Gravitational portals during reheating

TUG - Montpellier, 5th Oct 2022

Based on :

- *Gravitational portals in the early Universe*, SC, Y.Mambrini, K.A. Olive, S. Verner, **2112.15214**
- *Gravitational Portals with Non-Minimal Couplings*, SC, Y. Mambrini, K. A. Olive, A. Shkerin, S. Verner, **2203.02004**
- *Gravity as a Portal to Reheating, Leptogenesis and Dark Matter,* B. Barman, SC, R. Co, Y. Mambrini, K.A. Olive, **Soon on arXiv, stay tuned!**

Simon Cléry under the supervision of Yann Mambrini
simon.clery@ijclab.in2p3.fr
mambrini@ijclab.in2p3.fr

cnrs

IJCLab Irène Joliot-Curie
Laboratoire de Physique des 2 Infinis

université PARIS-SACLAY

Focus points

1 - Inflation and reheating

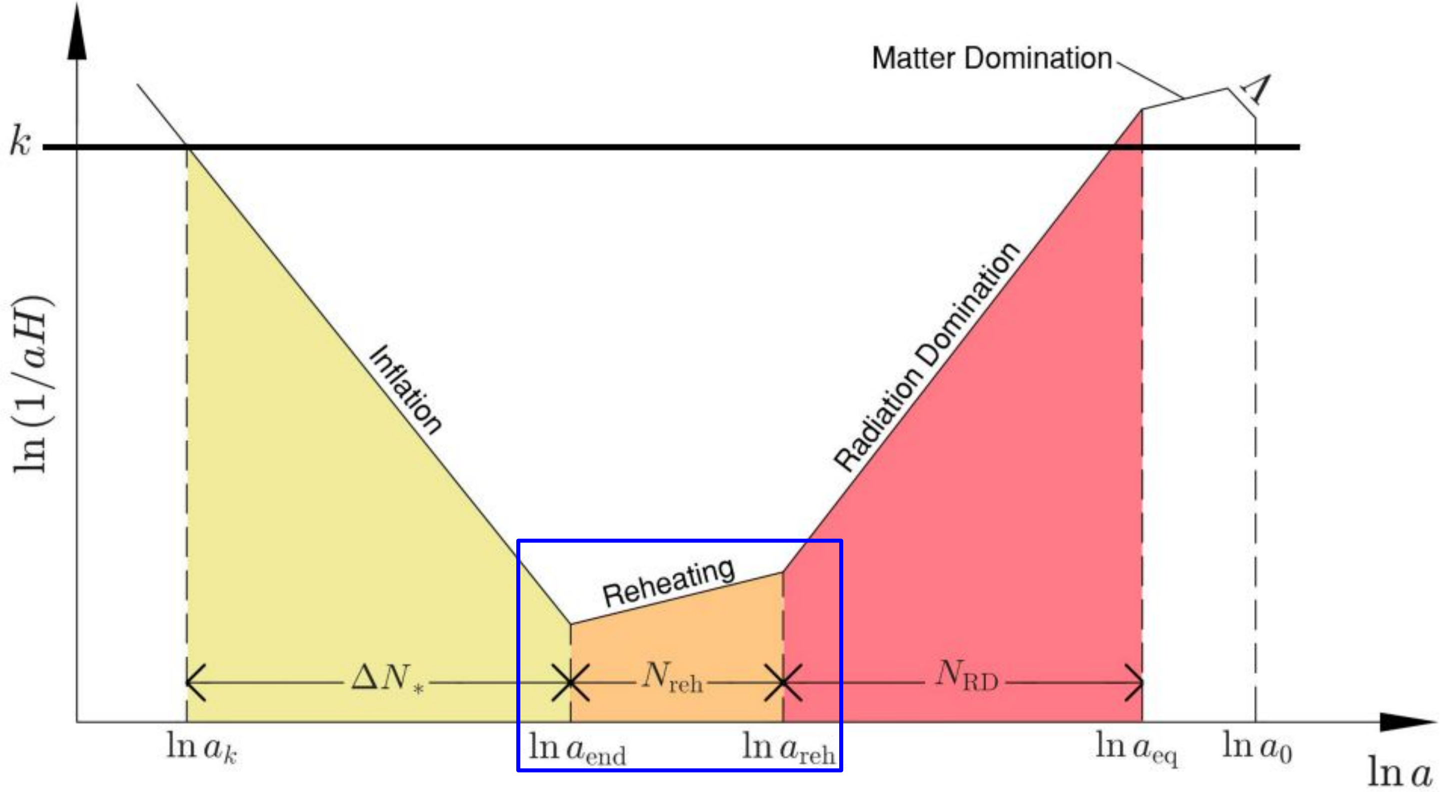
2 - Minimal gravitational portal

3 - Non-minimal coupling to gravity

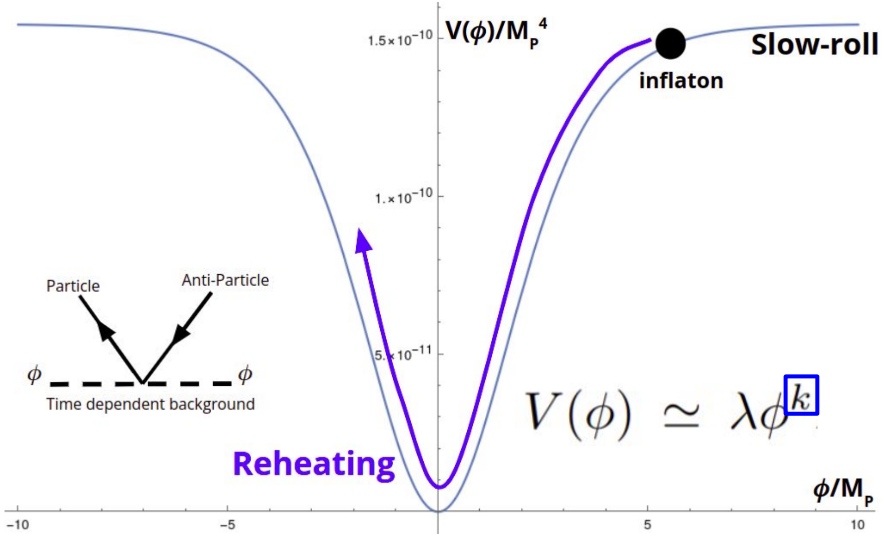
4 - Gravitational reheating

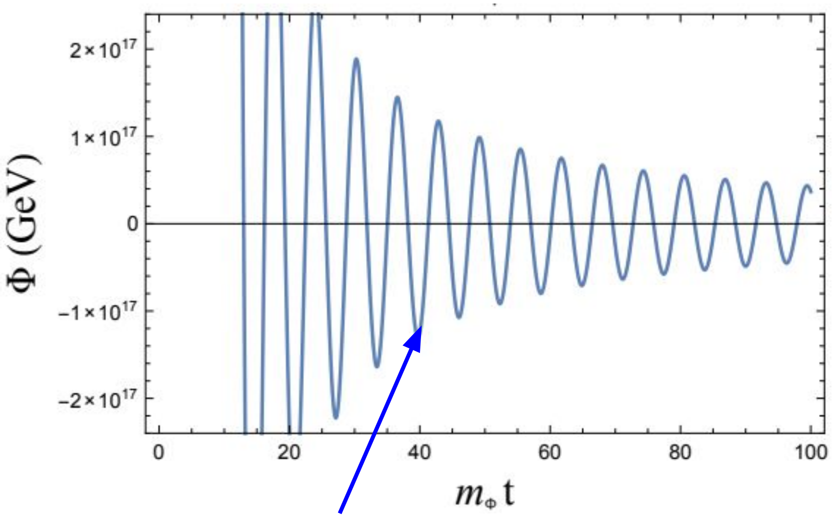
5 - Gravity as a portal to reheating leptogenesis and DM

1- Inflationary reheating



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





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

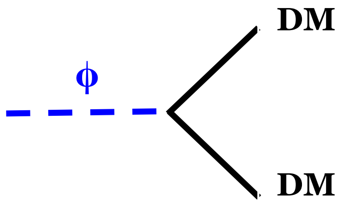
Redshifted envelop and frequency of the oscillations depend on the shape of the potential near the minimum

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

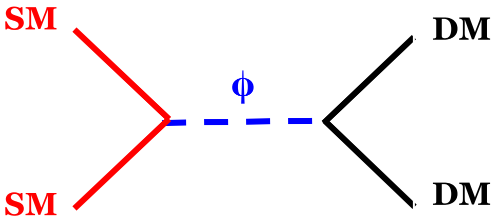
$$w = \frac{P_\phi}{\rho_\phi} = \frac{\frac{1}{2}\langle\dot{\phi}^2\rangle - \langle V(\phi)\rangle}{\frac{1}{2}\langle\dot{\phi}^2\rangle + \langle V(\phi)\rangle} = \boxed{\frac{k-2}{k+2}}$$

Perturbative processes (for non perturbative preheating and production during inflation →Mathias' talk !)

