Gravity as a Portal to Reheating, Dark Matter and Leptogenesis

Simon Cléry
simon.clery@ijclab.in2p3.fr

CosPT - 1st February 2024

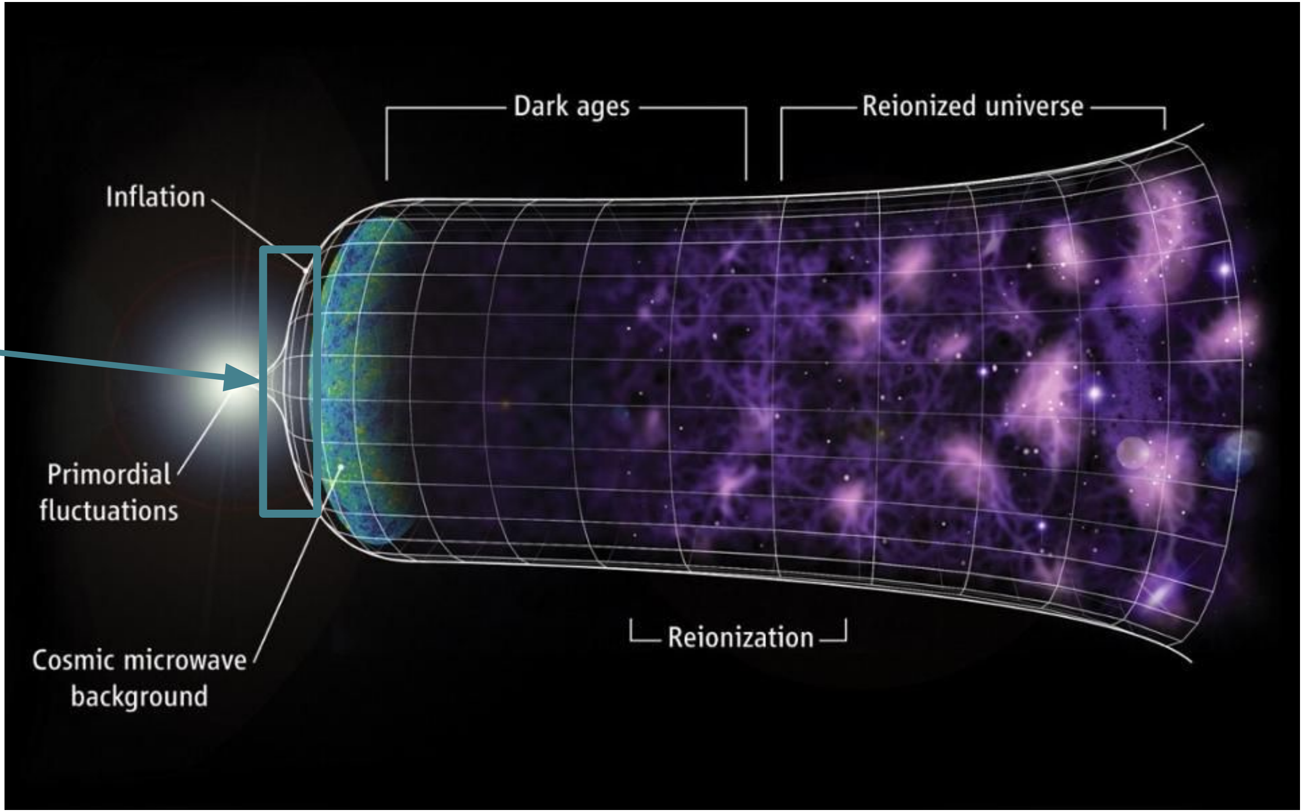
Based on :

- *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**

Outline

I - Inflation and Reheating

We will be interested in early Universe
production of particles after inflation



Inflation described as an exponential expansion of the Universe driven by an homogeneous scalar field ϕ in the potential :

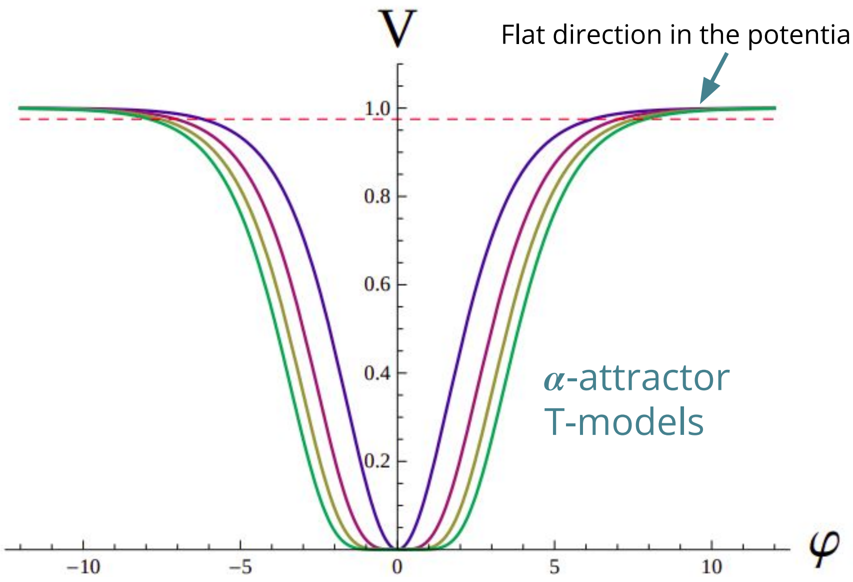


Figure 1: Potentials for the T-Model inflation $\tanh^{2n}(\varphi/\sqrt{6})$ for $n = 1, 2, 3, 4$

From *Universality Class in Conformal Inflation*, Kallosh and Linde, JCAP (2013)

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

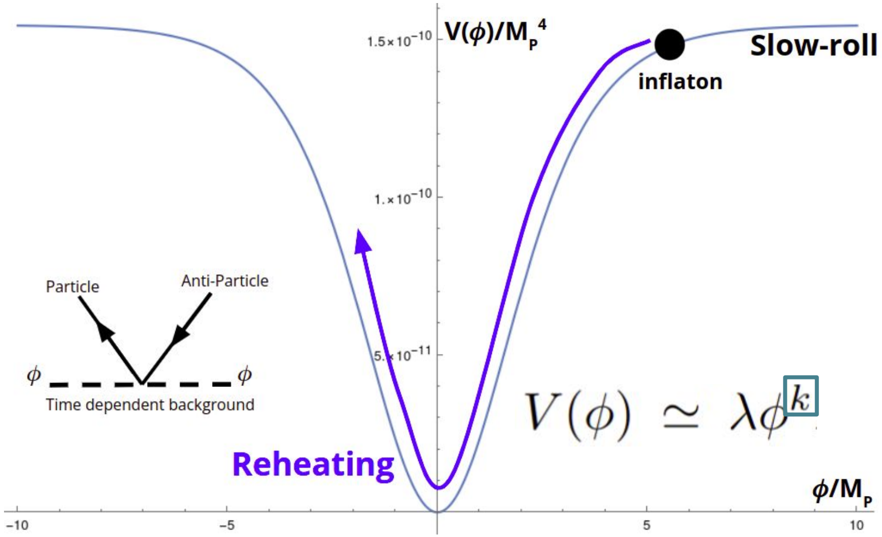
$$A_{S*} \simeq \frac{V_*}{24\pi^2\epsilon_* M_P^4} \simeq \frac{6^{\frac{k}{2}}}{8k^2\pi^2}\lambda\sinh^2\left(\sqrt{\frac{2}{3}}\frac{\phi_*}{M_P}\right)\tanh^k\left(\frac{\phi_*}{\sqrt{6}M_P}\right)$$

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

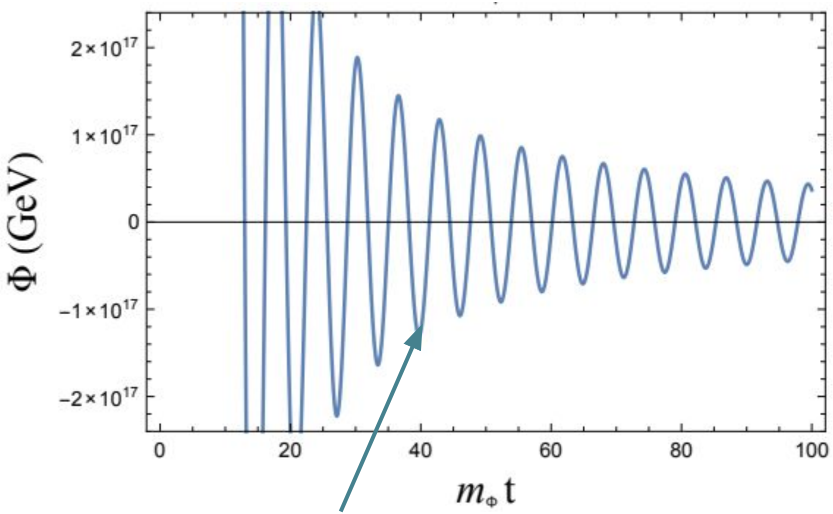
➞ Planck measurements give for k=2 : *λ ~ 10⁻¹¹* for N ~ 50 efolds

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

Reheating and Post-inflationary Production of Dark Matter, Marcos A.G. Garcia, Kunio Kaneta, Yann Mambrini, Keith A. Olive, Phys.Rev.D (2020)



