Gravitational production after inflation : Boltzmann and Bogoliubov approaches

Simon Cléry, TUM

DESY Theory Workshop 2025

* *Generalizing the Bogoliubov vs Boltzmann approaches in gravitational production,* Chakraborty, SC, Haque, Maity, Mambrini, **2503.21877**

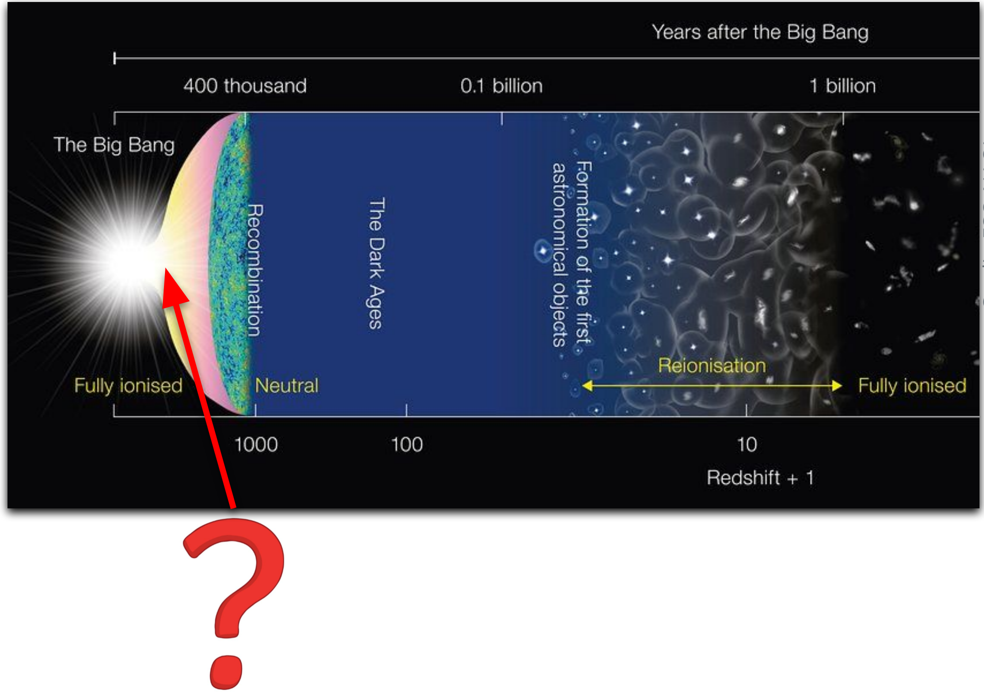
See also

* *Boltzmann or Bogoliubov? Approaches Compared in Gravitational Particle Production,* Kaneta, Lee, Oda, **2206.10929**
* *A New Window into Gravitationally Produced Scalar Dark Matter,* Garcia, Pierre, Verner, **2305.14446**
* *Cosmological gravitational particle production and its implications for cosmological relics,* Kolb and Long, **2312.09042**

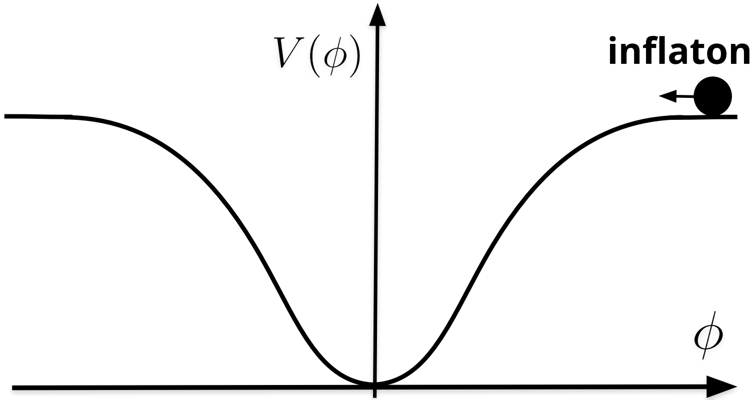
Technische Universität München

SFB 1258 Neutrinos Dark Matter Messengers

Reheating after inflation



Credit: ESO-NAOJ



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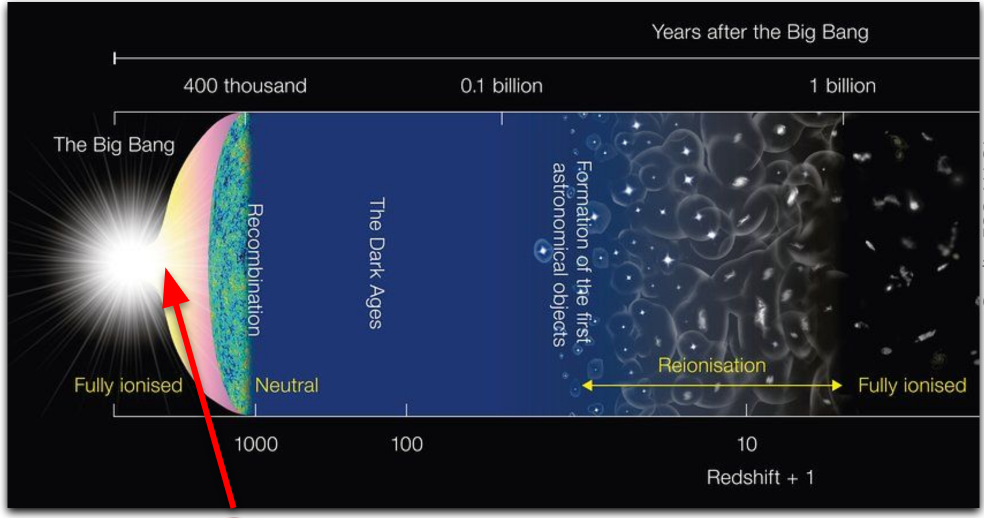

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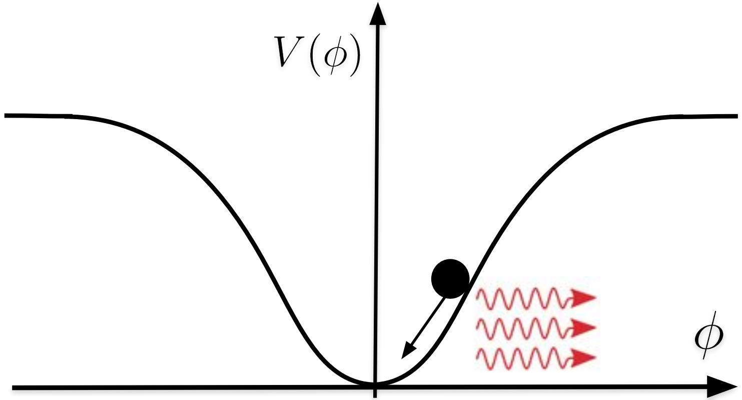
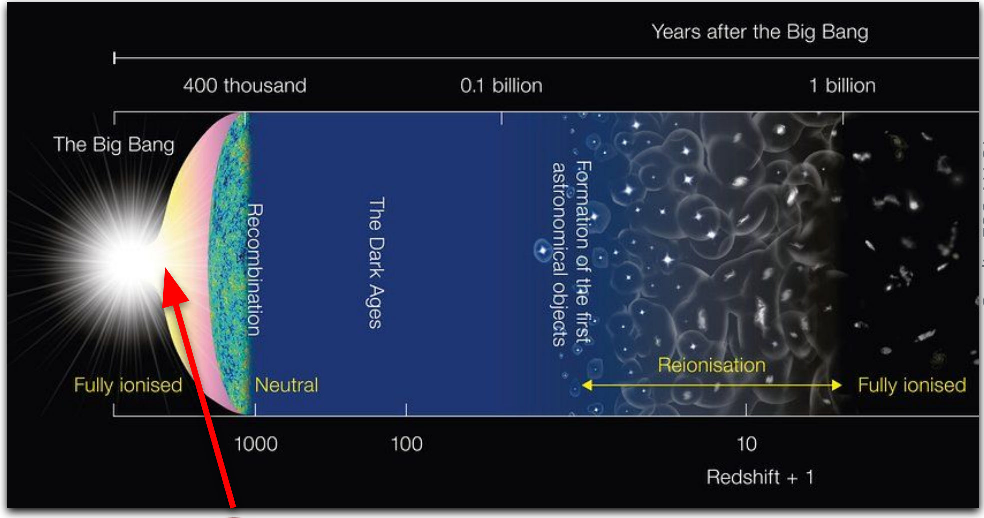


Transition from cold inflaton condensate to a hot thermal plasma : **Reheating**

Reheating after inflation



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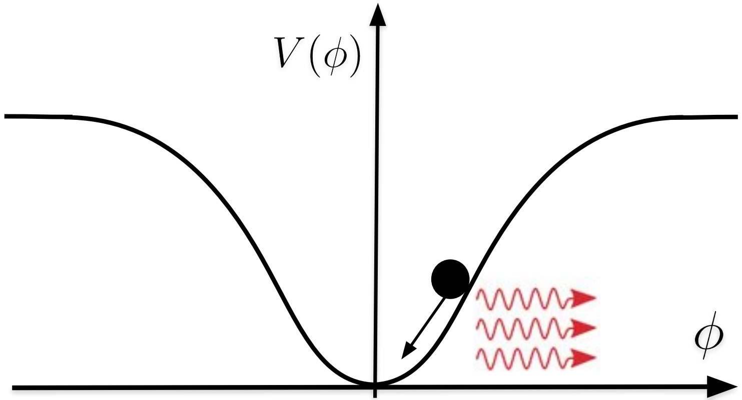
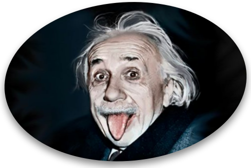


What if inflaton has no other coupling than **gravitational** ones ?



Scalar field in curved space-time

Consider a spectator scalar field minimally coupled, in a classical gravitational background

$$S = \int d^4x\sqrt{-g}\left[-\frac{1}{2}M_P^2 R + \frac{1}{2}\partial_\mu\chi\partial^\mu\chi - \frac{1}{2}m_\chi^2\chi^2 + \frac{1}{2}\partial_\mu\phi\partial^\mu\phi - V(\phi)\right]$$

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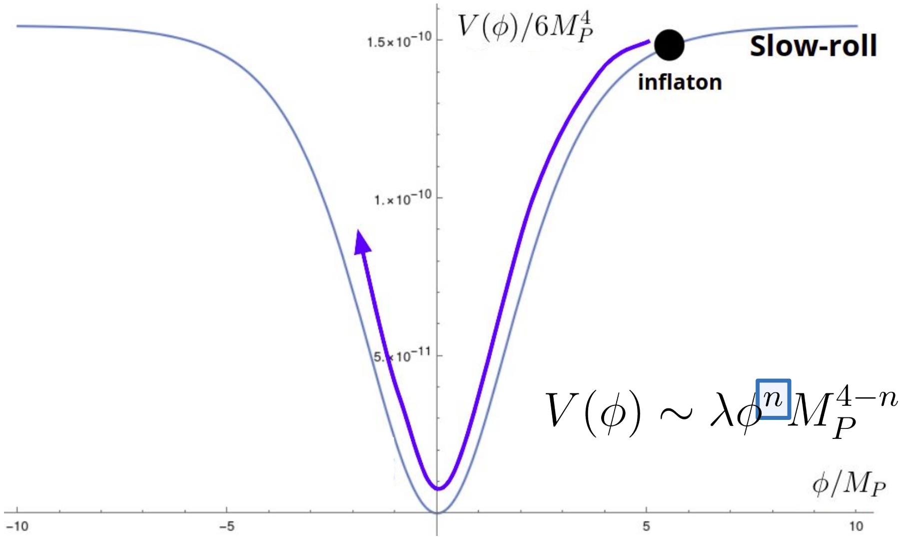
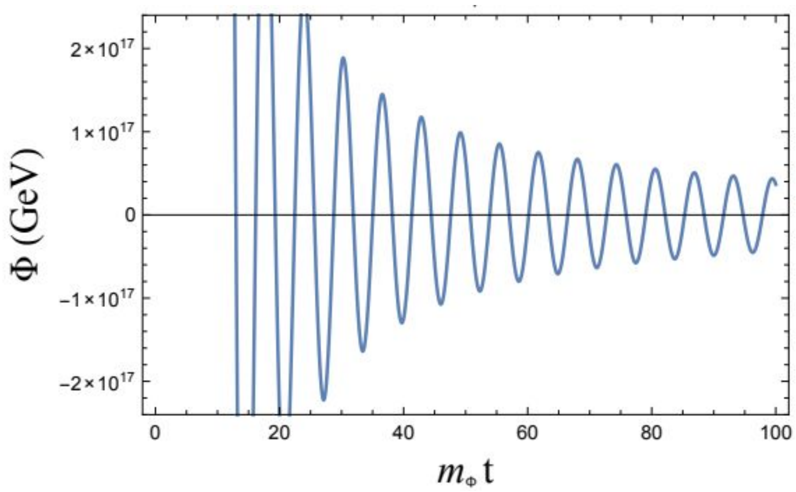
Inflaton oscillations during Reheating



$$V(\phi) \sim \lambda\phi^{\boxed{n}} M_P^{4-n}$$



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

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

Couplings of the inflaton induce friction and transfer of energy during the oscillations

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

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Cosmological background $\mathrm{g}_{\mu\nu}^{\mathrm{FLRW}}(x) = a^2(\eta)\,\mathrm{diag}(1,-1,-1,-1)$

$\boxed{R(\eta) = -6a''/a^3}$ gravitational “potential” term

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Cosmological background $\quad \mathrm{g}_{\mu\nu}^{\mathrm{FLRW}}(x) = a^2(\eta)\,\mathrm{diag}(1,-1,-1,-1)$

$\boxed{R(\eta) = -6a''/a^3}$ gravitational "potential" term

$$X_{\vec{k}} = a\chi_{\vec{k}} \longrightarrow X''_{\vec{k}} + \boxed{\left[k^2 + a^2 m_\chi^2 + \frac{a^2 R}{6}\right]} X_{\vec{k}} = 0$$

$$m_{\text{eff}}^2(\eta) = m_\chi^2 + \tfrac{1}{6}R(\eta)$$

➜ Time-dependent effective mass which sources gravitational effects

Modes equation in cosmological background

$$\underbrace{X''_{\vec{k}} + \left[k^2 + a^2 m_\chi^2 + \frac{a^2 R}{6}\right]}_{\omega_k\boxed{(\eta)}} X_{\vec{k}} = 0$$

Time-dependent frequency through the background evolution

➜ observers at different times may decompose operators onto different bases of mode functions and ladder operators

➜ vacuum can be further populated by scalar excitations throughout background evolution

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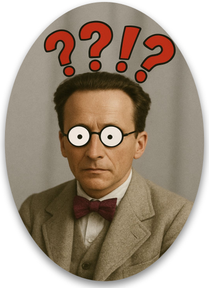