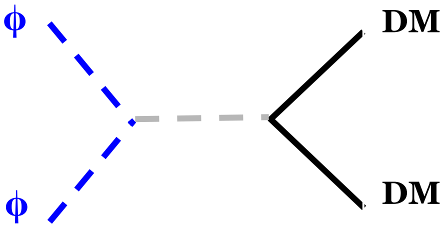
Inflaton sector can also handle non-thermal Dark Matter (DM) production through perturbative processes



➜ From inflaton background direct decay to DM, see for example *Reheating and Post-inflationary Production of Dark Matter*, Garcia, Kaneta, Mambrini, Olive, **2004.08404**



➜ From inflaton portal, in which the inflaton mediates between SM and DM sectors, see *The Inflaton Portal to Dark Matter*, Heurtier, **1707.08999**



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

2- Minimal gravitational portal

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

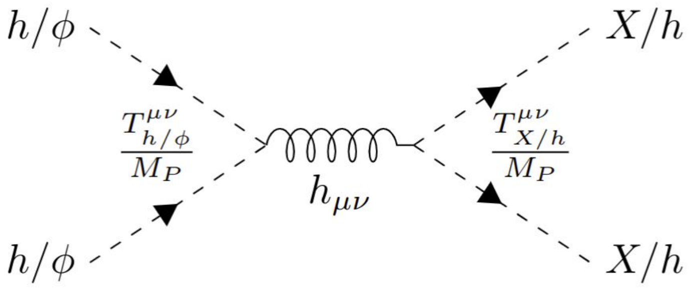
$$g_{\mu\nu} \simeq \eta_{\mu\nu} + 2h_{\mu\nu}/M_P$$

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

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

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

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



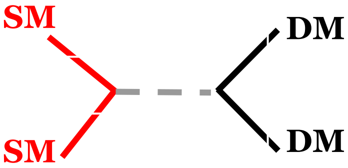
$$T_0^{\mu\nu} = \partial^\mu S \partial^\nu S - g^{\mu\nu} \left[\frac{1}{2} \partial^\alpha S \partial_\alpha S - V(S) \right],$$

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

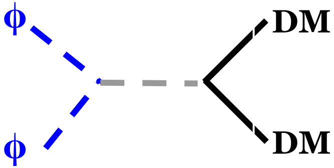
$$T_1^{\mu\nu} = \frac{1}{2} \left[F_\alpha^\mu F^{\nu\alpha} + F_\alpha^\nu F^{\mu\alpha} - \frac{1}{2} g^{\mu\nu} F^{\alpha\beta} F_{\alpha\beta} \right]$$

Graviton can play the portal between :

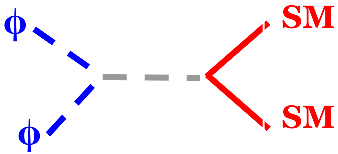
➜ Thermal bath and DM to populate DM through the FIMP scenario



➜ Inflaton and DM to directly produce DM from the condensate



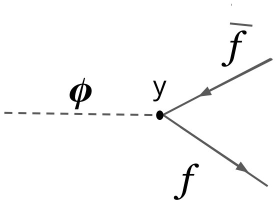
➜ Inflaton and the thermal bath to **initiate** the reheating process



BUT inflaton scattering cannot reheat entirely ($\rho_{\phi} = \rho_{Radiation}$) in a quadratic potential ($\propto \phi^2$) as the radiation produced is more "redshifted" than the inflaton energy density

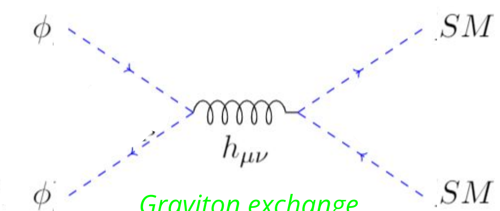
Gravitational portals in the early Universe, SC, Mambrini, Olive, Verner, **2112.15214**

