Gravitational portals in the early Universe

Planck Conference 2nd June 2022

Based on :

- *Gravitational Production of Dark Matter during Reheating*, Yann Mambrini, Keith A. Olive, **Phys.Rev.D (2021).**
- *Gravitational portals in the early Universe*, Simon Cléry, Yann Mambrini, Keith A. Olive, Sarunas Verner, **Phys.Rev.D (2022)**
- *Gravitational Portals with Non-Minimal Couplings*, Simon Cléry, Yann Mambrini, Keith A. Olive, Andrey Shkerin, Sarunas Verner, **arXiv 2203.02004 [PRD].**

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Focus points

1 - Inflationary reheating

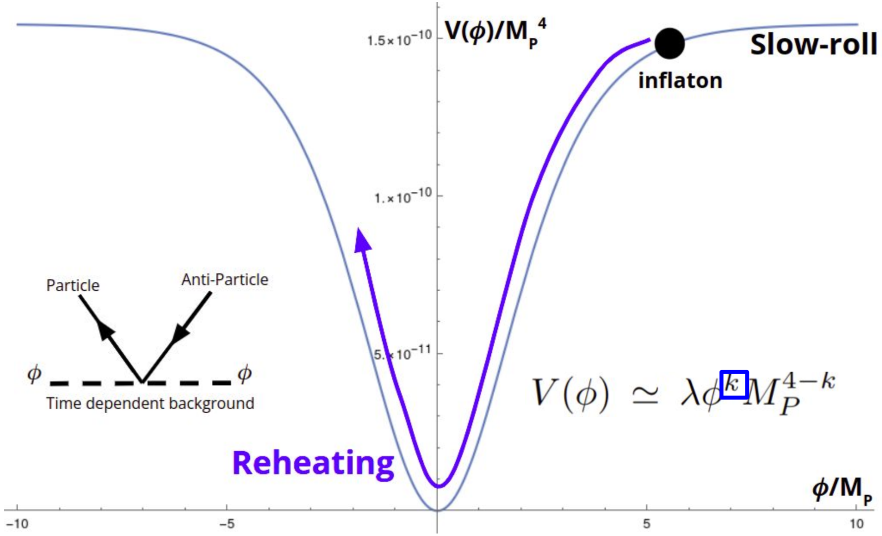
2 - Minimal gravitational portal

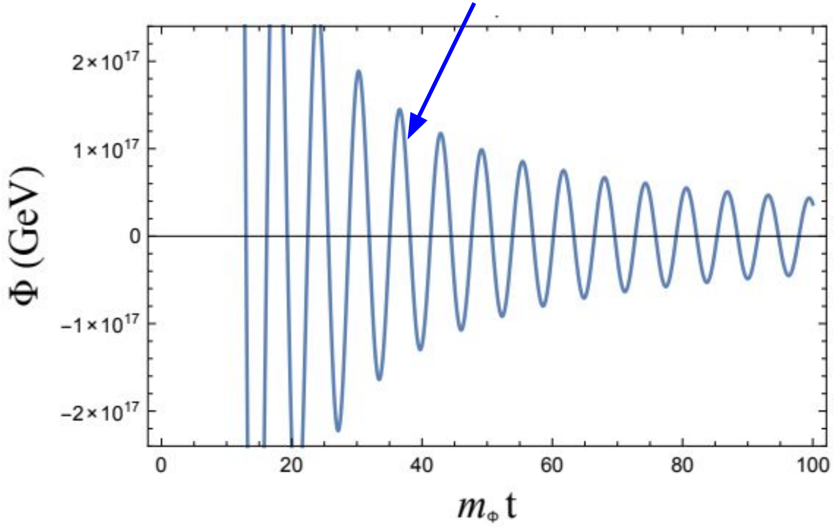
3 - Non-minimal coupling to gravity

4 - Gravitational reheating and leptogenesis

1- Inflationary reheating

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

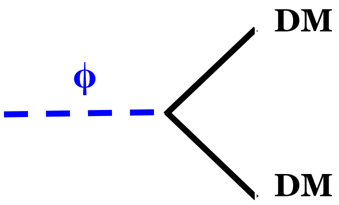




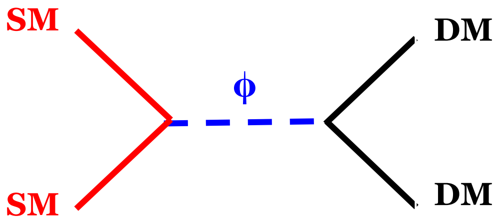
Inflation described as an exponential expansion of the Universe driven by an homogeneous scalar field ϕ

Reheating process and particles production occur at the end of the inflationary phase, during background field coherent oscillations

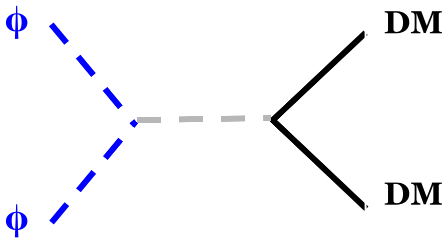
Inflaton sector is also a new gate to handle non-thermal Dark Matter (DM) production through perturbative processes



→ From inflaton background direct decay to DM, see for example *Reheating and Post-inflationary Production of Dark Matter*, Marcos A.G. Garcia, Kunio Kaneta, Yann Mambrini, Keith A. Olive, Phys.Rev.D (2020).



→ From inflaton portal, in which the inflaton mediates between SM and DM sectors, see *The Inflaton Portal to Dark Matter*, Lucien Heurtier, JHEP (2017).



→ From inflaton scattering mediated by a (massive) particle, see for example, *Gravitational Production of Dark Matter during Reheating*, Yann Mambrini, Keith A. Olive, Phys.Rev.D (2021).

2- Minimal gravitational portal

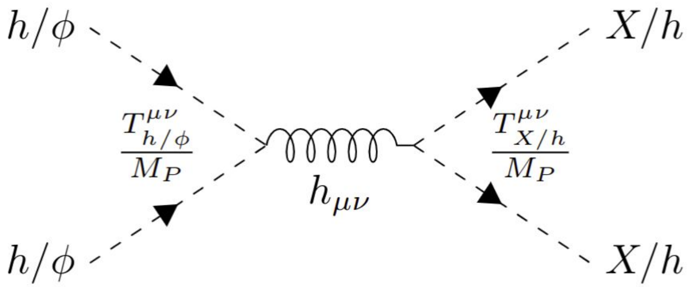
➜ Graviton portal arises from metric perturbation around its locally flat form

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

$$\downarrow$$

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

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



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

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

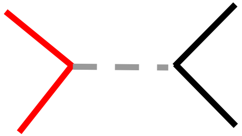
$$T_1^{\mu\nu} = \frac{1}{2}\left[F^\mu_\alpha F^{\nu\alpha} + F^\nu_\alpha F^{\mu\alpha} - \frac{1}{2} g^{\mu\nu} F^{\alpha\beta} F_{\alpha\beta}\right]$$

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

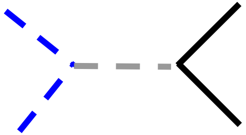
Gravitational Production of Dark Matter during Reheating, Yann Mambrini, Keith A. Olive, Phys.Rev.D (2021).

Graviton can play the portal between :

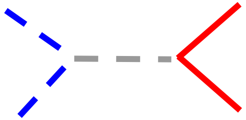
➜ Thermal bath and DM to populate DM through the FIMP scenario



➜ Inflaton and DM to directly produce DM from the condensate



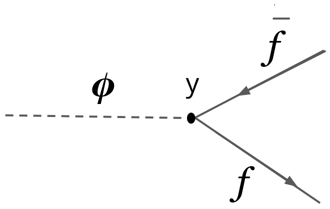
➜ Inflaton and the thermal bath to initiate the reheating process



Inflaton scattering cannot reheat the Universe ($\rho_\phi = \rho_{Radiation}$) in a quadratic potential ($\propto \phi^2$) as the rate of production is proportional to $\rho_\phi{}^2$, hence radiation produced is more “redshifted” than the inflaton

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

Graviton portal can drive the very early evolution of the thermal bath and its maximum temperature