Already outlined by Schrödinger in 1939 as an **“alarming phenomenon”** for expanding Universe
The Proper Vibrations of the Expanding Universe, Physica (1939)

Bogoliubov transformation

SU(1,1) Bogoliubov transformation from *in* to ***out*** base

$$X_{\vec{k}}^{\mathrm{IN}}(\eta) = \boxed{\alpha_k} X_{\vec{k}}^{\mathrm{OUT}}(\eta) + \boxed{\beta_k} X_{\vec{k}}^{\mathrm{OUT}*}(\eta)$$

$$a_{\boldsymbol{k}}^{\mathrm{IN}} = \alpha_k^* \, a_{\boldsymbol{k}}^{\mathrm{OUT}} - \beta_k^* \, a_{-\boldsymbol{k}}^{\mathrm{OUT}\dagger} \,,$$

$$\boxed{\eta \to +\infty}$$

➜ find "in" mode functions at late asymptotic times and project on the "out" base to "count" excitations

$$\langle 0|N|0\rangle = a^3 n_\chi = \int \frac{d^3k}{(2\pi)^3} \langle 0|\tilde{a}^\dagger_{-\vec{k}} \tilde{a}_{\vec{k}}|0\rangle = \int \boxed{\frac{d^3k}{(2\pi)^3} |\beta_k|^2}$$

spectrum for scalar modes sourced by gravity

$$\beta_k = i\left(X_k^{\mathrm{OUT}'} X_k^{\mathrm{IN}} - X_k^{\mathrm{IN}'} X_k^{\mathrm{OUT}}\right) \simeq \lim_{\eta\to+\infty} \tilde{\beta}_k(\eta)$$

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$$n_k = |\beta_{\vec{k}}|^2 = \frac{1}{2\omega_k} |\omega_k X^{\mathrm{IN}}_{\vec{k}} - i X^{\mathrm{IN}\prime}_{\vec{k}}|^2$$

$$\tilde{\alpha}'_k(\eta) = \tilde{\beta}_k(\eta) \frac{\omega'_k}{2\omega_k} e^{2i\int^\eta \omega_k(\tau)d\tau}$$

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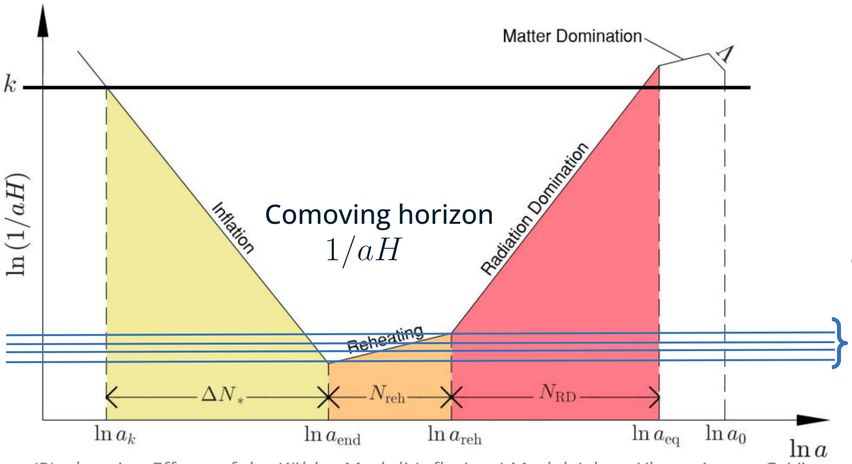
Long wavelength modes during Reheating



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

Super-horizon and reentry during reheating

$$k^2 < \left(\frac{a''}{a} - a^2 m_\chi^2\right)\Big|_{a_\mathrm{e}} = a_\mathrm{e}^2(2H_\mathrm{e}^2 - m_\chi^2)$$

➜ occupation number is affected by the equation of state during reheating $\boxed{w_\phi}$

➜ fast inflaton oscillations do not affect the occupation number of the long-wavelength modes

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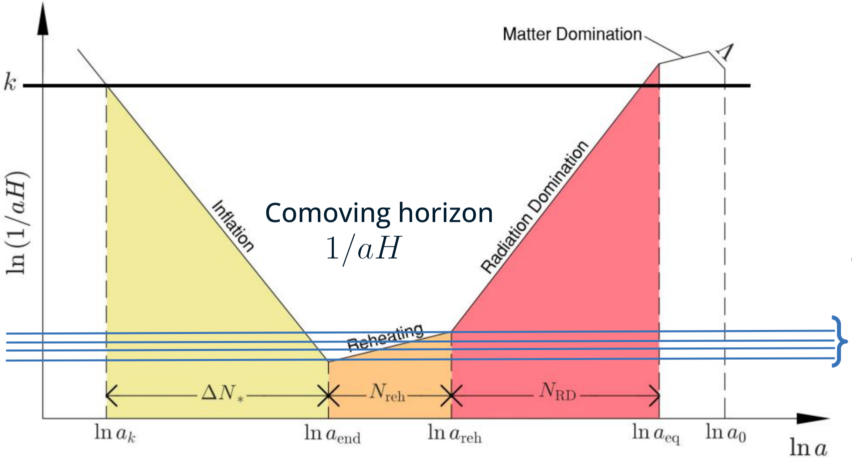

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Solve numerically mode equations

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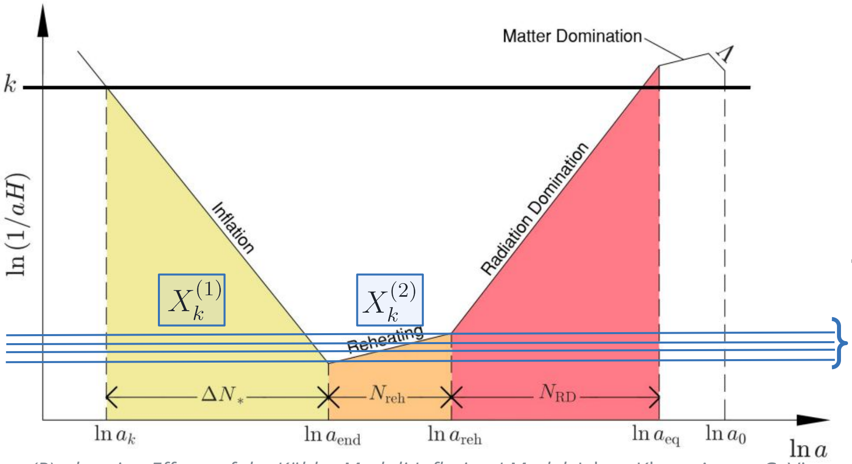

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Solve numerically mode equations

$$\beta_k = i\left(X_k^{(2)\prime} X_k^{(1)} - X_k^{(1)\prime} X_k^{(2)}\right)$$

Analytical derivation of the spectrum

Long wavelength modes during Reheating

$$X''_{\vec{k}} + \left[k^2 + a^2 \cancel{m}_\chi^2 + \frac{a^2 R}{6}\right] X_{\vec{k}} = 0$$

consider first a **massless scalar field**

Long wavelength modes during Reheating

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consider first a **massless scalar field**

$$\boxed{|\beta_k|^2_{\rm IR} = \frac{\mathcal{D}}{2\pi}\left(\frac{k_{\rm e}}{k}\right)^{(2\bar{\nu}+3)}},$$

$$\boxed{a^3 \left.\frac{dn_\chi}{d\ln k}\right|_{\rm IR} = 2\mathcal{D}\frac{k_{\rm e}^3}{(2\pi)^3}\left(\frac{k_{\rm e}}{k}\right)^{\boxed{2\bar{\nu}}}}$$

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w_ϕ	$\bar{\nu}$
0	3/2
1/3	1/2
1/2	3/10
3/5	3/14
2/3	1/6
5/7	3/22
3/4	3/26
4/5	3/34
9/10	3/74

$$\boxed{\bar{\nu} = \frac{3}{2}\frac{(1-w_\phi)}{(1+3w_\phi)}}$$

*Spectral behavior of gravitationally produced **massless** scalar perturbations (IR)*

Generalizing the Bogoliubov vs Boltzmann approaches in gravitational production,
Chakraborty, SC, Haque, Maity, Mambrini,
2503.21877

➜ spectral behavior in the IR varies from k^{-3} for $w_\phi = 0$ to a flat spectrum in the limit $w_\phi \to 1$

Long wavelength modes during Reheating

$$X''_{\vec{k}} + \left[k^2 + \boxed{a^2 m_\chi^2} + \frac{a^2 R}{6}\right] X_{\vec{k}} = 0$$

determine the effect of a **mass term**

$$\frac{k_m}{k_\mathrm{e}} = \left(\sqrt{\frac{2}{|3w_\phi - 1|}}\frac{m_\chi}{H_\mathrm{e}}\right)^{\frac{1+3w_\phi}{3(1+w_\phi)}}$$

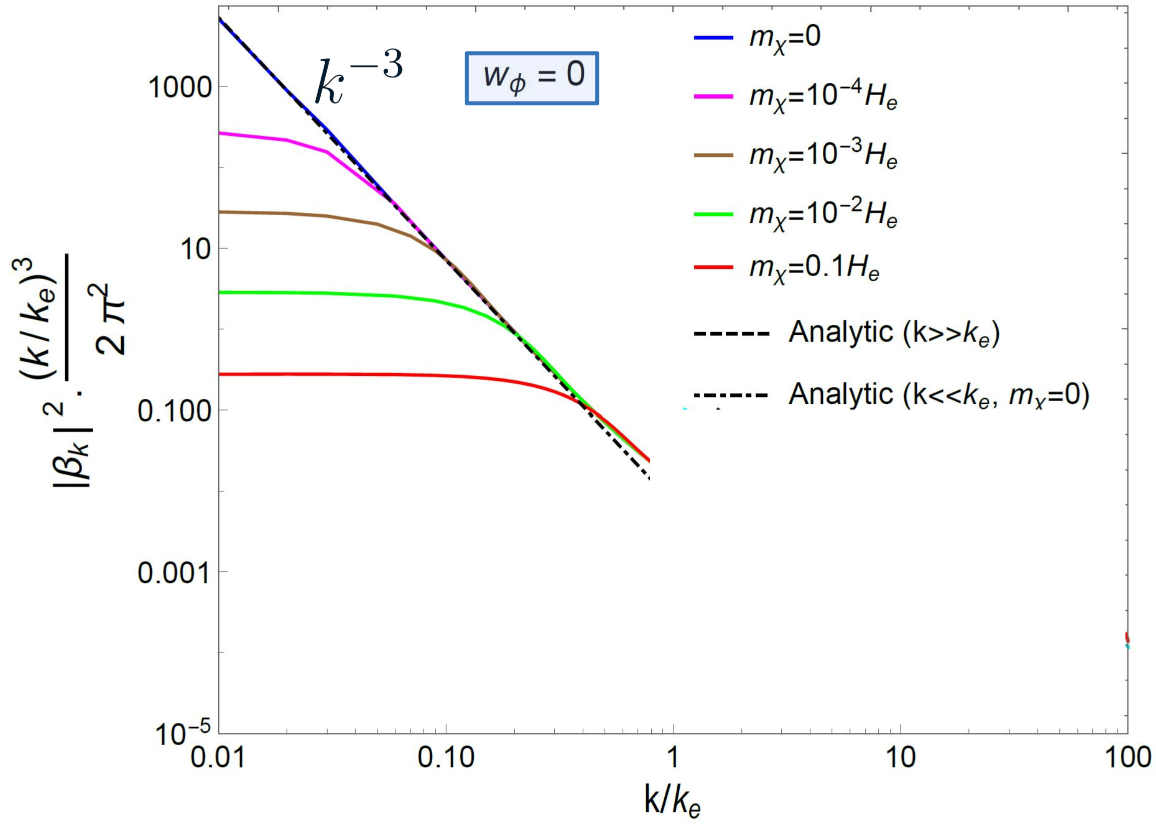
below this comoving scale, mass term dominates at horizon reentry

➜ at smaller comoving scales , we obtain a flat spectrum for massive scalar modes whatever the EoS w_ϕ

$$\boxed{|\beta_k|^2 \propto \left(k_\mathrm{e}/k\right)^3}$$

➜ at large mass, $(m_\chi/H_\mathrm{e}) > 3/2$, exponentially suppressed spectrum $\beta_k \propto e^{-\frac{m_\chi}{H_e}\frac{k^2}{(a_e H_e)^2}}$

Long wavelength modes during Reheating



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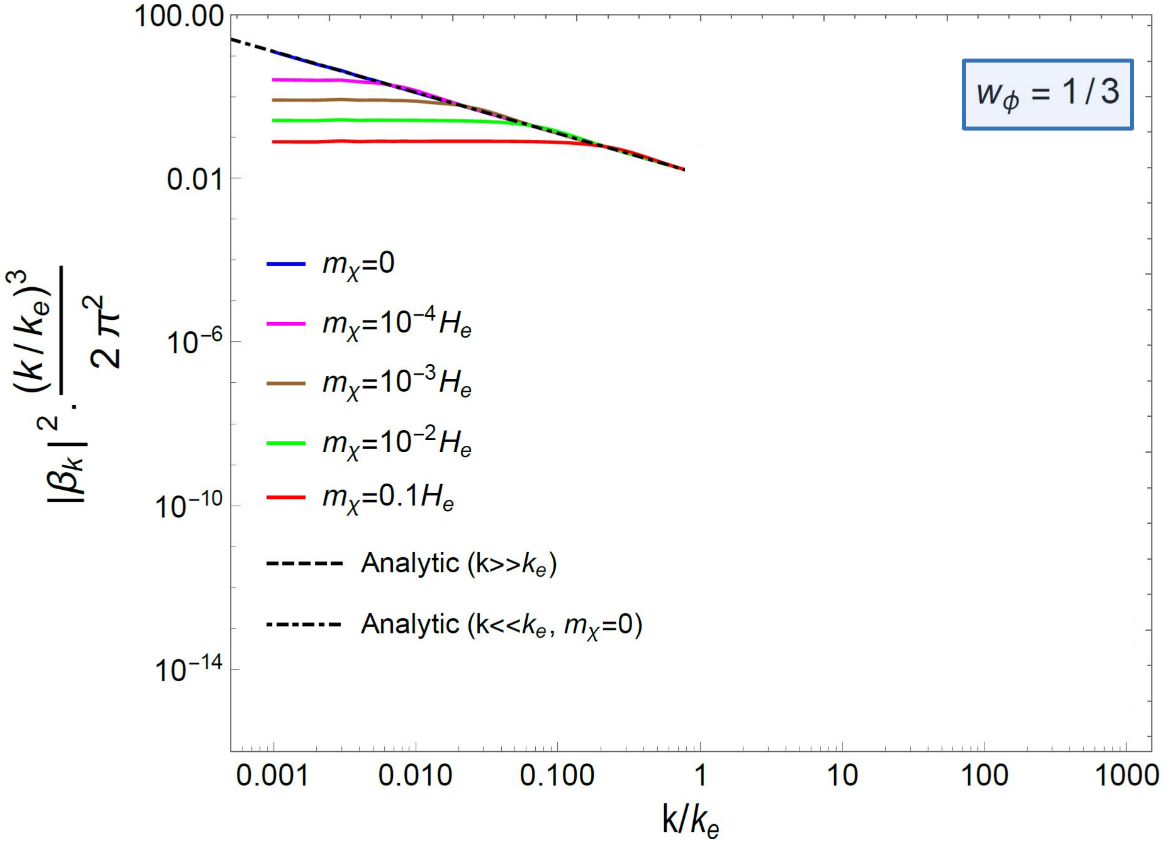

