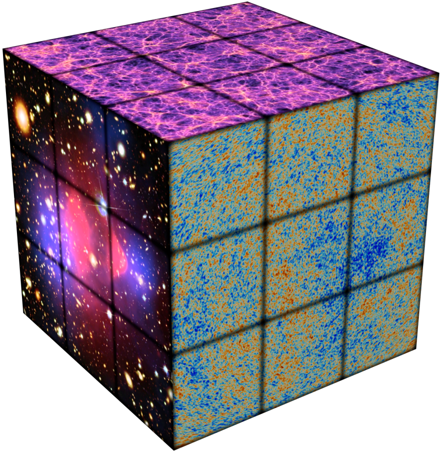
26/08/22

COSMO 22



# Dark Matter from Preheating


Marcos A. G. García (IFUNAM)

with

Mathias Pierre (DESY)

Sarunas Verner (Florida)


2206.08940

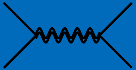

Universidad Nacional Autónoma de México

INSTITUTO DE FÍSICA

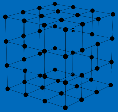
Instituto de Física UNAM

## 1. Preheating

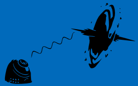
## 2. Weak coupling



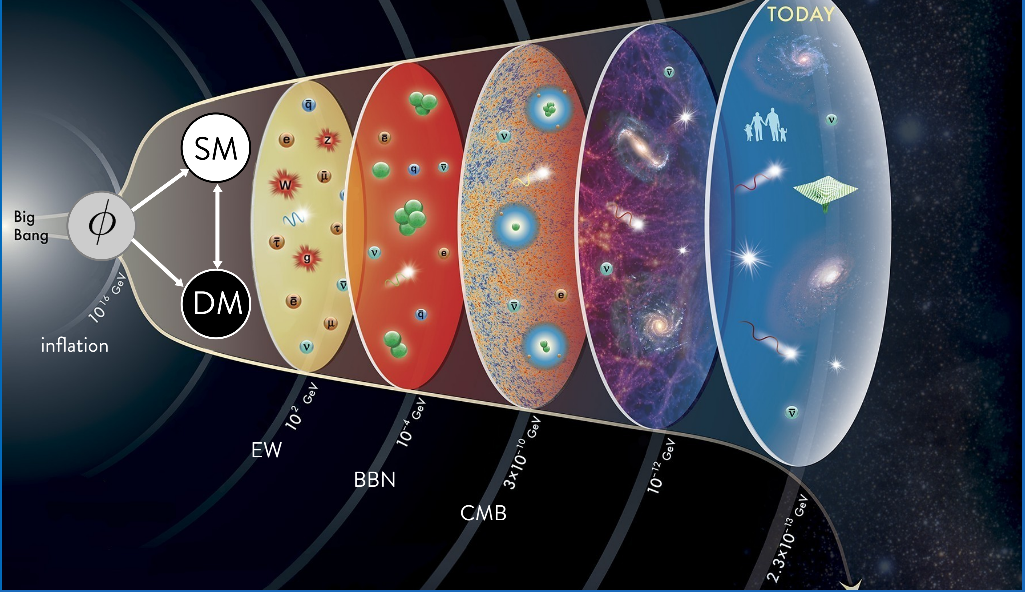
## 3. Strong coupling



## 4. Constraints



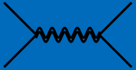
# Inflation & dark matter



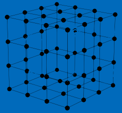
# Inflation & dark matter

## 1. Preheating

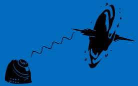
## 2. Weak coupling

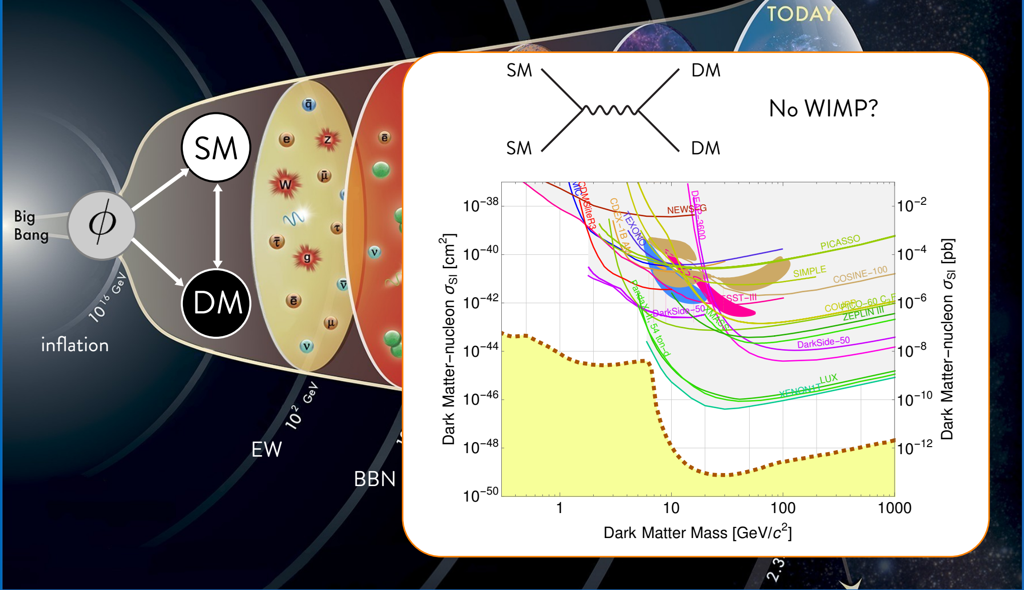


## 3. Strong coupling



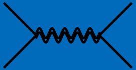
## 4. Constraints



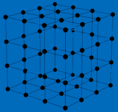


## 1. Preheating

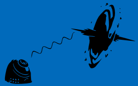
## 2. Weak coupling



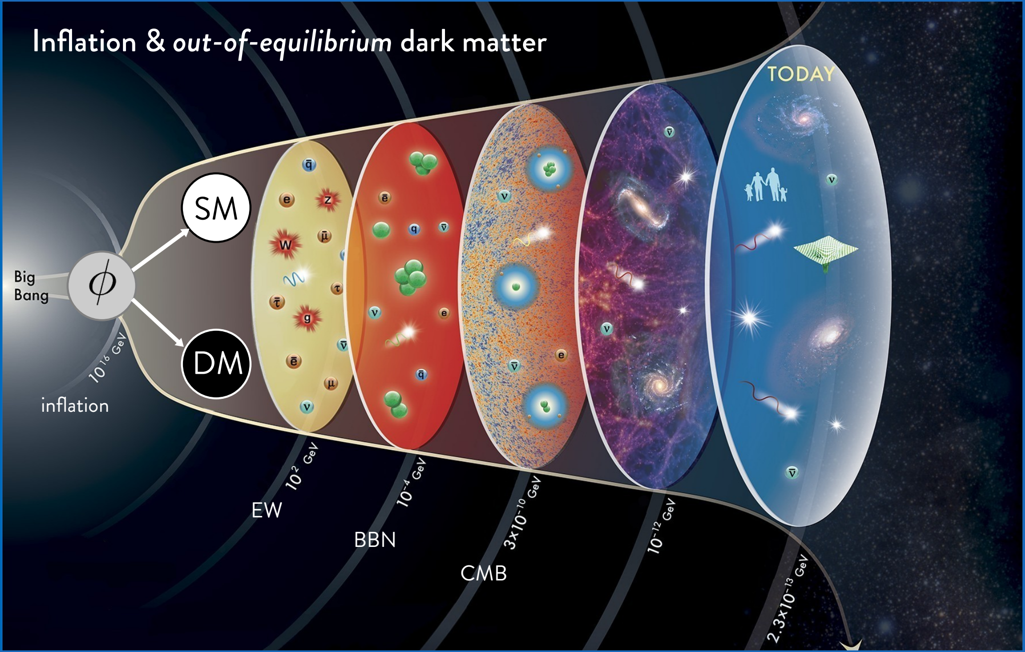
## 3. Strong coupling



## 4. Constraints

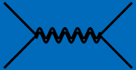


# Inflation & *out-of-equilibrium* dark matter

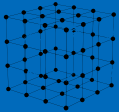


**1. Preheating**

**2. Weak coupling**



**3. Strong coupling**



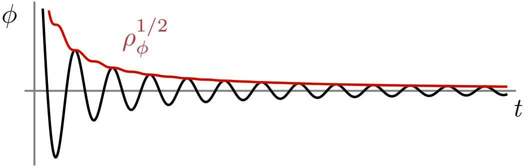
