Gravitational portals in the early Universe

Invisible Workshop - 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*, SC, Yann Mambrini, Keith A. Olive, Sarunas Verner, Phys.Rev.D (2022)
- *Gravitational Portals with Non-Minimal Couplings*, SC, Yann Mambrini, Keith A. Olive, Andrey Shkerin, Sarunas Verner, Phys.Rev.D (2022)

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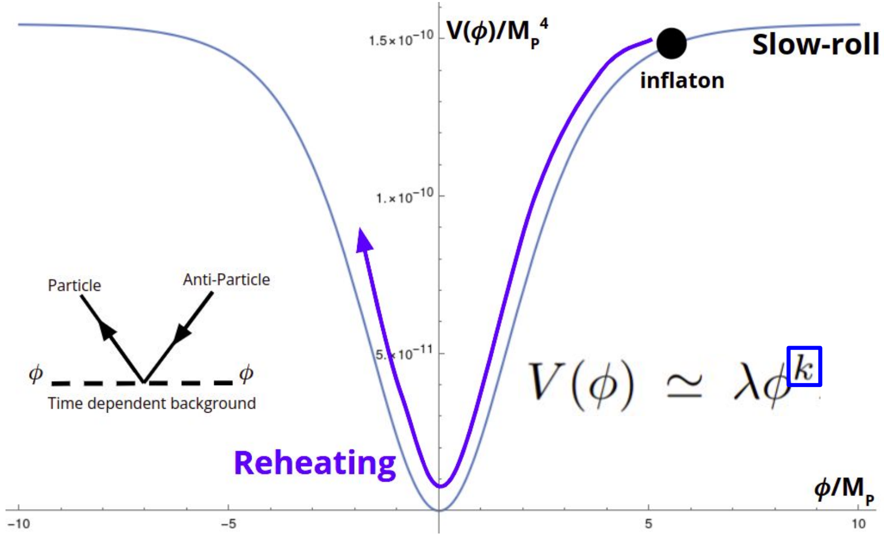
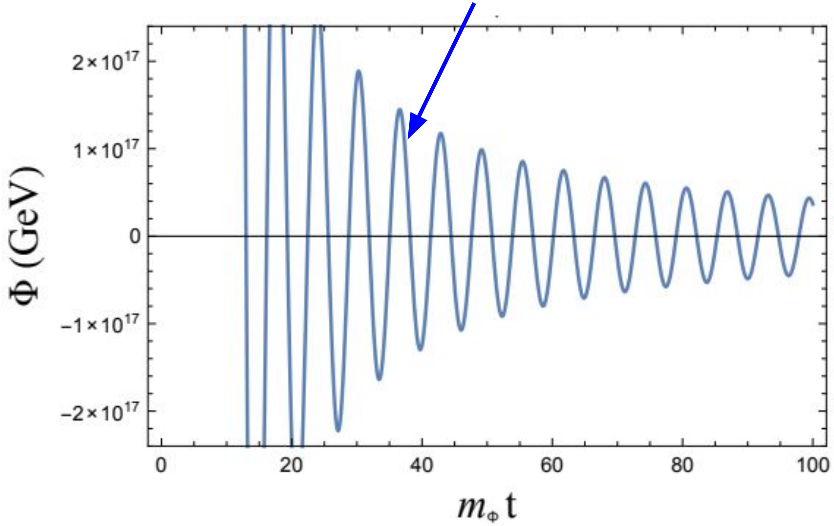
Inflationary reheating



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

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

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



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

Minimal gravitational portal

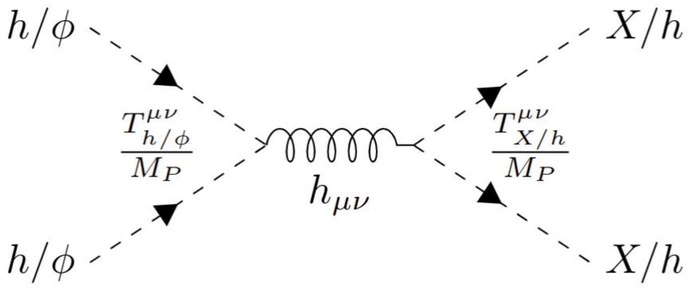
➜ Graviton portal arises from metric perturbation around its locally flat form

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

$$\downarrow$$

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

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



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

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

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

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).

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 :

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

in the Jordan frame

with

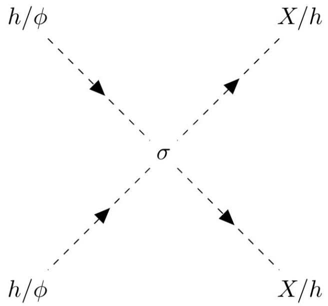
$$\Omega^2 \equiv 1 + \underbrace{\frac{\xi_\phi \phi^2}{M_P^2}}_{\text{inflaton}} + \underbrace{\frac{\xi_h h^2}{M_P^2}}_{\text{SM}} + \underbrace{\frac{\xi_X X^2}{M_P^2}}_{\text{DM}}$$

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

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

in the Einstein frame

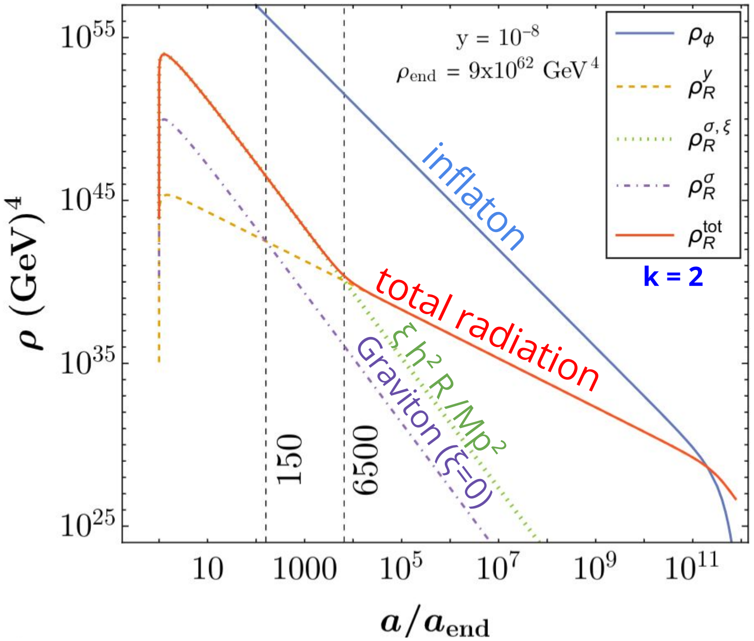
This non-minimal coupling induces leading-order interactions involved in radiation and DM production.



