



# A tale of dark matter production

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**Deutsches Elektronen-Synchrotron (DESY)**

April 7<sup>th</sup> 2022

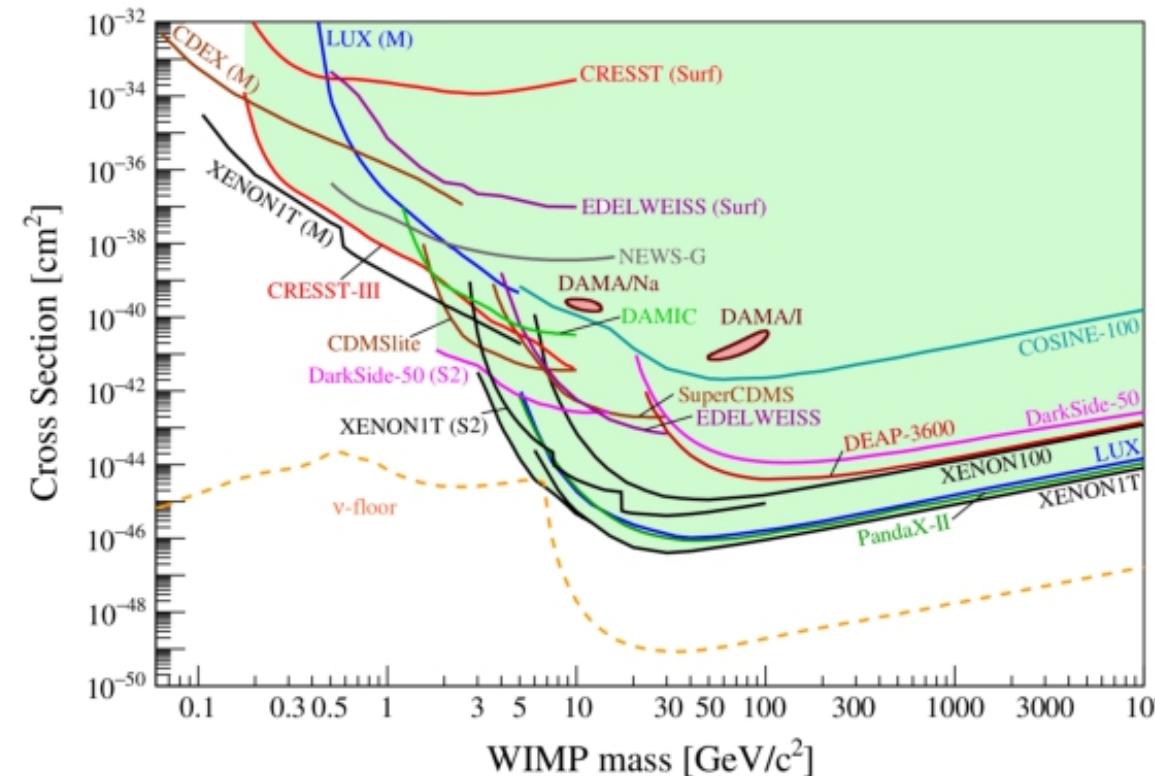
*Seminar - Laboratoire Charles Coulomb (L2C) & Laboratoire Univers et Particules de Montpellier (LUPM)*

Based on

[arXiv:2204.????] with **S. Verner & M. A. G. Garcia**

[arXiv:2011.13458] with **G. Ballesteros & M. A. G. Garcia**

# Introduction



**No dark matter-nucleon signal reported!**

# The waning of the WIMP?

Weakly Interacting Massive Particles (WIMP) most considered DM candidates

Simplest example: introduce **scalar dark matter**  $\chi$

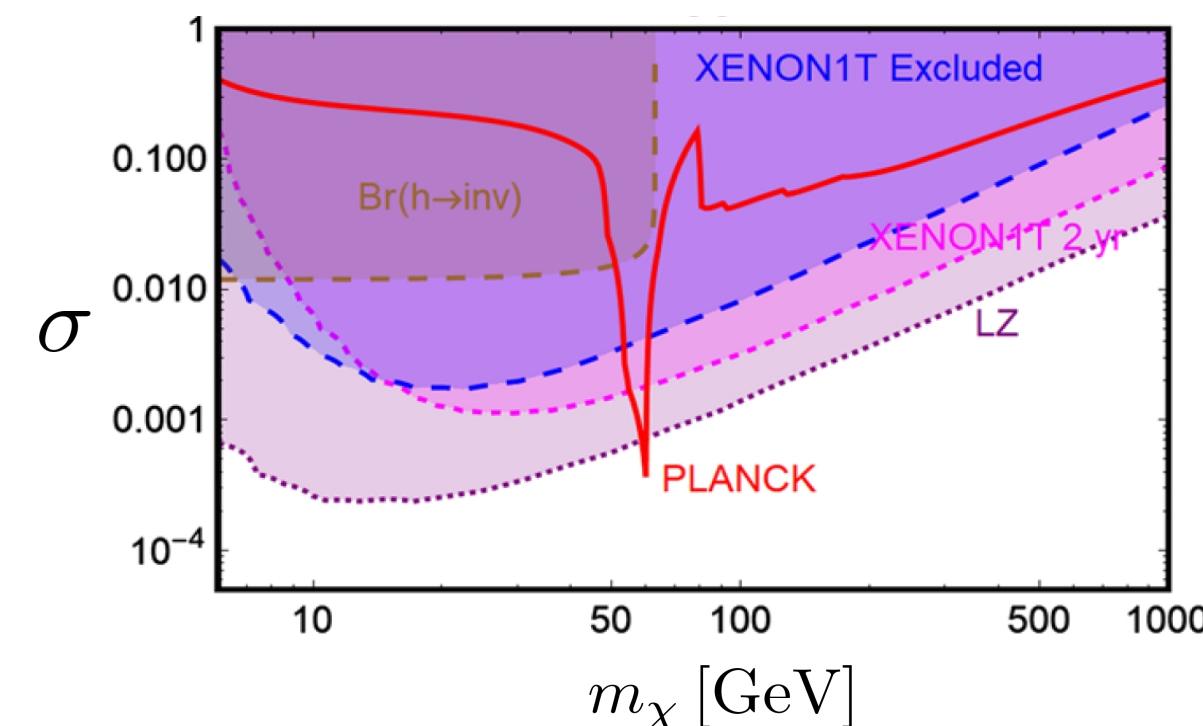
$$\mathcal{L} = \sigma\chi^2|H|^2$$

DM thermalizes with SM

Produced via **freeze-out**

(In)direct detection **signatures**

Independent on history **prior** thermalization



**Minimalistic WIMP models under siege!**

[M. Escudero, A. Berlin, D. Hooper, M.-X. Lin - JCAP 12 (2016) 029]

[G. Arcadi, M. Dutra, P. Ghosh, M. Lindner, Y. Mambrini, MP, S. Profumo, F. S. Queiroz EPJC 78 (2018) 203]

[G. Arcadi, A. Djouadi, M. Raidal - Phys.Rept. 842 (2020) 1-180]

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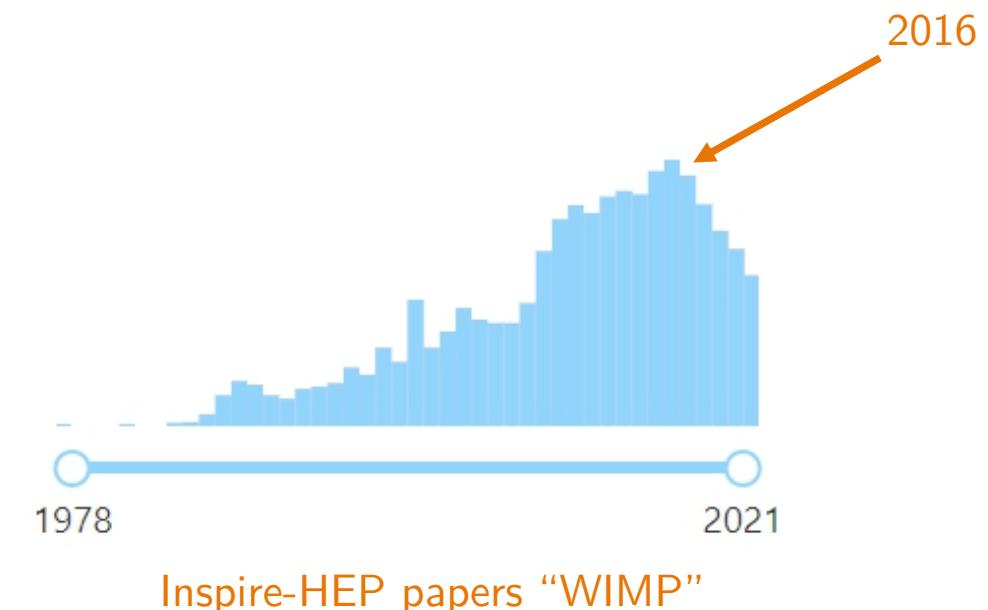
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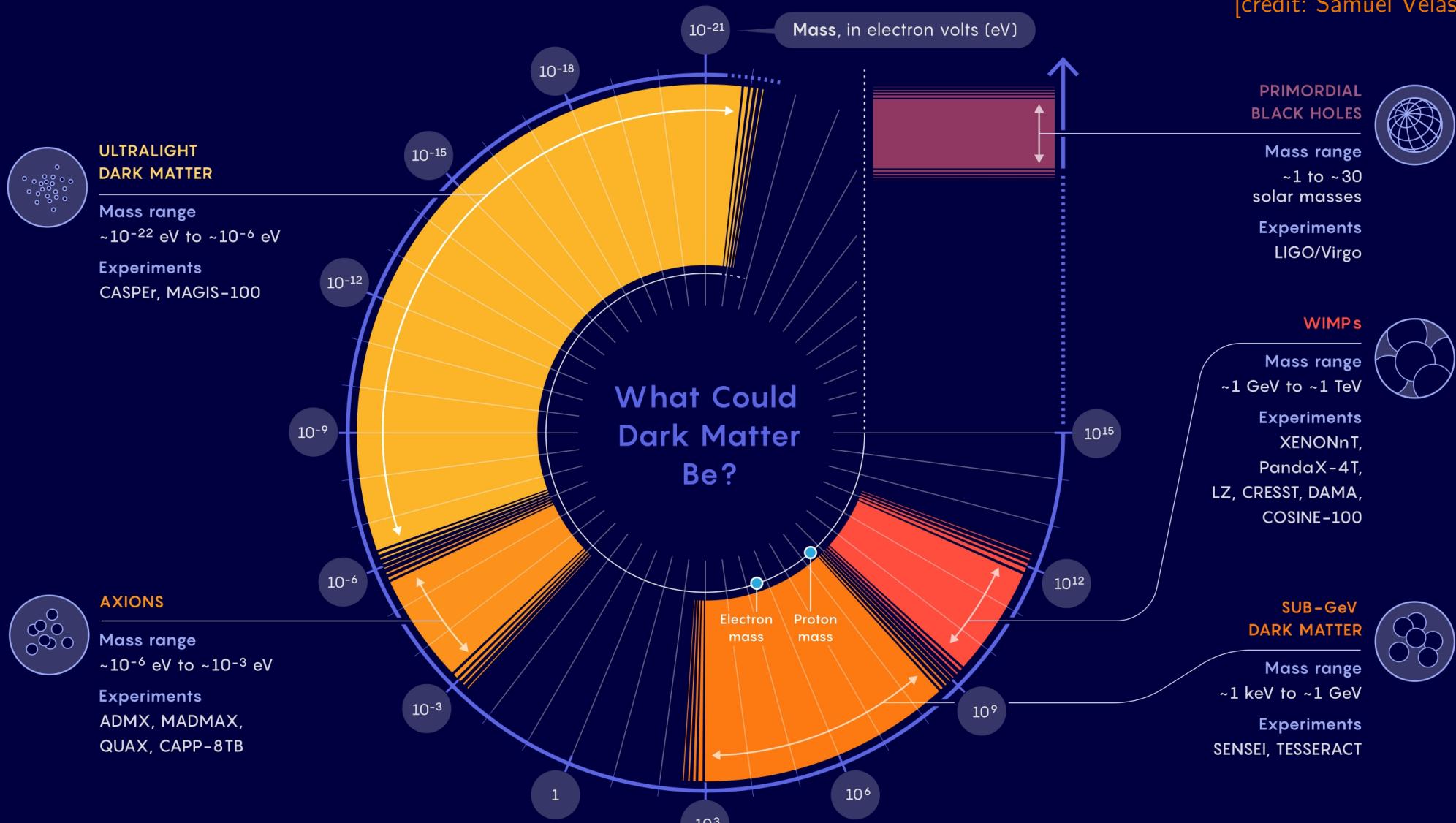
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# Introduction

[credit: Samuel Velasco/Quanta Magazine]



The dark matter landscape, circa 2022

**Where shall we look for dark matter?**

**What could source DM production?**

**Let's try to understand how to produce DM in the early universe.**

# The dawn of FIMP?

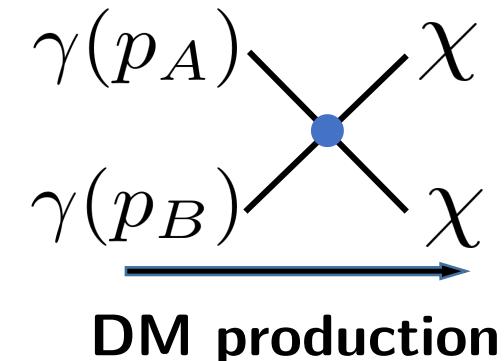
Consider Feebly Interacting Massive Particles (**FIMP**)

DM does not thermalize with SM  
→ Very feebly coupled to SM

Produced via **freeze-in**

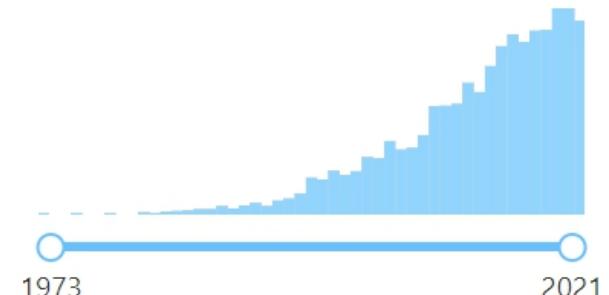
**Elusive** in (in)direct detection

Depends on early universe history



$$\frac{dn_\chi}{dt} + 3Hn_\chi = R(t)$$

[J. McDonald PRL 88 (2002) 091304 - K.-Y. Choi, L. Roszkowski AIP Conf.Proc. 805 (2005) 1, 30-36  
Kusenko PRL 97 (2006) 241301 - K. Petraki, A. Kusenko PRD 77 (2008) 065014  
L. J. Hall, K. Jedamzik, J. March-Russell, S. M. West JHEP 03 (2010) 080  
N. Bernal, M. Heikinheimo, T. Tenkanen, K. Tuominen and V. Vaskonen – IJMP A 32 (2017) 27, 1730023]



Inspire-HEP papers “freeze-in”

$\gamma$  Standard Model (SM) particle

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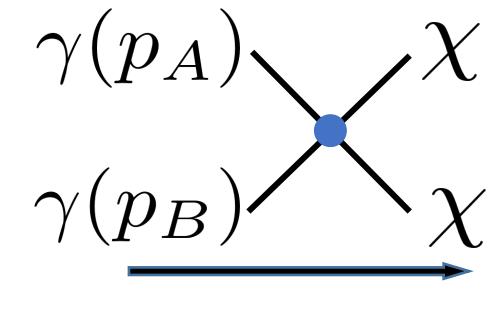
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$$\frac{dn_\chi}{dt} + 3Hn_\chi = R(t)$$

$$R(t) \equiv 2g_A g_B g_\chi^2 \int \frac{d^3 p_A}{(2\pi)^3 2p_1^0} \frac{d^3 p_B}{(2\pi)^3 2p_2^0} s \sigma(s) f_A(p_A) f_B(p_B) \quad : \text{Production rate}$$

Assume generic **cross section** for  $\gamma\gamma \rightarrow \chi\chi$

$\gamma$  Standard Model (SM) particle

$$\sigma(s) = \frac{s^{\frac{n}{2}}}{\Lambda^{n+2}}$$

$s$  : Center-of-mass energy  
 $\Lambda$  : High energy scale

# The dawn of FIMP?

$n = 0$  **Low-scale SUSY for gravitinos**  $\sigma \propto 1/M_{\text{Pl}}^2$  or **axinos**  $\sigma \propto 1/f_a^2$

[V. Rychkov, A. Strumia, PRD 75 (2007) 075011 - A. Strumia, JHEP 06 (2010) 036]

$n = 2$  **Heavy Z'** from gauge unification  $\sigma \propto s/m_{Z'}^4$  [Y. Mambrini, K. A. Olive, J. Quevillon, B. Zaldívar- PRL 110, 241306]

**Gravity** mediated freeze-in  $\sigma \propto s/M_{\text{Pl}}^4$  [M. Garny, M. Sandora, M. S. Sloth - PRL 116 (2016) 10, 101302  
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S. Clery, Y. Mambrini, K. Olive, S. Verner – ArXiv: 2112.15214]

$n = 4$  Non-SUSY **Spin-3/2 DM** + sterile neutrino  $\sigma \propto s^2/(m_{3/2} m_R M_{\text{Pl}})^2$

[M A. G. Garcia, Y. Mambrini, K. A. Olive, S. Verner - PRD 102 (2020) 8, 083533]

$n \geq 6$  **Inspiration from modified gravity**

[K. Benakli, Y. Chen, E. Dudas, Y. Mambrini - PRD 95 (2017) 9, 095002]