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

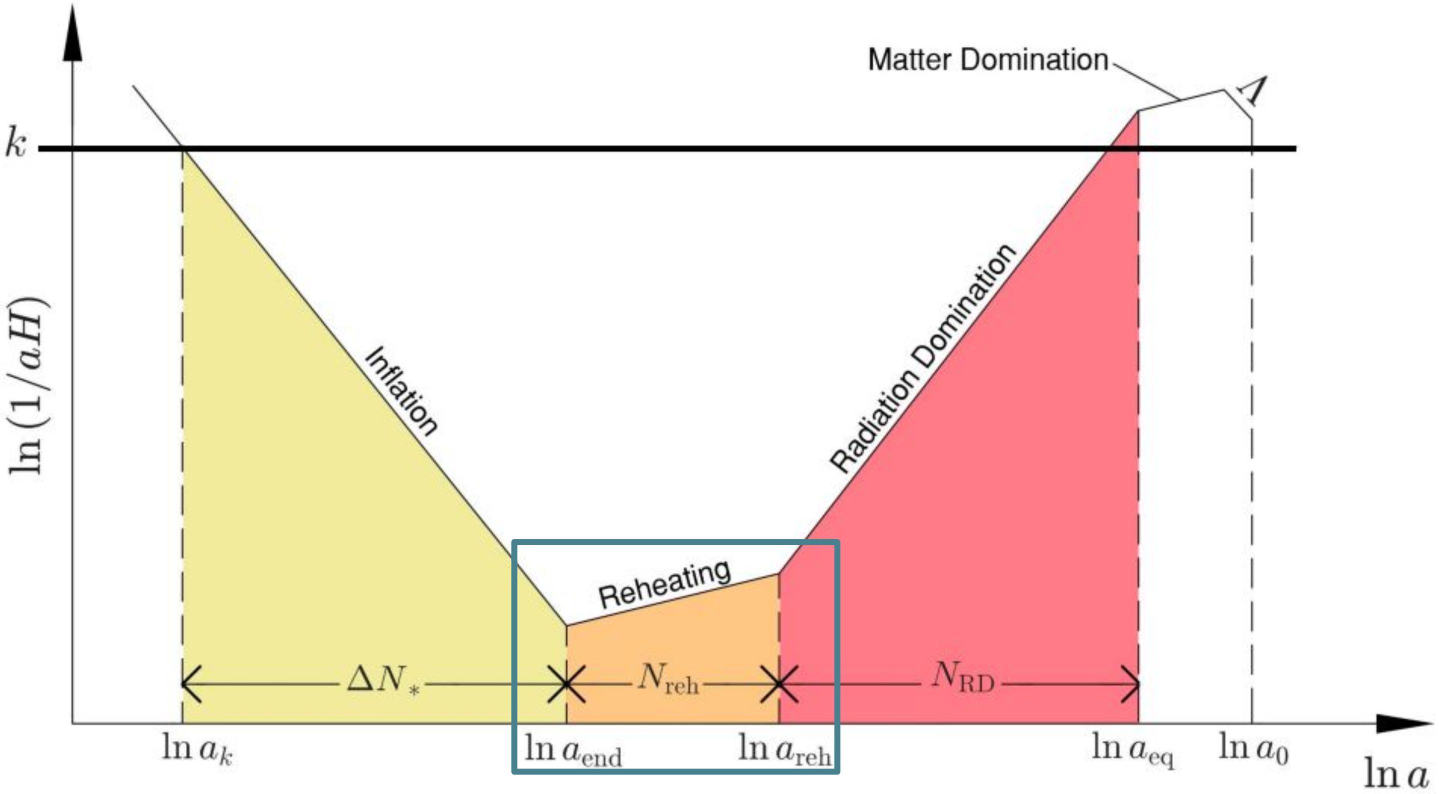


Redshifted envelop and frequency of the oscillations depend on the shape of the potential near the minimum

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

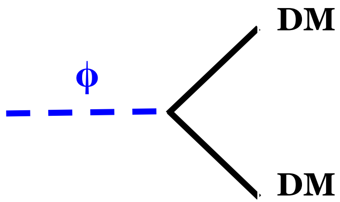
$$w = \frac{P_\phi}{\rho_\phi} = \frac{\frac{1}{2}\langle\dot{\phi}^2\rangle - \langle V(\phi)\rangle}{\frac{1}{2}\langle\dot{\phi}^2\rangle + \langle V(\phi)\rangle} = \boxed{\frac{k-2}{k+2}}$$



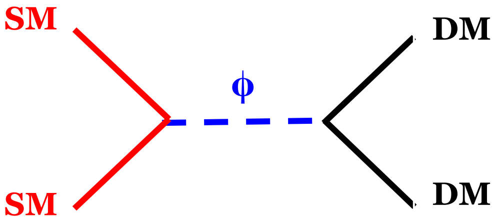
From *(P)reheating Effects of the Kähler Moduli Inflation I Model*, Islam Khan, Aaron C. Vincent and Guy Worthey, **2111.11050**

Perturbative processes

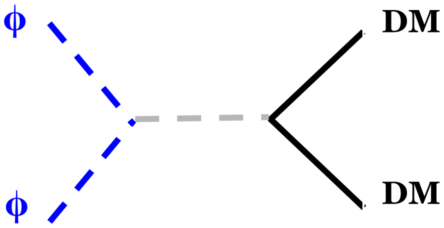
Inflaton sector can also handle non-thermal Dark Matter (DM) production through perturbative processes



➜ 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**



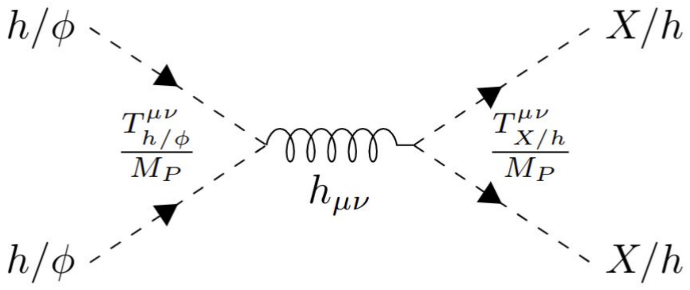
➜ From inflaton scattering mediated by a (massive) particle, see for example, *Gravitational Production of Dark Matter during Reheating*, Mambrini, Olive, **2102.06214**

II - Gravitational production : the framework

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

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

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



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

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

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

➜ 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**

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

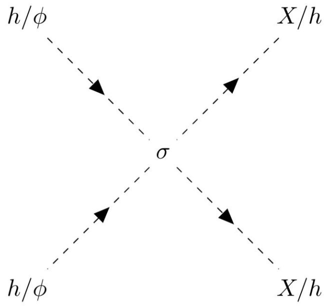
$$\Omega^2 \equiv 1 + \underbrace{\frac{\xi_\phi \phi^2}{M_P^2}}_{\text{inflaton}} + \underbrace{\frac{\xi_h h^2}{M_P^2}}_{\text{SM}} + \underbrace{\frac{\xi_X X^2}{M_P^2}}_{\text{DM}}$$

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

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

in the Einstein frame

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



Reheating and Dark Matter Freeze-in in the Higgs-R² Inflation Model, Aoki, Lee, Menkara, Yamashita, **2202.13063**

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

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**

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

➜ At the end of inflation we have $\phi_{\rm end} \sim M_P$ and the inflaton field is decreasing during the reheating

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

➜ 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, Front.Astron.Space Sci. 5 (2018)

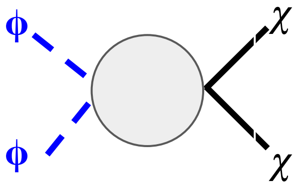
➜ To prevent the EW vacuum instability at inflation scale, we can stabilize through effective Higgs mass from the non-minimal coupling : $\xi_h > 10^{-1}$

➜ In the case of Higgs inflation, large ξh is fixed or can consider conformal coupling for inflation at the pole

See F. L. Bezrukov and M. Shaposhnikov, Phys. Lett. B (2008), and SC, HM. Lee, A. G. Menkara, ...

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**

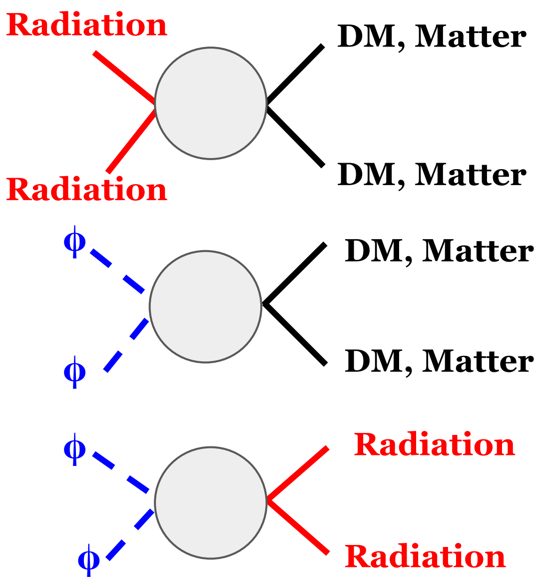
III - DM and Radiation production

Consider the fluid picture and local interactions, gravitational portals can connect different sectors :

