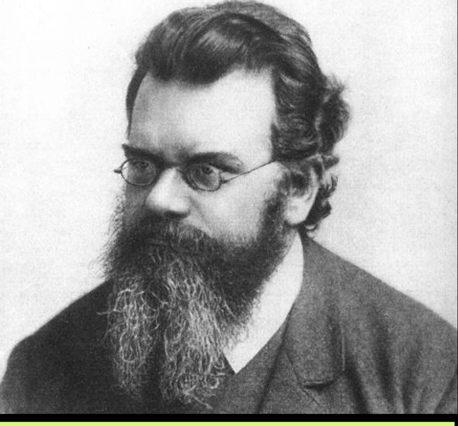


« Available energy is the main object at stake in the struggle for existence and the evolution of the world. »

L. Boltzmann

(Dark) matter production in the (very) early Universe

Yann Mambrini, IJCLab, Université Paris-Saclay

Simon Clery, Marcos Garcia, Kunio Kaneta, Keith Olive and Sarunas Verner

2022 CAU BSM workshop

09/02/2022

PhD students :

Simon Clery (IJCLab, Paris-Saclay)

Sarunas Verner (Minneapolis U.)

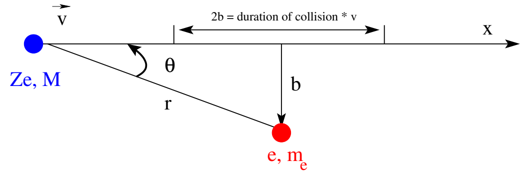


Fig. 5.9 Interaction of a high energy particle of charge Ze with an electron at rest.

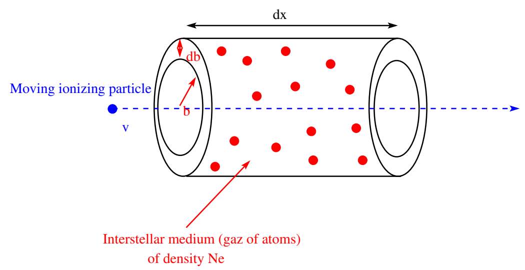


Fig. 5.10 Moving particle in an interstellar medium of density N_e.

distance at which the influence of the traveling particle on the electron is negligible. It corresponds roughly to the time when the orbital period is lower than the typical interaction time. In other words, if the electron takes more time to move around the nucleus than to interact with the moving particle, the electromagnetic influence of the later becomes weak. If one write τ the interacting time and ν_0 the frequency of the rotating electron in the atom ($\nu_0 = \omega_0/2\pi$), it corresponds to

$$\tau \simeq \frac{2b}{v} < \frac{1}{\nu_0} \;\Rightarrow\; b < \frac{v}{2\nu_0} = b_{max} \qquad (5.37)$$

The lower limit b_{min} can be obtained if we suppose, by a quantum treatment and the application of the uncertainty principle, that the maximum energy transfer is $\Delta p_{max} = 2m_e v$ (because as we discussed earlier, the maximum velocity transferred to the electron is $2v$) from $\Delta p \Delta x \gtrsim \hbar$ (Heisenberg principle) we have $\Delta x \gtrsim \hbar/2m_e v$. We can then write

The two parts of the Lagrangian one needs to compute the scalar annihilation of Dark Matter $SS \rightarrow h \rightarrow \bar{f} f$ are (see B.235)[9]

$$\mathcal{L}_{HSS} = -\lambda_{HS}\frac{M_W}{2g} hSS \;\rightarrow C_{HSS} = -i\frac{\lambda_{HS}M_W}{g}$$
$$\text{and}\;\; \mathcal{L}_{Hff} = -\frac{g m_f}{2M_W} h\bar{f}f \;\rightarrow C_{Hff} = -i\frac{g m_f}{2M_W} \qquad (B.145)$$

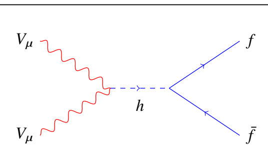
which gives

$$|\mathcal{M}|^2 = \frac{\lambda_{HS}^2 m_f^2 (s/2 - 2m_f^2)}{(s-M_H^2)^2 + \Gamma_H^2 M_H^2} \qquad (B.146)$$

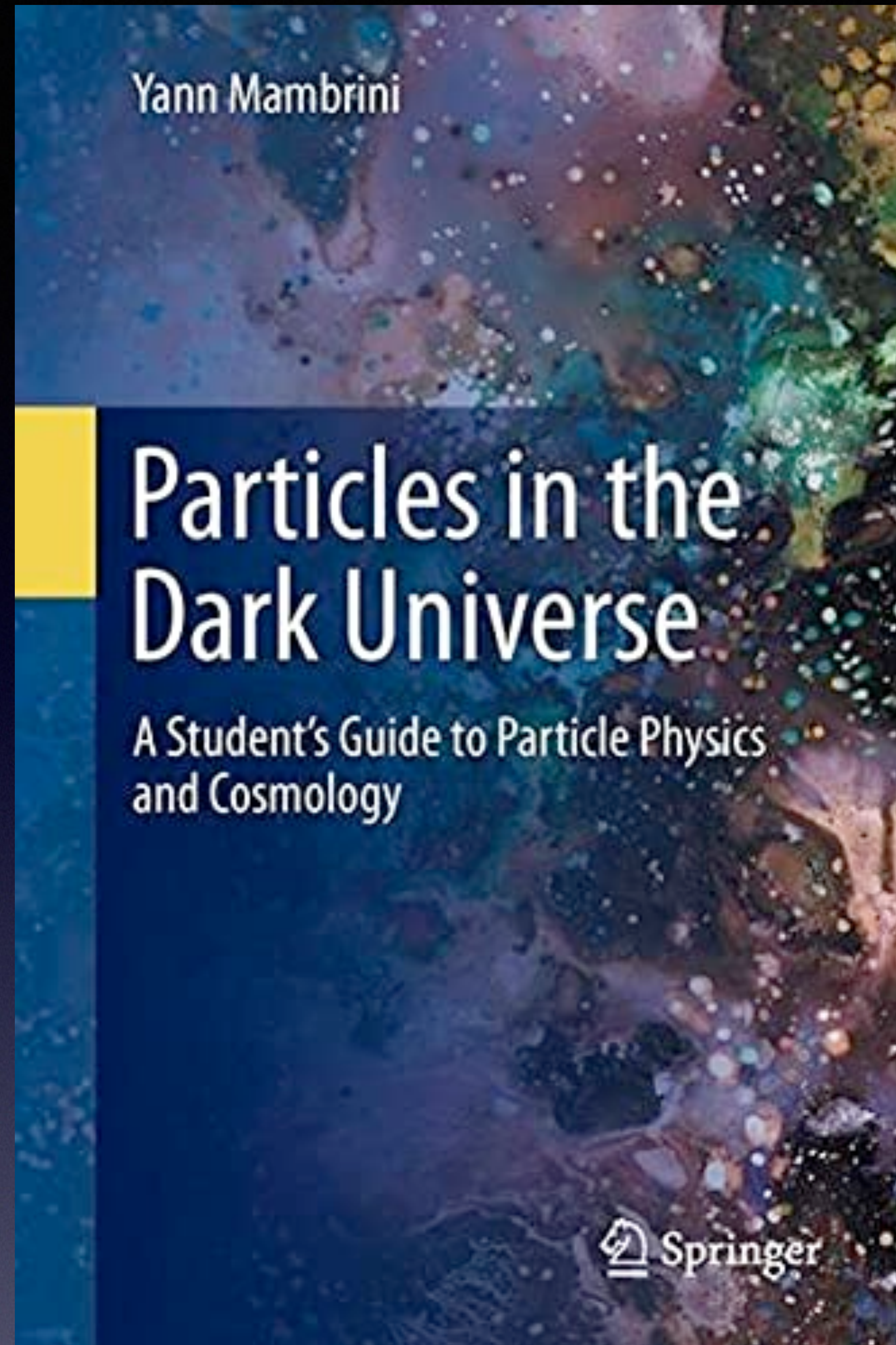
Γ_H being the width of the Higgs boson (including its own decay into SS, see next section). When ones implement this value of $|\mathcal{M}|^2$ into Eq.(B.111) one obtains after simplification

$$\langle\sigma v\rangle^S_{f\bar f} = \frac{|\mathcal{M}|^2}{8\pi s}\sqrt{1-\frac{m_f^2}{M_S^2}} = \frac{\lambda_{HS}^2 (M_S^2 - m_f^2) m_f^2}{16\pi M_S^2 (4M_S^2 - M_H^2)^2}\sqrt{1-\frac{m_f^2}{M_S^2}}. \qquad (B.147)$$

B.4.4.11 Annihilation in the case of vectorial Dark Matter to pairs of fermions



One can compute this annihilation cross section by the normal procedure or noticing that a neutral vectorial dark matter of spin 1 corresponds to 3 degrees of freedom. After averaging on the spin one can then write $\langle\sigma v\rangle^V = \frac{3}{3\times 3}\langle\sigma v\rangle^S = \frac{1}{3}\langle\sigma v\rangle^S$. The academical computation for $V_\mu(p_1)V_\mu(p_2) \rightarrow f\bar{f}$ gives



$$\ddot{S} + 3H\dot{S} + \left[\frac{k^2}{a^2} + \mu\Phi_0\cos(m_\Phi t)\right] S = 0 \qquad (2.170)$$

Supposing $a \simeq$ constant, we can neglect H. This equation is one form of the Mathieu equation, which is the equation for an oscillator with a time dependant frequency $\omega^2(t) = \frac{k^2}{a^2} + \mu\Phi_0\cos(m_\Phi t)$, and is present in a lot of classic phenomena involving periodical force. It can be shown that for

$$\frac{m_\Phi}{2} - \frac{\mu\Phi_0}{2m_\Phi} < \frac{k}{a} < \frac{m_\Phi}{2} + \frac{\mu\Phi_0}{2m_\Phi}, \qquad (2.171)$$

we enter in a regime where the solution grows exponentially with time[23]. We can understand it easily, from the shape of the Mathieu equation, where, periodically, the coefficient $\cos(m_\Phi t)$ becomes negative and drives the evolution of S toward an exponential solution, periodically. The evolution of S is shown in Fig.(2.8). A more refined treatment necessitate to compute the Bogoliubov coefficient to extract the occupation number [10], but we give in the following section a more intuitive view of the phenomena, solving the equation for the density of the ϕ decay products. For the analytical solution of the Mathieu equation (2.170) the reader is directed to [9] which is without doubt the best textbook treating it, and [10] which is (paradoxically) the seminal *research* paper on the subject and one of the clearer and more detailed in the literature.

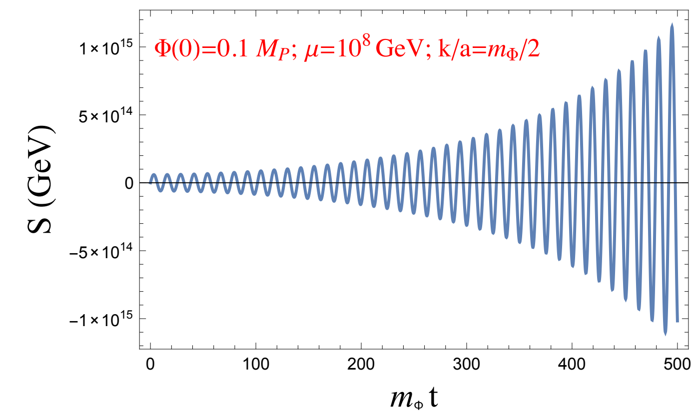
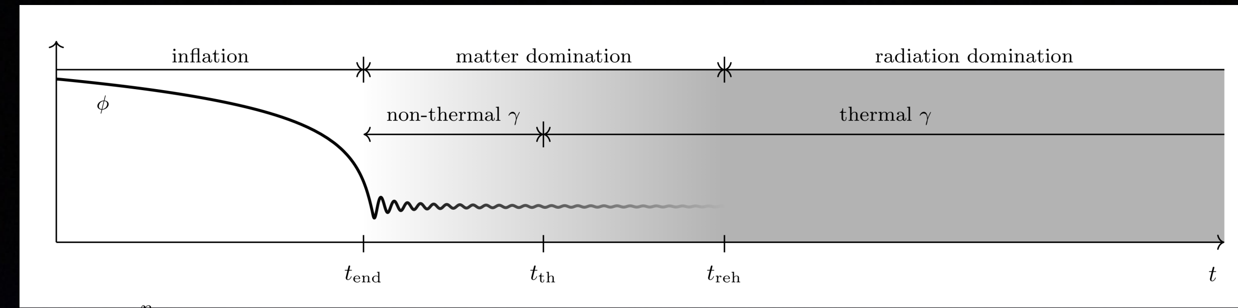


Fig. 2.8 Illustration of the parametric (also called *narrow*) resonance in the context of preheating. We can see clearly the exponential envelop of the periodic solution.

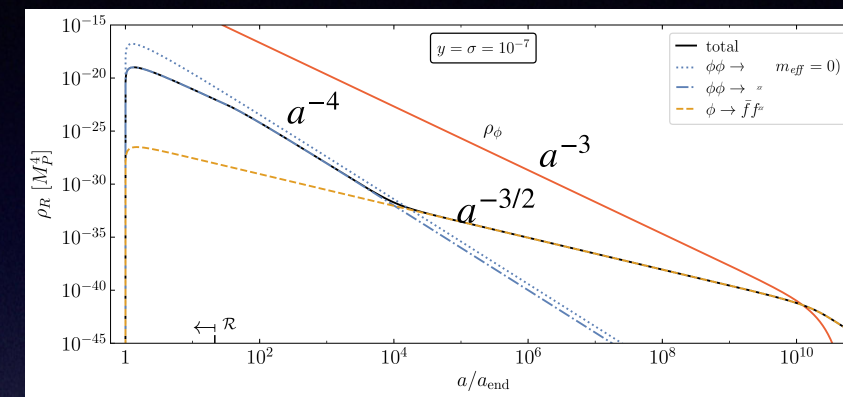
500+ pages, from inflation to dark matter detection.
All what is needed to compute cross-sections, relic abundance, and retrace the history of a Dark Universe.

Preface and forewords by K. Olive, J. Peebles and J. Silk

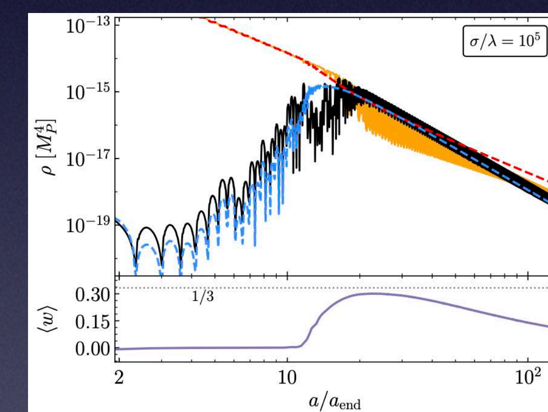
1). Reheating : generalities



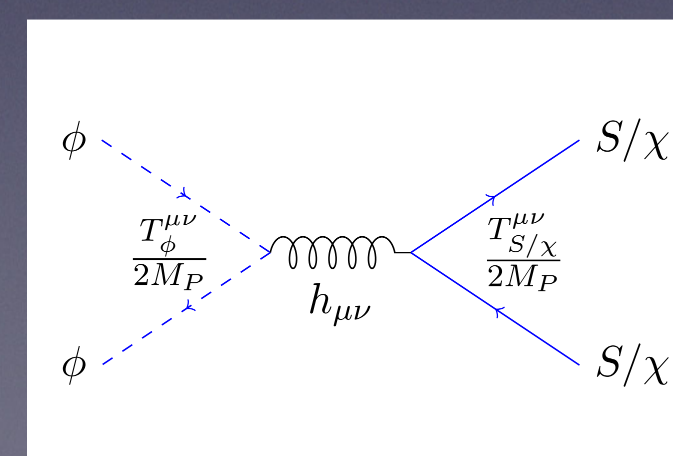
2). Non-instantaneous reheating



3). Preheating phase

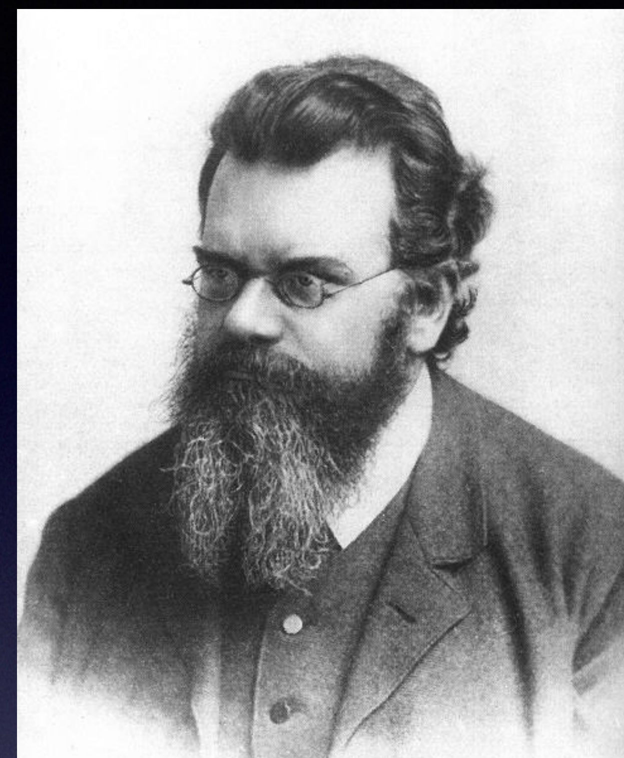


4). Application to gravitational production



5). Conclusion

A brief history of the energy in the Early Universe



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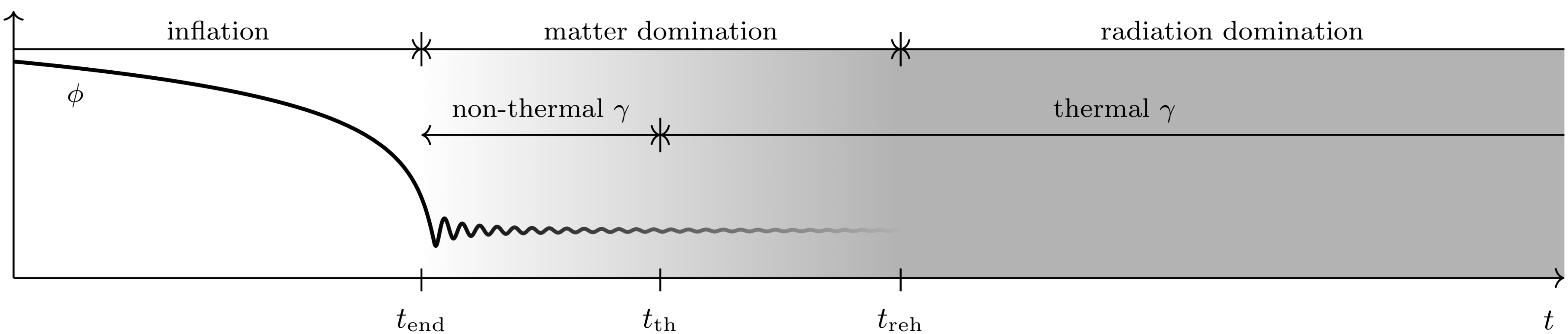
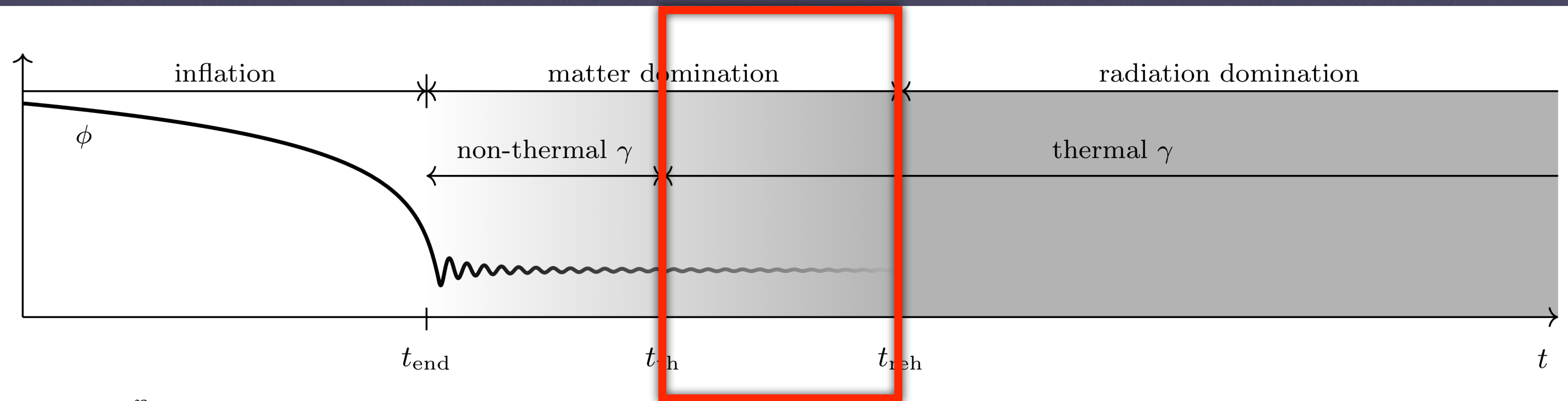