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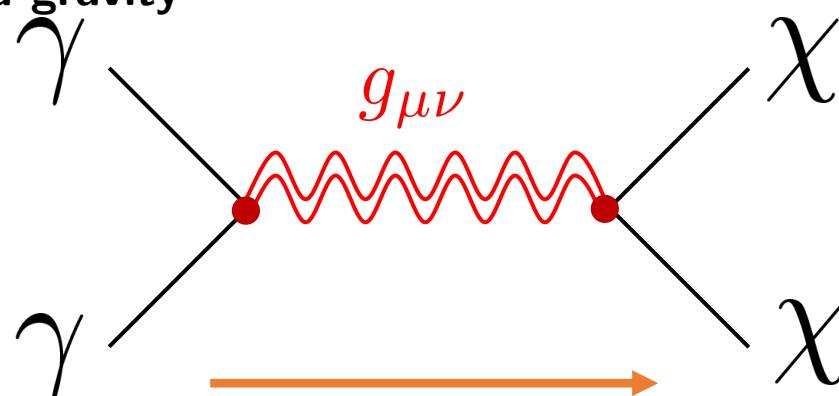
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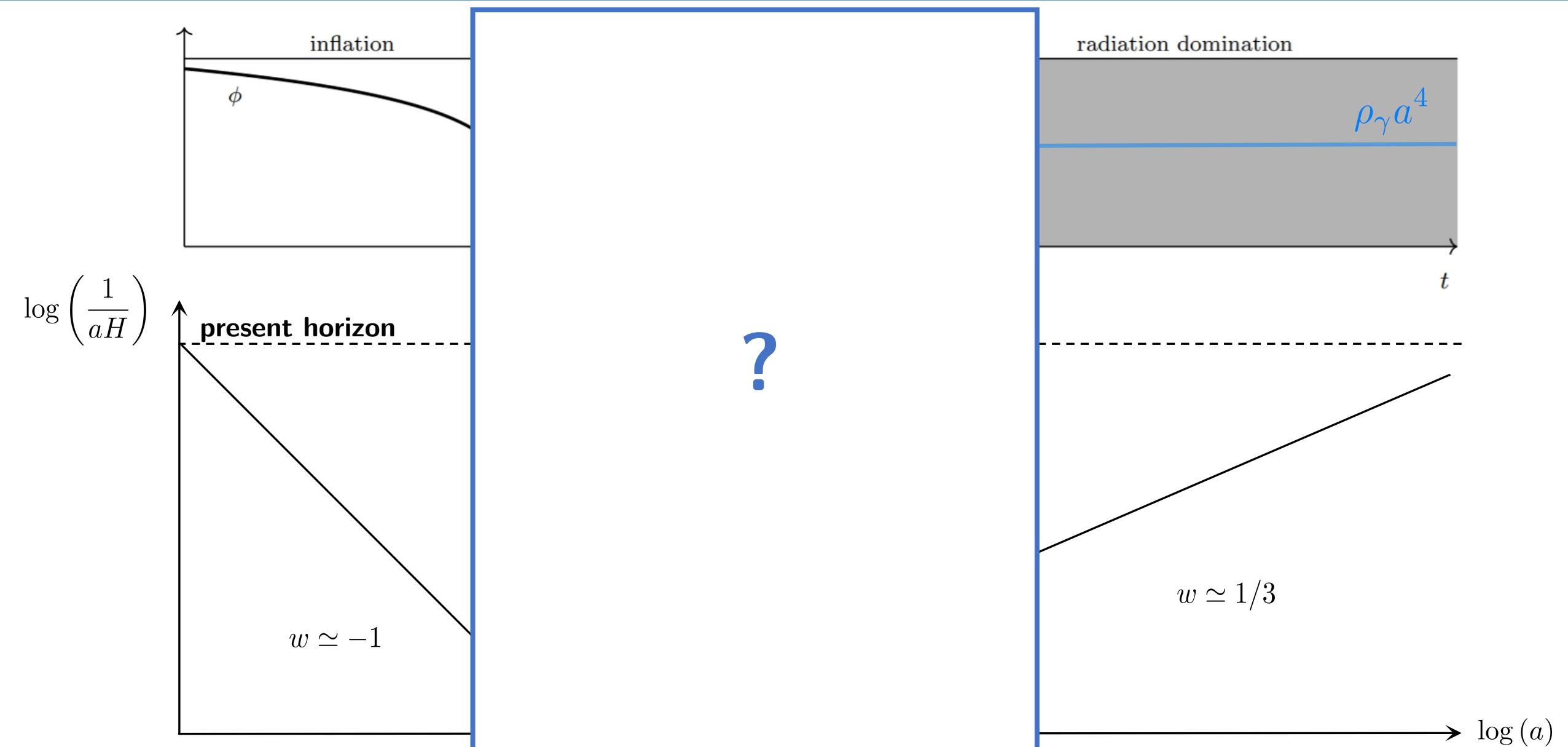
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$$R(T) \propto \frac{T^{n+6}}{\Lambda^{n+2}} \quad \rightarrow \quad \text{Production UV dominated for } n > -1$$

# What's in the UV?



# **Dark matter production from preheating**

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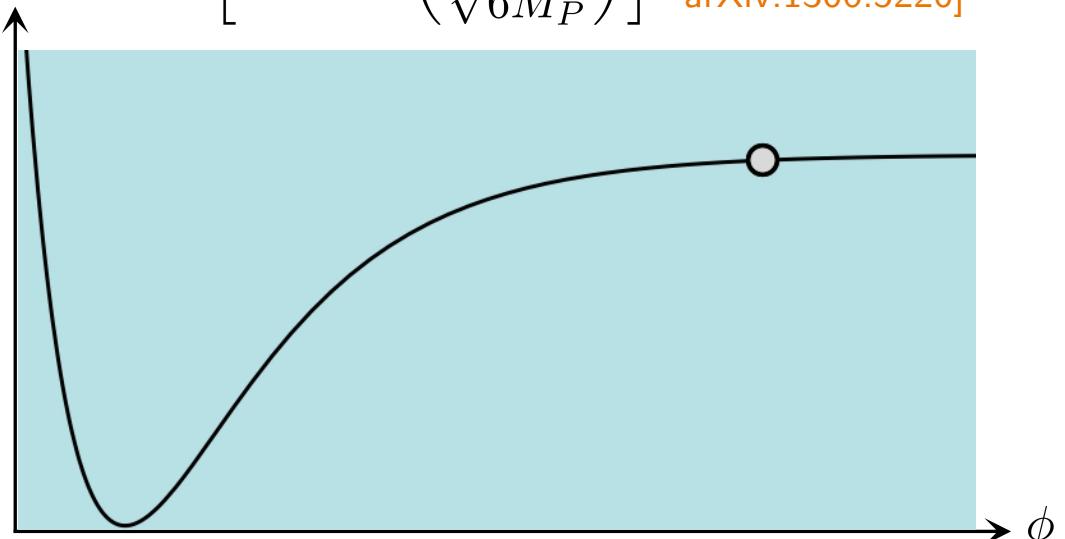
# End of inflation

For concreteness, consider

$$\mathcal{S} = \int d^4x \sqrt{-g} \left( \frac{1}{2} (\partial_\mu \phi)^2 - V(\phi) \right)$$

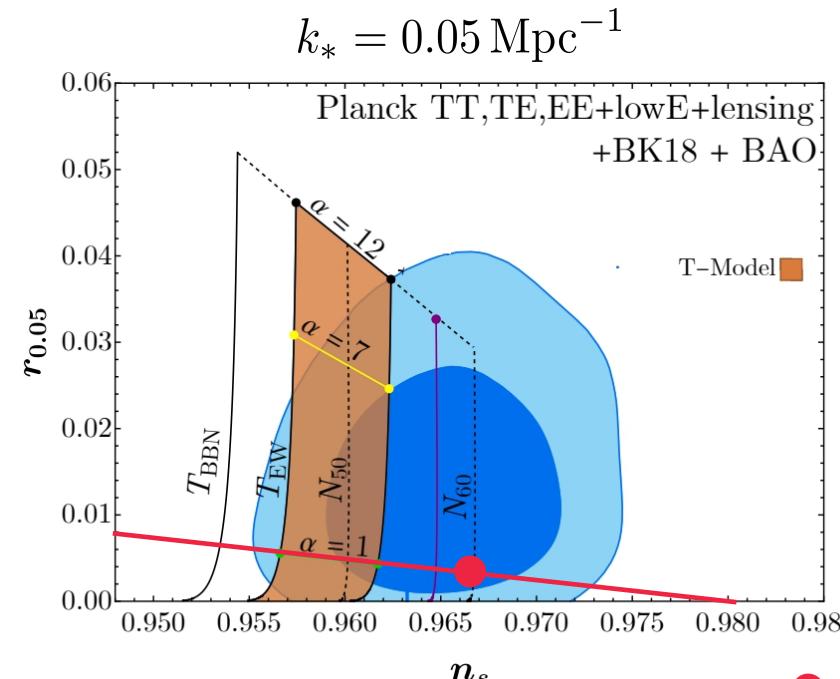
$$\ddot{\phi} + 3H\dot{\phi} + V_\phi = 0$$

$$V(\phi) = \lambda M_P^4 \left[ \sqrt{6} \tanh \left( \frac{\phi}{\sqrt{6}M_P} \right) \right]^2 \quad [\text{Kallosh \& Linde arXiv:1306.5220}]$$



$$\lambda \simeq \frac{18\pi^2 A_s(k_*)}{6N_*^2} \sim 10^{-11}$$

[J. Ellis, M. A. G. Garcia, D. V. Nanopoulos, K. A. Olive, and S. Verner - arXiv:2112.04466]



●  $N_* = 60$

$$r \simeq 16\epsilon_* \simeq \frac{12}{N_*^2}$$

$$A_s(k_*) \simeq 2.1 \times 10^{-9} \quad [\text{Planck 18'}]$$

$$n_s \simeq 1 - 6\epsilon_* + 2\eta_* \simeq 1 - \frac{2}{N_*}$$

$\phi$  inflaton

# End of inflation

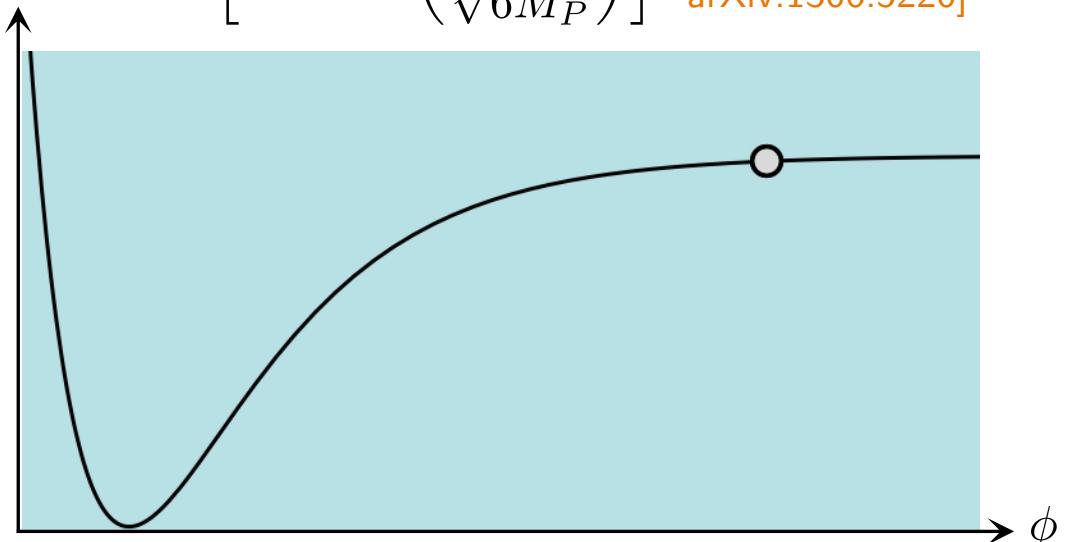
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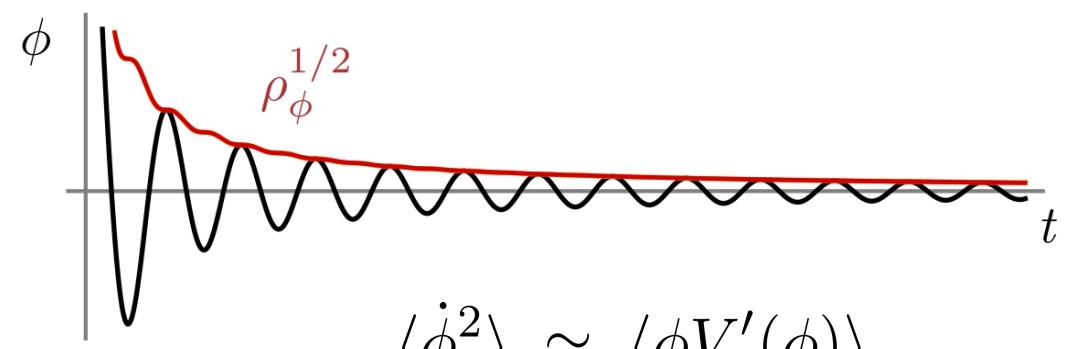
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**Close to the minimum**

$$V(\phi) \simeq \frac{1}{2} m_\phi^2 \phi^2 = \lambda \phi^2 M_P^2 \quad (\phi \ll M_P)$$



$$\langle \dot{\phi}^2 \rangle \simeq \langle \phi V'(\phi) \rangle$$

→  $\phi(t) \simeq \phi_0(t) \cos(m_\phi t) \quad \phi_0(t) \sim a(t)^{-3/2}$

$$\langle P_\phi \rangle = \frac{1}{2} \langle \dot{\phi}^2 \rangle - \langle V(\phi) \rangle \simeq 0$$

$$\langle \rho_\phi \rangle = \frac{1}{2} \langle \dot{\phi}^2 \rangle + \langle V(\phi) \rangle \simeq V(\phi_0)$$

$$\langle w_\phi \rangle \simeq 0$$

# Reheating

- In **fluid picture**: transition to radiation era via **dissipation** term  $\equiv \Gamma_\phi \rho_\phi (1 + w_\phi)$

$$T_{\text{tot}}^{\mu\nu} = T_\phi^{\mu\nu} + T_\gamma^{\mu\nu}$$

$$\nabla_\mu T_{\text{tot}}^{\mu\nu} = 0$$

$$\nabla_\mu T_\phi^{\mu\nu} = -\nabla_\mu T_\gamma^{\mu\nu}$$

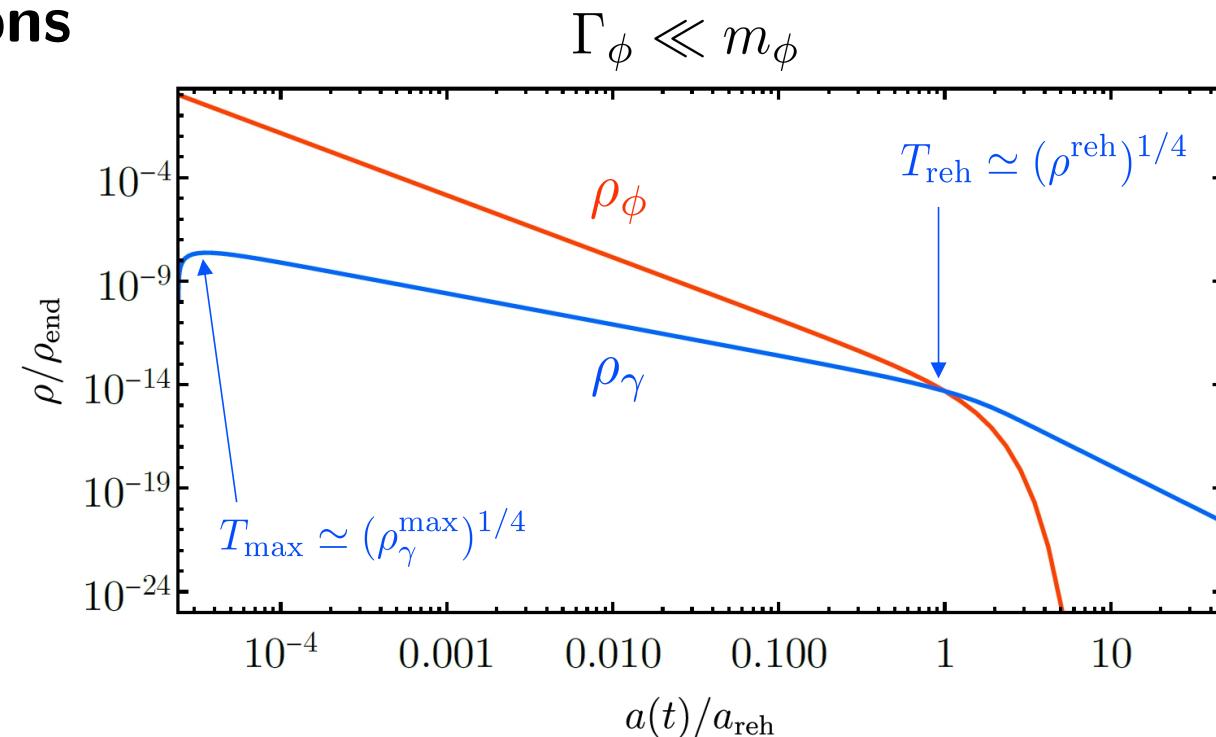
- System of **Friedmann-Boltzmann equations**

$$\dot{\rho}_\phi + 3H(1 + w_\phi)\rho_\phi = -\Gamma_\phi \rho_\phi (1 + w_\phi)$$

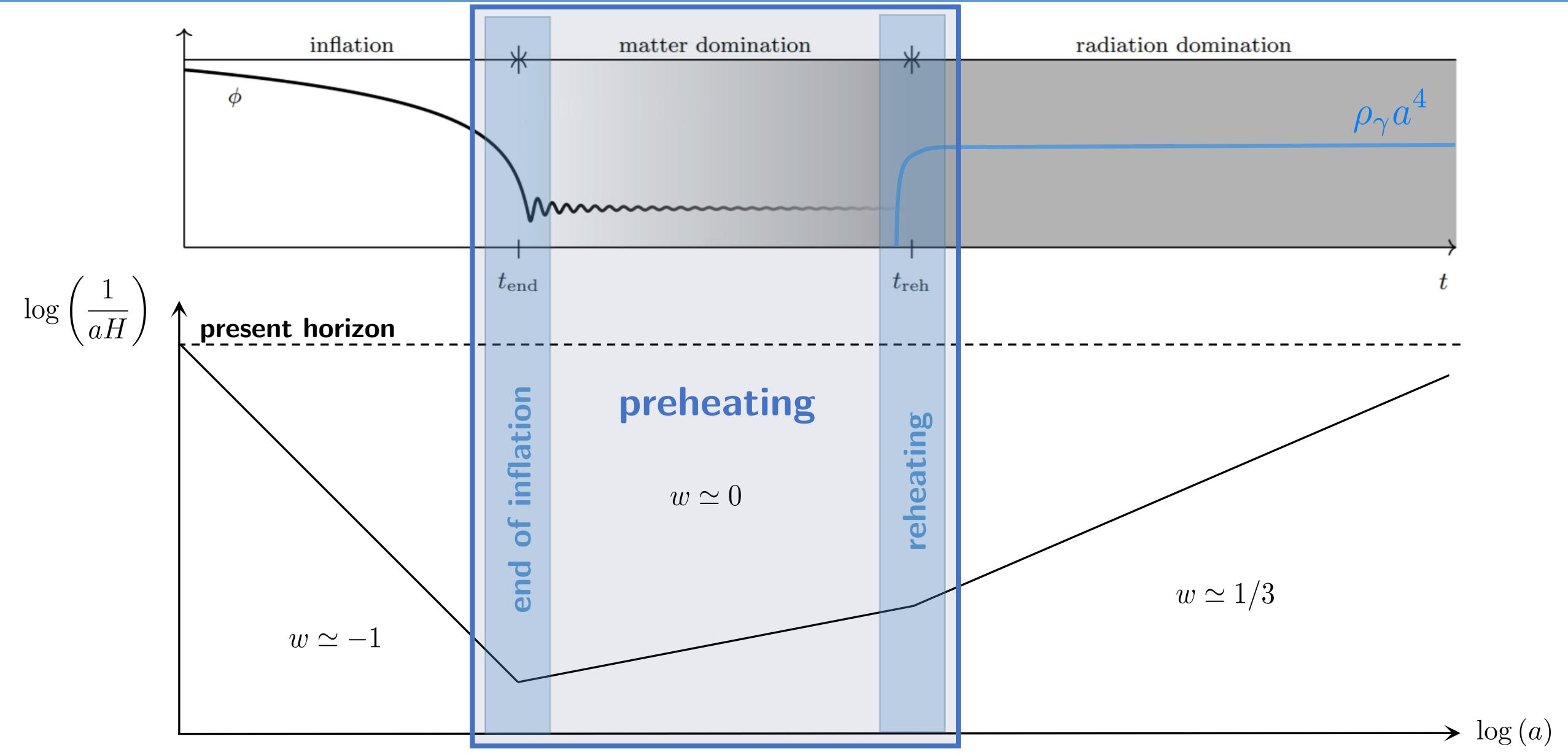
$$\dot{\rho}_\gamma + 4H\rho_\gamma = \Gamma_\phi \rho_\phi (1 + w_\phi)$$

$$H^2 = \frac{1}{3M_{\text{Pl}}}(\rho_\phi + \rho_\gamma)$$

$$\rightarrow \rho_\phi(t) \simeq \rho_{\text{end}} \left( \frac{a}{a_{\text{end}}} \right)^{-3} e^{-\Gamma_\phi(t-t_{\text{end}})}$$



