Gravitational portals during reheating

AstroParticle Symposium - 2nd November 2022

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

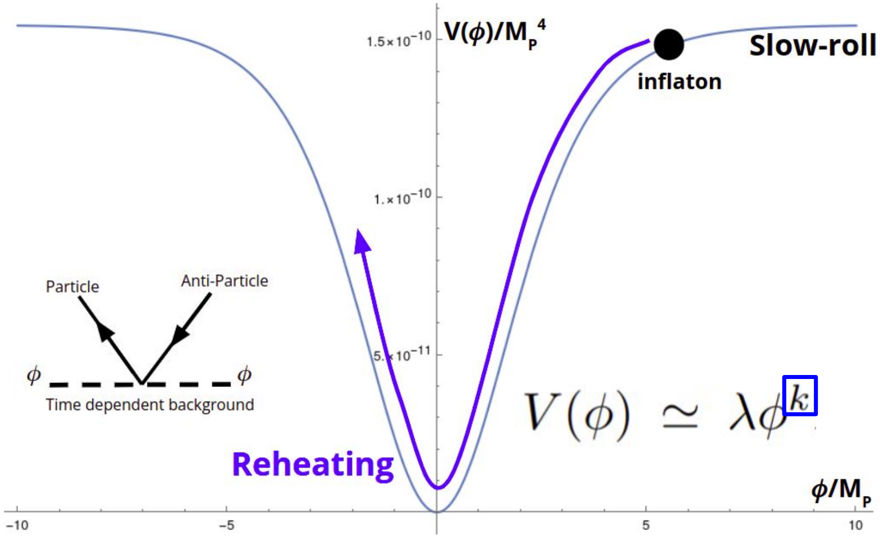
2 - Minimal gravitational portal

3 - Non-minimal coupling to gravity

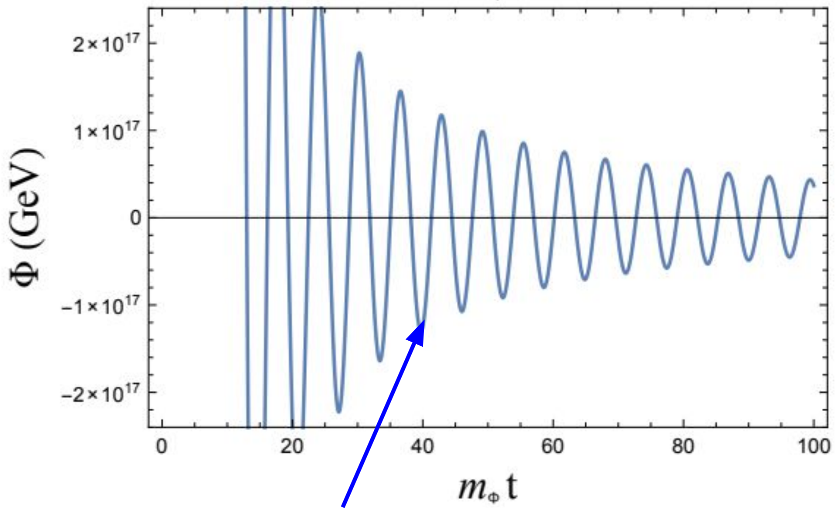
4 - Gravitational reheating and GWs

5 - Gravity as a portal to reheating, leptogenesis and DM

1- Reheating after inflation



$$V(\phi) \simeq \lambda\phi^{\boxed{k}}$$



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

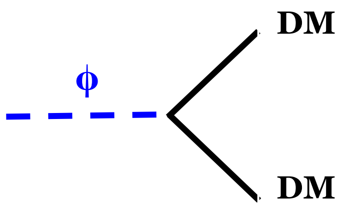
EOM : $$\ddot{\phi}(t) + 3H\dot{\phi}(t) + \boxed{\Gamma\dot{\phi}(t)} + V'(\phi(t)) = 0$$

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

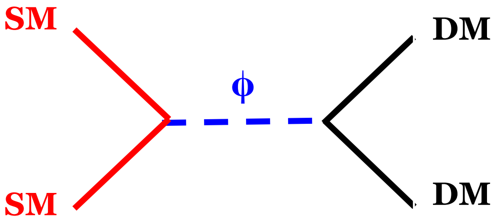
$$w = \frac{P_\phi}{\rho_\phi} = \frac{\frac{1}{2}\langle\dot{\phi}^2\rangle - \langle V(\phi)\rangle}{\frac{1}{2}\langle\dot{\phi}^2\rangle + \langle V(\phi)\rangle} = \boxed{\frac{k-2}{k+2}}$$

Perturbative processes

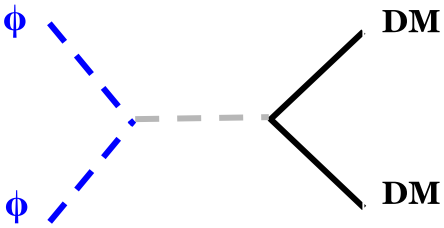
Inflaton sector can also handle non-thermal Dark Matter (DM) production through perturbative processes



→ 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**

2- Minimal gravitational portal

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

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

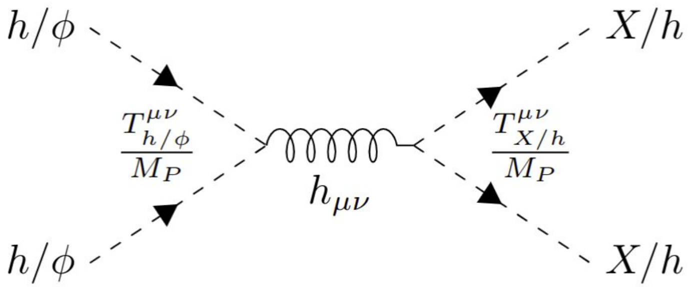
$$\downarrow$$

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

➜ 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**



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

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

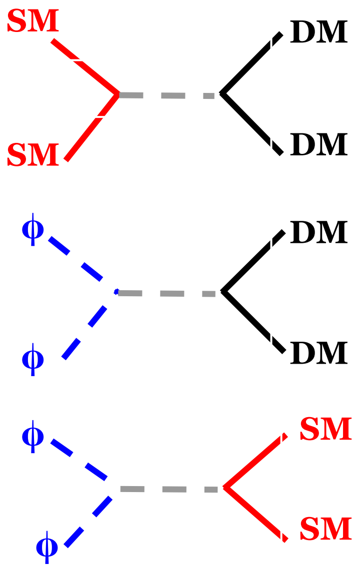
$$T_1^{\mu\nu} = \frac{1}{2} \left[F^\mu_\alpha F^{\nu\alpha} + F^\nu_\alpha F^{\mu\alpha} - \frac{1}{2} g^{\mu\nu} F^{\alpha\beta} F_{\alpha\beta} \right]$$

Graviton can play the portal between :

→ Thermal bath and DM to populate 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**

3- Non-minimal coupling to gravity

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

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

in the Jordan frame

with

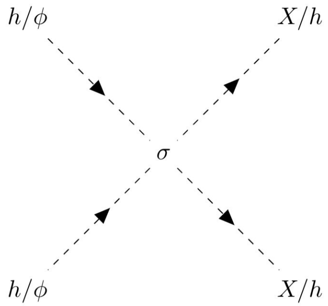
$$\Omega^2 \equiv 1 + \underbrace{\frac{\xi_\phi \phi^2}{M_P^2}}_{\text{inflaton}} + \underbrace{\frac{\xi_h h^2}{M_P^2}}_{\text{SM}} + \underbrace{\frac{\xi_X X^2}{M_P^2}}_{\text{DM}}$$

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

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

in the Einstein frame

This non-minimal coupling induces 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-R² Inflation Model, Aoki, Lee, Menkara, Yamashita, **2202.13063**