Radiation production in minimal framework



Yukawa decay

+

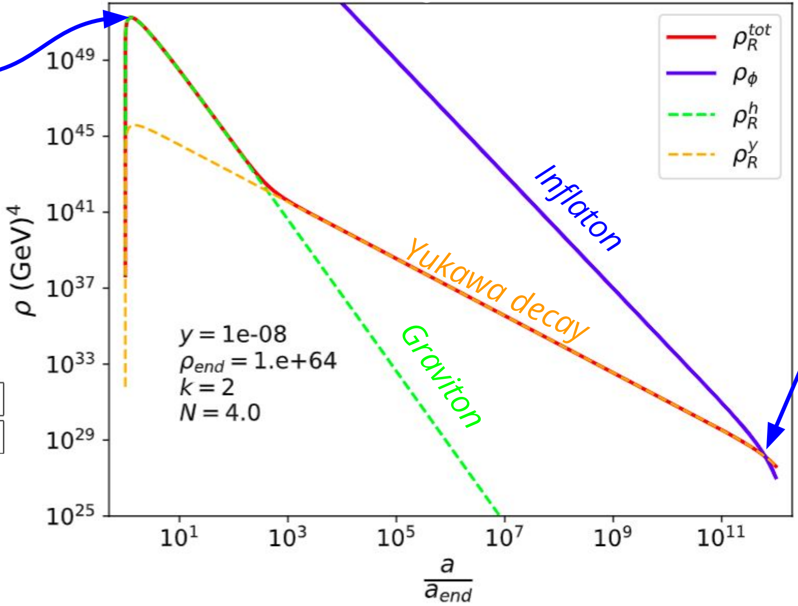


Graviton exchange

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

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

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



Reheating is still given by the decay width of the inflaton

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

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

DM production in minimal framework

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

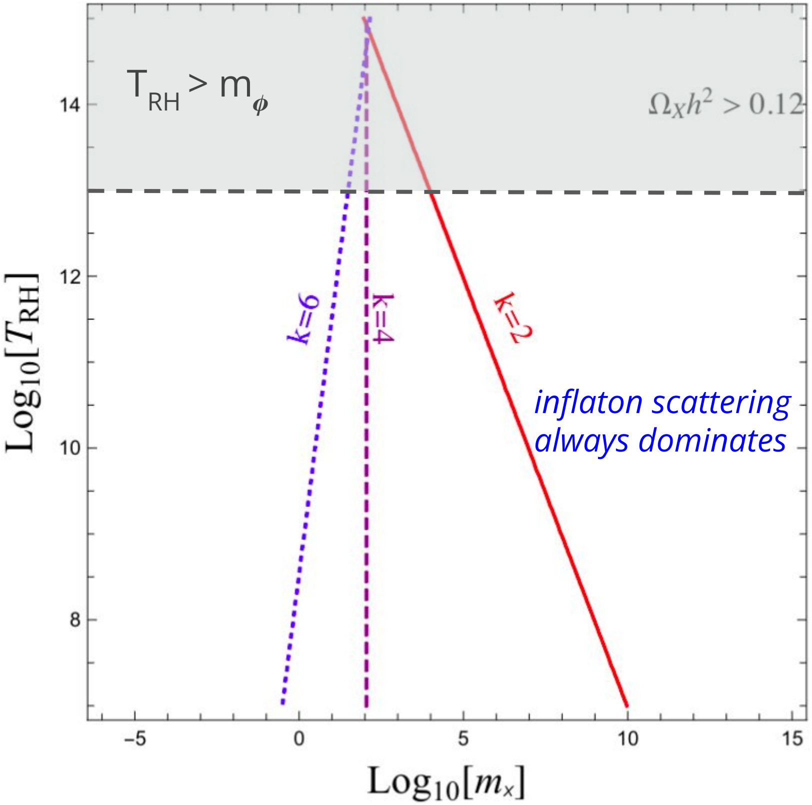


Figure 2 : DM relic, $\Omega h^2 = 0.12$ in the case of a ***spin 0 DM***

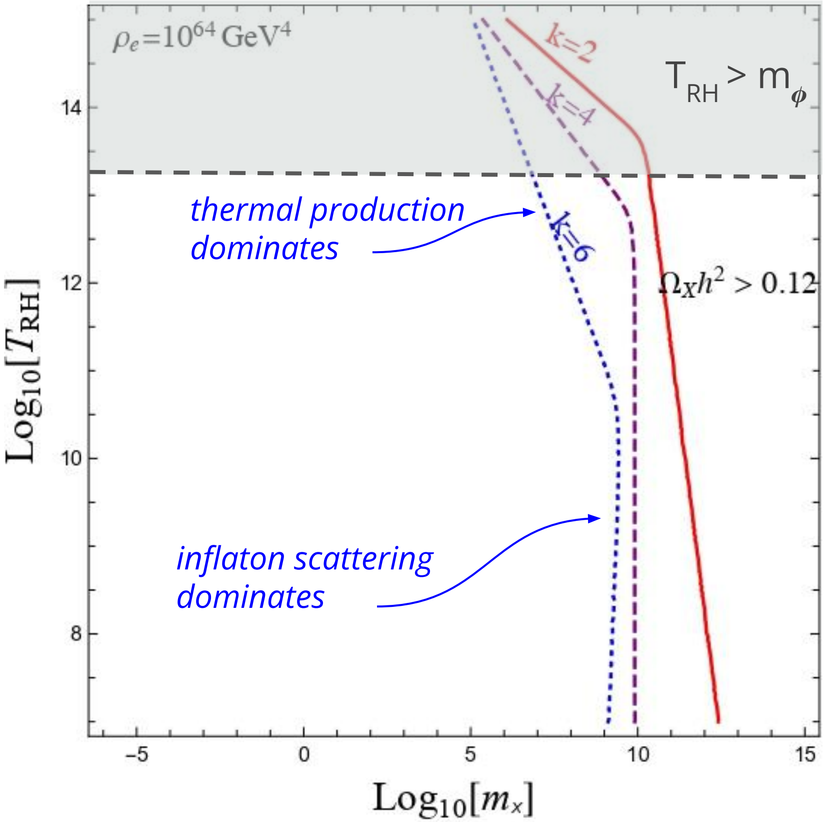


Figure 3 : DM relic, $\Omega h^2 = 0.12$ in the case of a ***spin ½ DM***

3- Non-minimal coupling to gravity

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

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

in the Jordan frame

with

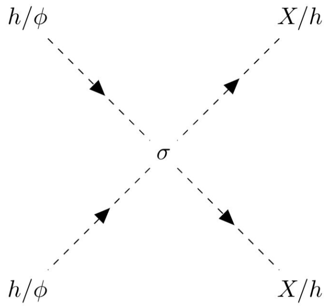
$$\Omega^2 \equiv 1 + \underbrace{\frac{\xi_\phi \phi^2}{M_P^2}}_{\text{inflaton}} + \underbrace{\frac{\xi_h h^2}{M_P^2}}_{\text{SM}} + \underbrace{\frac{\xi_X X^2}{M_P^2}}_{\text{DM}}$$

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

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

in the Einstein frame

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



Gravitational Portals with Non-Minimal Couplings, SC, Mambrini, Olive, Shkerin, Verner, **2203.02004** *Reheating and Dark Matter Freeze-in in the Higgs-R² Inflation Model*, Aoki, Lee, Menkara, Yamashita, **2202.13063**

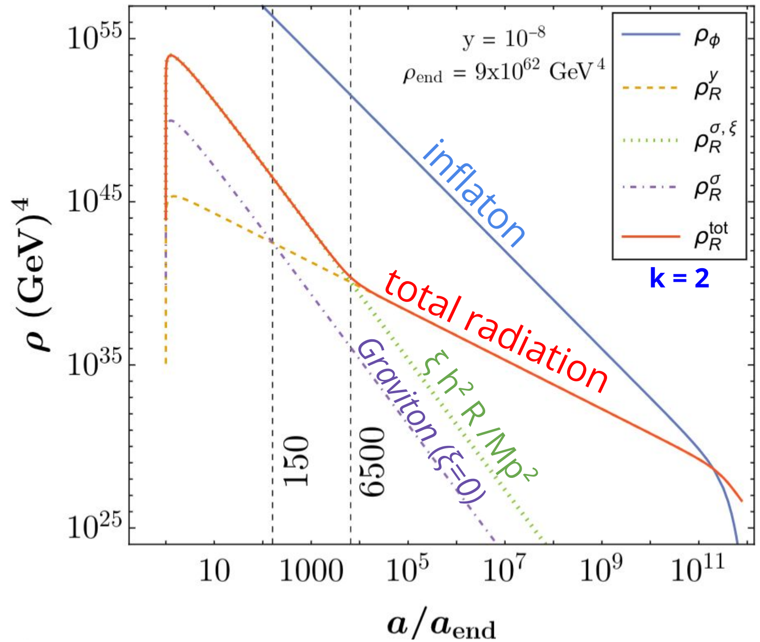


Figure 4 : Energy densities of *inflaton (blue)*, *total radiation (red)*, radiation from *inflaton decay (orange)*, from *scattering mediated by graviton (purple)* and from *non-minimal coupling (green)*, with $\xi_h = \xi = 2$

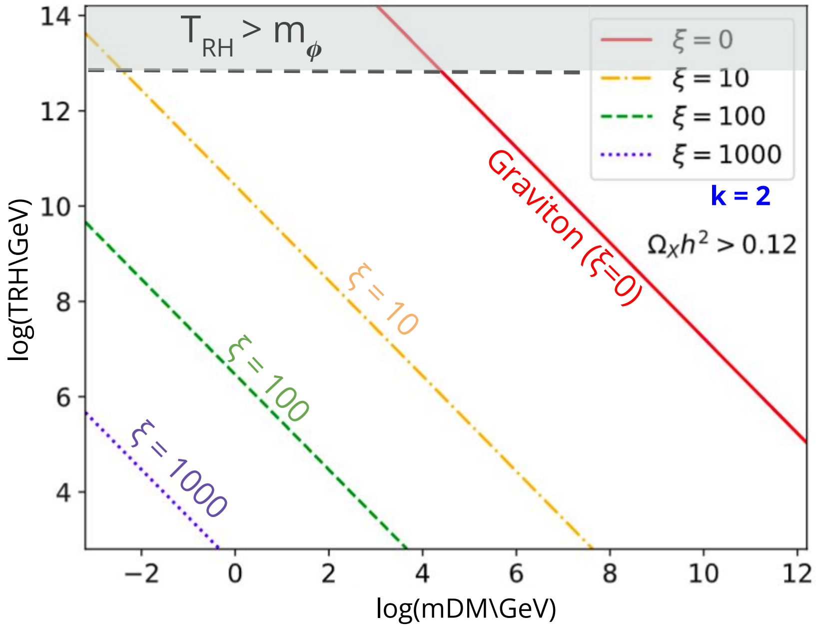
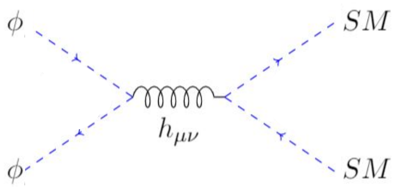


Figure 5 : Contours respecting $\Omega_X h^2 = 0.12$ *for spin 0 DM*, for different values of $\xi_h = \xi_X = \xi$. Both *minimal and non-minimal contributions are added.*

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

4 - Gravitational reheating

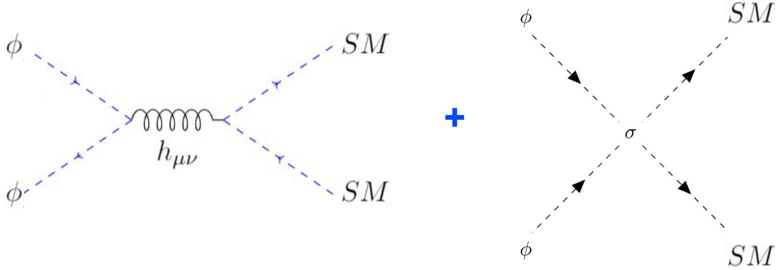


➜ Graviton exchange processes can be sufficient to reheat entirely, for sufficiently steep inflaton potential : k > 9

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

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

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



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

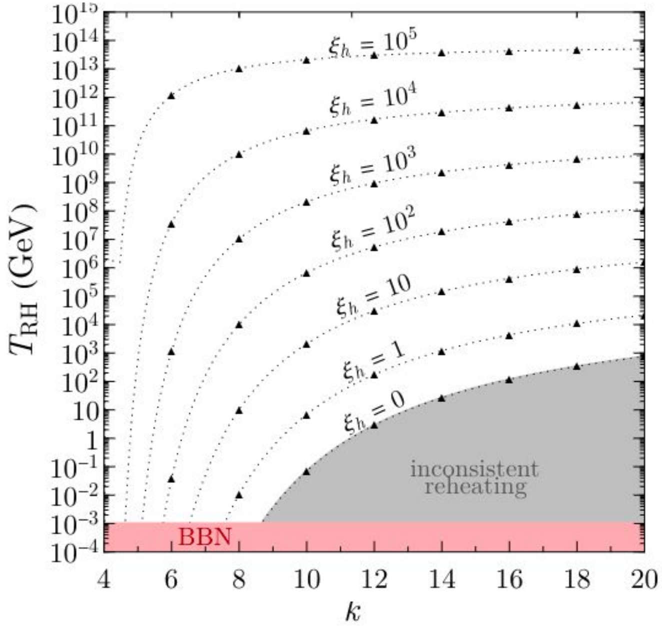
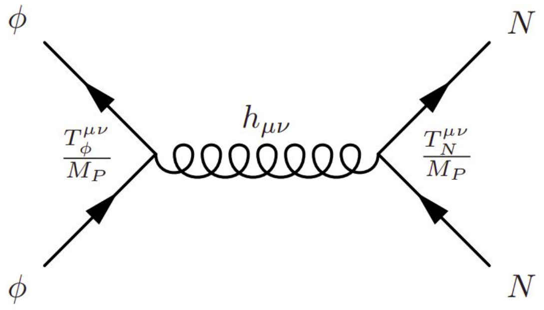
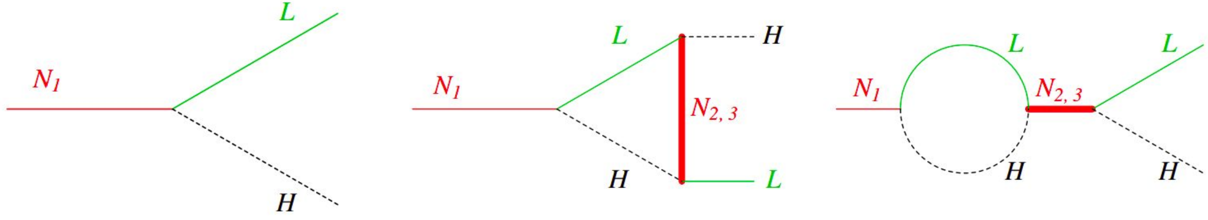


Figure 6 : Reheating temperature from gravitational portals as function of k, for different ξ_h

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





Baryogenesis via leptogenesis, Strumia, **0608347**

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 sterile neutrino.