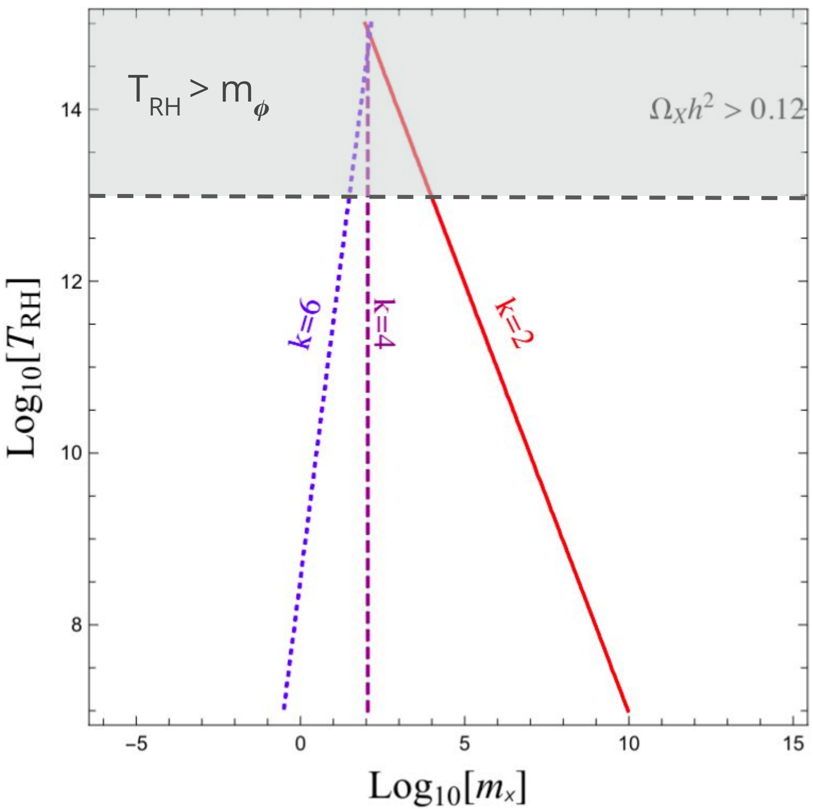
➜ Thermal bath and DM through the FIMP scenario

➜ Inflaton and DM to directly produce DM from the condensate

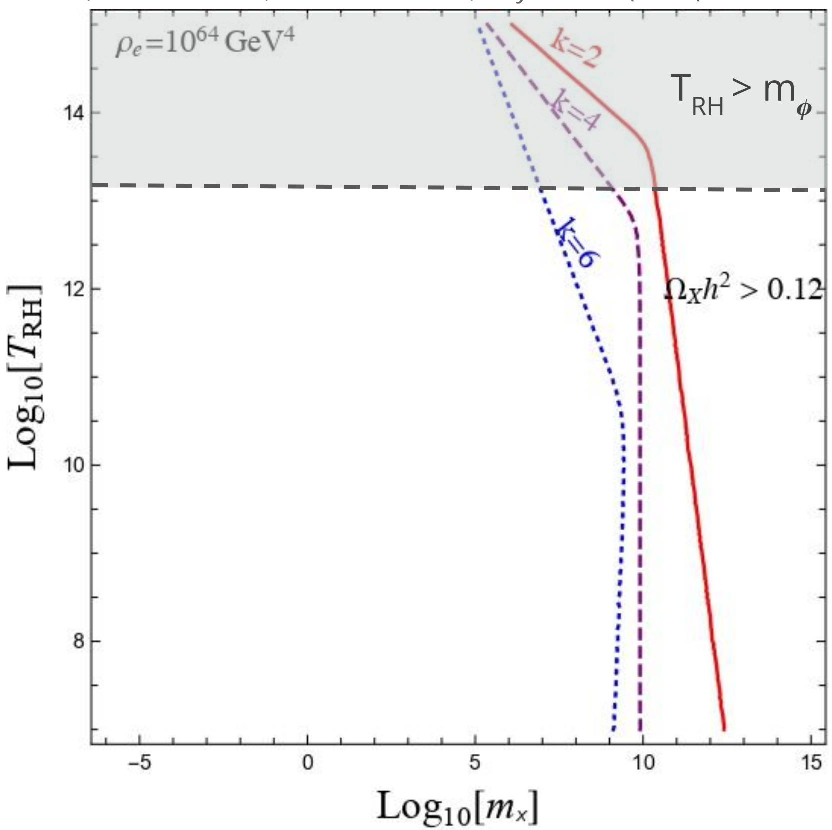
➜ Inflaton and the thermal bath to initiate the reheating process



Gravitational portals in the early Universe, Simon Cléry, Yann Mambrini, Keith A. Olive, Sarunas Verner, Phys.Rev.D (2022).



Ωh^2 = 0.12 in the case of a spin 0 DM all contributions added



Ωh^2 = 0.12 in the case of a spin ½ DM, all contributions added

Including non-minimal coupling

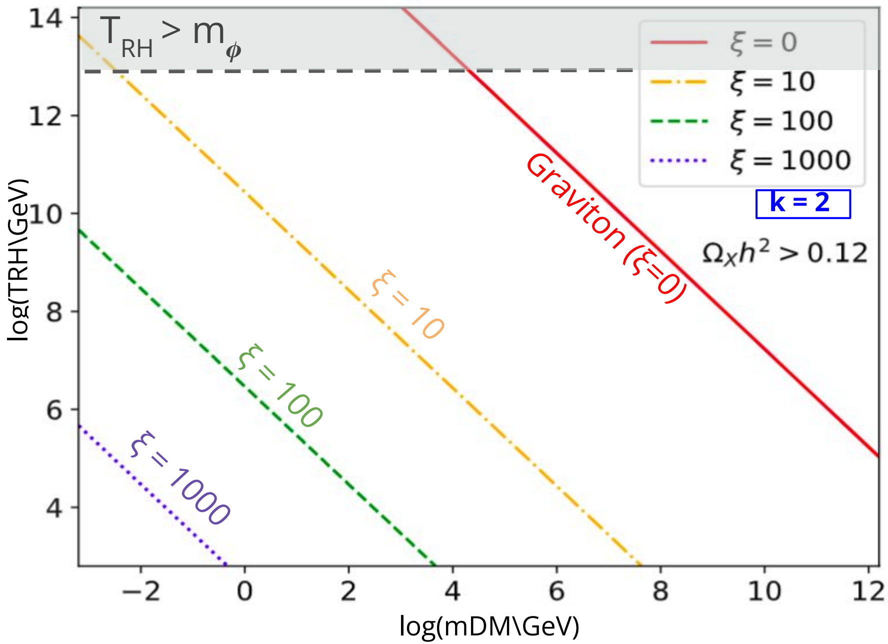


Figure 2 : Contours respecting $\Omega_X h^2 = 0.12$ for spin 0 DM, for different values of $\xi_h = \xi_X = \xi$.
Both minimal and non-minimal contributions are added.

➜ 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**

Radiation production

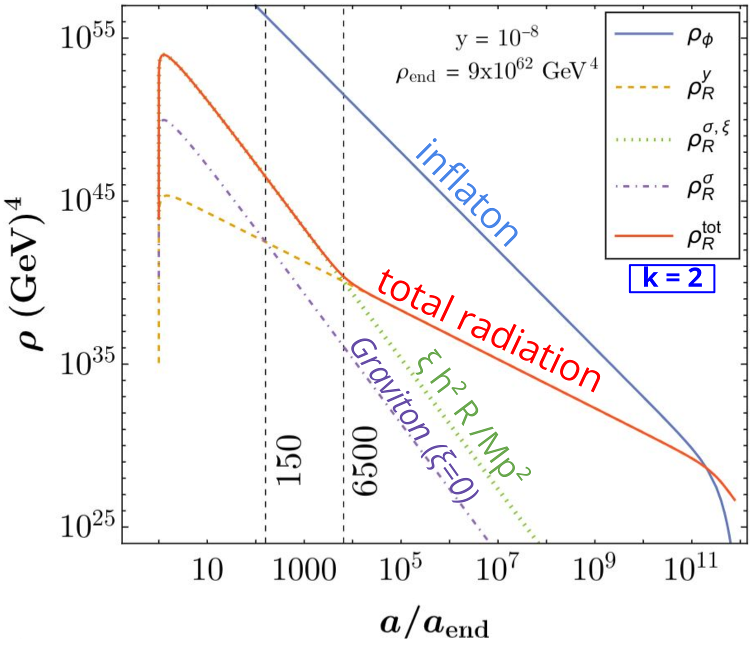
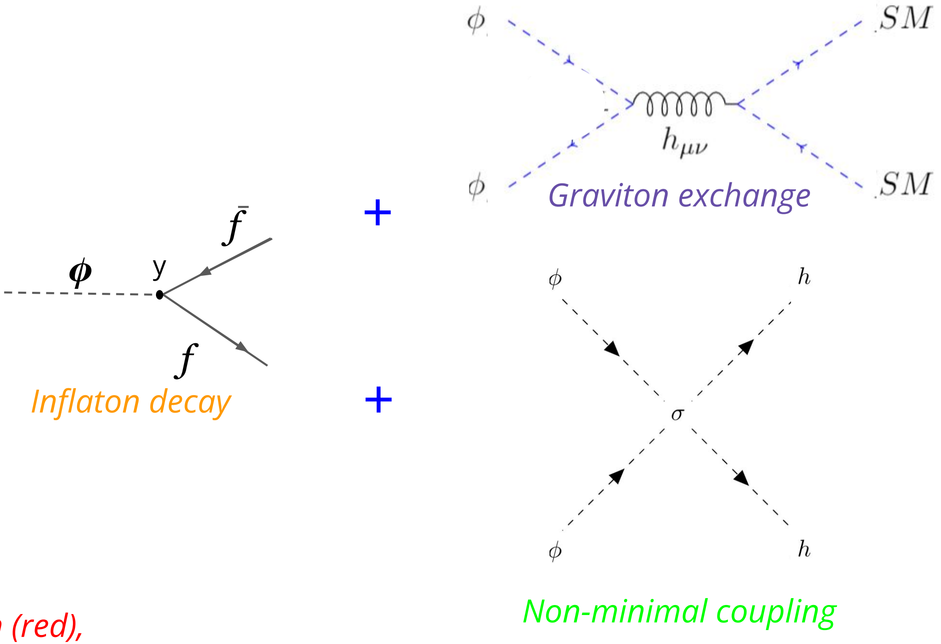