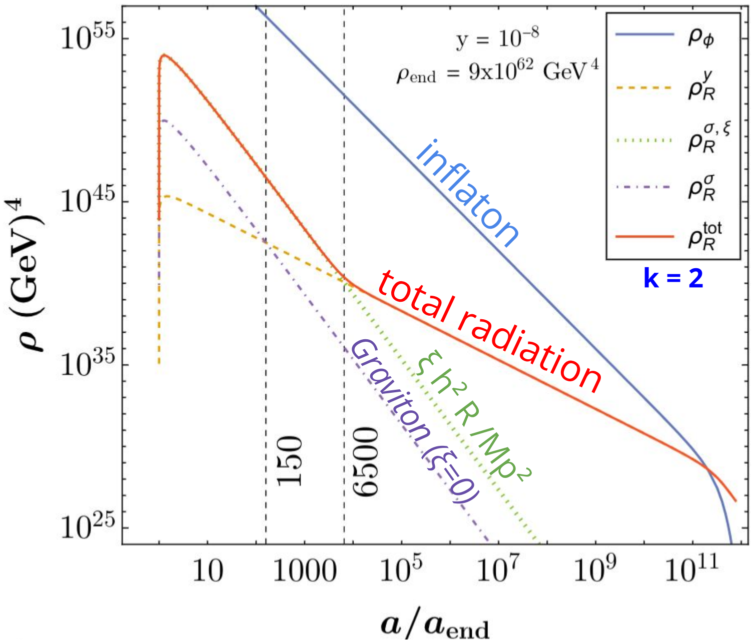


Figure 1 : Energy densities of inflaton (blue), total radiation (red), radiation from inflaton decay (orange), from scattering mediated by graviton (purple) and from non-minimal coupling (green), with $\xi_h = \xi = 2$

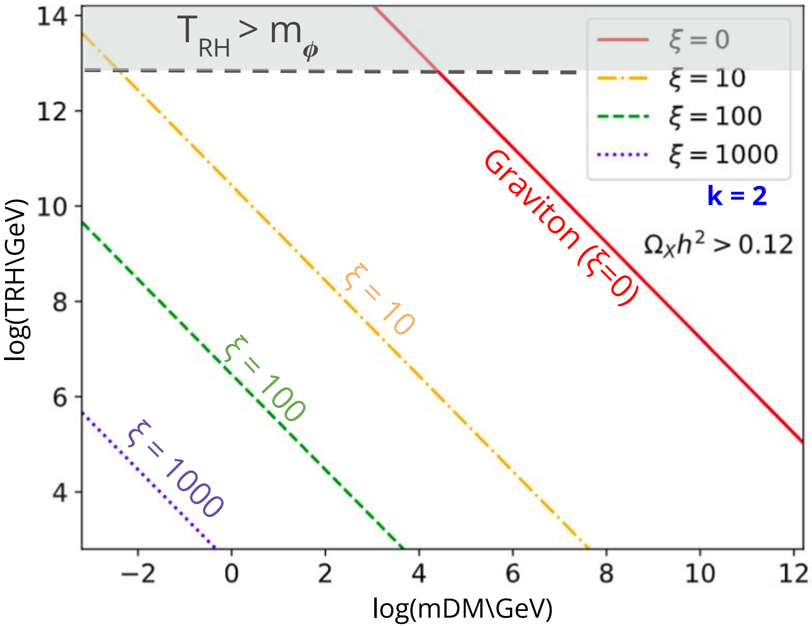
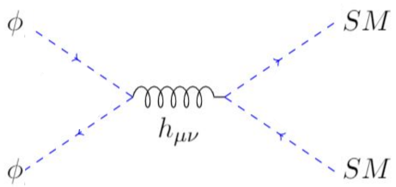


Figure 2 : Contours respecting $\Omega_X h^2 = 0.12$ for spin 0 DM, for different values of $\xi_h = \xi_X = \xi$. Both minimal and non-minimal contributions are added.

→ 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**

4 - Gravitational reheating and GWs

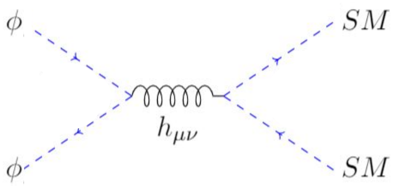


➜ Graviton exchange processes can be sufficient to reheat entirely, for sufficiently steep inflaton potential : k > 9

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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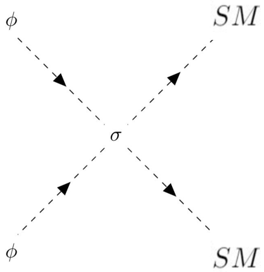


➜ The requirement of large k can be relaxed if we add the non-minimal contribution to radiation production, (but still need k>4).

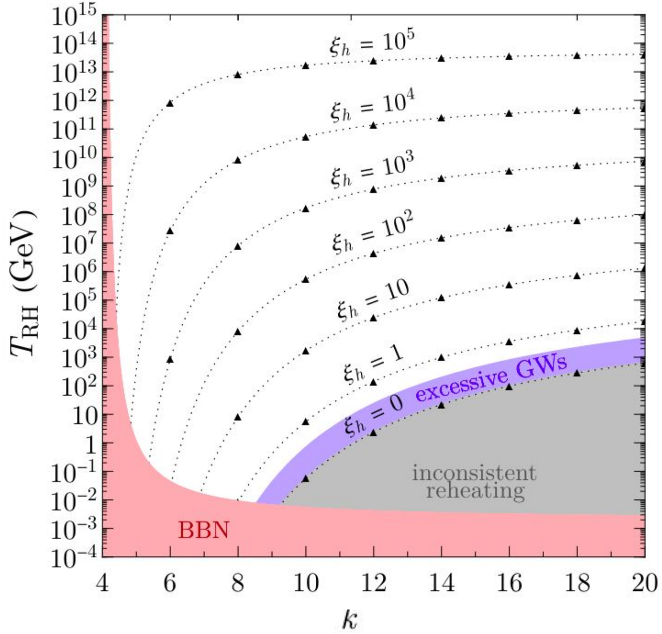


Figure 3 : Reheating temperature from gravitational portals as function of k, for different ξ_h

➜ Primordial GWs re-entering the horizon during reheating, if inflaton redshifts faster than radiation (k>4), are enhanced.

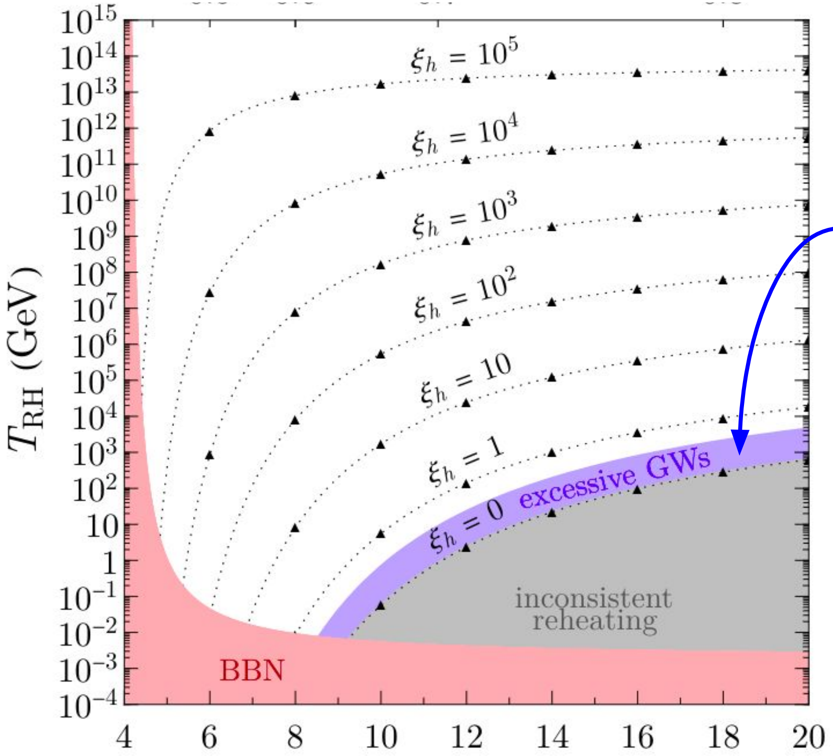


Figure 3 : Reheating temperature from gravitational portals as function of k, for different ξ_h

