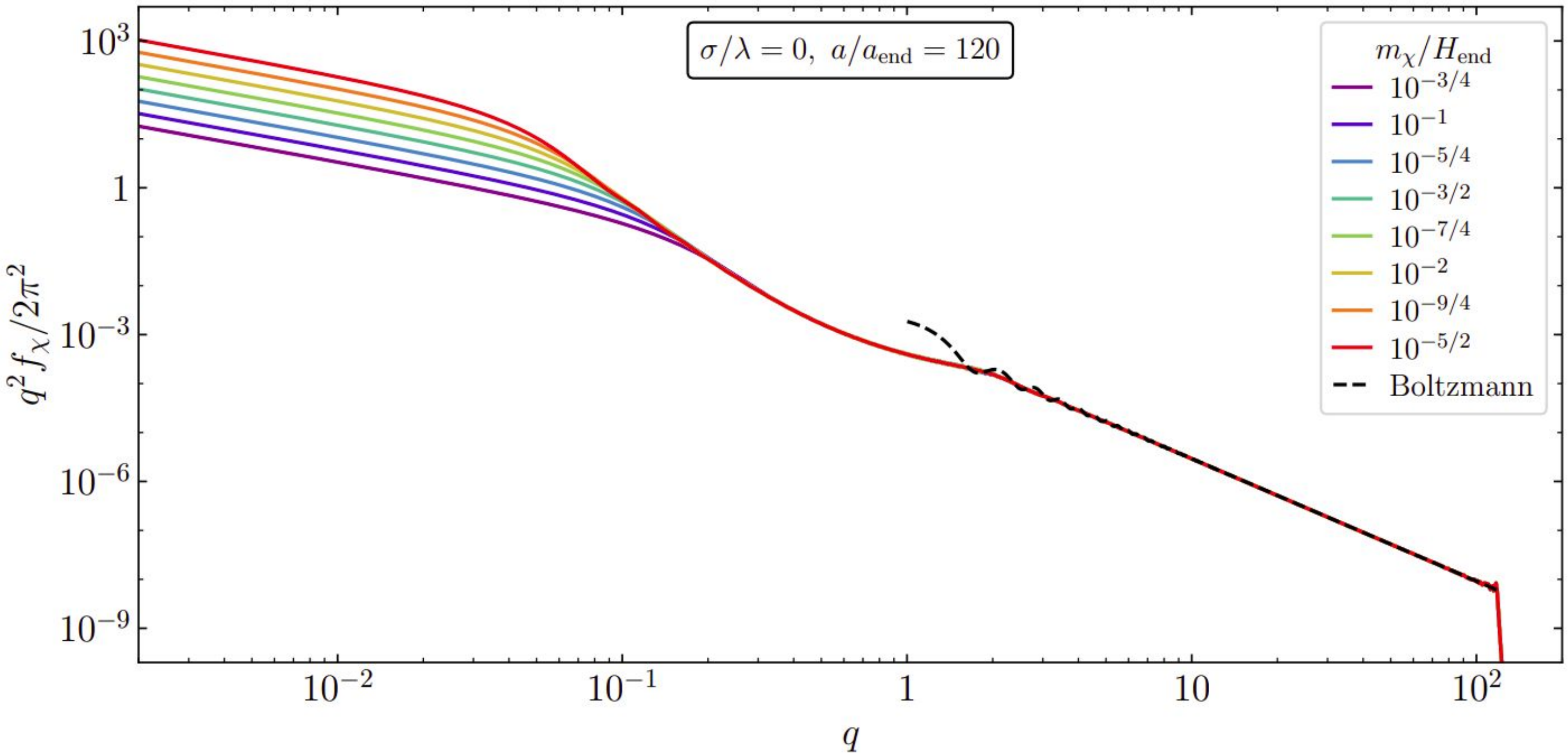
$$\rightarrow \begin{cases} u_k = \dfrac{\boxed{A_k}}{\sqrt{2\omega_k}} e^{-i\int \omega_k d\eta} + \dfrac{\boxed{B_k}}{\sqrt{2\omega_k}} e^{i\int \omega_k d\eta} \\ \alpha_k \equiv A_k e^{-i\int \omega_k d\eta}, \quad \beta_k \equiv B_k e^{i\int \omega_k d\eta} \end{cases}$$

Bogoliubov coefficients

→ the occupation number is given by

$$|\beta_k|^2$$

See Boltzmann or Bogoliubov? Approaches Compared in Gravitational Particle Production, Kunio Kaneta, Sung Mook Lee, Kin-ya Oda, **2206.10929**



