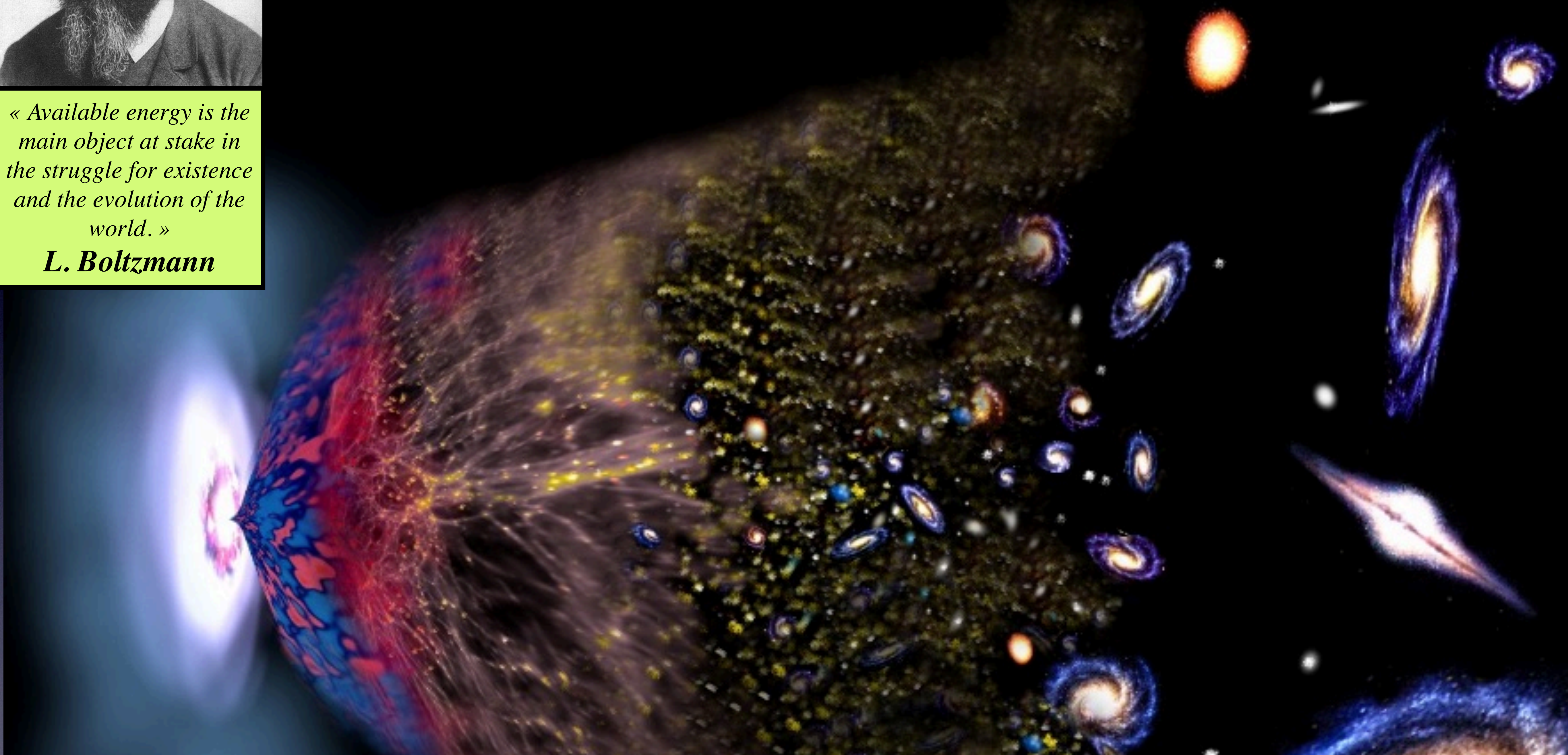
FKPPL project FNEPS

Finding New Physics: From Earth to Sky

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

L. Boltzmann



Yann Mambrini, IJCLab, Université Paris-Saclay

Simon Clery, Kunio Kaneta, Hyun Min Lee Yann Mambrini and M. Pierre

[Jong-Hyun Yoon]

11th Joint TYL/FJPPL and FKPPL Workshop

18/05/2022

CNRS IN2P3 Les deux infinis

IJCLab Irène Joliot-Curie Laboratoire de Physique des 2 Infinis

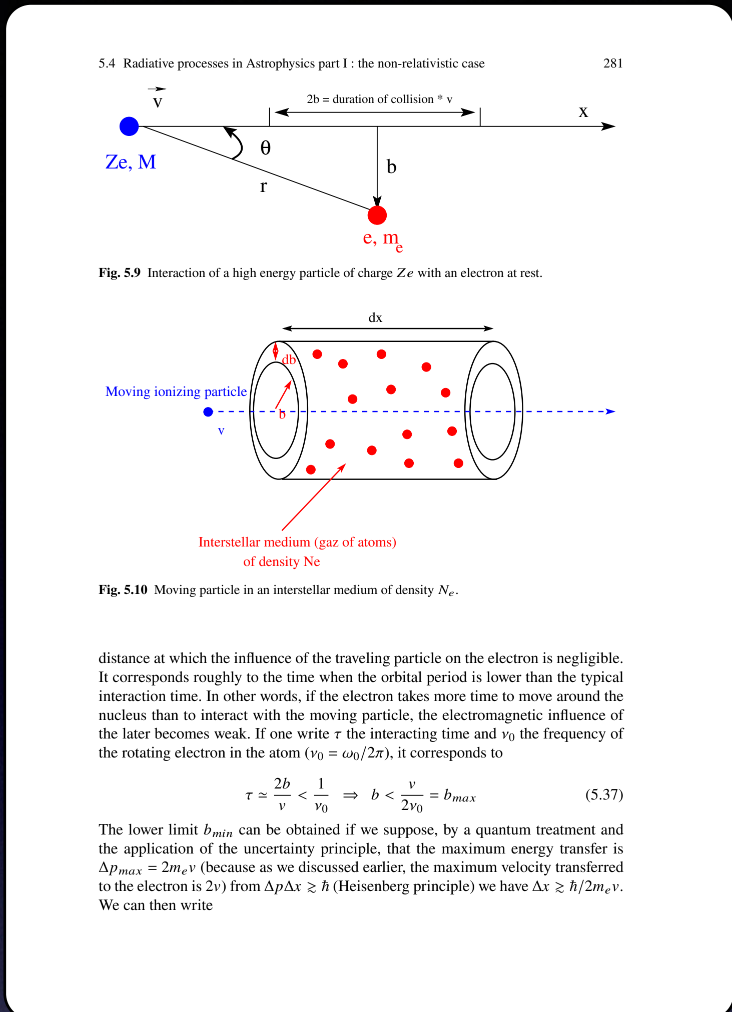

5.4 Radiative processes in Astrophysics part I : the non-relativistic case 281

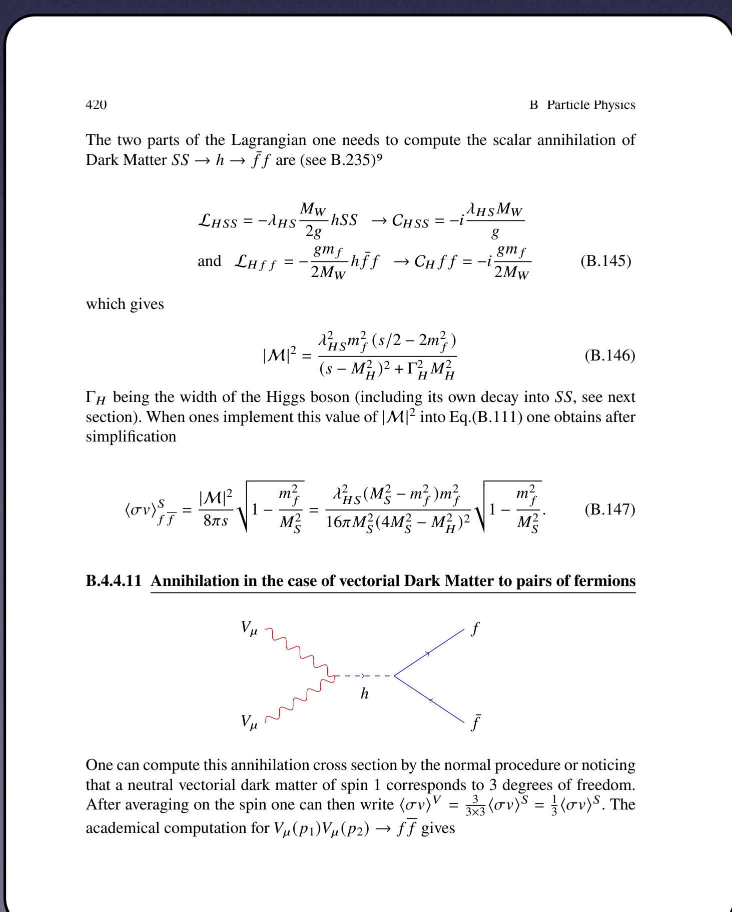
Fig. 5.9 Interaction of a high energy particle of charge Ze with an electron at rest.