Figure 1 : Energy densities of inflaton (blue), total radiation (red), radiation from inflaton decay (orange), from scattering mediated by graviton (purple) and from non-minimal coupling (green), with $\xi_h = \xi = 2$



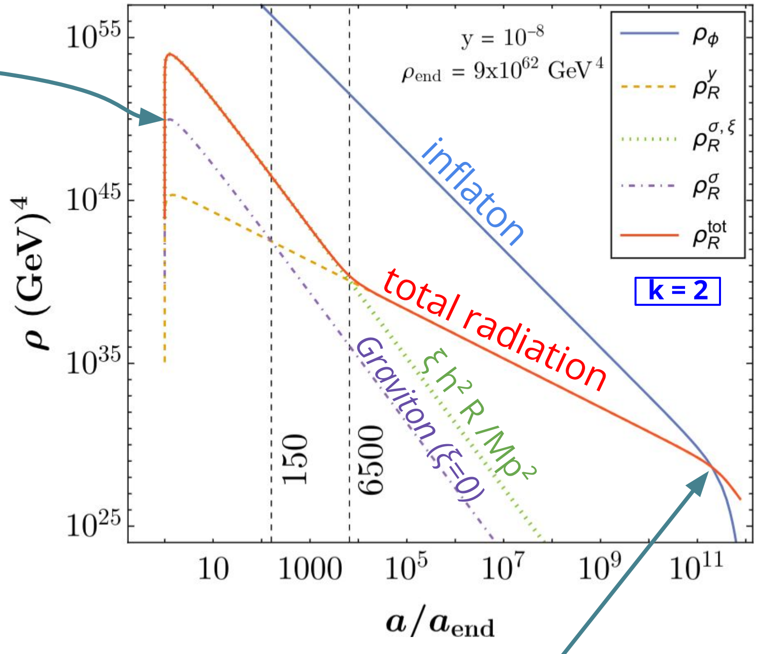
Gravitational Portals with Non-Minimal Couplings, SC, Mambrini, Olive, Shkerin, Verner, **2203.02004**

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

➜ This is a minimal T_{max} that the thermal bath had experienced, maximum temperature cannot go below this value.

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

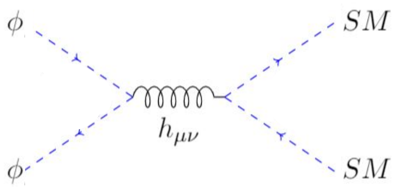
Gravitational portals in the early Universe, SC, Yann Mambrini, Keith A. Olive, Sarunas Verner, Phys.Rev.D (2022).



The late time reheating is still given by the decay

➜ No gravitational reheating when k=2 (quadratic)

IV - Gravitational reheating and GWs constraints

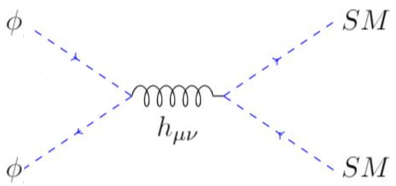


➜ Graviton exchange processes can be sufficient to reheat entirely, for sufficiently steep inflaton potential : k > 9

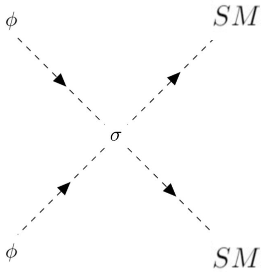
Gravitational Reheating, Haque, Maity, **2201.02348**

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

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



+



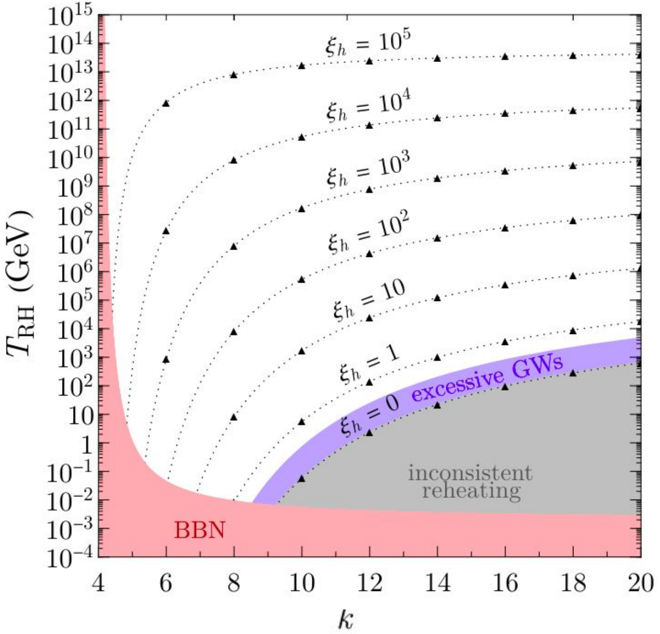


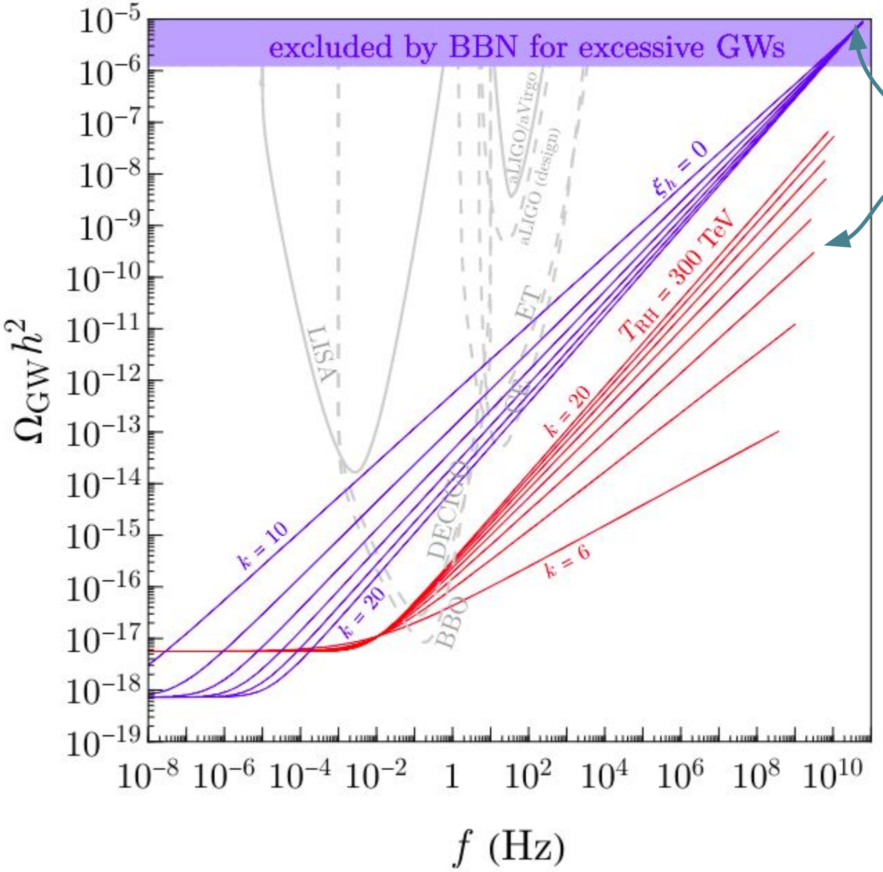
Figure 3 : Reheating temperature from gravitational portals as function of k, for different ξ_h

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

➜ 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.

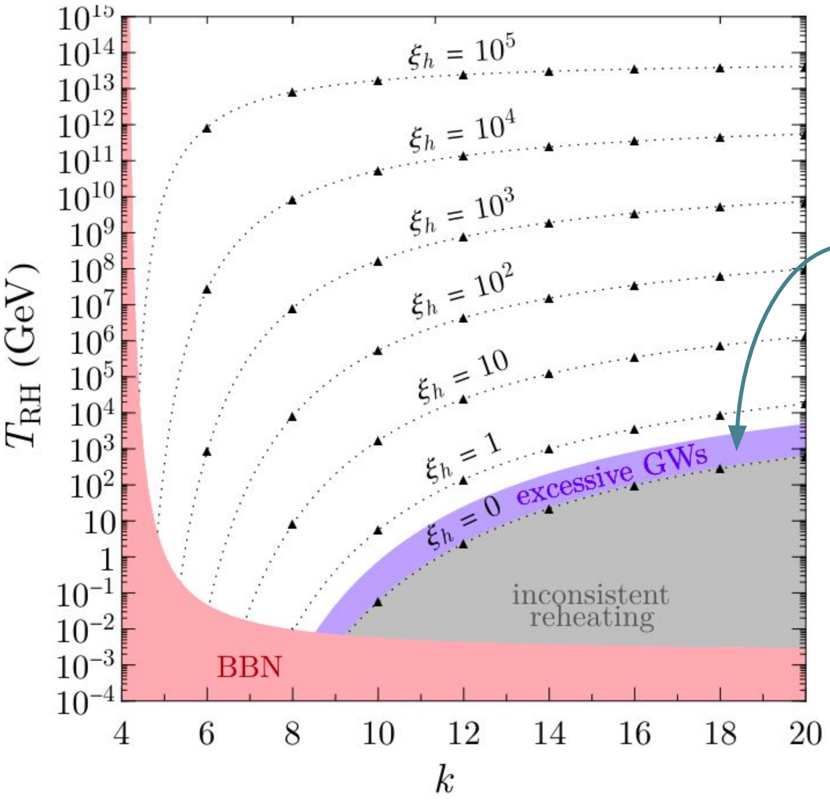


Figure 3 : Reheating temperature from gravitational portals as function of k, for different ξ_h