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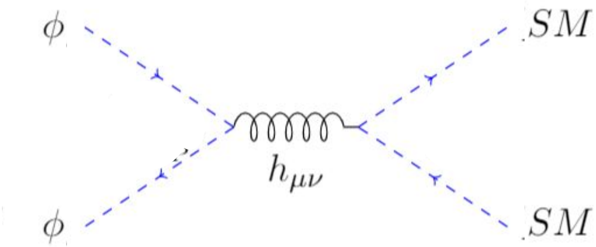
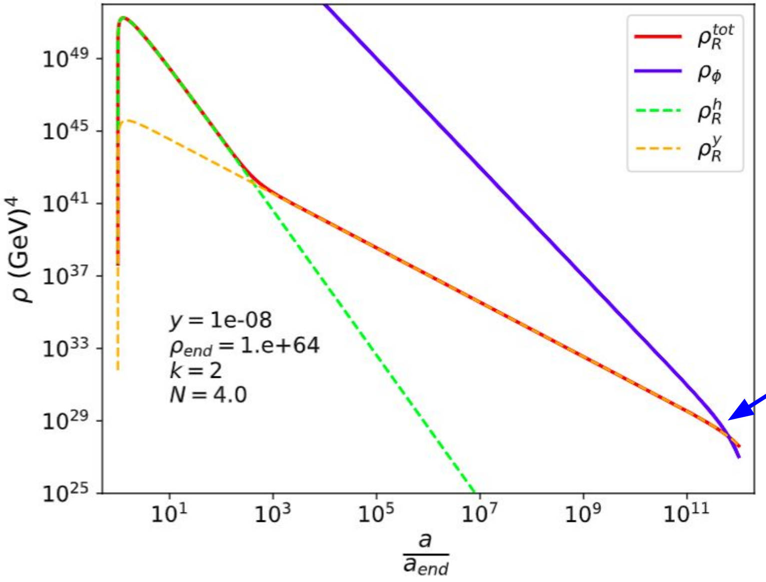


For sufficiently low Yukawa coupling, scattering process dominates the maximum temperature

$$y \lesssim 0.4\sqrt{\frac{\rho_{\rm end}}{M_P^4}} \simeq 6.9\times 10^{-6}\left(\frac{\rho_{\rm end}}{10^{64}{\rm GeV}^4}\right)^{\frac{1}{2}}$$

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

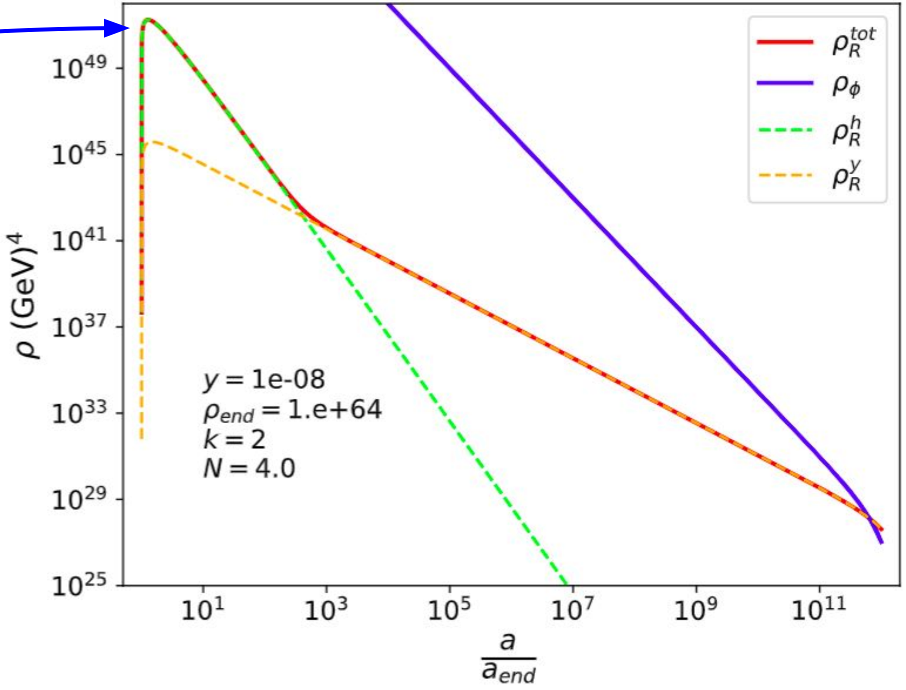


The late time reheating is still given by the width of inflaton decay

Figure 1 : Evolution of energy densities of the inflaton (blue), radiation from Yukawa decay (orange) and graviton exchange (green)

This maximum temperature $T_{max} \sim 10^{12}$ 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
$y_{\max}$	1.8×10^{-6}	1.4×10^{-6}	1.1×10^{-6}
T_{RHmax}	7.9×10^{8} GeV	470 GeV	9.7×10^{-4} GeV

The reheating temperature driven by the Yukawa coupling is highly k-dependent but the maximum temperature is not.

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

Graviton portal can also handle DM production for a wide range of DM masses

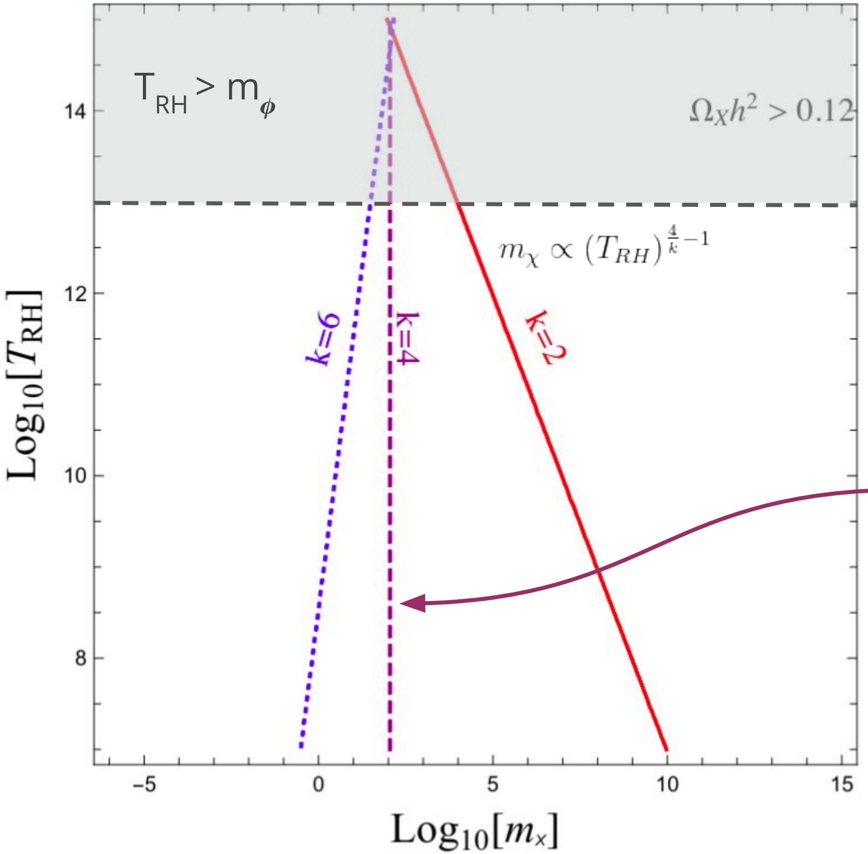


Figure 2 : $\Omega h^2 = 0.12$ in the case of a spin 0 DM, all contributions added

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

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).

3- Non-minimal coupling to gravity

In the case of scalar fields, the natural generalization of this minimal interaction is to introduce a non-minimal coupling to gravity of the form :

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

with

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

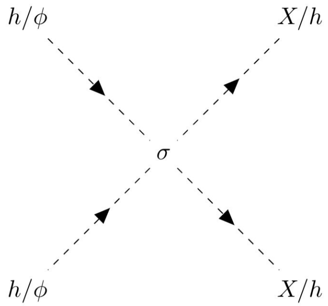
in the Jordan frame

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

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

in the Einstein frame

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



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

Reheating and dark matter freeze-in in the Higgs-R^2 inflation model, Shuntaro Aoki, Hyun Min Lee, Adriana G. Menkara, Kimiko Yamashita, JHEP (2022).

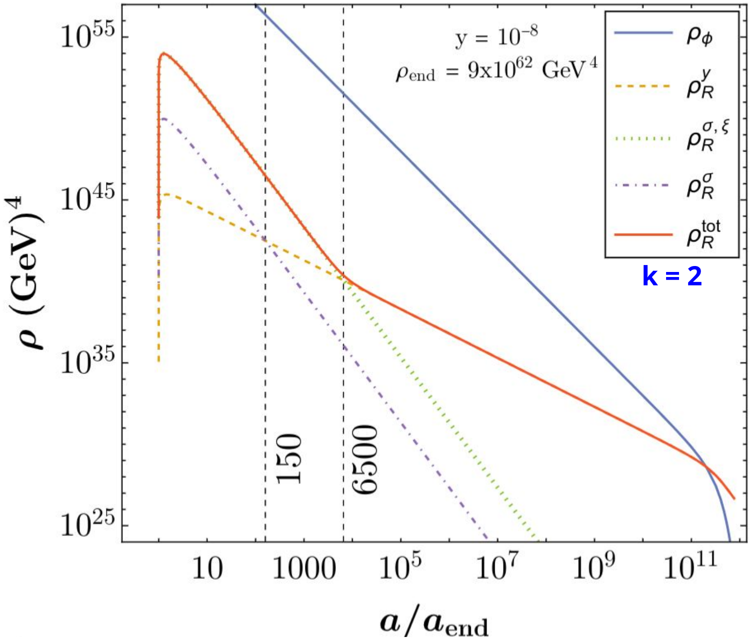


Figure 3 : Energy densities of inflaton (blue), total radiation (red), radiation from inflaton decay (orange), from scattering mediated by graviton (purple) and from non-minimal coupling (green), with $\sigma^\xi_{\varphi h}$ / $\sigma_{\varphi h}$ = 100.