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


420 B Particle Physics

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

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

which gives

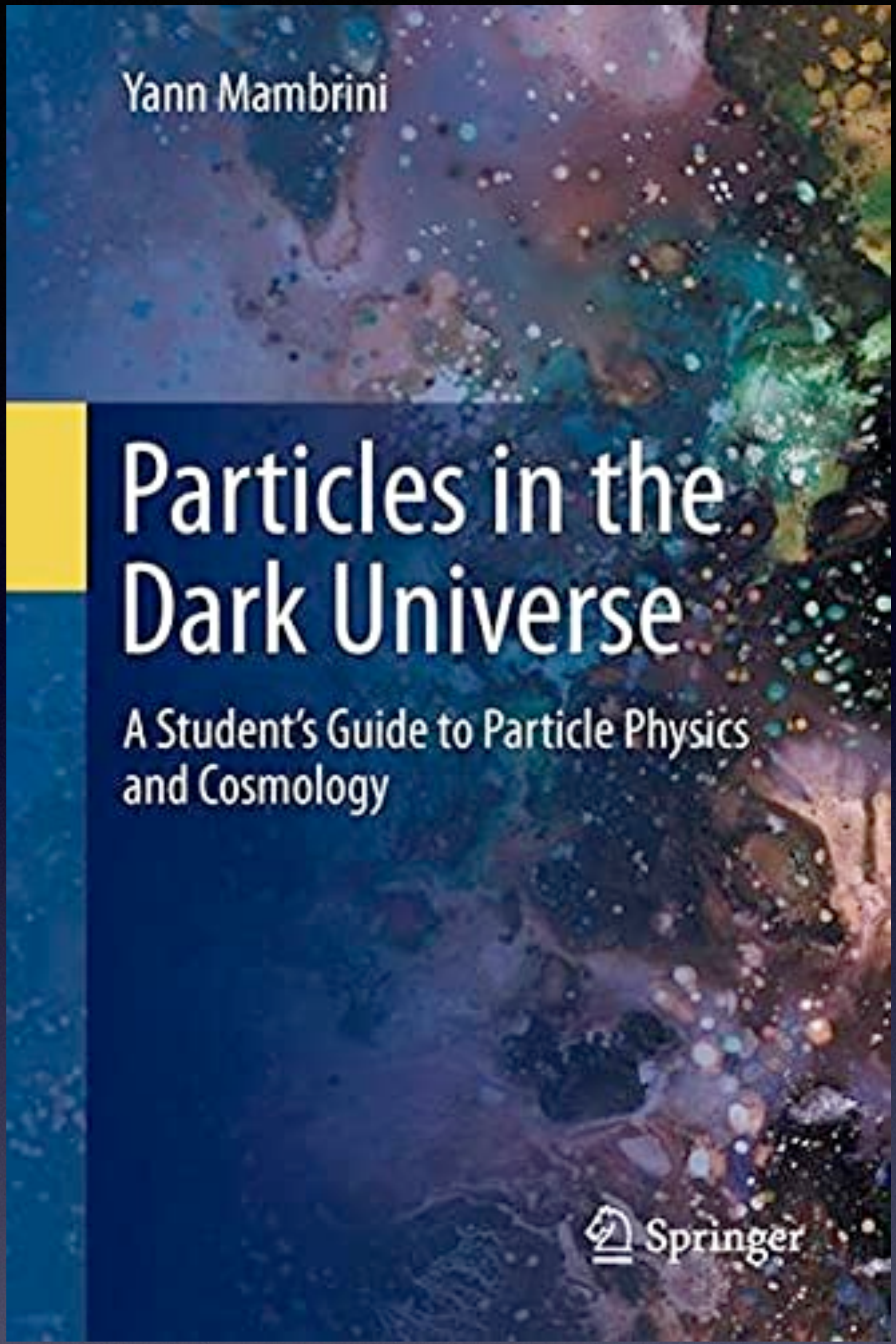
$$|\mathcal{M}|^2 = \frac{\lambda_{HS}^2 m_f^2 (s/2 - 2m_f^2)}{(s-M_H^2)^2 + \Gamma_H^2 M_H^2} \qquad (B.146)$$

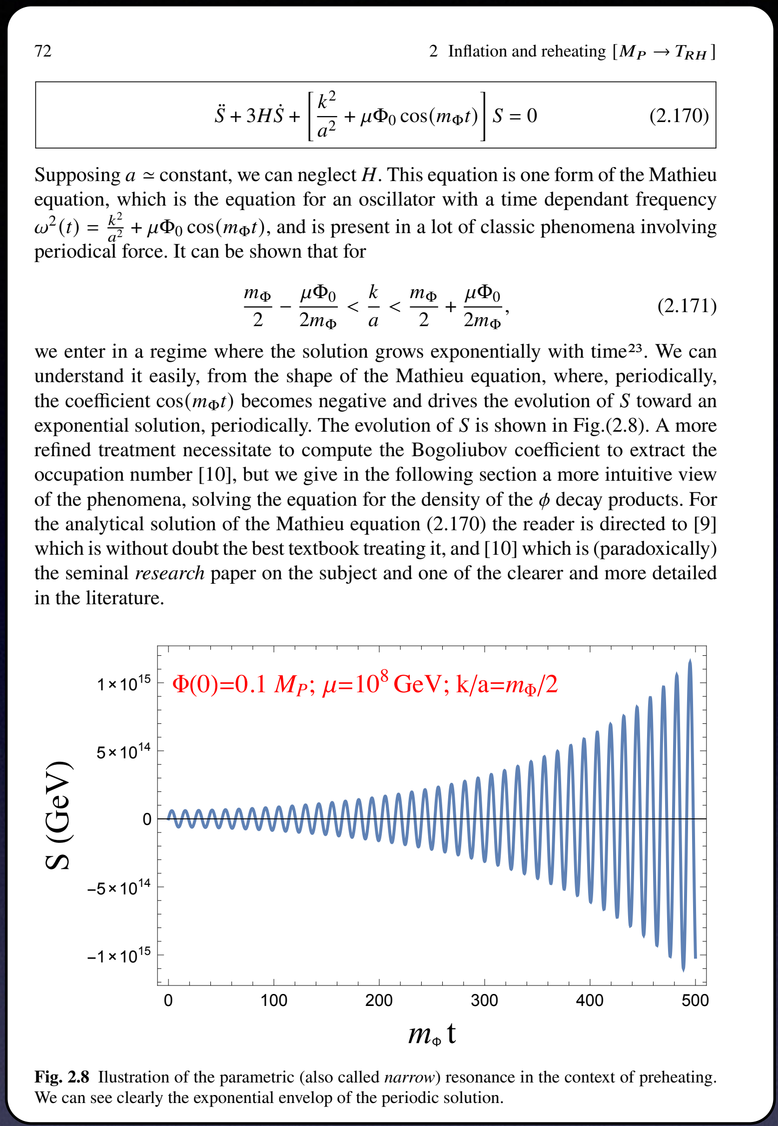
Γ_H being the width of the Higgs boson (including its own decay into SS, see next section). When ones implement this value of $|\mathcal{M}|^2$ into Eq.(B.111) one obtains after simplification

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

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 $V_\mu(p_1)V_\mu(p_2) \to f\bar{f}$ gives




72 2 Inflation and reheating [$M_P \to T_{RH}$]

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

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

Participants

PI:

Yann Mambrini (University of Paris -Saclay)
Hyun Min Lee, (Chung-Ang University, Seoul)

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Soo-Min Choi (CAU, 2016→ 2019)
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Maira Dutra (IJCLab, 2016 → 2019)
Simon Clery (IJCLab, 2021 → 2023)
Adriana Menkara (CAU, 2021 →2023)

Publications :

S. M. Choi, H. M. Lee, Y. Mambrini and M. Pierre,
``Vector SIMP dark matter with approximate custodial symmetry,''
JHEP **07** (2019), 049 ; [arXiv:1904.04109 [hep-ph]];

S. M. Choi, Y. Hochberg, E. Kuflik, H. M. Lee, Y. Mambrini, H. Murayama and M. Pierre,
``Vector SIMP dark matter,'' JHEP **10** (2017), 162 ; [arXiv:1707.01434 [hep-ph]].

P. Brax, K. Kaneta, Y. Mambrini and M. Pierre, ``Disformal dark matter,''
Phys. Rev. D **103** (2021) no.1, 015028 [arXiv:2011.11647 [hep-ph]];

S. Clery, Y. Mambrini, K. A. Olive, A. Shkerin and S. Verner, ``Gravitational Portals with Non-Minimal Couplings,'' [arXiv:2203.02004 [hep-ph]].

S. Aoki, H. M. Lee, A. G. Menkara and K. Yamashita, ``Reheating and Dark Matter Freeze-in in the Higgs-R^2 Inflation Model,'' ; [arXiv:2202.13063 [hep-ph]].

Event partly supported by FKPPL in 2019 and 2021 (2022):
The Sympsosium Astro@Paris-Saclay

250 participants, GGI format, 2 weeks minimum, outreach talks (Cedric Vilani, Hubert Reeves, Etienne Klein…), 43 articles directly written thanks to the workshop, artistic contribution (poster, comics…)

FKPPL financed Hyun Min Lee in 2019 *and* 2021 and we want him to come back in 2022.

The Paris-Saclay Astroparticle Symposium 2021

After being canceled in 2020 due to COVID-19 restrictions, the 2021 edition of the Paris-Saclay Astroparticle Symposium was organised from October 18 to November 26, 2021 at the Institut Pascal of the Paris-Saclay university. The organisation of this event was made possible thanks to support from P2IO, the P2I graduate school of the University of Paris-Saclay, IN2P3, APPEC and CEA. The symposium was a great success: nearly 230 researchers participated either by being present at the Pascal Institute (about 40 per week, many staying for several weeks) or by participating via videoconference.

Sketch from the illustrator Julie Borgese. She was invited to capture the atmosphere of the symposium and to transform scientific concepts into pieces of art.

The symposium was aimed at researchers specialised in the broad field of astroparticle physics, who were invited to come and work at the Institut Pascal in order to initiate, pursue or finalise research projects and publications. The format of the symposium is particularly well suited for this purpose, with a limited number of plenary sessions dedicated to presentations and leaving a significant amount of time reserved for joint work and informal discussions.

Due to the cancellation of the 2020 edition it was decided to extend the duration from the usual 4 to 6 weeks in 2021. Each week focused on specific topics and followed a similar outline: moderated by one or more specialists, informal discussions of about 2 hours on a specific topic triggered very fruitful exchanges and initiated joint works. One day per week was dedicated to presentations by participants who wished to present their work.

The following topics were discussed during the symposium (the details of the different sessions are available on the event website https://indico.ijclab.in2p3.fr/event/7119/):

- Week 1: Galactic Cosmic Rays
- Week 2: Ultra-High Energy Cosmic Rays
- Week 3: Dark Matter: Theories
- Week 4: Dark Matter: Theories versus Experiments
- Week 5: The transient sky (GWs and compact objects, multi-messenger astronomy)
- Week 6: Gravitational waves, theoretical point of view

In parallel, scientific colloquia were organised once a week. Details of the talks can be found at: https://indico.ijclab.in2p3.fr/event/7119/page/122-colloquia

In addition, a series of seven lectures for the general public, given by well-known external speakers, was organised. These lectures took place in the evening at the Institut Pascal and were a great success. Finally, an illustrator was invited to capture the atmosphere of the symposium and transform certain scientific concepts into pieces of art. A first sketch is shown below.
The 2022 edition of the Paris-Saclay Astroparticle Symposium is already in preparation!
Mark your agenda: it will take place from October 31 to November 25, 2022 at the Institut Pascal of the Paris-Saclay university.

Exemple of papers directly done thanks to our discussions in the Workshop

Reheating and Dark Matter Freeze-in in the Higgs-R^2 Inflation Model

Shuntaro Aoki[†], **Hyun Min Lee**[*], **Adriana G. Menkara**[⋆], **and Kimiko Yamashita**[♯]

Department of Physics, Chung-Ang University, Seoul 06974, Korea.