Mechanisms to produce (dark) matter at the thermal reheating stage



After several oscillations ($N \gtrsim 100$) :

The reheating phase

$$\rho_\phi = T^\phi_{00} = \frac{1}{2}\dot{\phi}^2 + V(\phi)$$

$$P_\phi = T^\phi_{ii} = \frac{1}{2}\dot{\phi}^2 - V(\phi)$$

$$\ddot{\phi}(t) + 3H\dot{\phi} - \frac{\nabla}{a^2}\phi(t) + V'(\phi) = 0$$

$$\rho_\phi = T^\phi_{00} = \frac{1}{2}\dot{\phi}^2 + V(\phi)$$

$$V(\phi) = \lambda_k \phi^k$$

$$P_\phi = T^\phi_{ii} = \frac{1}{2}\dot{\phi}^2 - V(\phi)$$

$$\ddot{\phi}(t) + 3H\dot{\phi} - \frac{\nabla}{a^2}\phi(t) + V'(\phi) = 0$$

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$$\ddot{\phi}(t) + 3H\dot{\phi} - \frac{\nabla}{a^2}\phi(t) + V'(\phi) = 0$$

$$V(\phi) = \lambda_k \phi^k$$

$$\dot{\rho}_\phi + \frac{6k}{k+2} H \rho_\phi = 0$$

$$\Rightarrow \rho_\phi \propto a^{-\frac{6k}{k+2}} = \langle V(\phi) \rangle$$

$$\rho_\phi = T^\phi_{00} = \frac{1}{2}\dot{\phi}^2 + V(\phi)$$

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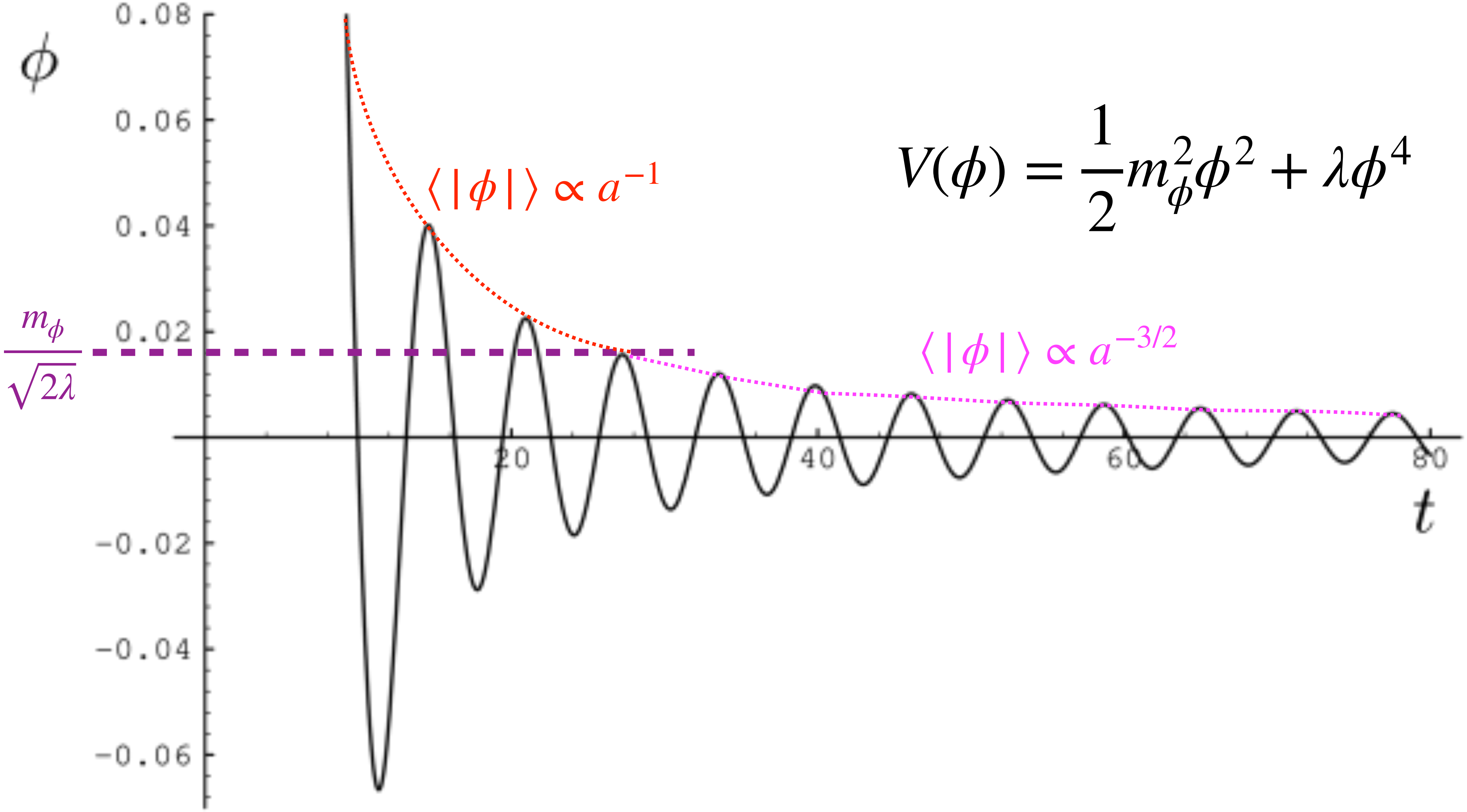
$$\Rightarrow \rho_\phi \propto a^{-\frac{6k}{k+2}} = \langle V(\phi) \rangle$$

$$V(\phi) = \frac{1}{2} m_\phi^2 \phi^2 + \lambda \phi^4$$



Adding a coupling to matter (1)

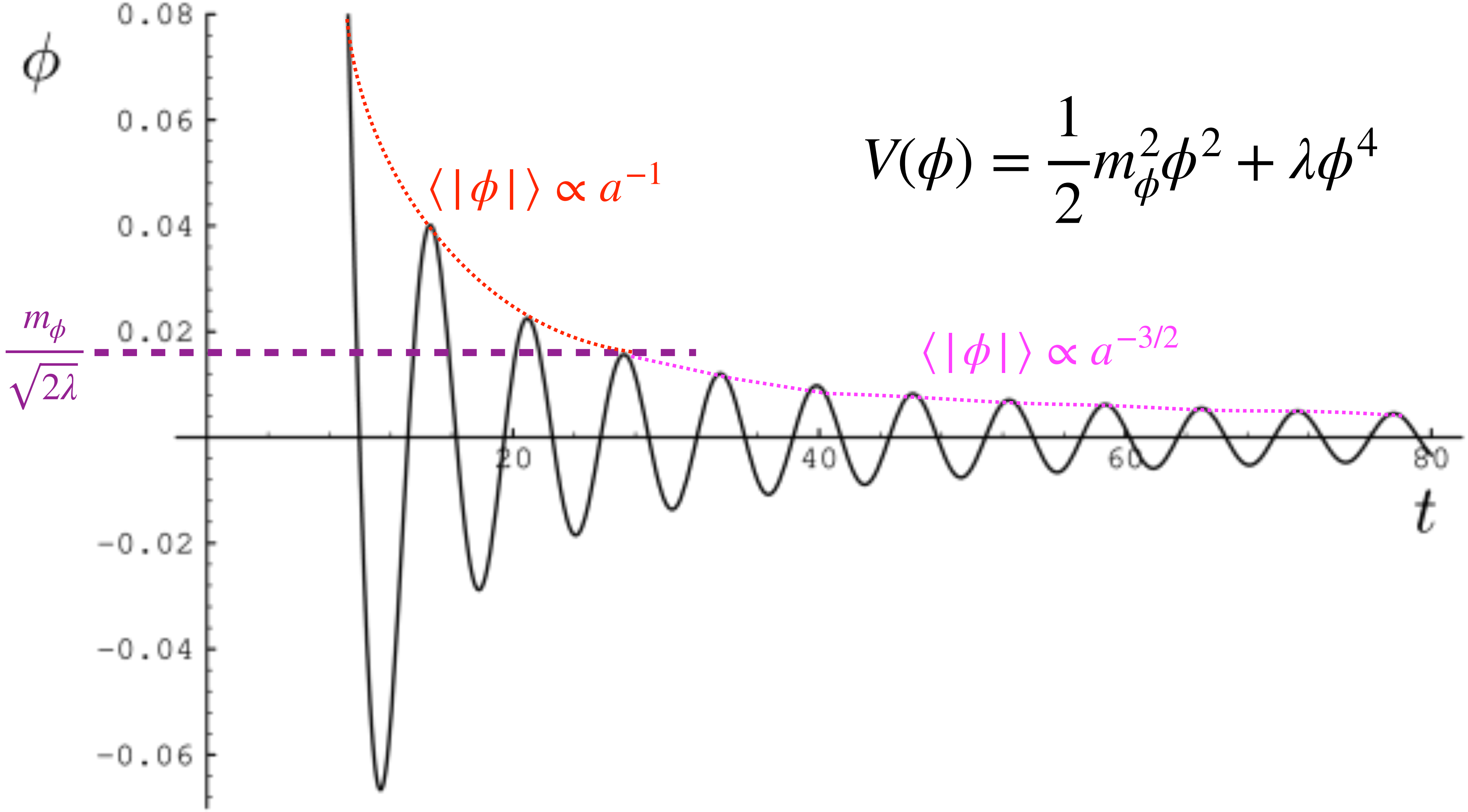
$$V = V(\phi) + y\phi\bar{f}f + \sigma\phi^2\chi^2$$

$$\sigma = 0$$

$$\ddot{\phi}(t) + 3H\dot{\phi} - \frac{\nabla}{a^2}\phi(t) + V'(\phi) = 0$$

$$\dot{\rho}_\phi + \frac{6k}{k+2}H\rho_\phi = 0$$

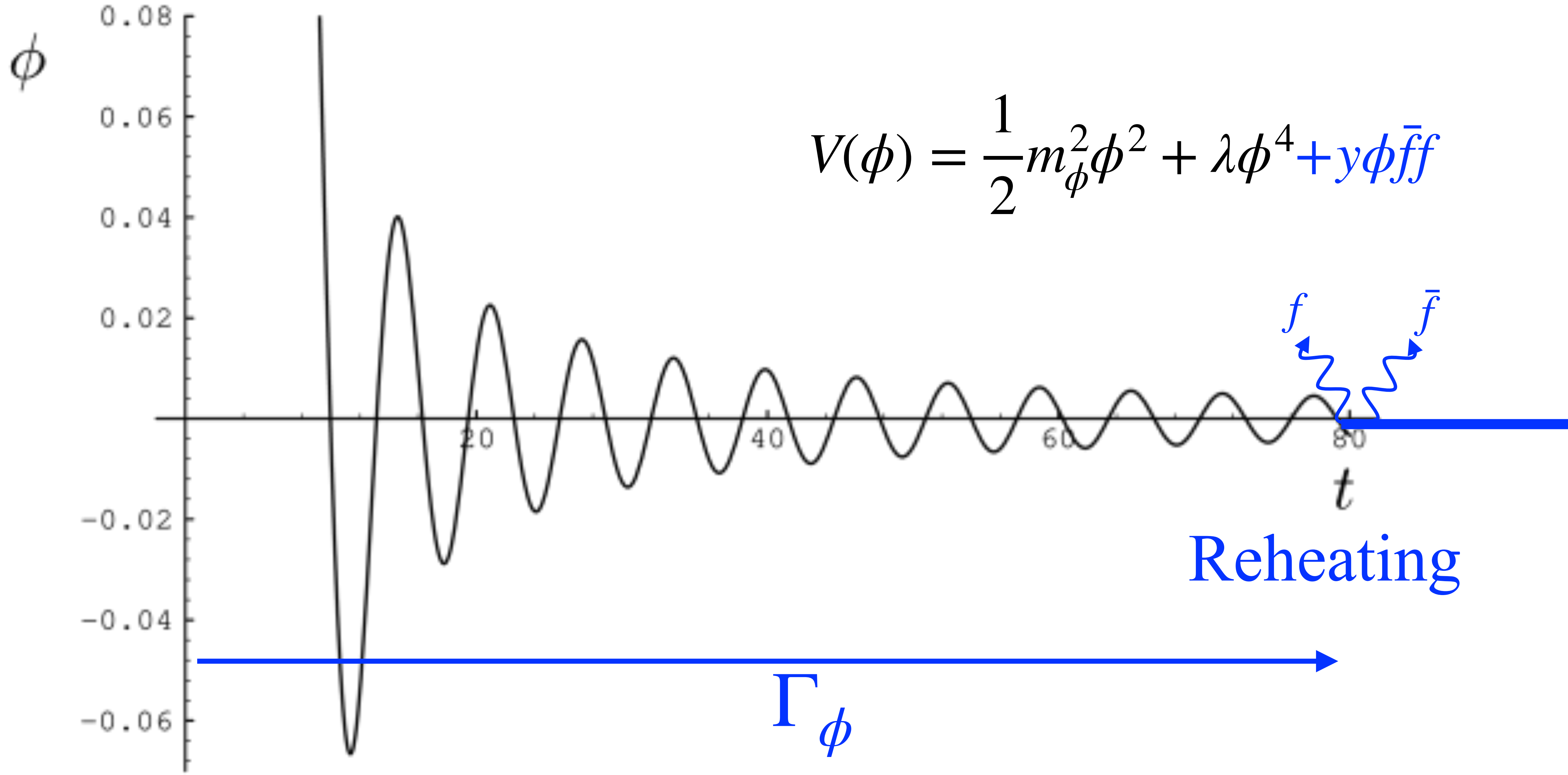
$$V(\phi) = \frac{1}{2}m_\phi^2\phi^2 + \lambda\phi^4$$



$$\ddot{\phi}(t) + 3H\dot{\phi} - \frac{\nabla}{a^2}\phi(t) + V'(\phi) = -\Gamma_\phi\dot{\phi}$$

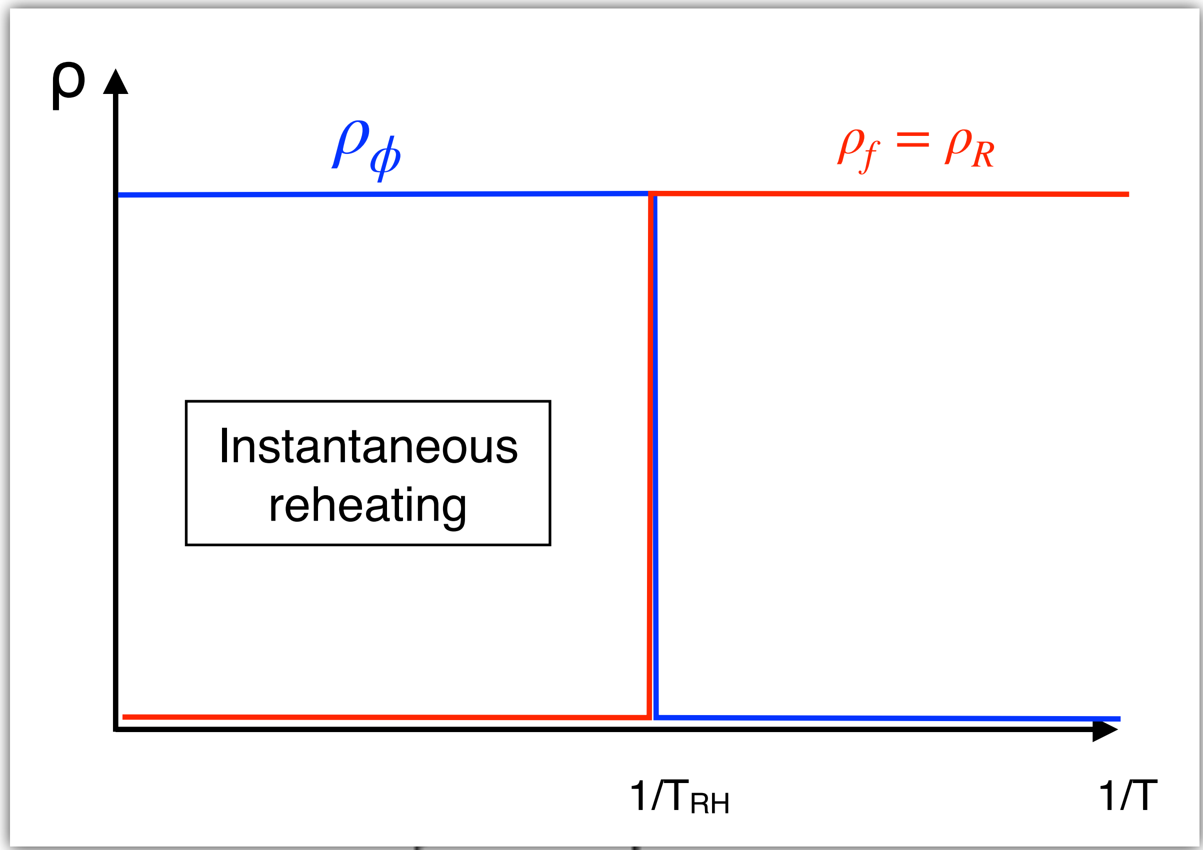
$$\dot{\rho}_\phi + \frac{6k}{k+2}H\rho_\phi = -\Gamma_\phi\rho_\phi$$