Gravitational Portals with Non-Minimal Couplings, SC, Yann Mambrini, Keith A. Olive, Andrey Shkerin, Sarunas Verner, Phys.Rev.D (2022)

Reheating and dark matter freeze-in in the Higgs-R² inflation model, Shuntaro Aoki, Hyun Min Lee, Adriana G. Menkara, Kimiko Yamashita, JHEP (2022).

Radiation production



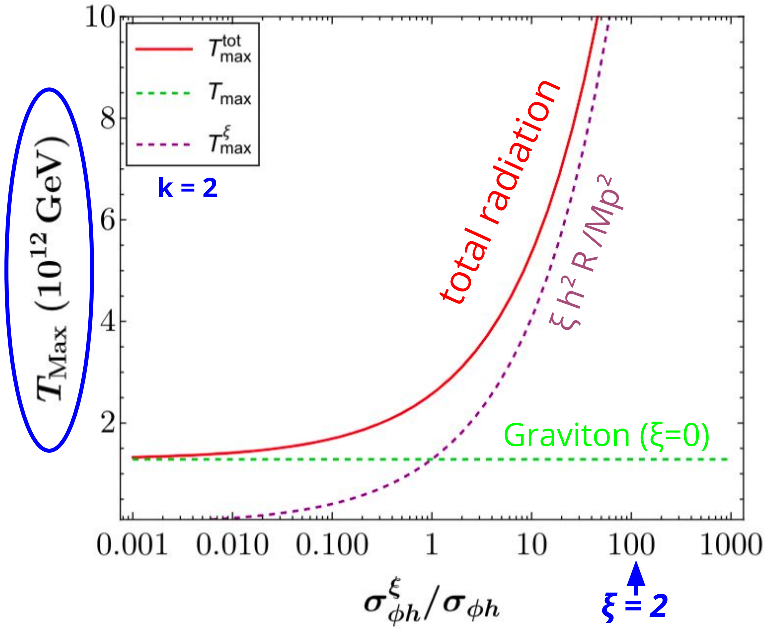
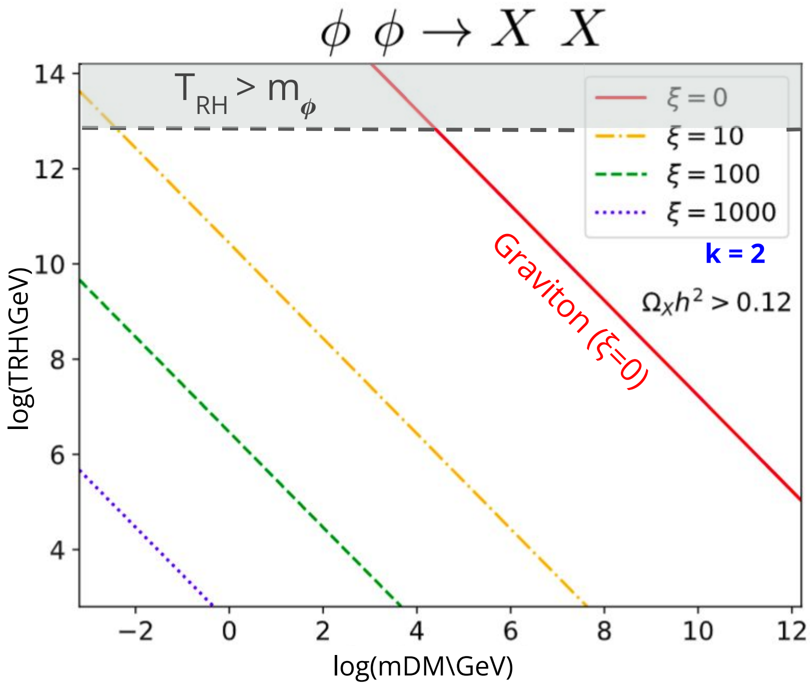


Figure 1 : Energy densities of inflaton (blue), total radiation (red), radiation from inflaton decay (orange), from scattering mediated by graviton (purple) and from non-minimal coupling (green), with ***ξ = 2***

Figure 2 : Maximum temperature generated by minimal and non-minimal gravitational interactions

Gravitational Portals with Non-Minimal Couplings, SC, Yann Mambrini, Keith A. Olive, Andrey Shkerin, Sarunas Verner, Phys.Rev.D (2022)

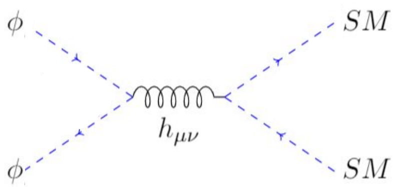
Dark Matter production



Figures 3, 4 : 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.

Gravitational Portals with Non-Minimal Couplings, SC, Yann Mambrini, Keith A. Olive, Andrey Shkerin, Sarunas Verner, Phys.Rev.D (2022)

Gravitational reheating

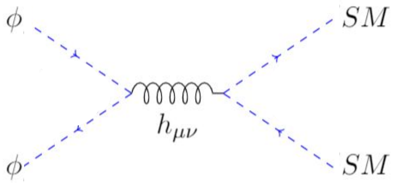


➜ Graviton exchange could be sufficient to ensure reheating, for sufficiently steep inflaton potential : k > 9

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

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

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



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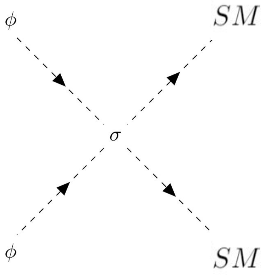


➜ The requirement of very large k can be relaxed if we add the non-minimal contribution to radiation production, (but still need k>4).

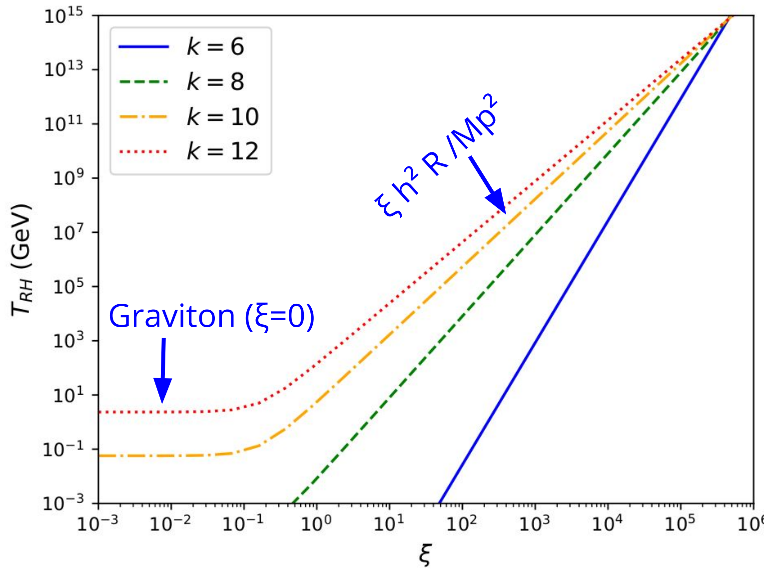


Figure 5 : Reheating temperature from gravitational portals as function of ξ for different k