[arXiv:2202.13063 [hep-ph]]

[arXiv:2203.02004 [hep-ph]]

Gravitational Portals with Non-Minimal Couplings

Simon Cléry[a,*] Yann Mambrini[a,b,†] Keith A. Olive[c,‡] Andrey Shkerin[c,§] and Sarunas Verner[c¶]
[a] *Université Paris-Saclay, CNRS/IN2P3, IJCLab, 91405 Orsay, France*
[b] *CERN, Theoretical Physics Department, Geneva, Switzerland and*
[c] *William I. Fine Theoretical Physics Institute, School of Physics and Astronomy, University of Minnesota, Minneapolis, MN 55455, USA*

We consider the effects of non-minimal couplings to curvature of the form $\xi_S S^2 R$, for three types of scalars: the Higgs boson, the inflaton, and a scalar dark matter candidate. We compute the abundance of dark matter produced by these non-minimal couplings to gravity and compare to similar results with minimal couplings. We also compute the contribution to the radiation bath during reheating. The main effect is a potential augmentation of the maximum temperature during reheating. A model independent limit of $\mathcal{O}(10^{12})$ GeV is obtained. For couplings $\xi_S \gtrsim \mathcal{O}(1)$, these dominate over minimal gravitational interactions.

Some Physics :

1) Before Covid

2) After Covid

2017 → 2019 : Vectorial Strongly Interacting Massive Particle (VSIMP)

$$\mathcal{L} = -\frac{1}{4}\vec{X}_{\mu\nu}\cdot\vec{X}^{\mu\nu} \qquad \vec{X}_{\mu\nu} = \partial_\mu\vec{X}_\nu - \partial_\nu\vec{X}_\mu + g_X(\vec{X}_\mu\times\vec{X}_\nu)$$

$$\mathcal{L} \supset -\frac{1}{2}g_X(\partial_\mu\vec{X}_\nu - \partial_\nu\vec{X}_\mu)\cdot(\vec{X}^\mu\times\vec{X}^\nu) - \frac{1}{4}g_X^2(\vec{X}_\mu\cdot\vec{X}^\mu)^2$$

S. M. Choi, H. M. Lee, Y. Mambrini and M. Pierre, ``Vector SIMP dark matter with approximate custodial symmetry,'' JHEP **07** (2019), 049 ; [arXiv:1904.04109 [hep-ph]];

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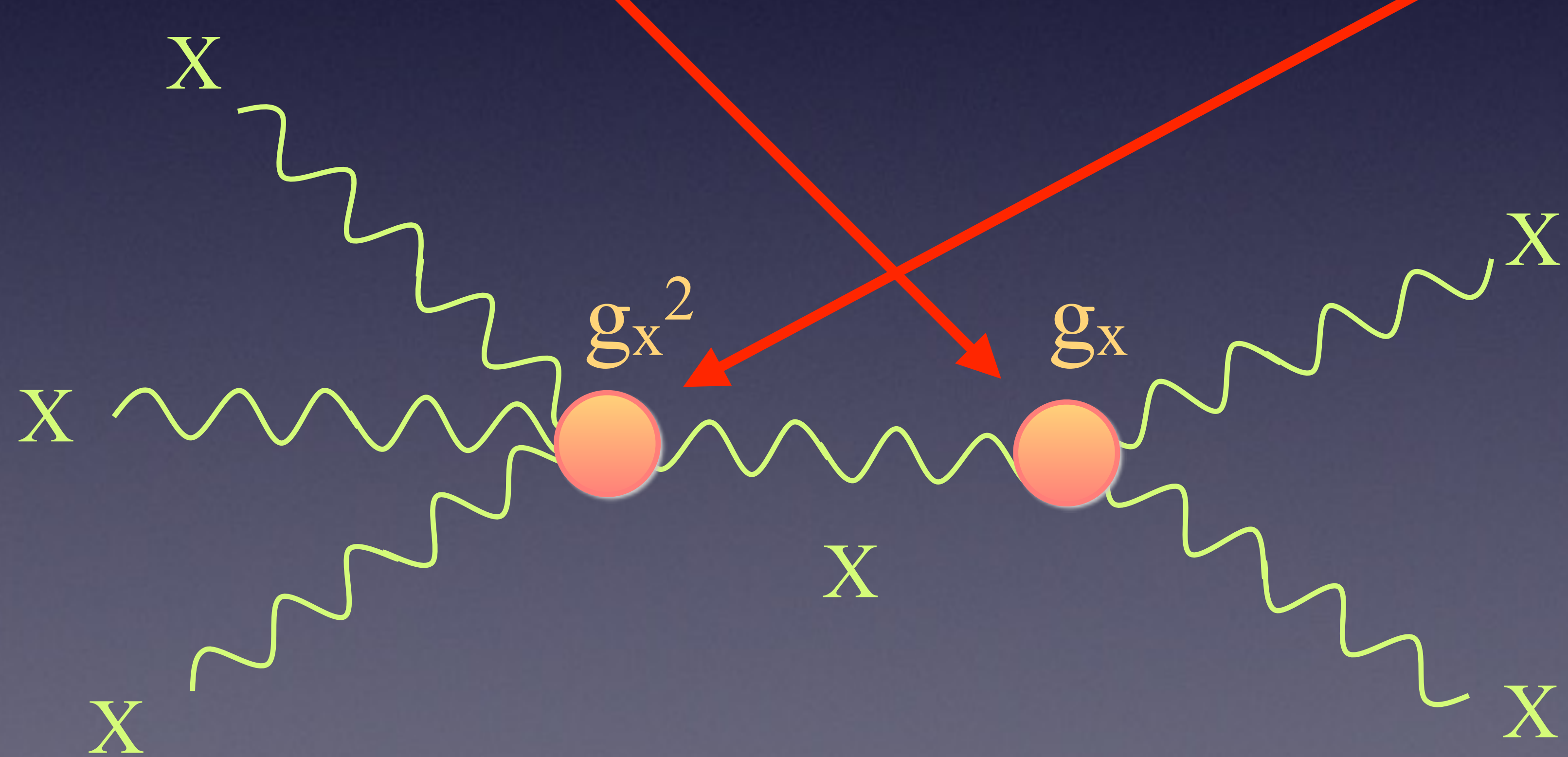
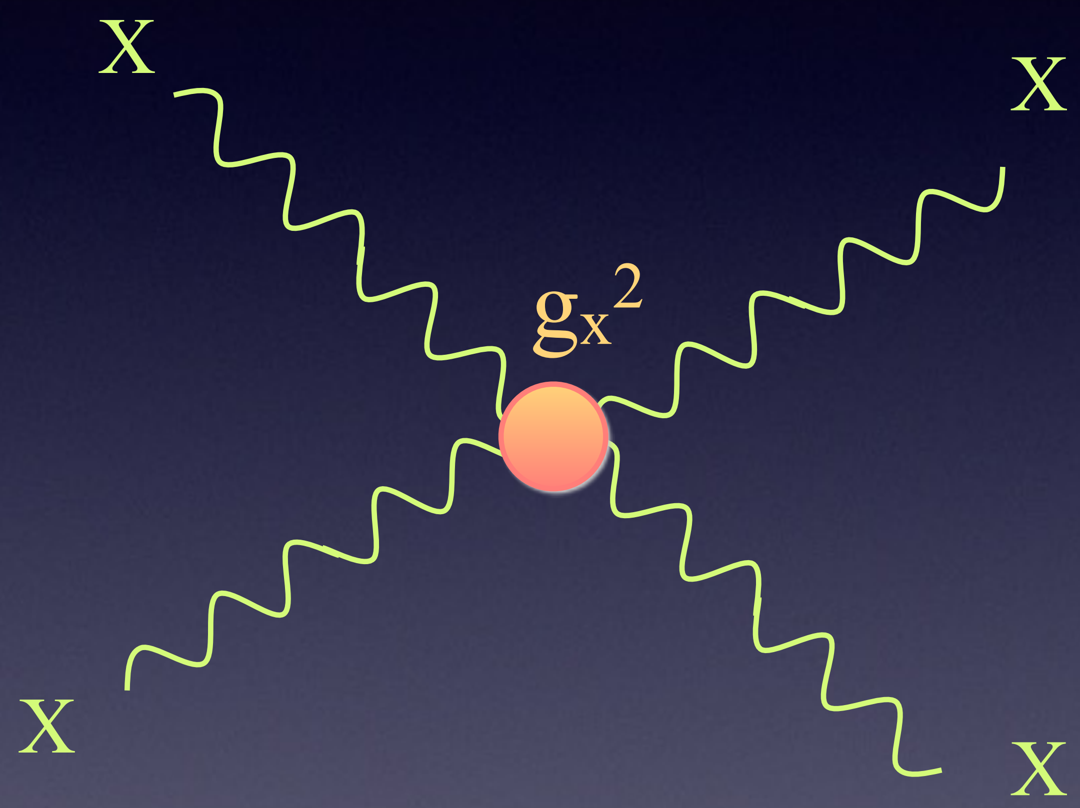