$$V(\phi) = \frac{1}{2}m_\phi^2\phi^2 + \lambda\phi^4 + y\phi\bar{f}f$$

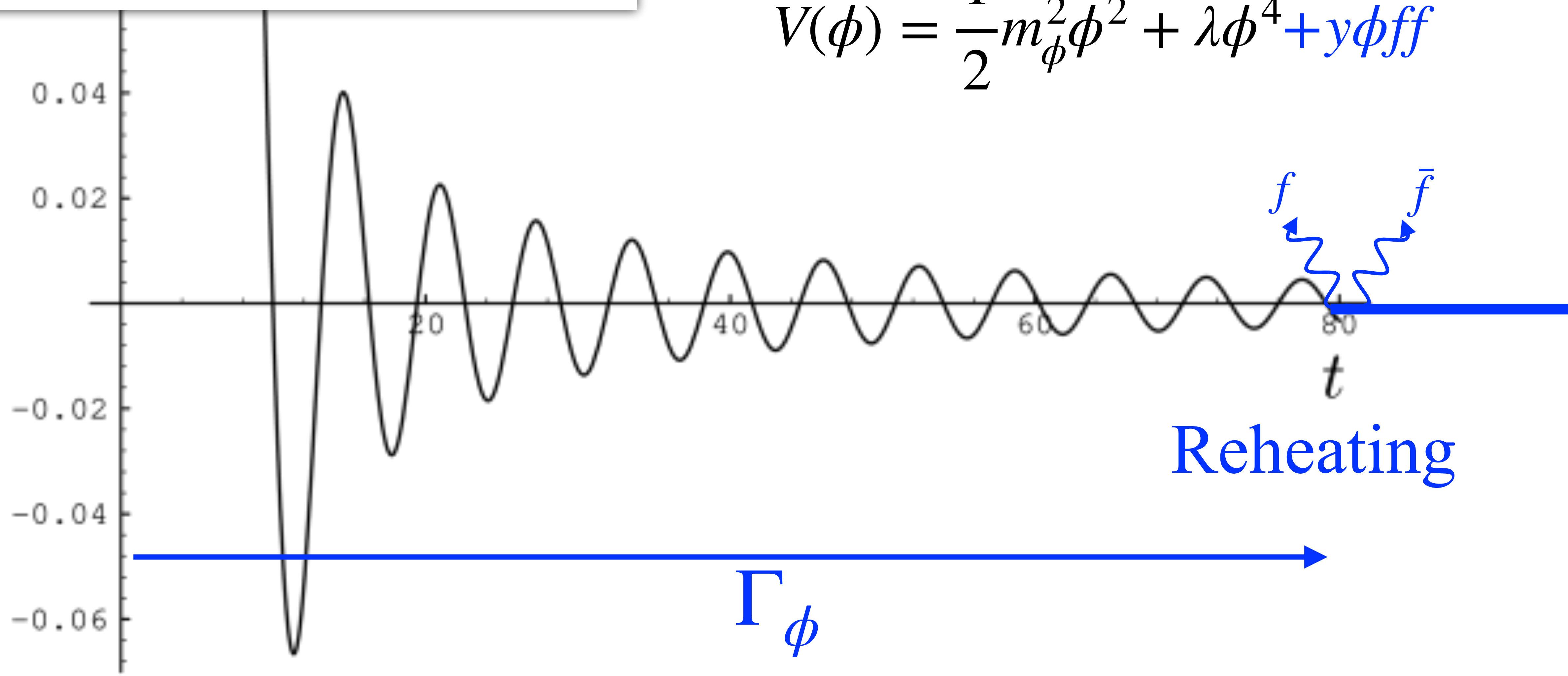


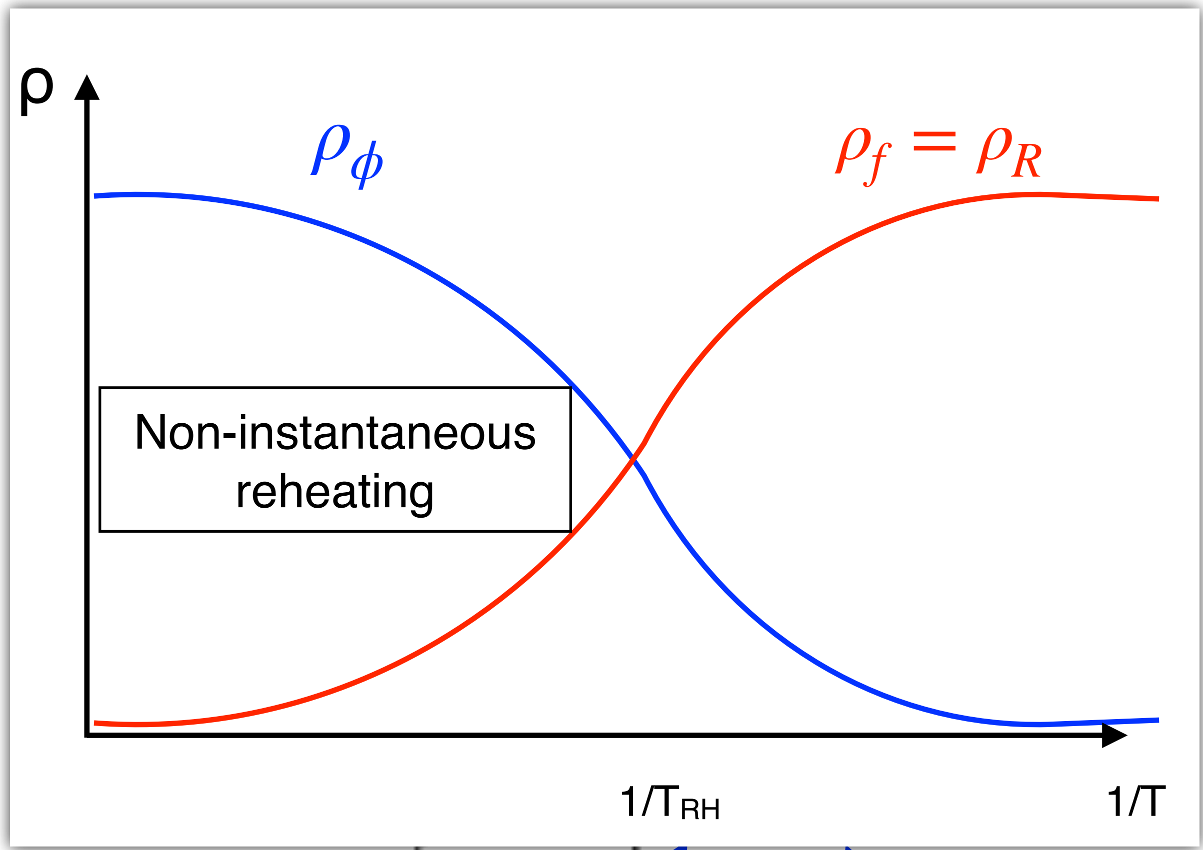
$$\ddot{\phi}(t) + 3H\dot{\phi} - \frac{\nabla}{a^2}\phi(t) + V'(\phi) = -\Gamma_\phi\dot{\phi}$$

$$\dot{\rho}_\phi + \frac{6k}{k+2}H\rho_\phi = -\Gamma_\phi\rho_\phi$$



$$V(\phi) = \frac{1}{2}m_\phi^2\phi^2 + \lambda\phi^4 + y\phi\bar{f}f$$





$$\ddot{\phi}(t) + 3H\dot{\phi} - \frac{\nabla}{a^2}\phi(t) + V'(\phi) = -\Gamma_\phi\dot{\phi}$$

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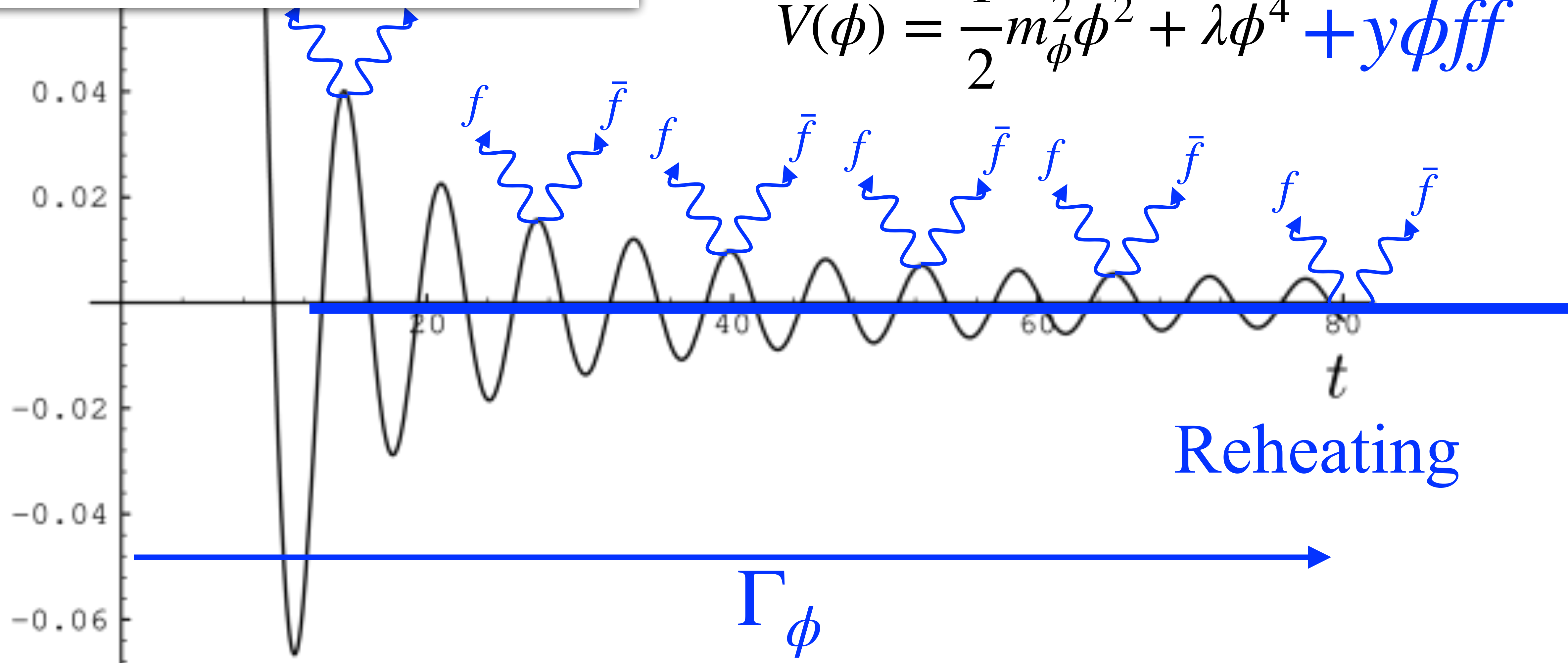
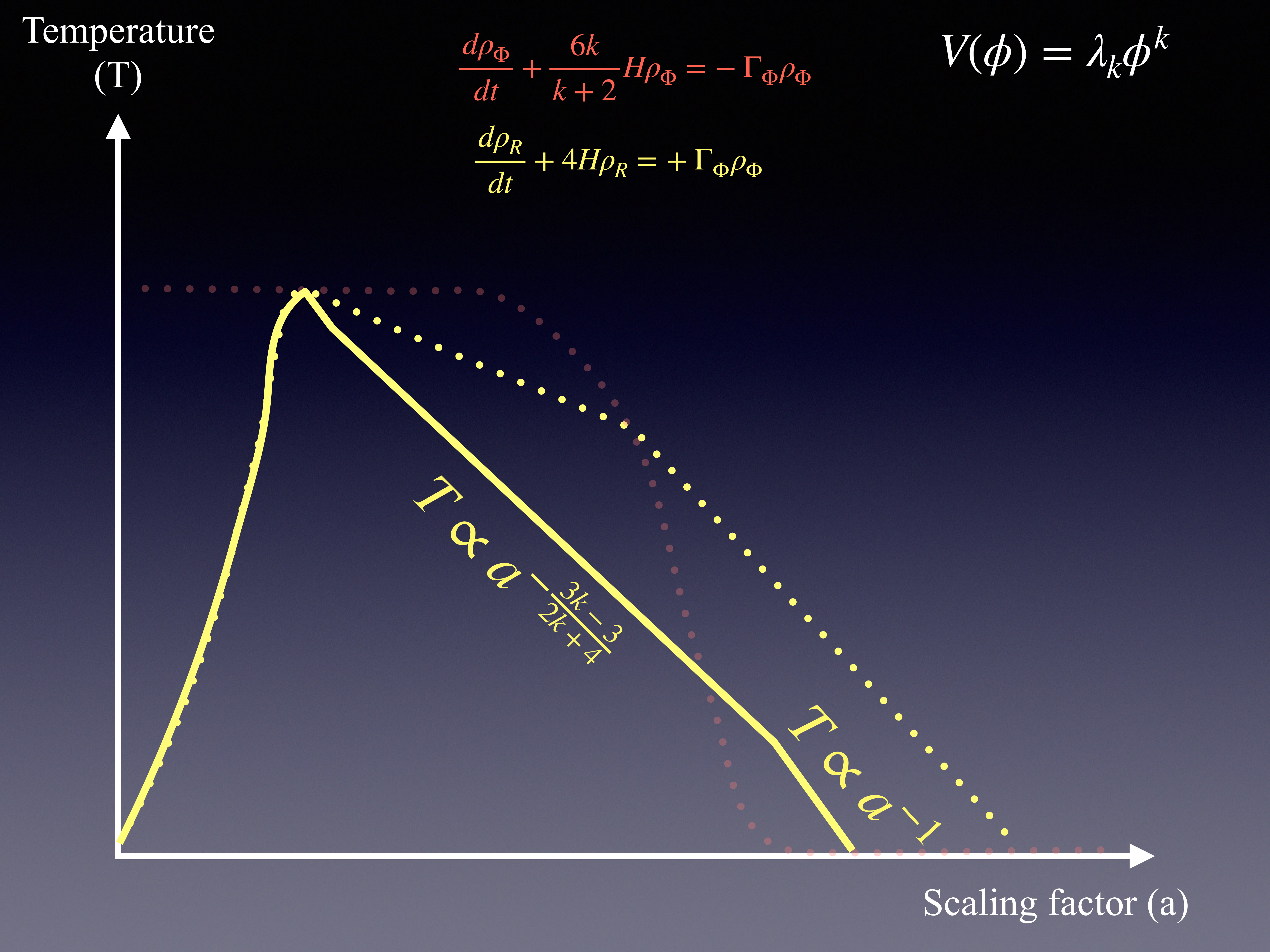



Temperature (T)
$$\frac{d\rho_\Phi}{dt} + \frac{6k}{k+2}H\rho_\Phi = -\Gamma_\Phi\rho_\Phi$$
$$V(\phi) = \lambda_k \phi^k$$
$$\frac{d\rho_R}{dt} + 4H\rho_R = +\Gamma_\Phi\rho_\Phi$$
$T \propto a^{-\frac{3k-3}{2k+4}}$
$T \propto a^{-1}$
Scaling factor (a)

Adding a coupling to matter (2)

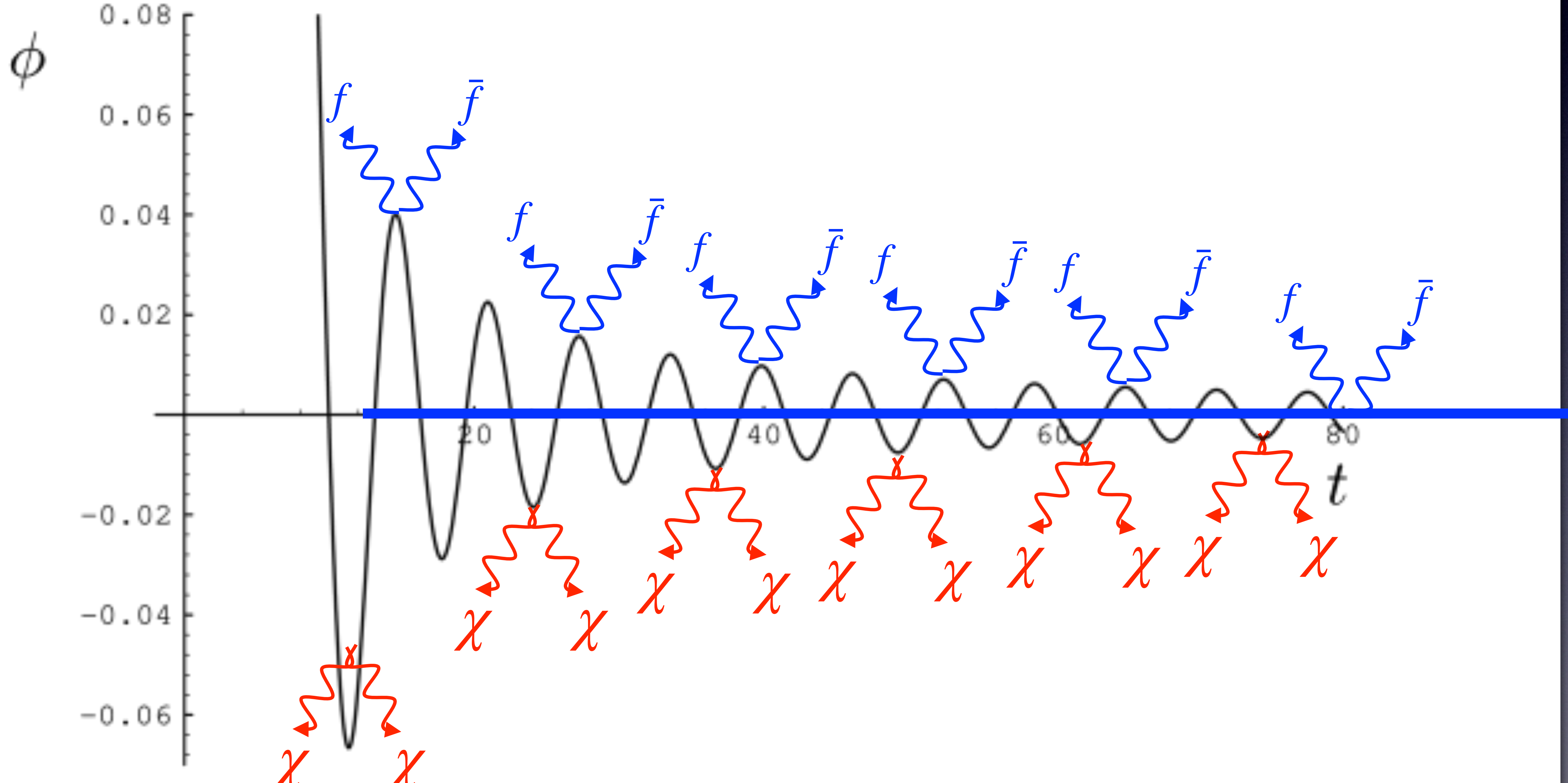
$$V = V(\phi) + y\phi\bar{f}f + \sigma\phi^2\chi^2$$

$$\sigma \neq 0, \qquad \sigma \times \phi_{\text{end}}^2 \ll m_\phi^2$$

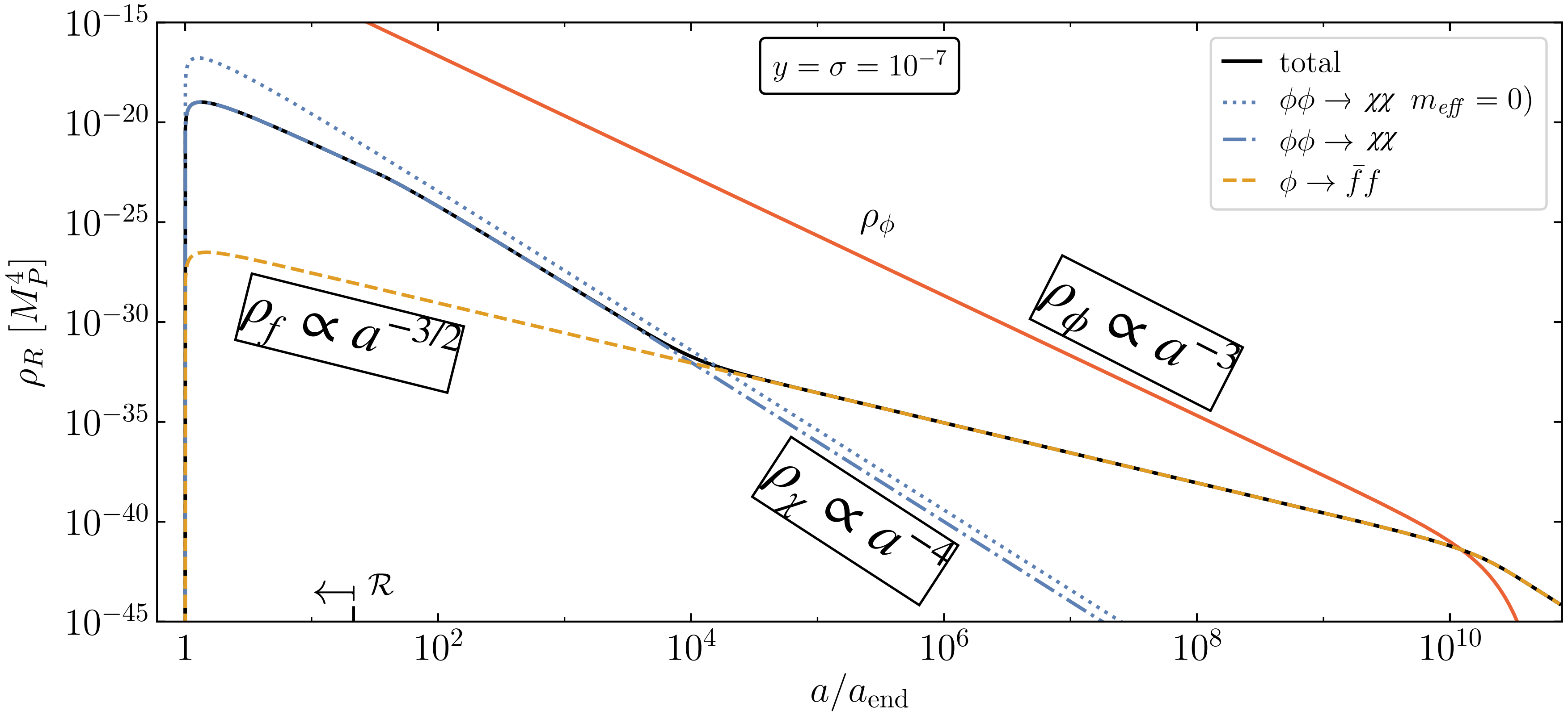
$$V(\phi) = \frac{1}{2}m_\phi^2\phi^2 + y\phi\bar{f}f + \sigma\phi^2\chi^2$$