➜ 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 $\xi_h > 0$

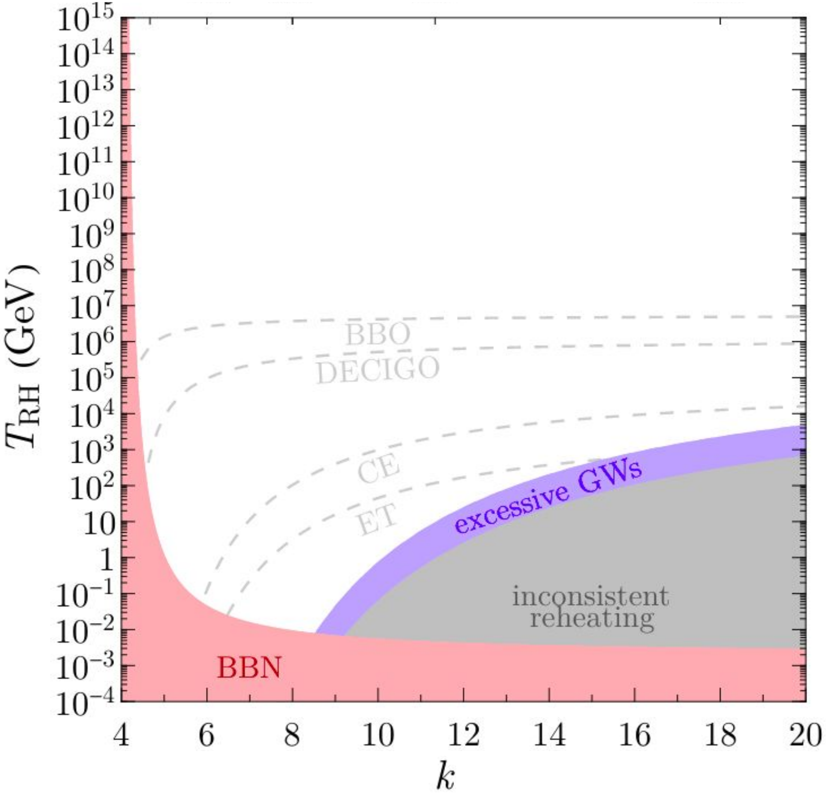


Figure 3 : Reheating temperature from gravitational portals as function of k, for different ξ_h

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

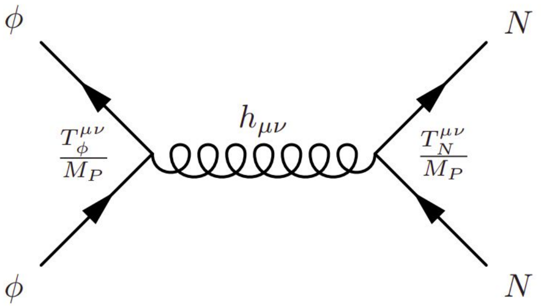
➜ The case of minimal gravitational reheating is excluded by the BBN bound of $\Omega^0_{GW}h^2 \sim 10^{-6}$, from excessive GWs as dark radiation.

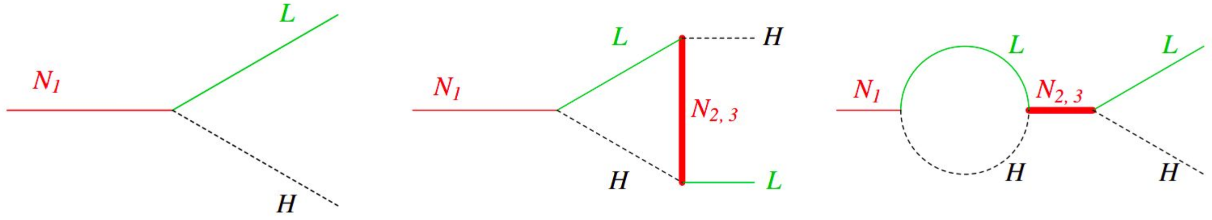
➜ The constraint is relaxed when radiation production is increased by non-minimal gravitational interactions $\xi_h > 0$

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

Done more generically in Barman, Ghoshal, Grzadkowski, Socha, **2305.00027**

V - 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.

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

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

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.**

Gathering all these results in one “purely” gravitational framework :

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

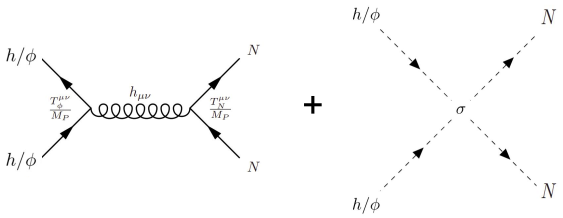
$$\Omega^2 \equiv 1 + \frac{\xi_\phi\,\phi^2}{M_P^2} + \frac{\xi_h\,h^2}{M_P^2}$$

Non-minimal couplings to gravity

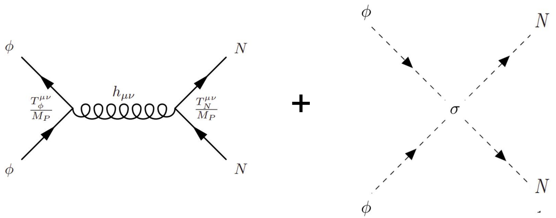
$$\widetilde{\mathcal{L}}_{N_i} = -\frac{1}{2}\,M_{N_i}\,\overline{N_i^c}N_i - (y_N)_{ij}\,\overline{N}_i\,\widetilde{H}^\dagger\,L_j + \text{h.c.}\,.$$

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

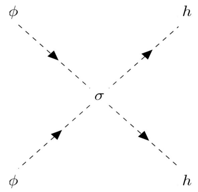
N_2, N_3 are much heavier and generate the lepton asymmetry through their gravitational production and out-of equilibrium decay



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

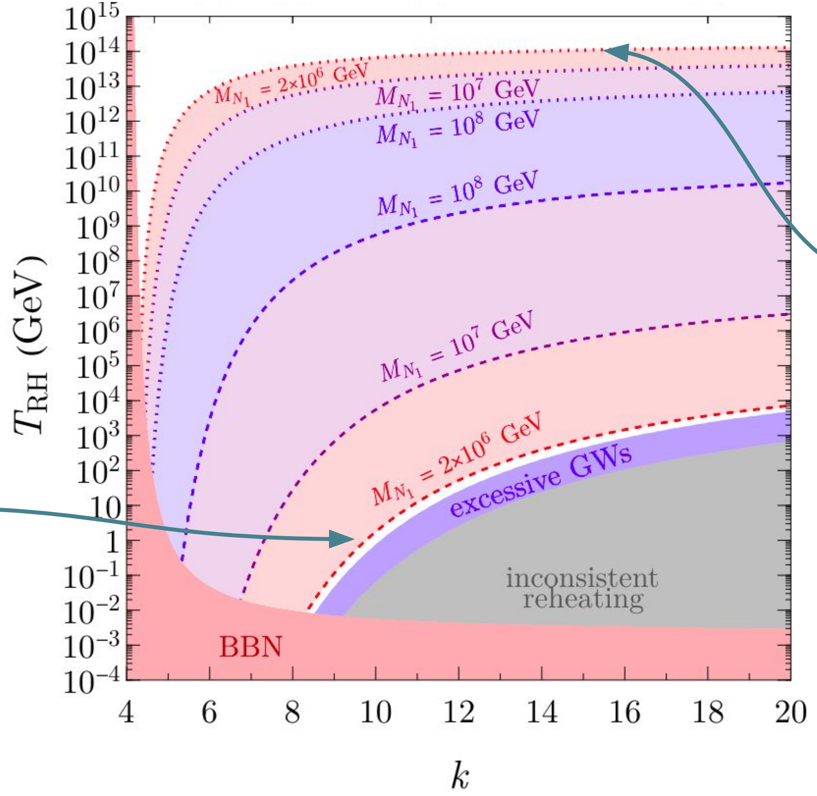


$\phi\phi \to N_2N_2$ (N_3 N_3) from gravitational portals



$\phi\phi \to$ 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 :