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

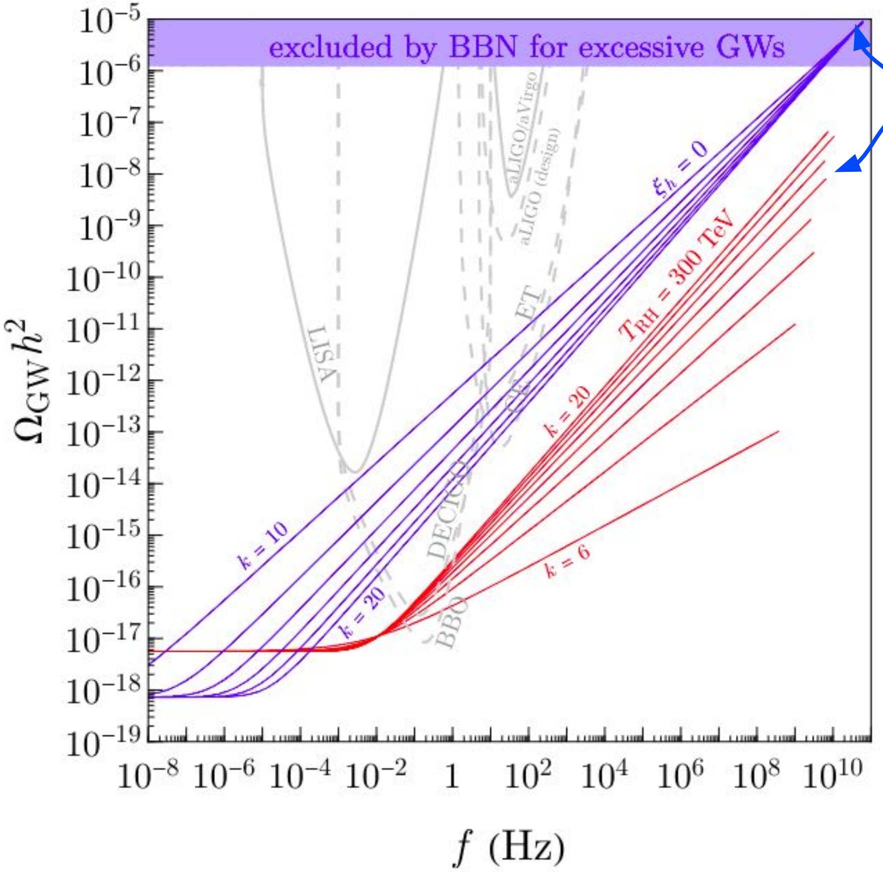
➜ The case of minimal gravitational reheating is excluded by the BBN bound of $\Omega^0_{GW}h^2 \sim 10^{-6}$, from excessive GWs as dark radiation.

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

Such enhanced GWs offer a signature to look for

➜ 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

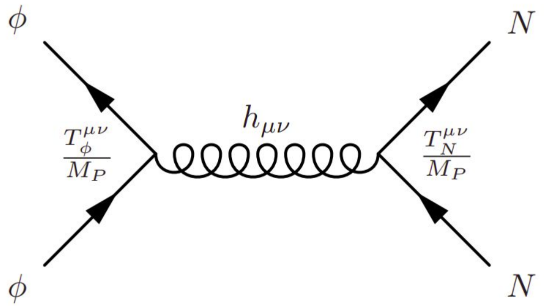


The largest enhancement is for the mode that re-enters the horizon right after inflation

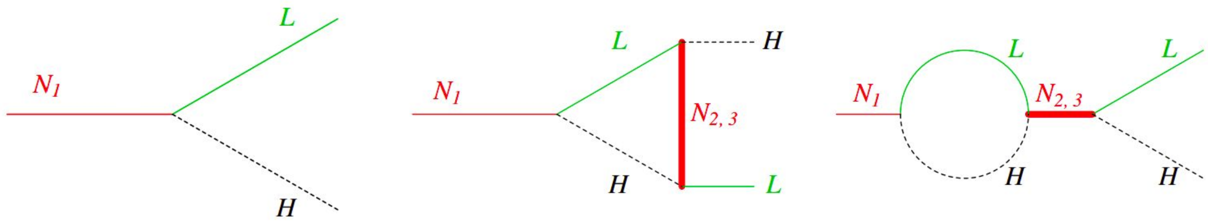
➜ A large region of the parameter space for low T_{RH} can be probed by future GWs detectors.

Figure 4 : 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.

5 - Gravity as a portal to reheating, leptogenesis and DM



Graviton portal can handle the production of sterile neutrinos



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.

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

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

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

Lepton asymmetry, out-of equilibrium

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

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

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

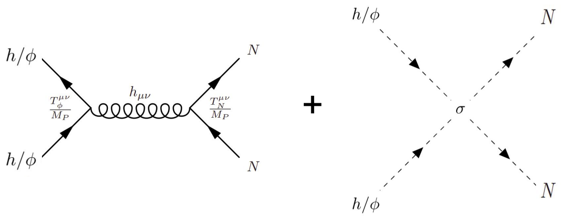
$$\Omega^2 \equiv 1 + \frac{\xi_\phi\,\phi^2}{M_P^2} + \frac{\xi_h\,h^2}{M_P^2}$$

Non-minimal couplings with gravity

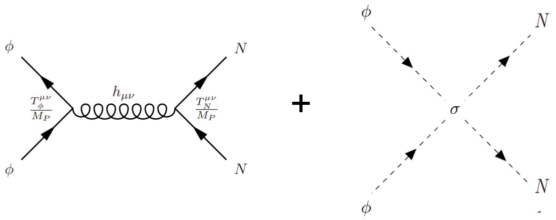
$$\widetilde{\mathcal{L}}_{N_i} = -\frac{1}{2}M_{N_i}\,\overline{N_i^c}N_i - (y_N)_{ij}\,\overline{N}_i\,\widetilde{H}^\dagger\,L_j + \text{h.c.}\,.$$

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

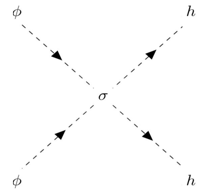
N_2, N_3 are much heavier and generate the lepton asymmetry through their gravitational production and out-of equilibrium decay



$\phi\phi \to N_1N_1$ and SM SM $\to N_1N_1$ from minimal and non-minimal couplings

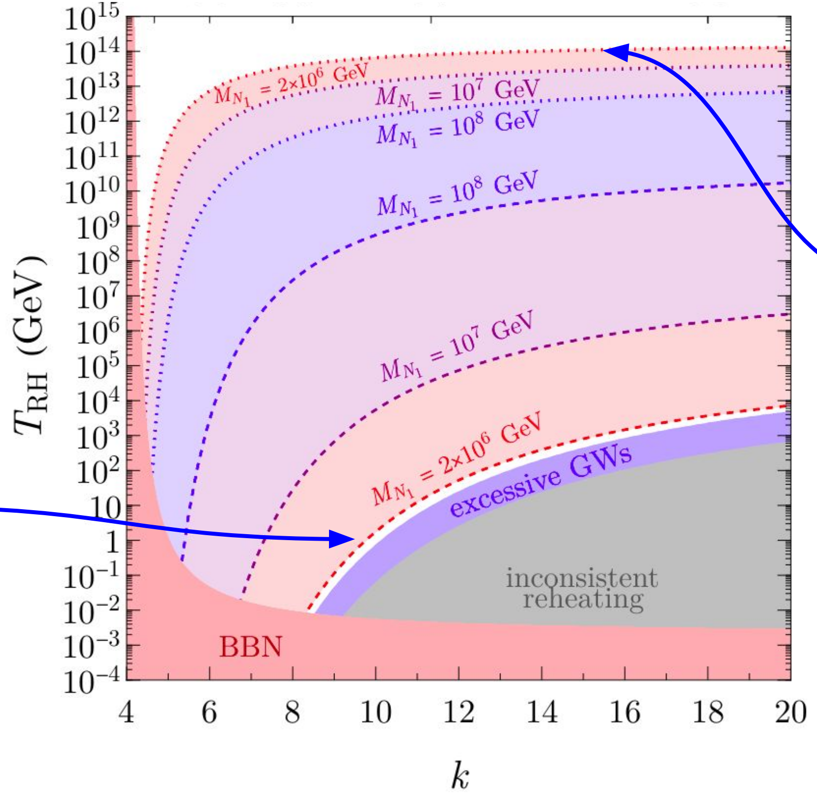


$\phi\phi \to N_2N_2$ (N_3 N_3) from minimal and non-minimal couplings



$\phi\phi \to$ SM SM Non-minimal coupling, for radiation production

DM (N_1) production



Upper limits are coming from thermal contribution

SM SM $\to N_1 N_1$

Lower limits are coming from inflaton contribution

$\phi\phi \to N_1 N_1$

Figure 5 : Lines correspond 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 :