Conclusion

➜ Reheating phase allows production from gravitational interaction

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

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

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

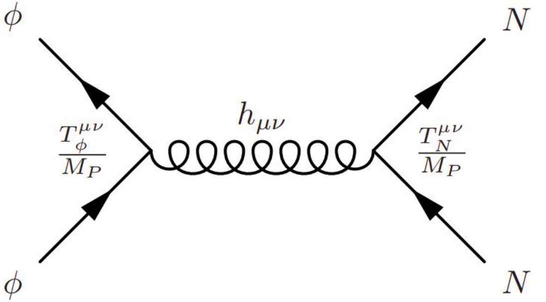
Work in progress : ➜ Taking care of the preheating analysis (non perturbative)

...

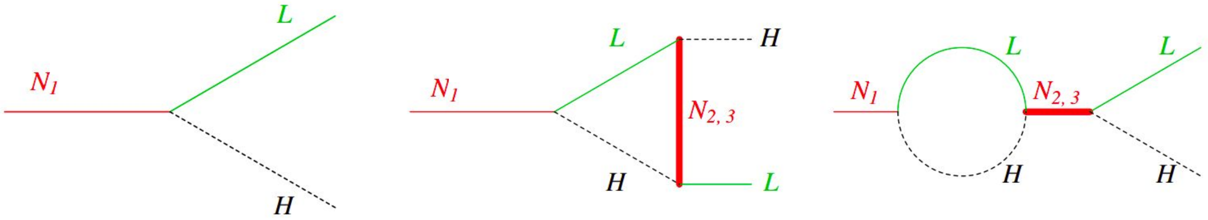
Thank you for your attention !

Appendix

Gravitational leptogenesis



Graviton portal can handle the production of sterile neutrinos



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

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.

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

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

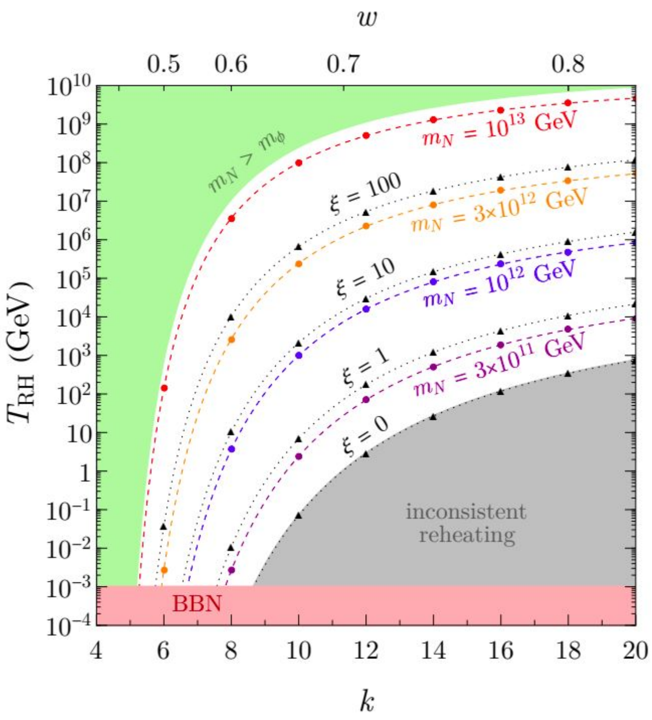
Considering type I see-saw mechanism with $m_N \lesssim m_\phi \ll m_{2,3}$, v = 174 GeV (Higgs VEV) and the effective CP violation phase $\boldsymbol{\delta}_{\rm eff}$

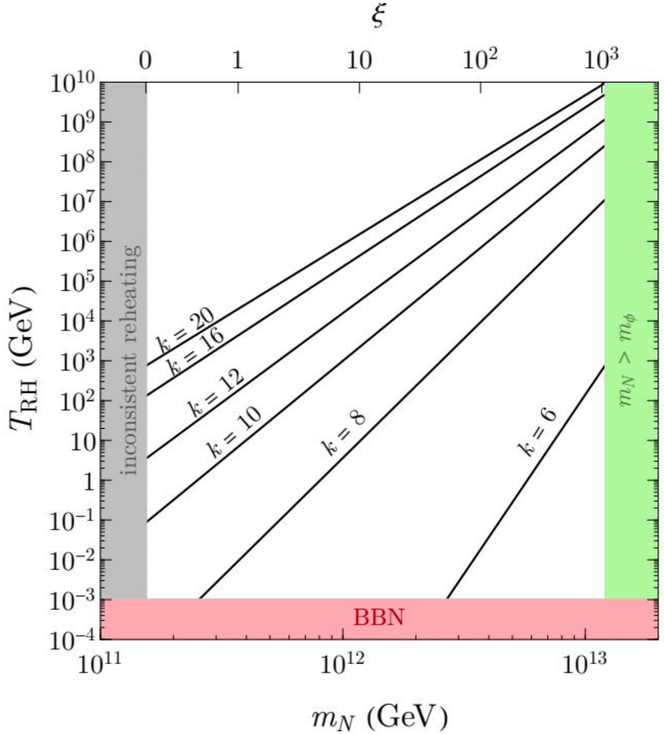
Lepton asymmetry out-of equilibrium

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

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

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





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

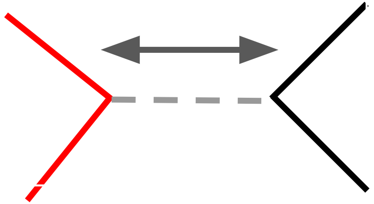
Inflationary Gravitational Leptogenesis, Raymond T. Co, Yann Mambrini, Keith A. Olive, arXiv 2205.01689.