$$\ddot{\chi}(t,x) + 3H\dot{\chi} - \frac{\nabla}{a^2}\chi(t,x) + 2\sigma\phi^2\chi = 0$$

$$m_\chi^{\mathrm{eff}} = \sqrt{2\sigma}\phi$$



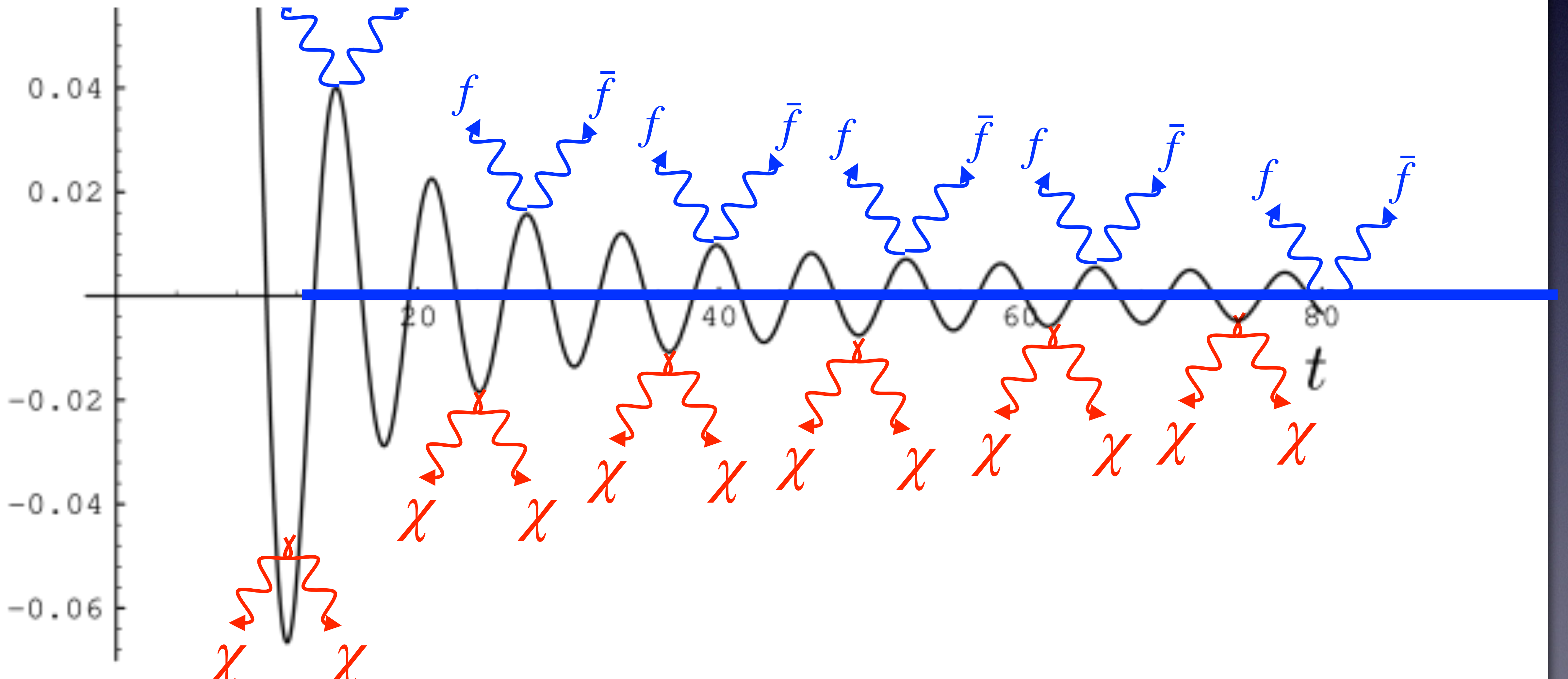
M. A. G. Garcia, K. Kaneta, Y. Mambrini and K. A. Olive, JCAP **04** (2021), 012[arXiv:2012.10756 [hep-ph]].



$$\frac{1}{2}m_\phi^2\phi^2 + y\phi\bar{f}f + \sigma\phi^2\chi^2$$

$$3H\dot{\chi} - \frac{\nabla}{a^2}\chi(t,x) + 2\sigma\phi^2\chi = 0$$

$$m_\chi^{\rm eff} = \sqrt{2\sigma\phi}$$



$$\ddot{\chi}(t,x) + 3H\dot{\chi}(t,x) - \frac{\nabla}{a^2}\chi(t,x) + 2\sigma\phi^2\chi(t,x) = 0$$

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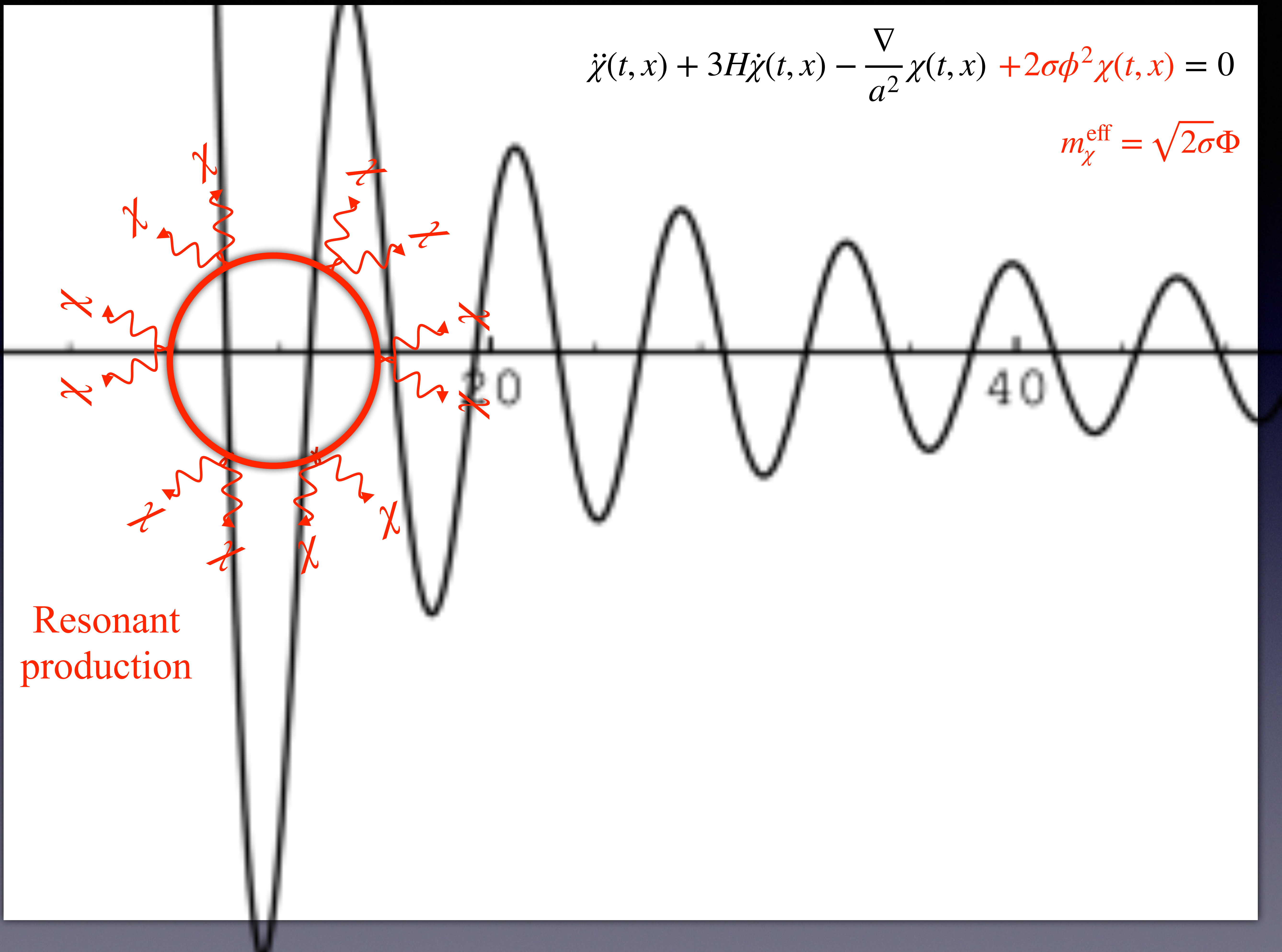
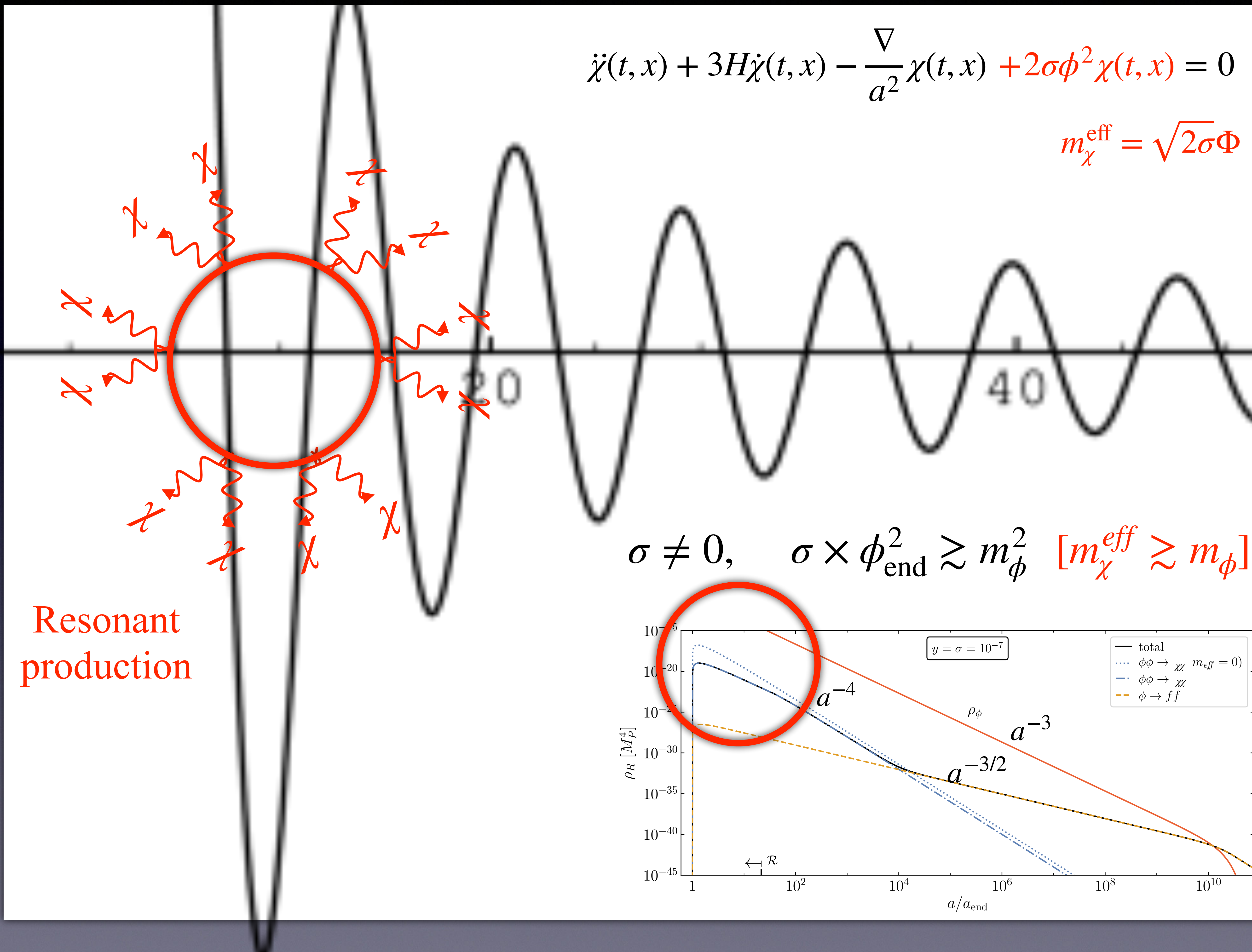




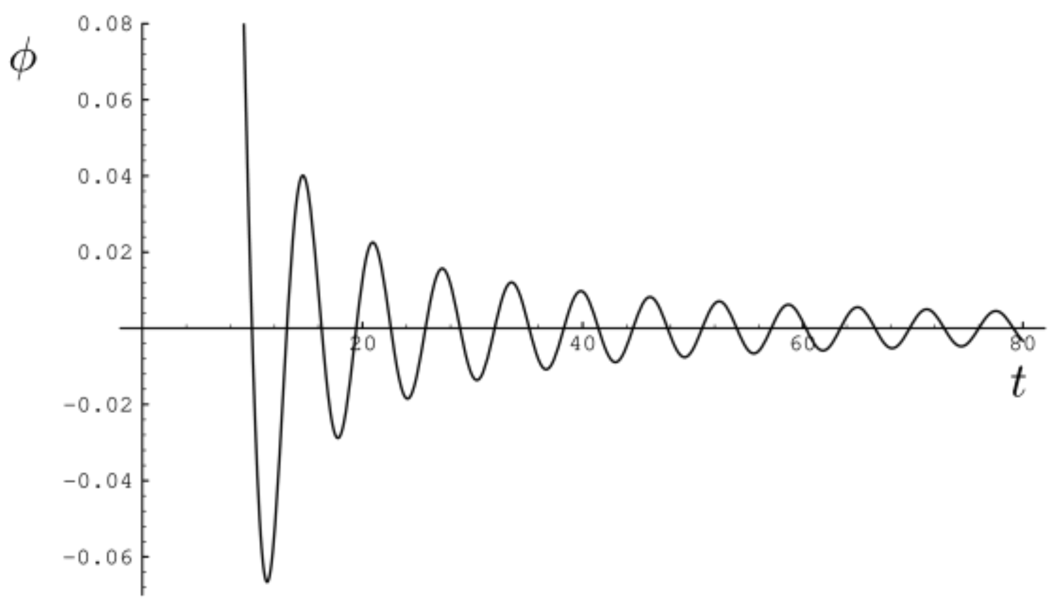
$\ddot{\chi}(t,x) + 3H\dot{\chi}(t,x) - \frac{\nabla}{a^2}\chi(t,x) + 2\sigma\phi^2\chi(t,x) = 0$
$m_\chi^{\rm eff} = \sqrt{2\sigma}\Phi$
$\sigma \neq 0, \quad \sigma \times \phi_{\rm end}^2 \gtrsim m_\phi^2 \quad [m_\chi^{eff} \gtrsim m_\phi]$
Resonant production
χ
20
40
$y = \sigma = 10^{-7}$
total
$\phi\phi \to \chi\chi$ $m_{\rm eff} = 0)$
$\phi\phi \to \chi\chi$
$\phi \to \bar{f}f$
a^{-4}
ρ_ϕ
a^{-3}
$a^{-3/2}$
$\mathcal{R}$
$\rho_R\ [M_P^4]$
$a/a_{\rm end}$
10^{-20}
10^{-30}
10^{-35}
10^{-40}
10^{-45}
1
10^2
10^4
10^6
10^8
10^{10}

$$\ddot{\chi}(t,x) + 3H\dot{\chi}(t,x) - \frac{\nabla}{a^2}\chi(t,x) + 2\sigma\phi^2\chi(t,x) = 0 \qquad m_\chi^{\text{eff}} = \sqrt{2\sigma}\Phi$$

$$\chi = \int \frac{d^3p}{(2\pi)^{3/2}} \left[e^{-ipx}\chi_p(t)a_p + e^{ipx}\chi_p^*(t)a_p^\dagger \right]$$

$$\ddot{\chi}_p(t) + \left[\frac{p^2}{a^2} + (m_\chi^{\text{eff}})^2 \; + \; \sigma\Phi^2(t) \times \cos 2m_\phi t \right] \chi_p(t) = 0$$

Mathieu equation



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$$\ddot{\chi}(t,x) + 3H\dot{\chi}(t,x) - \frac{\nabla}{a^2}\chi(t,x) + 2\sigma\phi^2\chi(t,x) = 0 \qquad m_\chi^{\rm eff} = \sqrt{2\sigma}\Phi$$

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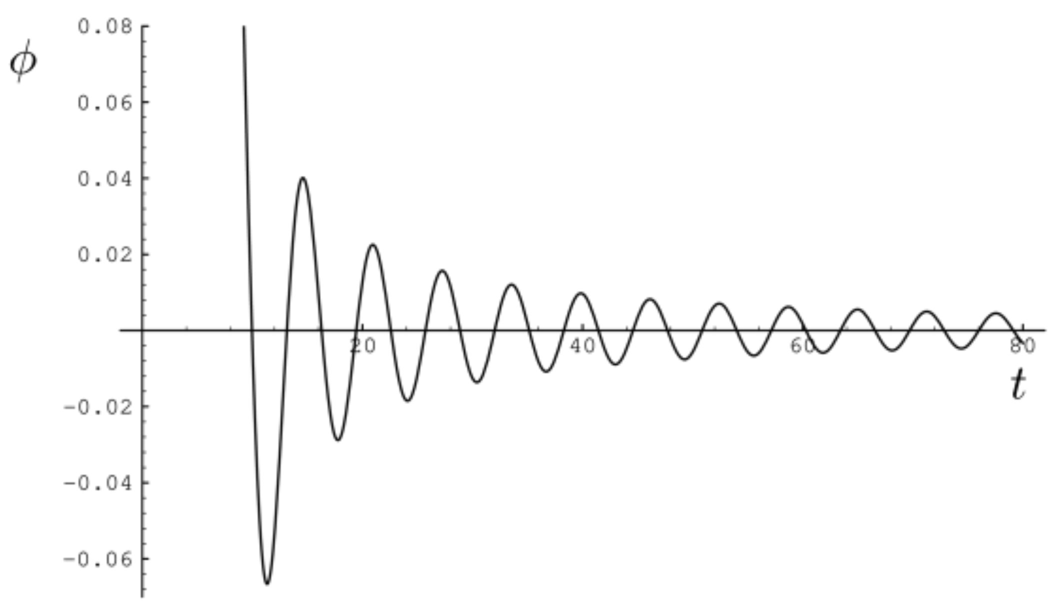
Mathieu equation

The Mathieu equation is present in any system with a periodical source of energy.
From electric circuit to mechanical balance, spring excitations…



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$$\ddot{\chi}(t,x) + 3H\dot{\chi}(t,x) - \frac{\nabla}{a^2}\chi(t,x) + 2\sigma\phi^2\chi(t,x) = 0 \qquad m_\chi^{\text{eff}} = \sqrt{2\sigma}\Phi$$

$$\chi = \int \frac{d^3p}{(2\pi)^{3/2}} \left[e^{-ipx}\chi_p(t)a_p + e^{ipx}\chi_p^*(t)a_p^\dagger \right]$$

$$\ddot{\chi}_p(t) + \left[\frac{p^2}{a^2} + (m_\chi^{\text{eff}})^2 + \sigma\Phi^2(t) \times \cos 2m_\phi t \right] \chi_p(t) = 0$$

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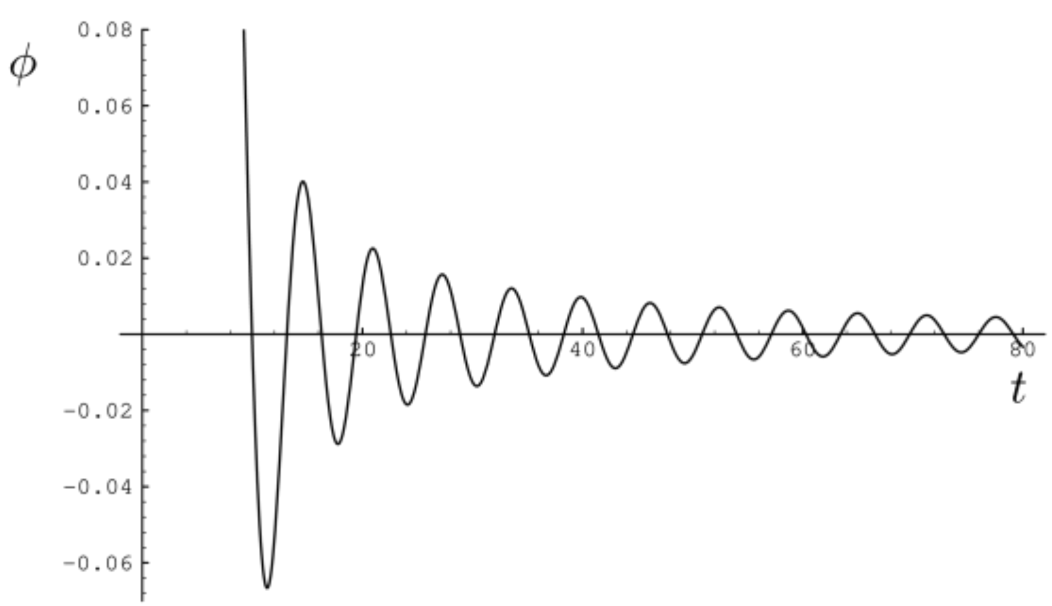