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

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

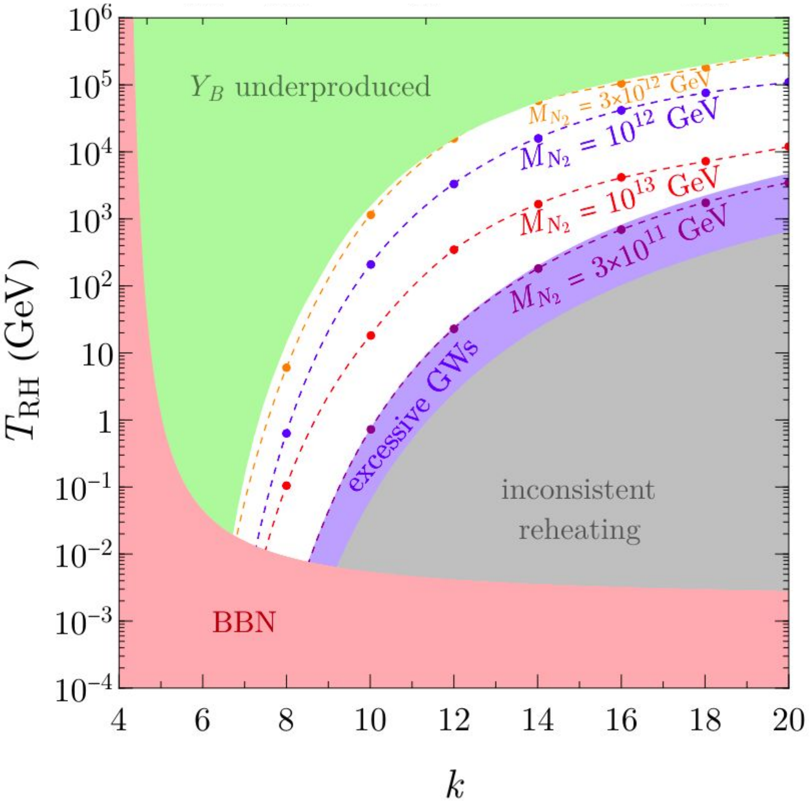
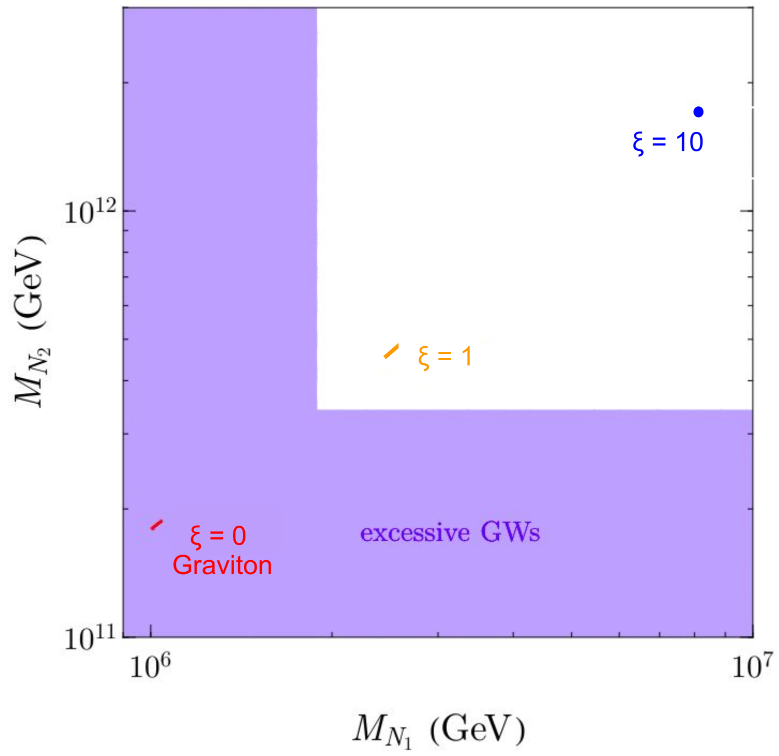


Figure 6 : Lines corresponding to the observed baryon asymmetry $\boxed{Y_B \simeq 8.7 \times 10^{-11}}$ *for different M_{N2}*

Gravitational leptogenesis 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 (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 at BBN

➜ GWs signal with a distinctive spectrum for different inflation potential near the minimum (different k)

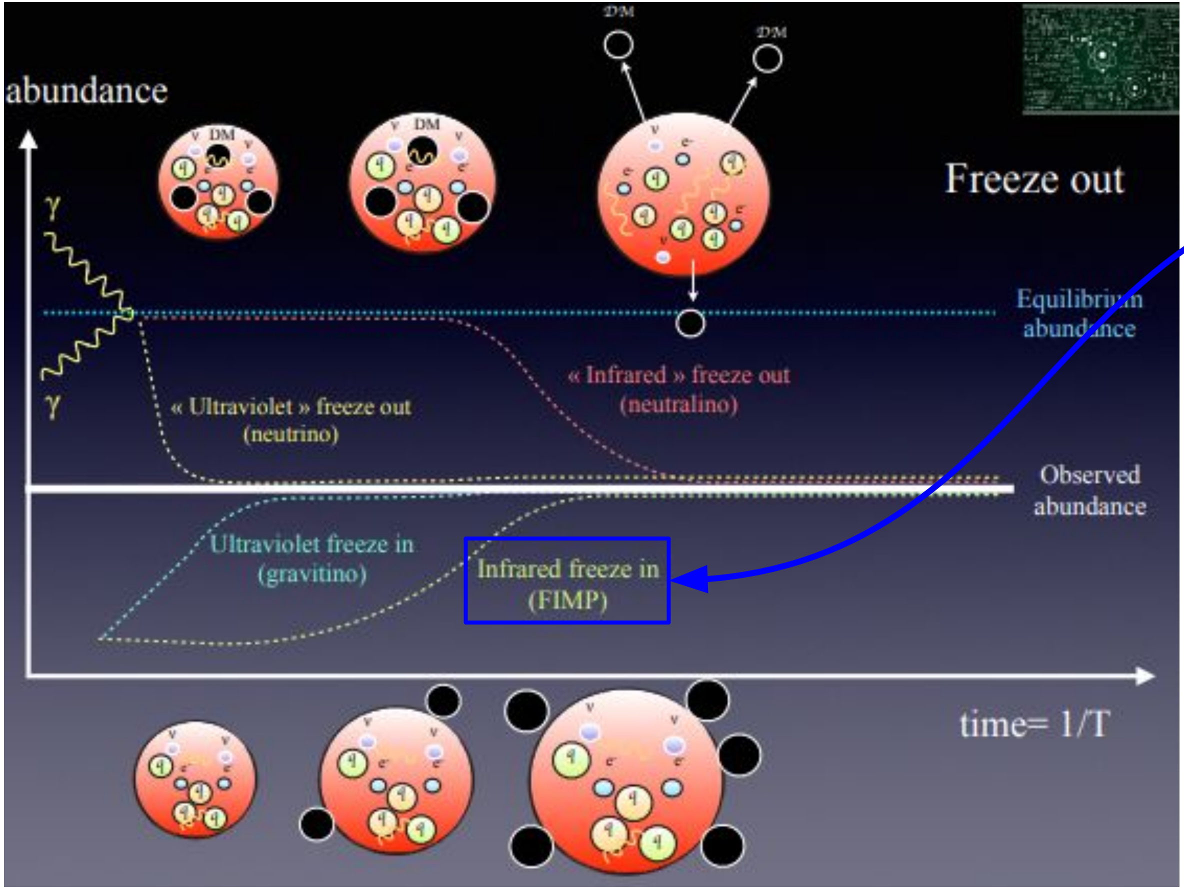
➜ It provides a minimal framework to produce sterile neutrinos that handle leptogenesis

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

Thank you for your attention !