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

Scalar Dark Matter Production from Preheating and Structure Formation Constraints, M. Garcia, M. Pierre, S. Verne, **2206.08940**

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

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 $E_n = n.\omega$

Thermal bath scattering

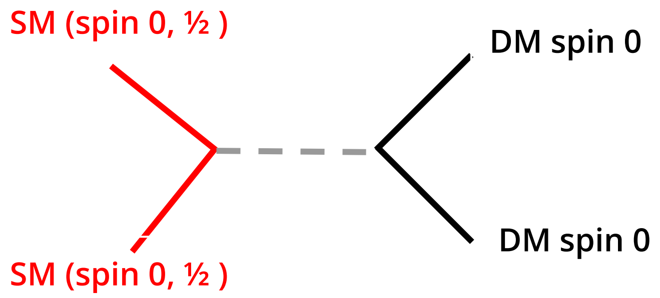
Usual amplitude computation for a s-channel scattering of (massless) SM particles giving DM particles

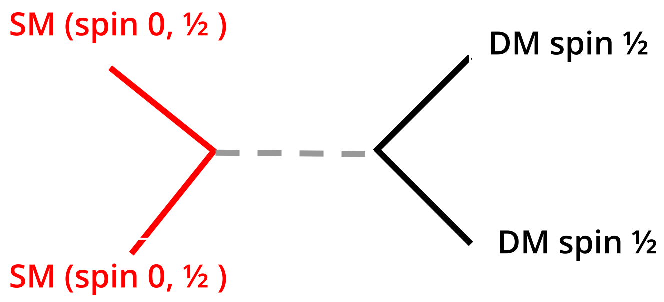
$$|\overline{\mathcal{M}}^{00}|^2 = \frac{1}{64M_P^4}\frac{t^2(s+t)^2}{s^2},$$

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

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

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



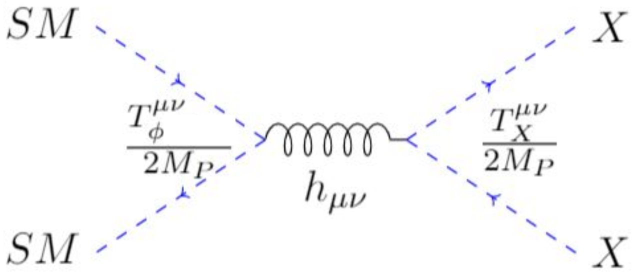


Gravitational portals in the early Universe, Simon Cléry, Yann Mambrini, Keith A. Olive, Sarunas Verner, **2112.15214**

From amplitudes compute the rate of DM production for each process

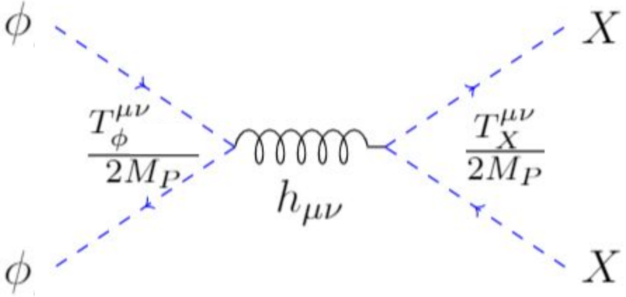
$$R_j^T = \beta_j \frac{\boxed{T^8}}{M_P^4}$$ for spin j = 0, ½ DM final state

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



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

$$R^{1/2}_{\phi^k} = \boxed{\frac{\rho_\phi^2}{64\pi M_P^4}} \sum_{n=1}^{\infty} \boxed{\frac{m_X^2}{E_n^2}} |(\mathcal{P}^k)_n|^2 \left(1 - \frac{4m_X^2}{E_n^2}\right)^{\frac{3}{2}}$$ spin ½



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

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

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_{RH} for larger value of k, slowing down the DM production

---

$$\frac{\Omega_0^\phi h^2}{0.1} \simeq \left(\frac{\rho_{end}}{10^{64} GeV^4}\right)^{1-\frac{1}{k}} \left(\frac{10^{40} GeV^4}{\rho_{RH}}\right)^{\frac{1}{4}-\frac{1}{k}} \left(\frac{k+2}{6k-6}\right) \left(\frac{3k-3}{2k+4}\right)^{\frac{3k-3}{7-k}} \Sigma_0^k \frac{m_X}{3.8 \times 10^{\frac{24}{k}-6}}$$

Spin 0 inflaton scattering case

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

Spin ½ inflaton scattering case

spin ½ helicity suppression !