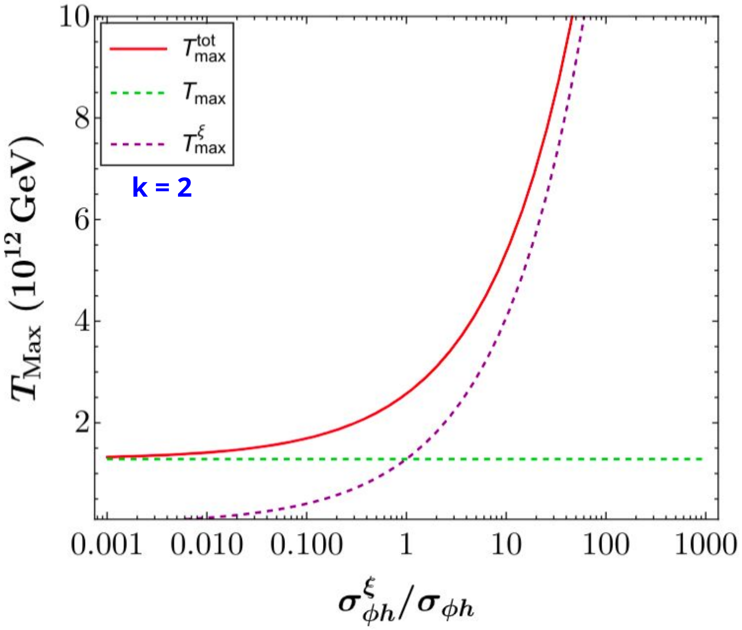


Figure 4 : Maximum temperature generated by minimal and non-minimal gravitational interactions

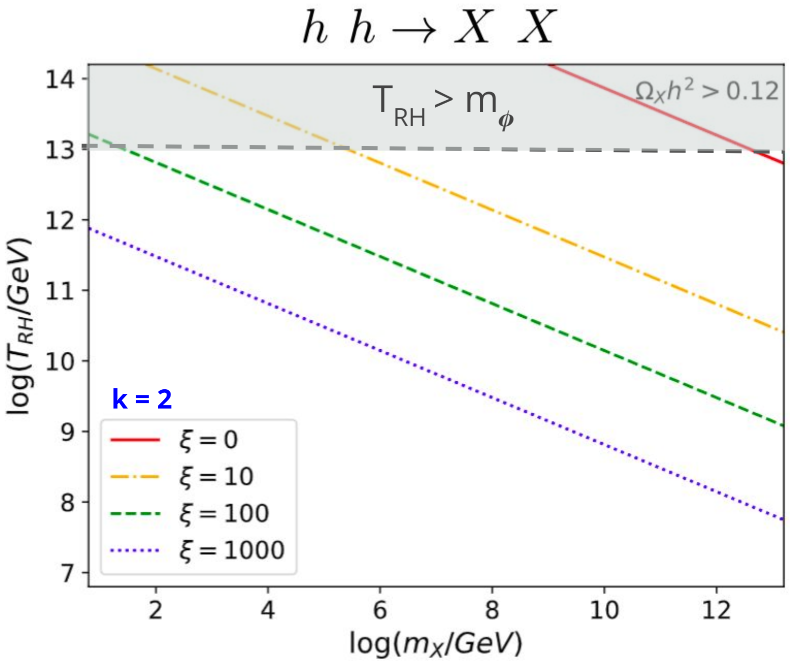
non-minimal

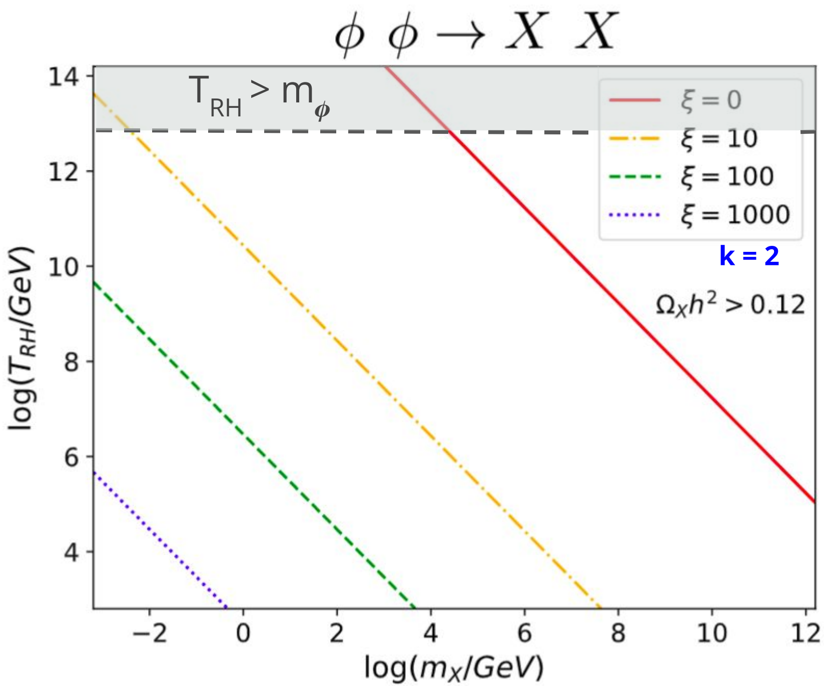
minimal

$$\sqrt{\frac{|\sigma^\xi_{\phi h}|}{|\sigma_{\phi h}|}} = \sqrt{2|\xi|}\,(|5+12\xi|)^{\frac{1}{2}} > 1$$

where we took $\xi_\phi = \xi_h = \xi$

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





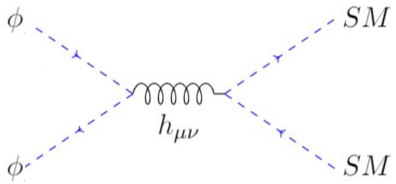
Figures 5, 6 : Region in the parameter space (m_X ,T_{RH}) respecting $\Omega_X h^2 = 0.12$, for different values of $\xi_\varphi = \xi_h = \xi_X = \xi$.
Both minimal and non-minimal contributions are added.

➜ Non-minimal couplings alleviate difficulties to produce DM from gravitational portal

➜ The contours allow us to place an upper bound on the non-minimal coupling ξ, knowing DM mass and T_{RH}

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

4- Gravitational reheating and leptogenesis

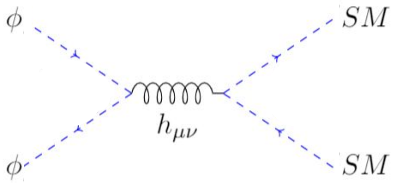


➜ Minimal gravitational coupling could be sufficient to ensure reheating, for sufficiently steep inflaton potential : k > 9

Gravitational Reheating, Md Riajul Haque, Debaprasad Maity, arXiv 2201.02348.

Inflationary Gravitational Leptogenesis, Raymond T. Co, Yann Mambrini, Keith A. Olive, arXiv 2205.01689.

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



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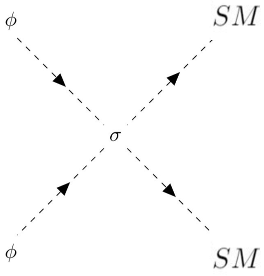


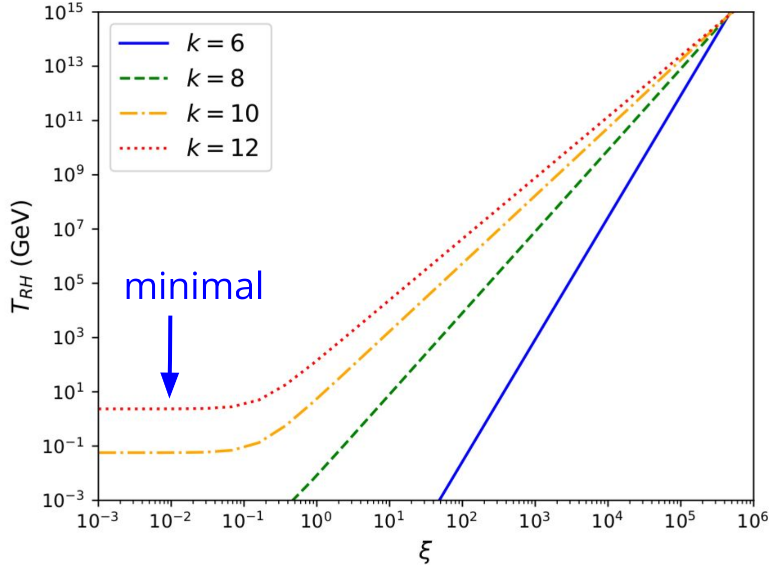
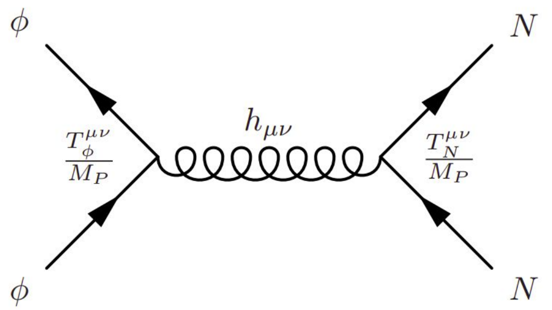
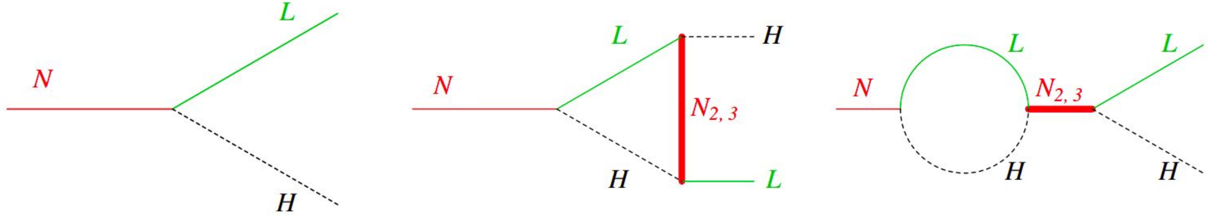