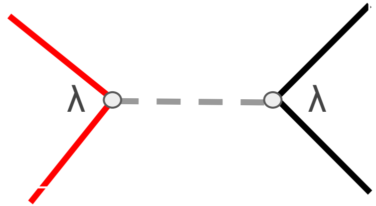
APPENDIX

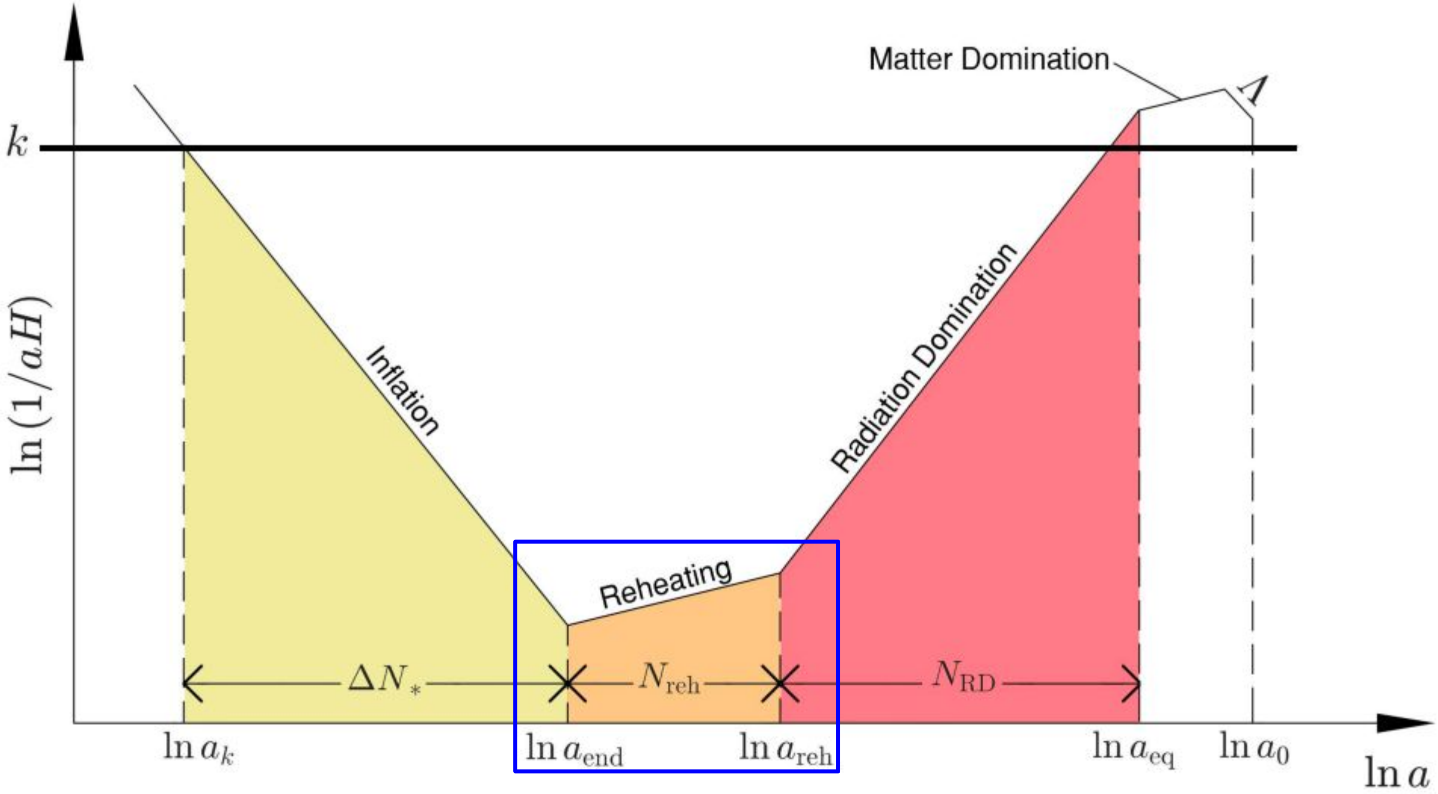
FIMP



Credit : Yann Mambrini

DM interacts so feebly that it never reaches equilibrium and it "freezes in"





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

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 : *λ ~ 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

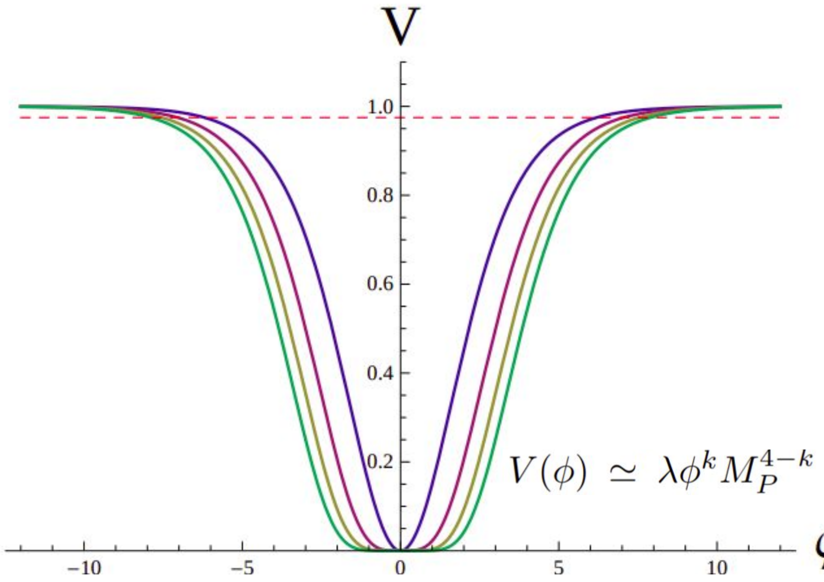


Figure 1: Potentials for the T-Model inflation $\tanh^{2n}(\varphi/\sqrt{6})$ for $n = 1, 2, 3, 4$

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

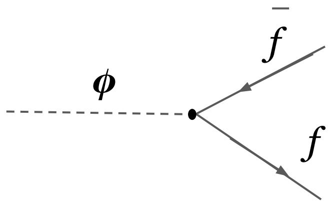
Reheating and Post-inflationary Production of Dark Matter, Marcos A.G. Garcia, Kunio Kaneta, Yann Mambrini, Keith A. Olive, **2004.08404**