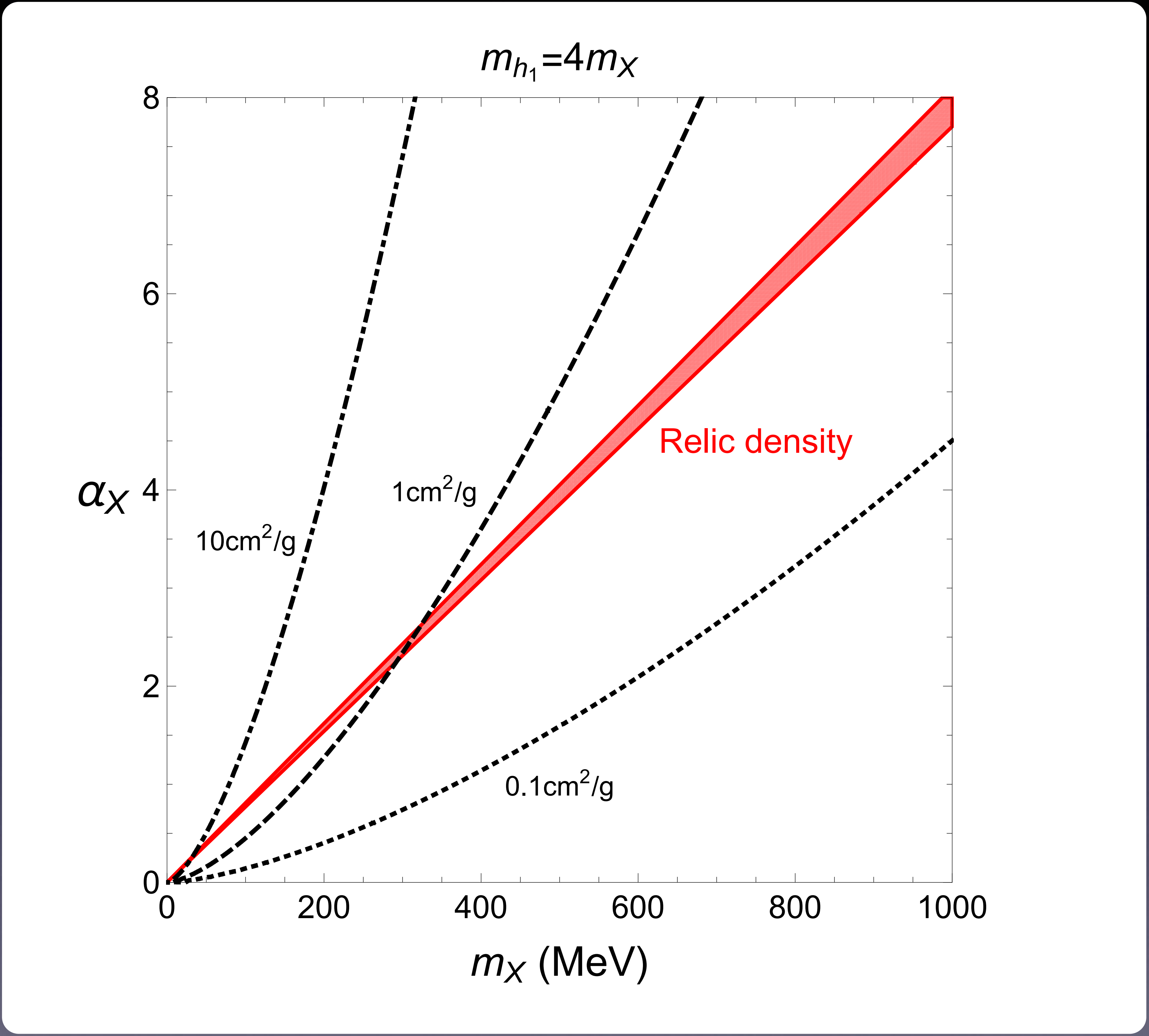
$$\frac{n_X}{n_\gamma} \simeq 10^{-9}$$

S. M. Choi, H. M. Lee, Y. Mambrini and M. Pierre, ``Vector SIMP dark matter with approximate custodial symmetry,'' JHEP **07** (2019), 049 ; [arXiv:1904.04109 [hep-ph]];

To check self-interaction constraints



S. M. Choi, H. M. Lee, Y. Mambrini and M. Pierre, ``Vector SIMP dark matter with approximate custodial symmetry,'' JHEP **07** (2019), 049 ; [arXiv:1904.04109 [hep-ph]];



S. M. Choi, H. M. Lee, Y. Mambrini and M. Pierre, ``Vector SIMP dark matter with approximate custodial symmetry,'' JHEP **07** (2019), 049 ; [arXiv:1904.04109 [hep-ph]];

Conclusion:

The simplest VSIMP extension could be compatible with the observation of a (future) self-scattering cross section while still being a dark matter candidate compatible with PLANCK.

Exemple of papers directly done thanks to our discussions in the Workshop

Reheating and Dark Matter Freeze-in in the Higgs-R^2 Inflation Model

Shuntaro Aoki[†], **Hyun Min Lee**[*], **Adriana G. Menkara**[⋆], **and Kimiko Yamashita**[♯]

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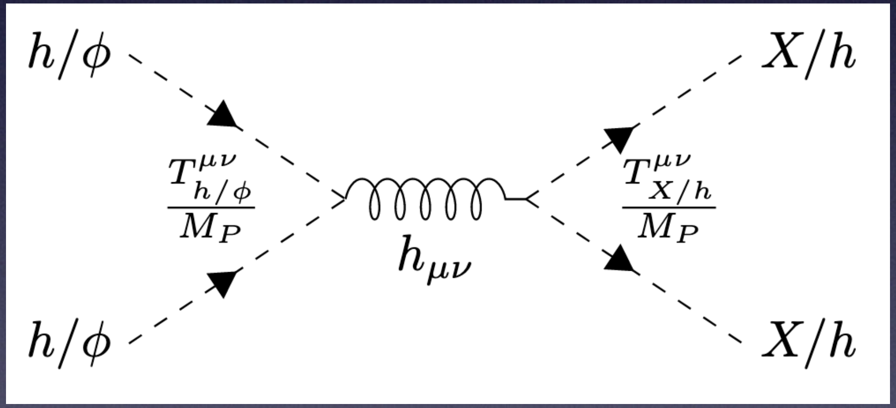
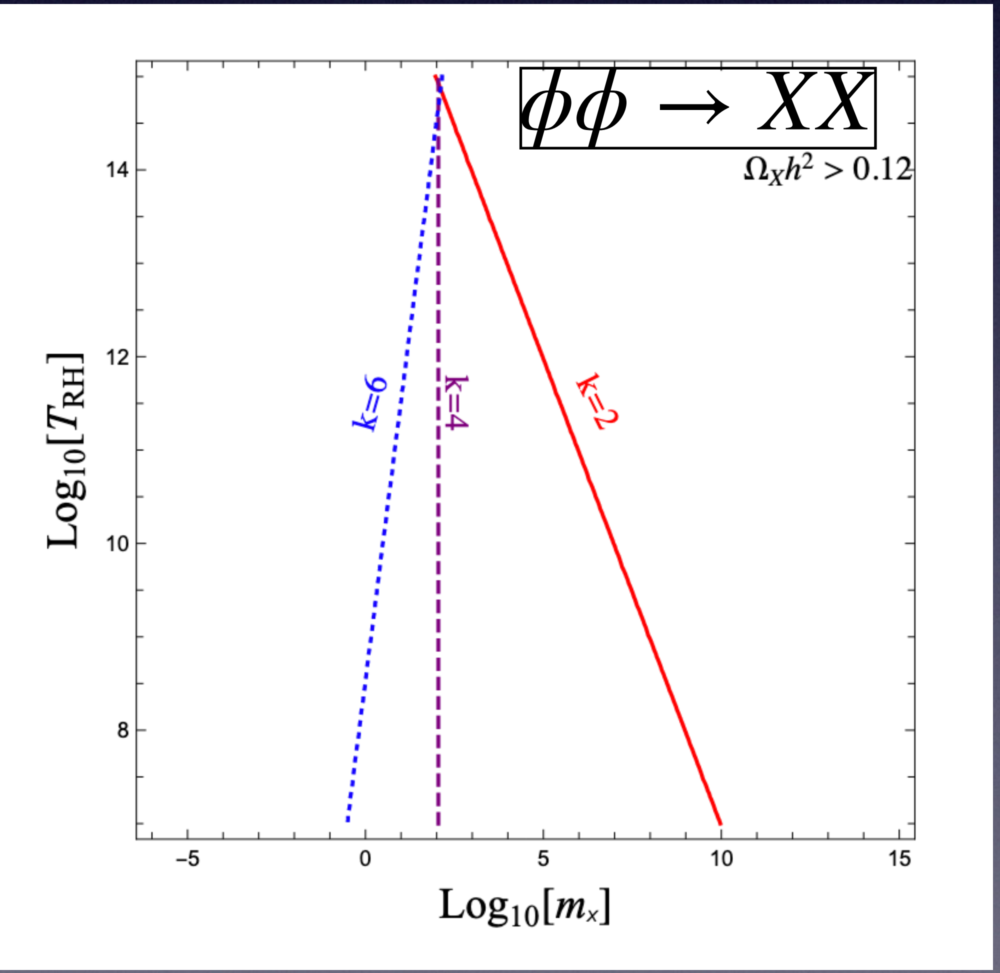
2019 → 2022 : Gravitational (and thus unavoidable) production of (dark) matter in the early Universe

$$\mathscr{L} = \sqrt{-g}\left(-\frac{M_P^2}{2}R + \mathscr{L}_\phi + \mathscr{L}_h + \mathscr{L}_X\right) \quad ; \quad g_{\mu\nu} = \eta_{\mu\nu} + \frac{2}{M_P}h_{\mu\nu}$$

$$\Rightarrow \quad \mathscr{L} \supset \frac{1}{M_P}h_{\mu\nu}\left(T^{\mu\nu}_\phi + T^{\mu\nu}_h + T^{\mu\nu}_X\right)$$



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



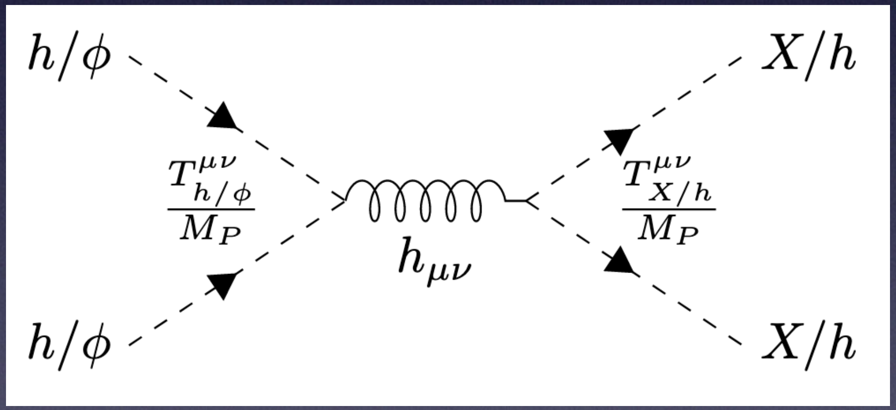
Y. Mambrini and K. A. Olive, Phys. Rev. D **103** (2021) no.11, 115009 [arXiv:2102.06214]

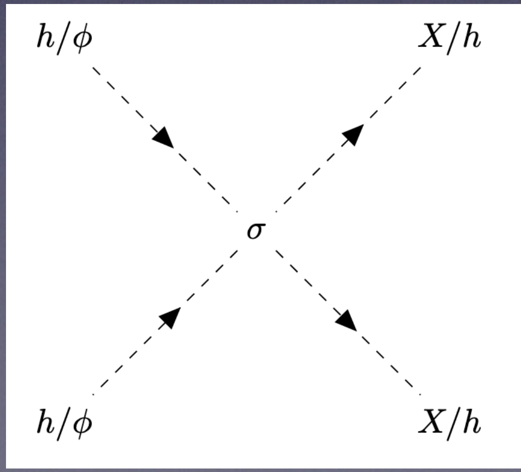
S. Clery, Y. Mambrini, K. A. Olive and S. Verner, Phys. Rev. D **105** (2022) no.7, 075005 ; [arXiv:2112.15214 [hep-ph]]