Figure 7 : Reheating temperature from gravitational portal as function of ξ for different k

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





From Baryogenesis via leptogenesis, Alessandro Strumia, arXiv 0608347 (2006)

Graviton portal can handle the production of sterile neutrinos

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

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

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

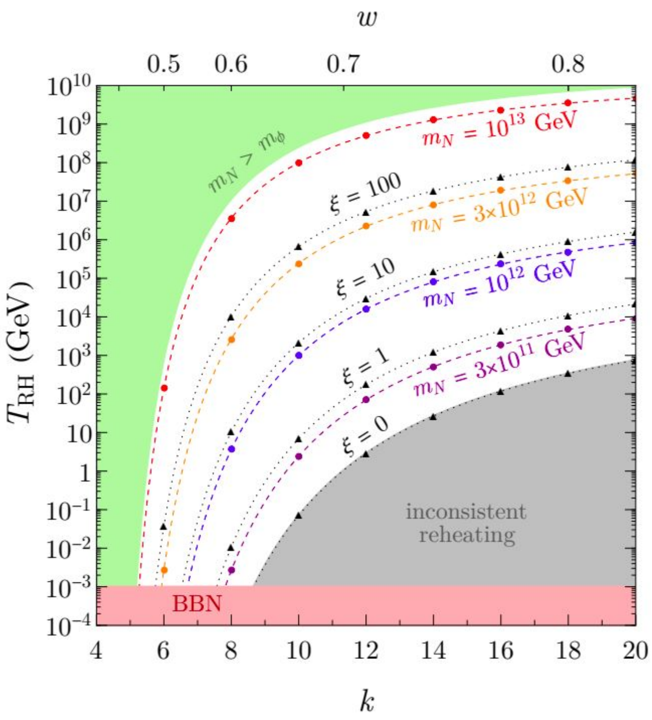
Considering type I see-saw mechanism with $m_N \lesssim m_\phi \ll m_{2,3}$,
v = 174 GeV (Higgs VEV) and the effective CP violation phase $\boldsymbol{\delta}_{\rm eff}$

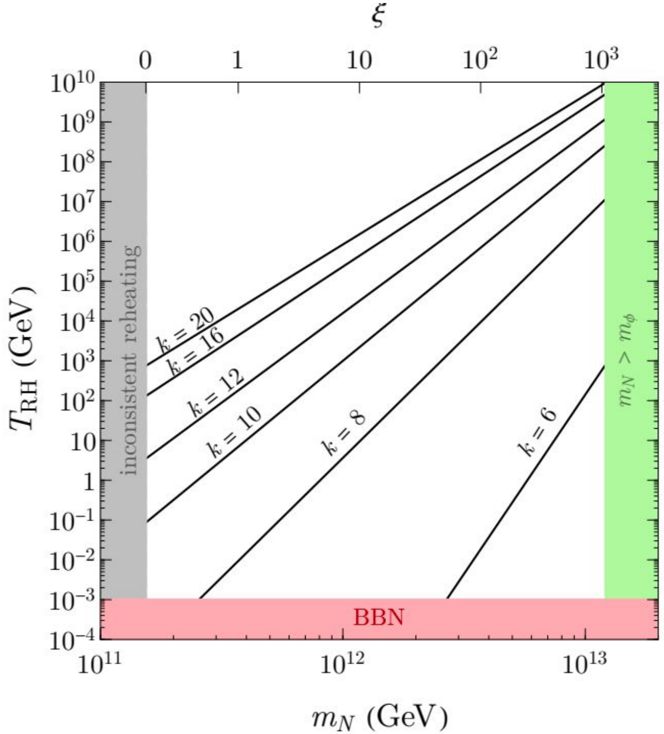
Lepton asymmetry out-of equilibrium

Inflationary Gravitational Leptogenesis, Raymond T. Co, Yann Mambrini, Keith A. Olive, arXiv 2205.01689.

Finally, this lepton asymmetry is converted into a baryon asymmetry.

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





Figures 8, 9 : Lines (colored) corresponding to the observed baryon asymmetry $Y_B \simeq 8.7 \times 10^{-11}$ *for different* m_N *and k*

Inflationary Gravitational Leptogenesis, Raymond T. Co, Yann Mambrini, Keith A. Olive, arXiv 2205.01689.

Conclusion

➜ Reheating phase allows production from Planck suppressed couplings : gravitational production

➜ Unavoidable lower limits on T_{max} and DM production

➜ Non-minimal coupling to gravity can enhance particle production during reheating process

➜ Graviton portal can complete the reheating for steep inflaton potential (large k)

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

Work in progress : ➜ Taking care of the preheating analysis (non perturbative)

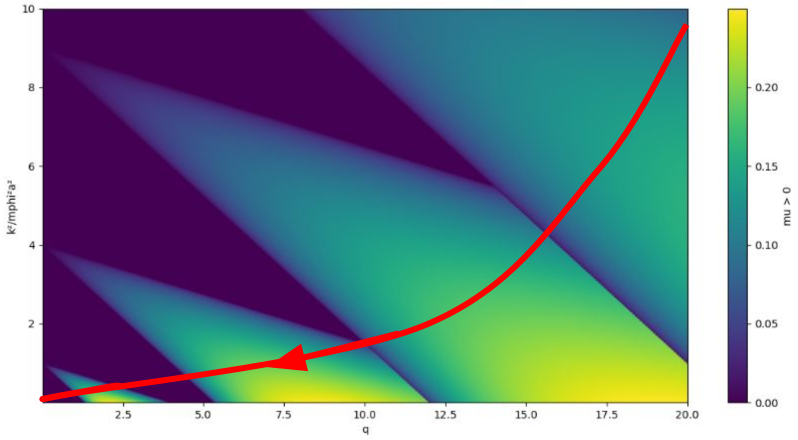
...

Classical non-perturbative approach : preheating

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

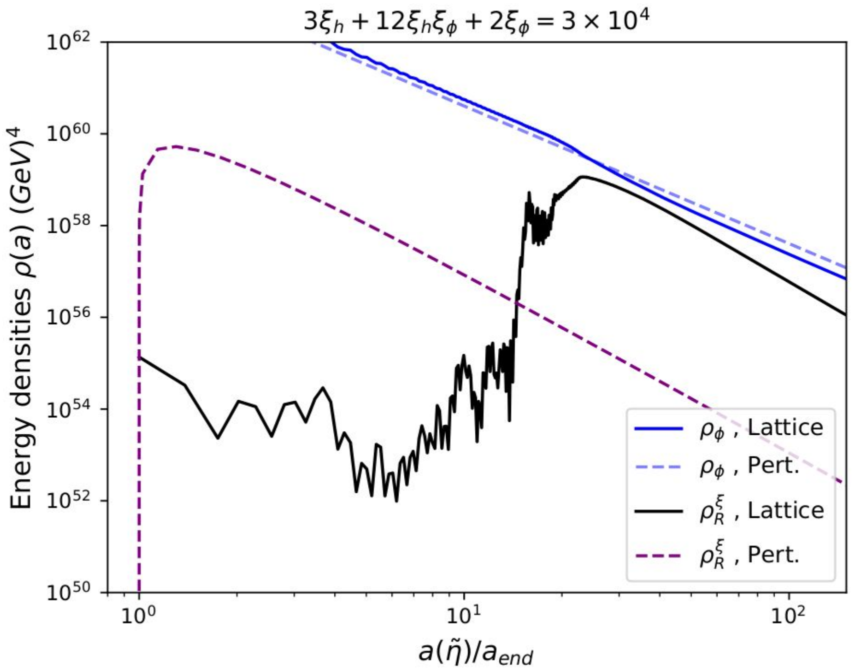
$$\chi_k'' + \left(\frac{k^2}{m_\phi^2 a^2} + 2q - 2q\cos(2z)\right)\chi_k = 0$$

Mathieu equation for Fourier modes in the oscillating background



Instabilities in the bands $\chi_k \propto exp[\mu_{k,q} z]$

➜ Increasing occupation number



Work in progress :

➜ Consider instabilities + backreaction simultaneously to compute non-perturbative production : Lattice simulations

See *Freeze-in from preheating*, Garcia, Kaneta, Mambrini, Olive, Verner, JCAP (2022)

Thank you for your attention !