**4. Constraints**

# The inflaton and its decay products

$$\mathcal{S} = \int d^4x\sqrt{-g}\left[\frac{1}{2}(\partial_\mu\phi)^2 - 6\lambda M_P^4 \tanh^2\left(\frac{\phi}{\sqrt{6}M_P}\right)\right.$$ inflaton

$$+\frac{1}{2}(\partial_\mu\chi)^2 - \frac{1}{2}(m_\chi^2+\sigma\phi^2)\chi^2$$ dark matter

$$\left. + \bar{\psi}i\bar{\gamma}^\mu\nabla_\mu\psi - y\phi\bar{\psi}\psi + \cdots \right]$$ radiation



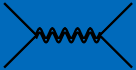

$$\langle p_\phi\rangle = \tfrac{1}{2}\langle\dot{\phi}^2 + m_\phi^2\phi^2\rangle \simeq 0$$

(matter)

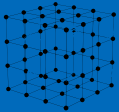
R. Kallosh and A. Linde, JCAP 10 (2013), 033

1. Preheating

2. Weak coupling



3. Strong coupling

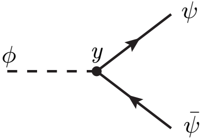


4. Constraints

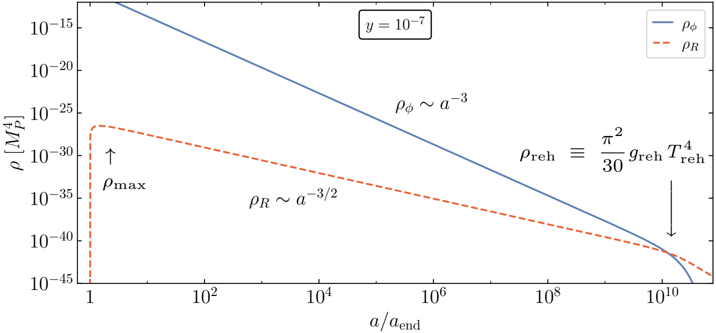
# Perturbative decay of the inflaton

Decay into visible sector is assumed to be perturbative

$$\mathcal{L} \supset -y\phi\bar{\psi}\psi$$



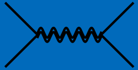

$$\Gamma_\phi = \frac{y^2}{8\pi} m_\phi$$



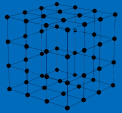

$$\begin{aligned} \dot{\rho}_\phi + 3H\rho_\phi &= -\Gamma_\phi \rho_\phi \\ \dot{\rho}_R + 4H\rho_R &= \Gamma_\phi \rho_\phi \\ \rho_\phi + \rho_R &= 3H^2 M_P^2 \end{aligned}$$