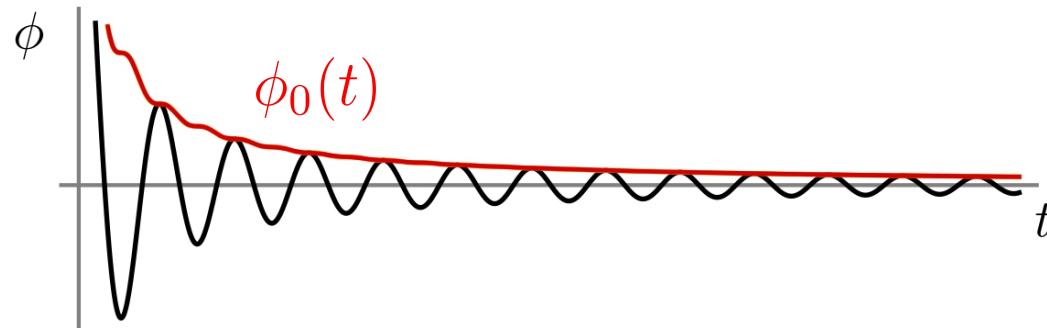
# Preheating



# Particle production during preheating

- Consider **coupling to dark matter**

$$\mathcal{S} = \int d^4x \sqrt{-g} \left( \frac{1}{2}(\partial_\mu \phi)^2 - \lambda \phi^2 M_P^2 \right. \text{inflaton}$$
$$+ \frac{1}{2}(\partial_\mu \chi)^2 - \frac{1}{2}\sigma \phi^2 \chi^2 - \frac{1}{2}m_\chi^2 \chi^2 \quad \text{scalar}$$
$$\left. + i\bar{\psi} \bar{\gamma}^\mu \nabla_\mu \psi - y \phi \bar{\psi} \psi \right) \text{fermion}$$



$$\rightarrow m_{\chi, \text{eff}}^2(t) = m_\chi^2 + \sigma \phi^2(t)$$
$$\rightarrow m_{\psi, \text{eff}}^2(t) = y^2 \phi^2(t)$$

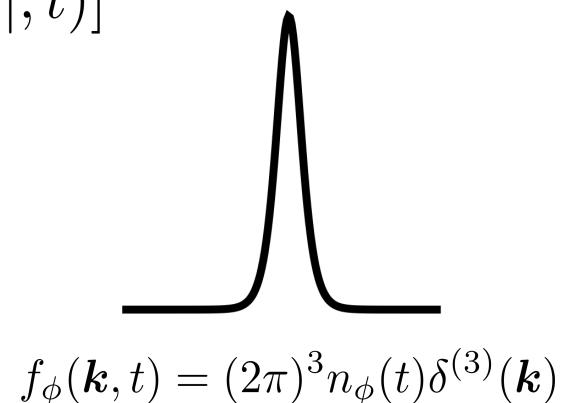
- Estimate **dark matter density produced from the inflaton**  $n_{\chi, \psi}(t) = \frac{g_{\chi, \psi}}{(2\pi)^3} \int d^3P f_{\chi, \psi}(P_0, t)$

# Preheating: perturbative approach

- **Phase space distribution** from

$$\frac{\partial f_\chi}{\partial t} - H|\mathbf{P}| \frac{\partial f_\chi}{\partial |\mathbf{P}|} = \mathcal{C}[f_\chi(|\mathbf{P}|, t)]$$

$$\begin{aligned} \mathcal{C}[f_\chi(|\mathbf{P}|, t)] &= \frac{1}{P^0} \int \frac{d^3 k}{(2\pi)^3 n_\phi} \frac{d^3 P'}{(2\pi)^3 2P'^0} (2\pi)^4 \delta^{(4)}(k - P - P') |\mathcal{M}|_{\phi\phi \rightarrow \chi\chi}^2 \\ &\quad \times \left[ f_\phi(k)(1 + f_\chi(P))(1 + f_\chi(P')) - f_\chi(P)f_\chi(P')(1 + f_\phi(k)) \right] \end{aligned}$$



- **Collision terms** given by:

$$\frac{\partial f_\psi}{\partial t} - H|\mathbf{P}| \frac{\partial f_\psi}{\partial |\mathbf{P}|} = \frac{8\pi^2}{\beta^2 m_\phi^3} \rho_\phi \Gamma_{\phi \rightarrow \bar{\psi}\psi} \delta\left(|\mathbf{P}| - \frac{\beta(t)}{2} m_\phi\right) (1 - 2f_\psi(|\mathbf{P}|)) \quad \text{Pauli blocking}$$

$$\frac{\partial f_\chi}{\partial t} - H|\mathbf{P}| \frac{\partial f_\chi}{\partial |\mathbf{P}|} = \frac{\pi^2}{\beta^2 m_\phi^3} \rho_\phi \Gamma_{\phi\phi \rightarrow \chi\chi} \delta(|\mathbf{P}| - m_\phi \beta(t)) (1 + 2f_\chi(|\mathbf{P}|)) \quad \text{Bose enhancement}$$

$$\beta(t) \equiv \sqrt{1 - \frac{m_{\text{eff}}^2(t)}{m_\phi^2}} : \text{kinematic blocking}$$

# Scalar preheating: perturbative approach

- Treat **inflaton** as **coherent oscillating condensate**

$$\phi(t) \simeq \phi_0(t) \sum_{n=-\infty}^{\infty} \mathcal{P}_n e^{-in\omega_\phi t} \quad E_n = n\omega_\phi \rightarrow \Gamma_{\phi\phi \rightarrow \chi\chi} = \frac{1}{8\pi(1+w_\phi)\rho_\phi} \sum_{n=1}^{\infty} E_n \beta_n |\mathcal{M}_n|^2$$

$$\langle \chi(p_1) \chi(p_2) | i \int d^4x \mathcal{L}_{\text{int}} | 0 \rangle = i(2\pi)^4 \sum_{n=-\infty}^{\infty} \mathcal{M}_n \delta^{(4)}(p_n - p_1 - p_2) \quad \beta_n \equiv \sqrt{1 - \frac{m_{\text{eff}}^2(t)}{E_n^2}}$$

[M. A. G. Garcia, K. Kaneta, Y. Mambrini, K. A. Olive, S. Verner, arXiv:2109.13280]

- For **quadratic potential**  $\omega_\phi = m_\phi$  and equivalent of treating inflaton as collection of **particles** in **Minkowski space-time!**

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

$$|\mathcal{M}|_{\phi\phi \rightarrow \chi\chi}^2 = \left| \phi \begin{array}{c} \diagup \\ \diagdown \end{array} h_{\mu\nu} \begin{array}{c} \diagdown \\ \diagup \end{array} \chi + \phi \begin{array}{c} \diagup \\ \diagdown \end{array} \sigma \begin{array}{c} \diagdown \\ \diagup \end{array} \chi \right|^2 = \left( \left| \phi \begin{array}{c} \diagup \\ \diagdown \end{array} h_{\mu\nu} \begin{array}{c} \diagdown \\ \diagup \end{array} \chi \right| \left| \phi \begin{array}{c} \diagup \\ \diagdown \end{array} \sigma \begin{array}{c} \diagdown \\ \diagup \end{array} \chi \right| \right)^2$$

$$\mathcal{L}_{\text{int}} = -\frac{1}{M_P} h_{\mu\nu} \left( T_\phi^{\mu\nu} + T_\chi^{\mu\nu} \right) - \frac{\sigma}{2} \phi^2 \chi^2 \quad \rightarrow$$

$$\Gamma_{\phi\phi \rightarrow \chi\chi} = \frac{1}{32\pi} \frac{\rho_\phi^2(t)}{m_\phi^3} \left[ \sigma \bigcirc \lambda \left( 1 + \frac{m_\chi^2}{2m_\phi^2} \right) \right]^2 \beta_2$$

# Preheating: perturbative approach

- **Approximate solution for**  $\beta \simeq 1$ ,  $t_{\text{end}} < t < t_{\text{reh}}$

$$f_\chi(|\mathbf{P}|, t) \simeq \frac{\pi \sigma^2 \rho_\phi^2(t)}{8m_\phi^7 H(t)} \left( \frac{m_\phi}{|\mathbf{P}|} \right)^{9/2} \theta \left( |\mathbf{P}| - \frac{a_{\text{end}}}{a(t)} m_\phi \right) \theta(m_\phi - |\mathbf{P}|) ,$$

$$f_\psi(|\mathbf{P}|, t) \simeq \frac{2\pi y^2 \rho_\phi(t)}{m_\phi^3 H(t)} \left( \frac{m_\phi}{2|\mathbf{P}|} \right)^{3/2} \theta \left( |\mathbf{P}| - \frac{a_{\text{end}}}{a(t)} \frac{m_\phi}{2} \right) \theta(m_\phi/2 - |\mathbf{P}|) ,$$

- **In terms of comoving momentum**

$$q \equiv \frac{P}{T_\star} \left( \frac{a}{a_0} \right)$$

$$T_\star \equiv m_\phi \left( \frac{a_{\text{end}}}{a_0} \right)$$

$$f_\chi(q, t) \sim q^{-9/2} \theta(q - 1) \theta \left( \frac{a}{a_{\text{end}}} - q \right)$$

$$f_\psi(q, t) \sim q^{-3/2} \theta \left( q - \frac{1}{2} \right) \theta \left( \frac{a}{a_{\text{end}}} - 2q \right)$$

$$n_\chi \left( \frac{a}{a_{\text{end}}} \right)^3 = \frac{m_\phi^3}{2\pi^2} \int dq q^2 f_\chi(q, t) \quad : \text{time independent when DM production stops}$$

# Scalar preheating: the field picture

- Treat dark matter as quantum field in curved space-time

Equation of motion:

$$\left( \frac{d^2}{dt^2} - \frac{\nabla^2}{a^2} + 3H\frac{d}{dt} + m_\chi^2 + \sigma\phi^2 \right) \chi = 0$$

- Quantize the (rescaled) field  $X(\tau, \mathbf{x}) \equiv a\chi = \int \frac{d^3\mathbf{p}}{(2\pi)^{3/2}} e^{-i\mathbf{p}\cdot\mathbf{x}} [X_p(\tau)\hat{a}_\mathbf{p} + X_p^*(\tau)\hat{a}_{-\mathbf{p}}^\dagger]$
- Harmonic oscillator with time-dependent frequency Gravity!

$$X_p'' + \omega_p^2 X_p = 0 \quad \omega_p^2(t) = p^2 + a^2(t)\hat{m}_{\text{eff}}^2(t) \quad \hat{m}_{\text{eff}}^2(t) = m_\chi^2 + \sigma\phi^2 + \frac{R}{6}$$

- Distribution function from occupation number

$$n_p = \frac{1}{2\omega_p} |\omega_p X_p - iX'_p|^2 \quad \rightarrow \quad f_\chi(P, t) = n_{aP}(t)$$

$$\begin{aligned} ' &\equiv \frac{d}{d\tau} \\ dt &= a d\tau \end{aligned}$$

[L. Kofman, A. Linde, A. Starobinsky - arXiv:9704452 – arXiv:9405187]

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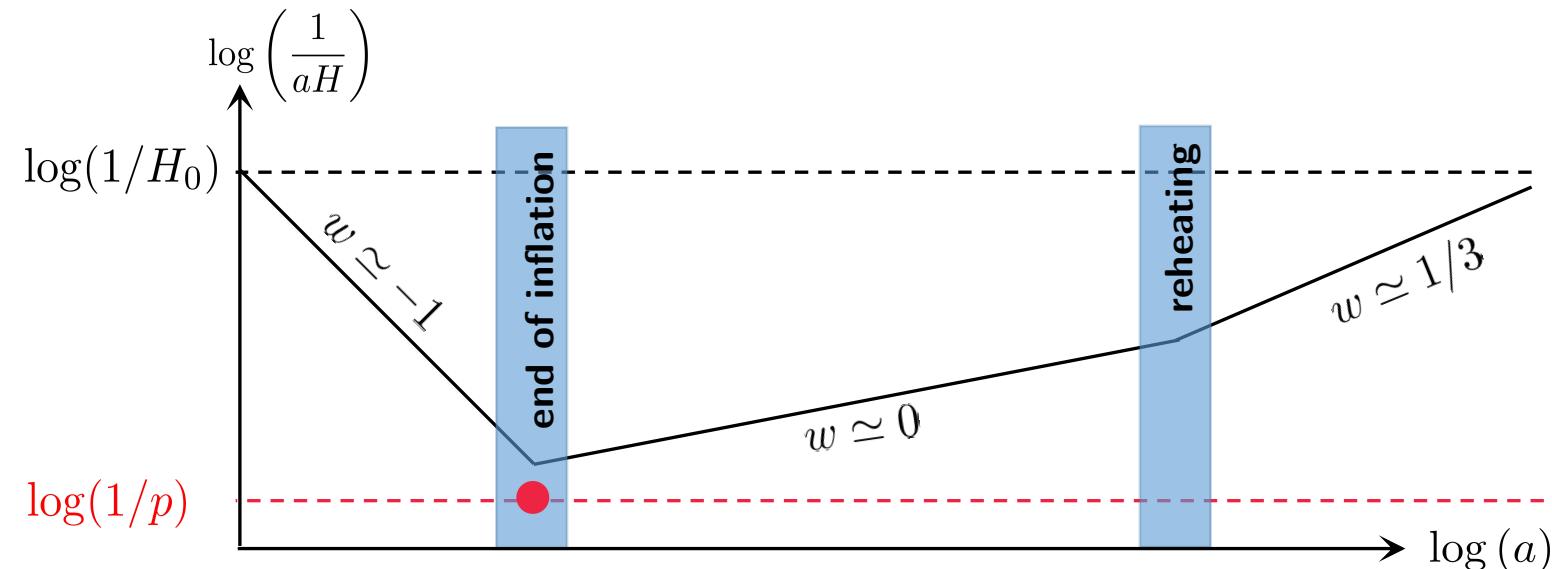
- Set **initial condition for mode functions** in **Bunch-Davies vacuum**

$$X_p(\tau_0) = \frac{1}{\sqrt{2\omega_p}}$$

$$X'_p(\tau_0) = -\frac{i\omega_p}{\sqrt{2\omega_p}}$$

$$\omega_p^2(t_{\text{end}}) = p^2 + a_{\text{end}}^2 (m_\chi^2 + \sigma \phi^2 - H_{\text{end}}^2)$$

- For small physical scales **modes always inside horizon**  $\omega_p^2 > 0$  ●  $\tau_0 = \tau_{\text{end}}$



# Scalar preheating: the field picture

- Set **initial condition for mode functions** in **Bunch-Davies vacuum**

$$X_p(\tau_0) = \frac{1}{\sqrt{2\omega_p}} \quad X'_p(\tau_0) = -\frac{i\omega_p}{\sqrt{2\omega_p}}$$

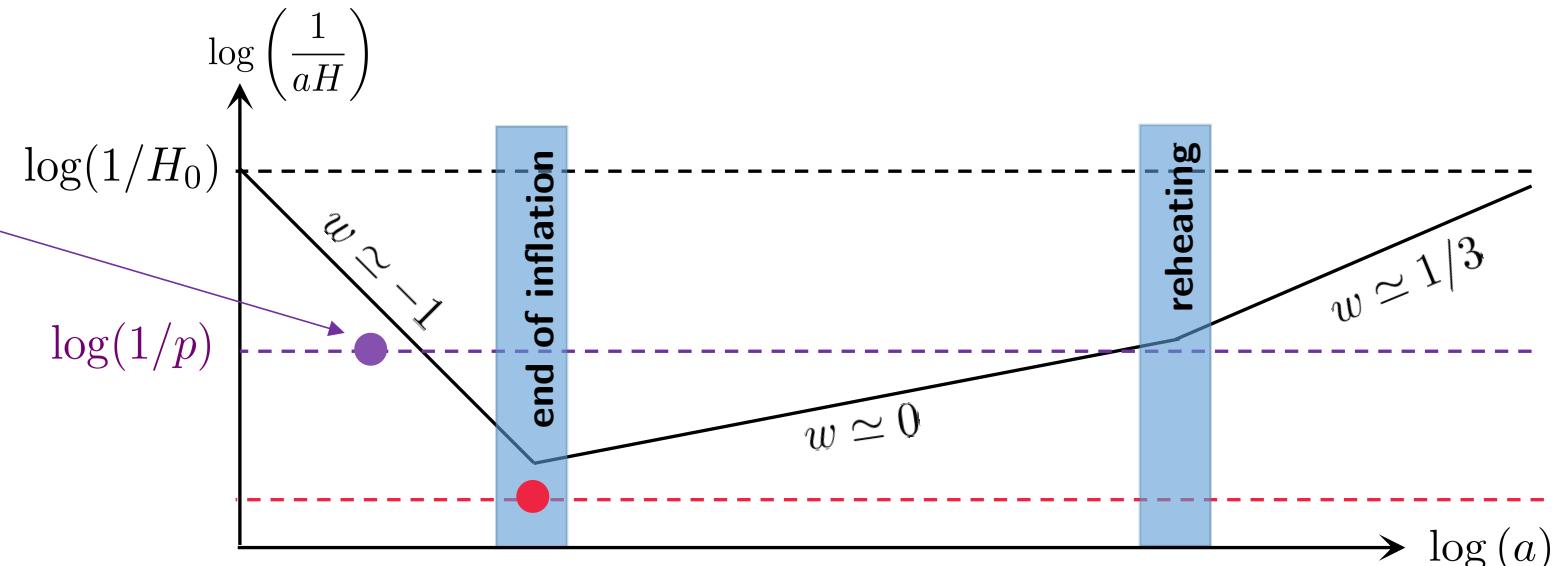
$$\omega_p^2(t_{\text{end}}) = p^2 + a_{\text{end}}^2 (m_\chi^2 + \sigma\phi^2 - H_{\text{end}}^2)$$