Gravitational portals in the early Universe, SC, Yann Mambrini, Keith A. Olive, **2112.15214**

DM production in minimal framework

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

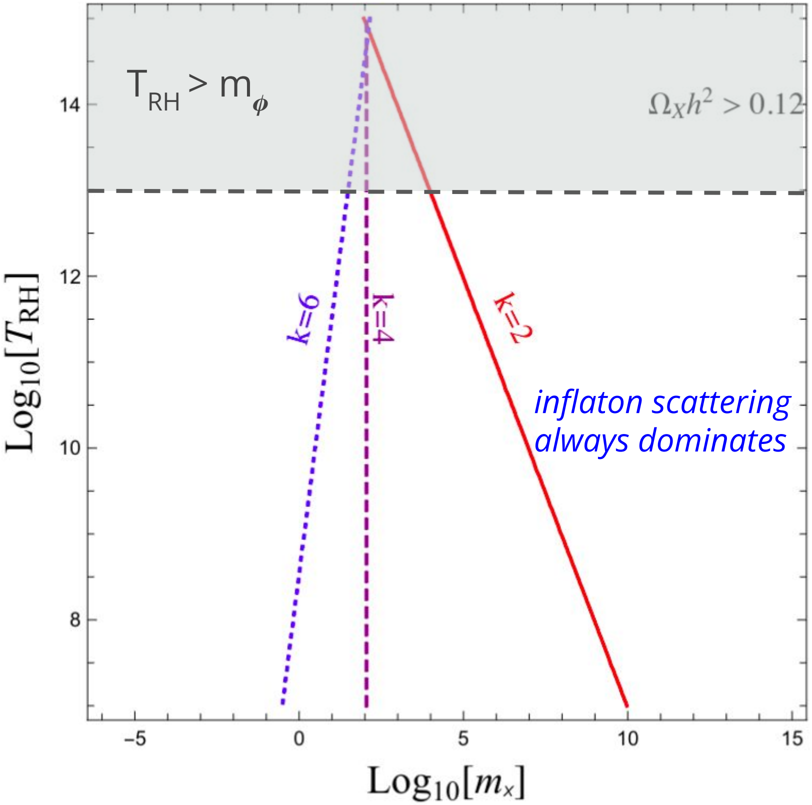


*Figure 2 : DM relic, $\Omega h^2 = 0.12$ in the case of a **spin 0 DM***

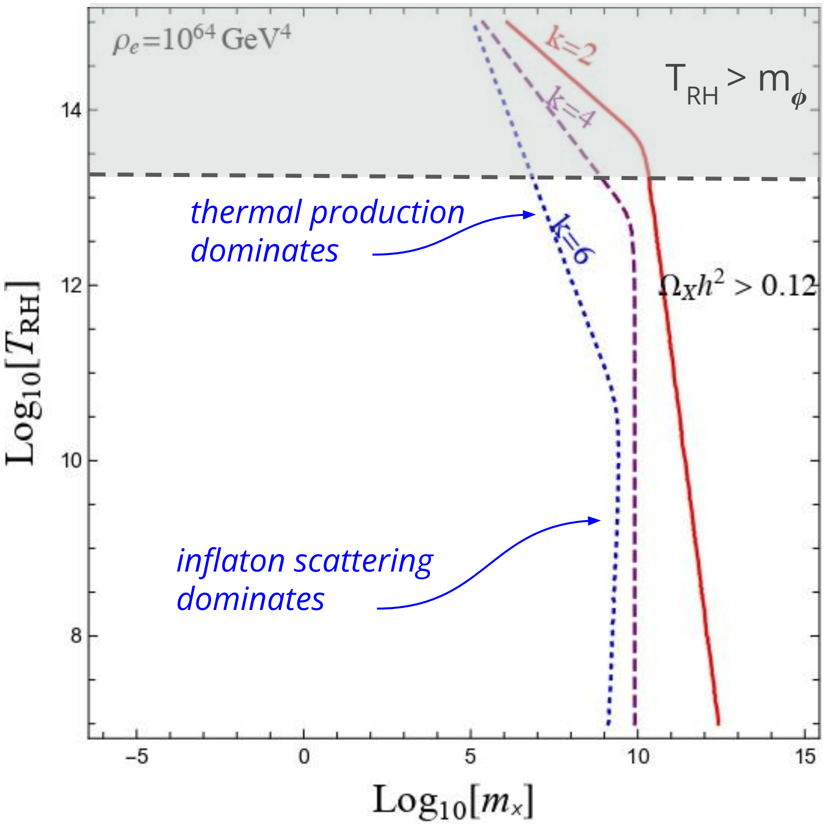
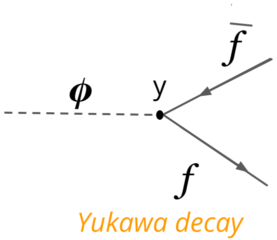
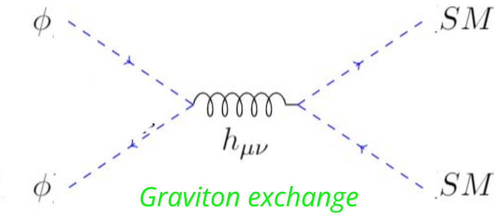