1. Preheating

2. Weak coupling



3. Strong coupling

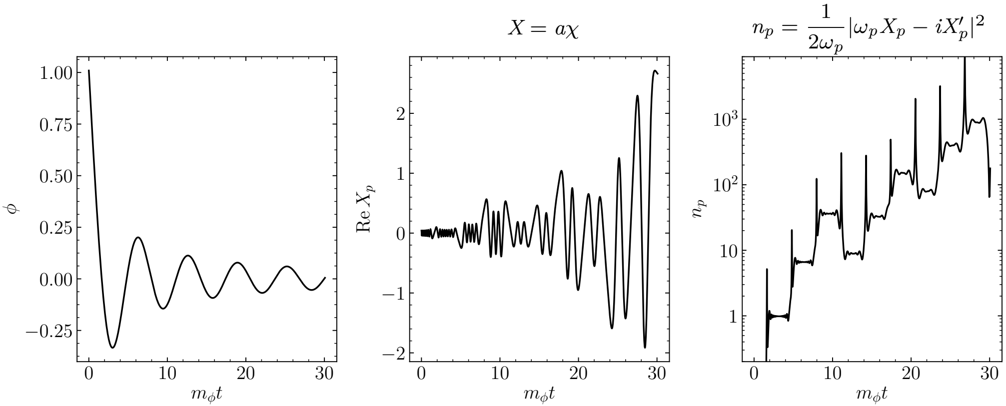


4. Constraints

# Scalar preheating

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

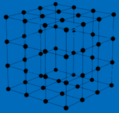
Resonant growth of fluctuations



1. Preheating

2. Weak coupling

3. Strong coupling



4. Constraints

# The Boltzmann approximation

Dissipation of fluctuations of the inflaton *condensate* into $\chi$ quanta

$$\phi(t) \simeq \phi_0(t)\mathcal{P}(t) = \phi_0(t)\sum_n \mathcal{P}_n e^{-in\omega t}$$

$$\frac{\partial f_\chi}{\partial t} - H|\boldsymbol{P}|\frac{\partial f_\chi}{\partial|\boldsymbol{P}|} = \frac{1}{P^0}\sum_{n=1}^{\infty}\int \frac{d^3\boldsymbol{K}}{(2\pi)^3 n_\phi}\frac{d^3\boldsymbol{P}'}{(2\pi)^3 2P'^0}(2\pi)^4\delta^{(4)}(K_n - P - P')|\overline{\mathcal{M}_n}|^2$$

$$\times\Big[f_\phi(K)(1+f_\chi(P))(1+f_\chi(P')) - f_\chi(P)f_\chi(P')(1+f_\phi(K))\Big]$$

$$= \frac{\pi|\overline{\mathcal{M}_2}|^2}{2m_\phi^2\beta(t)}\delta\left(|\boldsymbol{P}| - m_\phi\beta(t)\right)\left(1 + 2f_\chi(|\boldsymbol{P}|)\right)$$

Condensate PSD

$$f_\phi(P,t) = (2\pi)^3 n_\phi(t)\delta^{(3)}(\boldsymbol{P})$$

Mode momenta

$$K_n = (E_n, \boldsymbol{0}) = (nm_\phi, \boldsymbol{0})$$

Effective mass

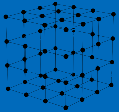
$$m_{\rm eff}^2 = m_\chi^2 + \sigma\phi^2$$

Kinematic factor

$$\beta(t) \equiv \sqrt{1 - \frac{m_{\rm eff}^2(t)}{m_\phi^2}}$$



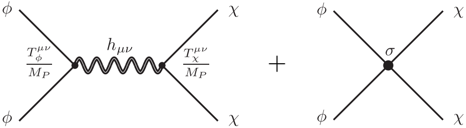






# The Boltzmann approximation

$$\mathcal{L}_I = -\frac{1}{M_P} h_{\mu\nu}\left(T^{\mu\nu}_{\phi} + T^{\mu\nu}_{\chi}\right) - \frac{\sigma}{2}\phi^2\chi^2$$




$$\mathcal{M} = -\frac{1}{M_P^2}\left[1 + \frac{2m_{\rm eff}^2}{s}\right] V(\phi) + \sigma\phi^2$$

Here $m_{\rm eff}^2 = m_\chi^2 + \sigma\phi^2$. For quadratic $V(\phi)$ only the second mode contributes

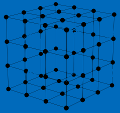
$$|\overline{\mathcal{M}_2}|^2 = \frac{\phi_0^4}{32}\left[\sigma - \lambda\left(1 + \frac{m_{\rm eff}^2}{2m_\phi^2}\right)\right]^2 \equiv \frac{1}{8}\frac{\rho_\phi^2}{m_\phi^4}\hat{\sigma}^2$$

- For $\sigma/\lambda > 1$, direct decay suppressed by graviton exchange
- For $\sigma/\lambda < 1$, gravitational production suppressed by direct coupling
- For $\sigma/\lambda = 1$, complete interference at $m_{\rm eff} = 0$

1. Preheating

2. Weak coupling

3. Strong coupling

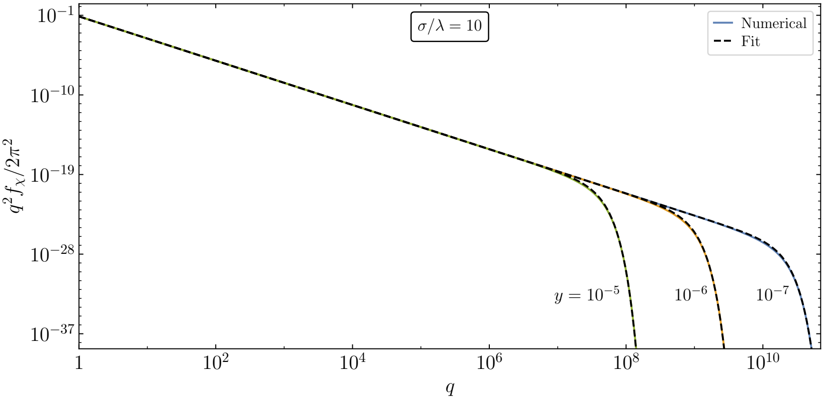


4. Constraints

# The Boltzmann approximation

With $f_\chi(|\boldsymbol{P}|, t) \equiv \frac{1}{2}\left[\exp\left(2f_\chi^c(|\boldsymbol{P}|, t)\right) - 1\right]$ and $q \equiv \frac{P}{T_\star}\left(\frac{a}{a_0}\right)$, $T_\star \equiv m_\phi\left(\frac{a_{\rm end}}{a_0}\right)$