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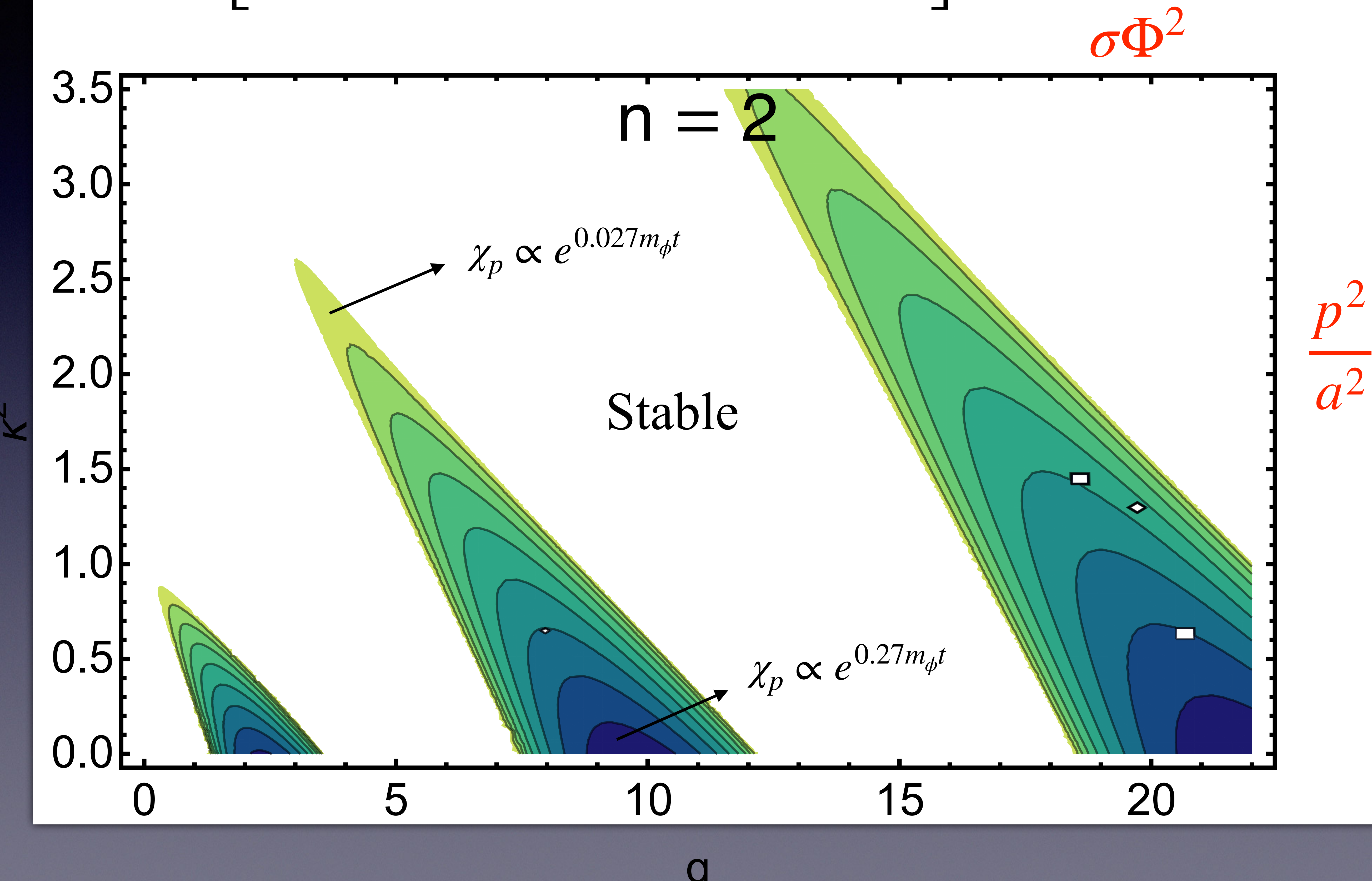
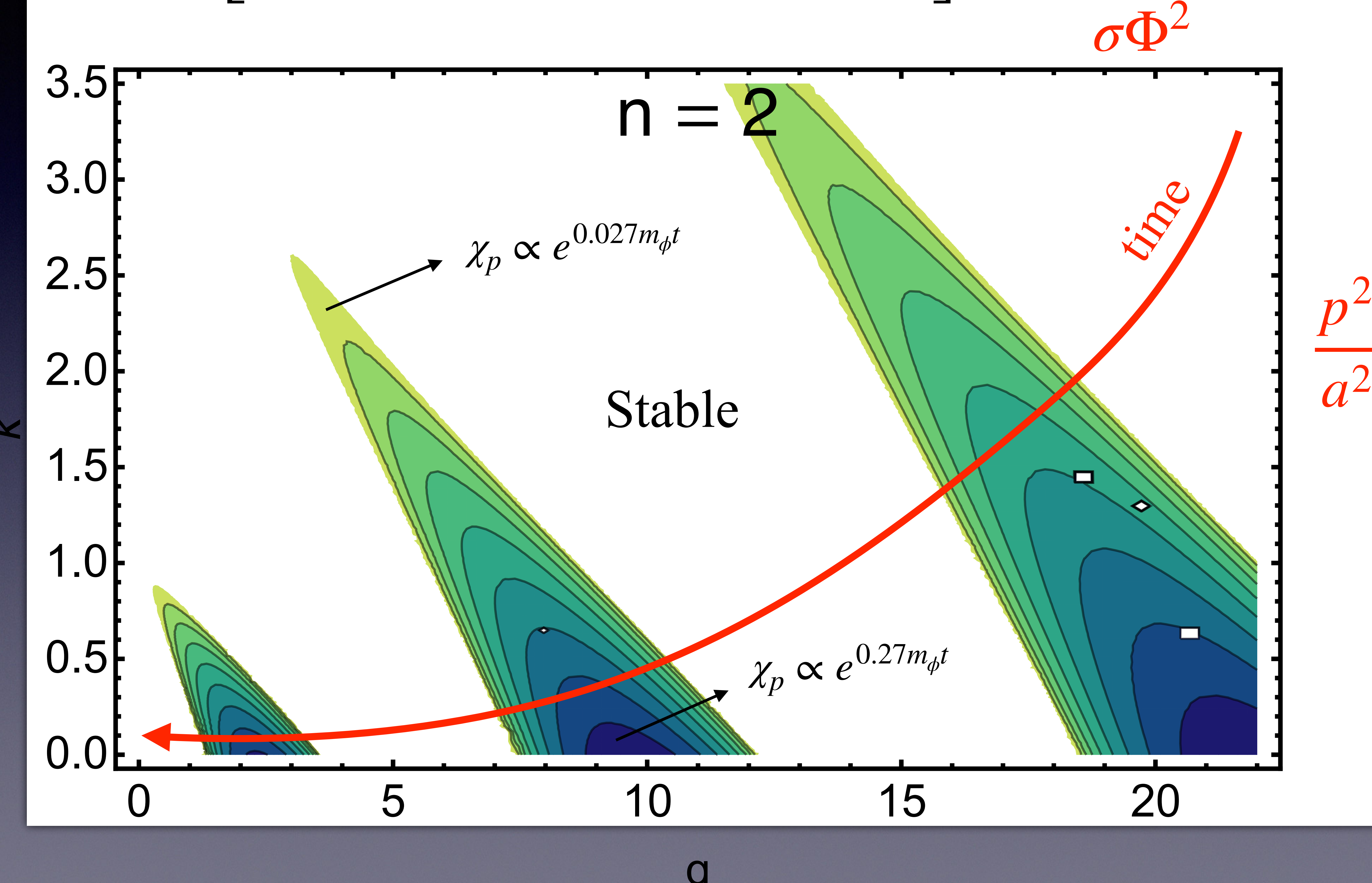
$$\ddot{\chi}_p(t) + \left[\frac{p^2}{a^2} + (m_\chi^{\text{eff}})^2 + \sigma\Phi^2(t) \times \cos 2m_\phi t\right]\chi_p(t) = 0$$

Mathieu equation



$$\ddot{\chi}_p(t) + \left[\frac{p^2}{a^2} + (m_\chi^{\text{eff}})^2 + \sigma\Phi^2(t) \times \cos 2m_\phi t\right]\chi_p(t) = 0$$

Mathieu equation



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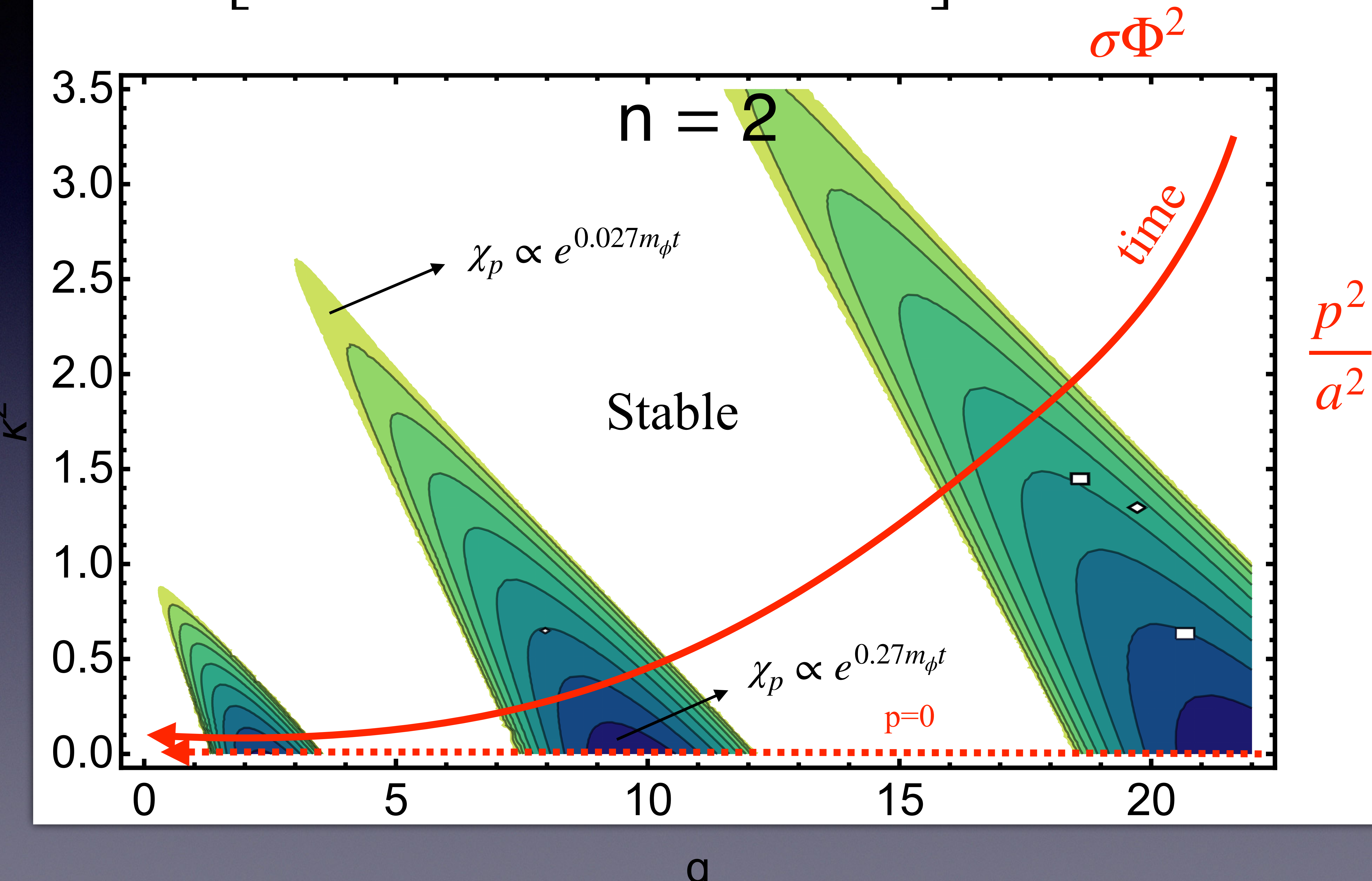
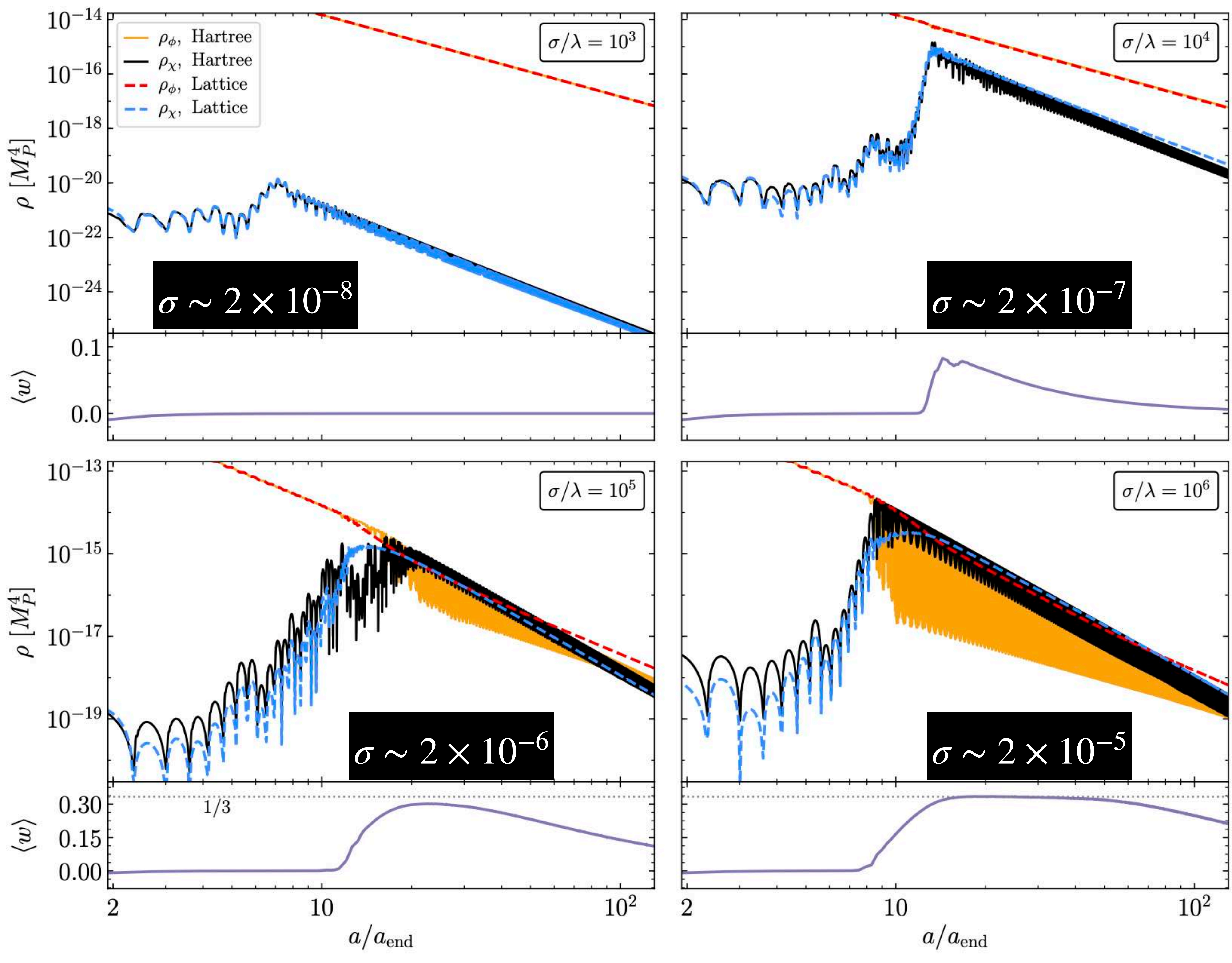
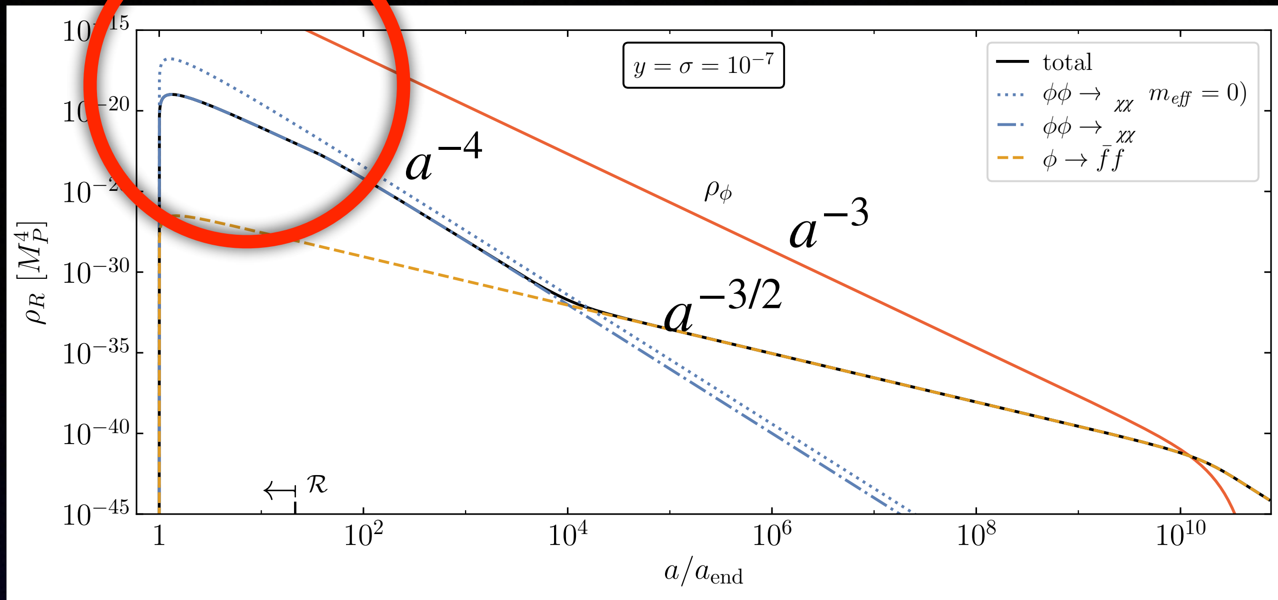
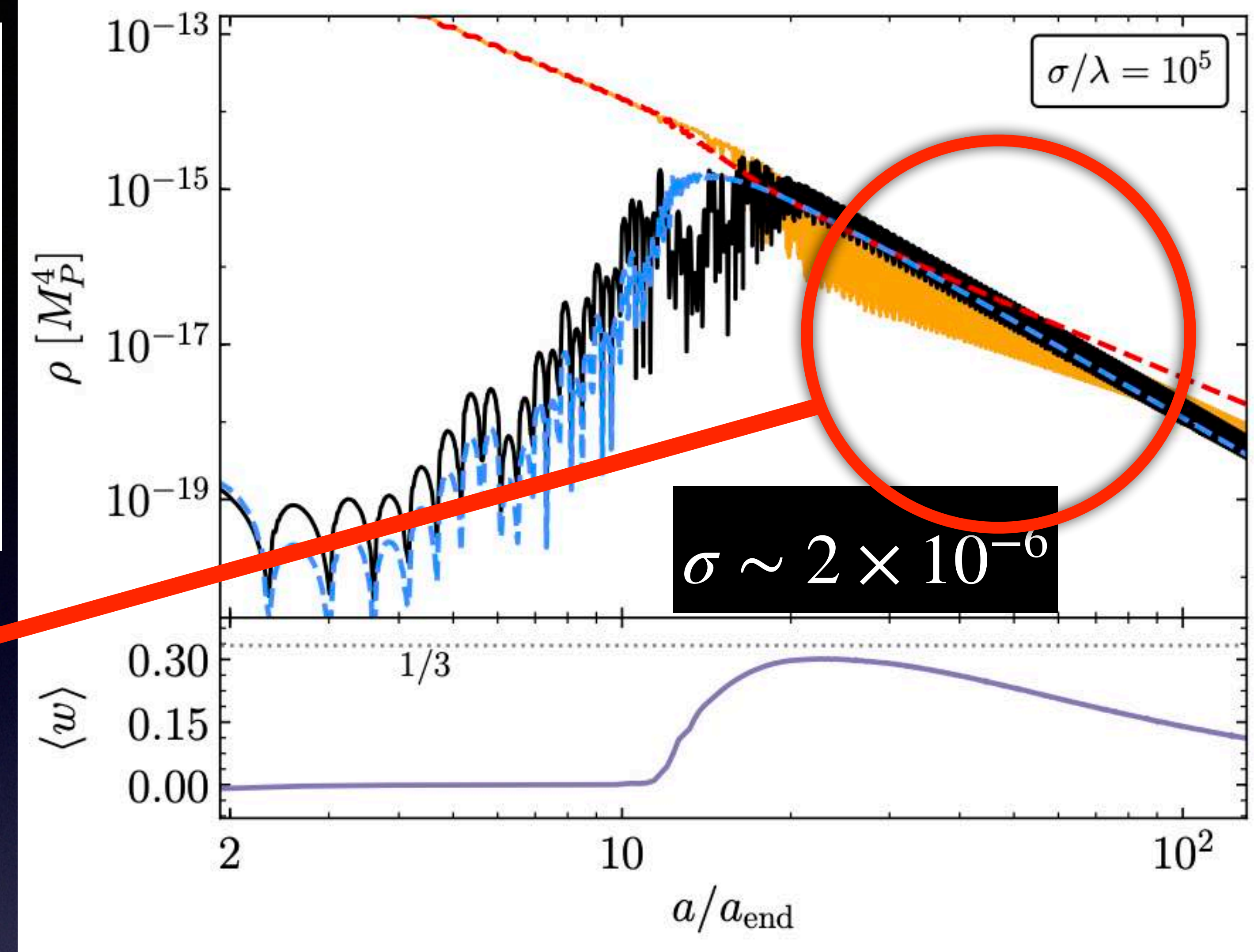
Mathieu equation