- For small physical scales**    **modes always inside horizon**     $\omega_p^2 > 0$     ●  $\tau_0 = \tau_{\text{end}}$
- For**  $m_\chi^2 + \sigma\phi^2 < H_{\text{end}}^2$     **modes** with  $p^2 < a_{\text{end}}^2 (H_{\text{end}}^2 - m_\chi^2 - \sigma\phi^2)$      $\omega_p^2(t_{\text{end}}) < 0$

- $\tau_0 < \tau_{\text{end}}$

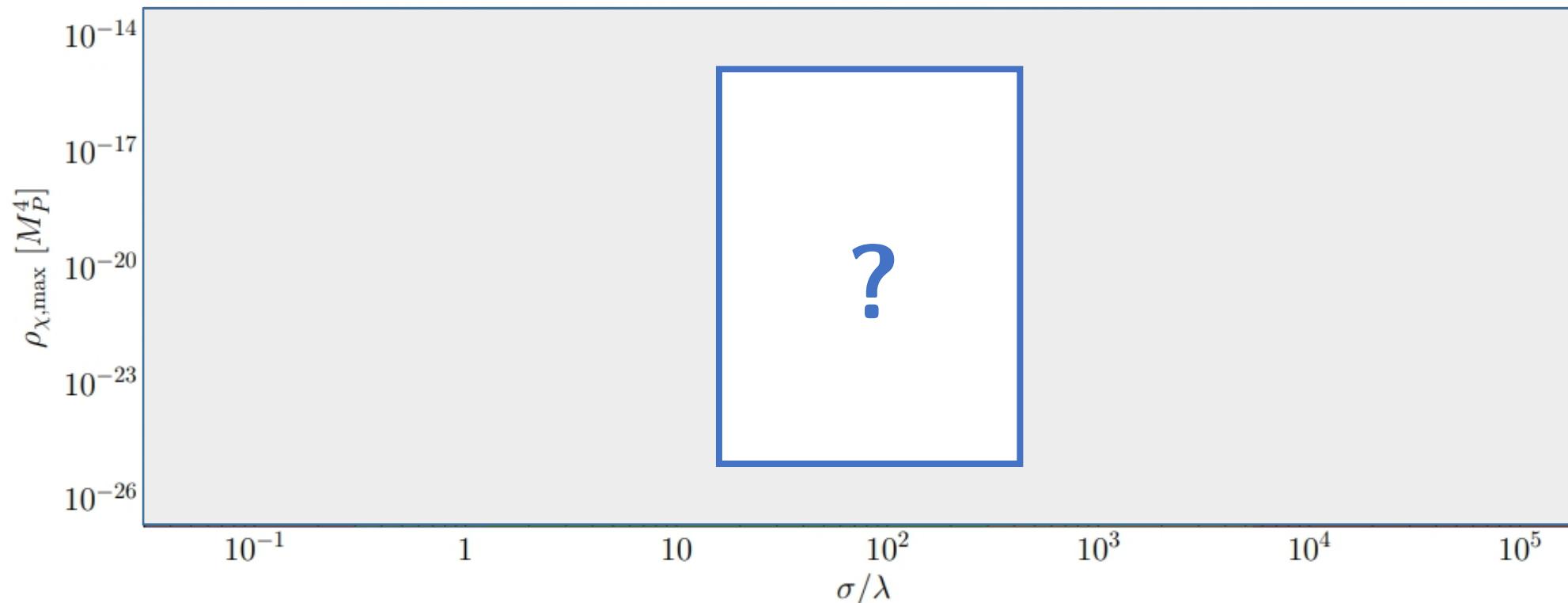
$$p^2 \gg a(\tau_0)^2 H(\tau_0)^2$$

→ **Particle production!**  
**Red-tilt of the spectrum!**



# Scalar preheating

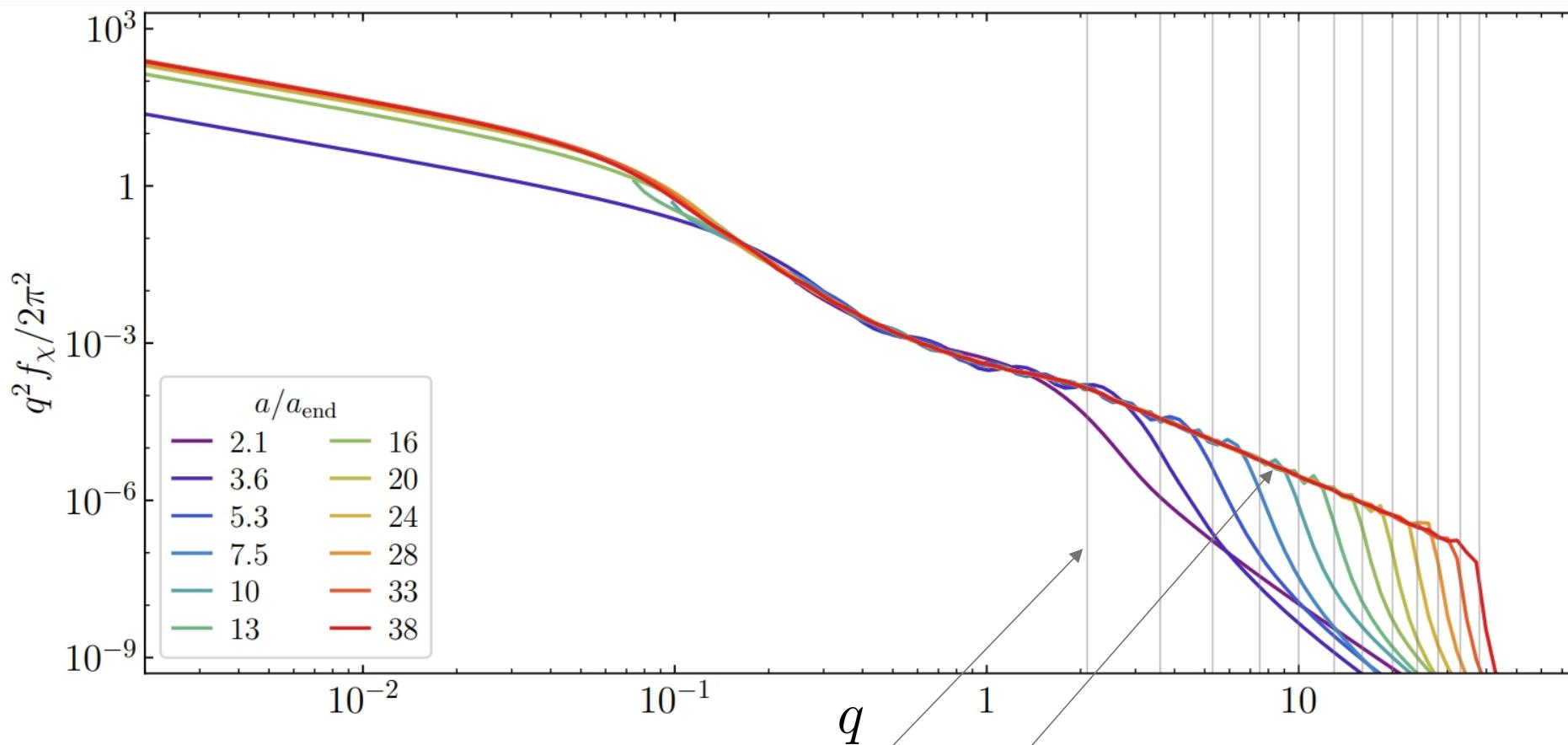
- Goal: identify the **various phases** of this plot
- Goal: check **validity** of perturbative approach



- Focus on the regime of small bare mass

# Scalar production: gravitational production $\sigma/\lambda \ll 1$

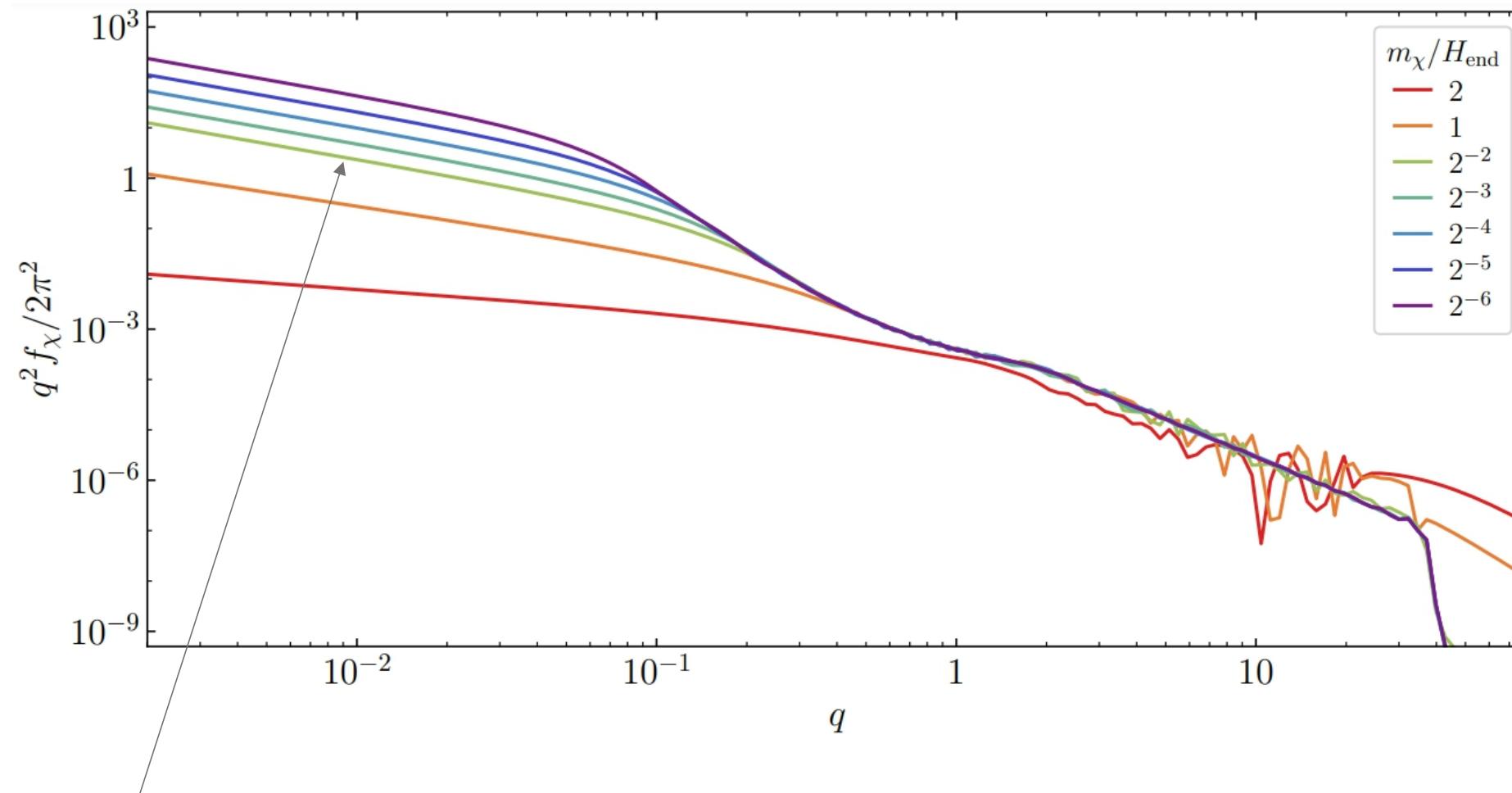
$$m_\chi \simeq 10^{-2} H_{\text{end}}$$



- Cutoff (vertical lines) grows with time  $q_{\text{cutoff}} \equiv a/a_{\text{end}}$
- Recover perturbative regime at large  $q$   $f_\chi \sim q^{-9/2}$

# Scalar production: gravitational production $\sigma/\lambda \ll 1$

$$a/a_{\text{end}} = 38$$



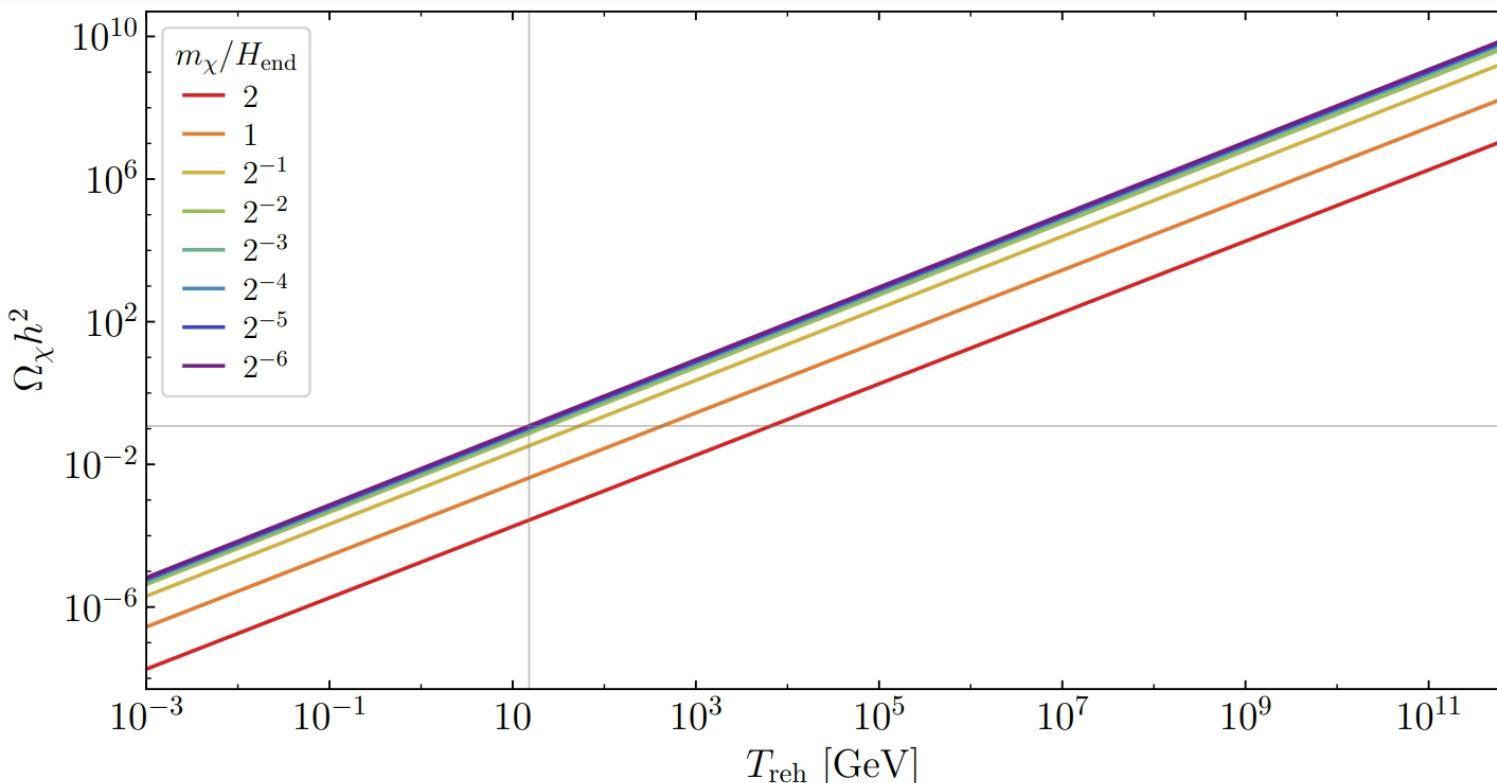
→ Increases as DM decreases

# Scalar production: gravitational production $\sigma/\lambda \ll 1$

→ Take IR cutoff as present horizon

$$q_{\text{IR}} = q_0 = \left(\frac{90}{\pi^2}\right)^{1/4} \left(\frac{11}{43}\right)^{1/3} g_{\text{reh}}^{1/12} \left(\frac{H_{\text{end}} M_P}{m_\phi^2}\right)^{1/2} \frac{H_0}{T_0} \left(\frac{a_{\text{reh}}}{a_{\text{end}}}\right)^{1/4}$$