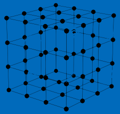
$$f_\chi^c(q,t) \simeq \frac{\sqrt{3}\pi\hat{\sigma}^2\rho_{\rm end}^{3/2}M_P}{16m_\phi^7}\, q^{-9/2} e^{-1.56\left(\frac{a_{\rm end}}{a_{\rm reh}}\right)^2 q^2}\theta(q-1)\,, \quad (t \gg t_{\rm reh},\, \beta \simeq 1)$$



1. Preheating

2. Weak coupling

3. Strong coupling



4. Constraints

# Non-perturbative particle production

Equation of motion for $\chi$

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

In terms of conformal time, $dt/d\tau = a$, and the re-scaled field $X = a\chi$

$$X(\tau,\mathbf{x}) \;=\; \int \frac{d^3\mathbf{p}}{(2\pi)^{3/2}} e^{-i\mathbf{p}\cdot\mathbf{x}} \left[X_p(\tau)\hat{a}_{\mathbf{p}} + X_p^*(\tau)\hat{a}^\dagger_{-\mathbf{p}}\right]$$

the equation of motion for the mode functions is

$$X_p'' + \omega_p^2 X_p \;=\; 0$$

with

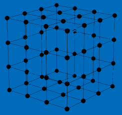
$$\omega_p^2 \;=\; p^2 + a^2 m_{\rm eff}^2 \;=\; p^2 + a^2\left(m_\chi^2 + \sigma\phi^2 + \frac{1}{6}R\right)$$

and Bunch-Davies initial condition $X_p(\tau_0) \;=\; \frac{1}{\sqrt{2\omega_p}}\,, \quad X_p'(\tau_0) \;=\; -\frac{i\omega_p}{\sqrt{2\omega_p}}$

1. Preheating

2. Weak coupling

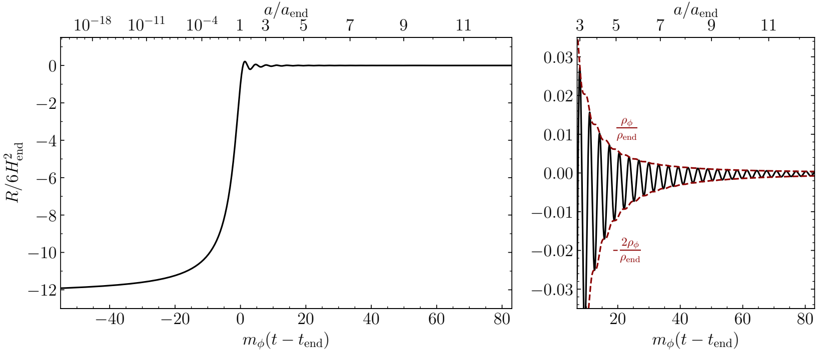
3. Strong coupling



4. Constraints

# Non-perturbative particle production

$$\frac{1}{6}R = -\frac{a''}{a^3} = -\frac{1}{6M_P^2}\left(4V - \dot{\phi}^2\right)$$



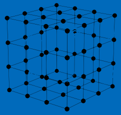

$$\omega_p^2(t_{\rm end}) = p^2 + a_{\rm end}^2\left(m_\chi^2 + \sigma\phi^2 - H_{\rm end}^2\right)$$

For $\sigma/\lambda \lesssim 10^{-1/2}$ superhorizon modes grow *during inflation* due to tachyonic instability

1. Preheating

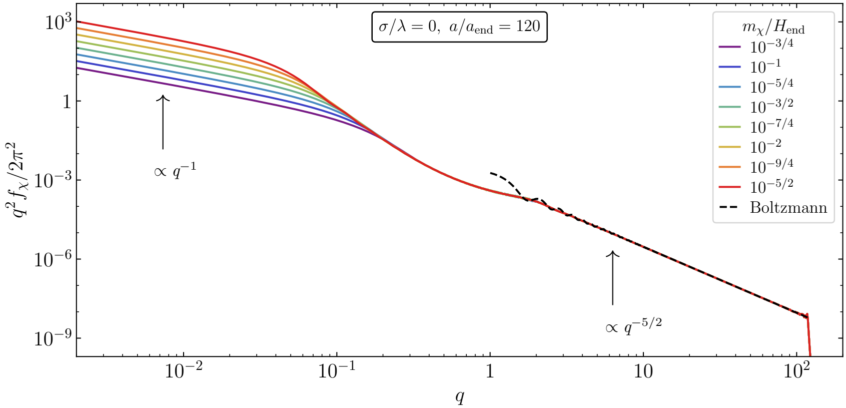
2. Weak coupling

3. Strong coupling



4. Constraints

# Pure gravitational production




IR regulated by the present comoving scale $p_0 = a_0 H_0$, or $q_0 = \dfrac{H_0}{m_\phi}\left(\dfrac{a_0}{a_{\rm end}}\right)$

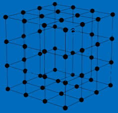
N. Herring, D. Boyanovsky and A. Zentner, PRD 101 (2020) , 083516

S. Ling and A. Long, PRD 103 (2021), 103532

1. Preheating

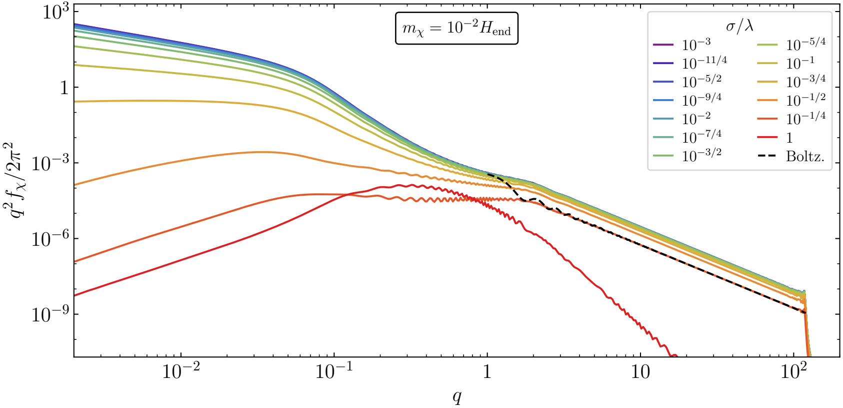
2. Weak coupling

3. Strong coupling



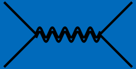
4. Constraints

# Weak coupling ($\sigma/\lambda \leq 1$)

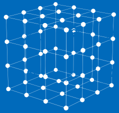



Non-perturbatively the interference is not exact for $\sigma/\lambda = 1$, and $f_\chi \sim q^{-15/2}$ in the UV