*Figure 3 : DM relic, $\Omega h^2 = 0.12$ in the case of a **spin ½ DM***

Radiation production in minimal framework



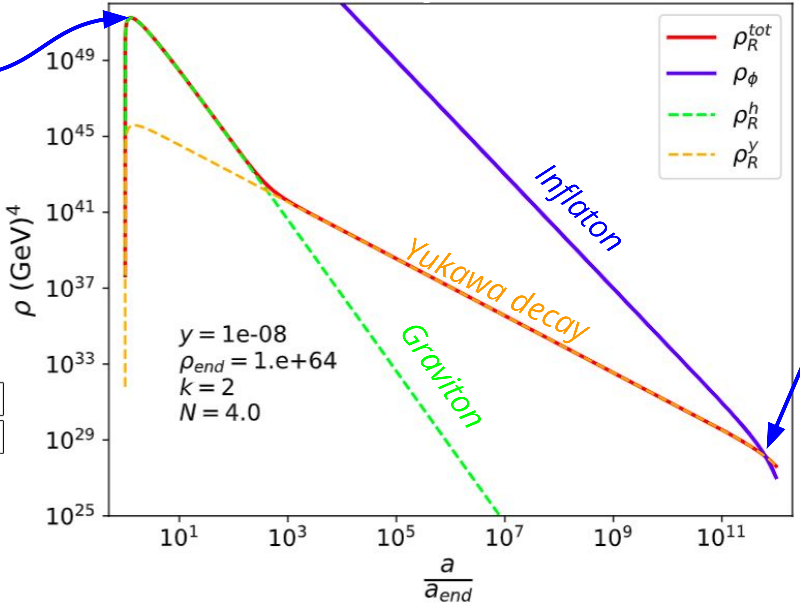
+



➜ This maximum temperature T_{max} ~ 10^{12} GeV reached by the bath is unavoidable !

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

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

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

$$\downarrow$$

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

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

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

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

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

with

$$\begin{cases} \widetilde{\mathcal{L}}_\phi = \frac{1}{2}\,\partial_\mu\phi\,\partial^\mu\phi - V(\phi) \\ \widetilde{\mathcal{L}}_h = \frac{1}{2}\,\partial_\mu h\,\partial^\mu h - V(h) \\ \widetilde{\mathcal{L}}_N = \frac{i}{2}\,\overline{\mathcal{N}_i}\,\overleftrightarrow{\nabla}\,\mathcal{N}_i - \frac{1}{2}\,M_{N_i}\,\overline{(\mathcal{N})^c}_i\,\mathcal{N}_i + \widetilde{\mathcal{L}}_{\rm yuk} \\ \widetilde{\mathcal{L}}_{\rm yuk} = -y_{N_i}\,\overline{\mathcal{N}_i}\,\widetilde{H}^\dagger\,\mathbb{L} + {\rm h.c}\,, \end{cases}$$

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

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

$$\mathcal{L}_{\rm non-min.} = -\sigma^\xi_{hN_i}\,h^2\,\overline{N_i^c}N_i - \sigma^\xi_{\phi N_i}\,\phi^2\,\overline{N_i^c}N_i$$

Leading order interactions of RHN

$$\sigma^\xi_{\phi N_i} = \frac{M_{N_i}}{2M_P^2}\xi_\phi$$
$$\sigma^\xi_{hN_i} = \frac{M_{N_i}}{2M_P^2}\xi_h\,.$$

Non-canonical kinetic term

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

in Einstein frame

with

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

and

$$K^{ij} = 6\frac{\partial \log\Omega}{\partial S_i}\frac{\partial \log\Omega}{\partial S_j} + \frac{\delta^{ij}}{\Omega^2}$$

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.

Gravitational Portals with Non-Minimal Couplings, SC, Yann Mambrini, Keith A. Olive, Andrey Shkerin, Sarunas Verner, **2203.02004**

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 $\phi_{\rm end} \sim M_P$ and that inflaton field is decreasing during the reheating

$$=> \quad |\xi_\phi| \lesssim 1$$

➜ Since our perturbative computations involve effective couplings in the Einstein frame that depend on all ξ, the small value of ξ_φ can be compensated by ξ_h . Current constraints on ξ_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, ξh 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**