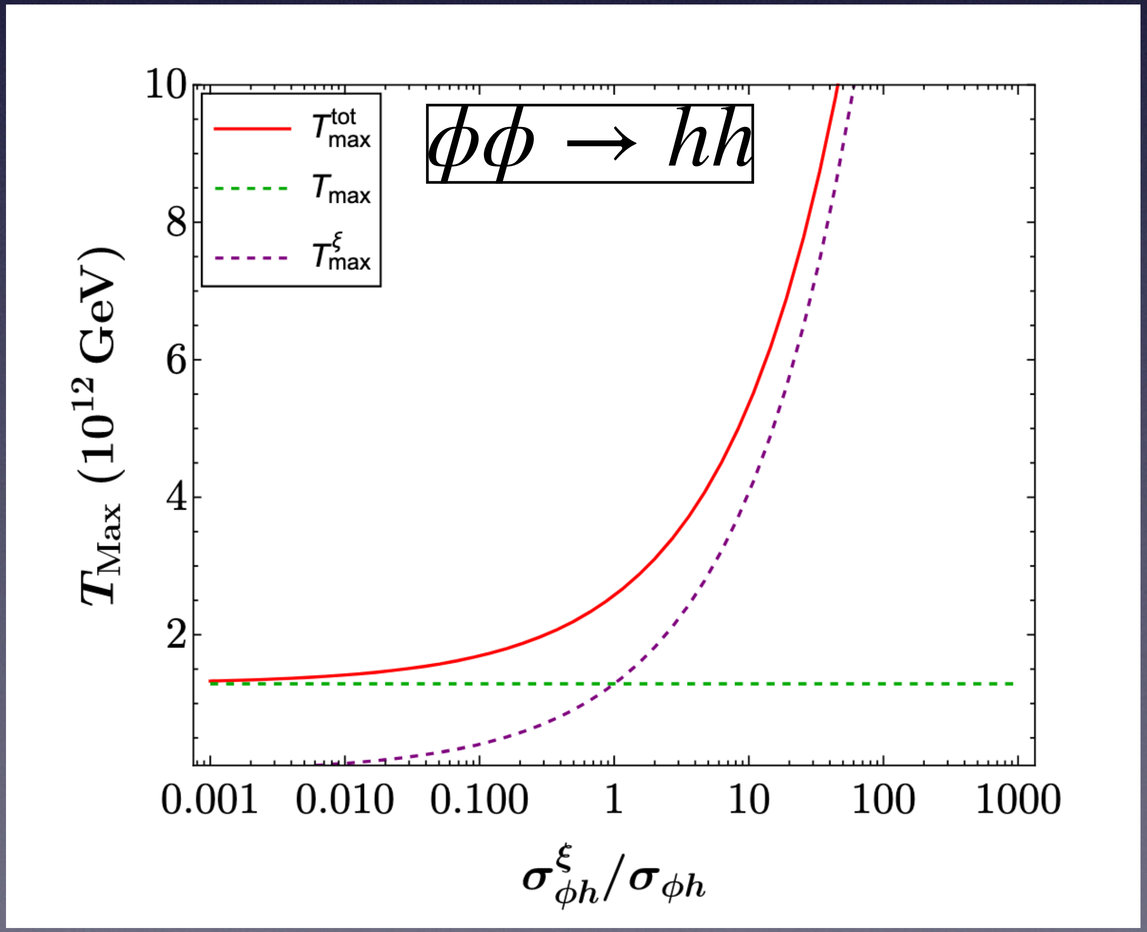
Adding the possibility for non-minimal gravitational coupling

$$\mathscr{L} = \sqrt{-g}\left(-\frac{M_P^2}{2}\left[1+\xi_\phi\frac{\phi^2}{M_P^2}+\xi_h\frac{h^2}{M_P^2}+\xi_X\frac{X^2}{M_P^2}\right]R+\mathscr{L}_\phi+\mathscr{L}_h+\mathscr{L}_X\right)$$

$$\Rightarrow \quad \mathscr{L} \supset \frac{1}{M_P}h_{\mu\nu}\left(T^{\mu\nu}_\phi+T^{\mu\nu}_h+T^{\mu\nu}_X\right)+\sigma^\xi_{\phi h}\phi^2h^2+\sigma^\xi_{\phi X}\phi^2X^2+\sigma^\xi_{hX}h^2X^2$$





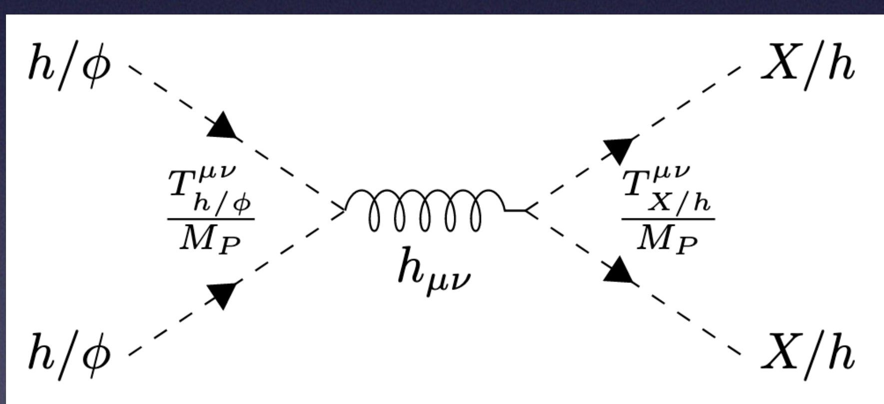


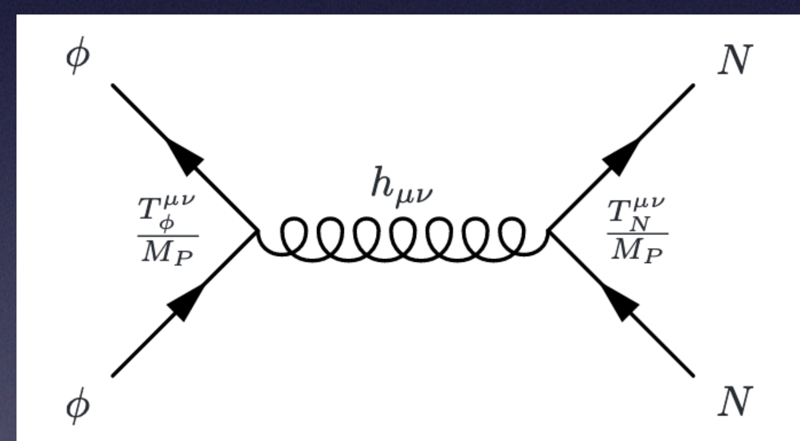
S. Clery, Y. Mambrini, K. A. Olive, A. Shkerin and S. Verner, ``Gravitational Portals with Non-Minimal Couplings,'' ; [arXiv:2203.02004 [hep-ph]].

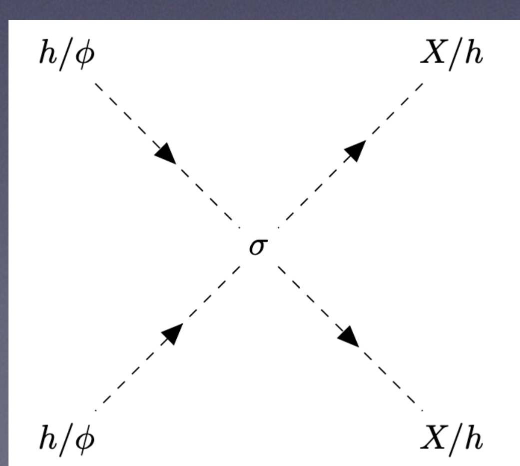
Adding the possibility for Leptognesis

$$\mathscr{L} = \sqrt{-g}\left(-\frac{M_P^2}{2}\left[1+\xi_\phi\frac{\phi^2}{M_P^2}+\xi_h\frac{h^2}{M_P^2}+\xi_X\frac{X^2}{M_P^2}\right]R+\mathscr{L}_\phi+\mathscr{L}_h+\mathscr{L}_X-M_R\bar{N}_R^cN_R\right)$$

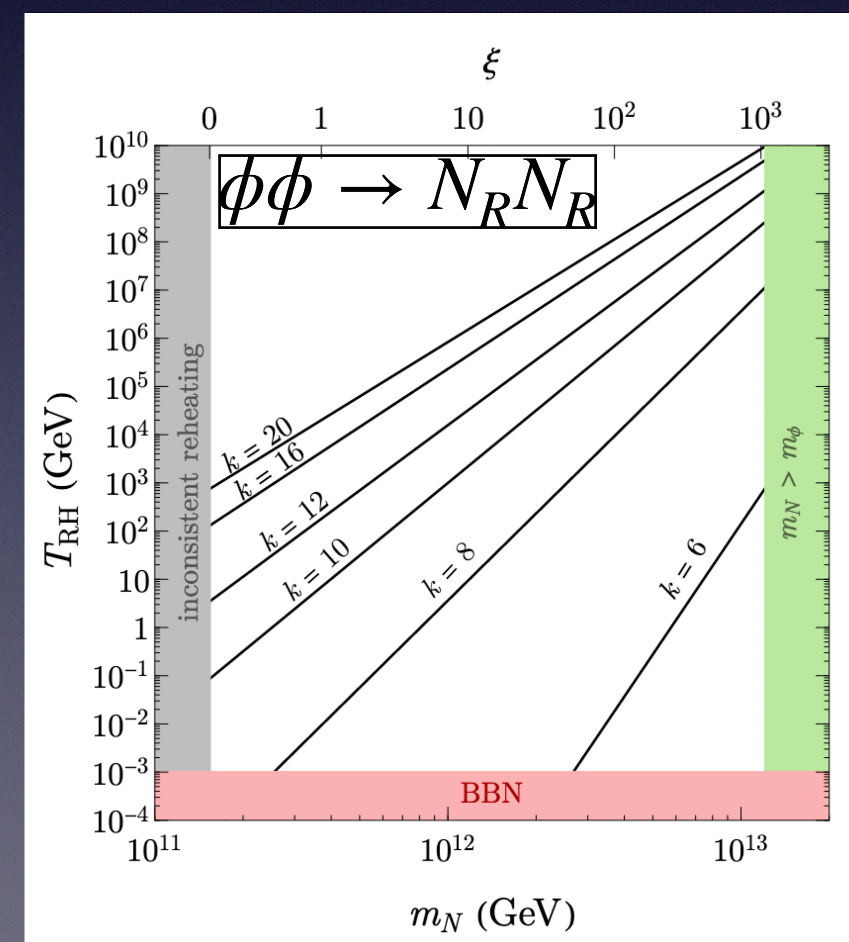
$$\Rightarrow \quad \mathscr{L} \supset \frac{1}{M_P}h_{\mu\nu}\left(T_\phi^{\mu\nu}+T_h^{\mu\nu}+T_X^{\mu\nu}+T_{N_R}^{\mu\nu}\right)+\sigma_{\phi h}^{\xi}\phi^2h^2+\sigma_{\phi X}^{\xi}\phi^2X^2+\sigma_{hX}^{\xi}h^2X^2$$