# Strong coupling: Hartree

At strong coupling the resonant production of $\chi$ can influence the background dynamics

Strong, but not too strong couplings ($\sigma/\lambda \lesssim 10^{7/2}$): **Hartree aproximation**

$$\rho_\phi + \rho_\chi \;=\; 3H^2 M_P^2\,,$$
$$\ddot{\phi} + 3H\dot{\phi} + V_\phi + \sigma\langle\chi^2\rangle\phi \;=\; 0\,,$$

where

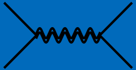
$$\langle\chi^2\rangle \;=\; \frac{1}{(2\pi)^3 a^2}\int d^3\boldsymbol{p}\left(|X_p|^2 - \frac{1}{2\omega_p}\right)\,.$$

L. Kofman, A. Linde, A. Starobinsky, PRD 56 (1997) 3258

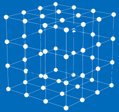
MG, K. Kaneta, Y. Mambrini, K. Olive, S. Verner, JCAP 03 (2022) 016

No backreaction if $\rho_\chi \lesssim 0.1\rho_\phi$







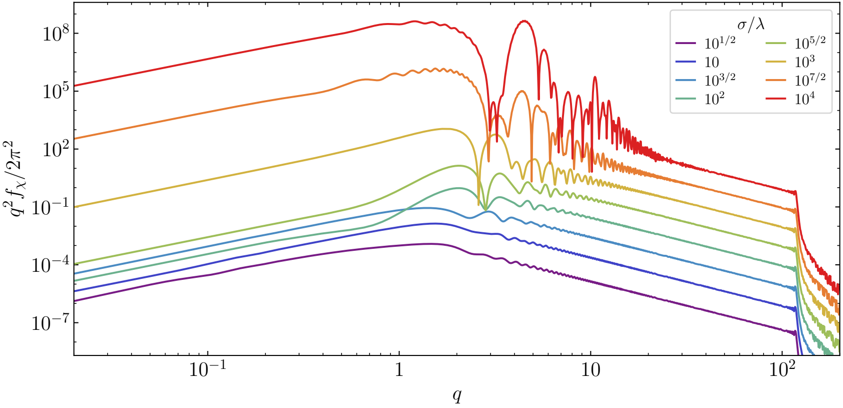




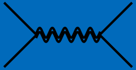
# Strong coupling: Hartree

At strong coupling the resonant production of $\chi$ can influence the background dynamics

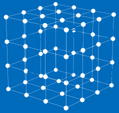
Strong, but not too strong couplings ($\sigma/\lambda \lesssim 10^{7/2}$): **Hartree aproximation**













# Strong coupling: Lattice

For stronger couplings the re-scattering of $\chi$ into $\phi$ disrupts the inflaton condensate

Mode-mode couplings of perturbations make spectral codes unsuitable for the task

Solution: **Classical fields on a configuration-space lattice**

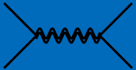
$$\begin{aligned} \ddot{\phi} + 3H\dot{\phi} - \frac{\nabla^2\phi}{a^2} + V_{,\phi} &= 0 \\ \ddot{\chi} + 3H\dot{\chi} - \frac{\nabla^2\chi}{a^2} + V_{,\chi} &= 0 \end{aligned}$$

Software of choice: `CosmoLattice (v1.0)`

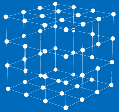
D. Figueroa, et al., arXiv:2102.01031 [astro-ph.CO]

Caveat: no metric perturbations

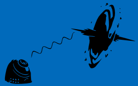








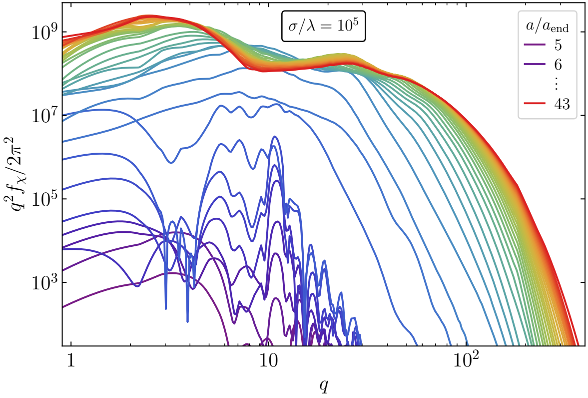


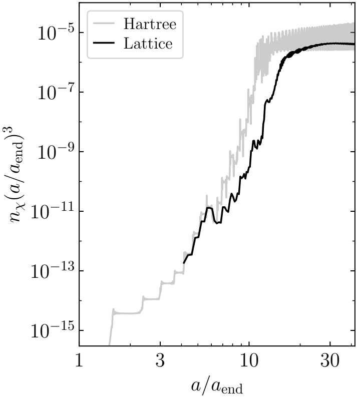


# Strong coupling: Lattice

Re-scattering leads to a broadening distribution with pseudo-thermal tail for $\phi$ and $\chi$

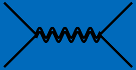
$$f_\chi \sim e^{-\alpha(\sigma/\lambda;t)\,q} \quad \text{in the UV}$$