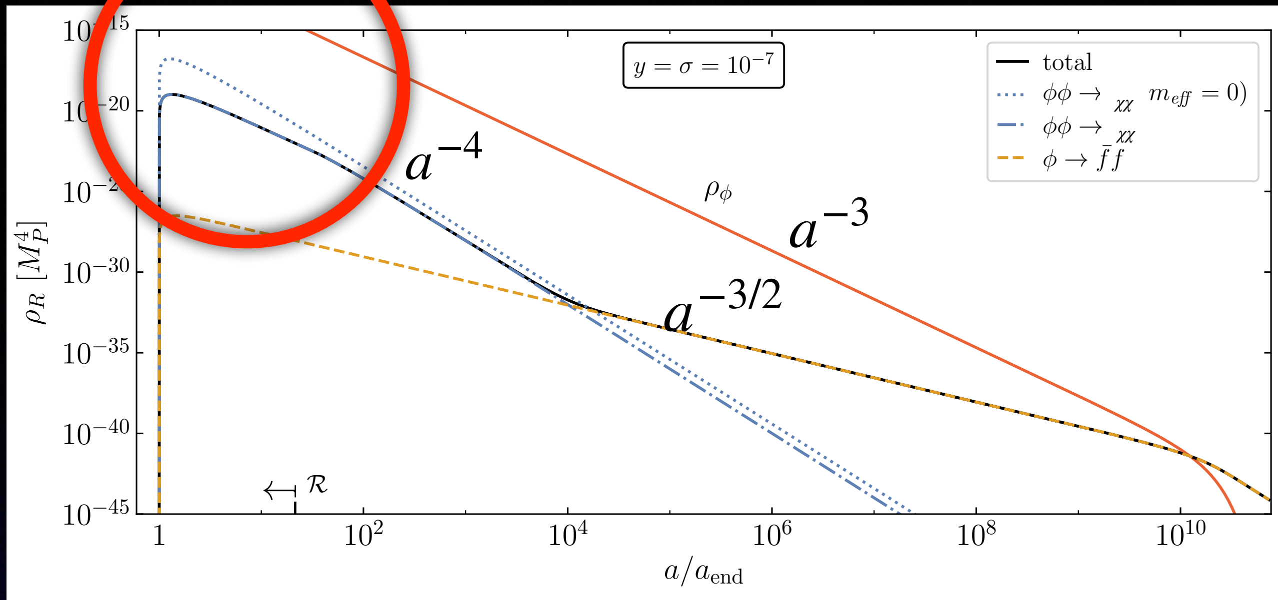
ρ_ϕ, Hartree
ρ_χ, Hartree
ρ_ϕ, Lattice
ρ_χ, Lattice
$\sigma/\lambda = 10^3$
$\sigma/\lambda = 10^4$
$\sigma/\lambda = 10^5$
$\sigma/\lambda = 10^6$
$\sigma \sim 2 \times 10^{-8}$
$\sigma \sim 2 \times 10^{-7}$
$\sigma \sim 2 \times 10^{-6}$
$\sigma \sim 2 \times 10^{-5}$
$\rho\ [M_P^4]$
$\langle w \rangle$
1/3
a/a_{end}

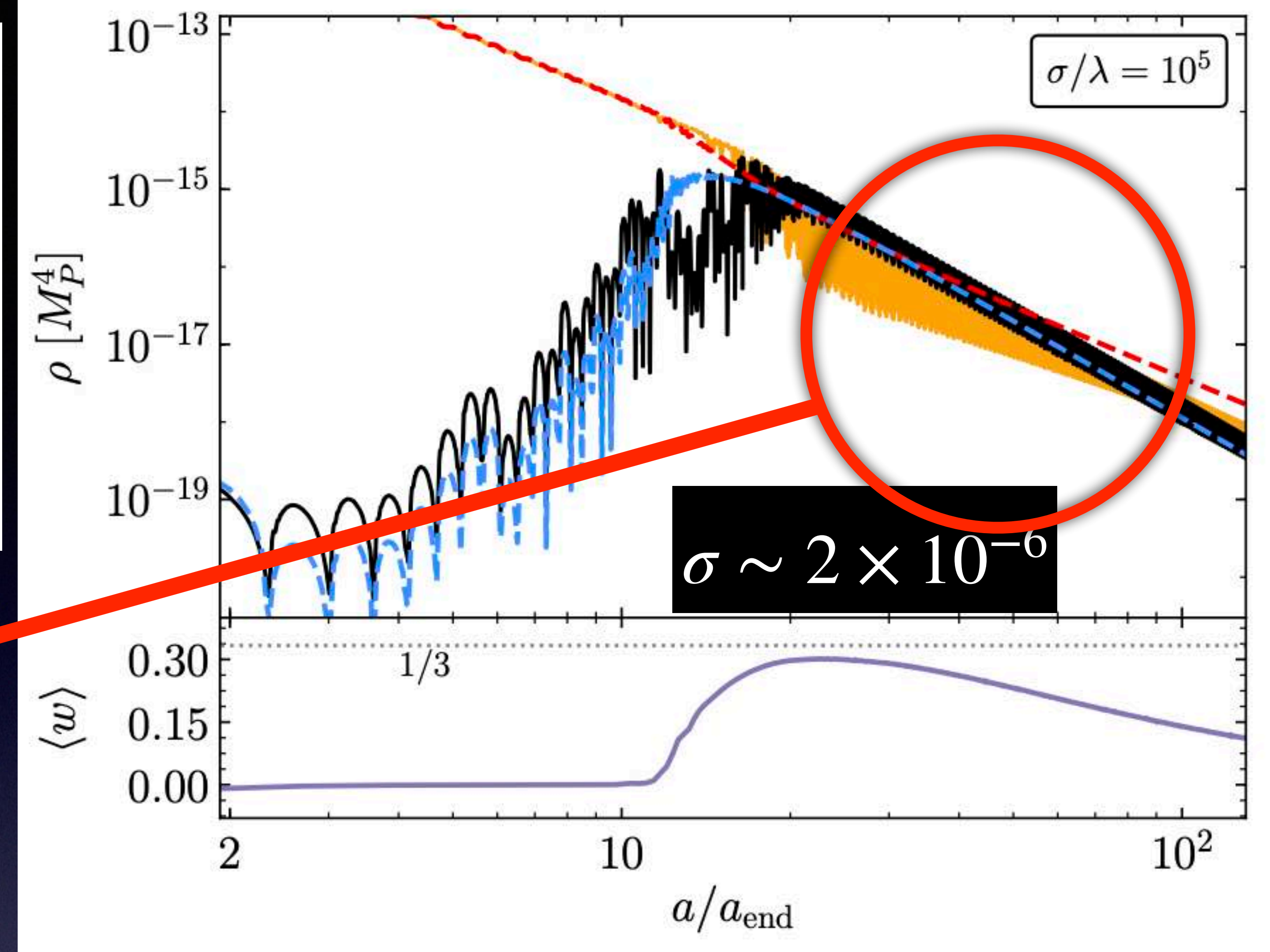




$$\sigma \Phi^2 \lesssim H^2$$

$$\ddot{\chi}(t) + 3H\dot{\chi} - \frac{\nabla}{a^2}\chi(t) + 2\sigma\phi^2\chi = 0$$





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Backreaction effects of χ on ϕ

Backreactions

Formally speaking, this is the effect of χ on the condensate ϕ through te equation of motion

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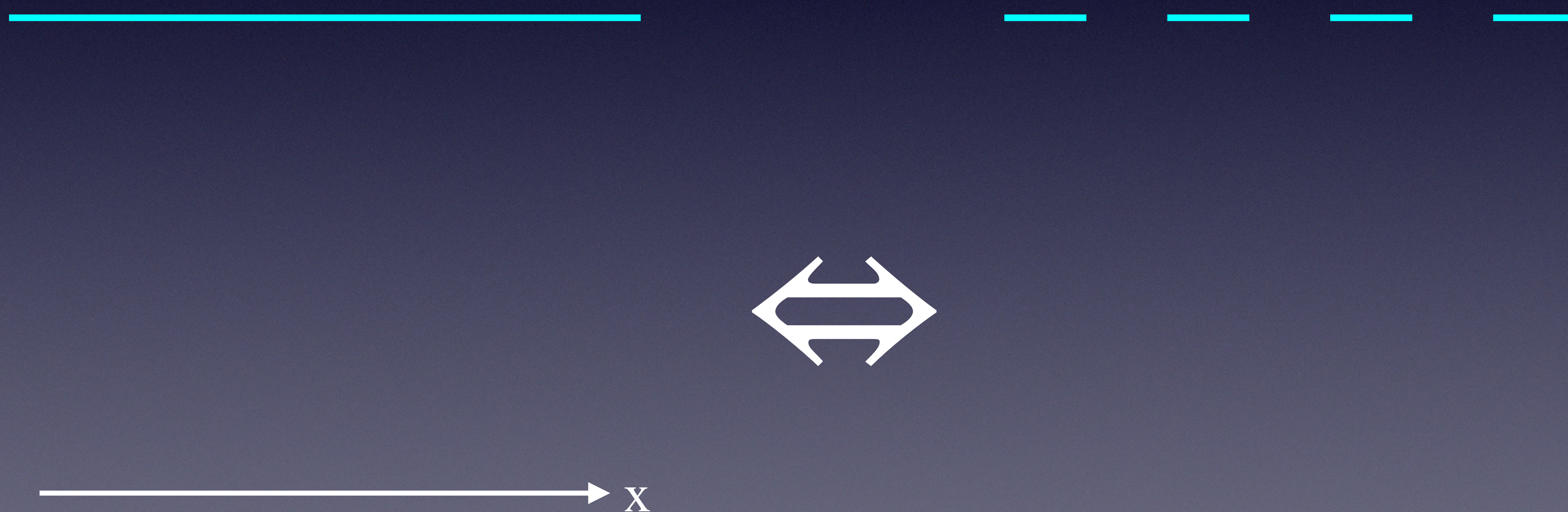

Frequency $\frac{1}{2}m_\phi$

$$\ddot{\phi}(t,x) + 3H\dot{\phi}(t,x) + m_\phi^2\phi(t,x) - \frac{\nabla}{a^2}\phi(t,x) + 2\sigma\chi^2\phi = 0$$

$\Leftrightarrow$

x

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$$\Leftrightarrow$$

x

Frequency $\frac{1}{2}m_\phi$

$\Leftrightarrow$ N coherent oscillators of density

$n_\phi = \frac{\rho_\phi}{m_\phi}$ and frequency $\frac{1}{2}m_\phi$

$$\ddot{\phi}(t,x) + 3H\dot{\phi}(t,x) + m_\phi^2\phi(t,x) - \frac{\nabla}{a^2}\phi(t,x) + 2\sigma\chi^2\phi = 0$$

$\chi(p_4)$

$\chi(p_1)$ $\chi(p_2)$

$\chi(p_3)$

$$\Leftrightarrow$$

x

Frequency m_ϕ

$\Leftrightarrow$ N coherent oscillators of density $n_\phi = \frac{\rho_\phi}{m_\phi}$ and frequency m_ϕ

$$\ddot{\phi}(t,x) + 3H\dot{\phi}(t,x) + m_\phi^2\phi(t,x) - \frac{\nabla}{a^2}\phi(t,x) + 2\sigma\chi^2\phi = 0$$

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x

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x

Frequency $\frac{1}{2}m_\phi$

$\Leftrightarrow$ N incoherent oscillators of mean momentum $p_* = \sqrt{m_\phi m_\chi}$

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$$\Leftrightarrow$$

x

Frequency $\frac{1}{2}m_\phi$

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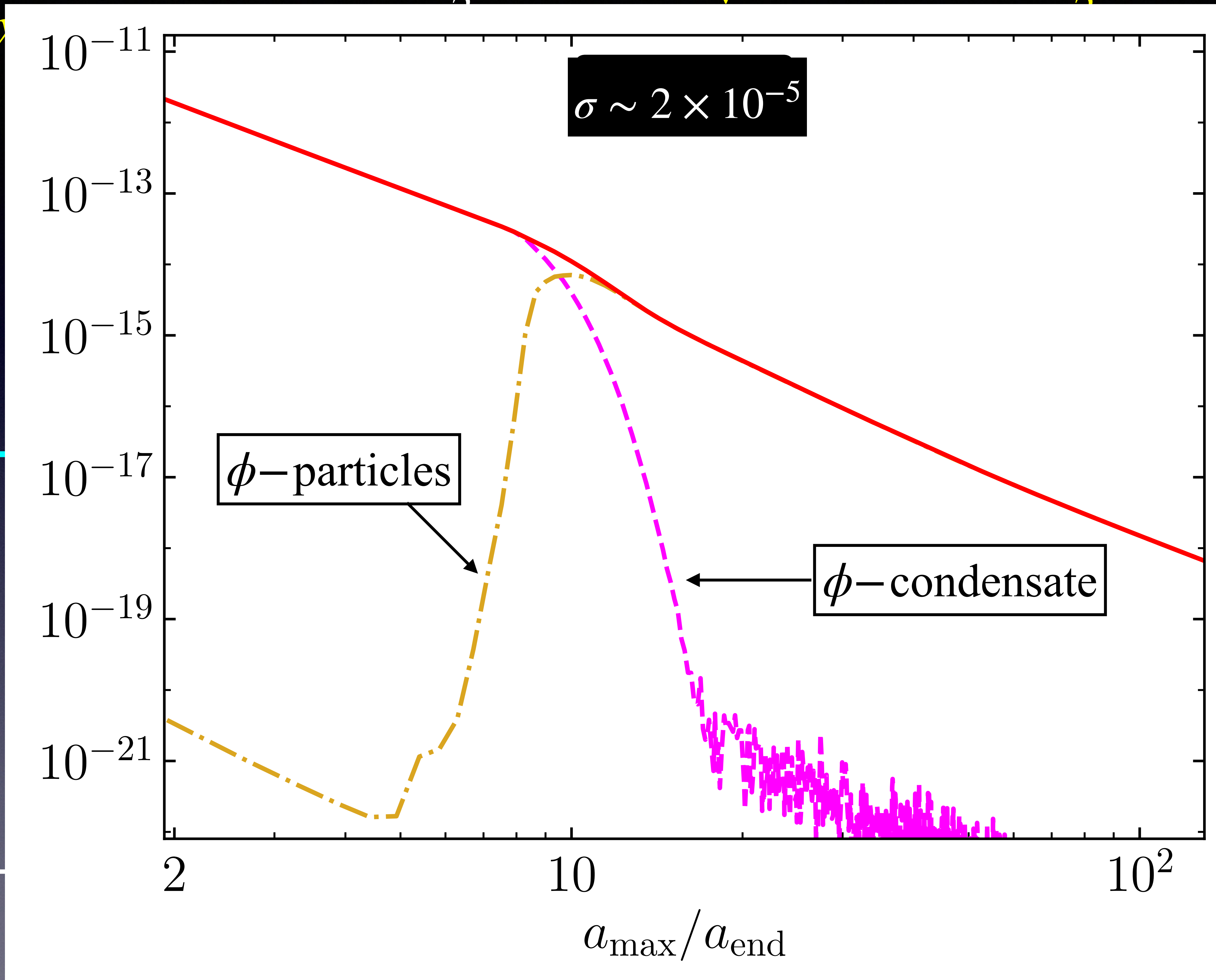


$\sigma \sim 2 \times 10^{-5}$
$\phi-$particles
$\phi-$condensate
10^{-11}
10^{-13}
10^{-15}
10^{-17}
10^{-19}
10^{-21}
2
10
10^2
$a_{\max}/a_{\rm end}$

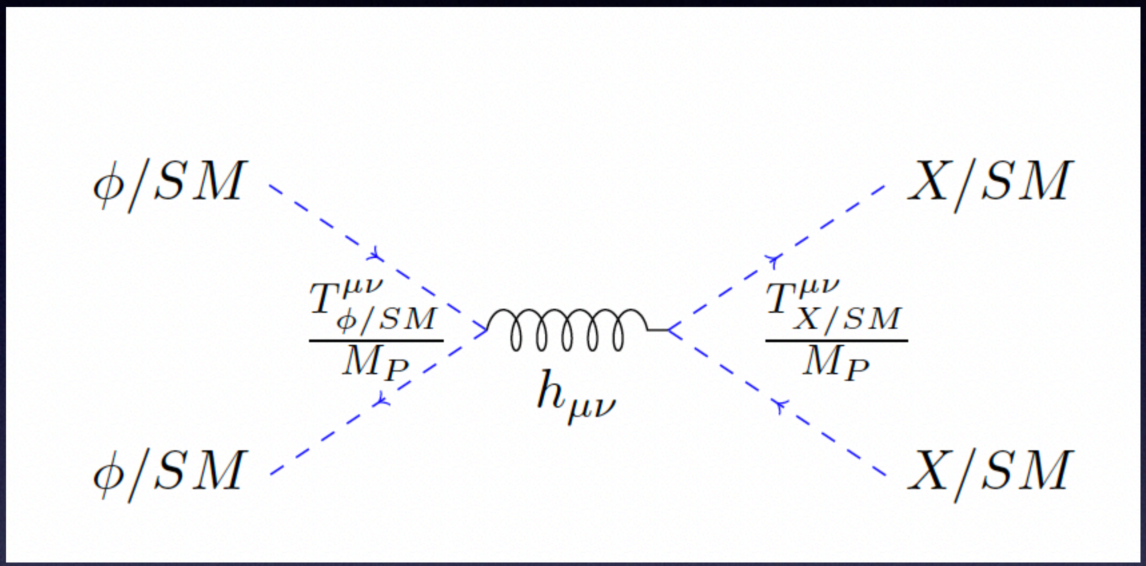
Example :