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

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

Considering type I see-saw mechanism with, v = 174 GeV (Higgs VEV) and the effective CP violation phase δ_{eff}

Lepton asymmetry, out-of equilibrium

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

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

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

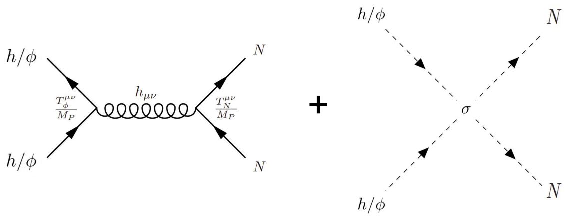
$$\Omega^2 \equiv 1 + \frac{\xi_\phi\,\phi^2}{M_P^2} + \frac{\xi_h\,h^2}{M_P^2}$$

Non-minimal couplings with gravity

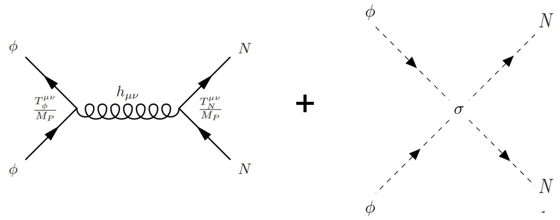
$$\widetilde{\mathcal{L}}_{N_i} = -\frac{1}{2}\,M_{N_i}\,\overline{N_i^c}N_i - (y_N)_{ij}\,\overline{N}_i\,\widetilde{H}^\dagger\,L_j + \text{h.c.}\,.$$

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

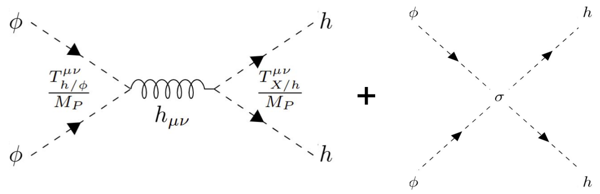
N_2, N_3 are much heavier and generate the lepton asymmetry through their gravitational production and out-of equilibrium decay



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

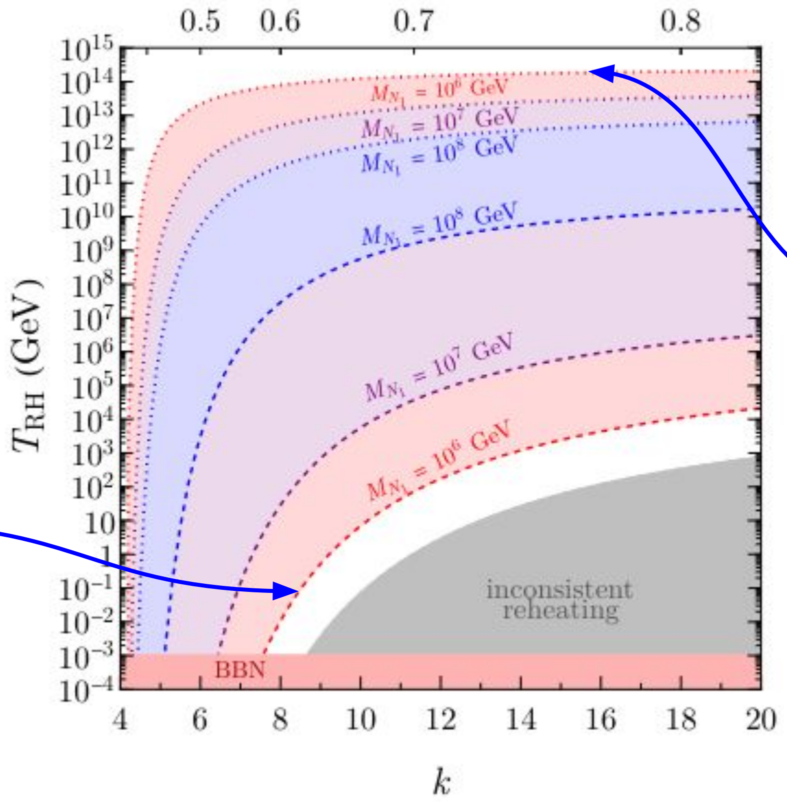


$\phi\phi \to N_2N_2$ (N_3 N_3) from minimal and non-minimal couplings



$\phi\phi \to$ SM SM from minimal and non-minimal couplings, for radiation production

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 7 : 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, ***Soon on arXiv, stay tuned!***

Baryon asymmetry from leptogenesis (N_2)

Lepton asymmetry is converted into a baryon asymmetry :

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

Gravity as a Portal to Reheating, Leptogenesis and Dark Matter, B. Barman, SC, R. Co, Y. Mambrini, K.A. Olive, ***Soon on arXiv, stay tuned!***

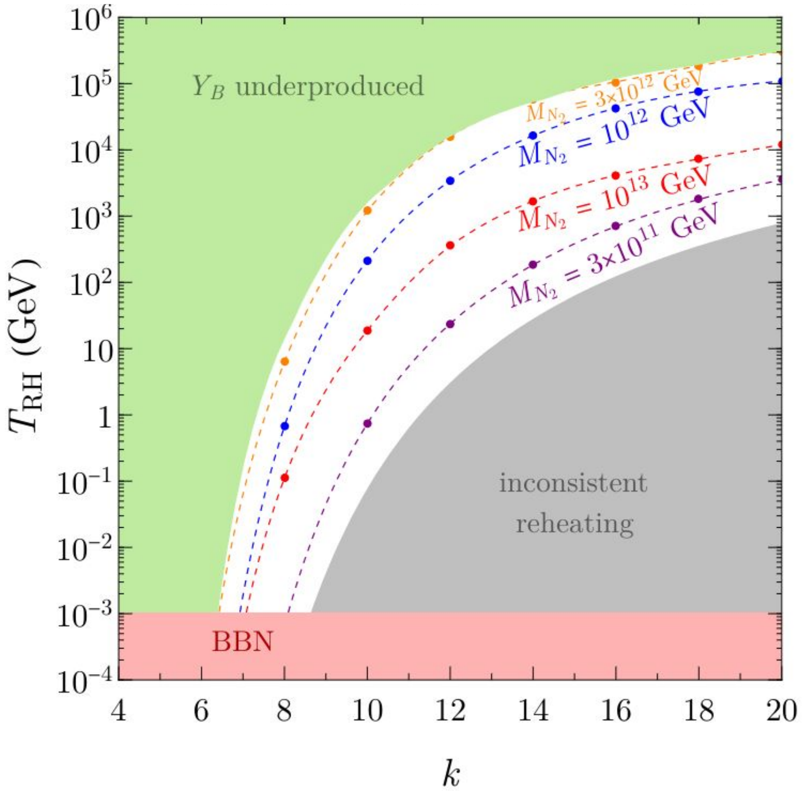
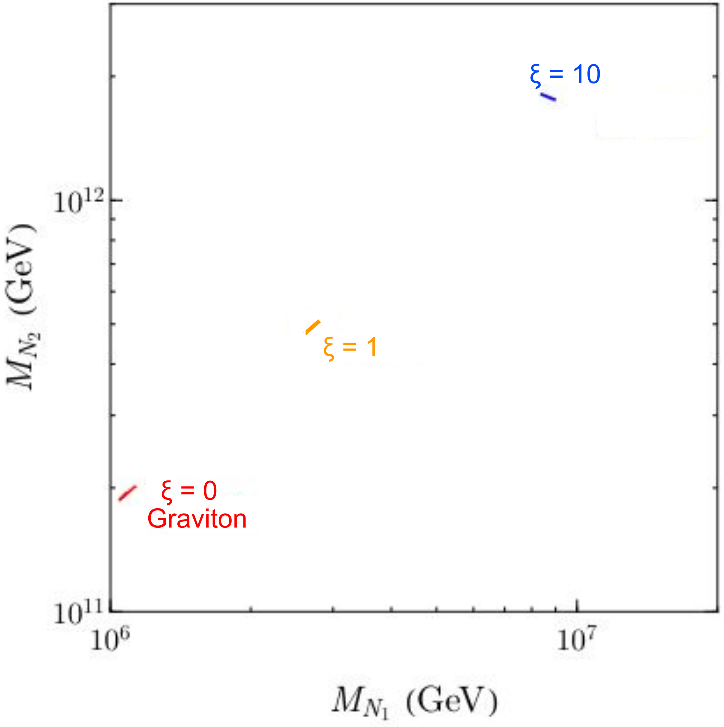


Figure 8 : Lines corresponding to the observed baryon asymmetry $Y_B \simeq 8.7 \times 10^{-11}$ *for different* M_{N2}

Gravitational leptogenesis and DM production simultaneously



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

We choose in this table k = 6 as a benchmark. For each ξ on the plot, the range runs over k ∈ [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, ***Soon on arXiv, stay tuned!***

Figure 9 : (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

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

➜ Unavoidable lower limits on radiation and DM production

➜ Non-minimal coupling to gravity can naturally enhance particle production

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

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

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

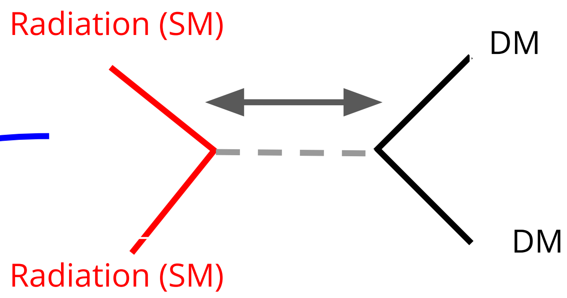
Thank you for your attention !