Particle production

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

Example : Yukawa like interaction

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



Constitute the primordial bath that will thermalize

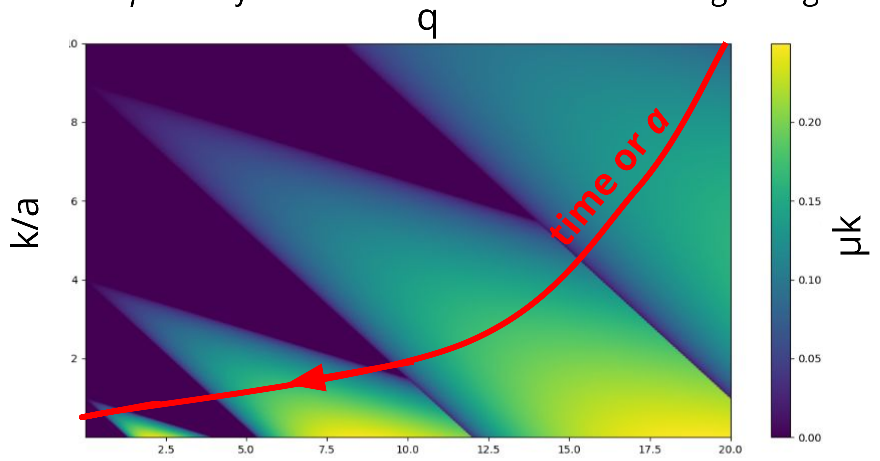
Freeze-in from preheating, Garcia , Kaneta, Mambrini, Olive, Verner, **2109.13280**

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

Time dependant background coupled to fields leads to parametric resonance or tachyonic instabilities

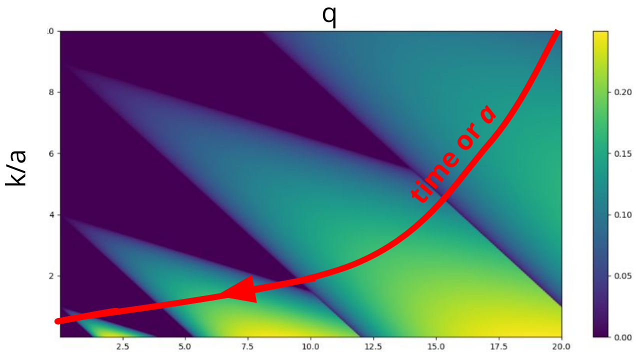
$$\chi_k'' + \left(\frac{k^2}{m_\phi^2 a^2} + 2q - 2q cos(2z)\right)\chi_k = 0$$

Mathieu equation for Fourier modes in the oscillating background



Instabilities in the colored regions
=> number of occupation increasing

Preheating : non-perturbative processes

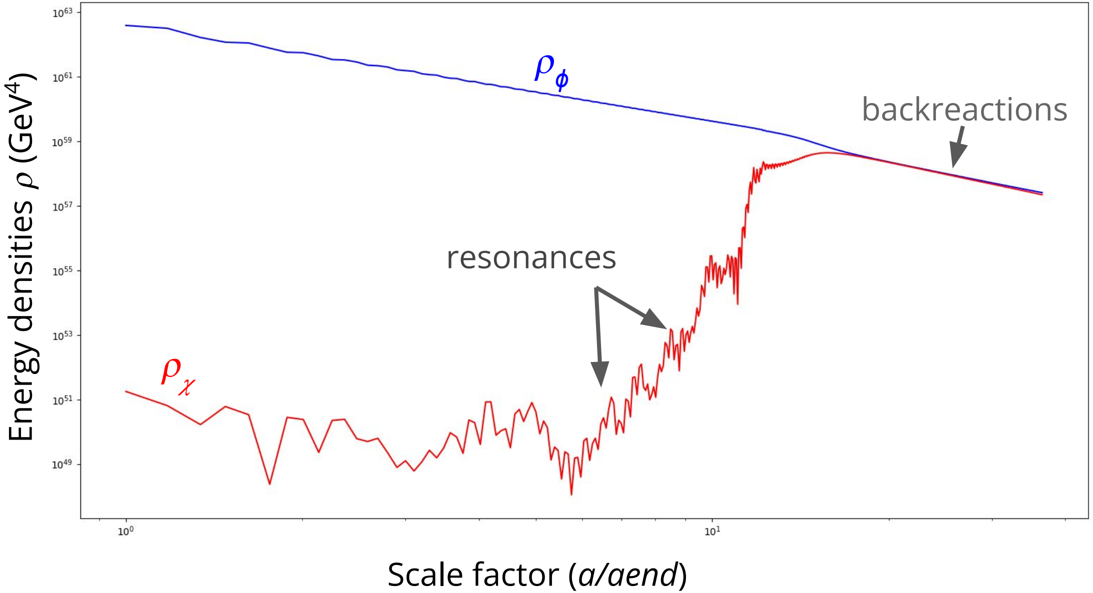


Instabilities in the colored regions
=> number of occupation increasing

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

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

$$\widetilde{\chi}(x) \equiv \int \frac{d^3k}{(2\pi)^{3/2}} e^{i\vec{k}\cdot\vec{x}}\widetilde{\chi}_k$$

$$\widetilde{\chi}_k \equiv a_{\vec{k}} u_k + a^\dagger_{-\vec{k}} u_k^*$$

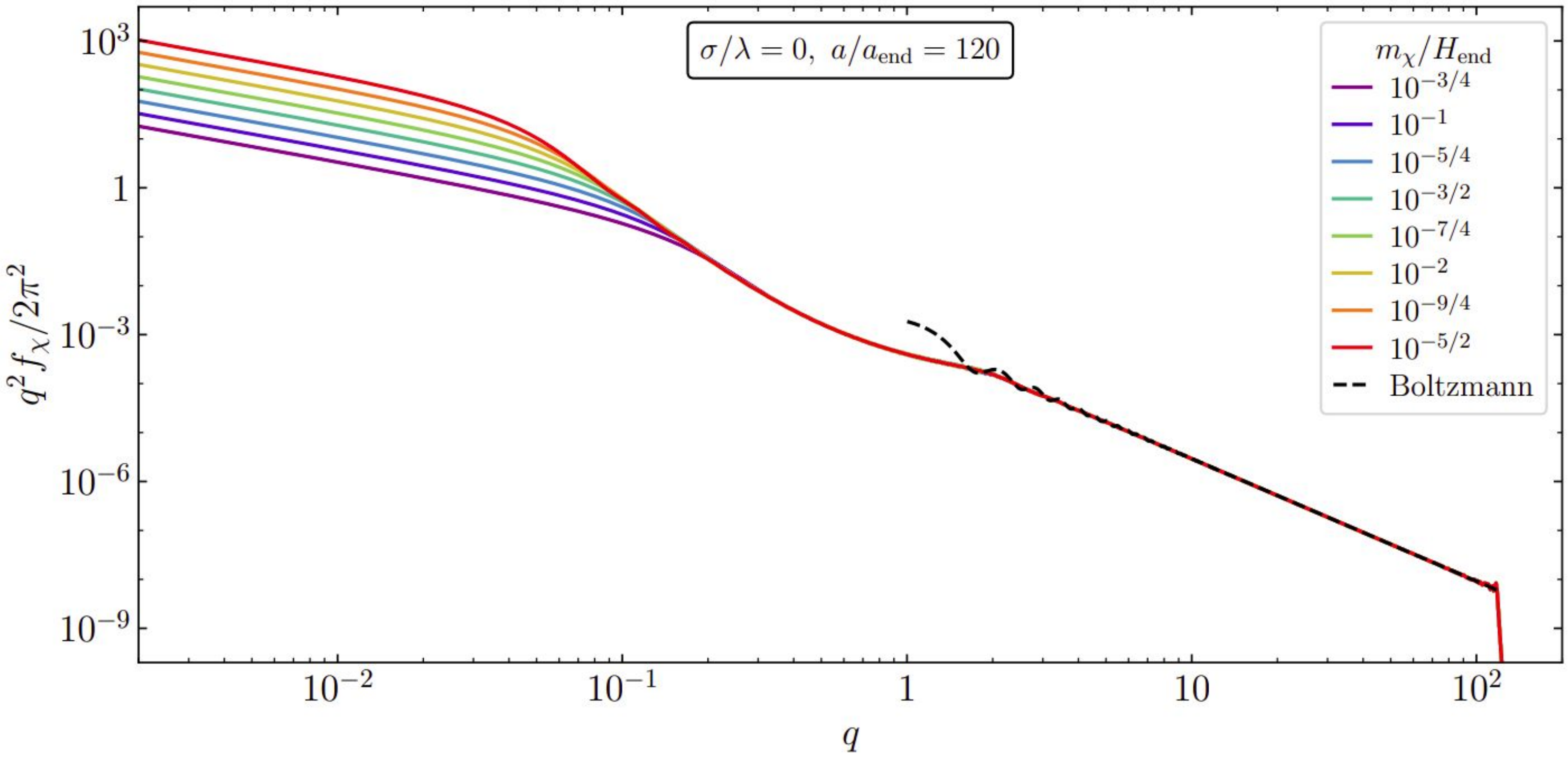
Bogoliubov coefficients

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

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**

Boltzmann approach

Assumes that the background geometry is Minkowskian and compute transition probability

$$dP^{(n)}_{\phi\phi\to AB} \equiv \frac{d^3p_A}{(2\pi)^3 2p^0_A}\frac{d^3p_B}{(2\pi)^3 2p^0_B}|\mathcal{M}_n|^2 \times (2\pi)^4\delta(n\omega - p^0_A - p^0_B)\delta^3(\vec{p}_A + \vec{p}_B)$$