(dark) matter from gravitational scattering of the inflaton

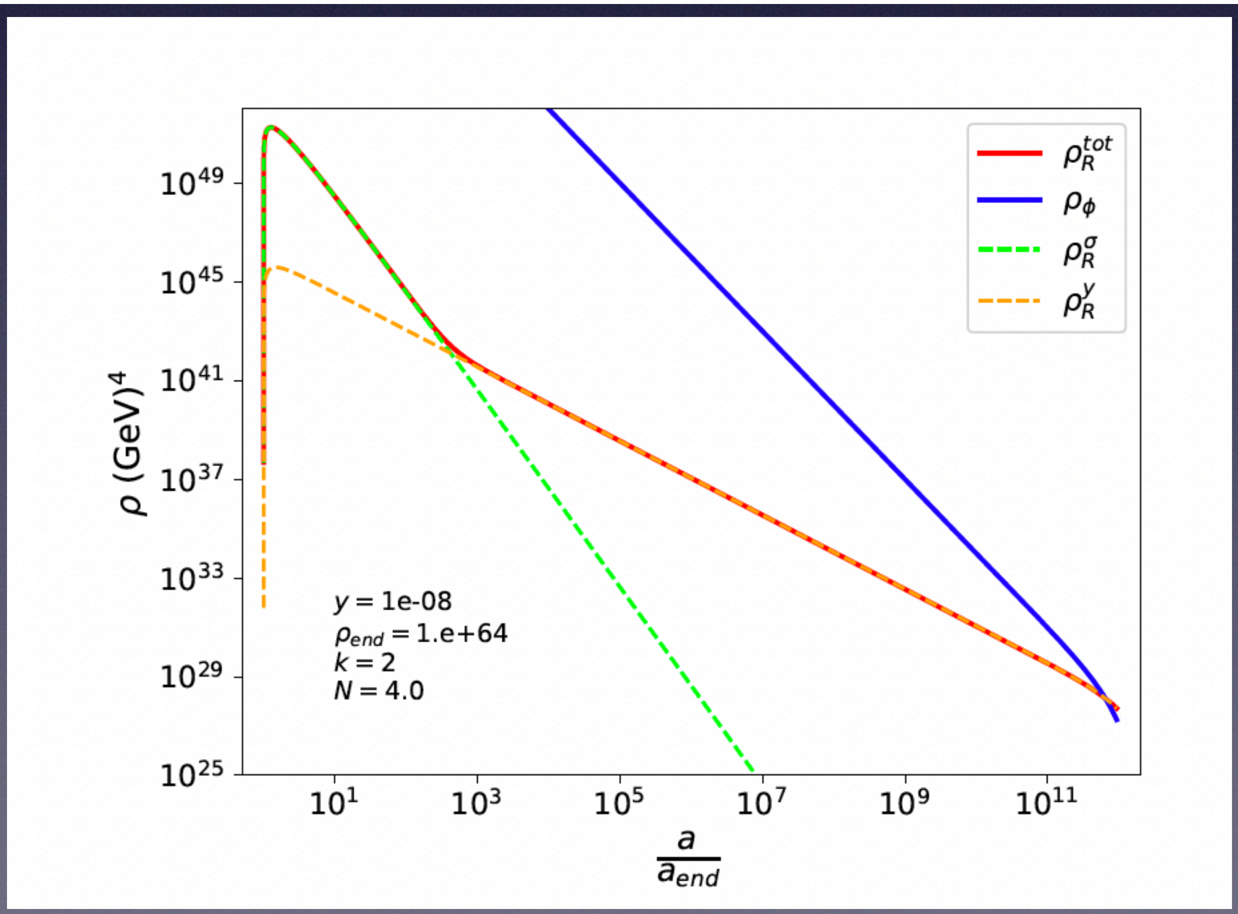
$$\mathscr{L} = \frac{1}{M_P} h_{\mu\nu} T^{\mu\nu}_{\phi} + \frac{1}{M_P} h_{\mu\nu} T^{\mu\nu}_{S} + y\phi\bar{f}f + \sigma\phi^2\chi^2$$

Y. Mambrini and K. A. Olive, Phys. Rev. D **103** (2021) no.11, 115009 [arXiv:2102.06214].

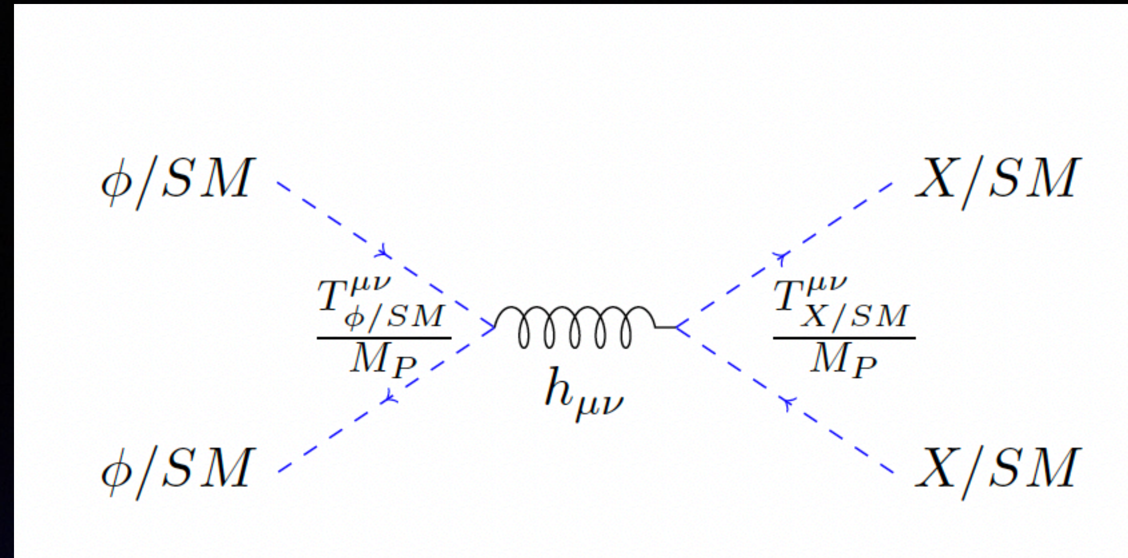
S. Clery, Y. Mambrini, K. A. Olive, and S. Verner, [arXiv:2112.15214].

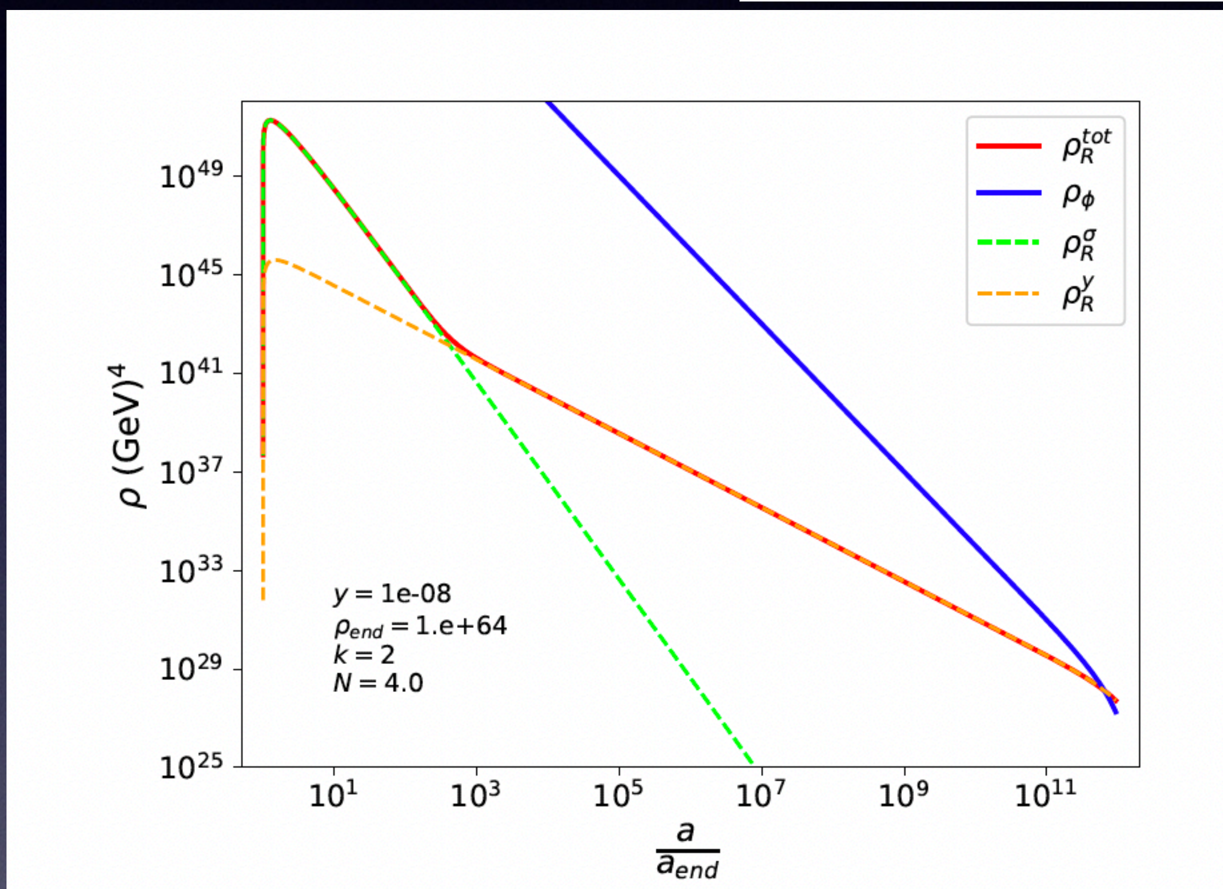


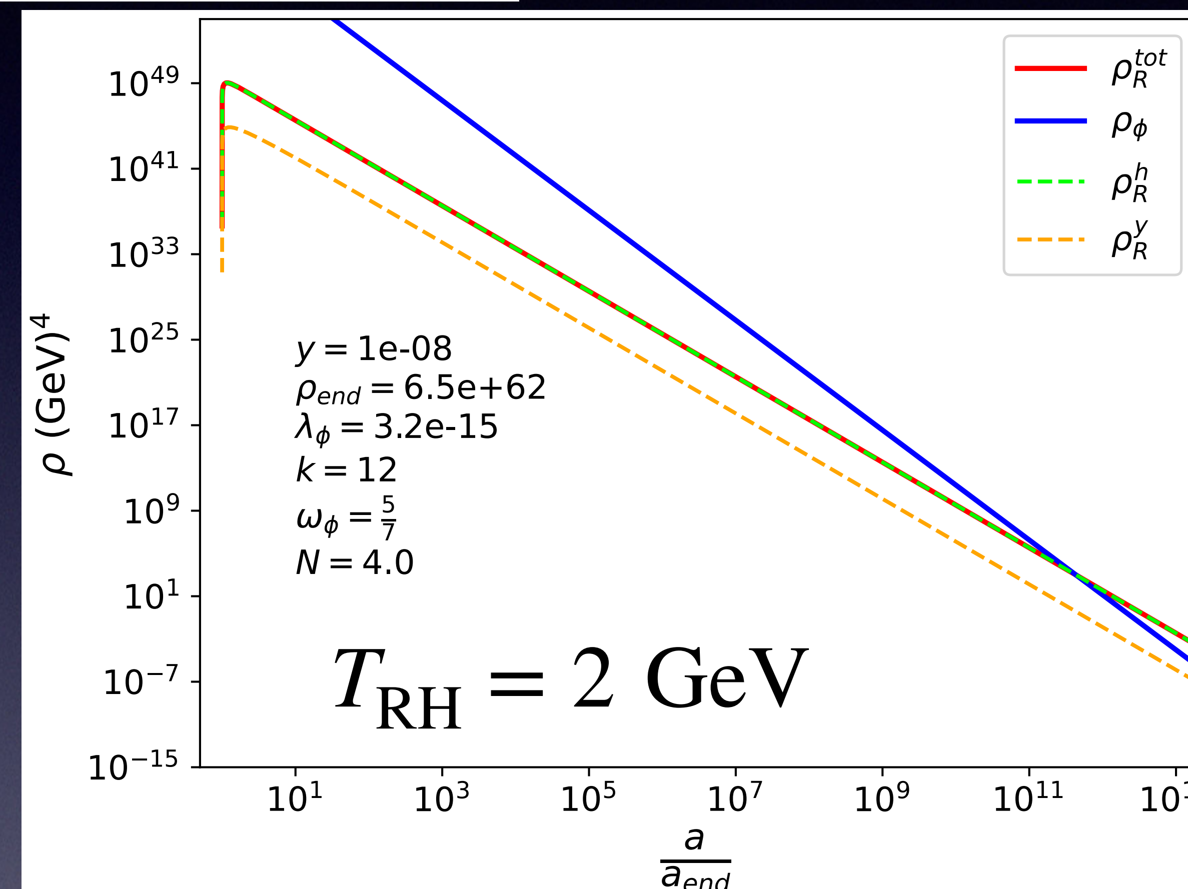
	$k=2$	$k=4$	$k=6$
$T_{\max}$	1.0×10^{12} GeV	7.5×10^{11} GeV	6.5×10^{11} GeV
$y_{\max}$	1.8×10^{-6}	1.4×10^{-6}	1.1×10^{-6}
$T_{\mathrm{RH}\max}$	7.9×10^{8} GeV	470 GeV	9.7×10^{-4} GeV



There exists a
<u>minimal maximal</u> temperature
in the Universe $\sim 10^{12}$ GeV



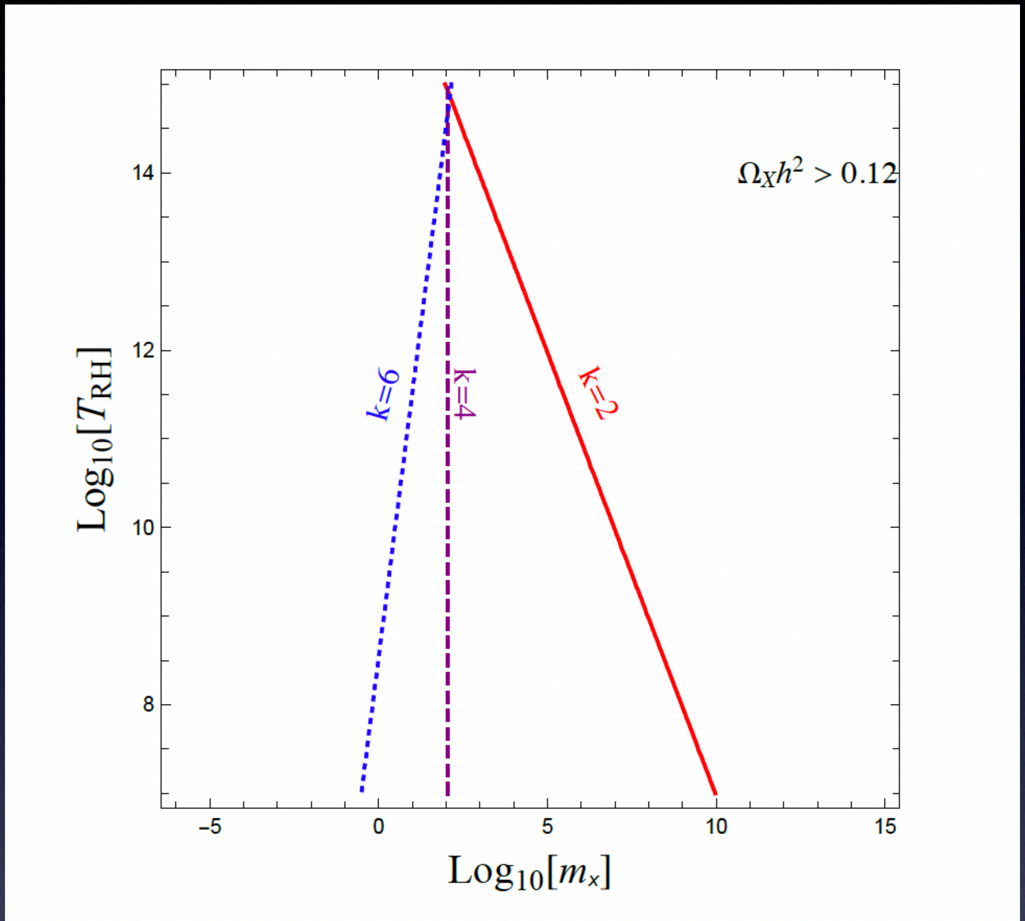


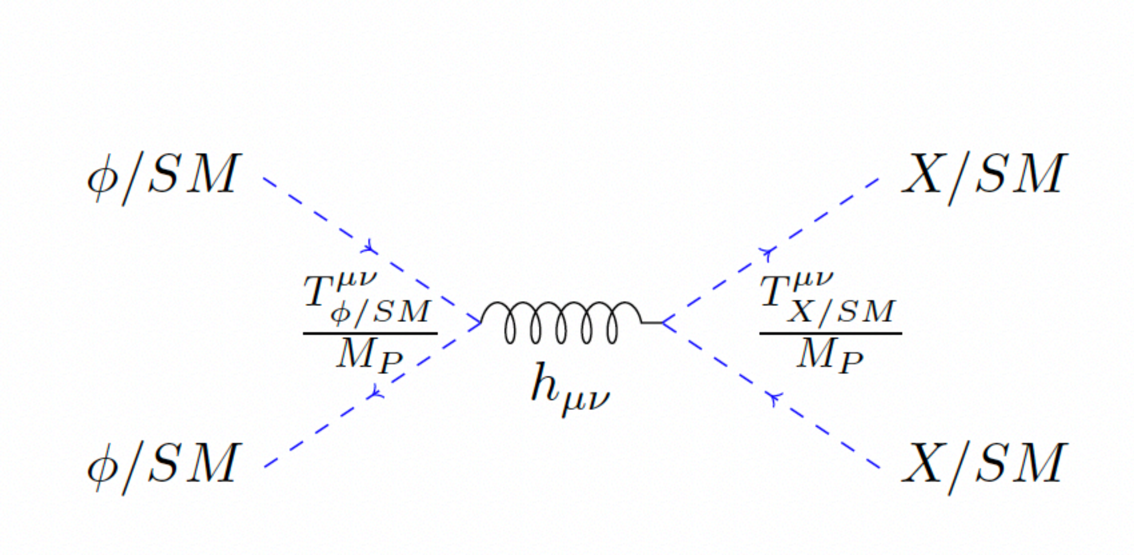


We can even gravitationally reheat!!