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 :

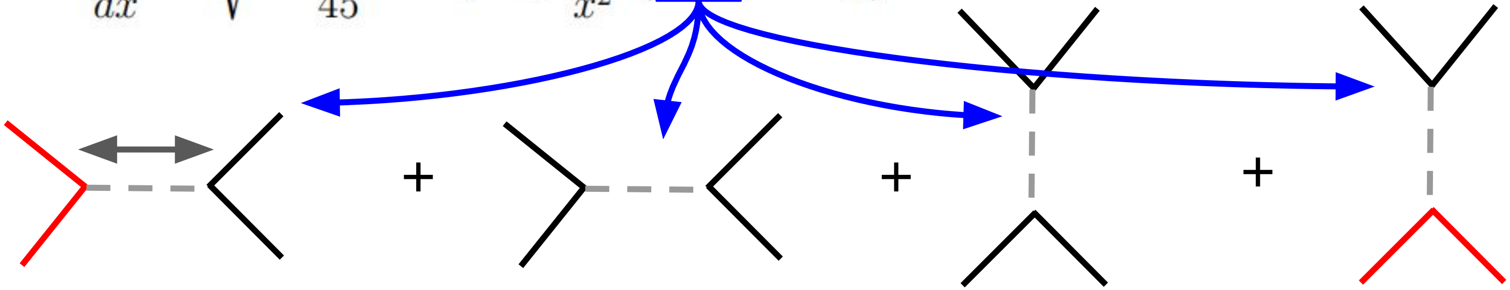


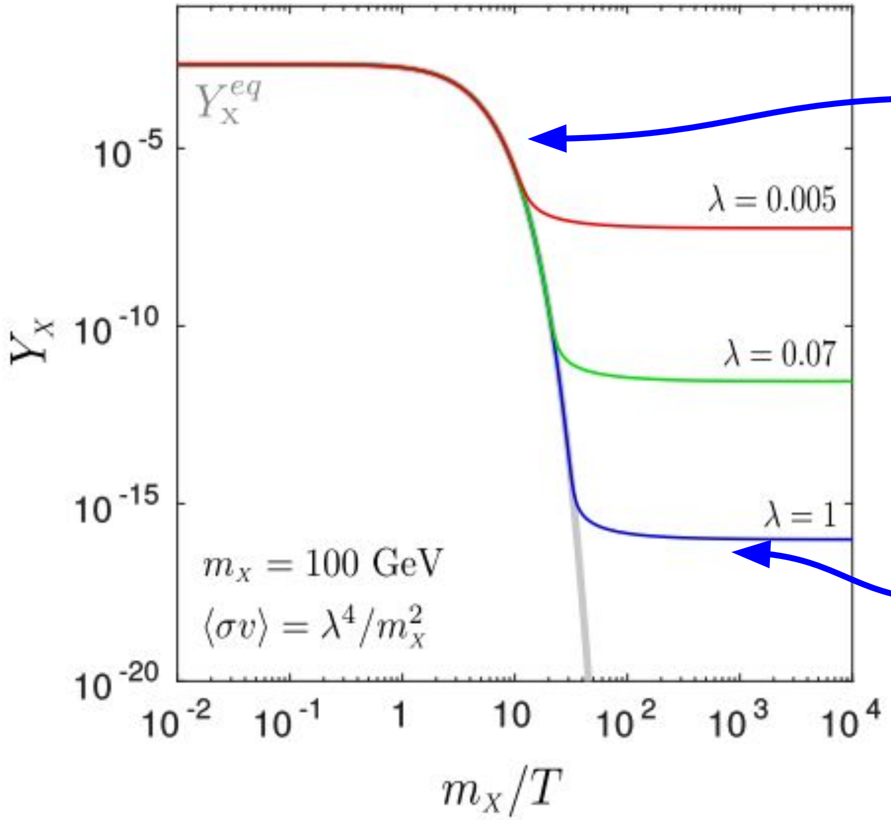
$$\dot{n}_\chi + 3Hn_\chi = g_\chi^2 \langle \sigma v \rangle n_r^2 \equiv \boxed{R(T)}$$

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

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

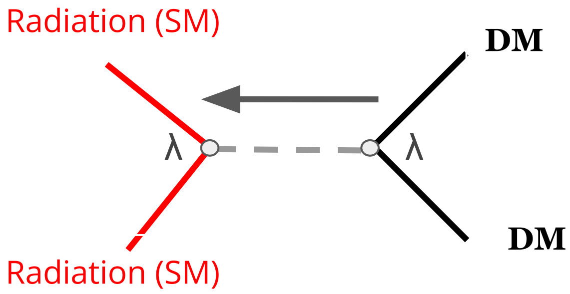
Thermal and chemical equilibrium



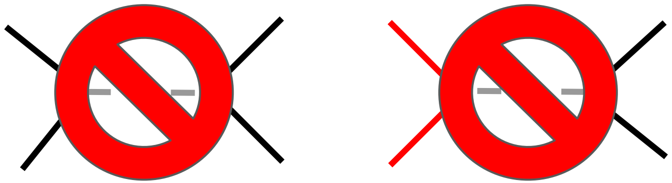


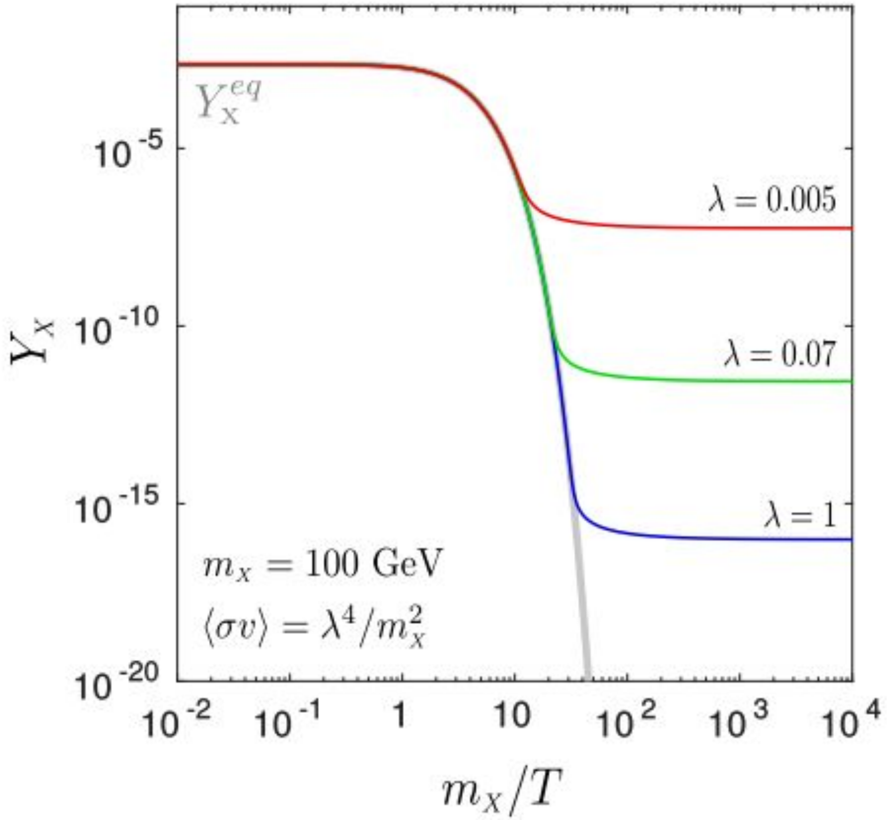
From *Origins for dark matter particles: from the "WIMP miracle" to the "FIMP wonder"* - Maira Dutra

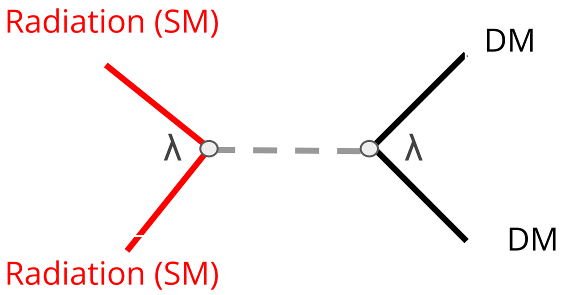
T ≪ mDM : WIMP becomes non-relativistic
→departs from its equilibrium value and starts chemical decoupling