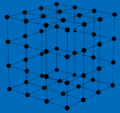



1. Preheating

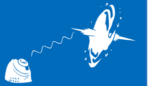
2. Weak coupling



3. Strong coupling

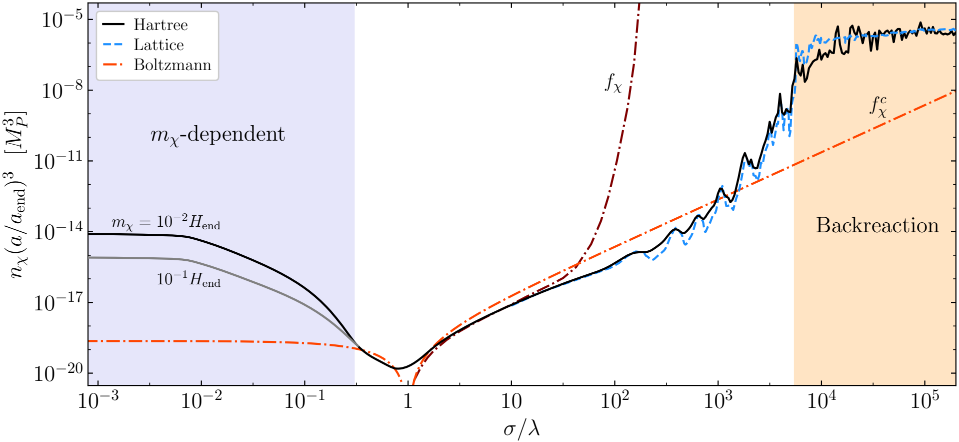


**4. Constraints**



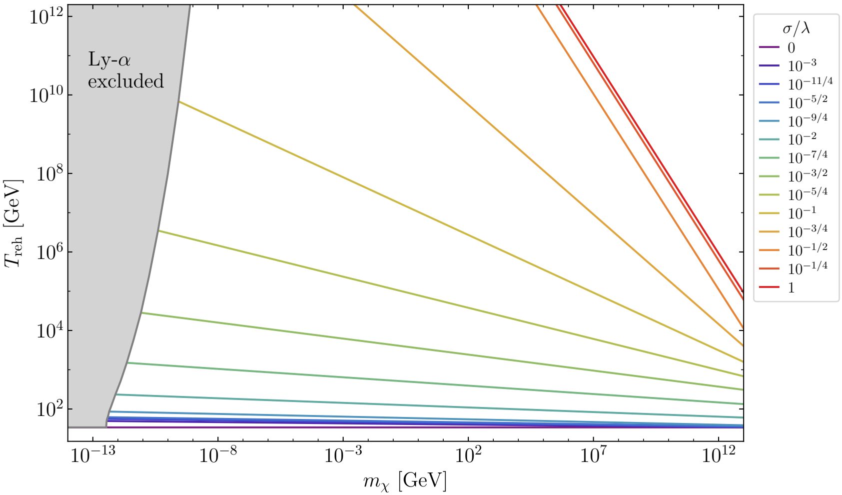
# Comoving number densities

Boltzmann has a very limited range of applicability



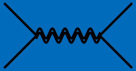
# Relic abundance at weak coupling

Saturating the DM relic abundance (curves of $\Omega_\chi h^2 = 0.12$):

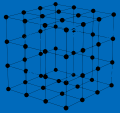


1. Preheating

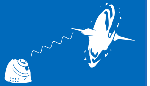
2. Weak coupling



3. Strong coupling

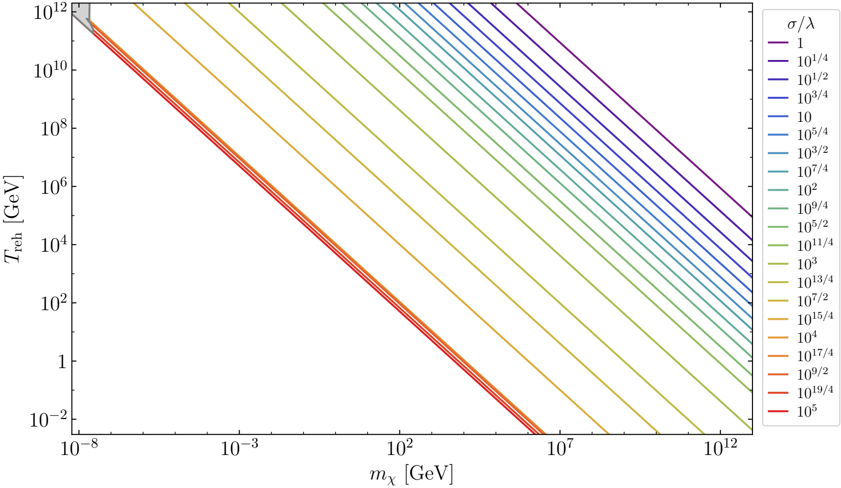


4. Constraints



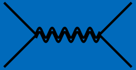
# Relic abundance at strong coupling

Saturating the DM relic abundance (curves of $\Omega_\chi h^2 = 0.12$):

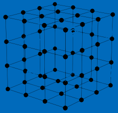


1. Preheating

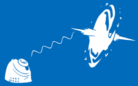
2. Weak coupling



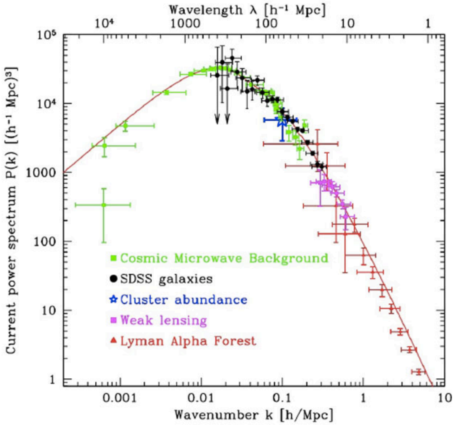
3. Strong coupling



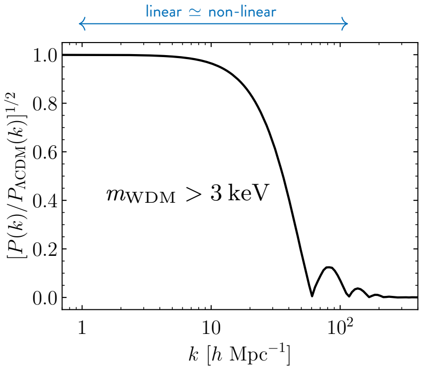
4. Constraints



# How warm is out-of-equilibrium dark matter?



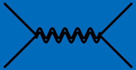

R. Murgia, V. Iršič and M. Viel, PRD 98 (2018), 083540



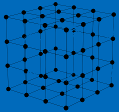

G. Ballesteros, MG and M. Pierre, JCAP 03 (2021), 101

1. Preheating

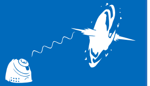
2. Weak coupling



3. Strong coupling



4. Constraints



# How warm is out-of-equilibrium dark matter?

$$f(\boldsymbol{x},\boldsymbol{p},\tau) = f_0(|\boldsymbol{p}|,\tau)\,[1+\Psi(\boldsymbol{x},\boldsymbol{p},\tau)]$$

$$\downarrow$$

$$\ddot{\delta} + \mathcal{H}\dot{\delta} - \frac{3}{2}\mathcal{H}^2\left(1 - w\,\frac{10}{9}\,\frac{k^2}{\mathcal{H}^2}\right)\delta = 0$$