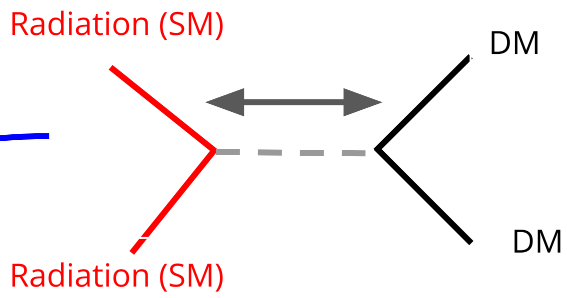
APPENDIX

The WIMP Miracle ?

DM production/annihilation from/to the thermal bath

Evolution of number density during radiation era following the classical Boltzmann equation in an expanding Universe :

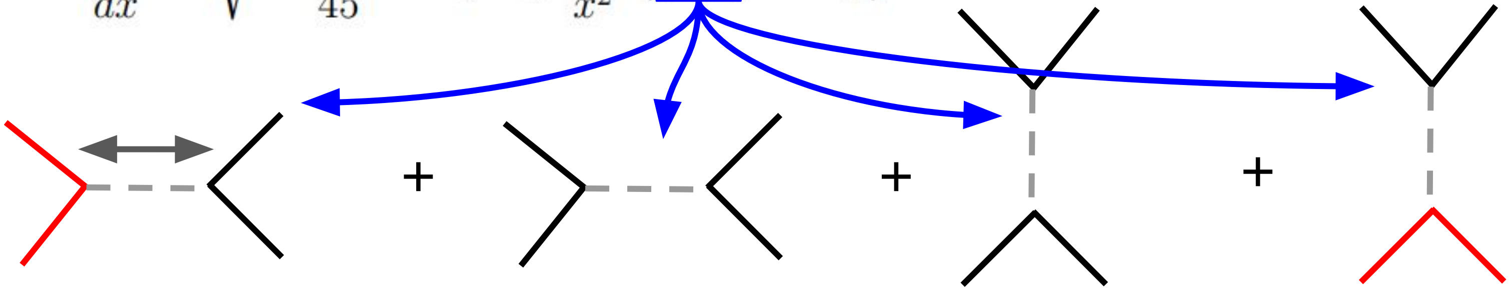
$$\dot{n}_\chi + 3Hn_\chi = g_\chi^2\langle\sigma v\rangle n_r^2 \equiv \boxed{R(T)}$$

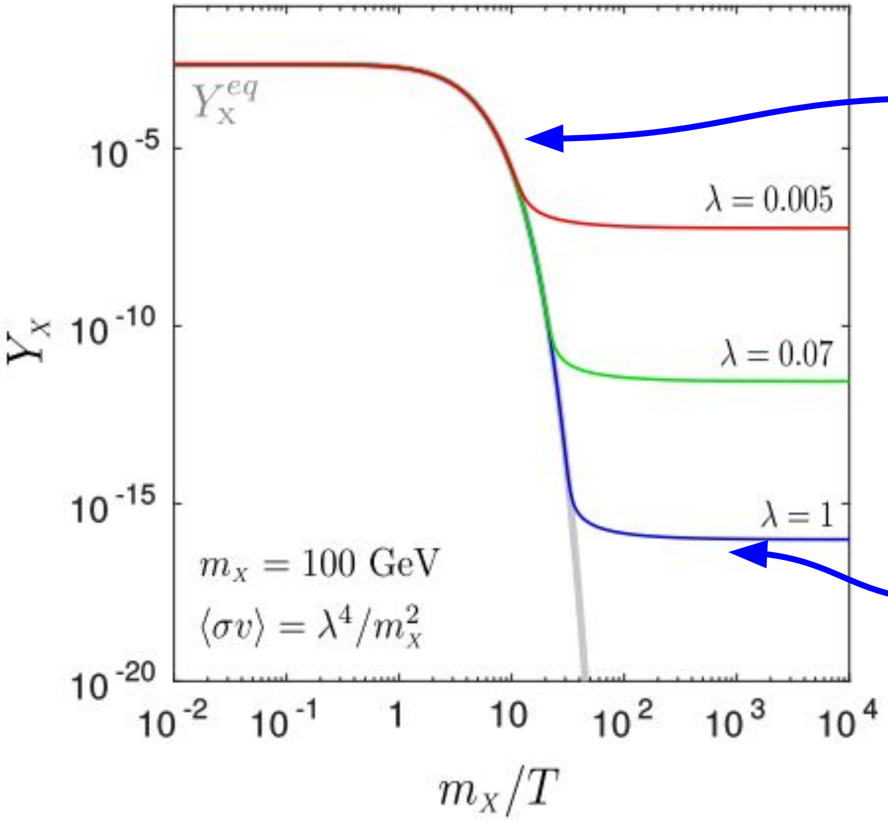


$$Y_X = \frac{N_X}{S} = \frac{n_X}{s}$$

$$\frac{dY_X}{dx} = \sqrt{\frac{8\pi^2 g_*(x)}{45}} M_P m_X \frac{\langle\sigma v\rangle}{x^2}\left(\boxed{(Y_X^{eq}}\,)^2 - Y_X^2\right)$$

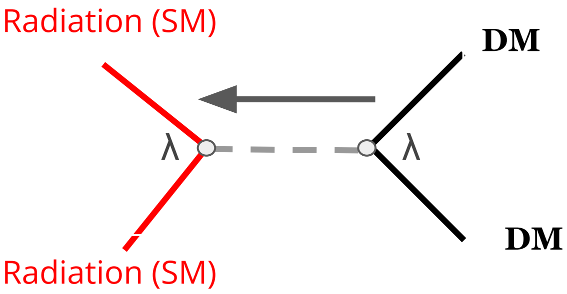
Thermal and chemical equilibrium



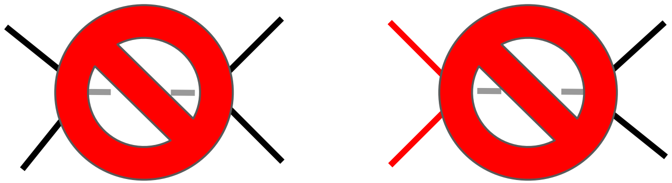


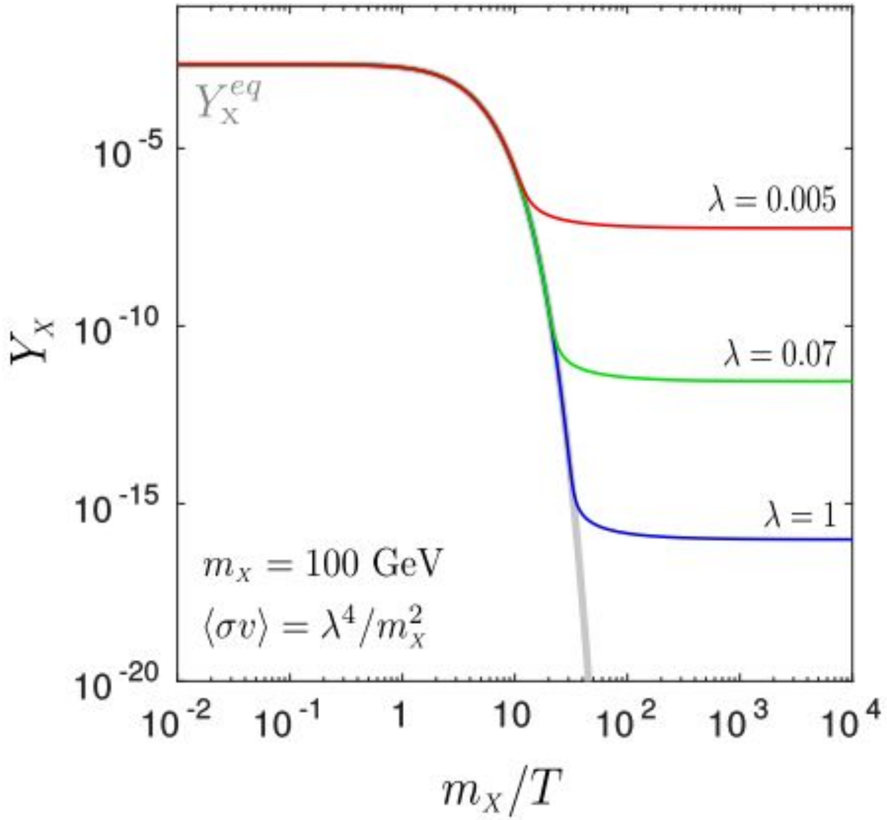
From *Origins for dark matter particles: from the "WIMP miracle" to the "FIMP wonder"* - Maira Dutra