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



R. T. Co, Y. Mambrini and K. A. Olive, ``Inflationary Gravitational Leptogenesis,'' ; [arXiv:2205.01689 [hep-ph]].

Conclusion

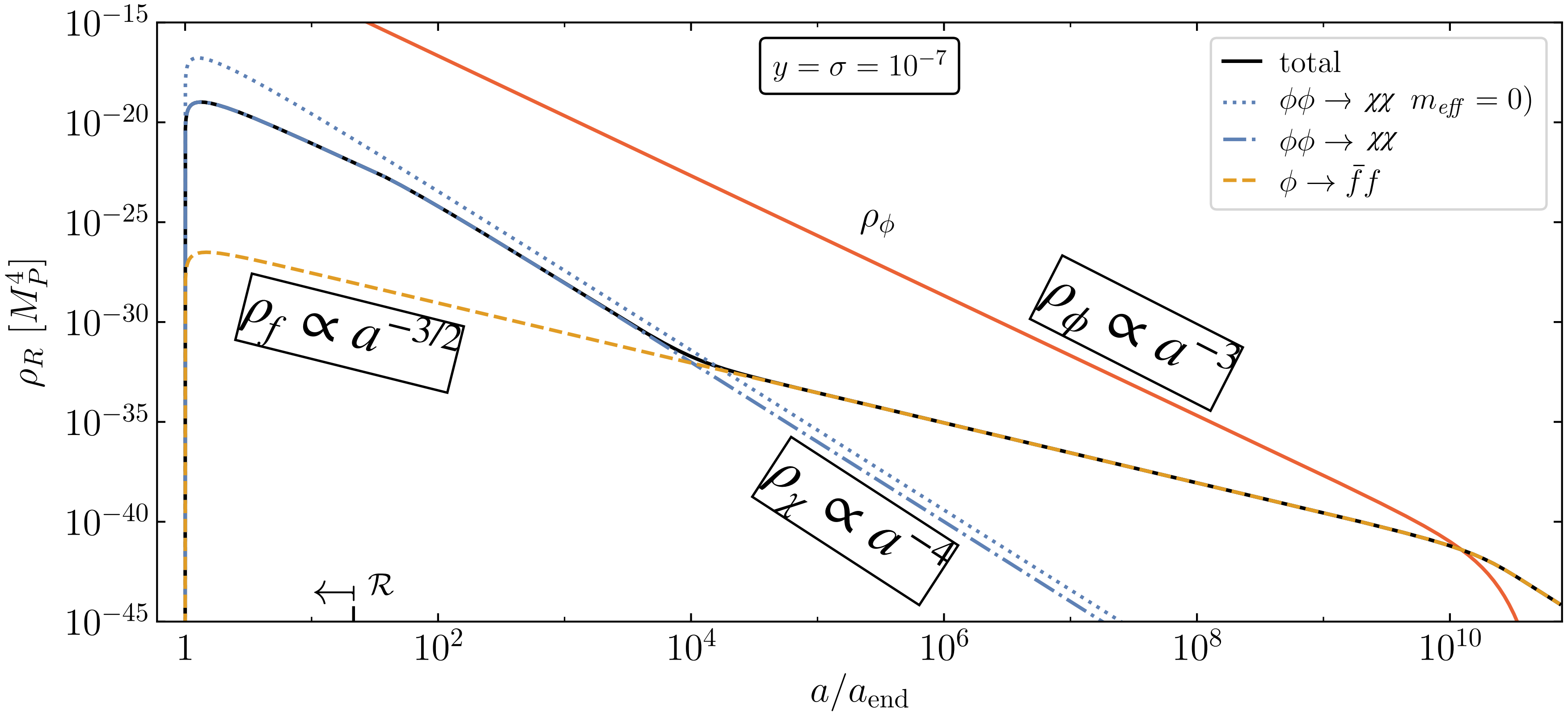
Minimal Extensions of the Standard Model still need to be studied to check every phenomenological corner for detection hints.

Bonus

Preheating

(Subject of J.H. Yoon)

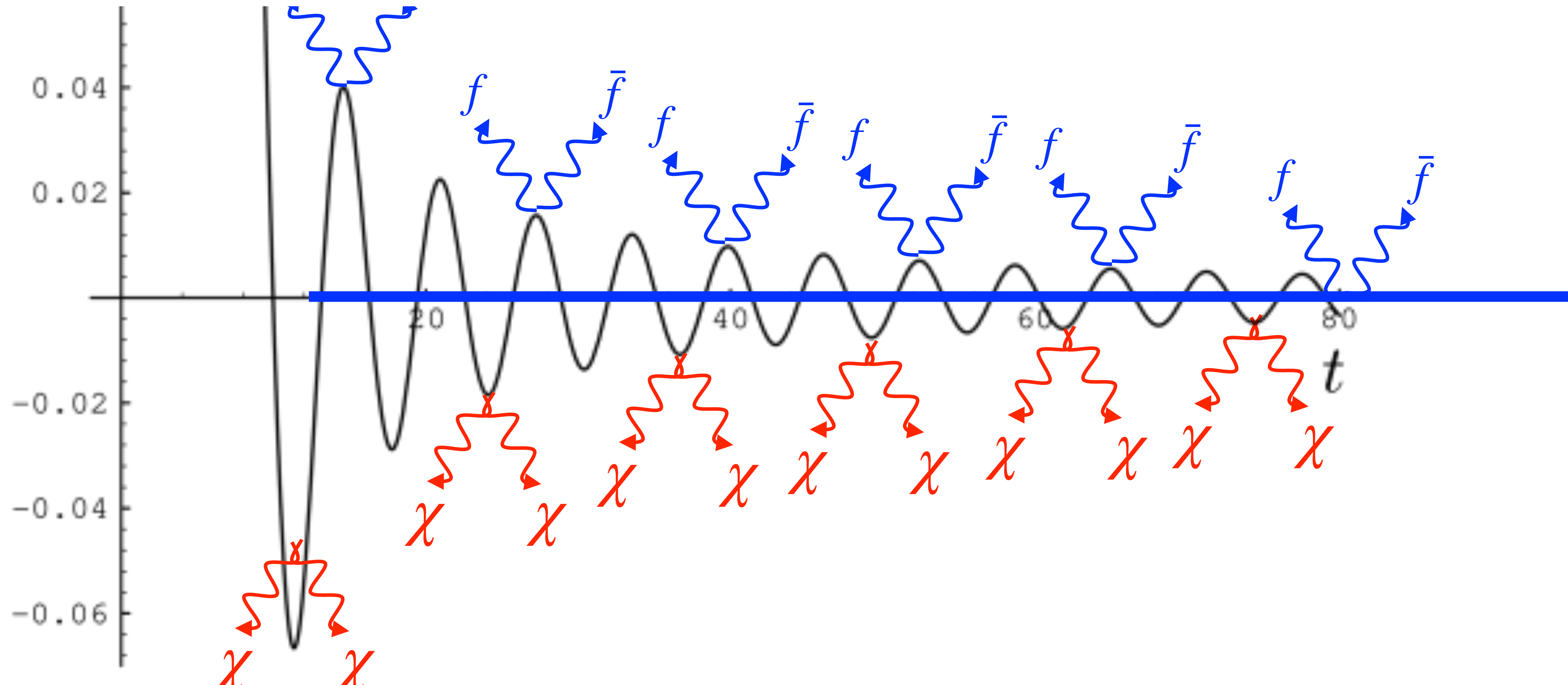
M. A. G. Garcia, K. Kaneta, Y. Mambrini and K. A. Olive, JCAP **04** (2021), 012[arXiv:2012.10756 [hep-ph]].



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

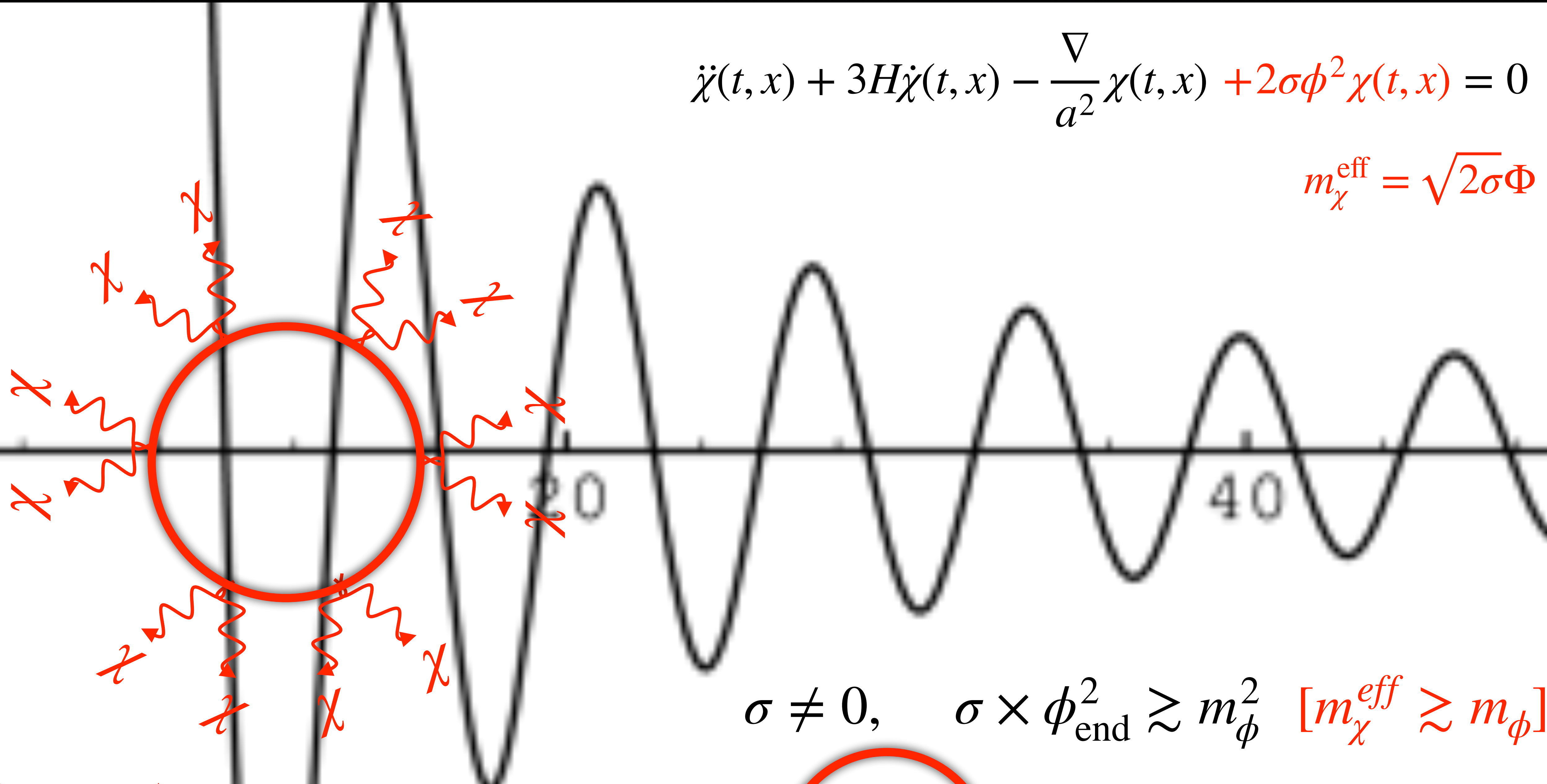
$$3H\dot{\chi} - \frac{\nabla}{a^2}\chi(t,x) + 2\sigma\phi^2\chi = 0$$