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

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

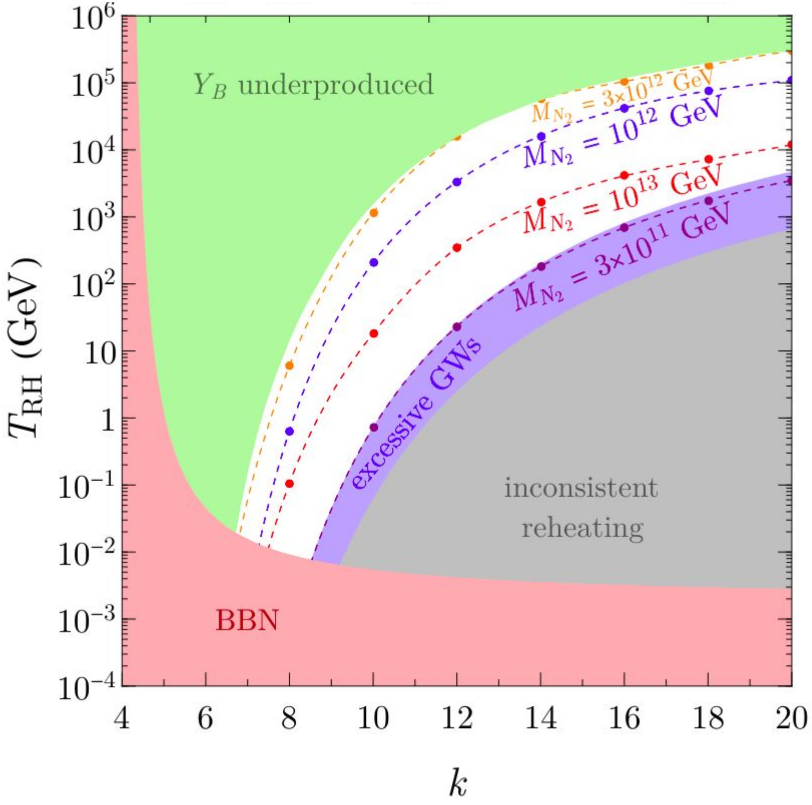
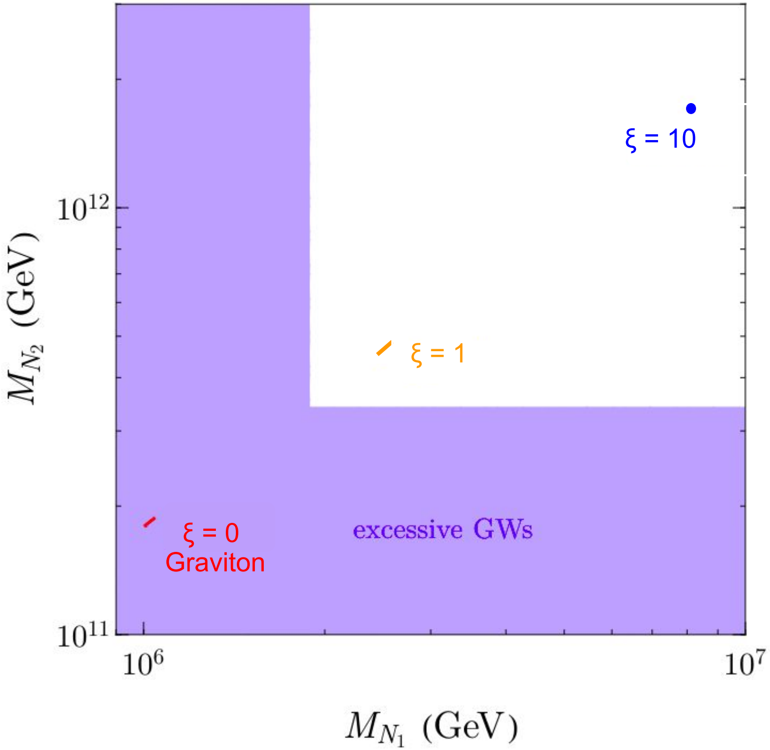


Figure 6 : Lines corresponding to the observed baryon asymmetry $Y_B \simeq 8.7 \times 10^{-11}$ *for different* M_{N2}

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 ∊ [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 !

Questions ?

Backup slides

Supergravity embedding

Consider a modulus chiral multiplet T and a matter field ϕ, which are conformally coupled to gravity in the Jordan frame

Kähler potential

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

Wess-Zumino like superpotential

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

Need tuned small coefficients of the superpotential for successful inflation

➡ See *Universality Class in Conformal Inflation*, Kallosh and Linde, **1306.5220**, also derived in the context of no-scale supergravity in *Building Models of Inflation in No-Scale Supergravity*, Ellis et al, **2009.01709**, and Garcia et al, **2004.08404**

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

After stabilizing the modulus by non perturbative effects $T + \bar{T} = 1$

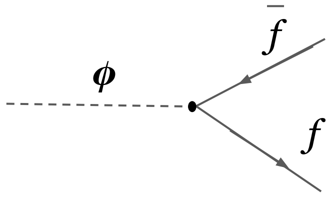
Particle production

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

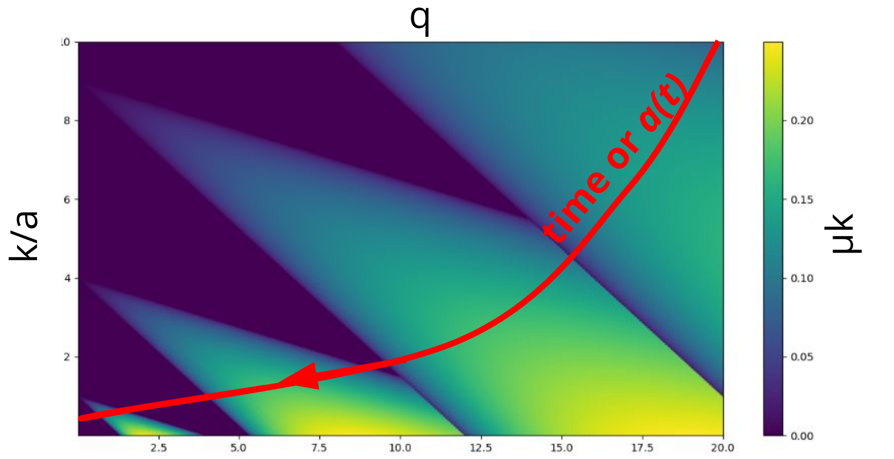
See Freeze-in from preheating, Garcia , Kaneta, Mambrini, Olive, Verner, **2109.13280**

Classical non-perturbative approach : preheating

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

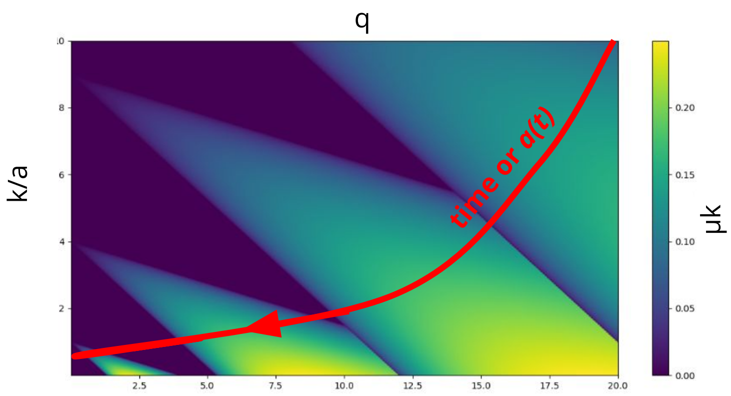
$$\chi_k'' + \left(\frac{k^2}{m_\phi^2 a^2} + 2q - 2q\cos(2z)\right)\chi_k = 0$$

EOM for Fourier modes in the oscillating background



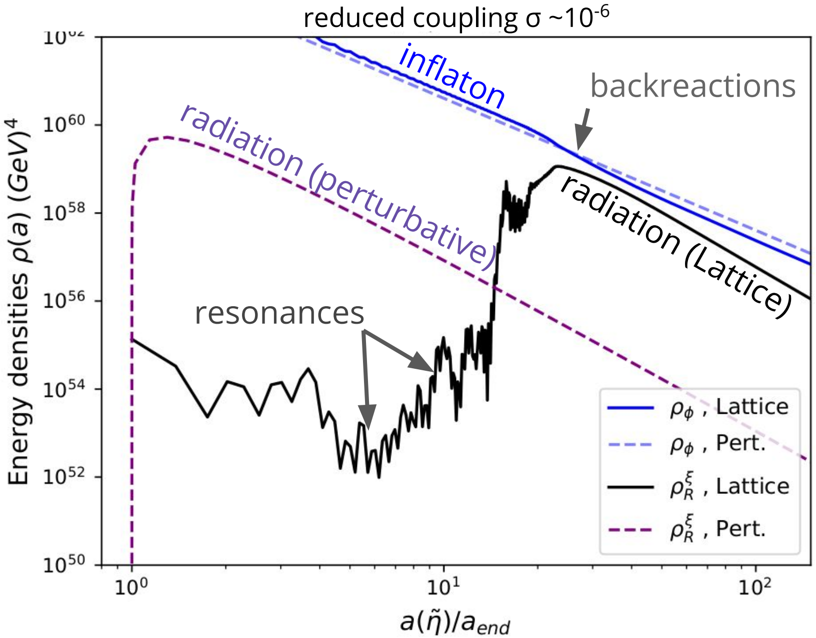
Instabilities in the colored regions
=> increasing occupation number of the modes

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)



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, JCAP (2022)

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 field experiencing coherent oscillations

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

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

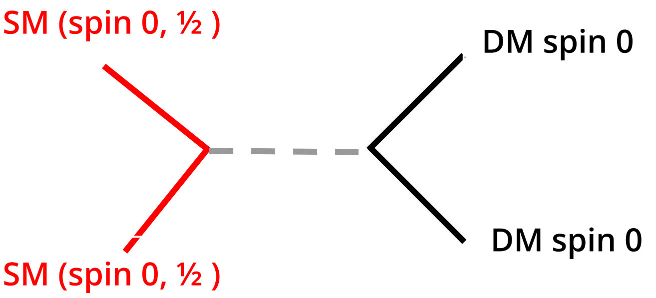
Usual amplitude computation for a s-channel scattering of (massless) SM particles giving DM particles