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

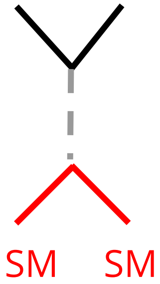






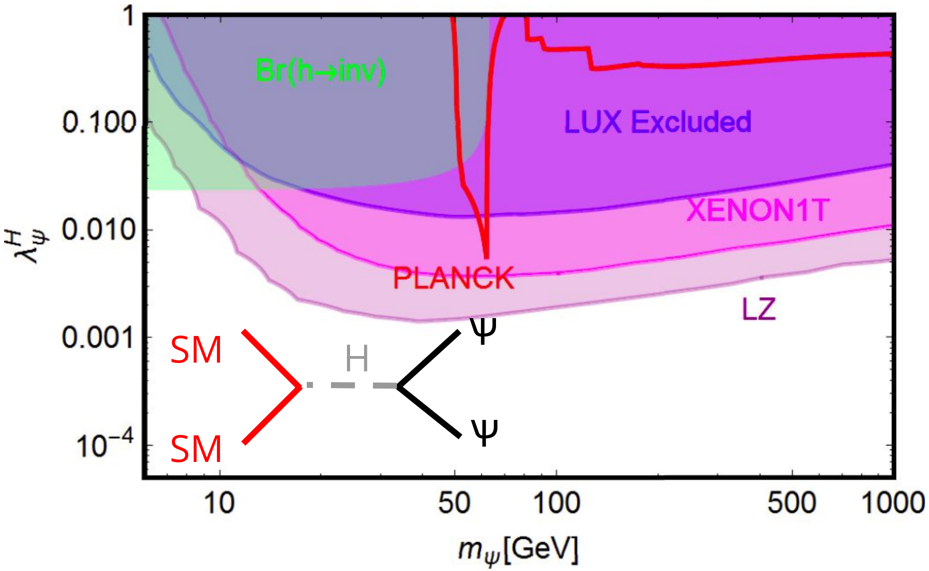
Typical electroweak scale massive particle (~100 GeV) with electroweak coupling production corresponds to the observed relic abundance of Dark Matter $\Omega h^2 \simeq 0.12$

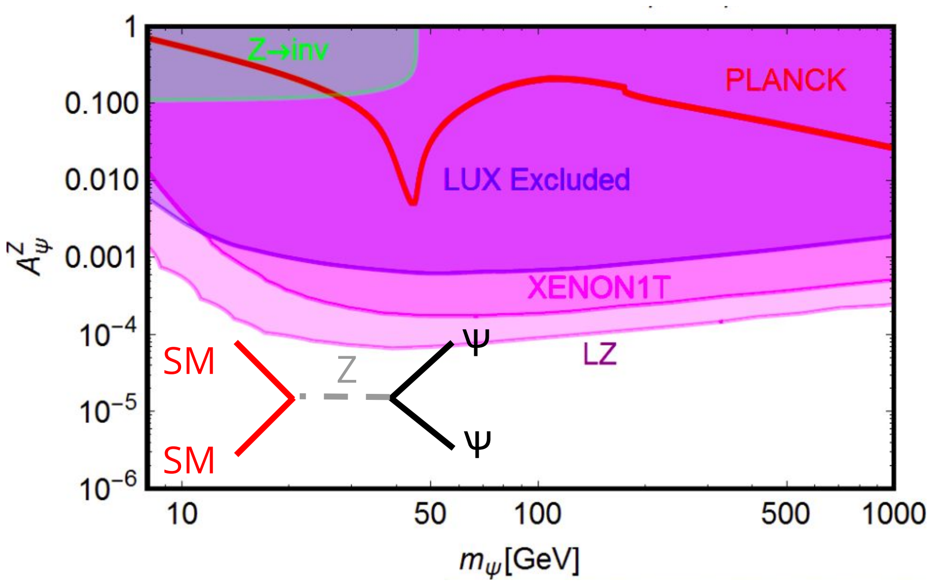
→ No new physical scale is needed, just a new sector to connect with the SM electroweak sector !



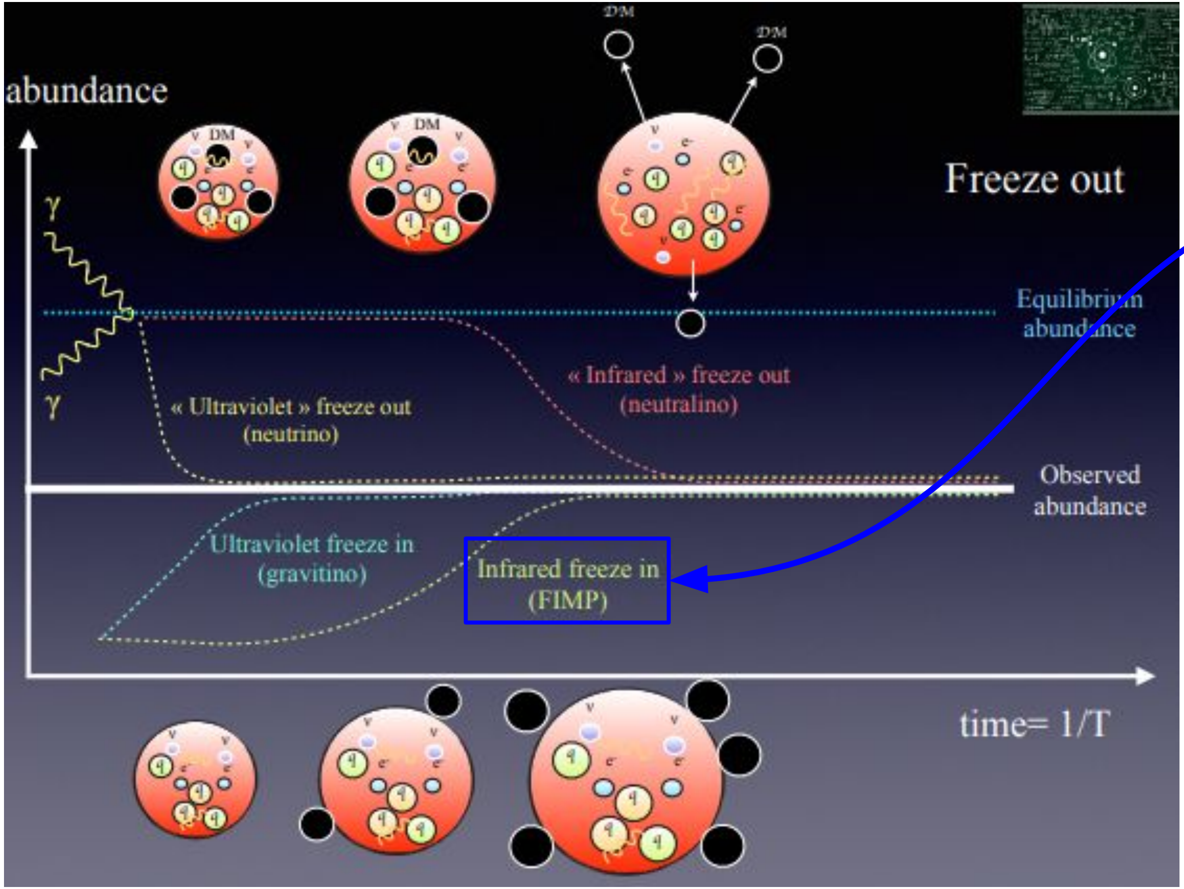
Probing DM scattering with nucleons, electrons = direct detection

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



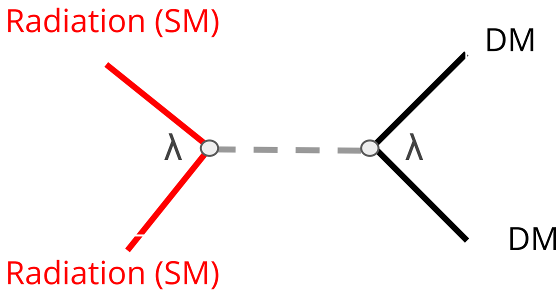


FIMP



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

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

Class of models : α-attractor T-model inflation

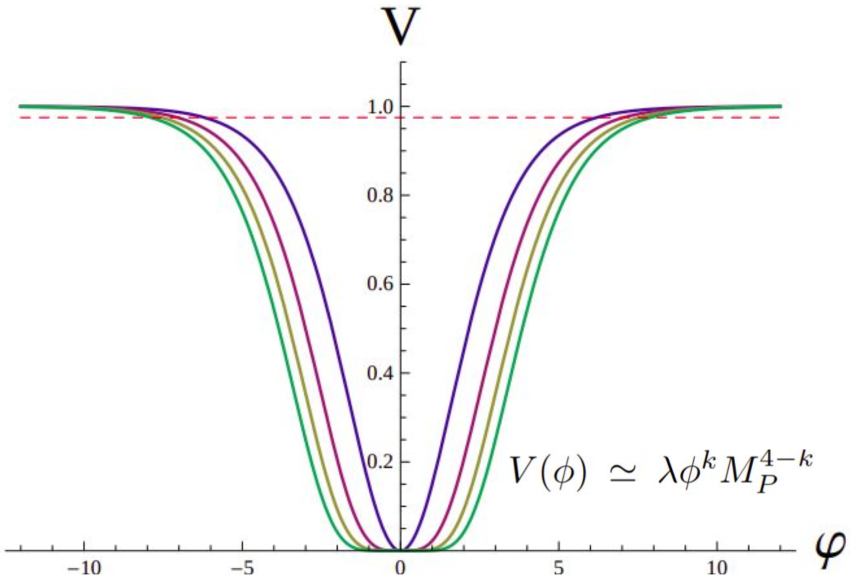


Figure 1: Potentials for the T-Model inflation $\tanh^{2n}(\varphi/\sqrt{6})$ for $n = 1, 2, 3, 4$

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

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

Boltzmann approach

Assumes that the background geometry is Minkowskian and compute transition probability

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

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

From this, production rate can be computed by

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

which is the right hand side of the Boltzmann equations

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

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

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

See Boltzmann or Bogoliubov? Approaches Compared in Gravitational Particle Production, K. Kaneta, S. M. Lee, K. Oda, **2206.10929**

Inflaton scattering

Potential near the minimum is a power k-dependant monomial

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

Treat the time dependent condensate as a time dependent coupling with an amplitude and quasi-periodic function which is k-dependent

$$\phi(t) \;=\; \phi_0(t) \cdot \mathcal{P}(t)$$

➔ An homogeneous classical field, not a quantum field !