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



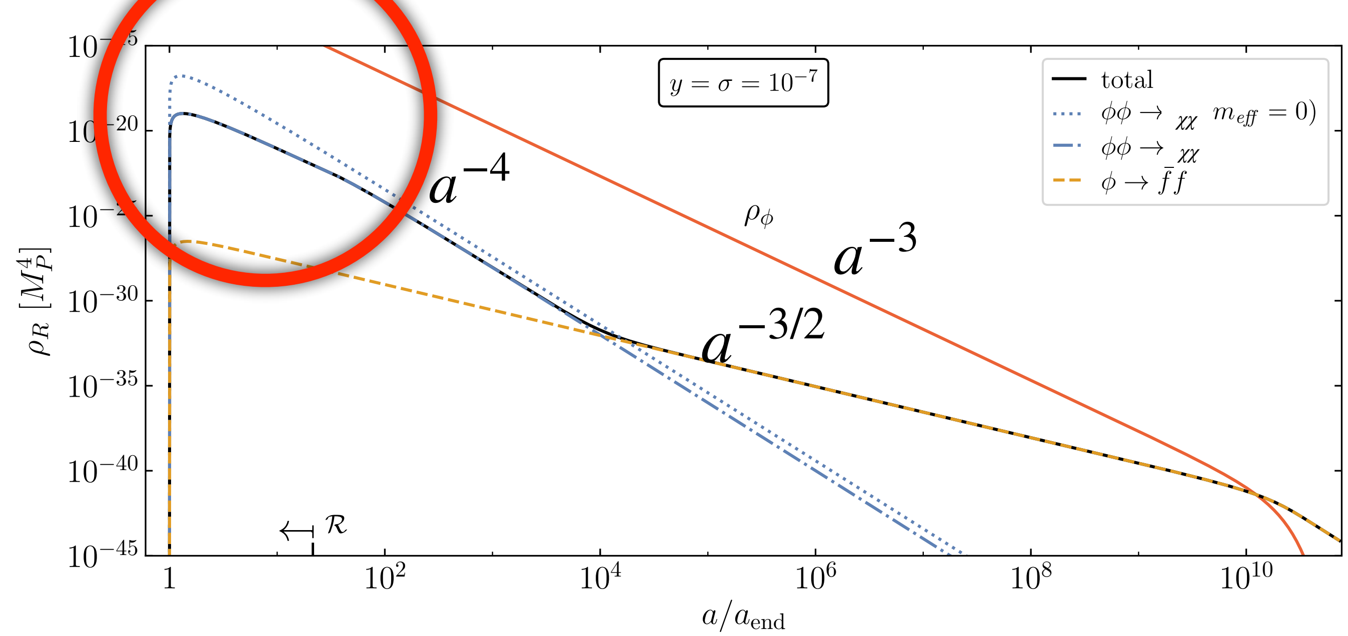
$$\ddot{\chi}(t,x) + 3H\dot{\chi}(t,x) - \frac{\nabla}{a^2}\chi(t,x) + 2\sigma\phi^2\chi(t,x) = 0$$

$$m_\chi^{\text{eff}} = \sqrt{2\sigma}\Phi$$



$$\sigma \neq 0, \quad \sigma \times \phi_{\text{end}}^2 \gtrsim m_\phi^2 \quad [m_\chi^{eff} \gtrsim m_\phi]$$

Resonant production



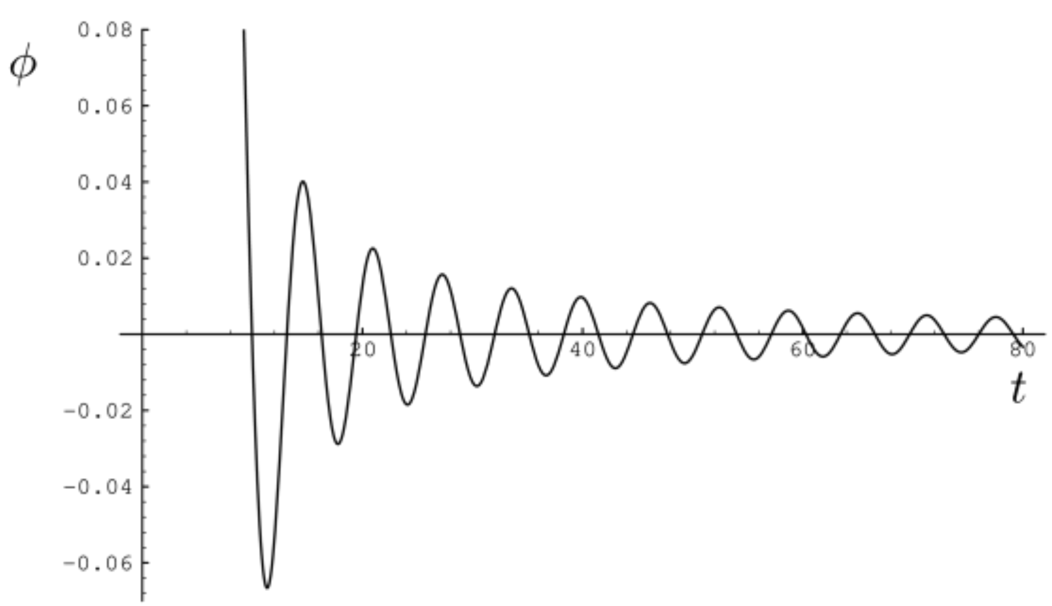
$$\ddot{\chi}(t,x) + 3H\dot{\chi}(t,x) - \frac{\nabla}{a^2}\chi(t,x) + 2\sigma\phi^2\chi(t,x) = 0 \qquad m_\chi^{\rm eff} = \sqrt{2\sigma}\Phi$$