Backup Slides

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 :

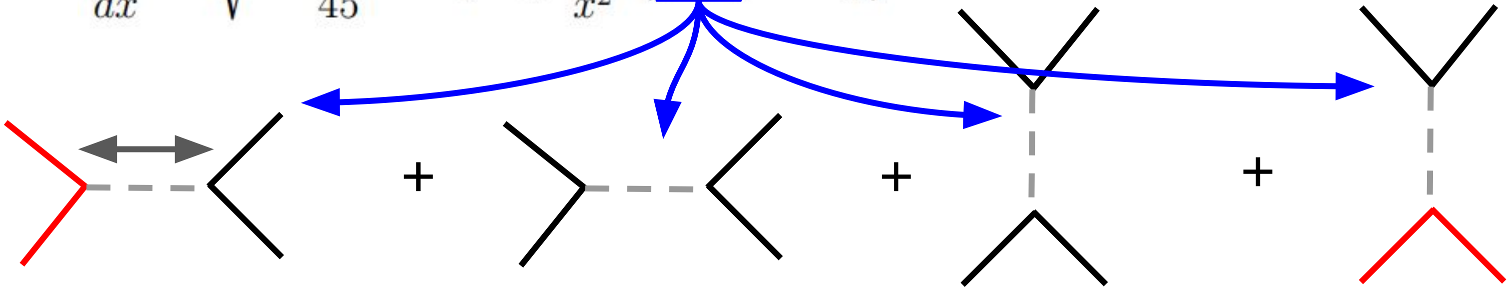


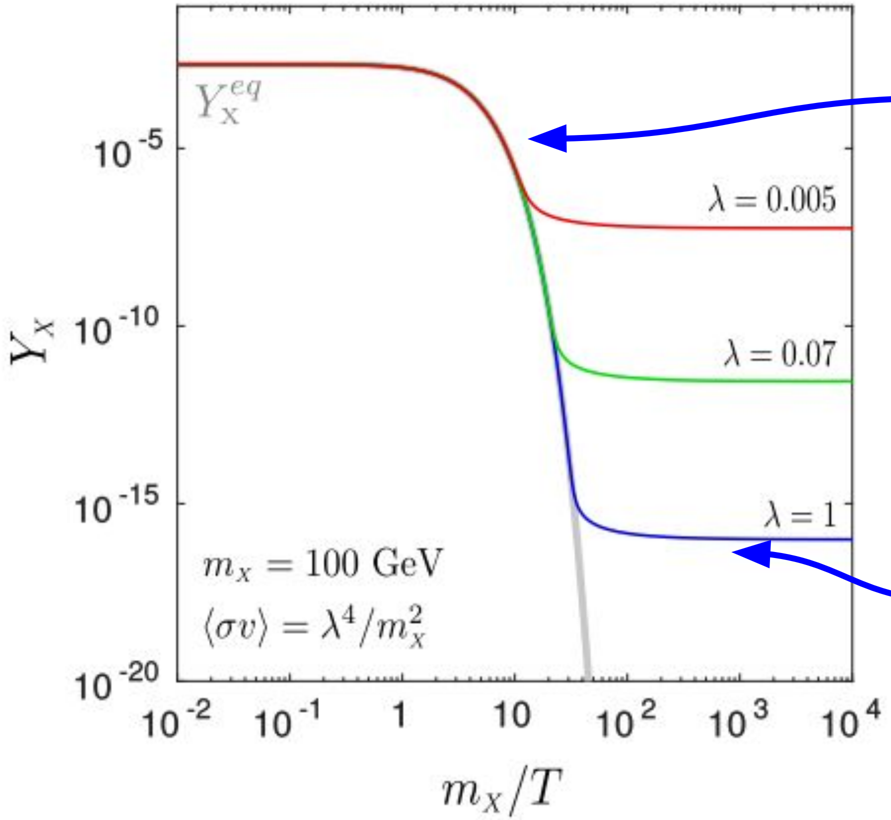
$$\dot{n}_\chi + 3Hn_\chi = g_\chi^2\langle\sigma v\rangle n_r^2 \equiv \boxed{R(T)}$$

$$Y_x = \frac{N_x}{S} = \frac{n_x}{s}$$

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

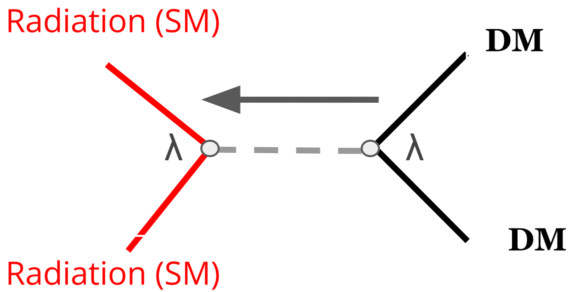
Thermal and chemical equilibrium



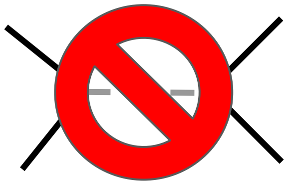


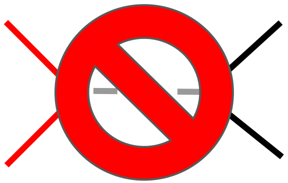
From *Origins for dark matter particles: from the "WIMP miracle" to the "FIMP wonder"* - Maira Dutra

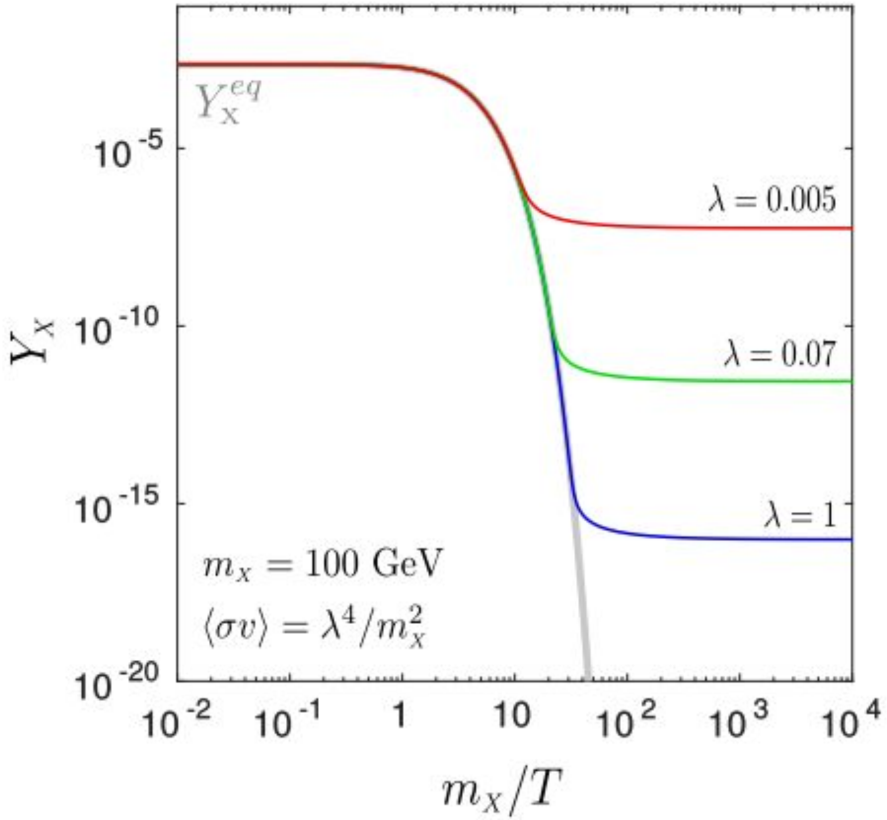
T ≪ mDM : WIMP becomes non-relativistic
→departs from its equilibrium value and starts chemical decoupling