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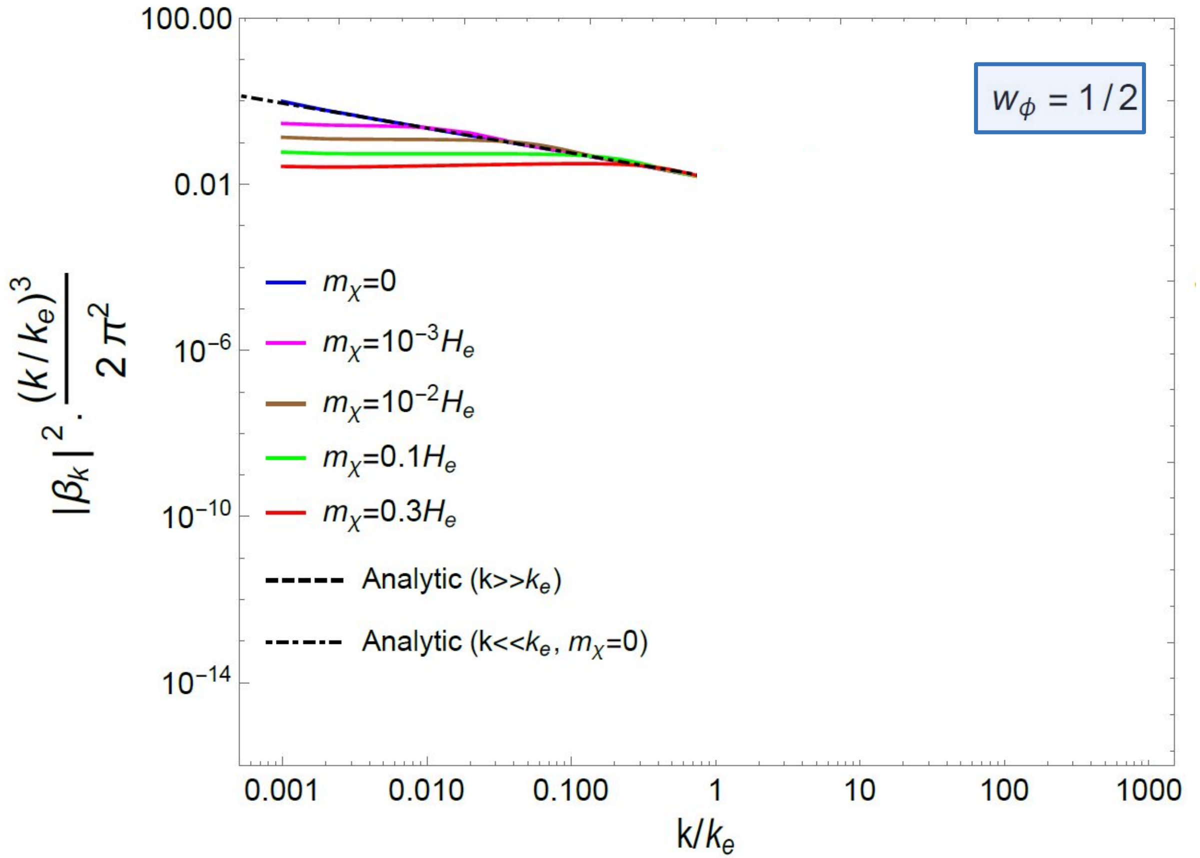

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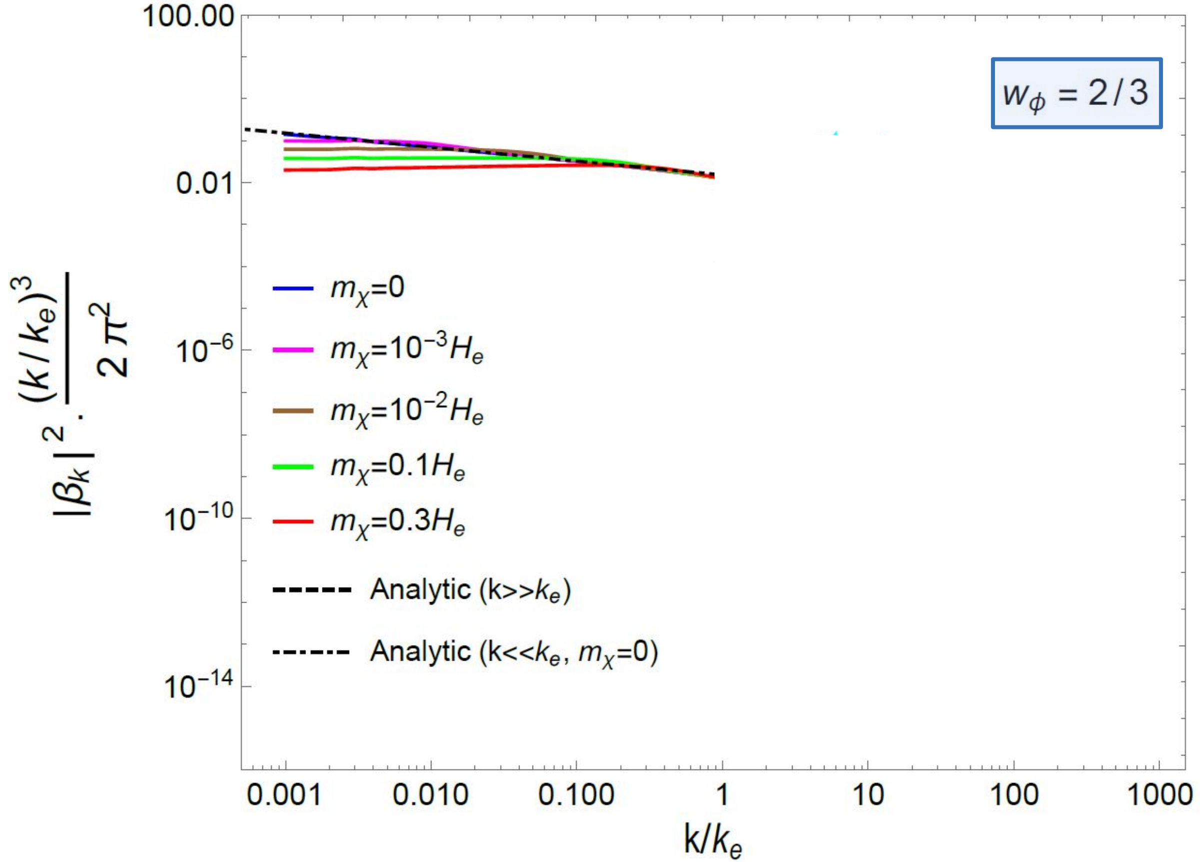

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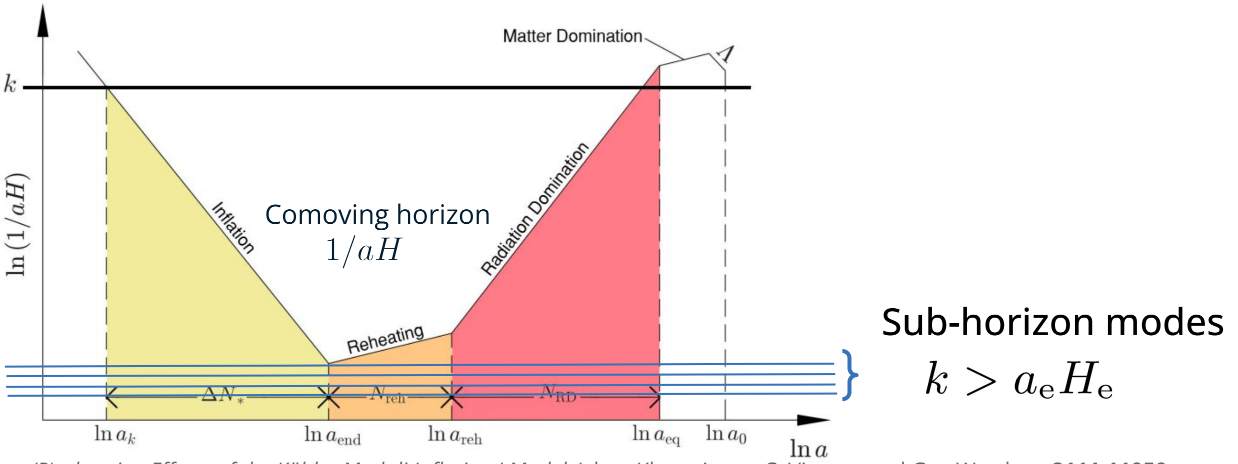


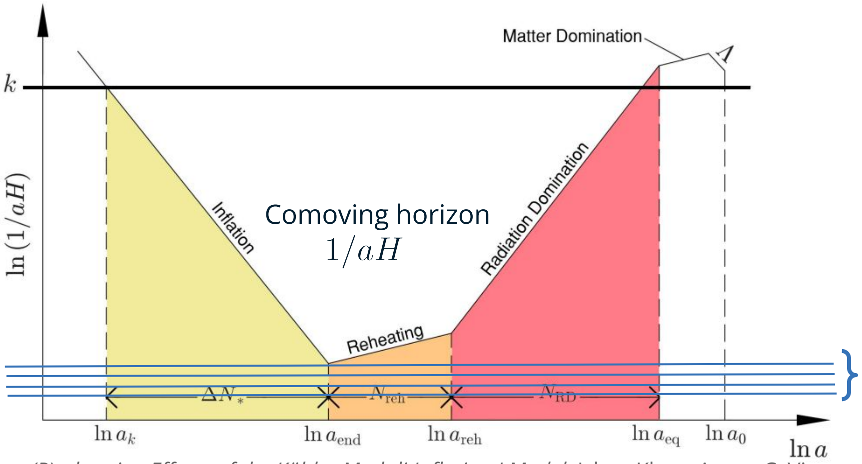
From *(P)reheating Effects of the Kähler Moduli Inflation I Model*, Islam Khan, Aaron C. Vincent and Guy Worthey, **2111.11050**

➜ no violation of adiabaticity in the evolution of mode frequency during inflation and reheating

➜ expect small occupation number in the UV spectrum induced by gravity

➜ fast inflaton oscillations affect the occupation number of the short-wavelength modes

Short wavelength modes during Reheating



Sub-horizon modes

$$k > a_{\rm e} H_{\rm e}$$

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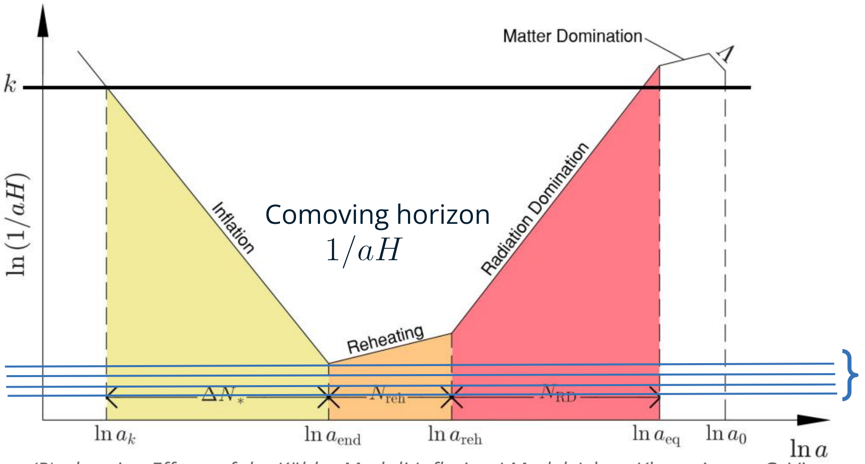
$$\beta_k(\eta) \simeq \int_{\eta_{\rm e}}^{\eta} d\eta' \, \frac{\omega'_k}{2\omega_k} e^{-2i\Omega_k(\eta')}$$

$$\Omega_k(\eta') = \int_{\eta_{\rm e}}^{\eta'} \omega_k(\eta) d\eta$$

➜ advantage to compute the Bogoliubov coefficient without solving exactly the mode equations

Short wavelength modes during Reheating



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Inflaton Fourier modes

Post-inflation background oscillations

$$\boxed{\phi(t) = \Phi(t)\mathcal{P}(t) = \Phi(t)\sum_{\nu\neq 0}\mathcal{P}_\nu e^{i\nu\omega t}}$$

➜ a decaying amplitude $\Phi(t)$ and a quasi-periodic part $\mathcal{P}(t)$ both depends on w_ϕ

➜ develop the oscillating part in Fourier modes $\mathcal{P}_\nu$

Inflaton Fourier modes

Post-inflation background oscillations

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➜ a decaying amplitude $\Phi(t)$ and a quasi-periodic part $\mathcal{P}(t)$ both depends on w_ϕ

➜ develop the oscillating part in Fourier modes $\mathcal{P}_\nu$

$$H(a) \simeq \boxed{\bar{H}}\left(1 + \frac{\boxed{\mathcal{P}\sqrt{6(1-\mathcal{P}^{2n})}}}{2(n+1)}\left(\frac{\phi_e}{M_P}\right)\left(\frac{a}{a_e}\right)^{-\frac{3}{n+1}}\right) \qquad \bar{H} = H_e\,(a/a_e)^{-\frac{3n}{n+1}}$$

$$\frac{\dot{\omega}_k(t)}{\omega_k(t)} = \frac{a^2}{\omega_k^2}\left[Hm_\chi^2 - 2H^3 - 3H\dot{H} - \frac{1}{2}\ddot{H}\right]$$

➜ adiabatic variation of modes frequency with inflaton slowly decaying amplitude and fast oscillation