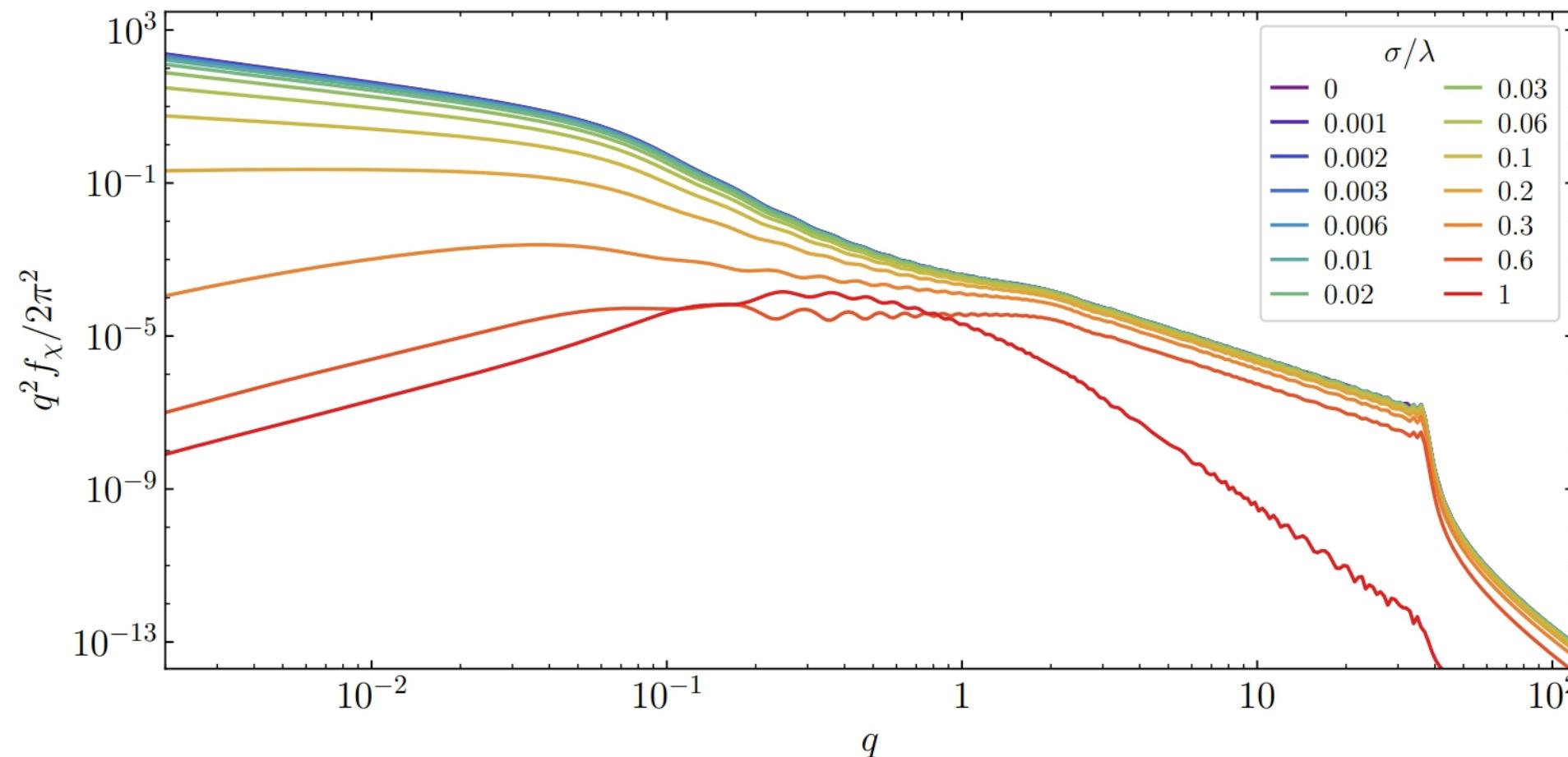
$$\Leftrightarrow p_0 = a_0 H_0$$



**For small DM mass**  
**For  $T_{\text{reh}} > 15$  GeV**  
**Overclose the universe!**

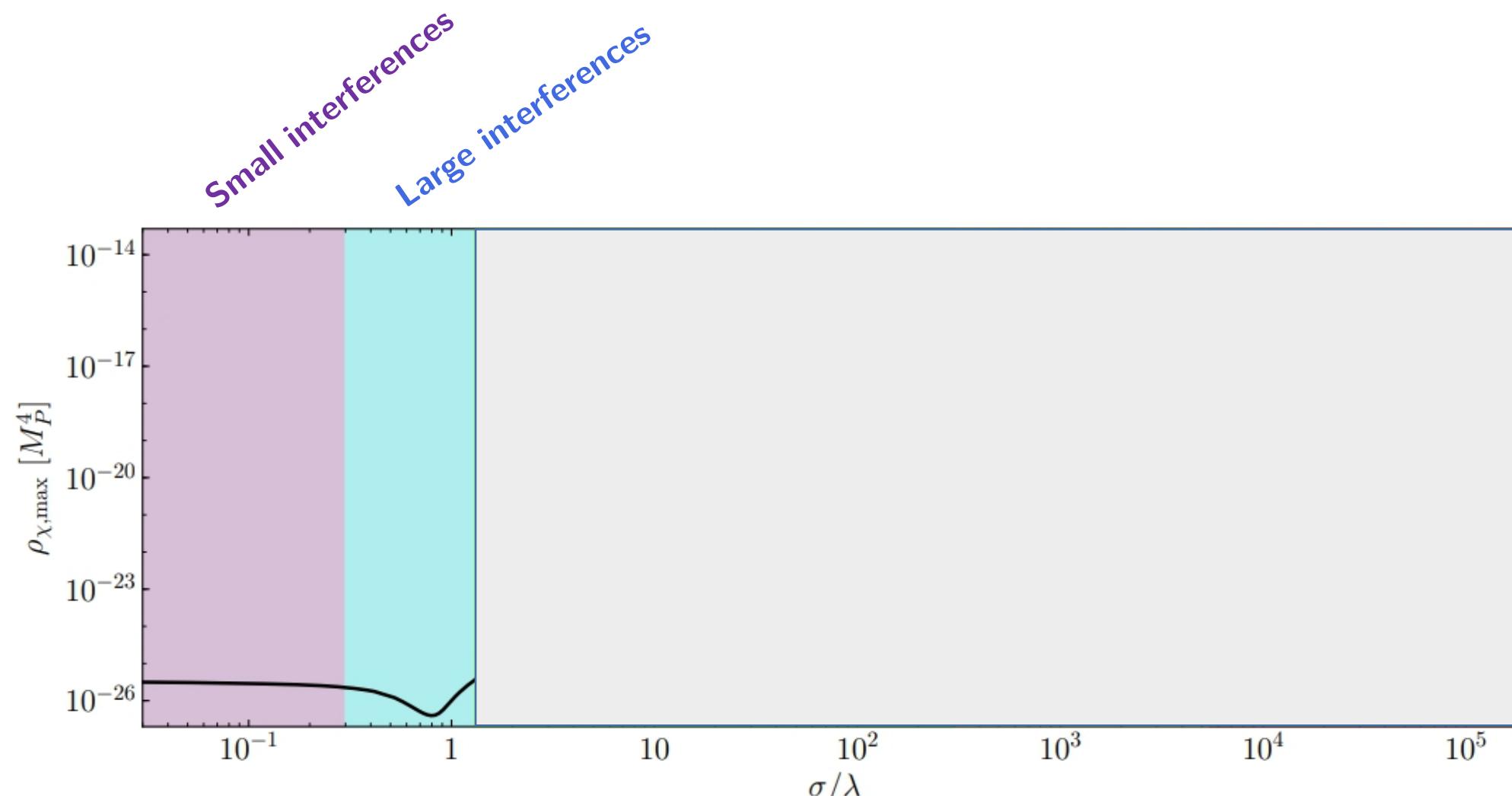
# Scalar production: gravitational interferences $0 < \sigma/\lambda < 1$

$$a/a_{\text{end}} = 38$$



→ Effective mass behaves a **IR modes regulator and suppresses density!**

# Scalar production: interferences



Pure gravitational production: not represented here

# Scalar production: resonance effects

- **Changing variables**

$$x_p \equiv a^{1/2} X_p \quad z \equiv m_\phi t + \frac{\pi}{2}$$

$$A_p = \frac{p^2}{m_\phi^2 a^2} + 2\hat{q}$$

("energy<sup>2</sup>")

$$\hat{q} = \frac{\sigma \phi_0^2}{4m_\phi^2}$$

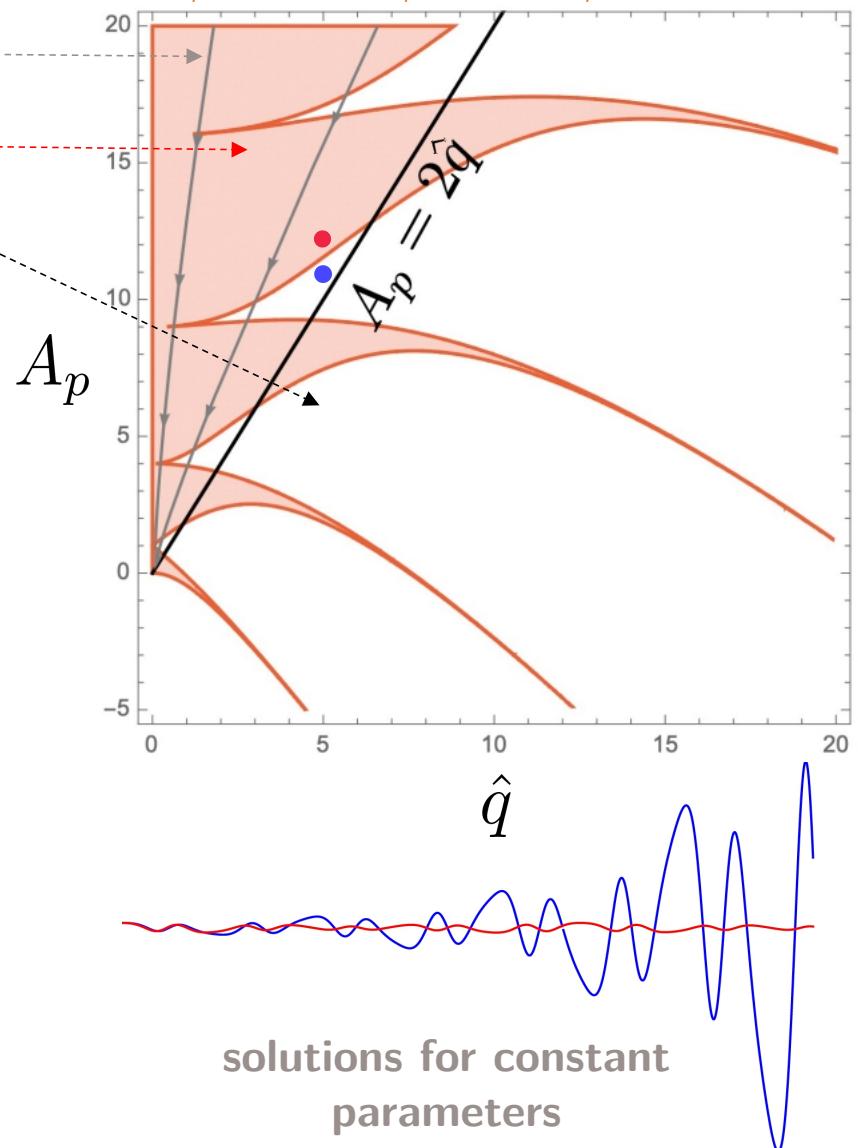
("mass<sup>2</sup>")

[M. A. G. Garcia, K. Kaneta, Y. Mambrini, K. A. Olive, S. Verner, arXiv:2109.13280]

mode evolution

**stable**

**unstable**



- **Equation for mode functions**  $\Leftrightarrow$  Mathieu equation

$$\ddot{x}_p + (A_p - 2\hat{q} \cos(2z))x_p = 0$$

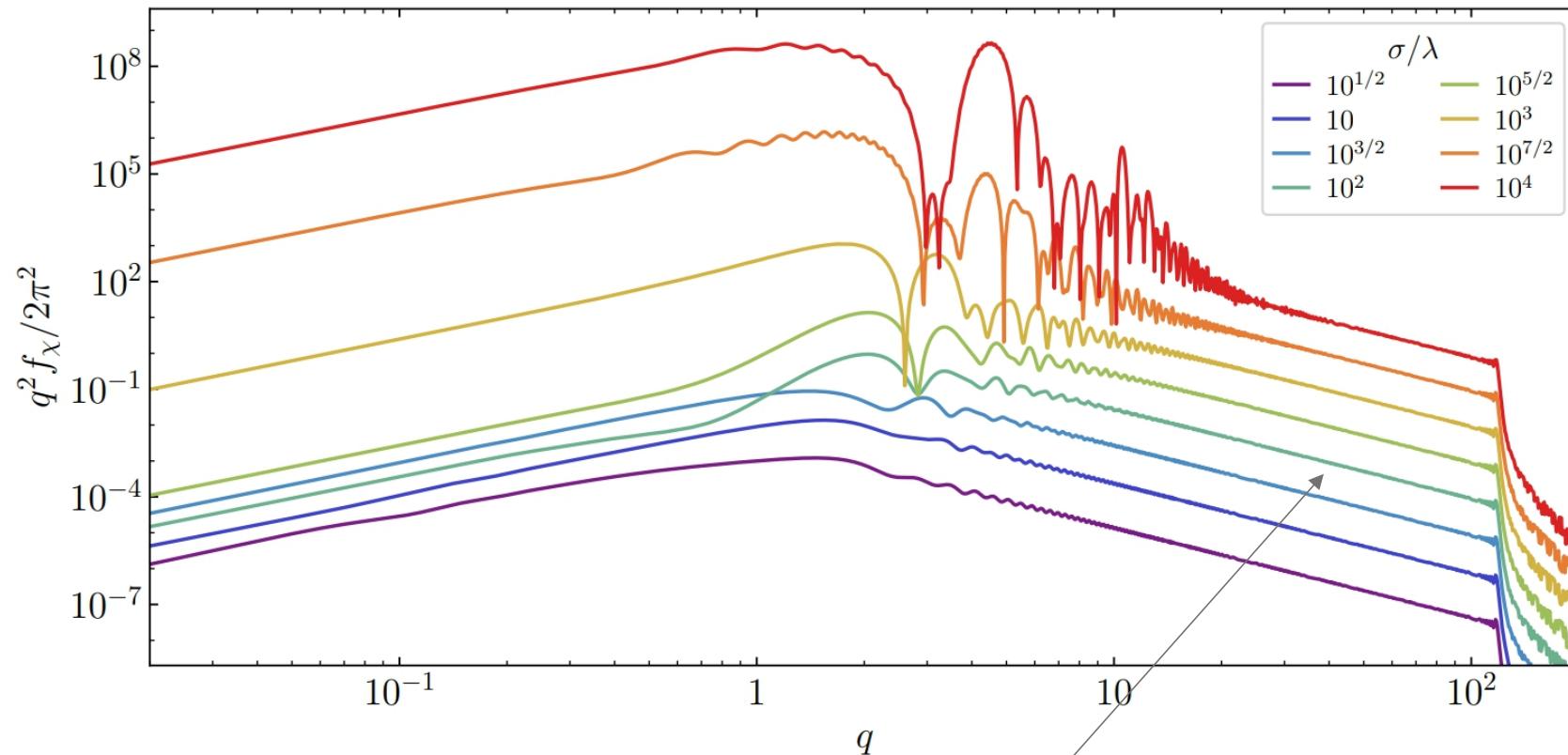
- For **large** momentum, i.e.  $A_p \gg \hat{q}$  **narrow resonance**  
 $A_p \sim 1 \pm \hat{q}$   $\rightarrow$  **stable**

- Close to  $A_p \sim 2\hat{q}$ , **efficient** particle production  
as **crossing** several **instability bands over**  $\Delta t \sim \hat{q}/H$

[L. Kofman, A. Linde, A. Starobinsky - arXiv:9704452]

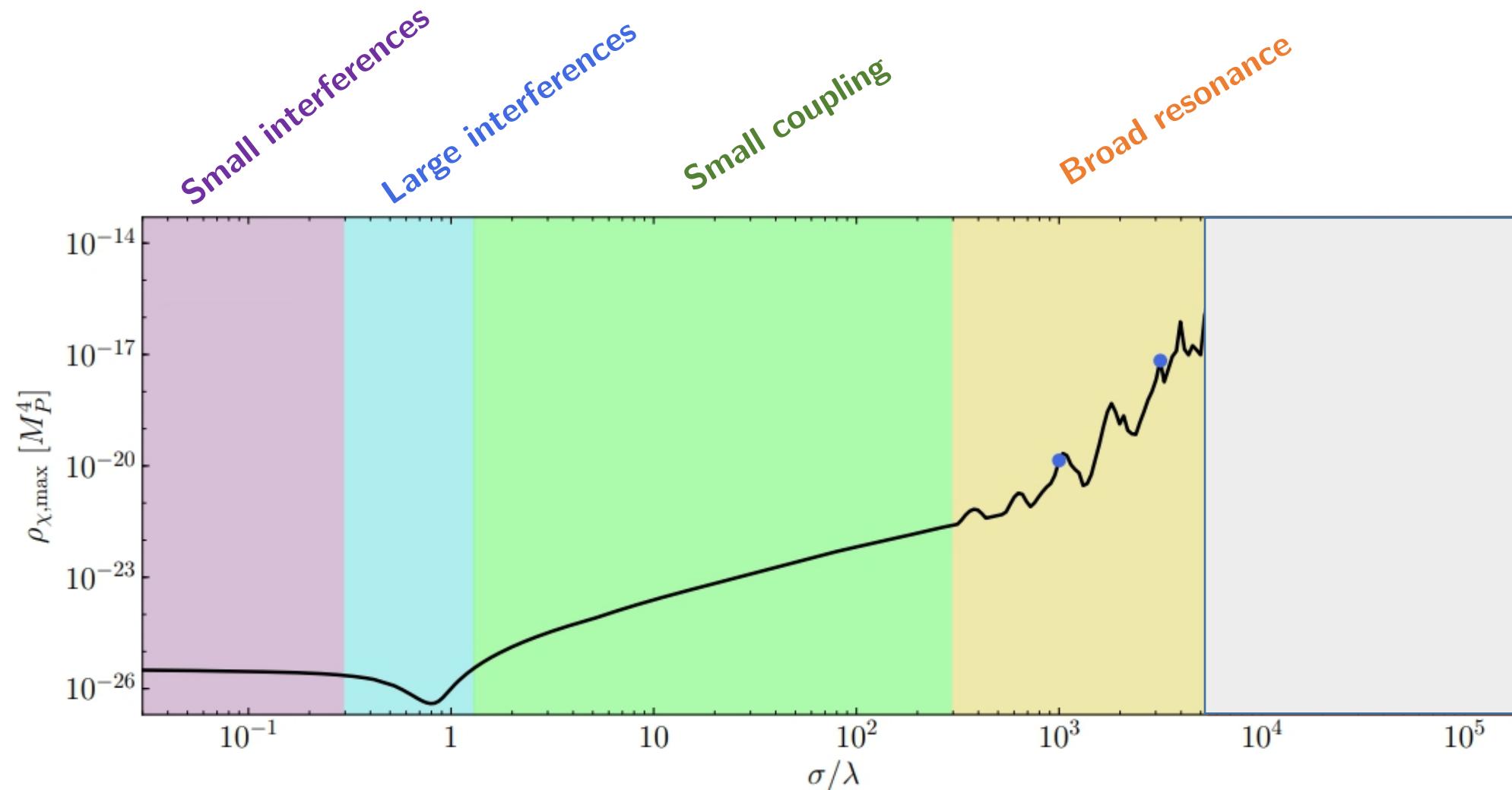
# Scalar production: $1 < \sigma/\lambda < 10^4$

$$a/a_{\text{end}} = 120$$



- Effective mass regulates IR modes
- Broad resonances at large coupling!
- Recover perturbative regime at large  $q$      $f_\chi \sim q^{-9/2}$