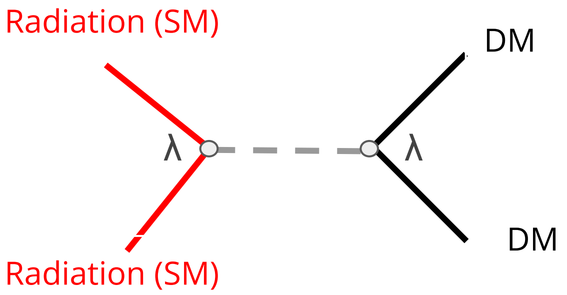


$n_\chi \langle \sigma v \rangle \ll H$: WIMP "freezes out"
→ comoving number density becomes constant



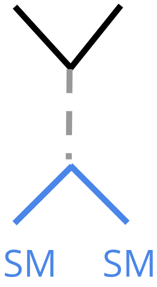






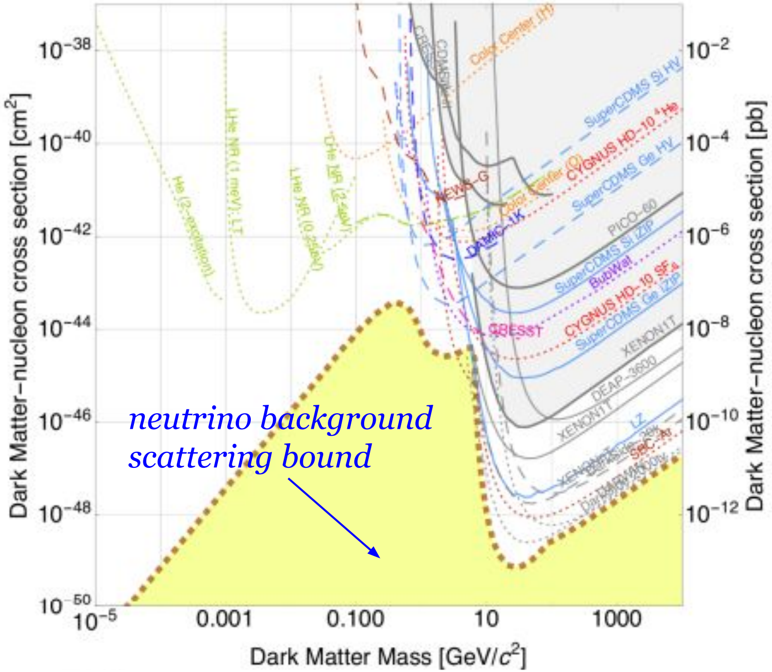
Typical electroweak scale massive particle (~100 GeV) with electroweak coupling production corresponds to the observed relic abundance of Dark Matter $\Omega h^2 \simeq 0.12$

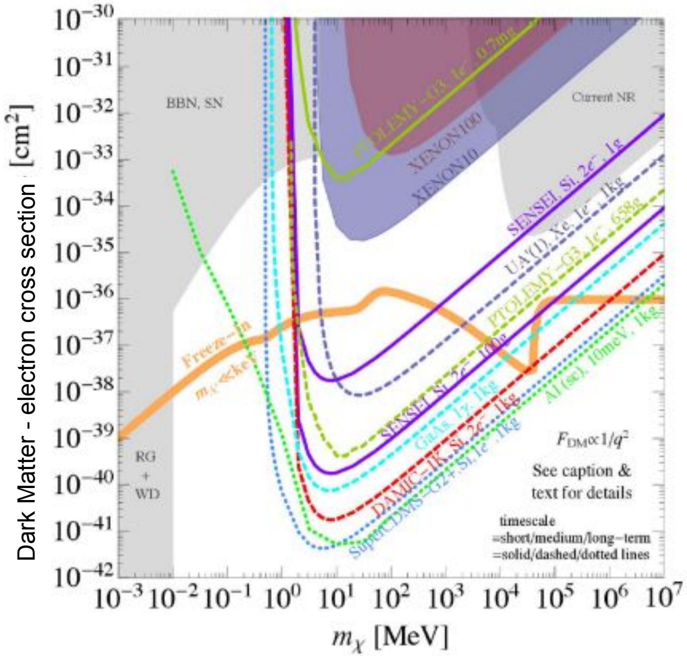
→ No new physical scale is needed, just a new sector to connect with the SM electroweak sector !



Probe DM scattering with nucleons, electrons = Direct Detection

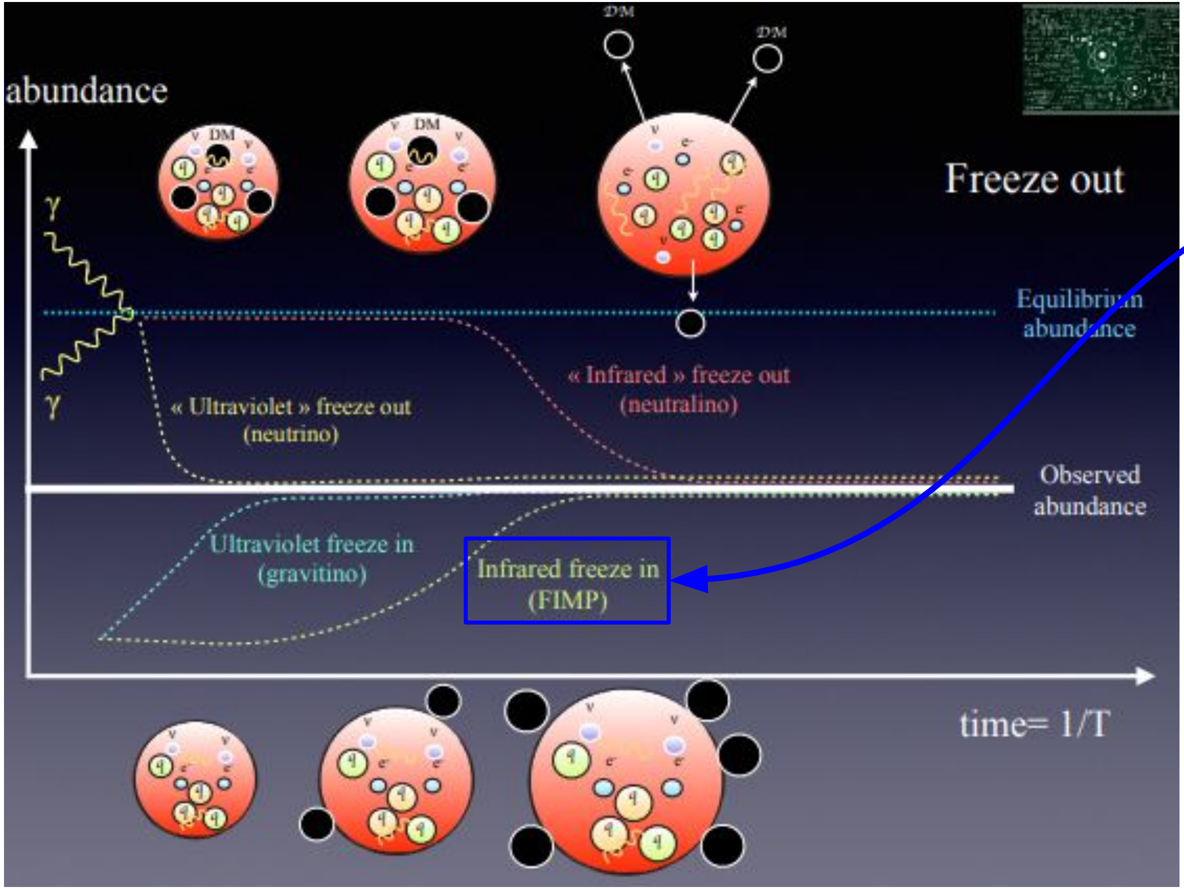
But... detection bounds still go down. Indirect detection and collider experiments should probe other processes involving WIMPs...but still without real success