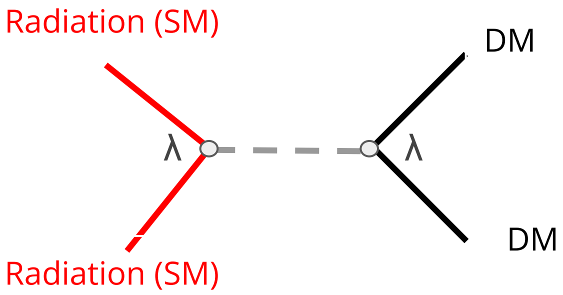
T ≪ mDM : WIMP becomes non-relativistic
→departs from its equilibrium value and starts chemical decoupling



$n_\chi \langle \sigma v \rangle \ll H$: WIMP "freezes out"
→ comoving number density becomes constant

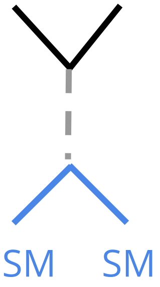






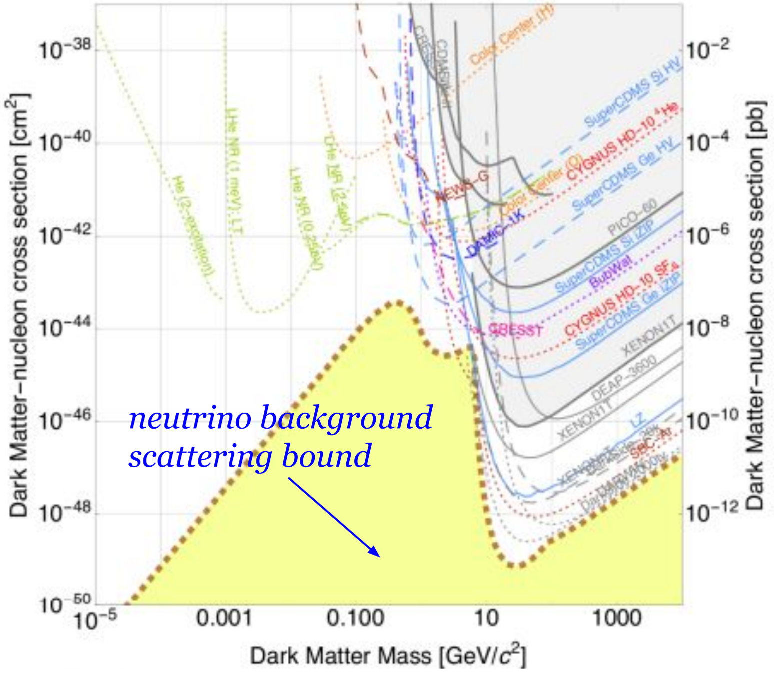
Typical electroweak scale massive particle (~100 GeV) with electroweak coupling production corresponds to the observed relic abundance of Dark Matter $\Omega h^2 \simeq 0.12$

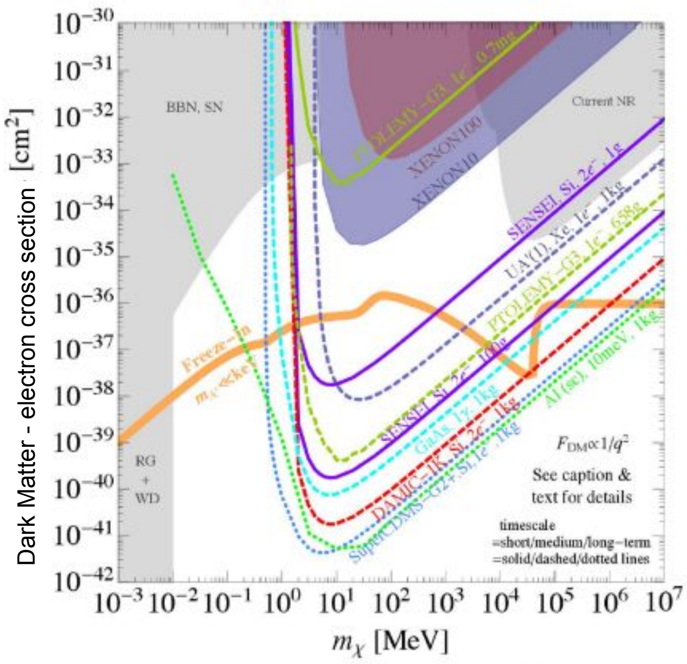
→ No new physical scale is needed, just a new sector to connect with the SM electroweak sector !



Probe DM scattering with nucleons, electrons = Direct Detection

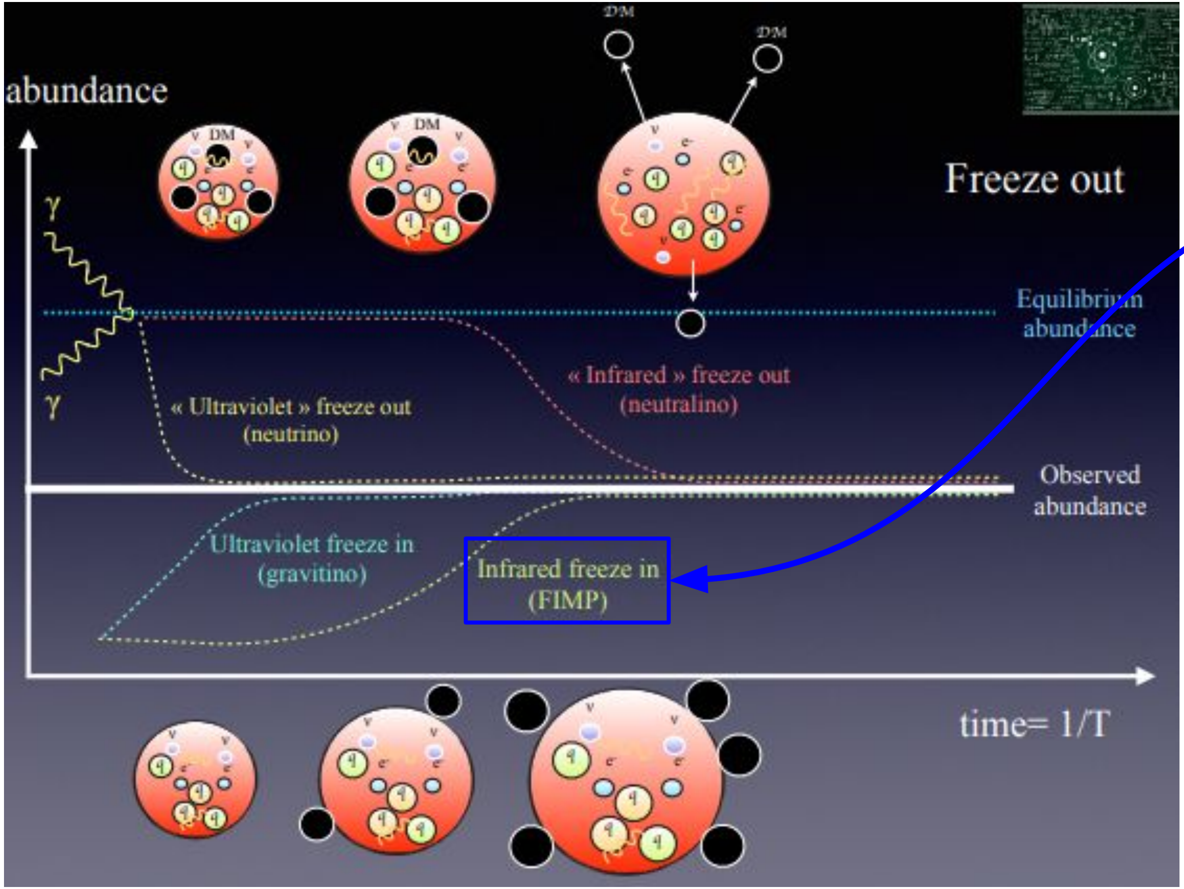
But… detection bounds still go down. Indirect detection and collider experiments should probe other processes involving WIMPs…but still without real success





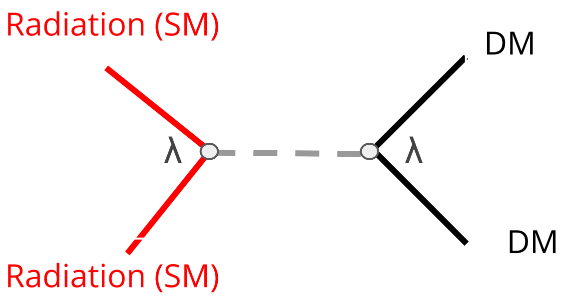
From M. Battaglieri et al. *US Cosmic Visions: New Ideas in Dark Matter* (2017) arXiv:1707.04591

FIMP



Credit : Yann Mambrini

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



Can arise from superpotential in no-scale supergravity :