# Scalar production: small coupling and broad resonance



# Scalar production: backreaction

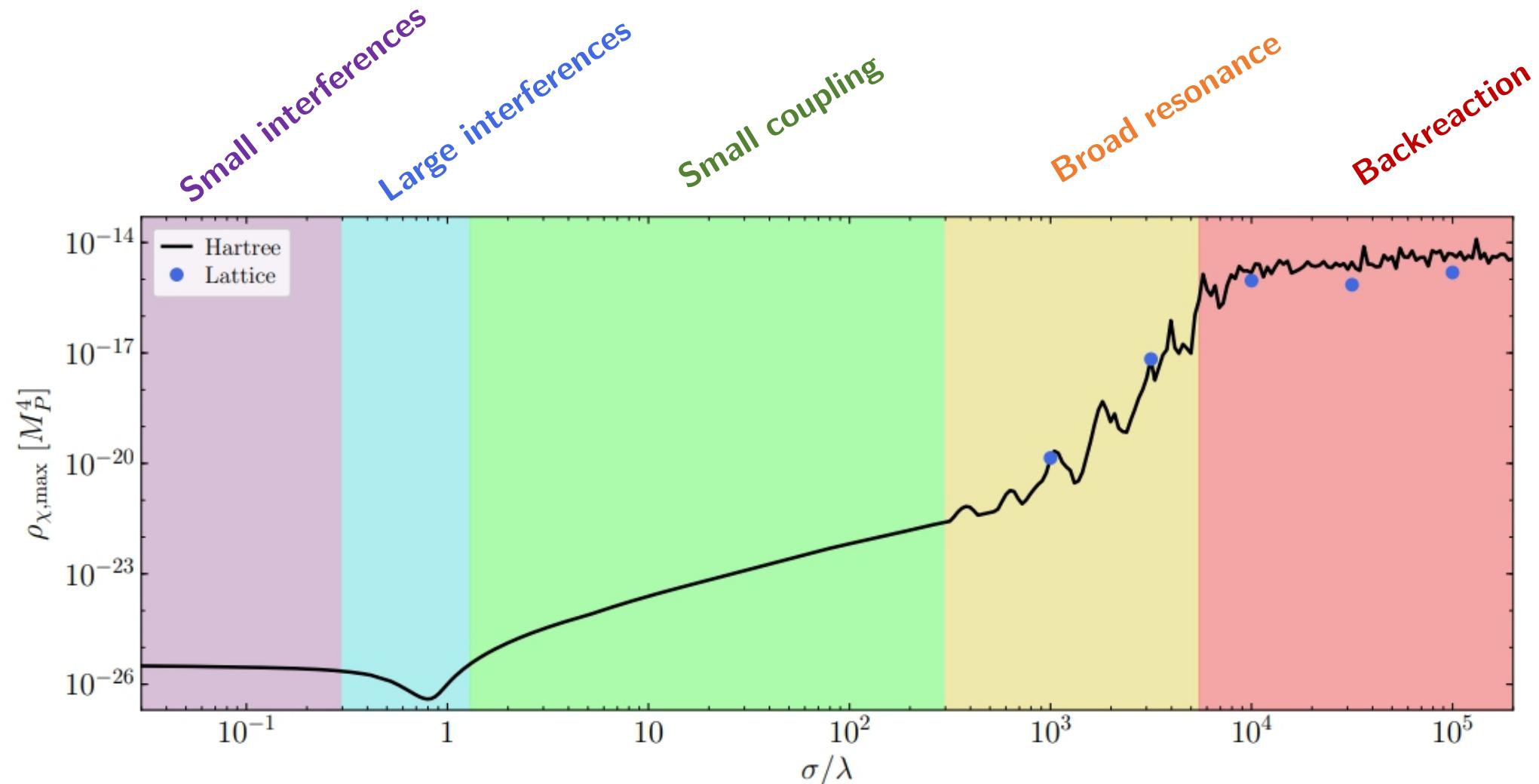
Backreaction important at **large coupling**  $\sigma/\lambda > 10^4$

- **Hartree approximation**  $\ddot{\phi} + 3H\dot{\phi} + V_\phi + \sigma\phi^2\langle\chi^2\rangle = 0$ 
  - To simulate **energy transferred** back to inflaton
  - Ok but neglects **rescattering** and **disruption** of the **condensate**
- **Lattice simulations** in real space
  - Occupation numbers are **large**, **classical approach** justified
  - Cannot be **used for smaller couplings**
  - Does not **account** for **metric perturbations**

**CosmoLattice**  
*A modern code for lattice simulations of scalar and gauge field dynamics in an expanding universe*

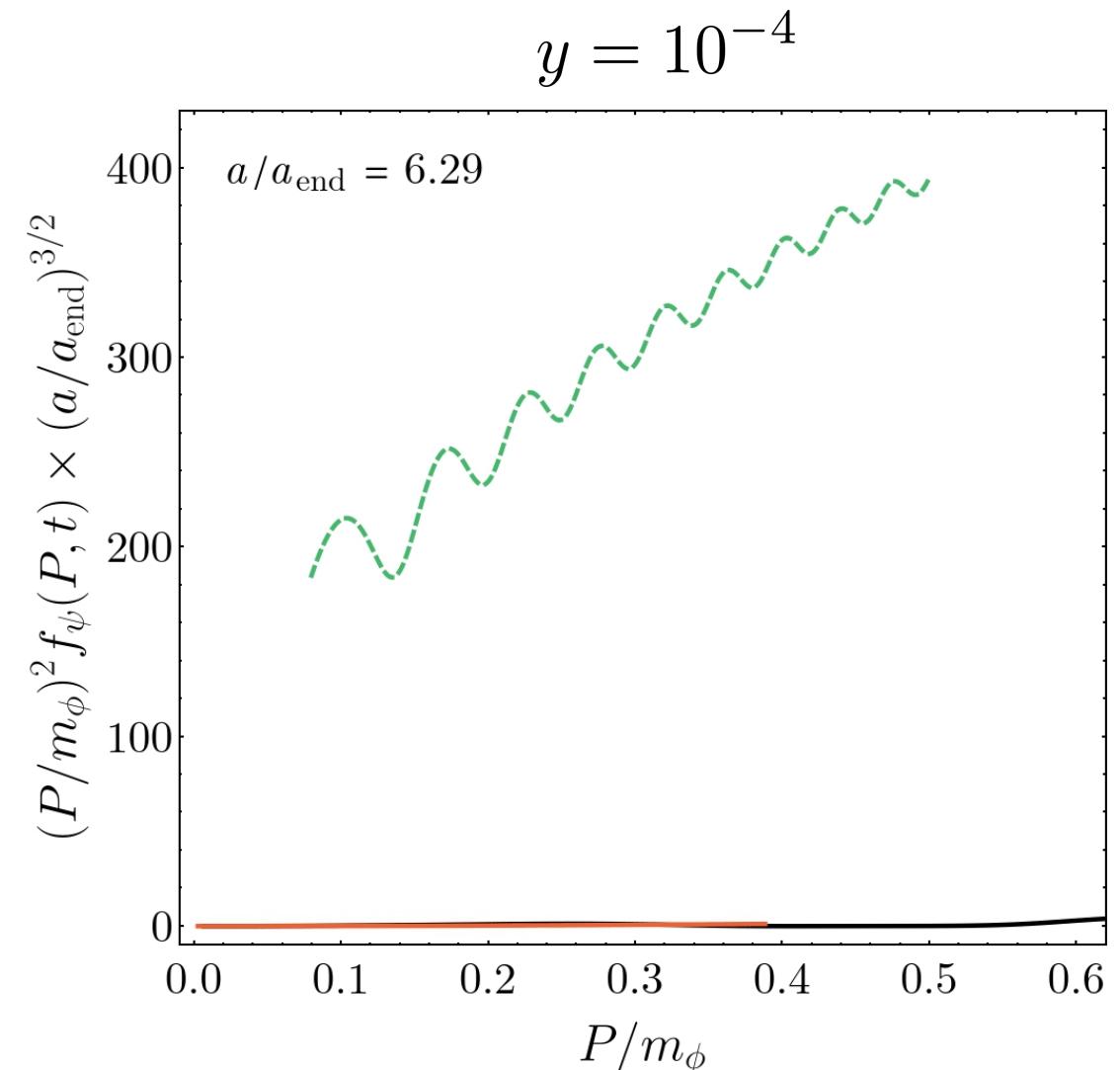
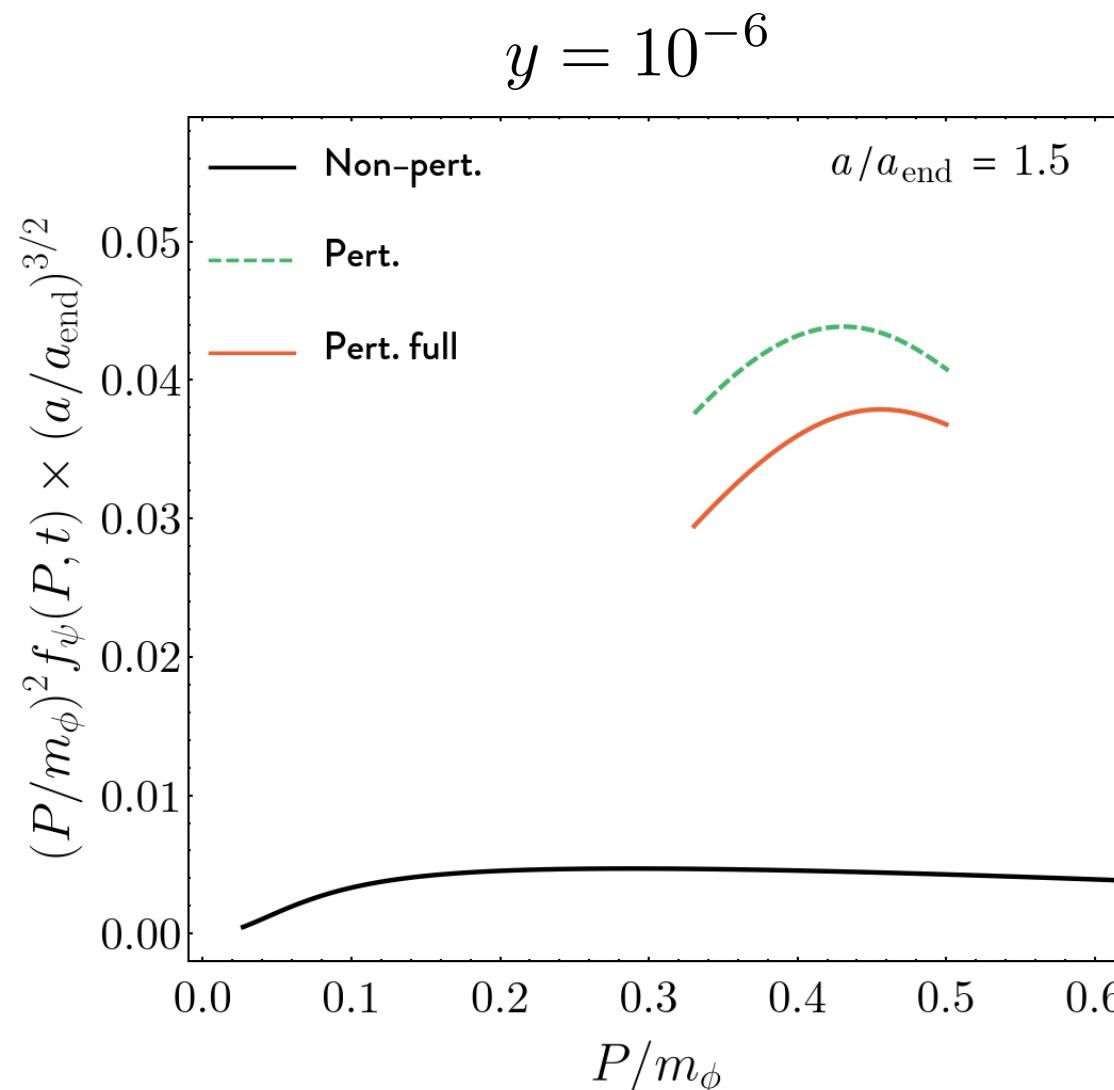
[D. G. Figueroa, A. Florio, F. Torrenti, W. Valkenburg, arXiv:2102.01031]

# Scalar production: backreaction

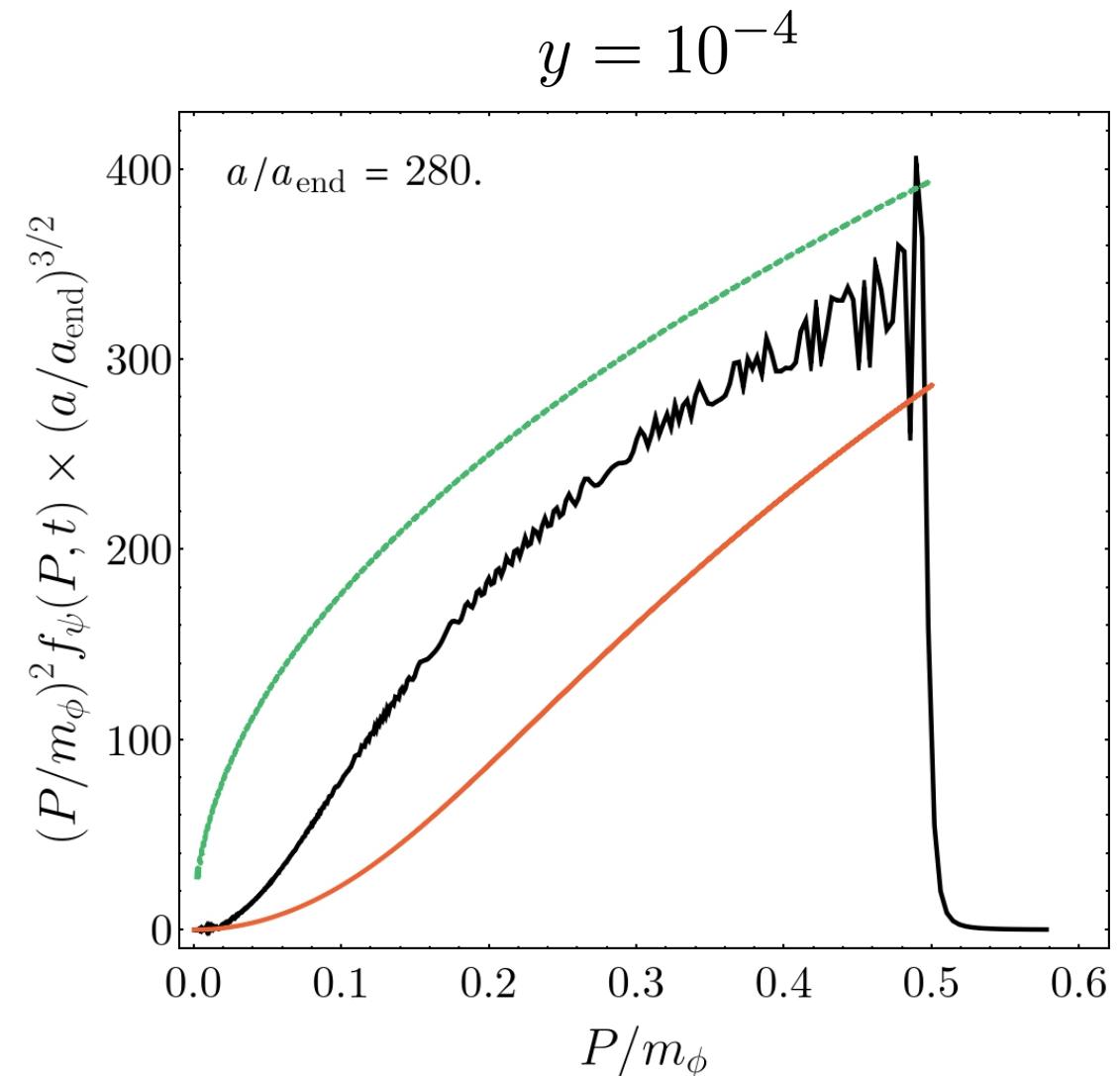
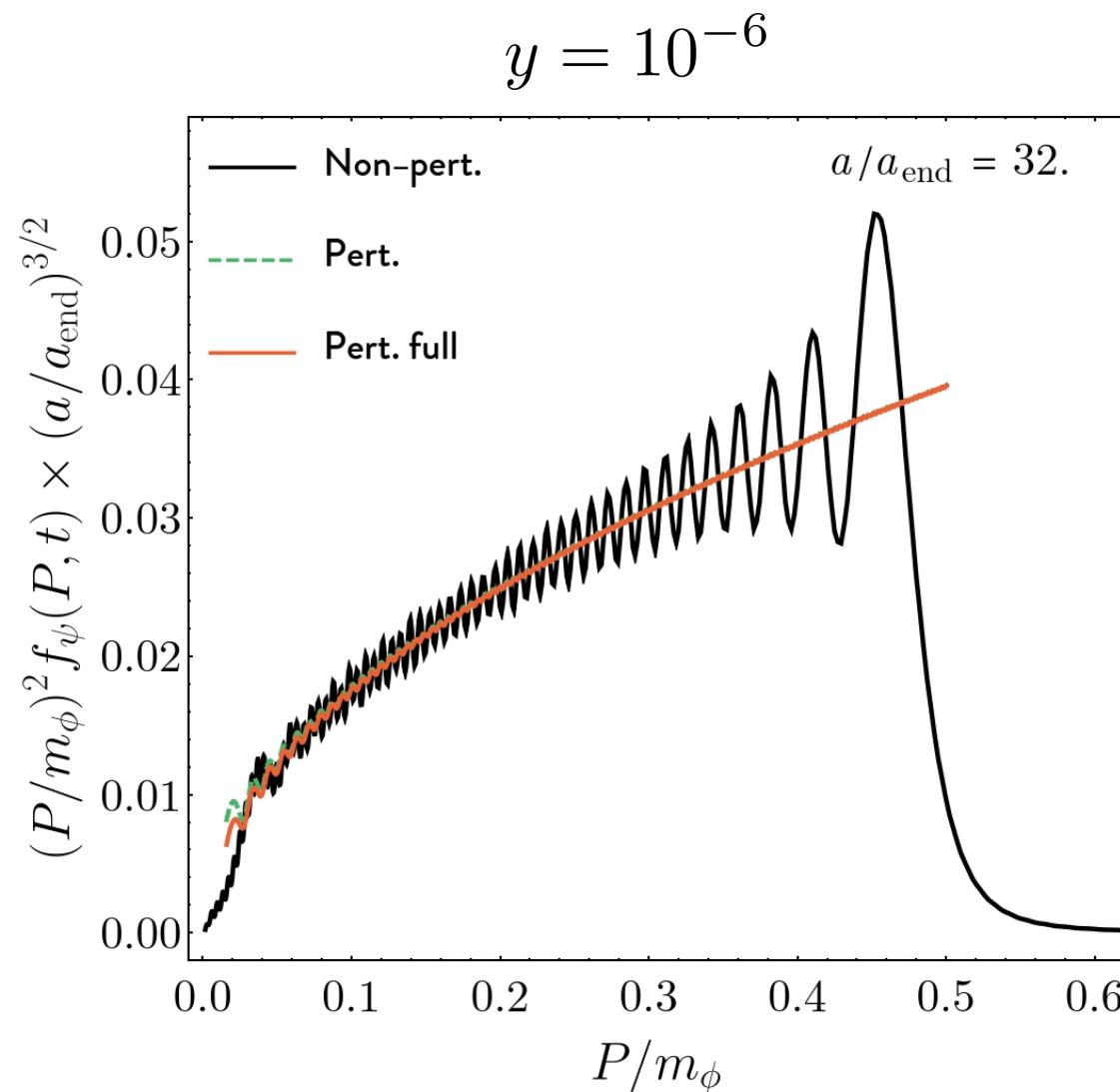


→ How good is the perturbative approach?