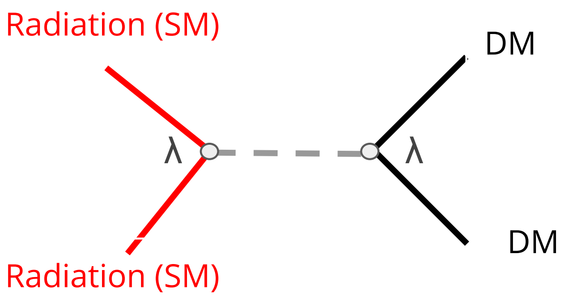
From M. Battaglieri et al. US *Cosmic Visions: New Ideas in Dark Matter* (2017) arXiv:1707.04591

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

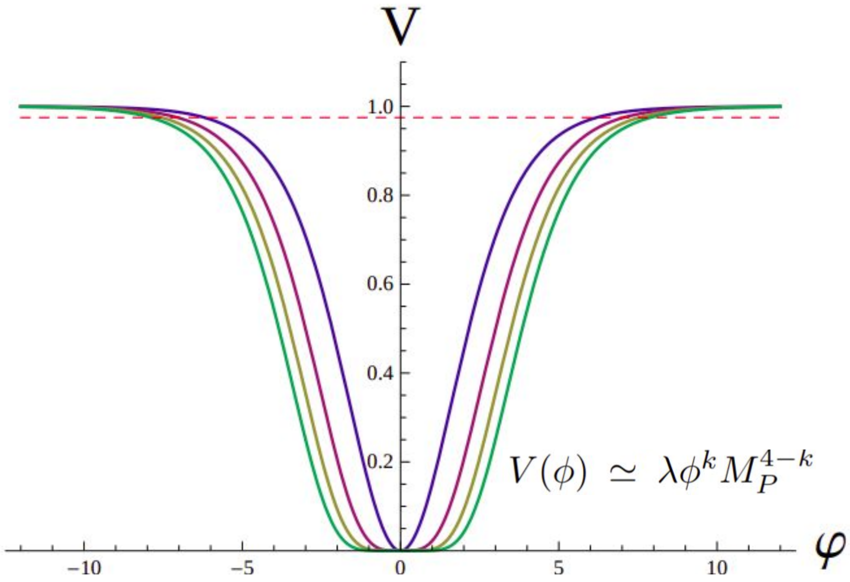
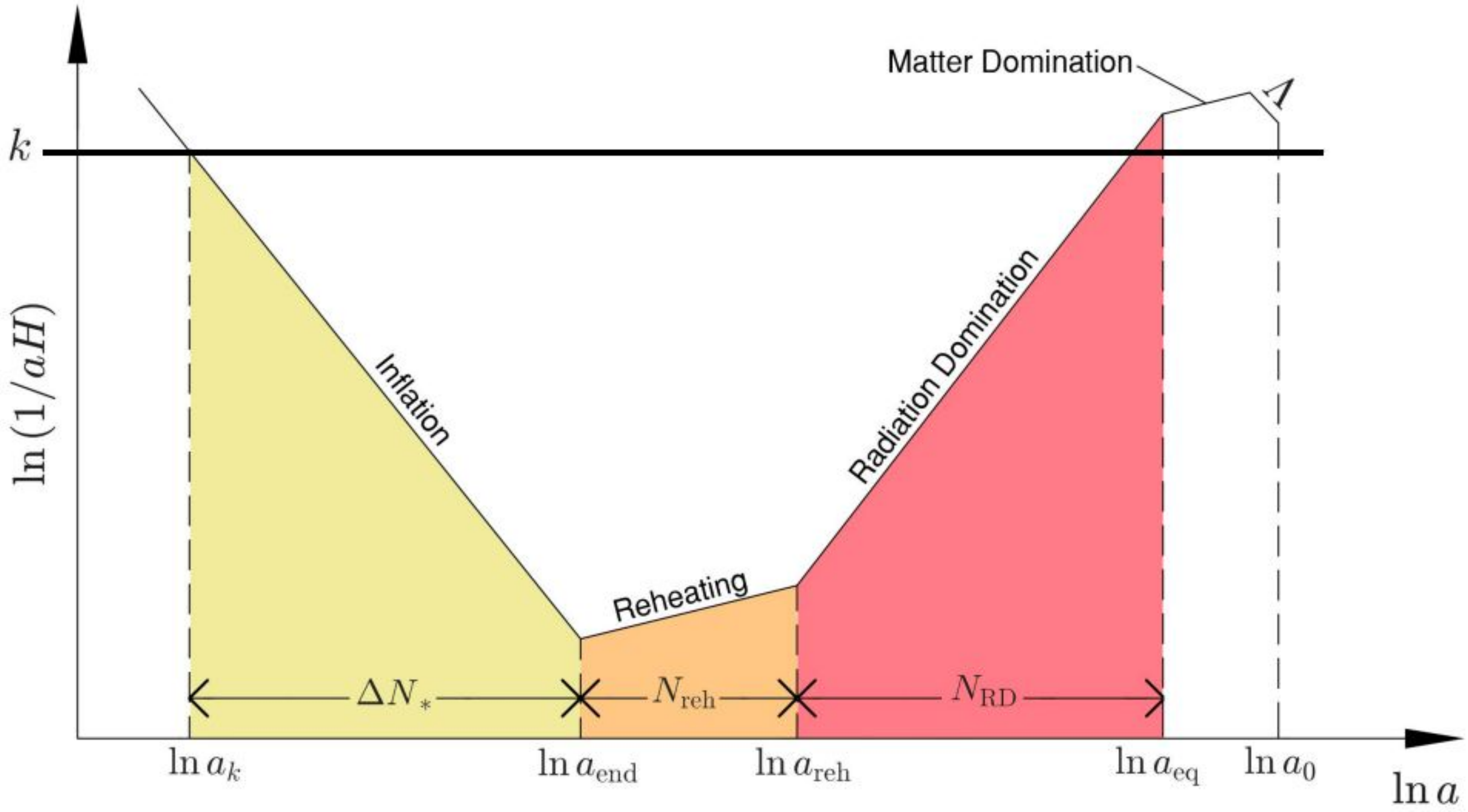