Initial state ϕ as a coherently oscillating Bose-Einstein condensate with no spatial momentum

From this, production rate can be computed by

$$R^{(\mathrm{N})}_{\phi\phi\to\chi\chi} = \sum_{n=1}^{\infty}\int dP^{(n)}_{\phi\phi\to\chi\chi}$$

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, K. Kaneta, S. M. Lee, K. Oda, **2206.10929**

Inflaton scattering

Potential near the minimum is a power k-dependant 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 *En = n.ω*

Gravitational portals in the early Universe, SC, Y. Mambrini, K. A. Olive, S Verner **2112.15214**

Thermal bath scattering

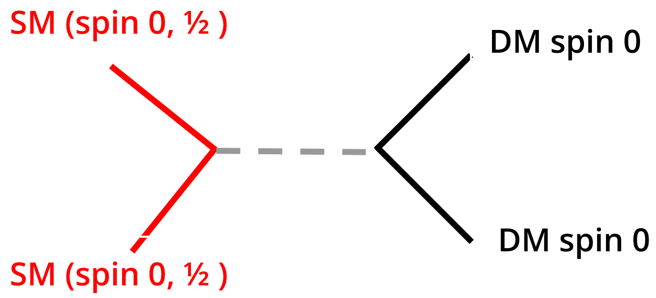
Usual amplitude computation for a s-channel scattering of (massless) SM particles giving DM particles

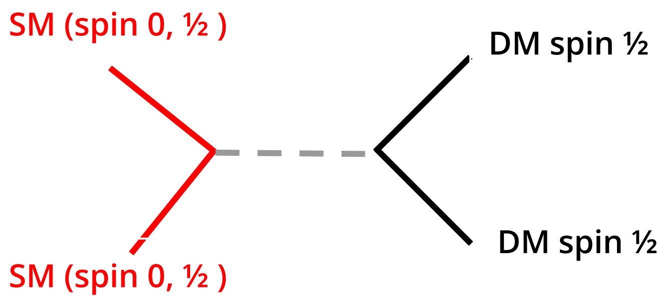
$$|\overline{\mathcal{M}}^{00}|^2 = \frac{1}{64M_P^4}\frac{t^2(s+t)^2}{s^2},$$

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

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

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



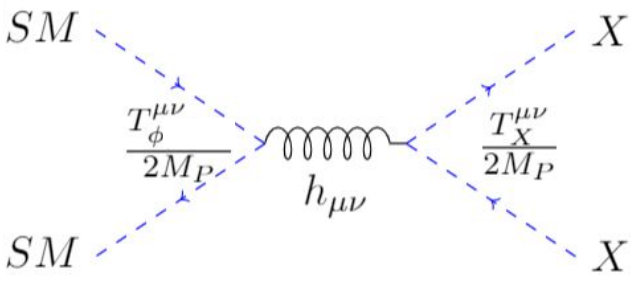


Gravitational portals in the early Universe, Simon Cléry, Yann Mambrini, Keith A. Olive, Sarunas Verner, **2112.15214**

From amplitudes compute the rate of DM production for each process

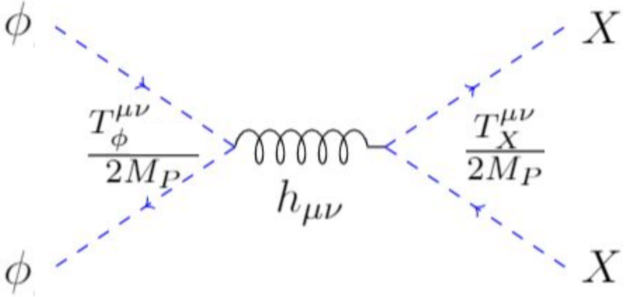
$$R_j^T = \beta_j \frac{\boxed{T^8}}{M_P^4}$$ for spin j = 0, ½ DM final state

See *Spin-2 Portal Dark Matter*, Nicolás Bernal, Maíra Dutra, Yann Mambrini, Keith Olive, Marco Peloso, Phys.Rev.D (2018).



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

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

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, Simon Cléry, Yann Mambrini, Keith A. Olive, **2112.15214**