Short wavelength modes during Reheating

Case $w_\phi < 1/3$

➜ Use the stationary phase approximation in the Bogoliubov integral and extract leading term

$$|\beta_k|^2_{\mathrm{UV},w_\phi<\frac{1}{3}} = \begin{cases} (\bar{\mathcal{N}}_0)^2 \boxed{k^{\frac{9(w_\phi-1)}{2-6w_\phi}}} + \underbrace{\bar{\mathcal{N}}_0\bar{\mathcal{N}}_2 k^{\frac{45w_\phi-21}{4(1-3w_\phi)}}\cos\psi}_{\text{interference term}} & w_\phi \leq 1/9 \\ (\bar{\mathcal{N}}_2)^2 \boxed{k^{-6}} + \underbrace{\bar{\mathcal{N}}_0\bar{\mathcal{N}}_2 k^{\frac{45w_\phi-21}{4(1-3w_\phi)}}\cos\psi}_{\text{interference term}} & w_\phi > 1/9 \end{cases}$$

➜ Recover the known result $k^{-3/2}$ spectral behavior for $w_\phi = 0$

Short wavelength modes during Reheating

Case $w_\phi \geq 1/3$

➜ No stationary phase within integration range: can extract only the large momentum contribution

$$|\beta_k|^2_{\mathrm{UV}, w_\phi \geq \frac{1}{3}} \simeq \frac{1}{16 f^2(w_\phi)} \boxed{\left(\frac{a_e}{k}\right)^6} \times \sum \sum \left[\mathcal{N}_0 + \mathcal{N}_1 + \mathcal{N}_2 + \mathcal{N}_3\right]^2$$

➜ On the whole range $1/9 < w_\phi \leq 1$ spectrum independent of w_ϕ in the UV and $\propto k^{-3}$

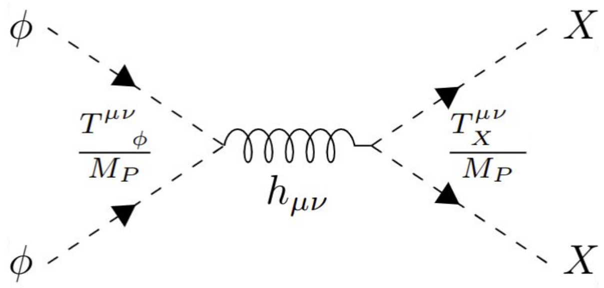
Effective graviton portal from perturbative computation

Graviton portal from effective gravitational interaction to small metric perturbations

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

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

➜ consider massless gravitons coupled to stress-energy and compute the amplitude of the process



$$T^{\mu\nu}_{0} = \partial^\mu S \partial^\nu S - g^{\mu\nu} \left[\frac{1}{2} \partial^\alpha S \partial_\alpha S - V(S) \right]$$

$$\boxed{\sum_{\nu=1}^{\infty} |\overline{\mathcal{M}_\nu}|^2 = \frac{1}{2} \times \sum_{\nu=1}^{\infty} \frac{\rho_\phi^2}{M_P^4} |\mathcal{P}_\nu^{2n}|^2}$$

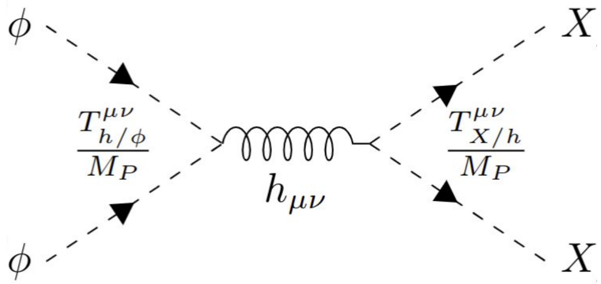
➜ each Fourier mode contribute to the transition amplitude

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

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

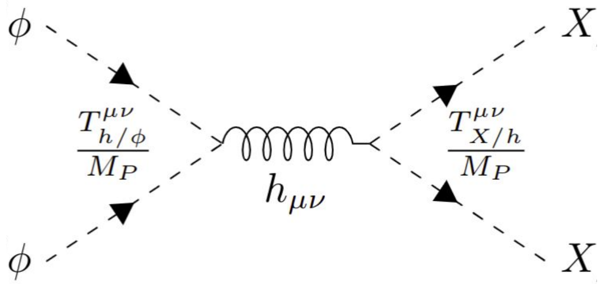
Gravitational portals in the early Universe, SC, Mambrini, Olive, Verner, **2112.15214**

Short wavelength modes from Boltzmann approach



$$\frac{\partial f_\chi}{\partial t} - H|\vec{p}|\frac{\partial f_\chi}{\partial |\vec{p}|} = C\left[f_\chi\left(|\vec{p}|, t\right)\right]$$

Short wavelength modes from Boltzmann approach

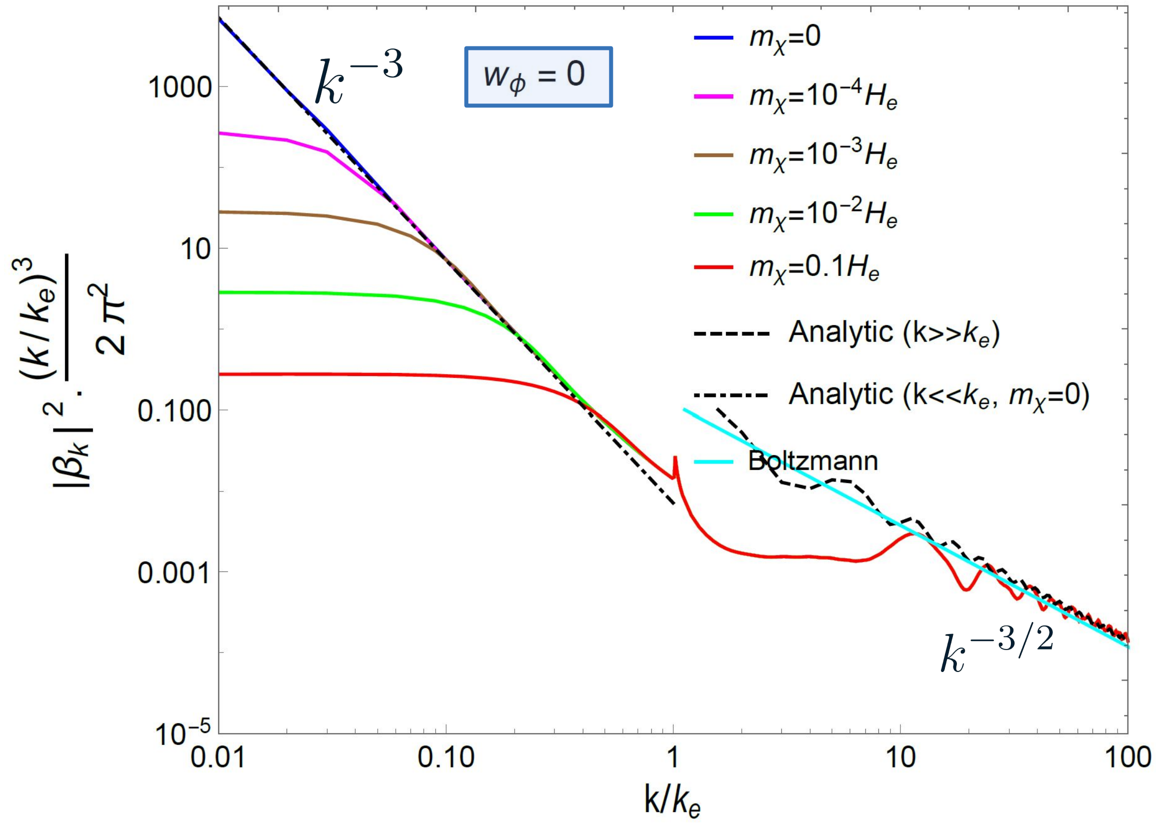


$$\frac{\partial f_\chi}{\partial t} - H|\vec{p}|\frac{\partial f_\chi}{\partial |\vec{p}|} = C\left[f_\chi(|\vec{p}|, t)\right]$$

$$f_\chi(k,a) = \frac{9\pi}{4|3w_\phi - 1|}\left(\frac{\bar{\alpha} m_\phi^{\mathrm{e}}}{H_{\mathrm{e}}}\right)^{\frac{3(1+3w_\phi)}{2(1-3w_\phi)}} \boxed{\left(\frac{k_{\mathrm{e}}}{k}\right)^{\frac{9(1-w_\phi)}{2(1-3w_\phi)}}} \sum_{\nu=1}^{\infty} |\mathcal{P}_\nu^{2n}|^2 \left(\frac{\nu}{2}\right)^{\frac{3(1+3w_\phi)}{2(1-3w_\phi)}} \theta\left(\left(\frac{2k}{\nu a_{\mathrm{e}} m_\phi^{\mathrm{e}} \bar{\alpha}}\right)^{\frac{1}{1-3w_\phi}} - 1\right)$$
$$\boxed{\times\, \theta\left(\left(\frac{a}{a_{\mathrm{e}}}\right)\left(\frac{2k}{\nu a_{\mathrm{e}} m_\phi^{\mathrm{e}} \bar{\alpha}}\right)^{\frac{1}{3w_\phi - 1}} - 1\right)}$$

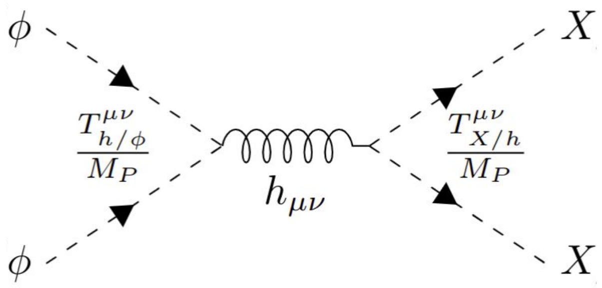
➜ for $\boxed{w_\phi < 1/3}$ same stationary phase contribution as in the Bogoliubov approach

Spectrum for w = 0



Generalizing the Bogoliubov vs Boltzmann approaches in gravitational production, Chakraborty, SC, Haque, Maity, Mambrini, **2503.21877**

Short wavelength modes from Boltzmann approach



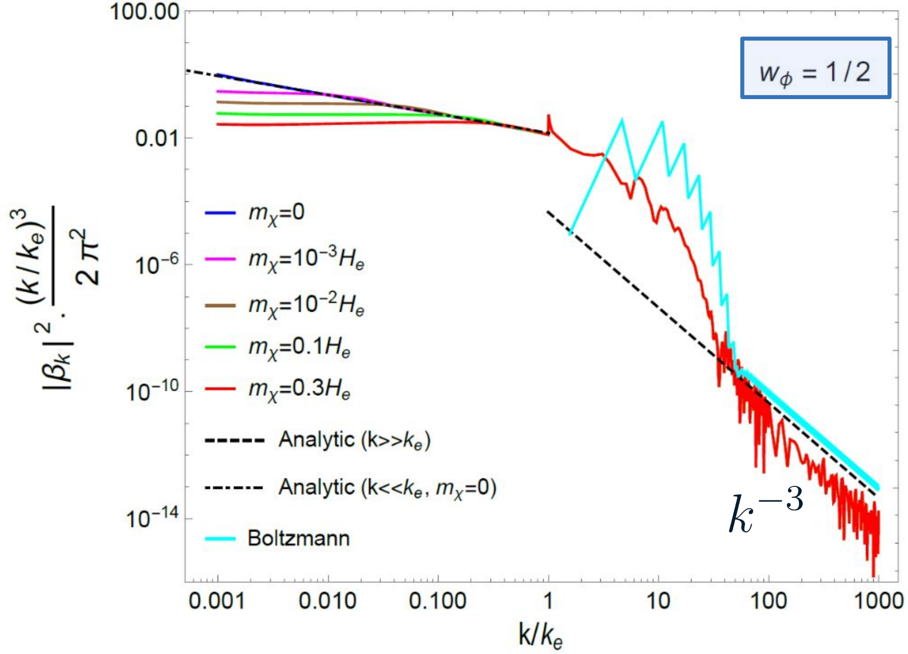
$$\frac{\partial f_\chi}{\partial t} - H|\vec{p}|\frac{\partial f_\chi}{\partial|\vec{p}|} = C\left[f_\chi(|\vec{p}|, t)\right]$$

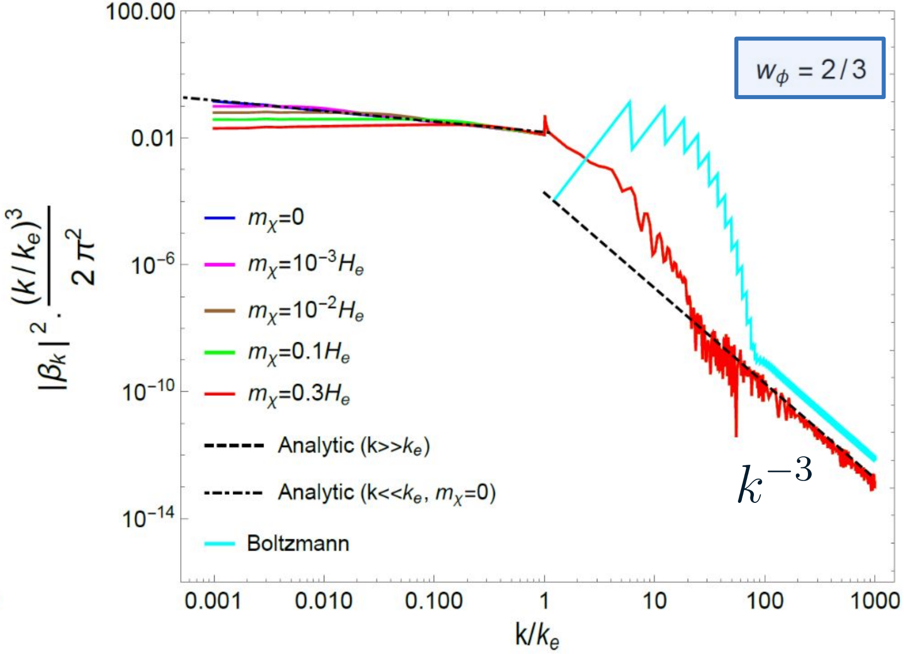
$$f_X(k,a) = \frac{9\pi}{4|3w_\phi - 1|}\left(\frac{\bar{\alpha} m_\phi^{\mathrm{e}}}{H_{\mathrm{e}}}\right)^{\frac{3(1+3w_\phi)}{2(1-3w_\phi)}}\left(\frac{k_{\mathrm{e}}}{k}\right)^{\frac{9(1-w_\phi)}{2(1-3w_\phi)}} \boxed{\sum_{\nu=1}^{\infty}|\mathcal{P}_\nu^{2n}|^2\left(\frac{\nu}{2}\right)^{\frac{3(1+3w_\phi)}{2(1-3w_\phi)}}} \boxed{\theta\left(\left(\frac{2k}{\nu a_{\mathrm{e}} m_\phi^{\mathrm{e}}\bar{\alpha}}\right)^{\frac{1}{1-3w_\phi}} - 1\right)}$$
$$\boxed{\times\,\theta\left(\left(\frac{a}{a_{\mathrm{e}}}\right)\left(\frac{2k}{\nu a_{\mathrm{e}} m_\phi^{\mathrm{e}}\bar{\alpha}}\right)^{\frac{1}{3w_\phi-1}} - 1\right)}$$

$$\nu\bar{\alpha}/2 \geq (k/a_{\mathrm{e}} m_\phi^{\mathrm{e}})$$

➜ for $\boxed{w_\phi > 1/3}$ negative spectral index but higher Fourier modes are heavily suppressed