Figure 1: Potentials for the T-Model inflation $\tanh^{2n}(\varphi/\sqrt{6})$ for $n = 1, 2, 3, 4$

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

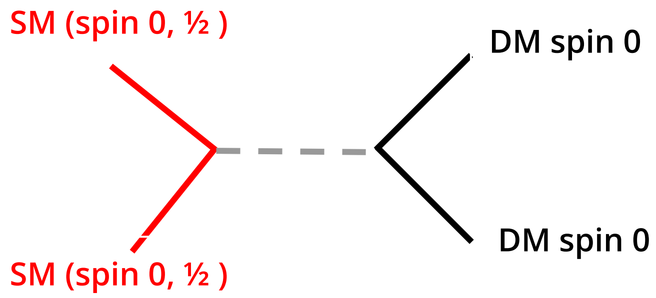
Usual amplitude computation for a s-channel scattering of (massless) SM particles giving DM particles

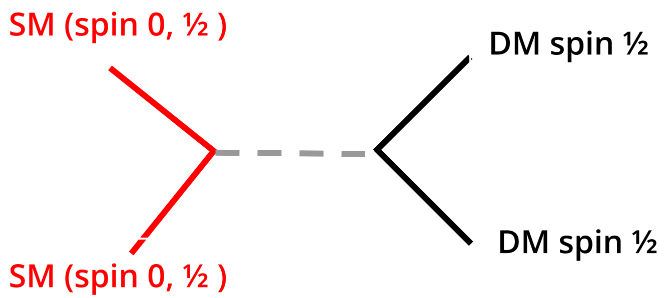
$$|\overline{\mathcal{M}}^{00}|^2 = \frac{1}{64M_P^4}\frac{t^2(s+t)^2}{s^2},$$

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

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

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



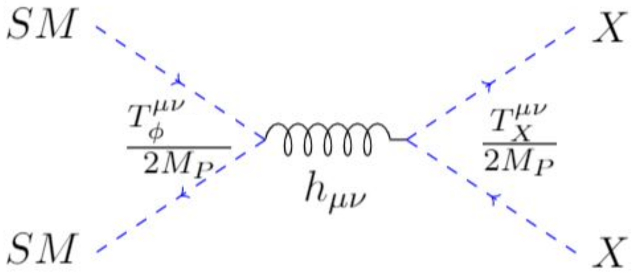


Gravitational portals in the early Universe, Simon Cléry, Yann Mambrini, Keith A. Olive, Sarunas Verner, Phys.Rev.D (2022).

From amplitudes compute the rate of DM production for each process

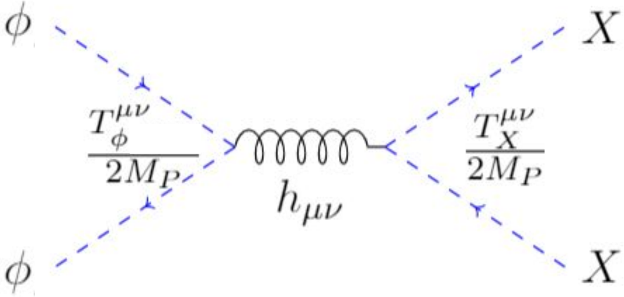
$$R_j^T = \beta_j \frac{\boxed{T^8}}{M_P^4}$$ for spin j = 0, ½ DM final state

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

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

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

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, Sarunas Verner, Phys.Rev.D (2022).

For fermionic DM

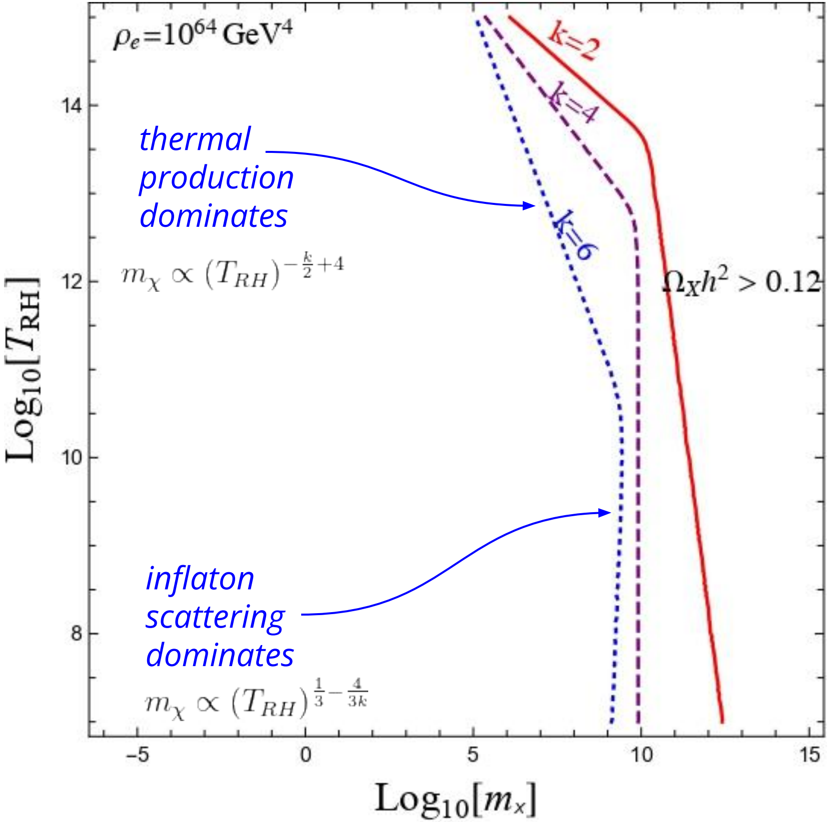
Inflaton scattering is helicity suppressed
➜ broken spectrum due to strong DM mass dependence