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

Expand the quasi-periodic function in Fourier modes

with $\omega = m_\phi \sqrt{\frac{\pi k}{2(k-1)}} \frac{\Gamma(\frac{1}{2}+\frac{1}{k})}{\Gamma(\frac{1}{k})}$

Each Fourier mode adds its contribution to the scattering amplitude with its energy *En* = *n*.ω

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

Bogoliubov approach

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

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

Consider simply a single field in the vacuum

EOM : $\widetilde{\chi}'' + \omega^2 \widetilde{\chi} = 0$ with $\omega^2 \equiv -\nabla^2 + \boxed{a^2} m_\chi^2 + \boxed{\Delta}$

time dependent frequency !

Then, it is clear that the Hamiltonian is changing with time through the time dependence in ω.
=> cannot decompose χ based on the positive/negative frequency in the Fourier space

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

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

→

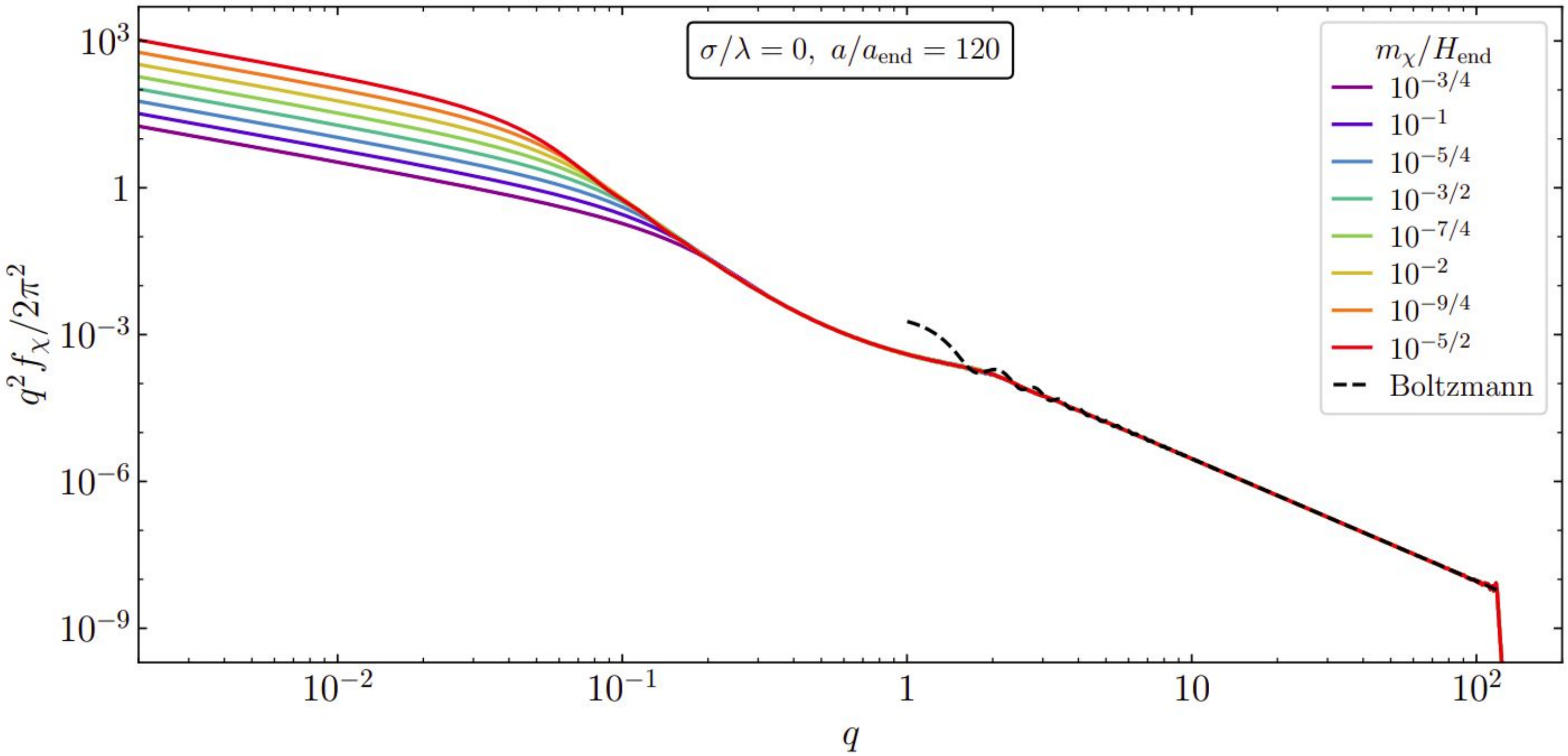
Bogoliubov coefficients

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

→ the occupation number is given by

$$|\beta_k|^2$$

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



Phase space distribution of a gravitationally excited scalar field for a range of DM masses, coded by color. The dashed black curve corresponds to the numerical integration of the Boltzmann equation, which is valid for q > 1

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

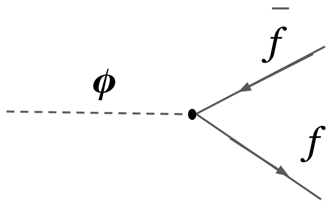
Particle production

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

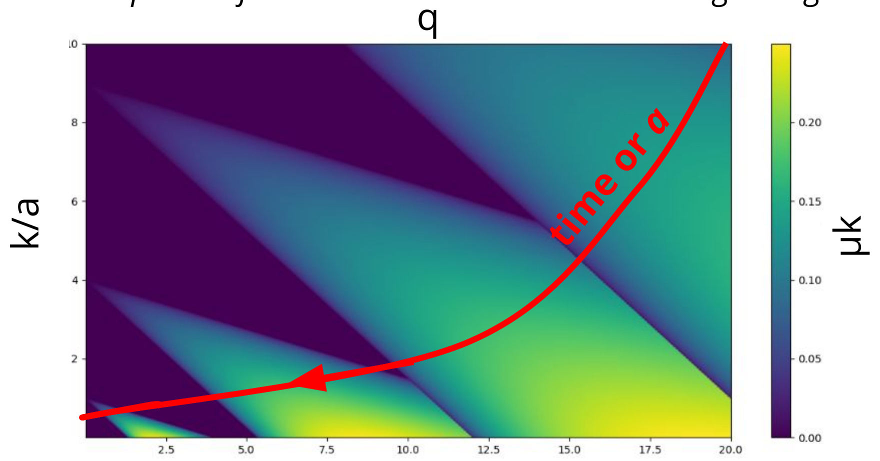
Freeze-in from preheating, Garcia , Kaneta, Mambrini, Olive, Verner, **2109.13280**

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

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

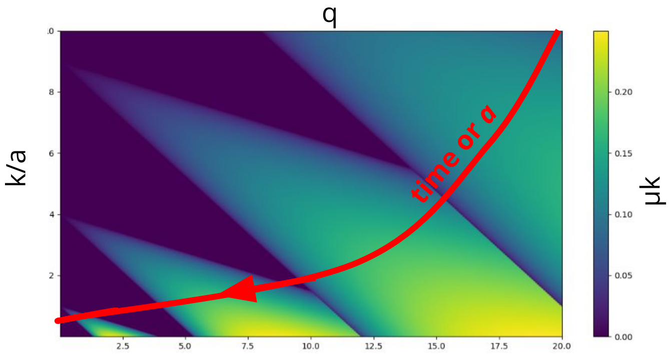
$$\chi_k'' + \left(\frac{k^2}{m_\phi^2 a^2} + 2q - 2q\cos(2z) \right) \chi_k = 0$$