Spectrum for higher EoS



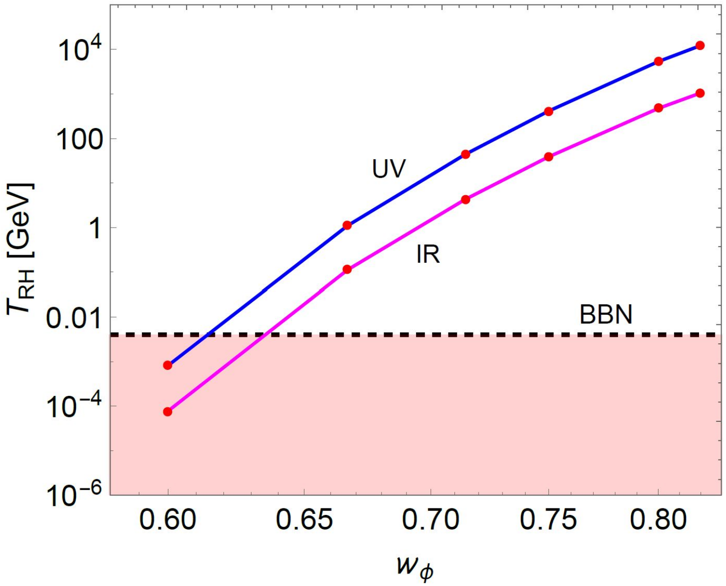


Generalizing the Bogoliubov vs Boltzmann approaches in gravitational production, Chakraborty, SC, Haque, Maity, Mambrini, **2503.21877**

UV and IR modes contributions to Reheating

Determine the contribution to radiation bath from gravitational production at the end of reheating

$$\rho_R a^4 = \int_{k_{\rm RH}}^{k_{\rm e}} \frac{k^3}{2\pi^2}|\beta_k|^2_{\rm IR}dk + \int_{k_{\rm e}}^{k_{\rm Planck}} \frac{k^3}{2\pi^2}|\beta_k|^2_{\rm UV}dk$$

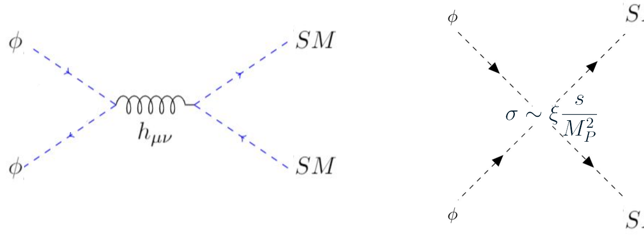


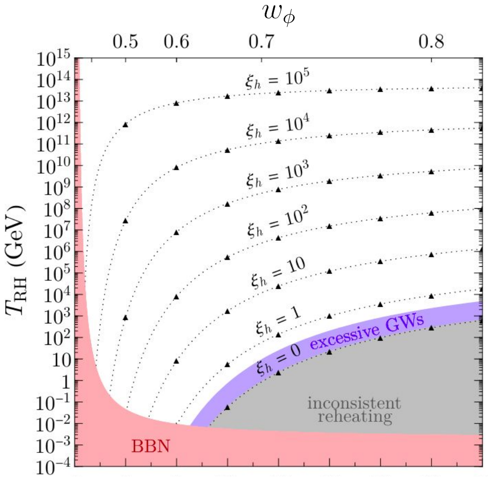
Bogoliubov		Boltzmann	
w_ϕ	$T_{\rm RH}$ (GeV)	w_ϕ	$T_{\rm RH}$ (GeV)
3/5	1.12×10^{-3}	3/5	9.40×10^{-4}
2/3	2.17	2/3	0.97
5/7	58.26	5/7	11.76
3/4	3.54×10^{2}	3/4	2.42×10^{2}
4/5	5.84×10^{3}	4/5	2.54×10^{3}

Generalizing the Bogoliubov vs Boltzmann approaches in gravitational production, Chakraborty, SC, Haque, Maity, Mambrini, **2503.21877**

Perspectives

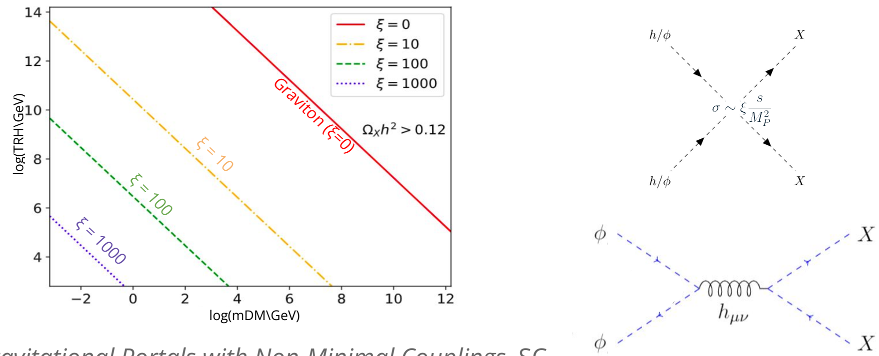
Gravitational reheating



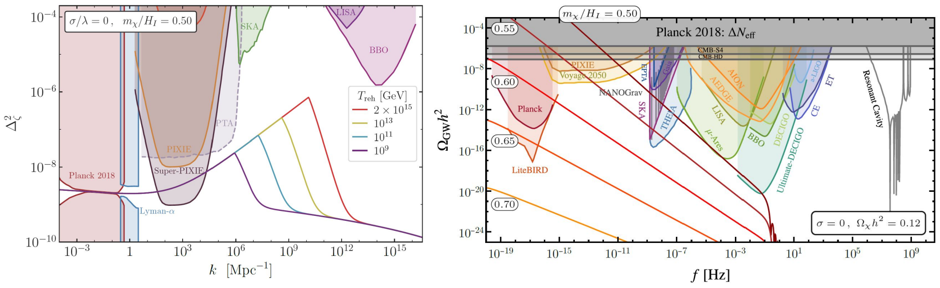


Gravity as a Portal to Reheating, Leptogenesis and Dark Matter, Barman, SC, Co, Mambrini, Olive, **2210.05716**

Gravitational DM and Isocurvature



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



Gravitational Waves from Spectator Scalar Fields, Garcia, Verner, **2506.12126**

Conclusions

- Generalize results of **scalar gravitational production** by including inflaton **dynamics after inflation**

- **IR spectrum flatter for increasing EoS** and **UV tail** is **independent of the EoS** for $1/9 < w_\phi \leq 1$

- **Same UV tail** power-law with the **non-perturbative Bogoliubov approach** and the solution to the **Boltzmann equation** from **perturbative gravitational portal**

Perspectives :

- Gravitational reheating
- Gravitational DM production
- SIGW from spectator scalar field

Conclusions

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Perspectives :

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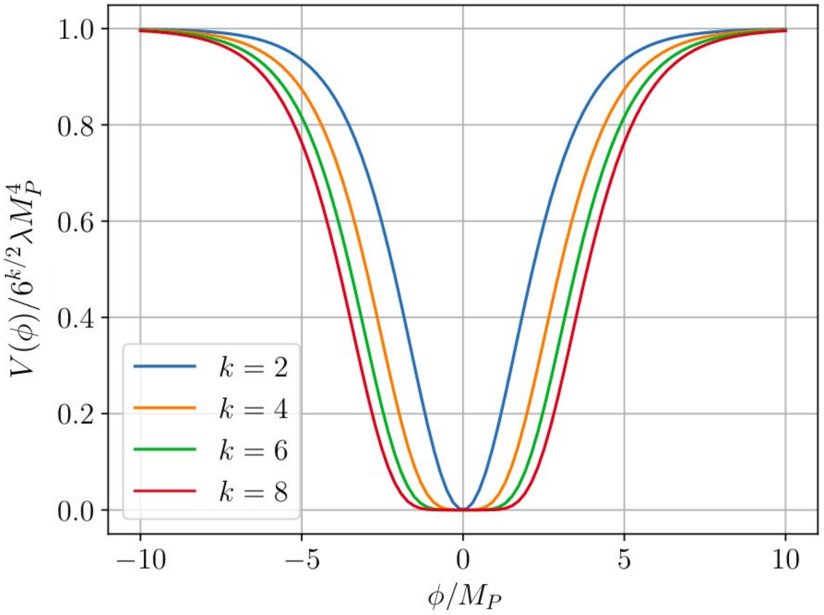
- SIGW from spectator scalar field

Thank you !

Backup

α-attractor Models

Inflation driven by an homogeneous scalar field ϕ in the potential $\boxed{V(\phi) = \lambda M_P^4 \left[\sqrt{6}\tanh\left(\frac{\phi}{\sqrt{6}M_P}\right)\right]^k}$



Inflaton potential for T-models and for different values of k.

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

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

➜ determined by the CMB scalar power spectrum amplitude A_S

➜ PLANCK measurements give $\boxed{\lambda \sim 10^{-11}}$ for $k=2$

Reheating and Post-inflationary Production of Dark Matter, Garcia, Kaneta, Mambrini, Olive, **2004.08404**

Conformal invariance and gravitational production

Cosmological spacetimes (FLRW) are related to Minkowski by a time-dependent conformal transformation

$$g_{\mu\nu}^{\mathrm{FLRW}}(\eta) = a^2(\eta)\eta_{\mu\nu}$$

Under a generic conformal transformation of the metric

$$g_{\mu\nu}(x) \to e^{2\Omega(x)} g_{\mu\nu}(x)$$

$$\delta\mathcal{S} = \frac{1}{2}\int d^4x\sqrt{-g}T_{\mu\nu}\delta g^{\mu\nu} = \int d^4x\sqrt{-g}\boxed{T^{\mu}{}_{\mu}}\delta\Omega(x)$$

For non-minimally coupled scalar

$$T^{\mu}{}_{\mu} = (6\xi - 1)\left(g^{\mu\nu}\partial_\mu\chi\partial_\nu\chi + \chi\Box\chi\right) + m_\chi^2\chi^2$$

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$$T^{\mu}{}_{\mu,\,A} = 0$$

For a massless spin-1 vector field

$$T^{\mu}{}_{\mu,\,1/2} \propto m$$

For a massive spin-1/2 fermion field

Asymptotic adiabatic modes and mixing of frequencies

How to track the excitations of the fields due to expansion ?

➜ consider asymptotic early and late times, for which the comoving frequency is slowly varying

$$X_{\vec{k}}^{\mathrm{IN}}(\eta) \sim \frac{\mathrm{e}^{-\mathrm{i}\int^{\eta} \mathrm{d}\eta' \omega_k(\eta')}}{\sqrt{2\omega_k(\eta)}}$$

$$X_{\vec{k}}^{\mathrm{OUT}}(\eta) \sim \frac{\mathrm{e}^{-\mathrm{i}\int^{\eta} \mathrm{d}\eta' \omega_k(\eta')}}{\sqrt{2\omega_k(\eta)}}$$

$$\boxed{\frac{\omega_k'(\eta)}{\omega_k^2(\eta)} \ll 1} \quad (\eta \to \pm\infty)$$ asymptotic adiabatic condition

➜ at intermediate times, write the mixing of positive and negative frequency modes

$$X_{\vec{k}}^{\mathrm{IN}}(\eta) = \boxed{\alpha_k(\eta)} \frac{1}{\sqrt{2\omega_k(\eta)}} e^{-i\int^{\eta} \omega_k(\tau) d\tau} + \boxed{\beta_k(\eta)} \frac{1}{\sqrt{2\omega_k(\eta)}} e^{i\int^{\eta} \omega_k(\tau) d\tau}$$

$$\boxed{|\alpha_k(\eta)|^2 - |\beta_k(\eta)|^2 = 1}$$ CCR preserved by EOM

Mode functions during and after inflation (IR)

Massless scalar mode in de Sitter

$$X_k^{(1)}(\eta) = \frac{e^{-ik\eta}}{\sqrt{2k}}\left[1 - \boxed{\frac{i}{k\eta}}\right] \simeq -\frac{i}{\sqrt{2}k^{\frac{3}{2}}\eta}e^{-ik\eta}$$

Massless scalar mode during Reheating

$$X_k^{(2)}(\eta) = \sqrt{\frac{\bar{\eta}}{\pi}}e^{i\left(3\bar{\mu}\frac{k}{k_e}+\frac{\pi}{4}\right)} \times K_{\bar{\nu}}(ik\bar{\eta})$$

K are modified Bessel function with

$$\boxed{\bar{\nu} = \frac{3}{2}\frac{(1-\omega_\phi)}{(1+3w_\phi)}} \qquad \bar{\mu} = \frac{(1+w_\phi)}{(1+3w_\phi)}$$

Massive scalar mode in de Sitter

$$X_k^{(1)}(\eta) = \frac{\sqrt{-\pi\eta}}{2}e^{i(\pi/4+\pi\bar{\nu}_1/2)}H_{\bar{\nu}_1}^{(1)}(k|\eta|)$$

H are modified Hankel function with $\bar{\nu}_1 = \sqrt{\frac{9}{4} - \boxed{\frac{m_\chi^2}{H_e^2}}}$