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

↓

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

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

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

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

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

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

Class of models : α-attractor T-model inflation

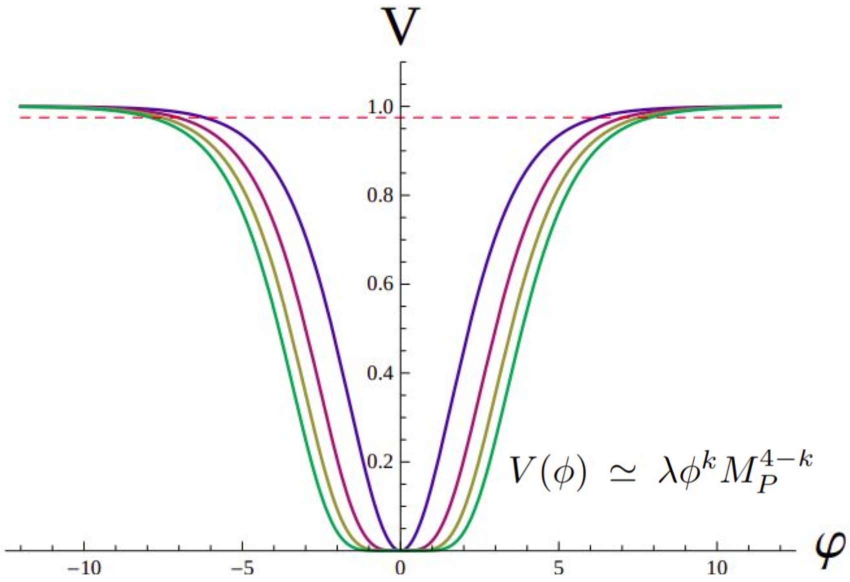
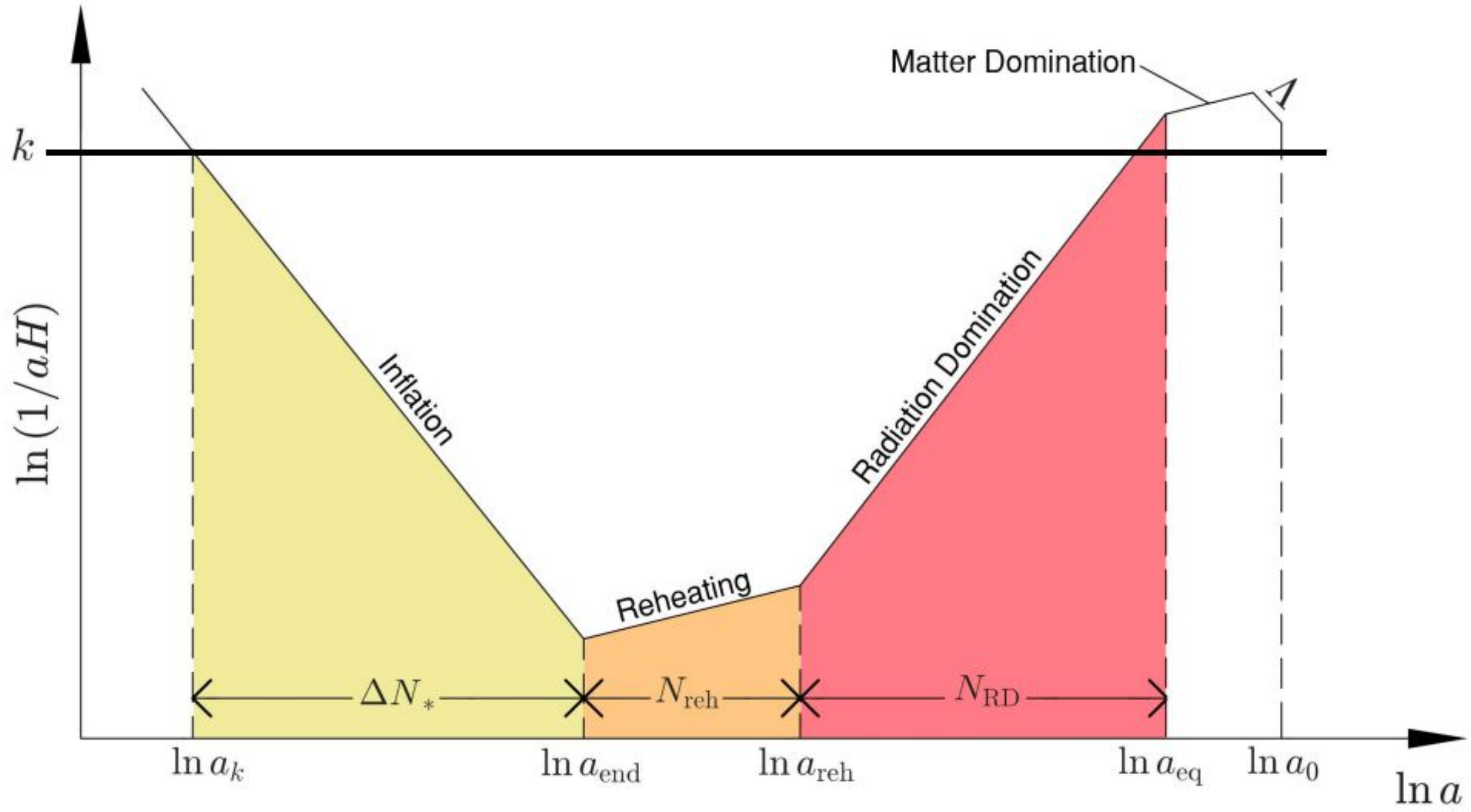


Figure 1: Potentials for the T-Model inflation $\tanh^{2n}(\varphi/\sqrt{6})$ for $n = 1, 2, 3, 4$

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



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

Inflaton scattering

To treat properly the inflaton scattering we expand the potential near the minimum with a power k-dependant monomial

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

Then parametrized the time dependent background field as an amplitude times a 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 and use the fact that at the end of inflation, energy density of the inflaton is potential energy

From the inflaton stress-energy tensor, each Fourier mode adds its contribution to the scattering amplitude with its energy $En^2 = s$

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

Thermal bath scattering

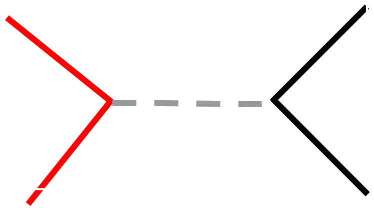
Usual amplitude computation for a s-channel scattering of (massless) SM particles giving DM particles

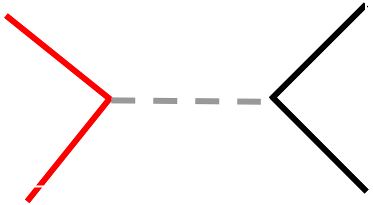
$$|\overline{\mathcal{M}}^{00}|^2 = \frac{1}{64M_P^4}\frac{t^2(s+t)^2}{s^2},$$

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

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

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





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

From amplitudes compute the rate of DM production for each process

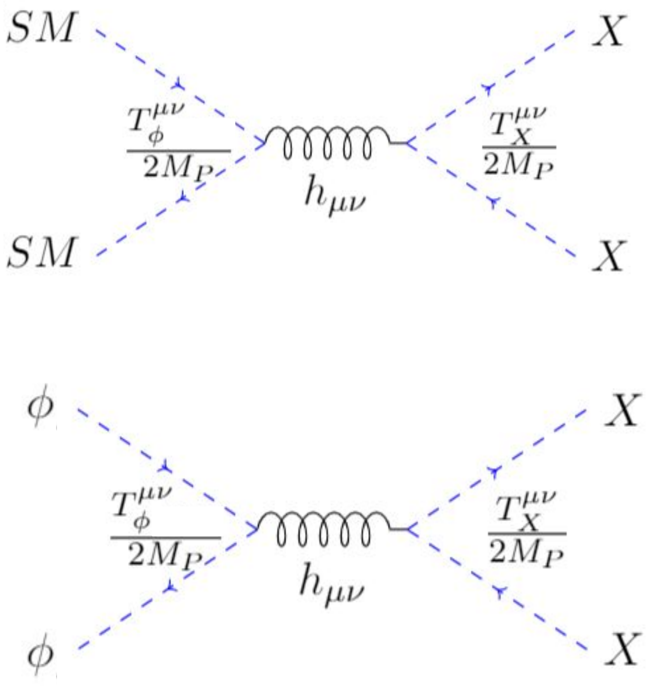
$$R_j^T = \beta_j \frac{T^8}{M_P^4}$$ for spin j = 0, ½ DM final state

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

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

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

See *Gravitational Production of Dark Matter during Reheating*, Yann Mambrini, Keith A. Olive, Phys.Rev.D (2021).



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, Simon Cléry, Yann Mambrini, Keith A. Olive, Sarunas Verner, Phys.Rev.D (2022).