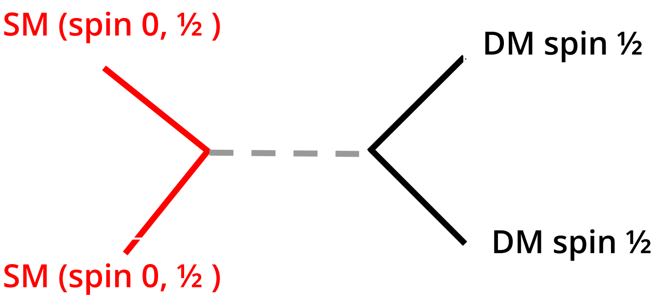
$$|\overline{\mathcal{M}}^{00}|^2 = \frac{1}{64M_P^4}\frac{t^2(s+t)^2}{s^2},$$

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

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

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



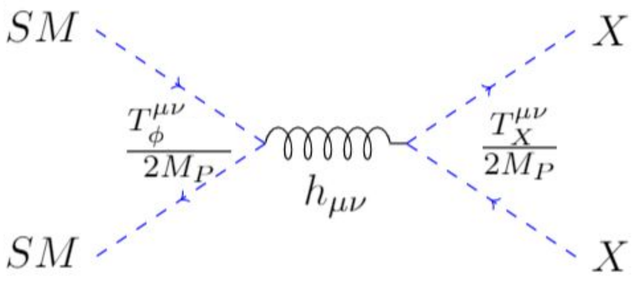


Gravitational portals in the early Universe, Simon Cléry, Yann Mambrini, Keith A. Olive, Sarunas Verner, **2112.15214**

From amplitudes compute the rate of DM production for each process

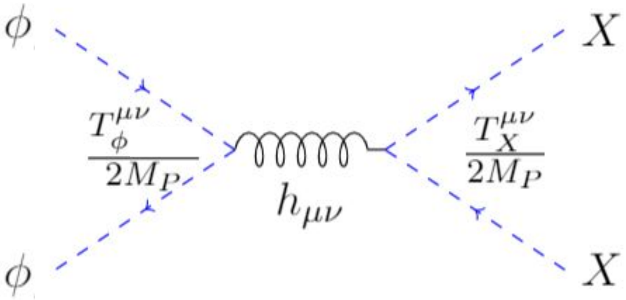
$$R_j^T = \beta_j \frac{T^8}{M_P^4}$$ for spin j = 0, ½ DM final state

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



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

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

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

Spin ½ inflaton scattering case

spin ½ helicity suppression !

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

For scalar DM

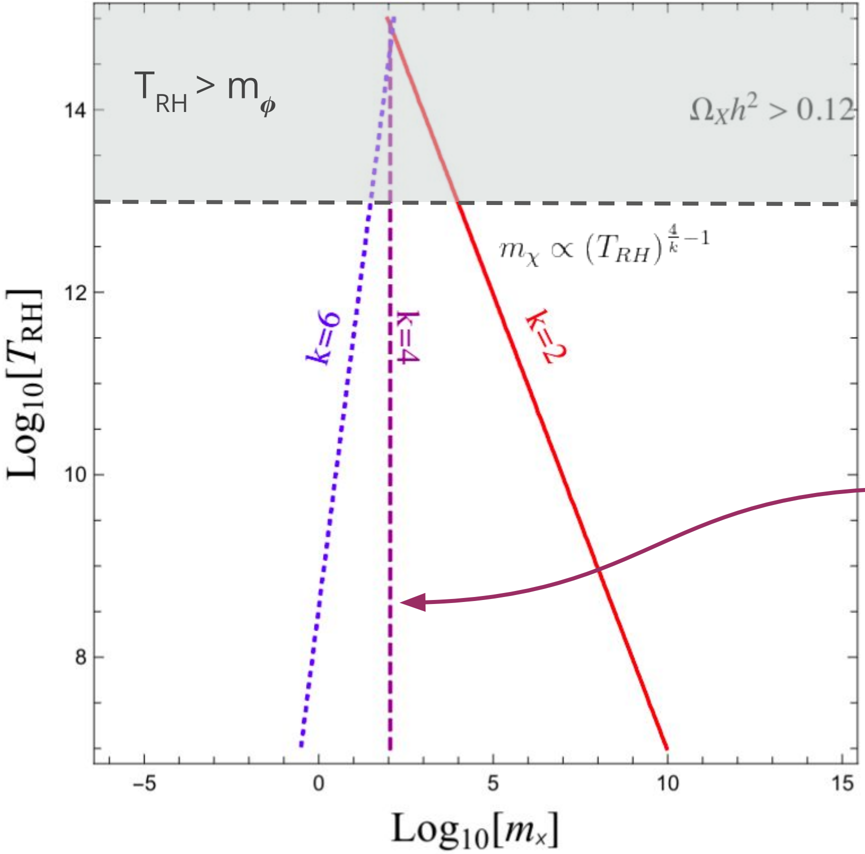


Figure 2 : $\Omega h^2 = 0.12$ in the case of a spin 0 DM, all contributions added

$$\frac{R_0^{\phi^k}(a_{\max})}{R_0^T(a_{\max})} = g_{\max}^2 \frac{5760\Sigma_0^k}{3997} \left(\frac{3k-3}{2k+4}\right)^{\frac{6}{7-k}} \left(\frac{\rho_{\mathrm{end}}}{\rho_{\mathrm{RH}}}\right)^{\frac{2}{k}} \gg 1$$

Inflaton scattering always dominates over thermal bath production

For **k = 4**, relic abundance is independent of the reheating process and depends only on the inflaton energy density

A unique limit on spin 0 DM mass
$m_\chi < 100$ GeV for k = 4

Gravitational portals in the early Universe, SC, Yann Mambrini, Keith A. Olive, Sarunas Verner, Phys.Rev.D (2022).

For fermionic DM

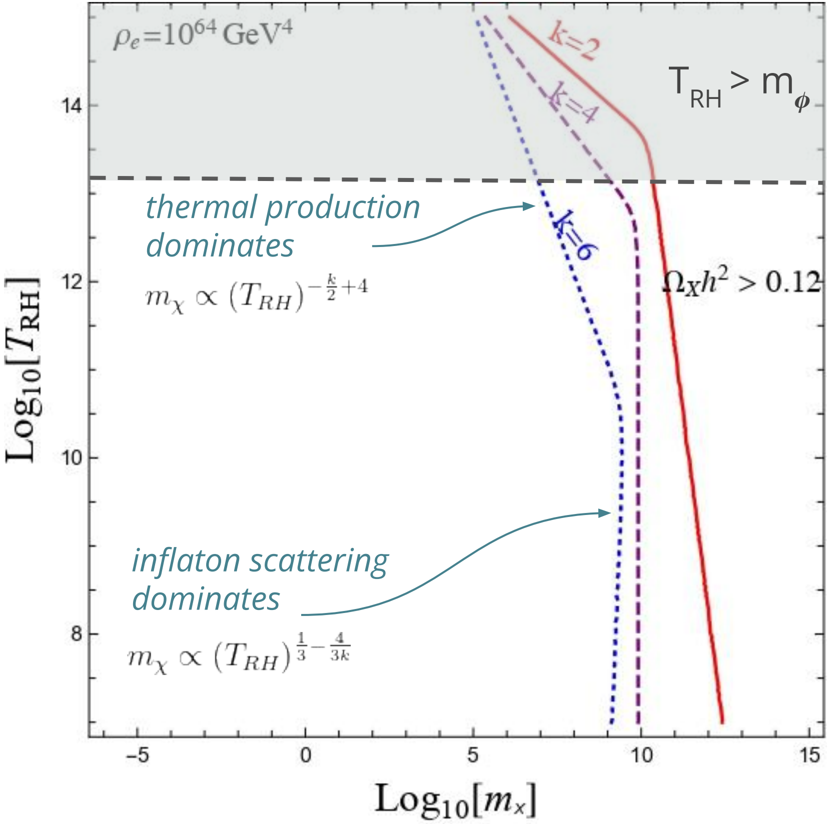
Inflaton scattering is helicity suppressed
➜ broken spectrum due to strong DM mass dependence

$$\frac{R^{\phi^k}_{1/2}(a_{\max})}{R^T_{1/2}(a_{\max})} = (106.75)^2 \frac{11520\Sigma^k_{1/2}}{11351} \frac{m_X^2}{m_\phi^2} \left(\frac{3k-3}{2k+4}\right)^{\frac{6}{7-k}} \left(\frac{\rho_{end}}{\rho_{\rm RH}}\right)^{\frac{2}{k}}$$

There is a mass value below which the DM production is dominated by thermal production

$$m_X^k \sim 3.5 \times 10^{-4} (\rho_{\rm RH}/\rho_{end})^{2/k} m_\phi$$

Gravitational portals in the early Universe, Simon Cléry, Yann Mambrini, Keith A. Olive, Sarunas Verner, Phys.Rev.D (2022).