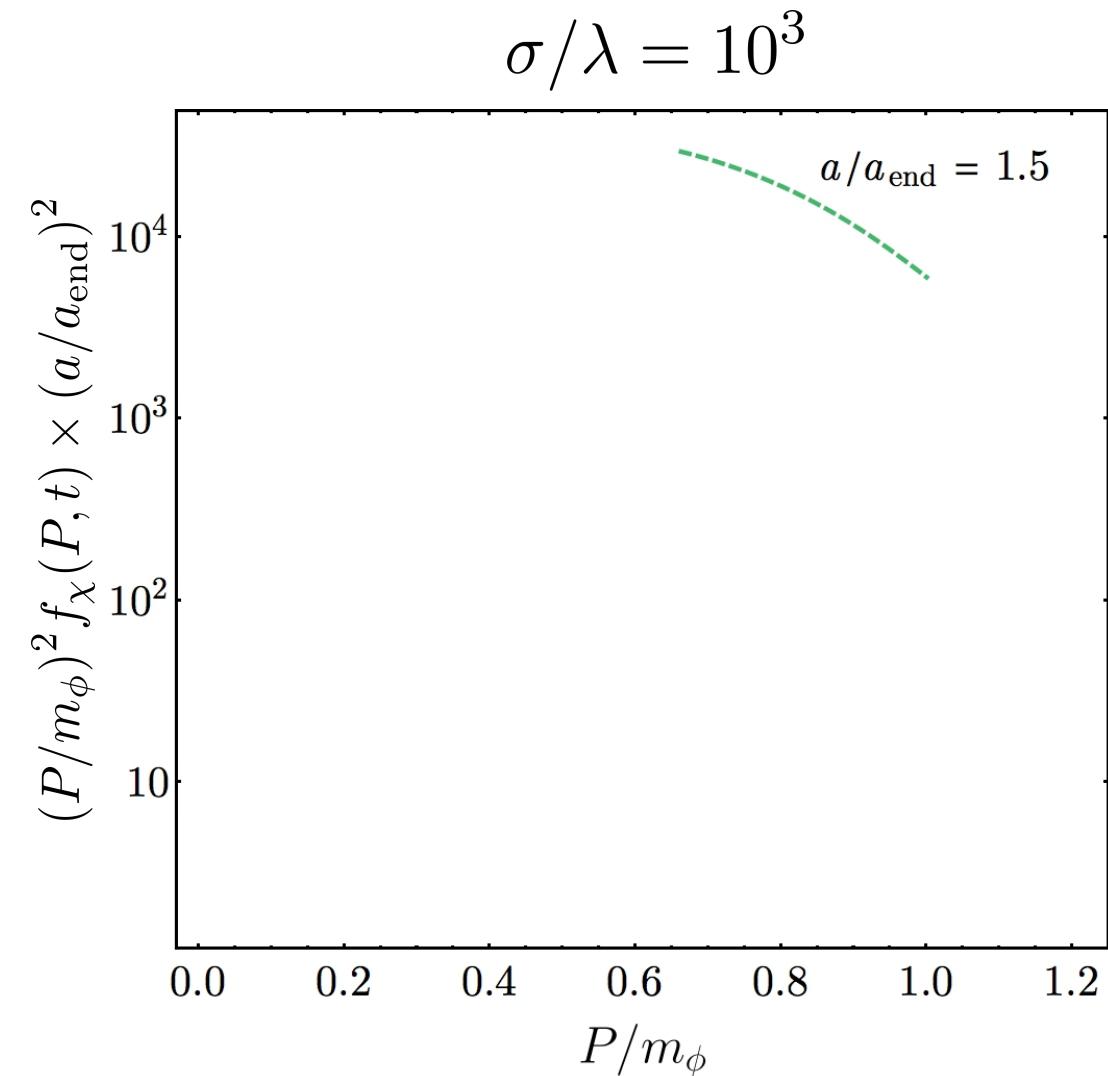
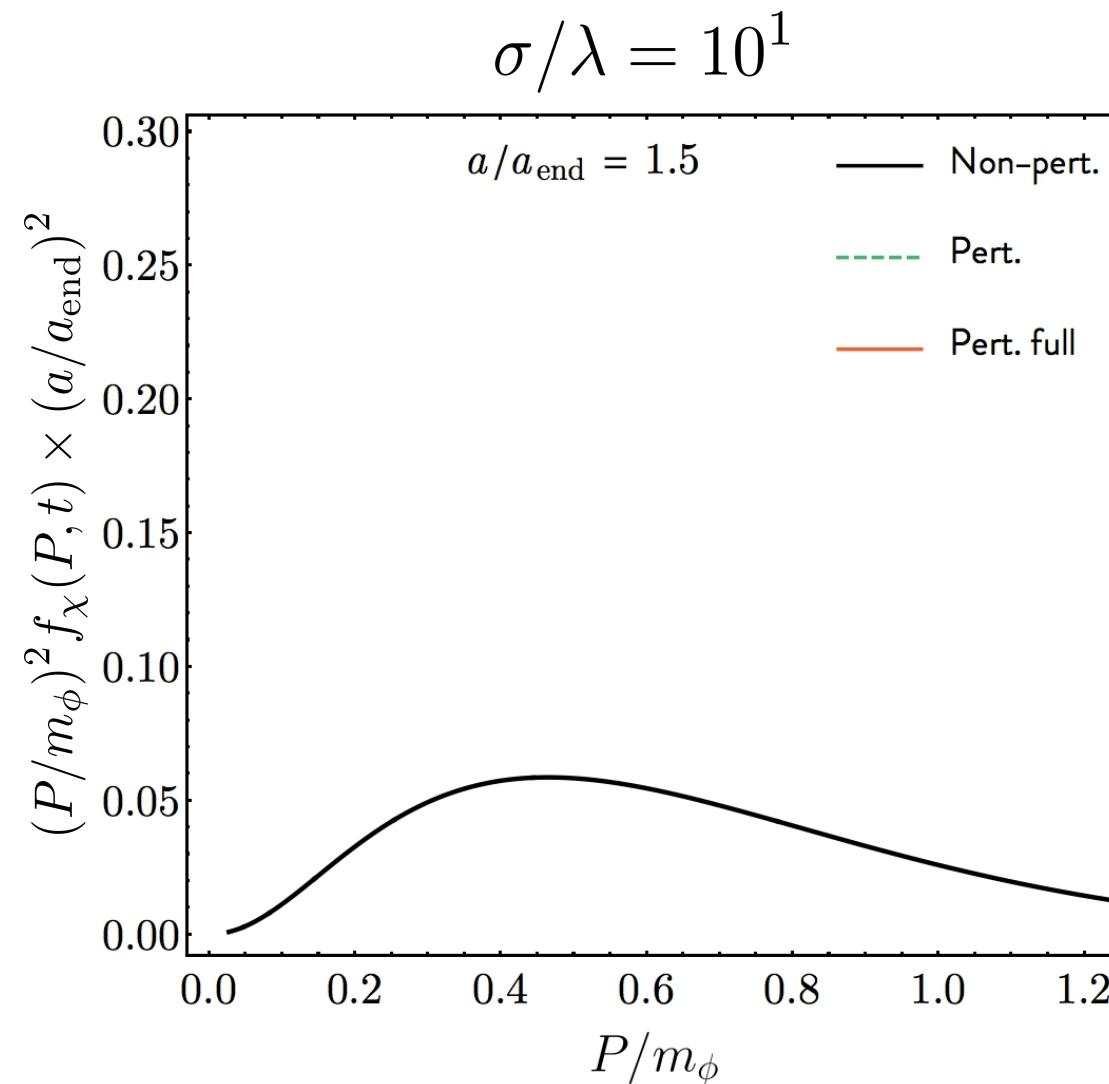
# Fermion production: the phase space distribution



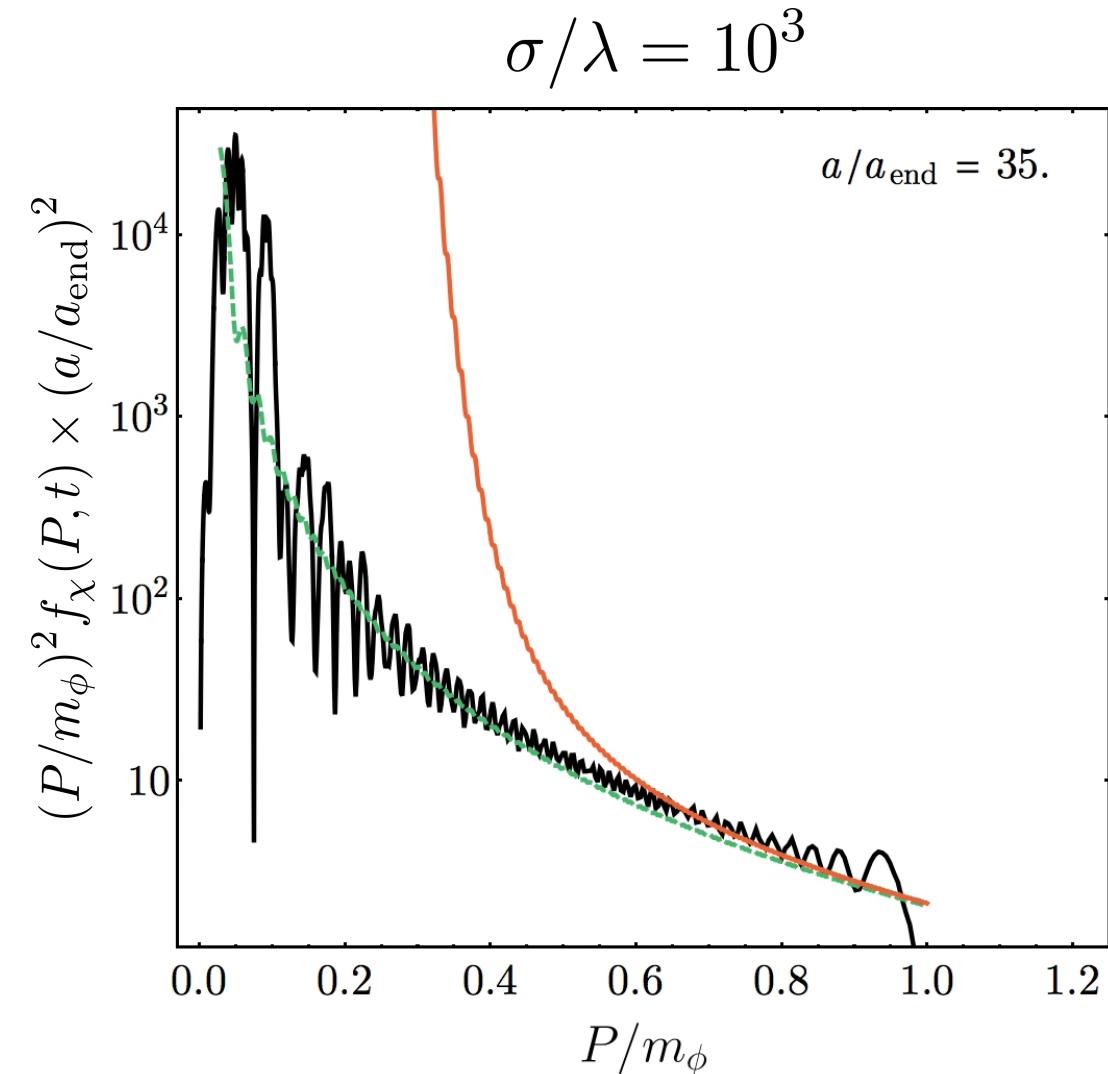
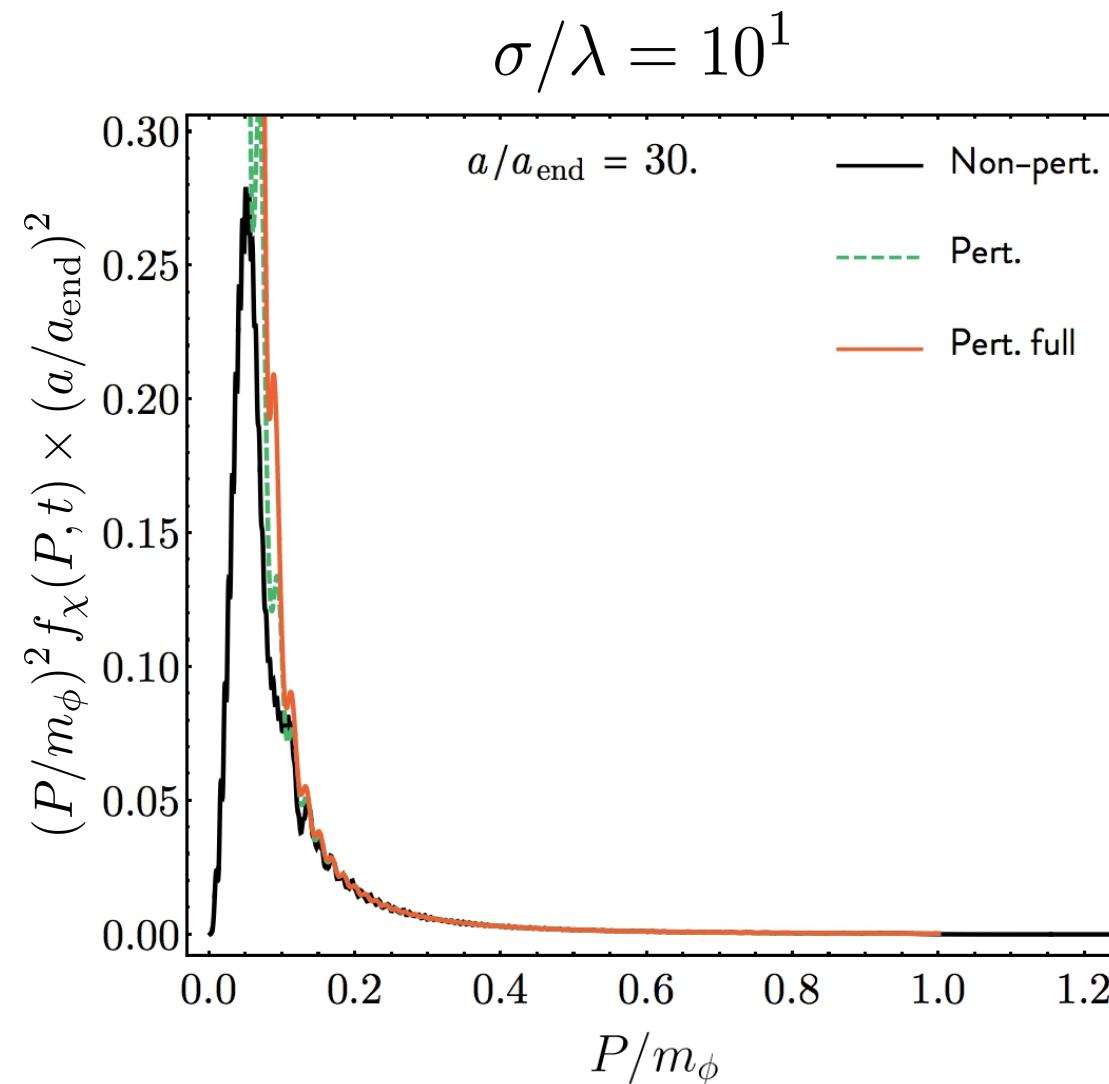
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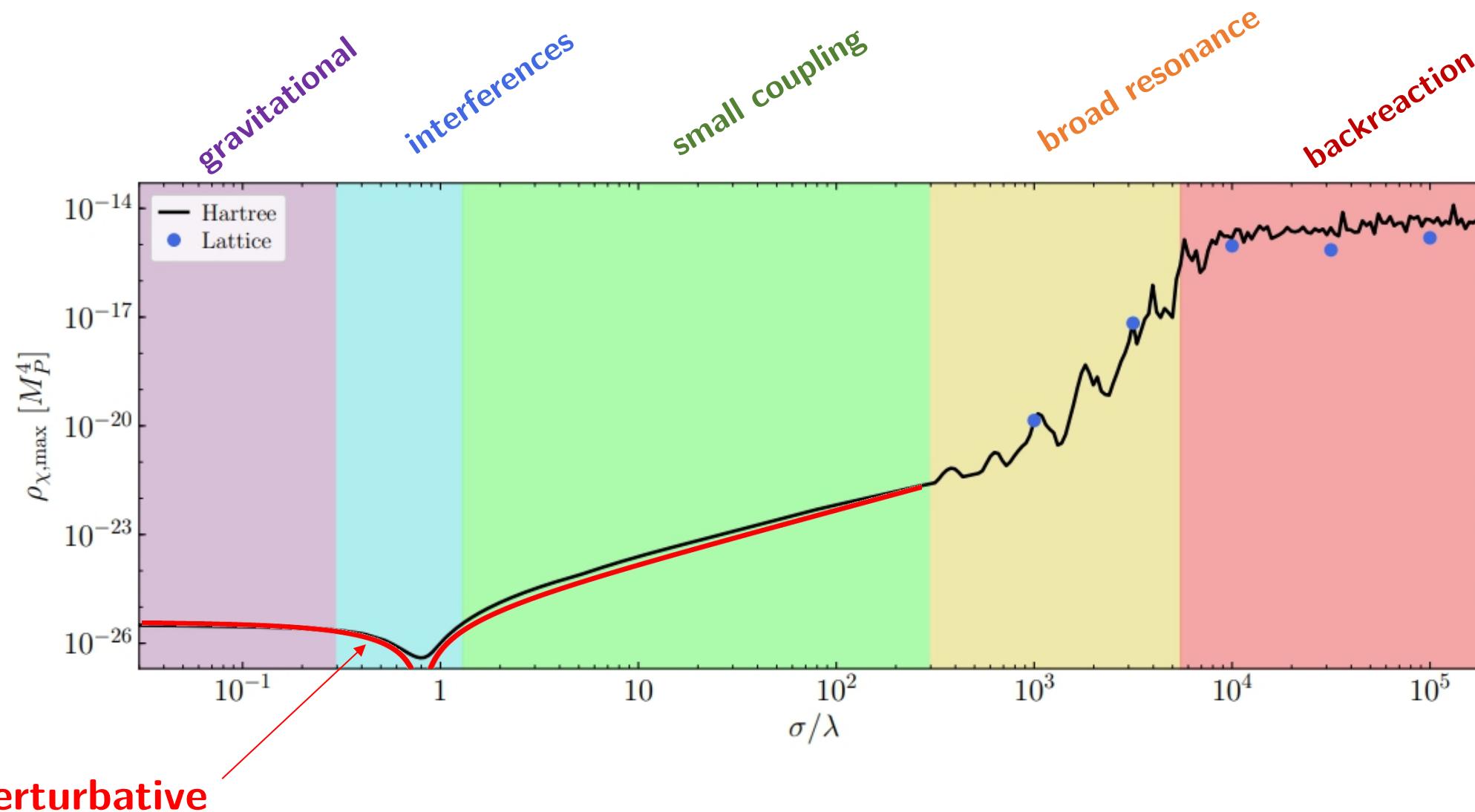
# Scalar production: the phase space distribution