Mathieu equation for Fourier modes in the oscillating background



Instabilities in the colored regions
=> number of occupation increasing

Preheating : non-perturbative processes

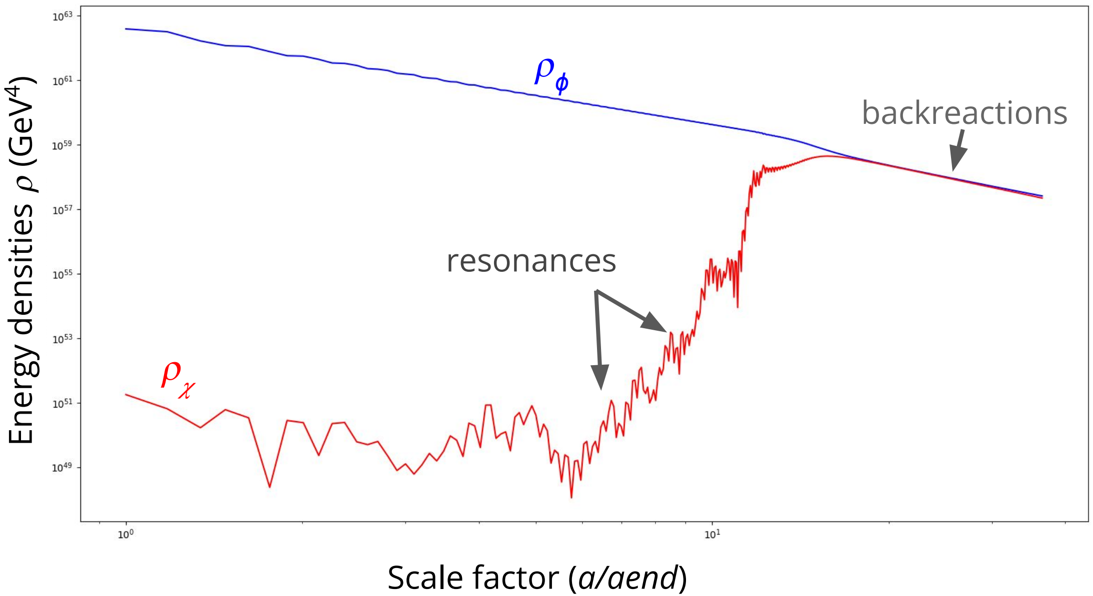


Instabilities in the colored regions
=> number of occupation increasing

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

with q ~ σ.(ϕ / M_P)

reduced coupling σ ~10^{-6}



Preheating corresponds to the first oscillations of the background => resonances and exponential production

For large couplings, reach a regime of large backreactions of the fields on the background

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

Thermal bath scattering

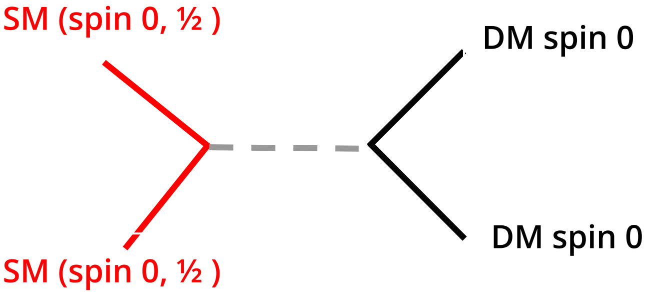
Usual amplitude computation for a s-channel scattering of (massless) SM particles giving DM particles

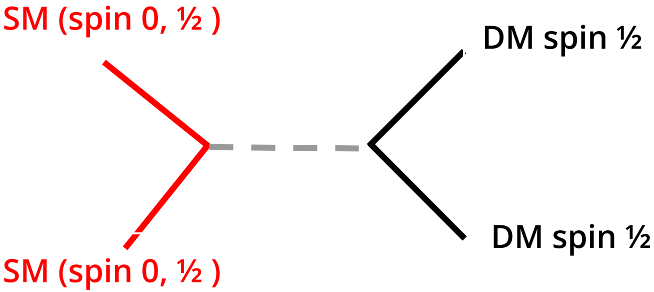
$$|\overline{\mathcal{M}}^{00}|^2 = \frac{1}{64M_P^4}\frac{t^2(s+t)^2}{s^2},$$

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

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

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



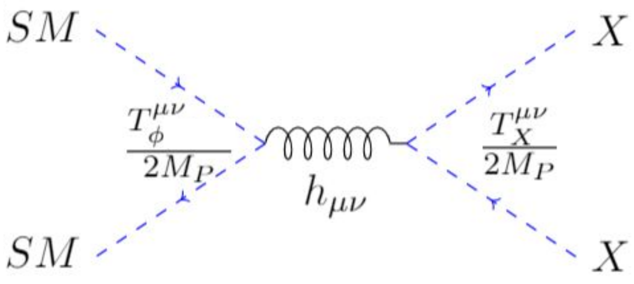


Gravitational portals in the early Universe, Simon Cléry, Yann Mambrini, Keith A. Olive, Sarunas Verner, **2112.15214**

From amplitudes compute the rate of DM production for each process

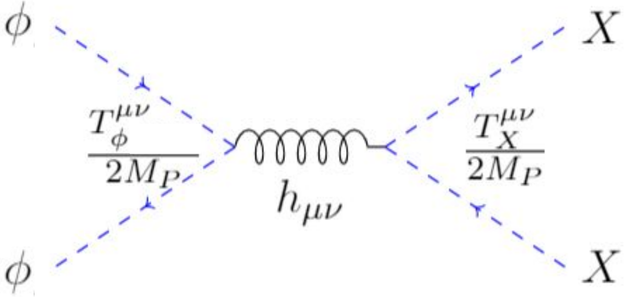
$$R_j^T = \beta_j \frac{T^8}{M_P^4}$$ for spin j = 0, ½ DM final state

See *Spin-2 Portal Dark Matter*, Nicolás Bernal, Maíra Dutra, Yann Mambrini, Keith Olive, Marco Peloso, 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, **2112.15214**

Compute the number density of DM as a function of the scale factor to have the relic abundance

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

Thermal case

The relic abundance decreases with k coming from the fact that the Hubble parameter is dominated by inflaton evolution ➞ greater dependence on T_{RH} for larger value of k, slowing down the DM production

---

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

Spin 0 inflaton scattering case

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

Spin ½ inflaton scattering case

spin ½ helicity suppression !

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

For fermionic DM

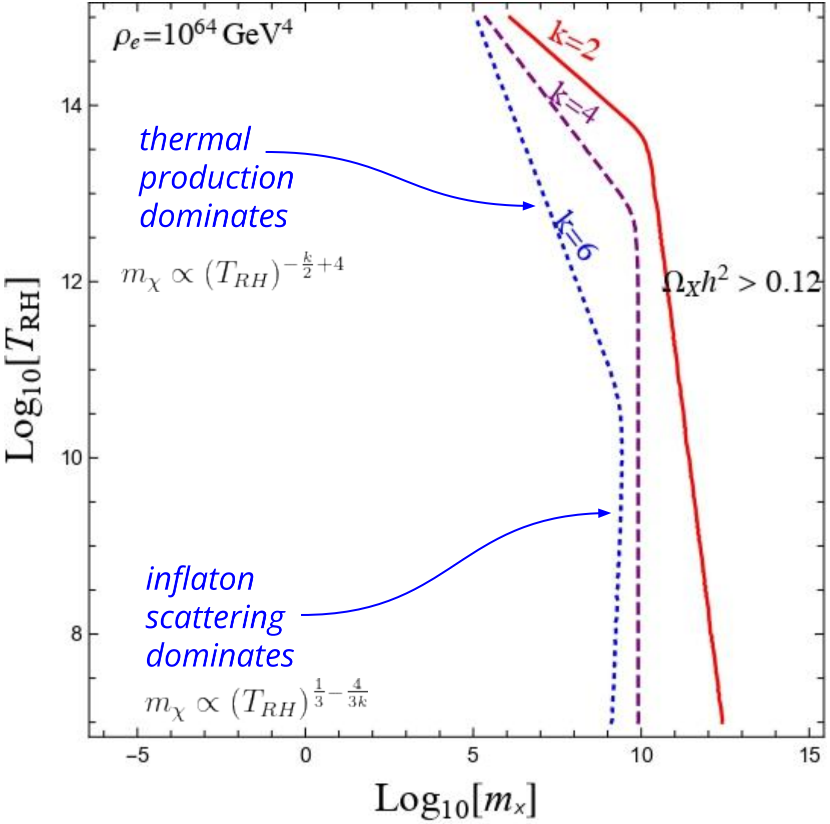
Inflaton scattering is helicity suppressed
➜ broken spectrum due to strong DM mass dependence

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

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, **2112.15214**



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

Leading order interactions

in Einstein frame

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

↓

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

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

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

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

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

with

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

and

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

→ in the Einstein frame

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

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

→ Leading order interactions of RHN

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

Non-canonical kinetic term

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

in Einstein frame

with

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

and

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

non-canonical kinetic term

In general, it is impossible to make a field redefinition that would bring it to the canonical form, unless all three non-minimal couplings vanish.

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

In the small-field limit, we can expand the action in powers of M_P^{-2} and obtain canonical kinetic term and deduce the leading-order interactions induced by the non-minimal couplings.

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

Non-minimal couplings bounds

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

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

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

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

See for example *Cosmological Aspects of Higgs Vacuum Metastability,* Tommi Markkanen, Arttu Rajantie, Stephen Stopyra, **1809.06923**

➜ On the other hand, to prevent the EW vacuum instability at high energy scale, during inflation, we can invoke stabilization through effective Higgs mass from the non-minimal coupling : $\xi_h > 10^{-1}$

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

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

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**