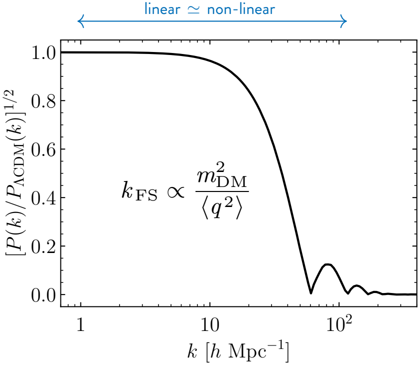
$$k_{\rm FS}^2(a) = \frac{9}{10}\,\frac{\mathcal{H}^2}{w}$$

$$k_{\rm H}(a) = \left[\int_0^a \frac{d\tilde{a}}{\tilde{a}\,k_{\rm FS}(\tilde{a})}\right]^{-1}$$

$$w \simeq \frac{\delta P}{\delta\rho} = \frac{T_\star^2}{3m_{\rm DM}^2}\,\frac{\langle q^2\rangle}{a^2}$$

$$w(m_{\rm DM}) = w_{\rm WDM}(m_{\rm WDM}) \longrightarrow$$

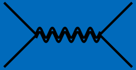
R. Murgia, V. Iršič and M. Viel, PRD 98 (2018), 083540



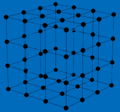

G. Ballesteros, MG and M. Pierre, JCAP 03 (2021), 101

$$m_{\rm DM} = m_{\rm WDM}\left(\frac{T_\star}{T_{\rm WDM}}\right)\sqrt{\frac{\langle q^2\rangle}{\langle q^2\rangle_{\rm WDM}}}$$











# Lyman-$\alpha$ constraint

From Boltzmann $f_\chi^c$,

$$\langle q^2 \rangle \simeq 0.641 \left(\frac{a_{\rm reh}}{a_{\rm end}}\right)^2 \frac{\Gamma\left(1/4, 1.56(a_{\rm end}/a_{\rm reh})^2\right)}{\Gamma\left(-3/4, 1.56(a_{\rm end}/a_{\rm reh})^2\right)} \simeq 2.433\sqrt{\frac{a_{\rm reh}}{a_{\rm end}}}$$

for $a_{\rm reh} \gg a_{\rm end}$, and

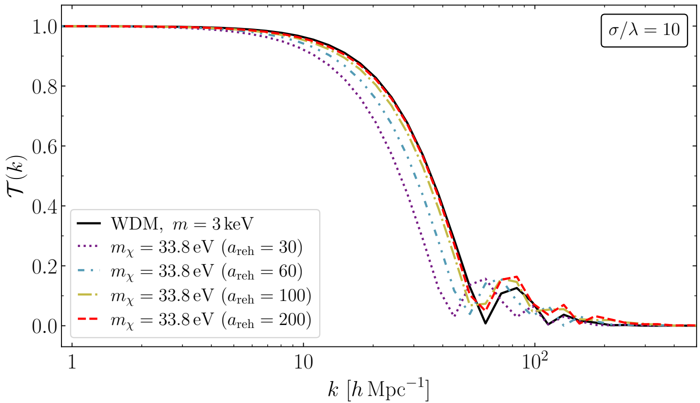
$$\begin{aligned} m_{\rm DM} &> 15.78\,{\rm keV}\left(\frac{m_{\rm WDM}}{3\,{\rm keV}}\right)^{4/3} m_\phi\, \rho_{\rm end}^{-1/4}\, g_{\rm reh}^{-1/12} \\ &\simeq 32.4\,{\rm eV}\left(\frac{m_{\rm WDM}}{3\,{\rm keV}}\right)^{4/3}\left(\frac{\lambda}{2.05\times 10^{-11}}\right)^{1/4}\left(\frac{427/4}{g_{\rm reh}}\right)^{1/12} \end{aligned}$$

Weaker than WDM one, and without dependence on duration of reheating!

# Lyman-$\alpha$ constraint

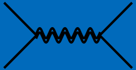
For all non-lattice, $\sigma \neq \lambda$ cases, the perturbative tail is present

$$(m_{\rm DM})_{\text{non-pert}} = (m_{\rm DM})_{\text{pert}} \sqrt{\frac{\langle q^2 \rangle_{\text{non-pert}}}{\langle q^2 \rangle_{\text{pert}}}}$$

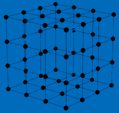


1. Preheating

2. Weak coupling



3. Strong coupling

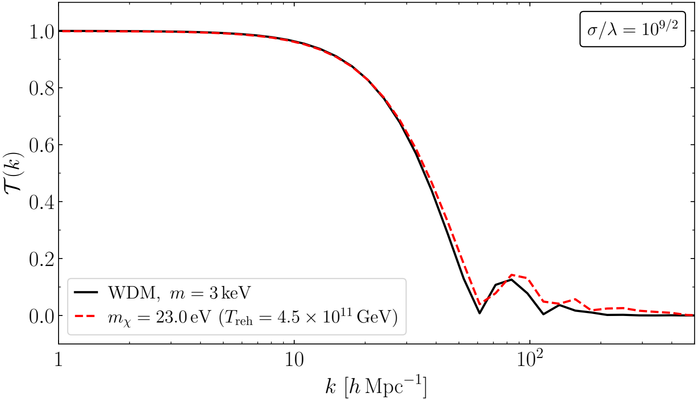


4. Constraints

# Lyman-$\alpha$ constraint

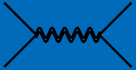
For strong backreaction, or $\sigma = \lambda$, $\langle q^2 \rangle \;\to\;$ const. during reheating

$$m_{\rm DM} \;>\; 9.58\,{\rm keV}\,\left(\frac{m_{\rm WDM}}{3\,{\rm keV}}\right)^{4/3}\sqrt{\langle q^2\rangle}\,\frac{m_\phi\,T_{\rm reh}^{1/3}}{\rho_{\rm end}^{1/3}}\,.$$