S. Clery, Y. Mambrini, K. A. Olive, and S. Verner, [arXiv:2112.15214].

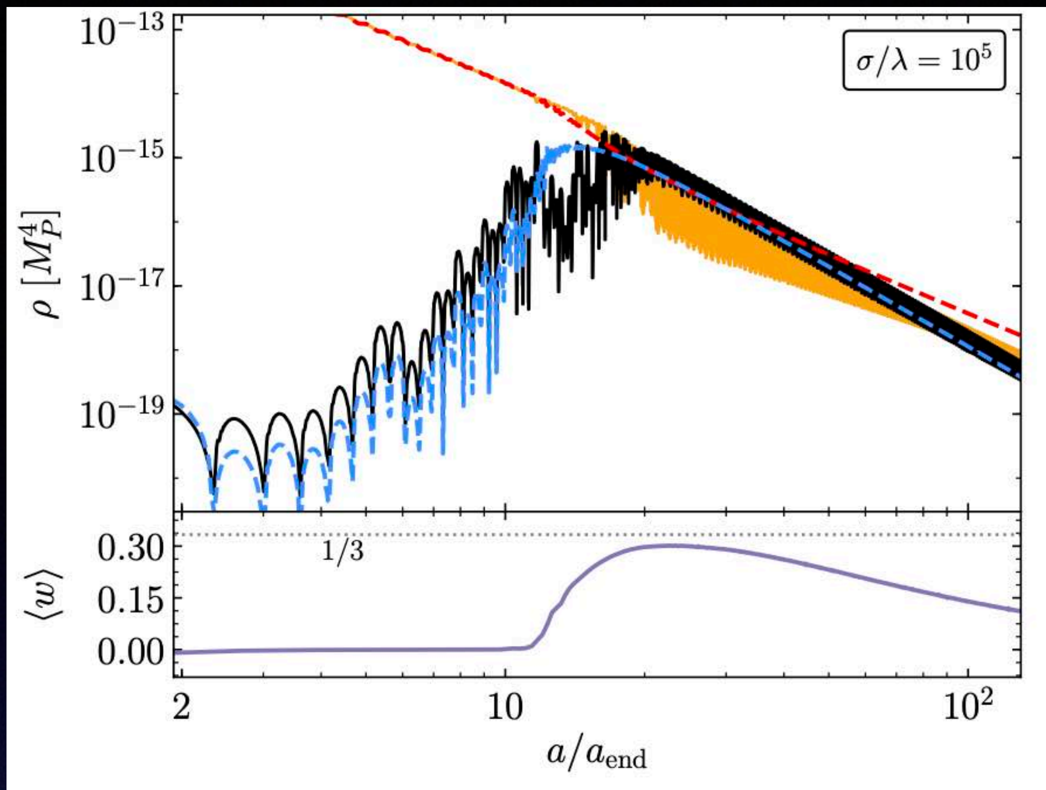
Also working for Dark Matter



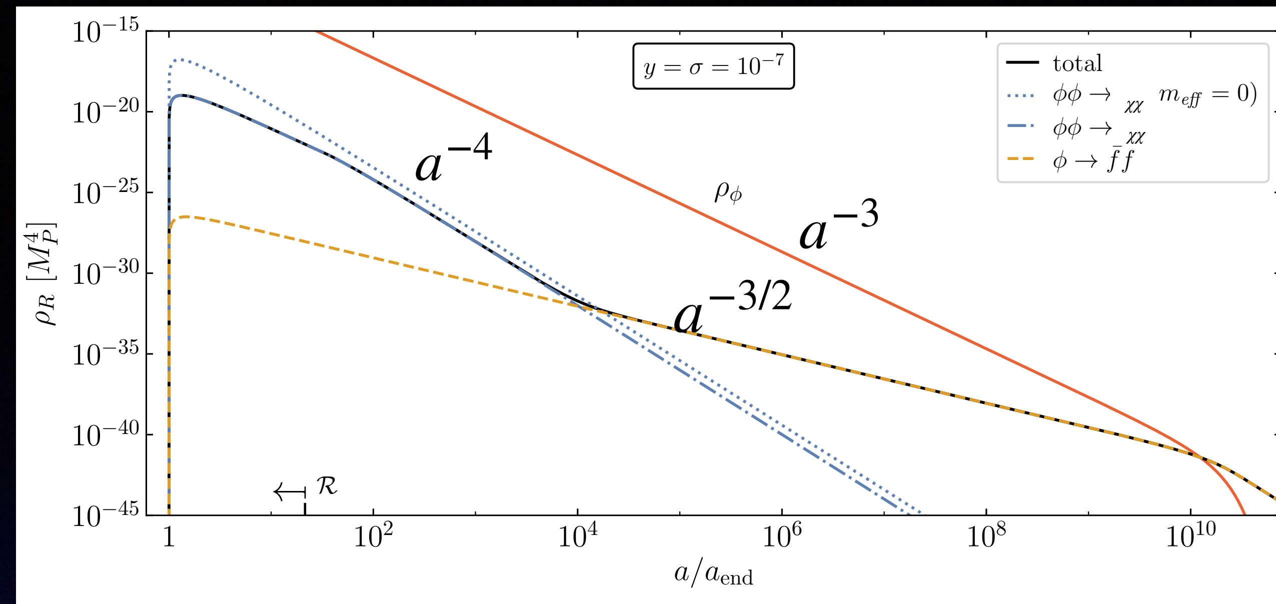


S. Clery, Y. Mambrini, K. A. Olive, and S. Verner, [arXiv:2112.15214].

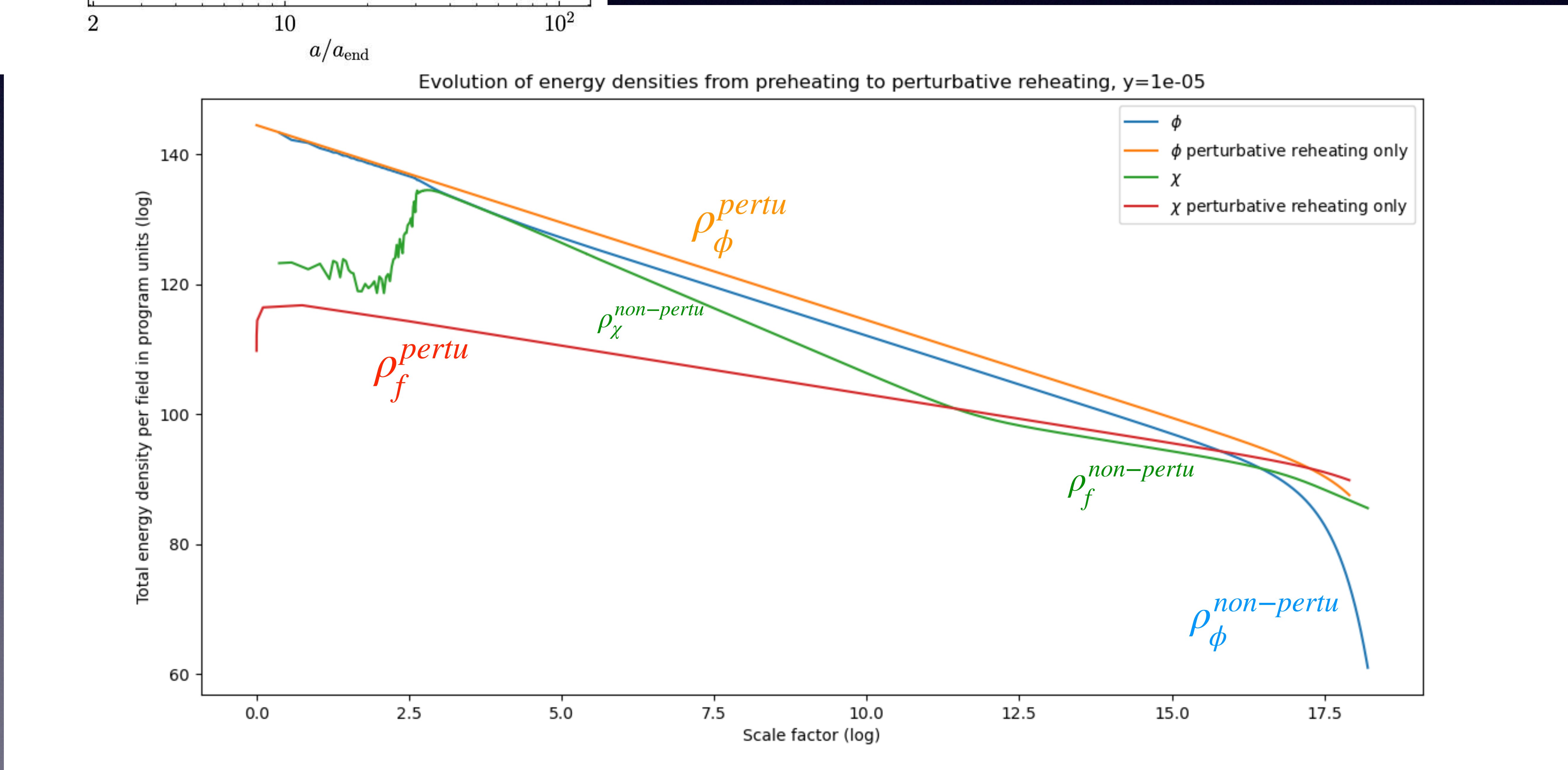
Summary



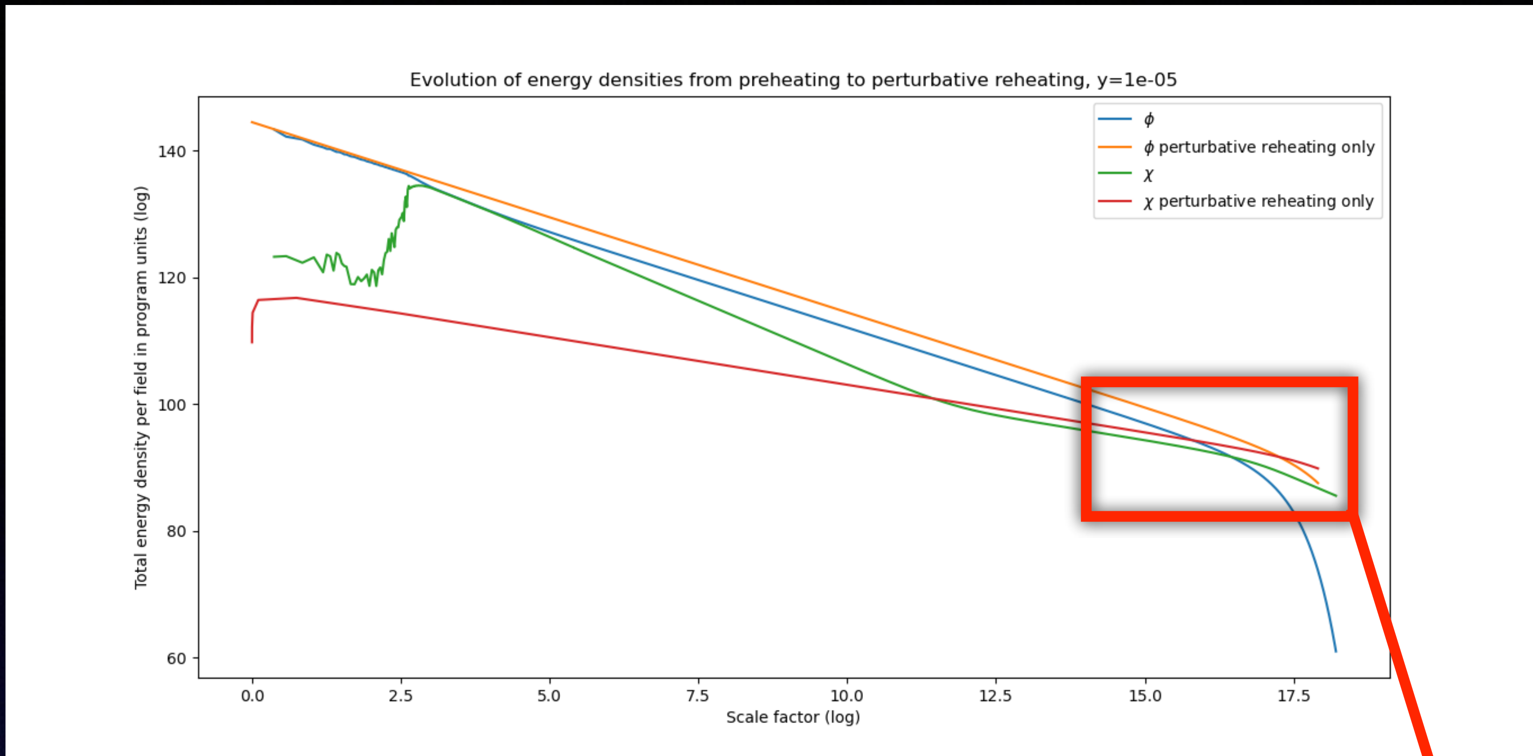
$\sigma/\lambda = 10^5$
$\rho\ [M_P^4]$
10^{-13}
10^{-15}
10^{-17}
10^{-19}
$\langle w \rangle$
0.30
0.15
0.00
1/3
2
10
10^2
$a/a_{\rm end}$



$y = \sigma = 10^{-7}$
total
$\phi\phi \to \chi\chi$ ($m_{\rm eff} = 0$)
$\phi\phi \to \chi\chi$
$\phi \to \bar{f}f$
$\rho_R\ [M_P^4]$
10^{-15}
10^{-20}
10^{-25}
10^{-30}
10^{-35}
10^{-40}
10^{-45}
a^{-4}
ρ_ϕ
a^{-3}
$a^{-3/2}$
$\mathcal{R}$
1
10^2
10^4
10^6
10^8
10^{10}
$a/a_{\rm end}$



Evolution of energy densities from preheating to perturbative reheating, y=1e-05
ϕ
ϕ perturbative reheating only
χ
χ perturbative reheating only
Total energy density per field in program units (log)
140
120
100
80
60
ρ_ϕ^{pertu}
$\rho_\chi^{non-pertu}$
ρ_f^{pertu}
$\rho_f^{non-pertu}$
$\rho_\phi^{non-pertu}$
0.0
2.5
5.0
7.5
10.0
12.5
15.0
17.5
Scale factor (log)

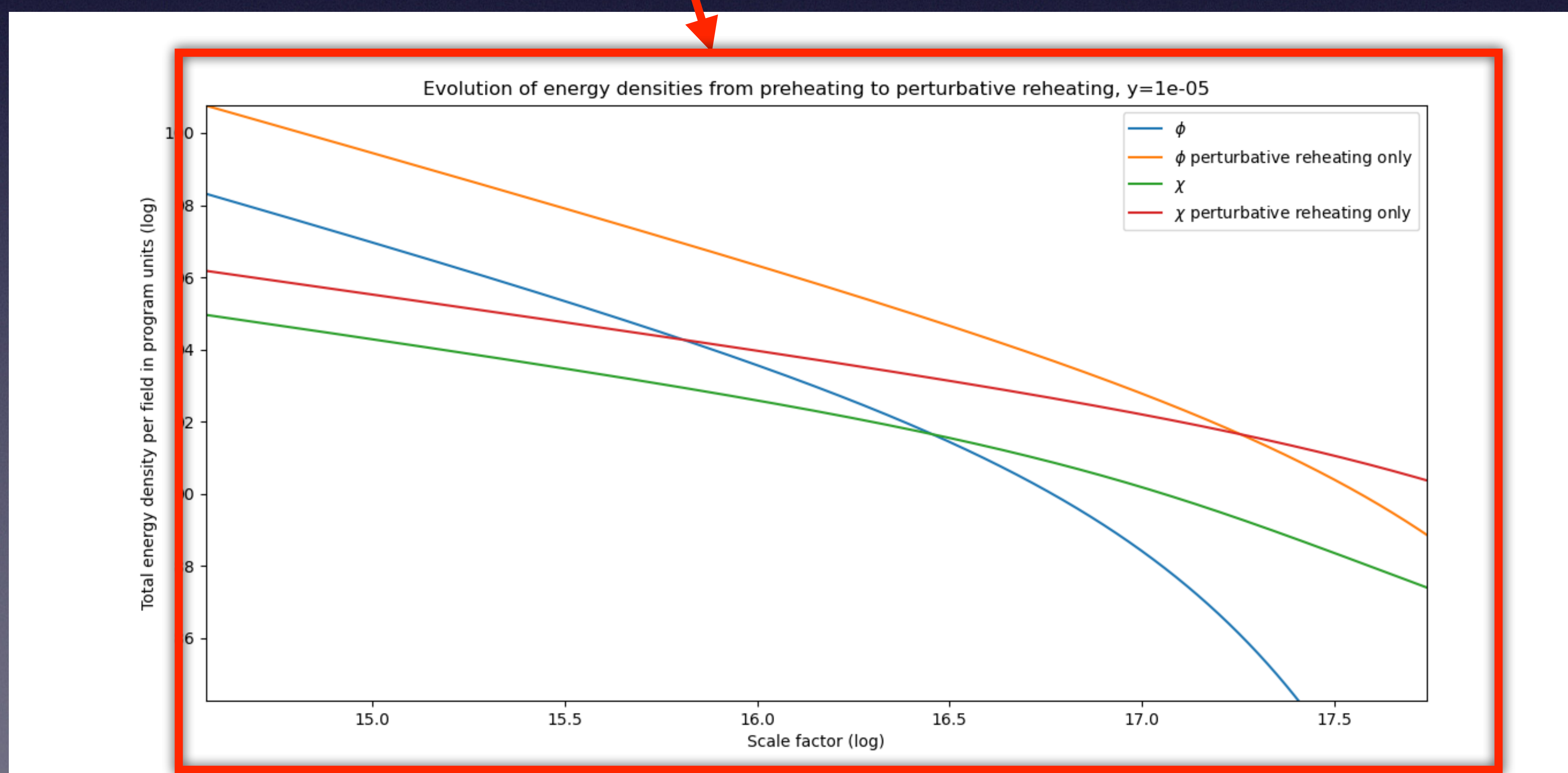


<u>Important remark</u> : the preheating *says nothing about reheating*, and especially gives the same reheating temperature than a perturbative treatment.

This comes from the fact that the reheating happens for

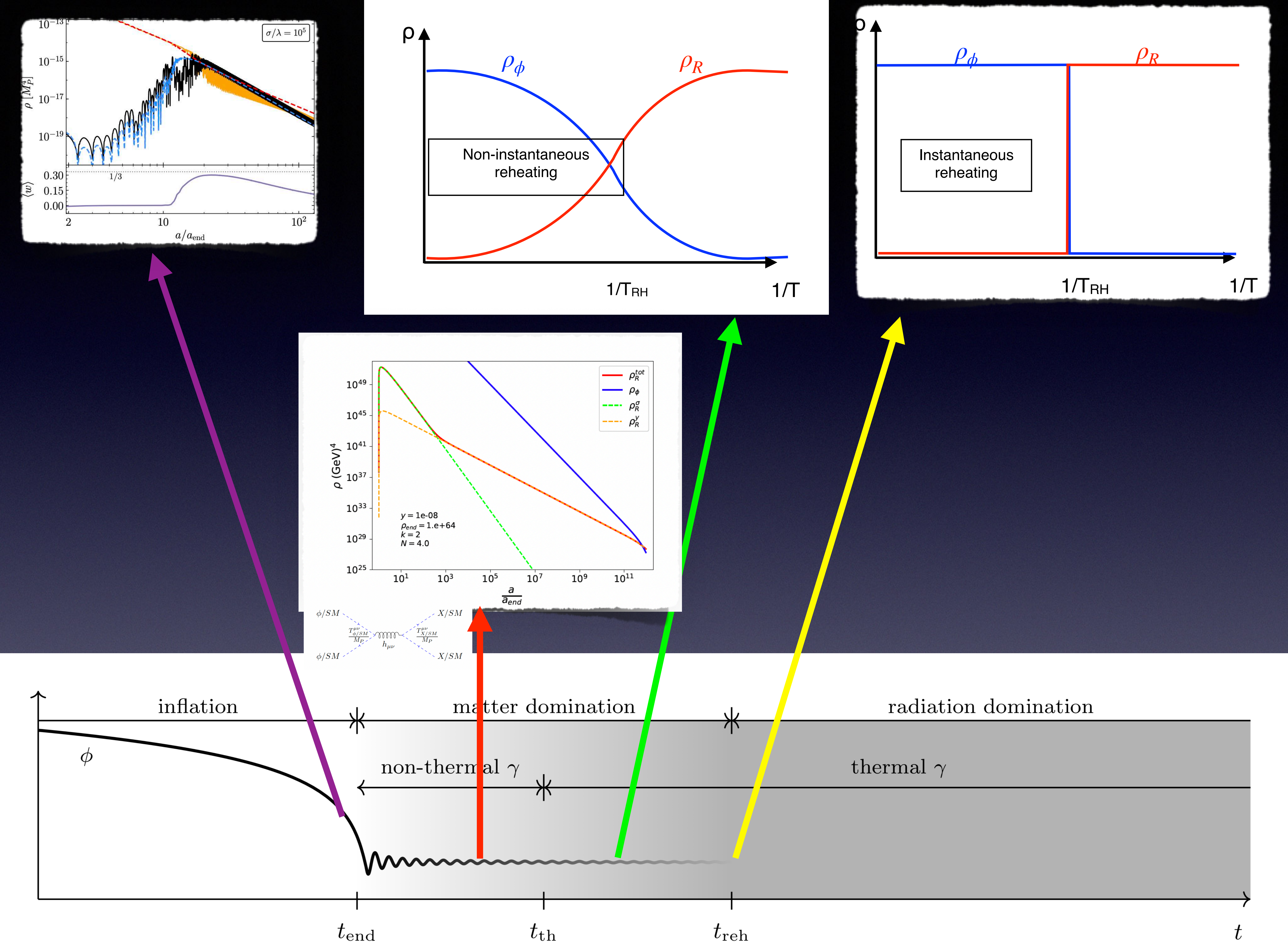
$$\rho_R = \rho_\phi \simeq \sqrt{\Gamma_\phi M_P} \sim T_{RH}^4,$$

It just happens *before*.



Conclusion

Studying the details of dark matter production in the earliest phase of the Universe is important for DM production in freeze-in scenario



$\sigma/\lambda = 10^5$
$\rho\ [M_P^4]$
10^{-13}
10^{-15}
10^{-17}
10^{-19}
$\langle w \rangle$
0.30
0.15
0.00
1/3
2
10
10^2
$a/a_{\rm end}$
ρ
ρ_ϕ
ρ_R
Non-instantaneous reheating
1/T_RH
1/T
Instantaneous reheating
ρ_R^{tot}
ρ_ϕ
ρ_R^σ
ρ_R^y
ρ (GeV)^4
10^{49}
10^{45}
10^{41}
10^{37}
10^{33}
10^{29}
10^{25}
$y = 1e-08$
$\rho_{end} = 1.e+64$
$k = 2$
$N = 4.0$
10^1
10^3
10^5
10^7
10^9
10^{11}
$\frac{a}{a_{end}}$
ϕ/SM
X/SM
$h_{\mu\nu}$
inflation
matter domination
radiation domination
ϕ
non-thermal γ
thermal γ
$t_{\rm end}$
$t_{\rm th}$
$t_{\rm reh}$
t