For fermionic DM

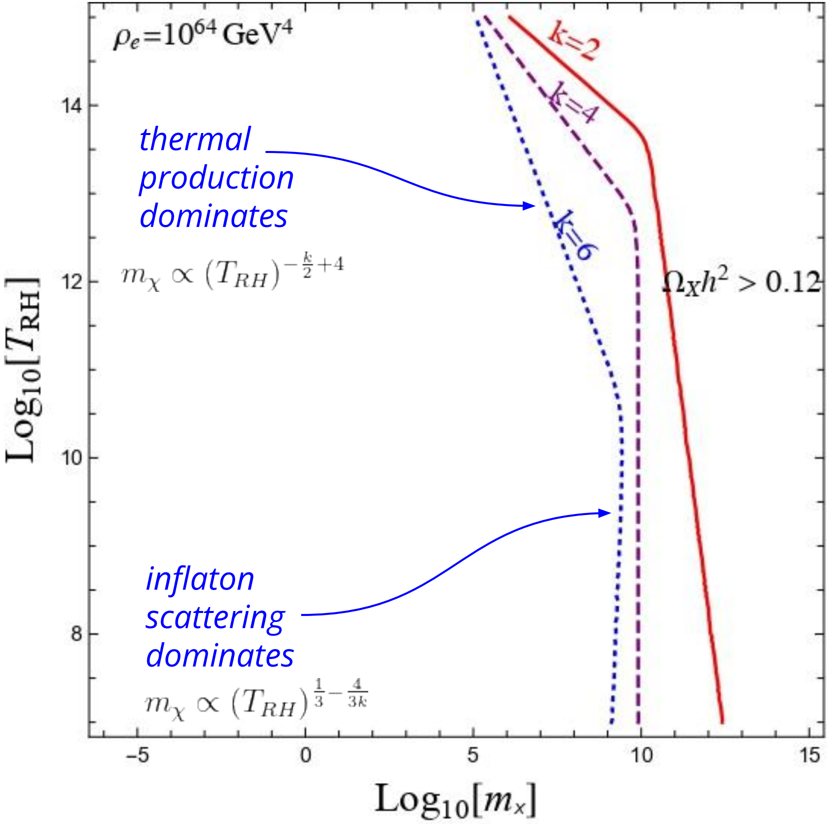
Inflaton scattering is helicity suppressed
➜ broken spectrum due to strong DM mass dependence

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

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

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

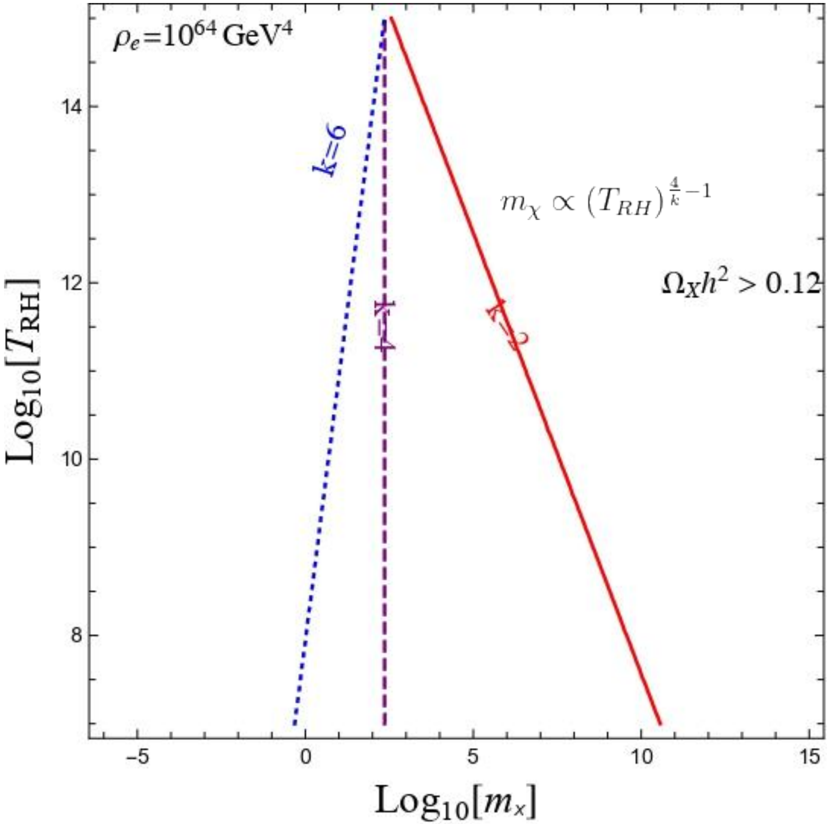
Gravitational portals in the early Universe, Simon Cléry, Yann Mambrini, Keith A. Olive, Sarunas Verner, Phys.Rev.D (2022).



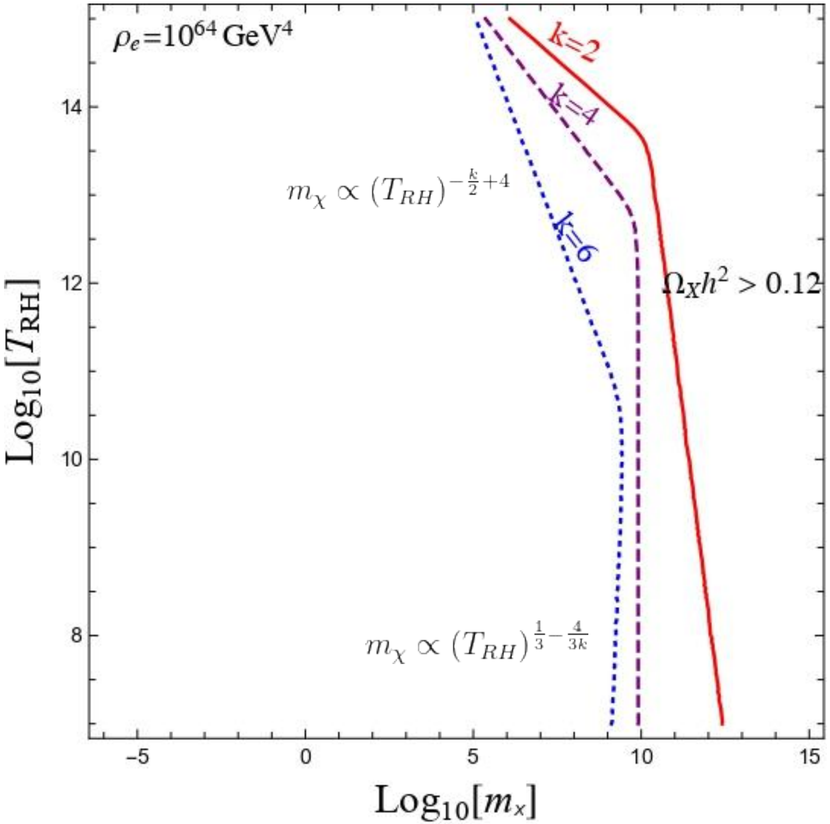
$\Omega h^2 = 0.12$ in the case of a spin ½ DM, all contributions added

DM production in minimal framework

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

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, arXiv 2203.02004 [PRD].

Leading order interactions

in Einstein frame

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

↓

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

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

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

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

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, Front.Astron.Space Sci. 5 (2018)

➜ 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 : $\xi_h > 10^{-1}$

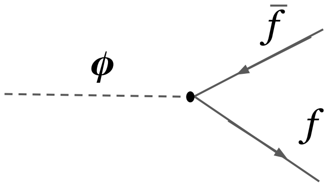
➜ In the case of Higgs inflation, ξh is fixed from CMB (Planck)

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

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

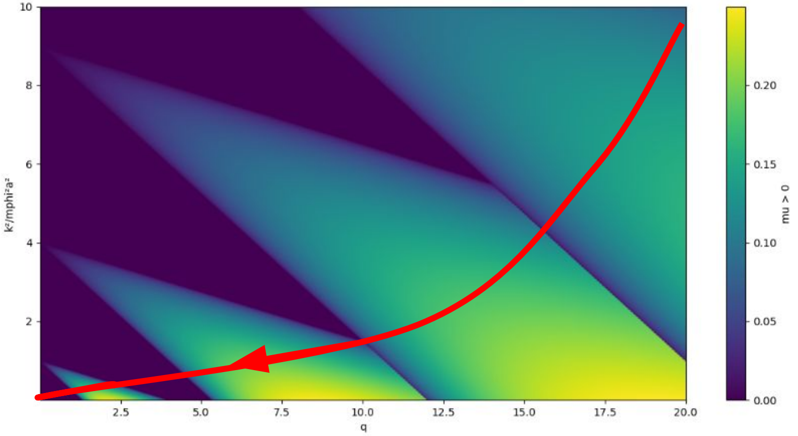
See *Freeze-in from preheating*, Garcia, Kaneta, Mambrini, Olive, Verner, JCAP (2022)

Classical non-perturbative approach : preheating

Time dependant background coupled to fields leads to parametric resonance, 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 bands $\chi_k \propto exp[\mu_{k,q} z]$
➔ Increasing occupation number

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. Z Phys C - Particles and Fields, (1997)