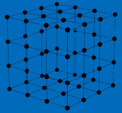


1. Preheating

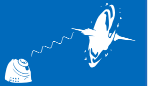
2. Weak coupling



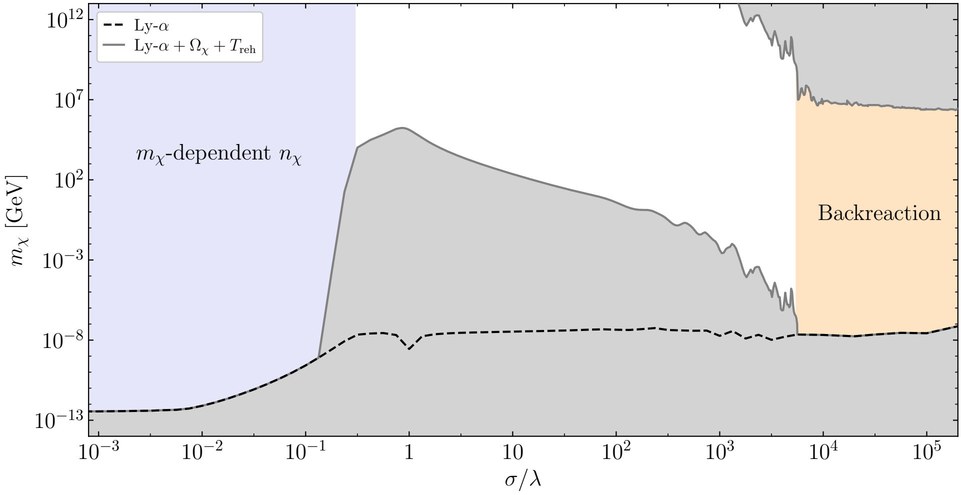
3. Strong coupling



4. Constraints

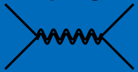


# The allowed parameter space

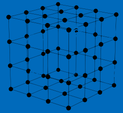


1. Preheating

2. Weak coupling

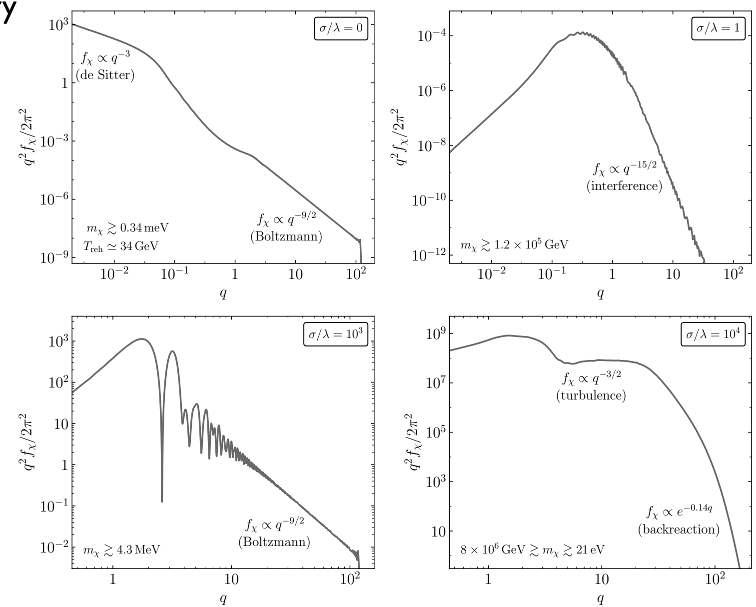


3. Strong coupling



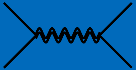
4. Constraints

# Summary

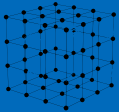


1. Preheating

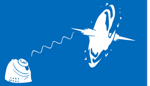
2. Weak coupling



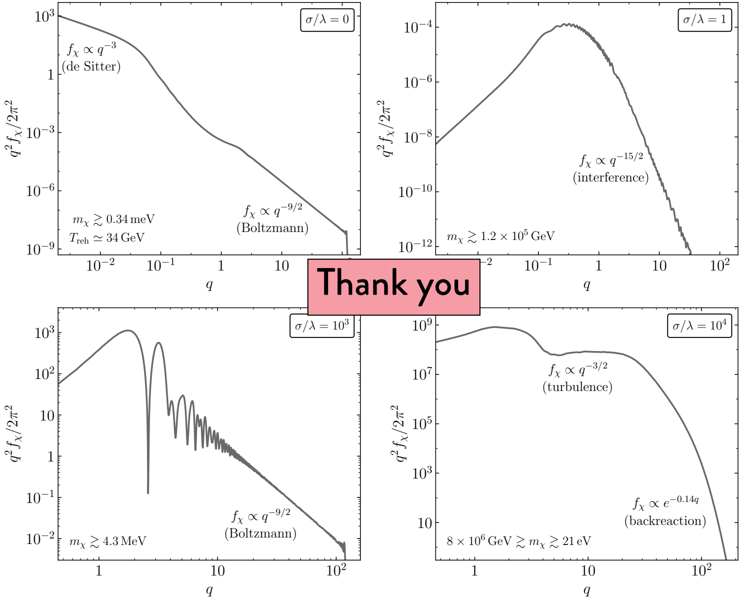
3. Strong coupling



4. Constraints



# Summary




**Thank you**