No generic solution for arbitrary EoS and for massive scalar
➜ Use a WKB approximation :

$$X_k^{(2)}(\eta) \simeq \frac{e^{-i\Omega_k(\eta)}}{\sqrt{2\omega_k(\eta)}}$$

Short wavelength modes during Reheating

Case $w_\phi < 1/3$

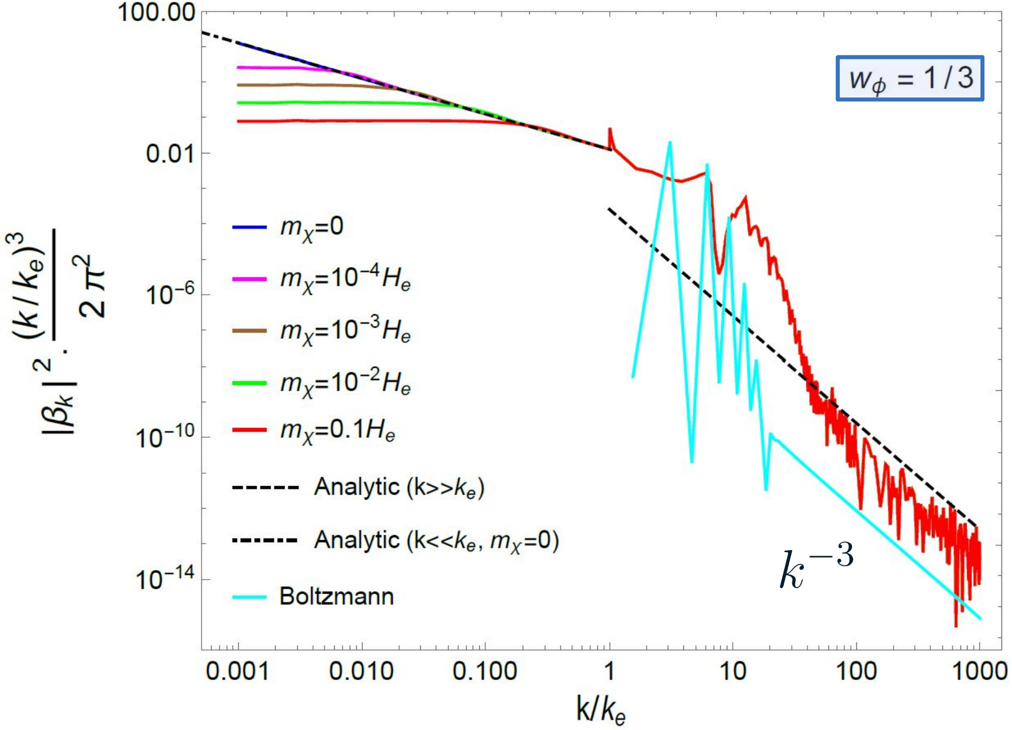
$$\beta_k \simeq \frac{1}{2}\sum_{\nu,l\neq 0}\int_{t_e}^{t} dt' \left(\frac{t_e}{t'}\right)^3 \left[\mathcal{N}_0 e^{i(\nu+l)\omega t'}\left(\frac{t'}{t_e}\right)^{\frac{1}{n}} + \cancel{\mathcal{N}_1 e^{i\nu\omega t'}} + \mathcal{N}_2 + \cancel{\mathcal{N}_3 e^{i(\nu+l)\omega t'}}\left(\frac{t_e}{t'}\right)^{\frac{1}{n}}\right] \times \frac{e^{-2i\Omega_k(t')}}{\left(\frac{k^2}{a^2}+m_\chi^2\right)}$$

use stationary phase approximation

integrate by parts and take the large momentum contribution

$$|\beta_k|^2_{\mathrm{UV},w_\phi<\frac{1}{3}} = \begin{cases} (\bar{\mathcal{N}}_0)^2 \boxed{k^{\frac{9(w_\phi-1)}{2-6w_\phi}}} + \underbrace{\bar{\mathcal{N}}_0\bar{\mathcal{N}}_2 k^{\frac{45w_\phi-21}{4(1-3w_\phi)}}\cos\psi}_{\text{interference term}} & w_\phi \leq 1/9 \\ (\bar{\mathcal{N}}_2)^2 \boxed{k^{-6}} + \underbrace{\bar{\mathcal{N}}_0\bar{\mathcal{N}}_2 k^{\frac{45w_\phi-21}{4(1-3w_\phi)}}\cos\psi}_{\text{interference term}} & w_\phi > 1/9 \end{cases}$$

Short wavelengths spectrum for w = 1/3



$$f_\chi^{w_\phi=1/3}(k,a) = 3\pi\left(\frac{H_e}{m_\phi^e\bar{\alpha}}\right)^2\left[1-\left(\frac{a_e}{a}\right)^3\right]\boxed{\sum_{\nu=1}^{+\infty}\frac{|\mathcal{P}_\nu^{2n}|^2}{\nu^2}\delta\left(\frac{k}{k_e}-\frac{\nu\bar{\alpha}m_\phi^e}{2H_e}\right)}$$

Bogoliubov approach with non-minimal coupling

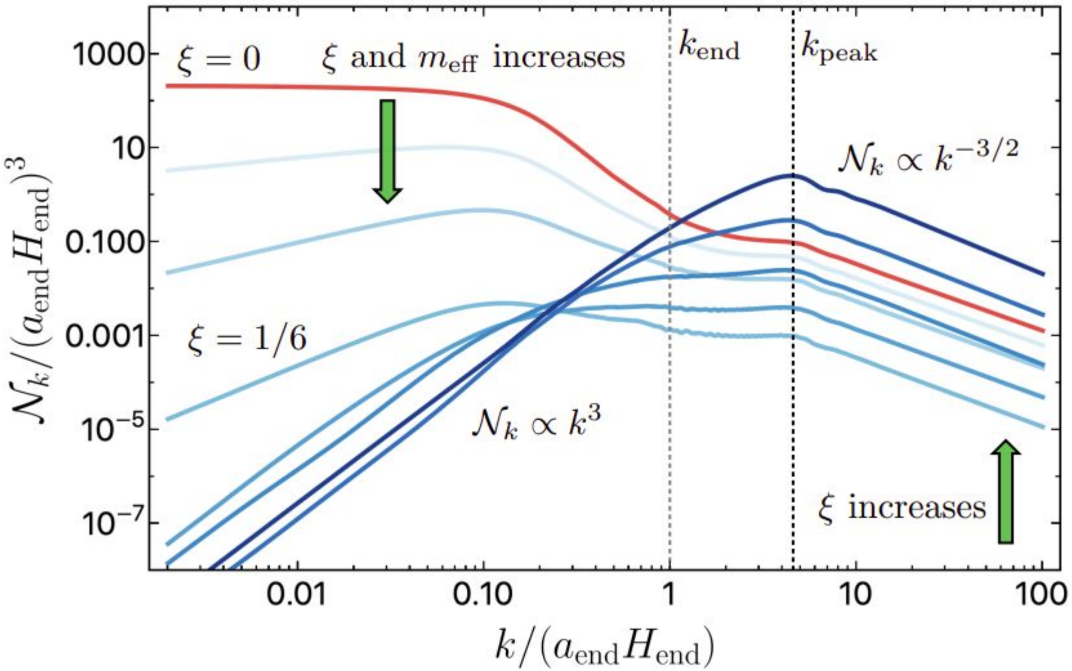
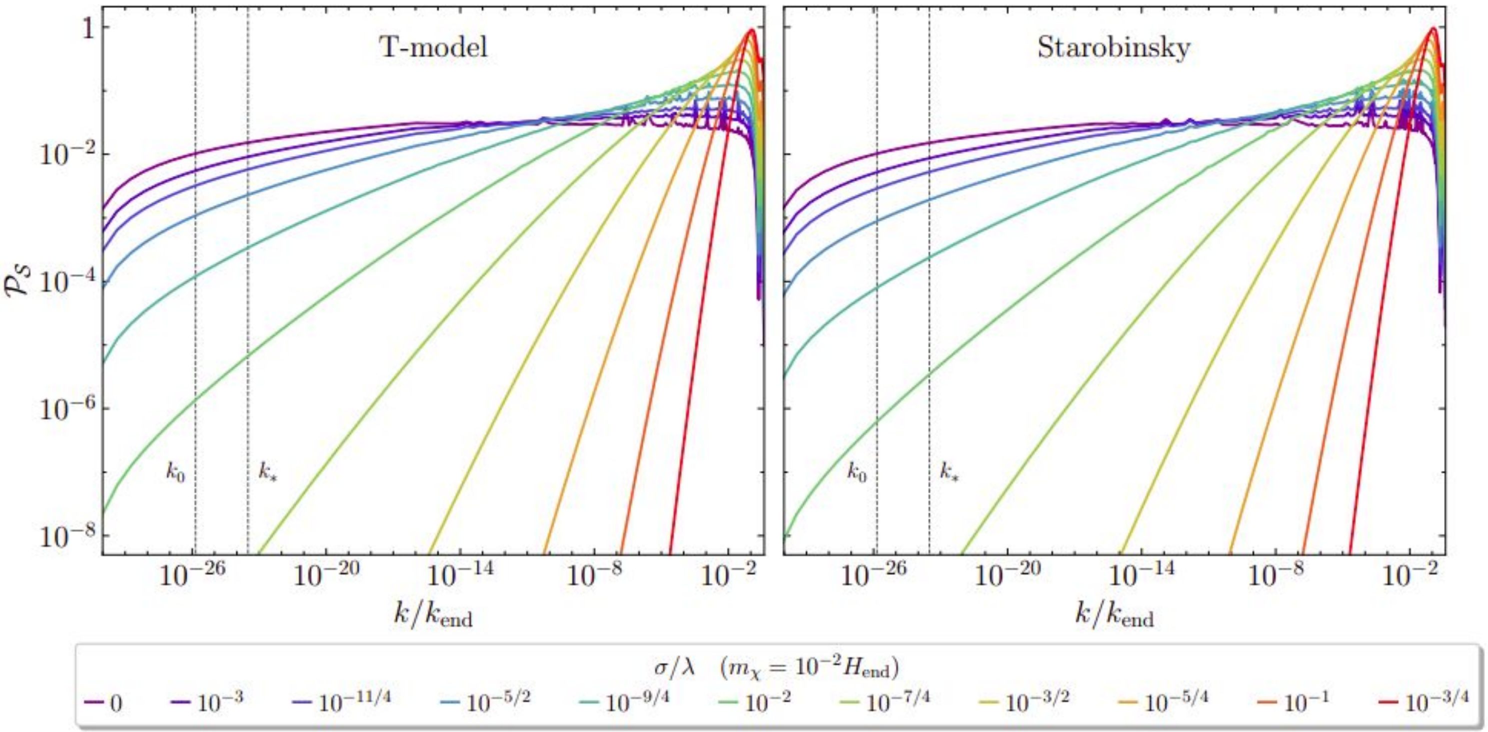


Diagram illustrating the dependence of the produced comoving number density spectrum Nk on non-minimal coupling ξ as a function of rescaled horizon modes momenta

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

Isocurvature perturbations



DM isocurvature power spectrum for different inflaton-DM couplings with $m\chi/Hend = 10^{-2}$

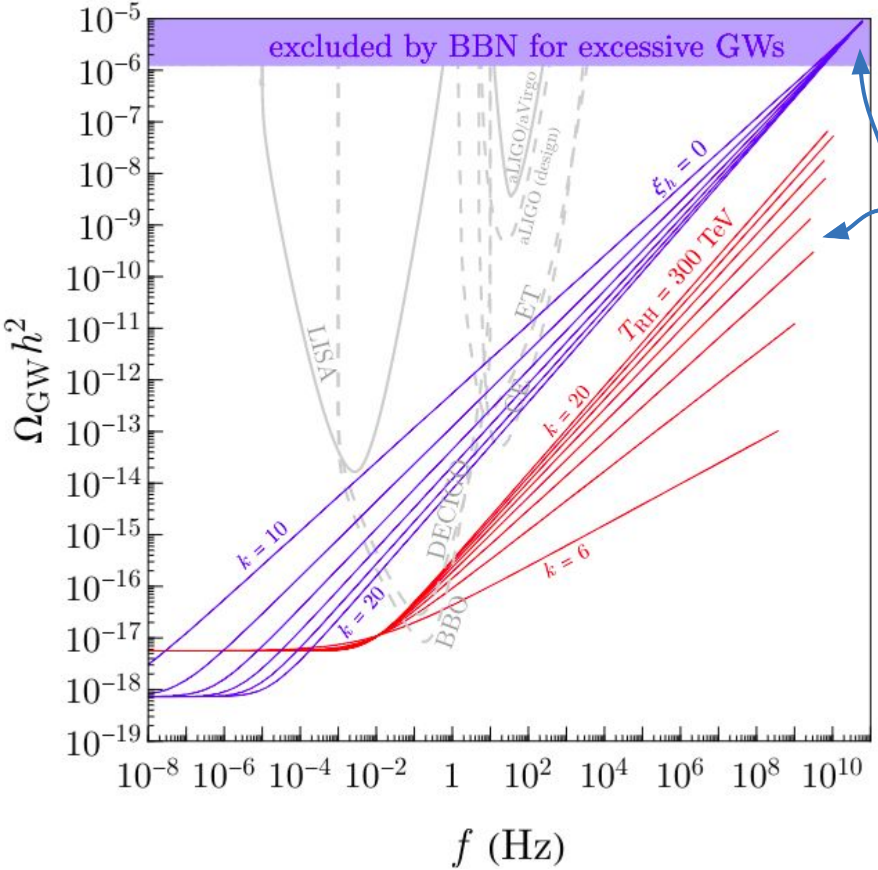
From *Isocurvature Constraints on Scalar Dark Matter Production from the Inflaton,* Garcia, Pierre, Verner, **2303.07459**

Primordial GWs constraints

➜ Primordial GWs re-entering the horizon during reheating, can be enhanced.

$$\boxed{\Omega^0_{\rm GW} h^2 \propto f^{\frac{k-4}{k-1}}}$$

➜ The slope of this spectrum depends on inflaton potential

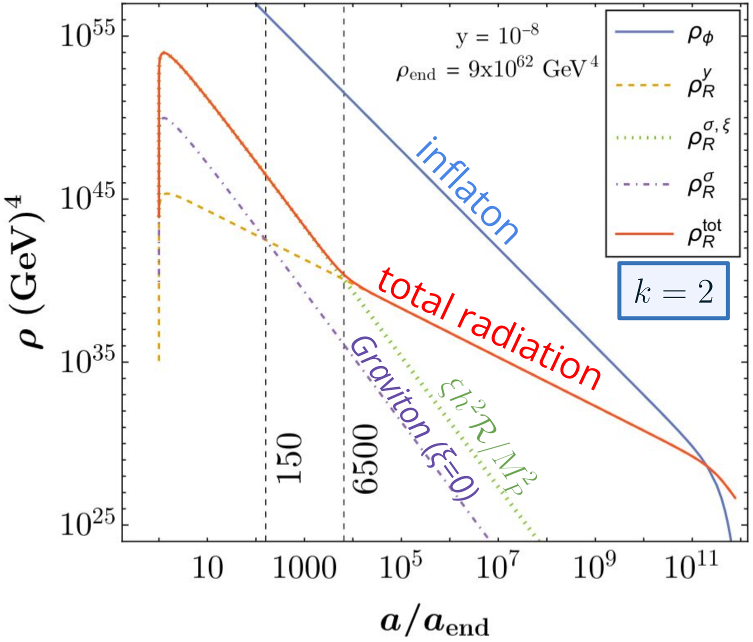


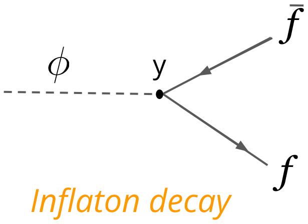
Largest enhancement for modes re-entering the horizon right after inflation

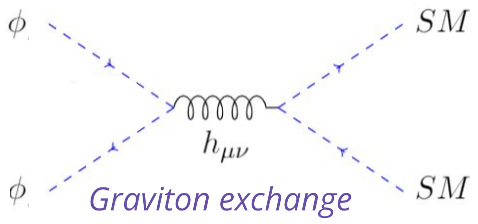
*Gravity as a Portal to Reheating, Leptogenesis and Dark Matter, Barman, **SC**, Co, Mambrini, Olive,* **2210.05716**

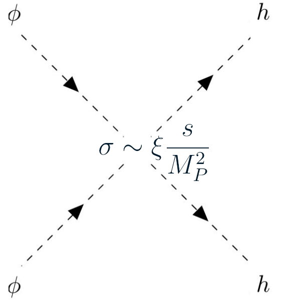
Primordial GWs strength as function of its frequency f. Blue curves fix ξ_h = 0 and Red curves fix $T_{\rm RH} = 300\,{\rm TeV}$ for k in [6,20]. The sensitivity of several future GWs experiments are shown.