# Scalar production: the phase space distribution



# Scalar preheating phases

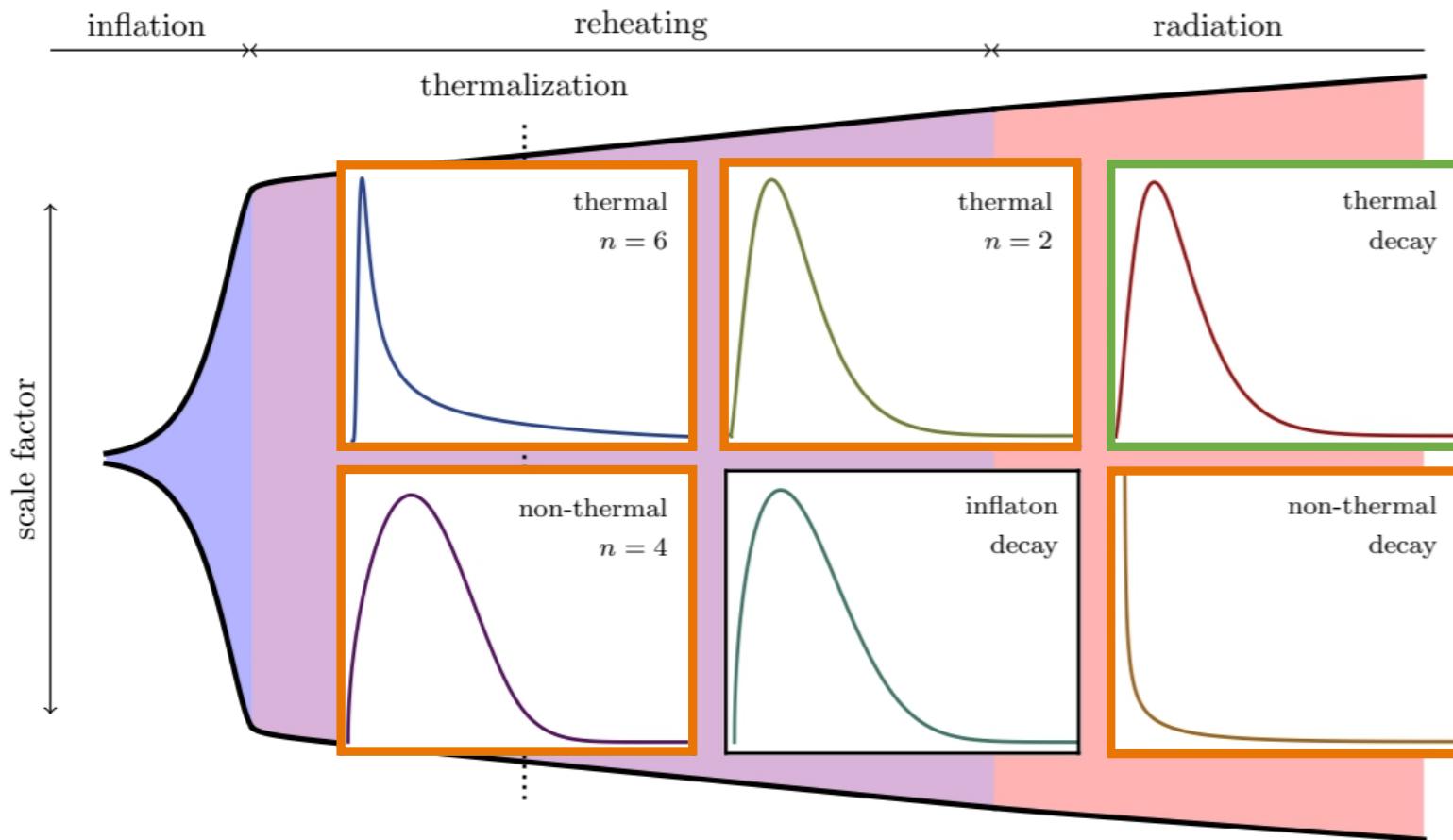


## **Cosmological signatures**

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# DM phase space distribution from freeze-in scenarios

→ Previously in [G. Ballesteros, M A. G. Garcia, MP, JCAP 03 (2021) 101] (or during my seminar last year)



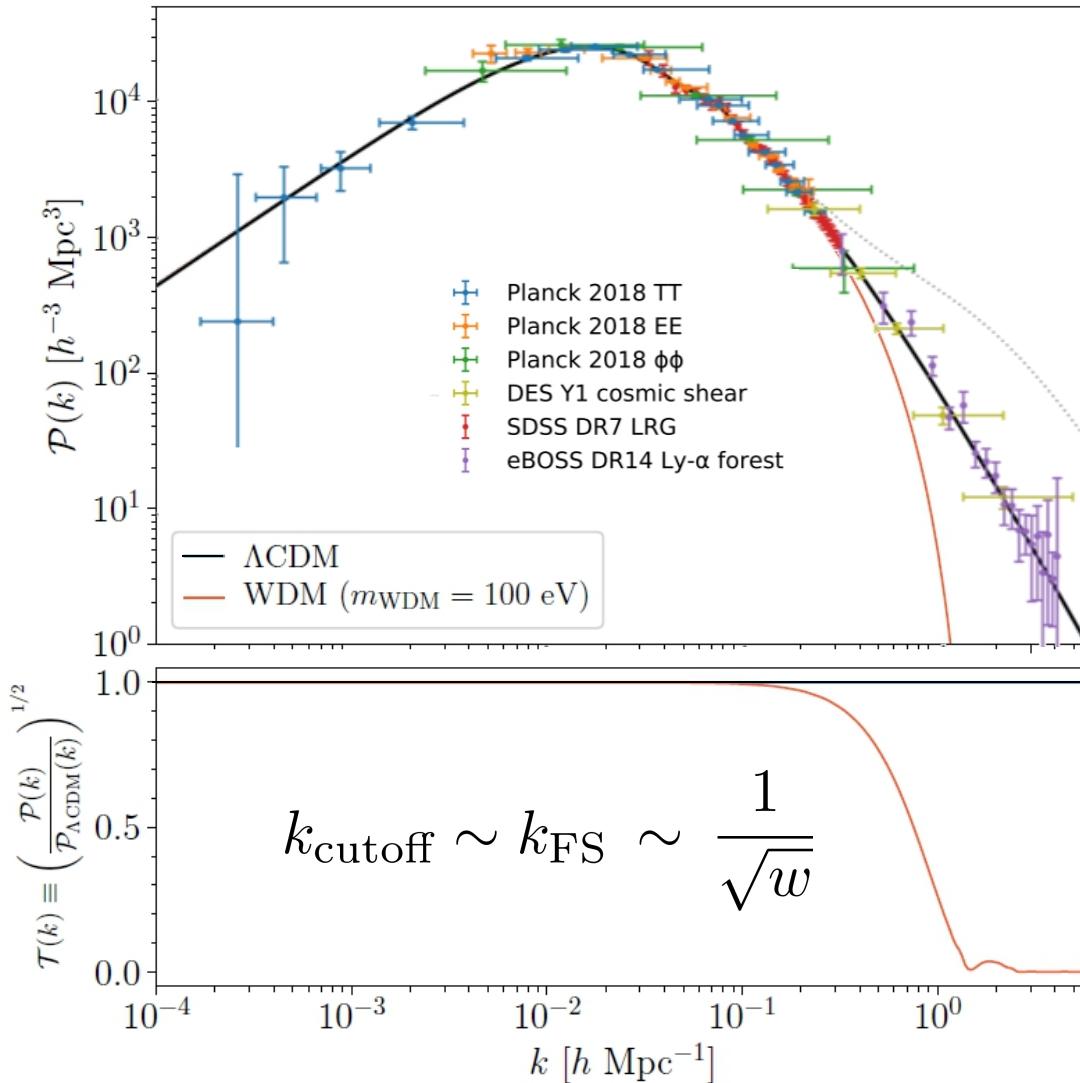
Freeze-in via  
scattering

$$\sigma(s) = \frac{s^{\frac{n}{2}}}{\Lambda^{n+2}}$$

Freeze-in via  
decay

→ Previous analysis for cases with “well-behaved” distributions  $f(q) \propto q^\alpha \exp(-\beta q^\gamma)$

# Translate constraints on non-cold dark matter



- **Cutoff determined by equation-of-state parameter**

$$w \sim \frac{\delta P}{\delta \rho} = \frac{T_\star^2}{3m_\chi^2} \frac{\langle q^2 \rangle}{a^2}$$

- **Find mass that reproduces cutoff constrained by Lyman- $\alpha$**

$$m_\chi > 7.5 \text{ keV} \left( \frac{m_{\text{WDM}}^{\text{Ly-}\alpha}}{3 \text{ keV}} \right)^{4/3} \left( \frac{T_\star}{T_\gamma^0} \right) \sqrt{\langle q^2 \rangle}$$

$$q \equiv \frac{P}{T_\star} \left( \frac{a}{a_0} \right)$$

Photon temperature now

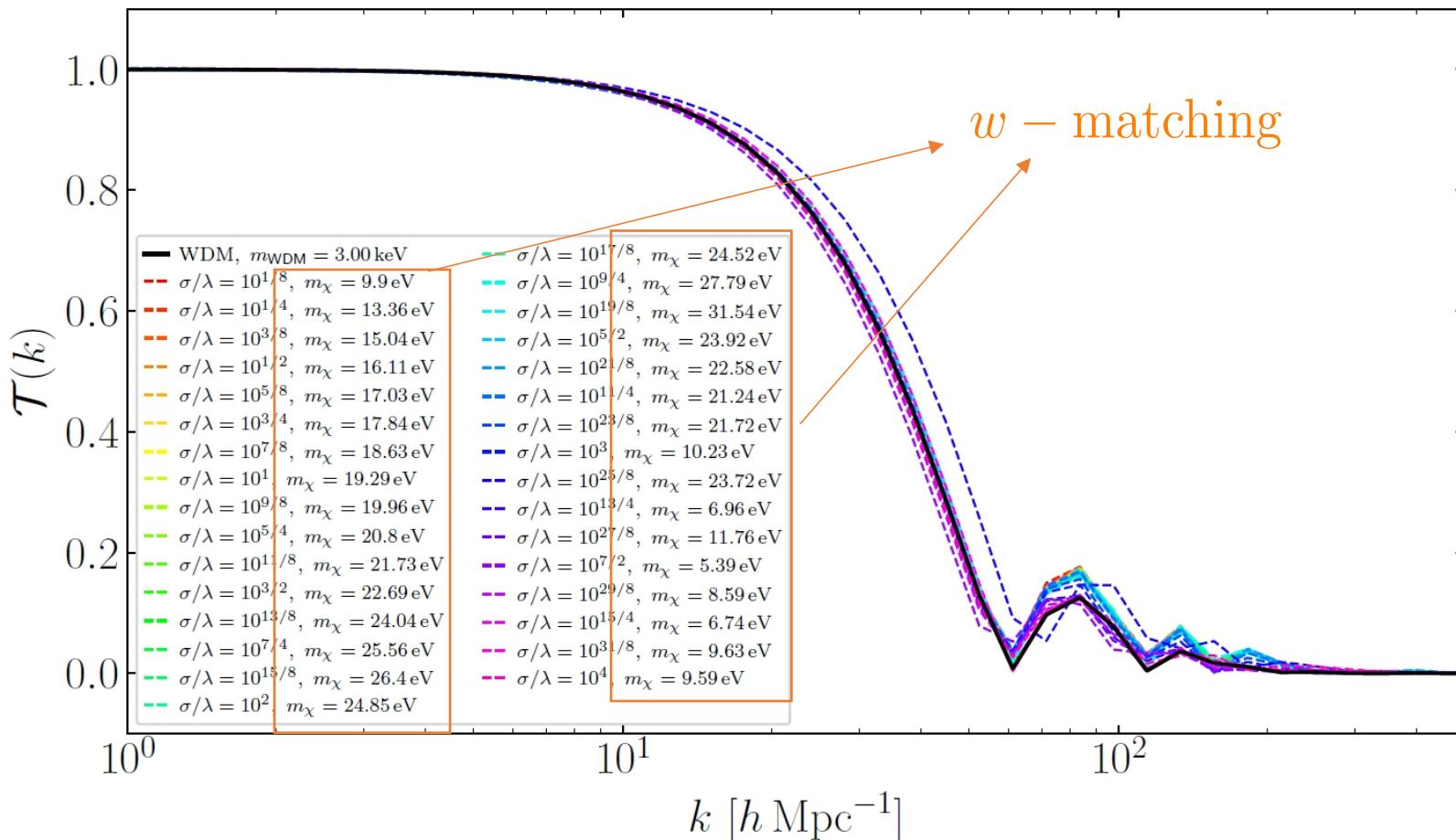
$$\langle q^2 \rangle \equiv \frac{\int dq q^4 f(q)}{\int dq q^2 f(q)}$$

[S. Chabanier, M. Millea, N. Palanque-Delabrouille, MNRAS 489 (2019) 2, 2247-2253]

# Constraints on preheating production $1 < \sigma/\lambda < 10^4$

- Power spectrum computed numerically with **CLASS**

[D. Blas, J. Lesgourgues & T. Tram JCAP 07 (2011) 034 - J. Lesgourgues & T. Tram, JCAP 09 (2011) 032]

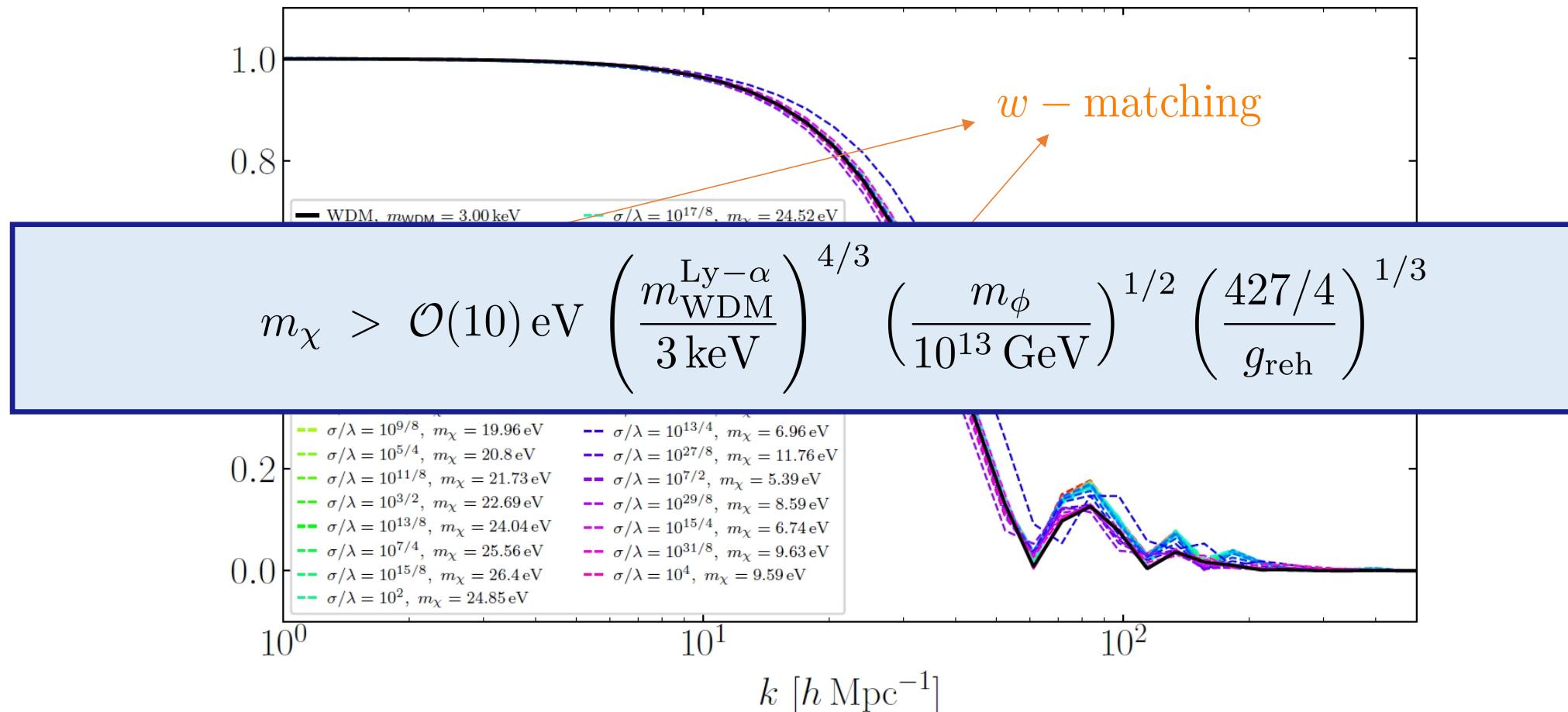


- Excellent agreement with  $w$  – matching for all distributions! Even the nasty ones!

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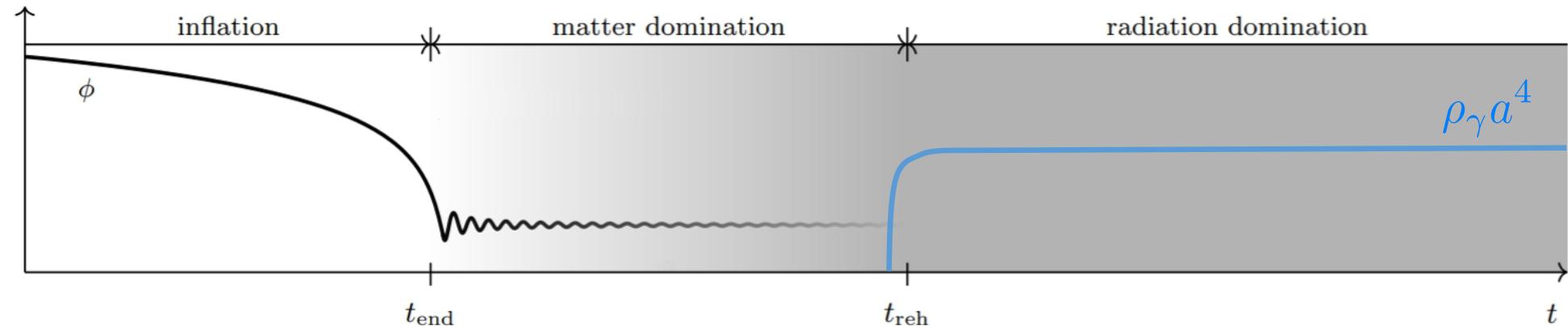
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- Excellent agreement with  $w$  – matching for all distributions! Even the nasty ones!

# Take home message



- The **expanding universe** as a **source for particle production**
- We tracked DM production, through **preheating**, from the **De-Sitter era** up to **now**
- **Lyman- $\alpha$**  can probe **preheating** dark matter production
- **Gravitational** dark matter production as **consequence of inflation**
  - Stay tuned for details about  $\sigma/\lambda \ll 1$  and the **paper release!**

**Thank you for your attention**