Ωh^2 = 0.12 in the case of a spin ½ DM, all contributions added

Leading order interactions

in Einstein frame

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

↓

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

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

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

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

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

with

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

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

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

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

→ Leading order interactions of RHN

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

Bogoliubov approach

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

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

Consider simply a single field in the vacuum

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

Then, it is clear that the Hamiltonian is changing with time through the time dependence in ω.
=> no preferred choice of basis of positive/negative frequency for χ in the Fourier space at all time

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

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

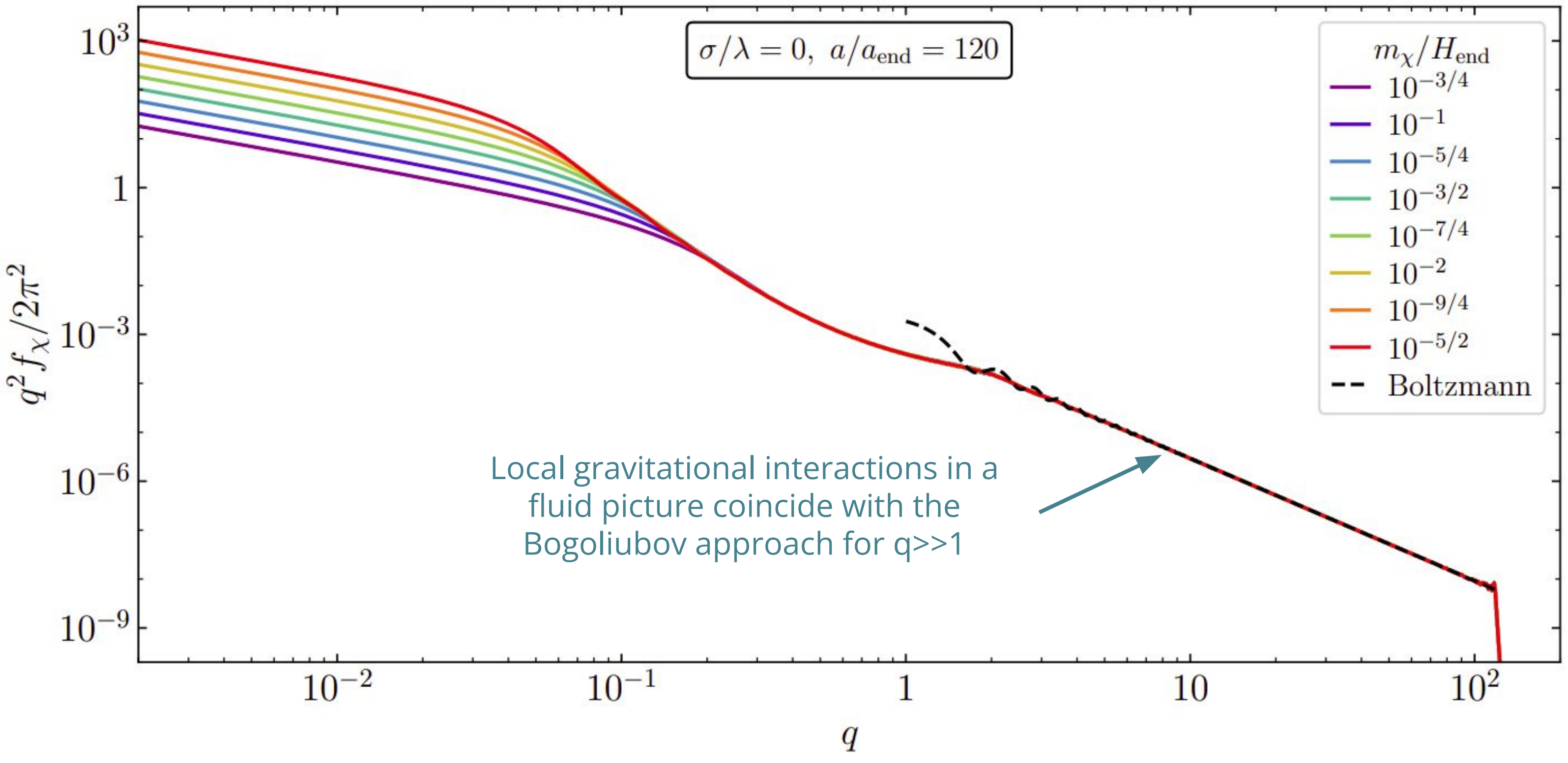
→

Bogoliubov transformation 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 varies and is given by $|\beta_k|^2$

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

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

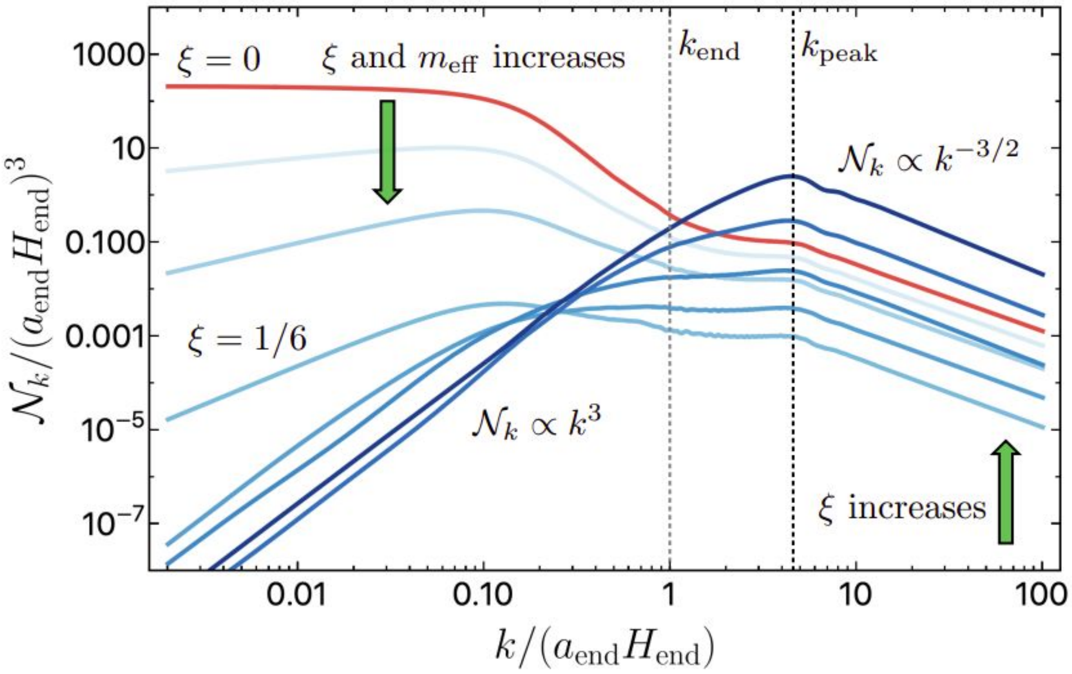
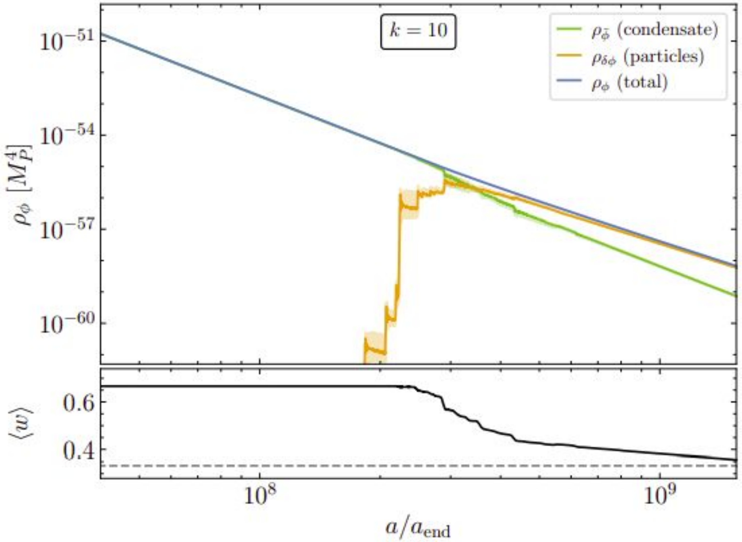
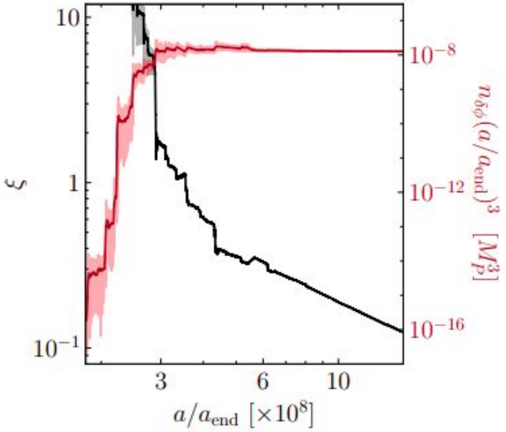


Diagram illustrating the dependence of the comoving number density spectrum Nk on non-minimal coupling ξ as a function of rescaled horizon modes k/(aendHend).

From *A New Window into Gravitationally Produced Scalar Dark Matter,* Garcia, Pierre, Verner, **2305.14446**

Inflation self-fragmentation





k	$y_{\rm eff}$	$\mu_{\rm eff}$	$\sigma_{\rm eff}$	$T_{\rm RH}$
4	1.61×10^{-1}	3.57×10^{10} GeV	3.57×10^{-6}	1.14×10^{13} GeV
6	1.58×10^{-2}	1.84×10^{5} GeV	5.37×10^{-10}	1.19×10^{10} GeV
8	1.32×10^{-3}	6.33×10^{-1} GeV	9.59×10^{-15}	1.50×10^{7} GeV
10	3.62×10^{-5}	1.49×10^{-6} GeV	6.47×10^{-20}	1.80×10^{4} GeV

From Garcia , Gross, Mambrini , Olive, Pierre, and Yoon, **2308.16231**

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**