Radiation perturbative production







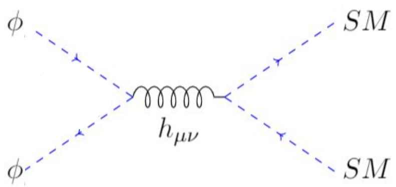


Non-minimal coupling

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 $\xi = 2$

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

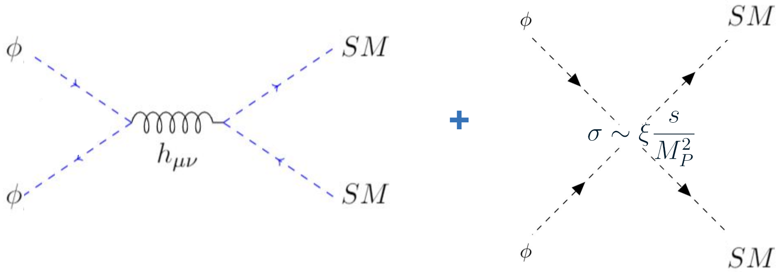
Gravitational reheating



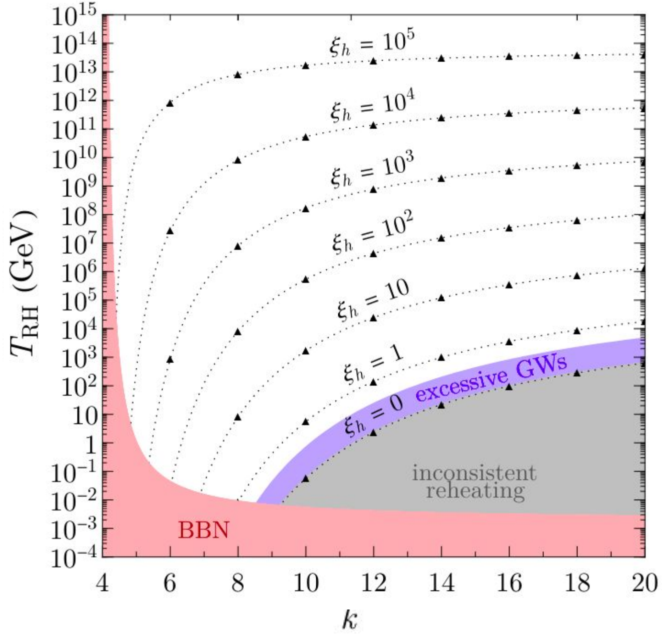
➜ Graviton exchange processes can be sufficient to reheat entirely, for sufficiently steep inflaton potential : $k > 9$

Gravity as a Portal to Reheating, Leptogenesis and Dark Matter, Barman, ***SC,*** *Co, Mambrini, Olive,* **2210.05716**

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

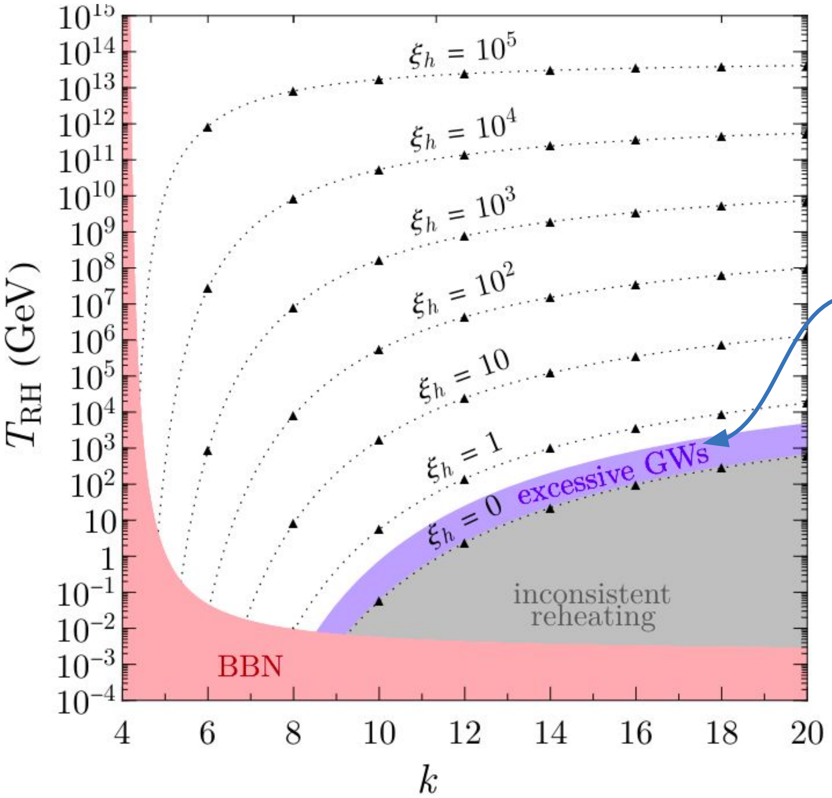


➜ Requirement of large k can be relaxed adding the non-minimal contribution to radiation production (but still need $k > 4$)



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

Primordial GWs constraints



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

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

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

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

*Gravity as a Portal to Reheating, Leptogenesis and Dark Matter, Barman, **SC**, Co, Mambrini, Olive,* **2210.05716**

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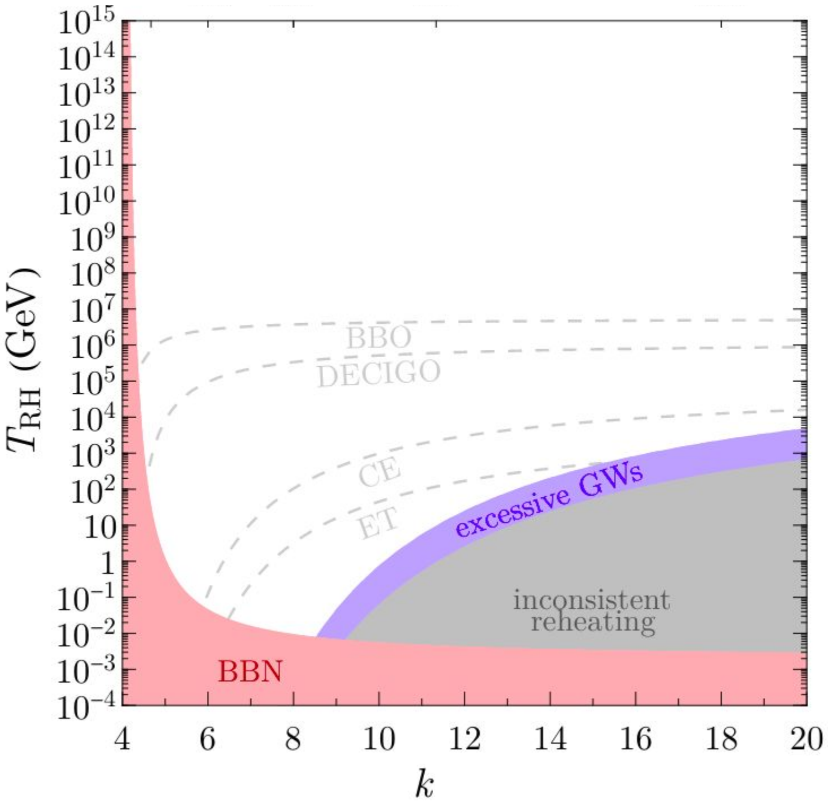

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➜ The constraint is relaxed when radiation production is increased by non-minimal gravitational interactions $\xi_h > 0$

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

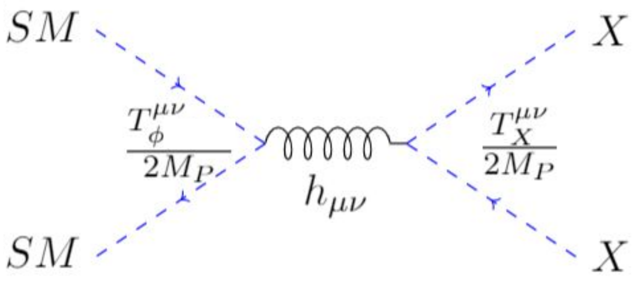
Done more generically in *Measuring Inflaton Couplings via Primordial Gravitational Waves*, Barman, Ghoshal, Grzadkowski, Socha, **2305.00027**

Gravitational portals

$$R_j(T) = \beta_j \frac{\boxed{T^8}}{M_P^4}$$

for spin j = 0, ½ DM final state

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

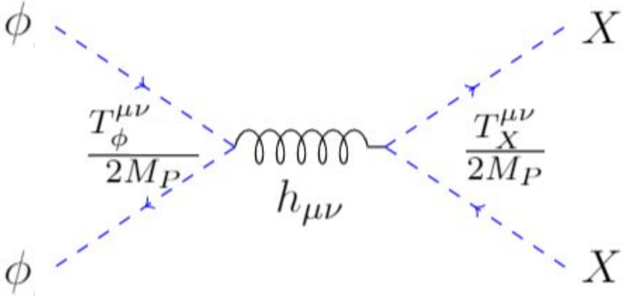


$$R_0^{\phi^k} = \boxed{\frac{2\times\rho_\phi^2}{16\pi M_P^4}} \sum_{n=1}^{\infty} |\mathcal{P}_n^k|^2 \left[1+\frac{2m_X^2}{E_n^2}\right]^2 \sqrt{1-\frac{4m_X^2}{E_n^2}}$$

spin 0

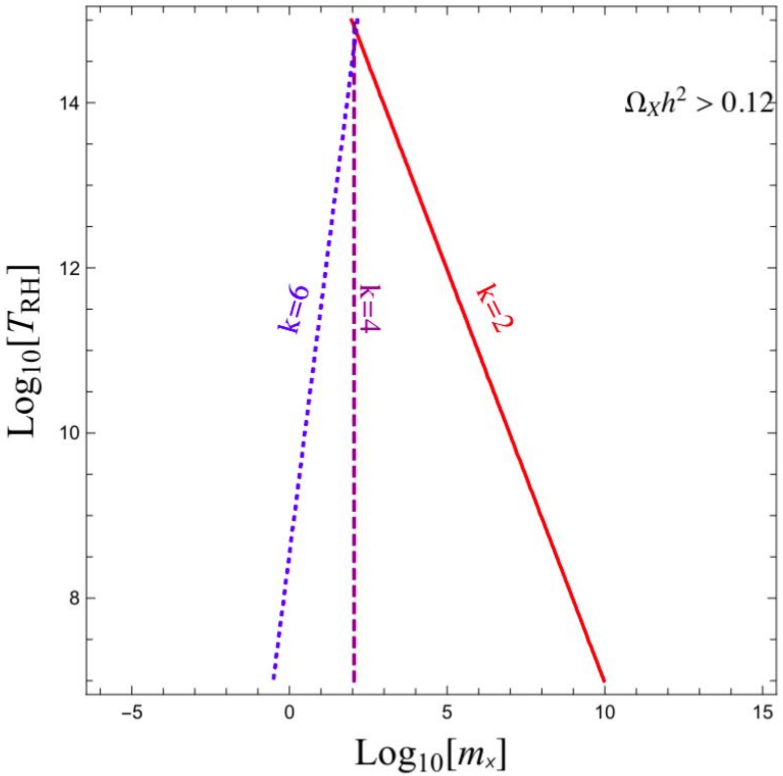
$$R_{1/2}^{\phi^k} = \frac{2\times\rho_\phi^2 \boxed{m_X^2}}{4\pi M_P^4\, m_\phi^2} \sum_{n=1}^{+\infty} |\mathcal{P}_n^k|^2 \frac{m_\phi^2}{E_n^2}\left[1-\frac{4m_X^2}{E_n^2}\right]^{3/2}$$

spin ½

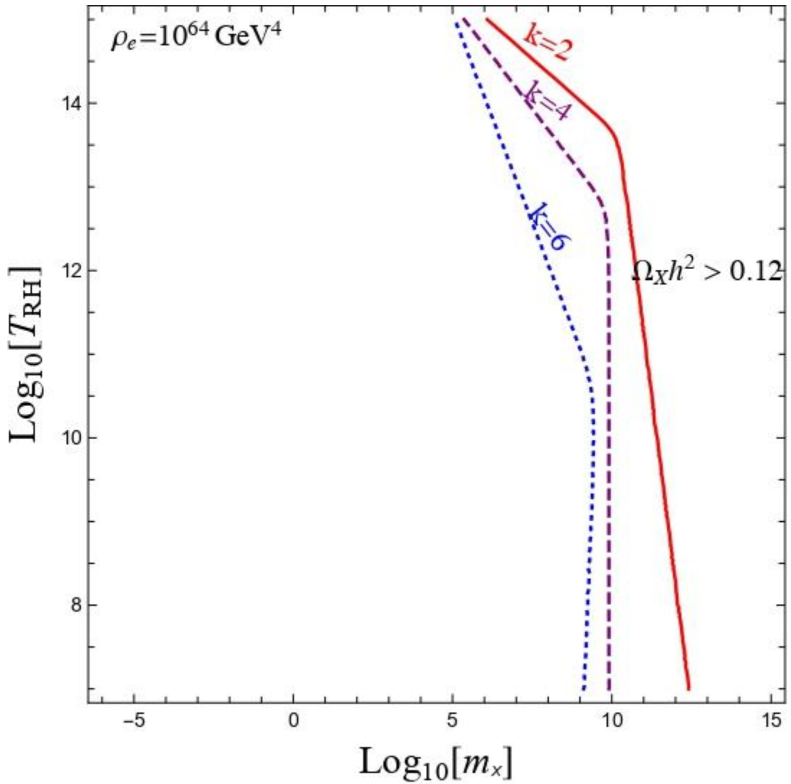


Gravitational portals in the early Universe, **SC,** Mambrini, Olive, Verner, **2112.15214**