DM production in minimal framework

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

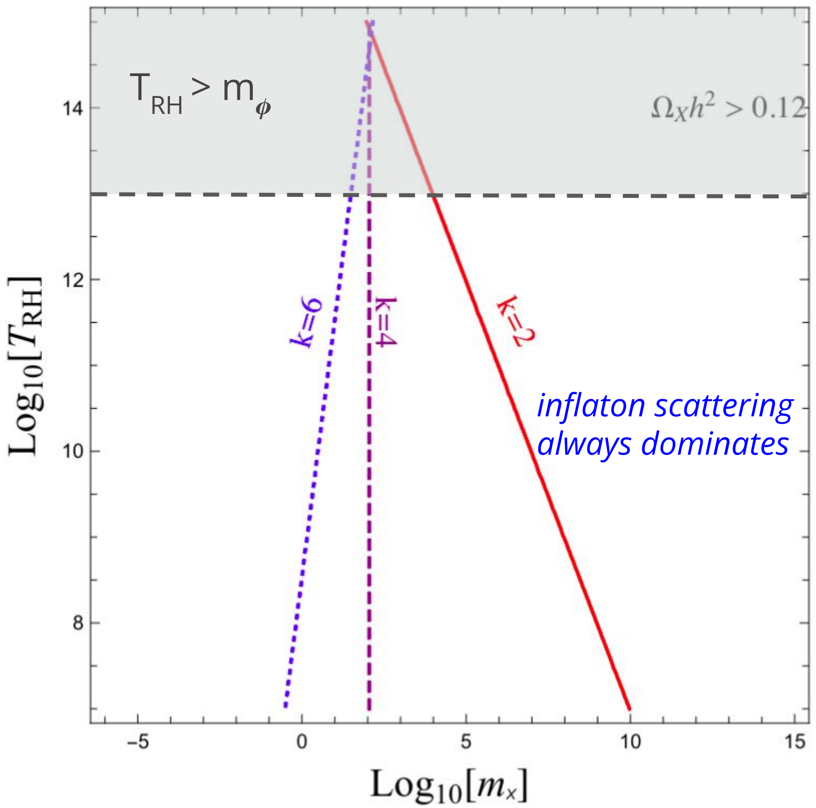


*Figure 2 : DM relic, $\Omega h^2 = 0.12$ in the case of a **spin 0 DM***

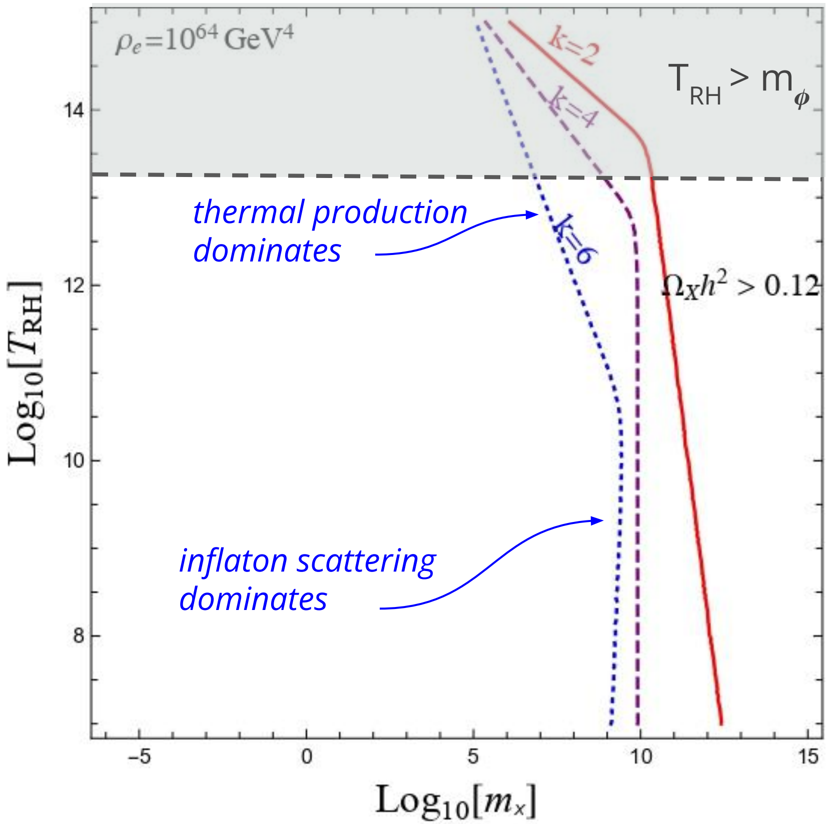
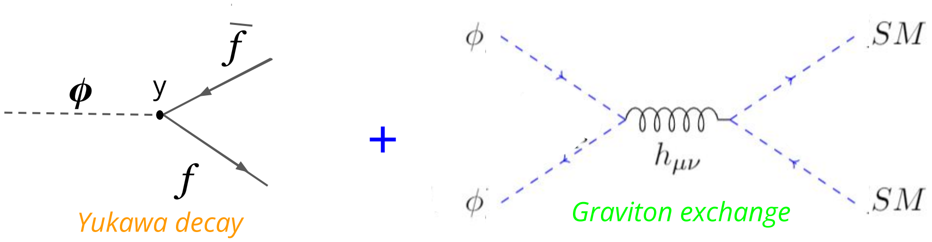


*Figure 3 : DM relic, $\Omega h^2 = 0.12$ in the case of a **spin ½ DM***

Radiation production in minimal framework

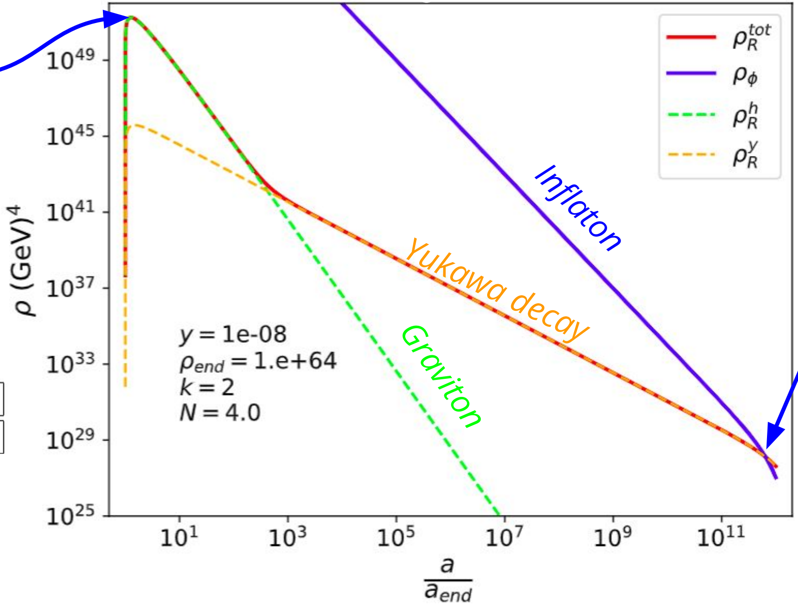


➜ This maximum temperature $T_{max} \sim 10^{12}$ GeV reached by the bath is unavoidable !

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

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

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



Reheating is still given by the decay width of the inflaton

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

Leading order interactions

in Einstein frame

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

$$\downarrow$$

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

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

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

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

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

with

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

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

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

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

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, Simon Cléry, 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

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

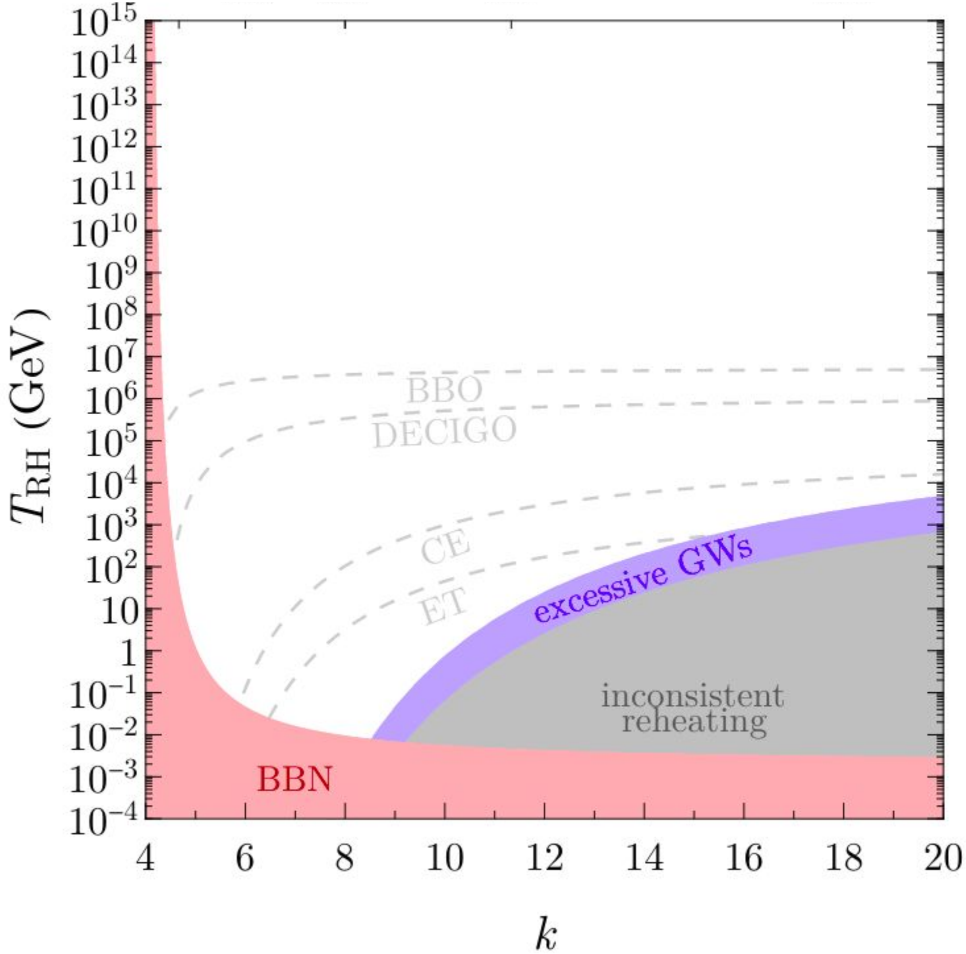
➜ Since our perturbative computations involve effective couplings in the Einstein frame that depend on all ξ, the small value of ξ_φ can be compensated by ξ_h . Current constraints on ξ_h from collider experiments is $\xi_h < 10^{15}$

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)



The blue region is excluded by BBN for the excessive GW energy as dark radiation.
The regions below the gray dashed curves can be probed by the GW experiments as specified

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**