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

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

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

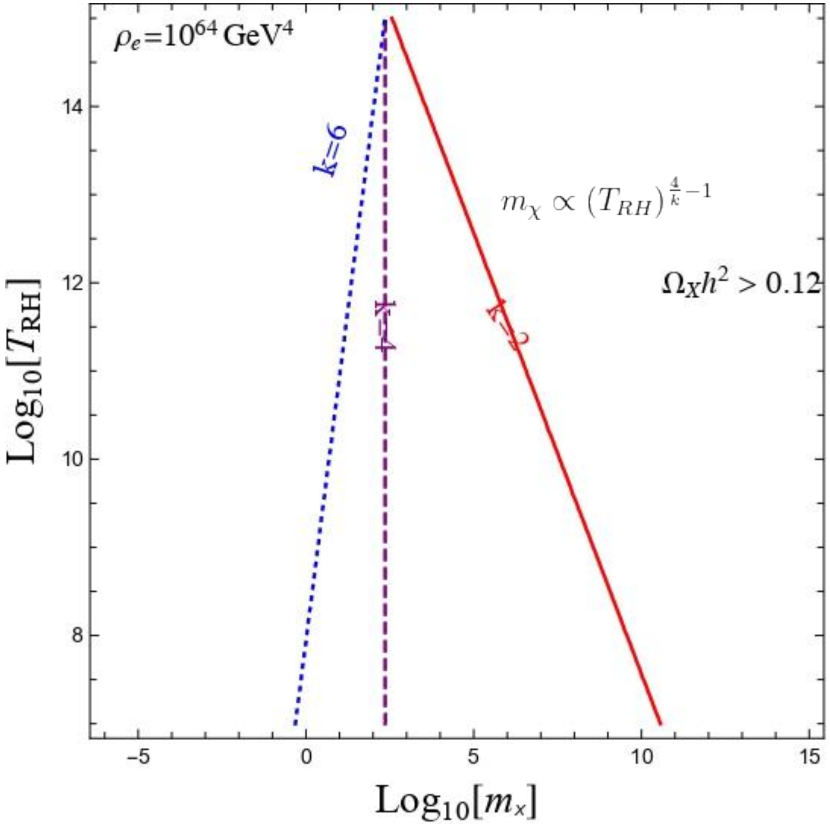
Gravitational portals in the early Universe, Simon Cléry, Yann Mambrini, Keith A. Olive, Sarunas Verner, Phys.Rev.D (2022).



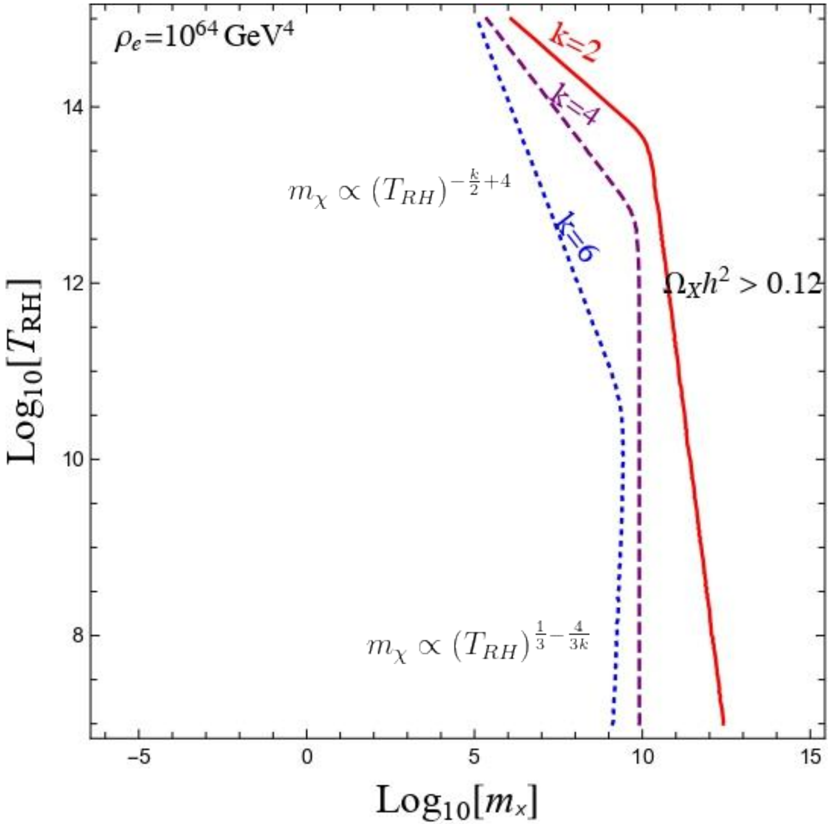
Ωh^2 = 0.12 in the case of a spin ½ DM, all contributions added

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.

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

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

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

$$\downarrow$$

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

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

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

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

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 $\phi_{\text{end}} \sim M_P$ 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 : $\xi_h > 10^{-1}$

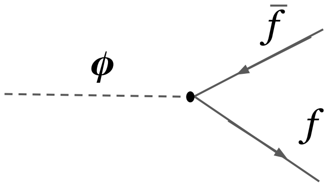
➜ In the case of Higgs inflation, ξh is fixed from CMB (Planck)

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

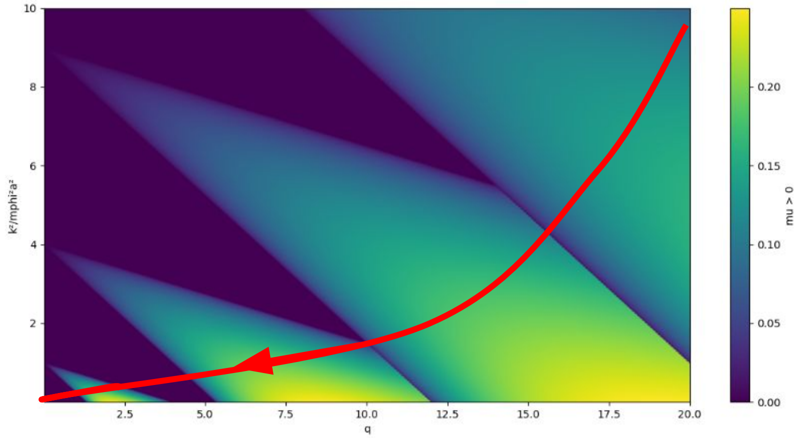
See *Freeze-in from preheating*, Garcia , Kaneta, Mambrini, Olive, Verner, JCAP (2022)

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)