Dark Matter gravitational production during reheating



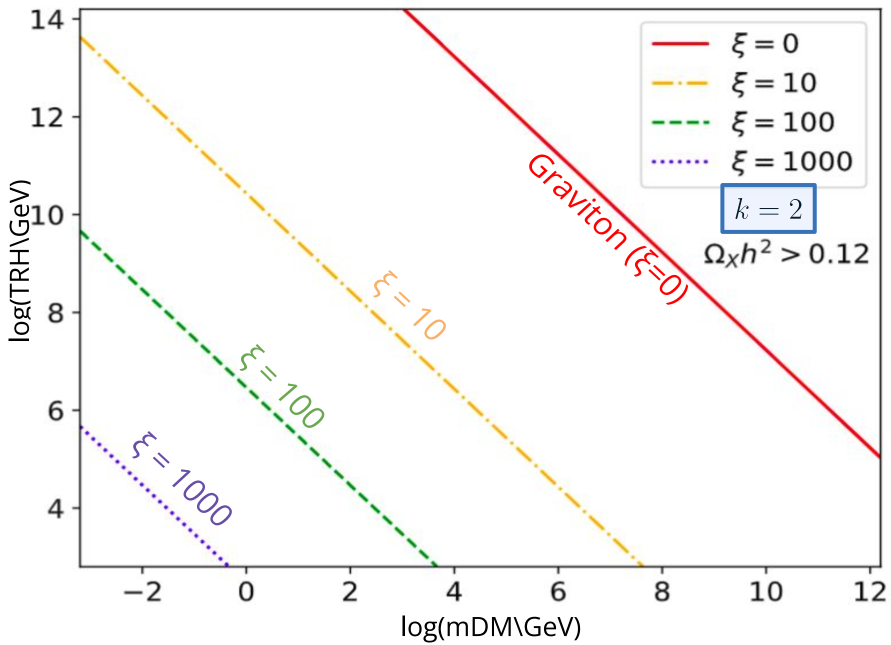
$\Omega_X h^2 = 0.12$ in the case of a spin 0 DM all contributions added

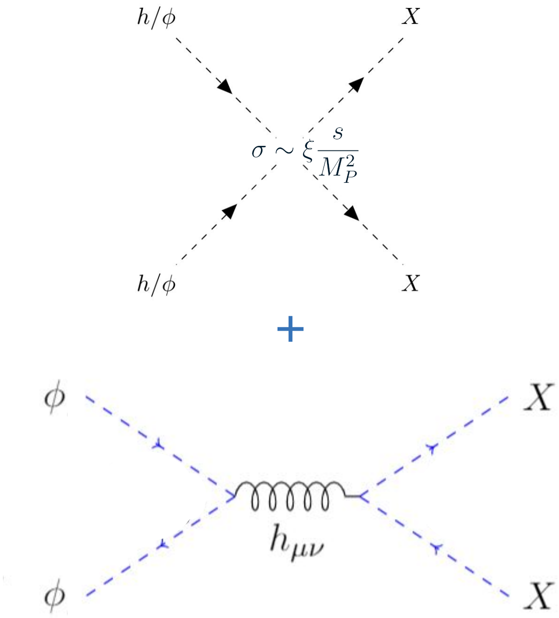


$\Omega_X h^2 = 0.12$ in the case of a spin ½ DM, all contributions added

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

Non-minimal production of Dark Matter



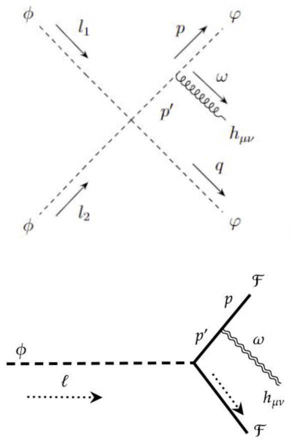


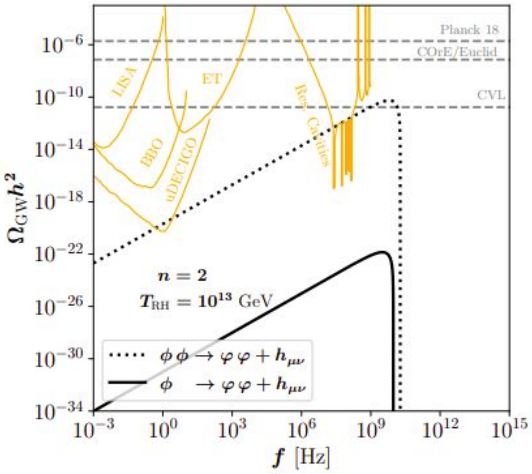
Contours respecting $\Omega_X h^2 = 0.12$ *for spin 0 DM, for different values of* $\xi_h = \xi_X = \xi$.
Both minimal and non-minimal contributions are added.

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

Observable signal of effective gravitational interaction

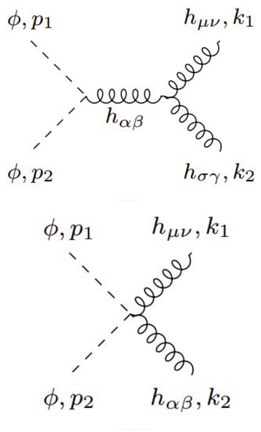
➔ Look at particle origin for stochastic GWs background that generates a spectrum at high frequencies, and depends on the details of reheating

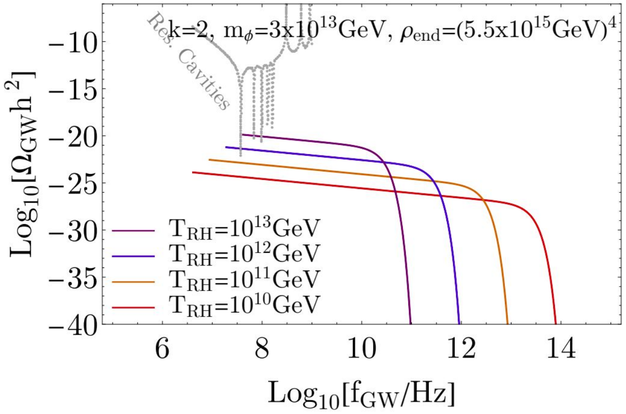




Graviton bremsstrahlung

Probing Reheating with Graviton Bremsstrahlung, Bernal, **SC,** Mambrini and Xu, **2311.12694**





Direct gravitons production

Minimal production of prompt gravitational waves during reheating, Choi, Ke, Olive, **2402.04310**

Non minimal coupling to gravity

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

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

in the Jordan frame

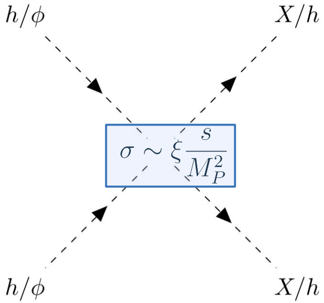
with $$\Omega^2 \equiv 1 + \underbrace{\frac{\xi_\phi \phi^2}{M_P^2}}_{\text{inflaton}} + \underbrace{\frac{\xi_h h^2}{M_P^2}}_{\text{SM}} + \underbrace{\frac{\xi_X X^2}{M_P^2}}_{\text{DM}}$$

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

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

in the Einstein frame

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



Reheating and Dark Matter Freeze-in in the Higgs-R^2 Inflation Model, Aoki, Lee, Menkara, Yamashita, **2202.13063**
Gravitational Portals with Non-Minimal Couplings, **SC,** Mambrini, Olive, Shkerin, Verner, **2203.02004**

Non-minimal coupling : the small-field limit

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

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

No field redefinition to the canonical form, unless all three non-minimal couplings vanish

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

Small-field limit: expand the action in powers of M_P^{-2} obtain canonical kinetic term and leading-order interactions induced by the non-minimal couplings

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

$$\boxed{|\xi_\phi| \lesssim 1}$$

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

Parametric resonances

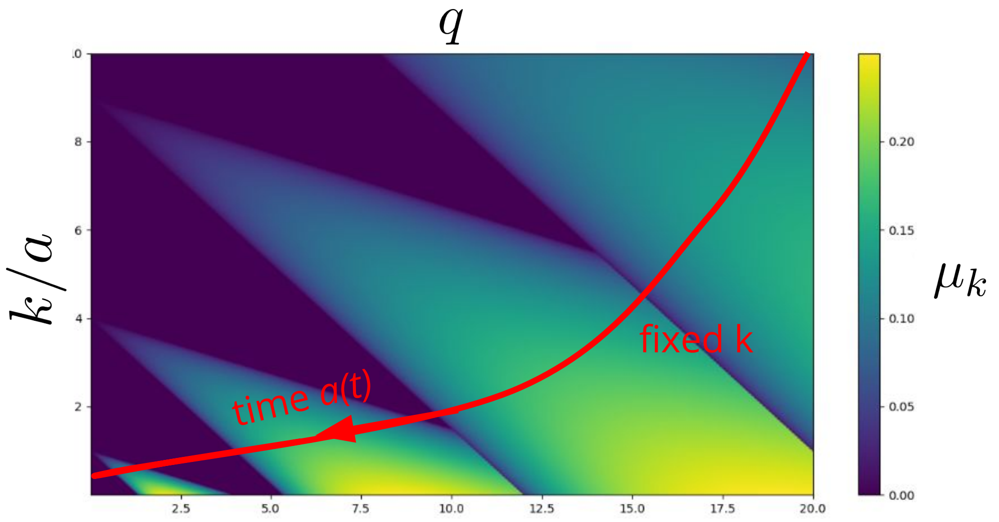
Time dependent background coupled to fields can lead to parametric resonance or tachyonic instability

$$\mathcal{L} \supset \sigma\phi^2\chi^2 \; + \; \lambda\phi^k M_P^{4-k}$$

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

EOM for Fourier modes in the oscillating background

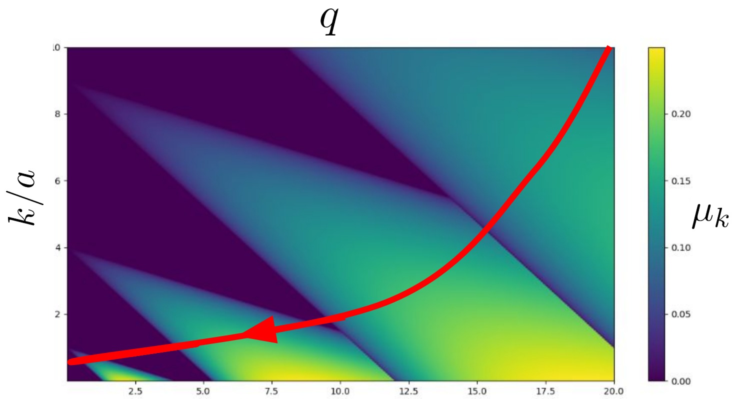
$$q \equiv \frac{\sigma\phi_0^2}{2m_\phi^2} \sim \frac{\sigma}{\lambda}$$



Instabilities in the colored regions
➜ increasing occupation number of the modes

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

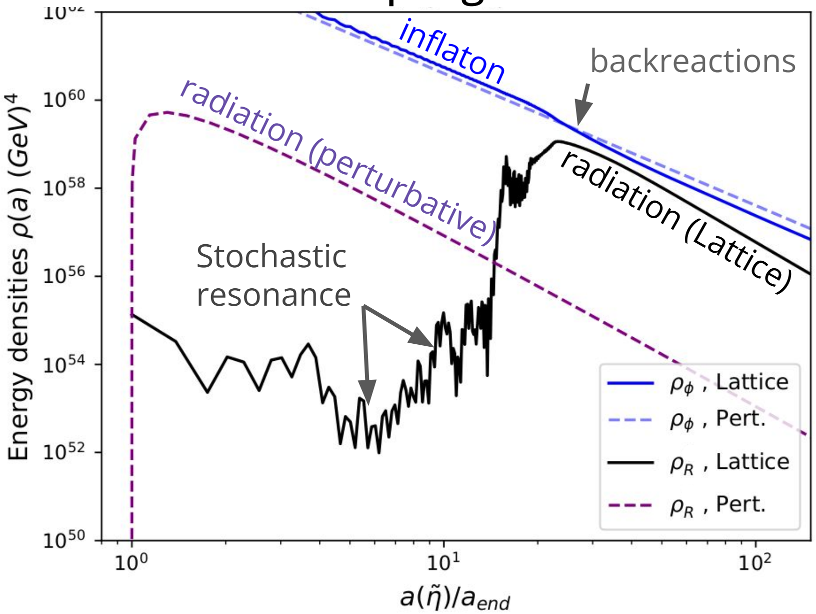
Preheating through non-perturbative processes



Instabilities in the colored regions
➜ number of occupation increasing

$$\chi_k \propto \exp\left[\mu_k t\right]$$

coupling σ ~10^{-6}

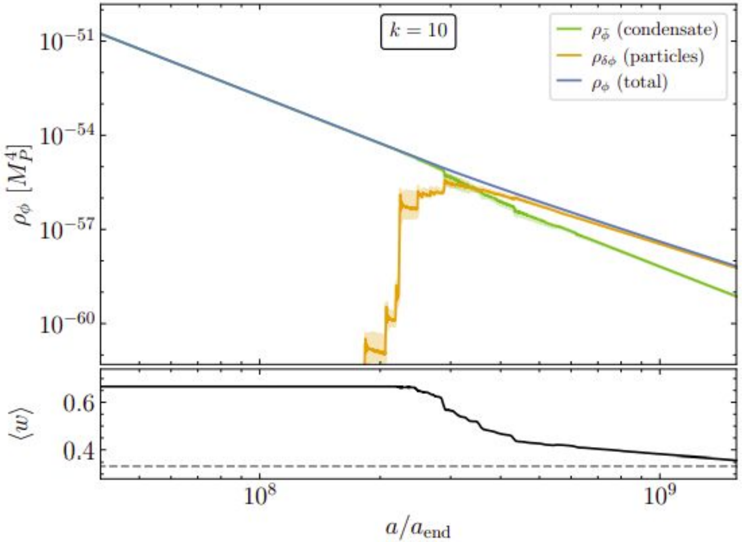


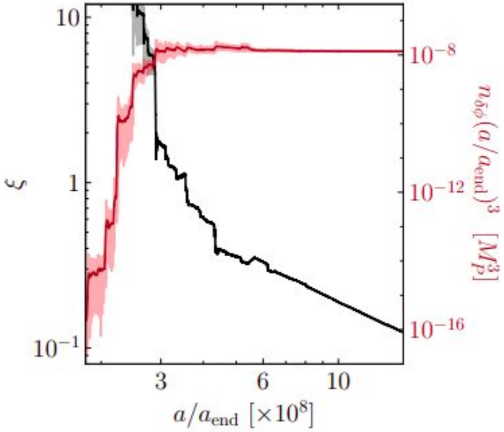
Preheating corresponds to resonances and exponential production

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

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

Inflation self-fragmentation





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

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