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

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

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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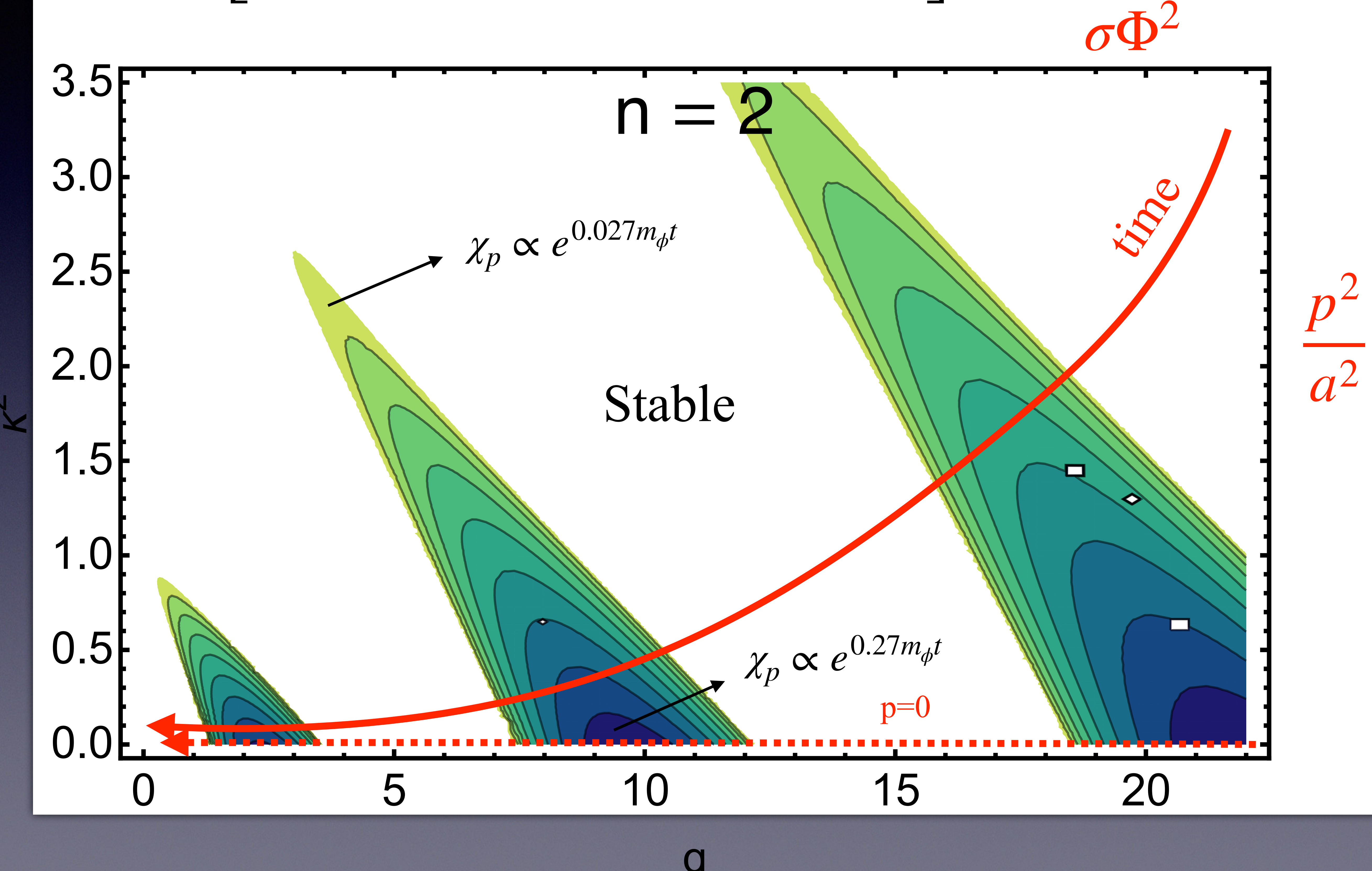
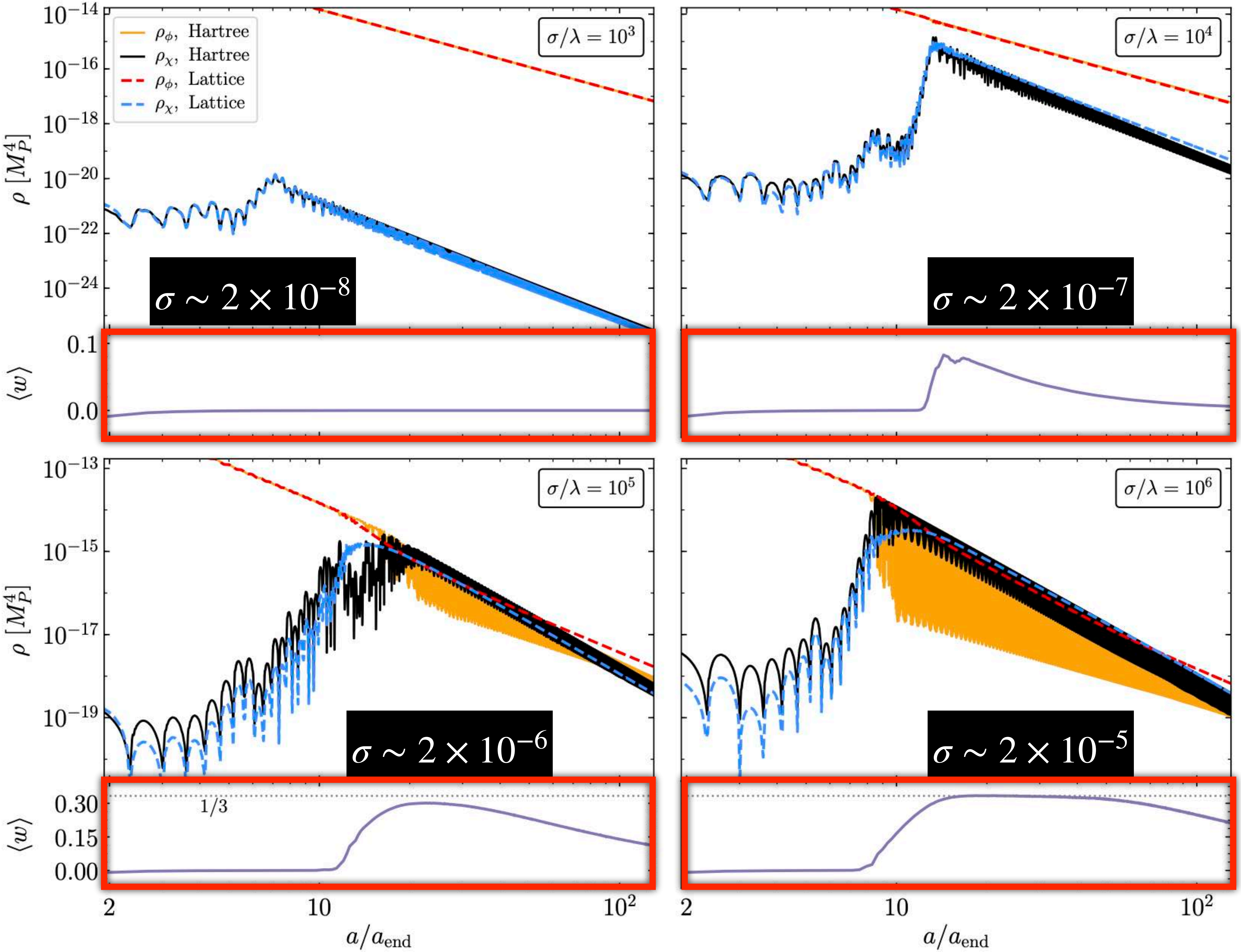
CSIC Cambridge Centre for Smart Infrastructure and Construction

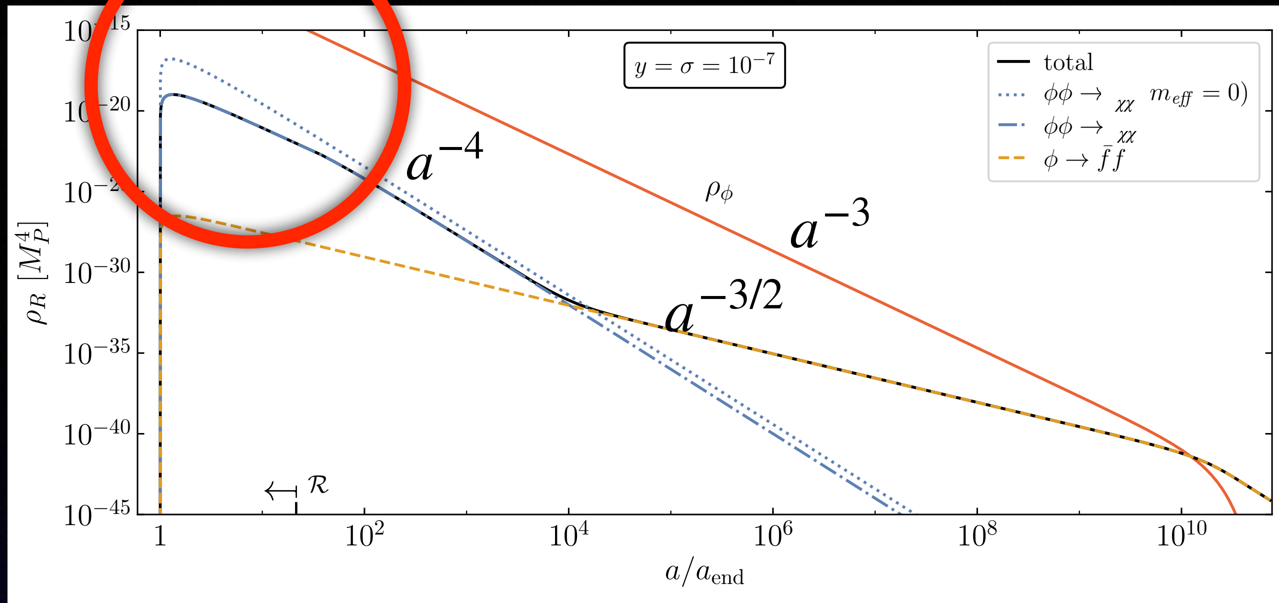
$$\ddot{\chi}_p(t) + \left[\frac{p^2}{a^2} + (m_\chi^{\rm eff})^2 + \sigma\Phi^2(t)\times\cos 2m_\phi t\right]\chi_p(t) = 0$$

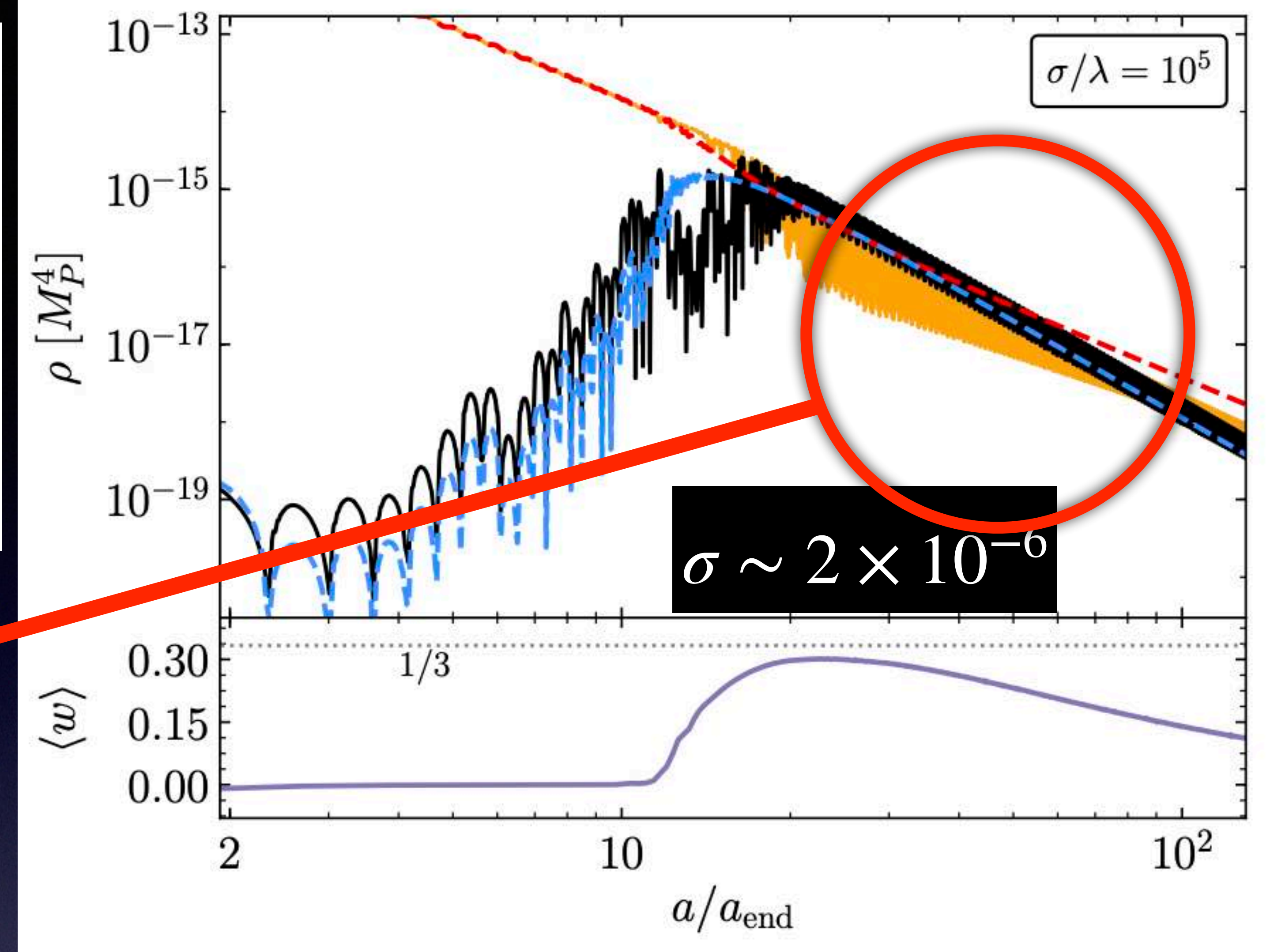
Mathieu equation





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
$a/a_{\rm end}$





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

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

Back-reaction effects of χ on ϕ