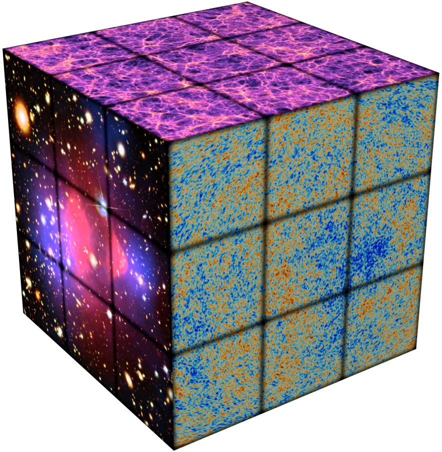
22/06/22

Cosmology From Home 2022



Dark Matter from Preheating

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with

Mathias Pierre (DESY)

Sarunas Verner (U. Minnesota)

2206.08940

Universidad Nacional Autónoma de México

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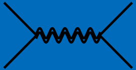
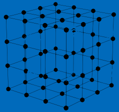
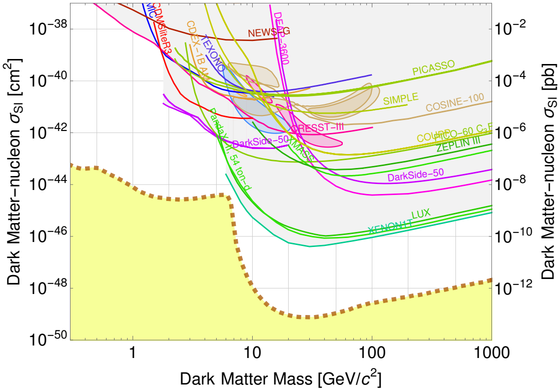




The case for FIMP dark matter

No detection of WIMPs yet!



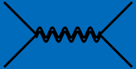
SuperCDMS Dark Matter Limit Plotter

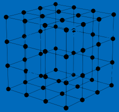
Consider FIMPs:

- Never in thermal equilibrium
- Produced via freeze-in
- Elusive (in)direct detection
- Dependence on initial conditions (inflation, reheating)

A simple possibility:

(Scalar) dark matter that couples only to the inflaton



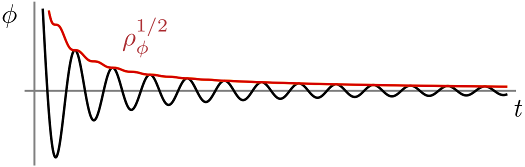


The inflaton and its decay products

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

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

$$+ \bar{\psi} i \bar{\gamma}^\mu \nabla_\mu \psi - y\phi\bar{\psi}\psi + \cdots \Big] \qquad \text{radiation}$$



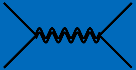
$$\langle p_\phi \rangle = \tfrac{1}{2}\langle \dot{\phi}^2 + m_\phi^2 \phi^2 \rangle \simeq 0$$

(matter)

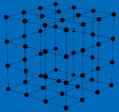
R. Kallosh and A. Linde, JCAP 10 (2013), 033

1. Preheating

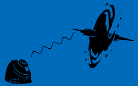
2. Weak coupling



3. Strong coupling



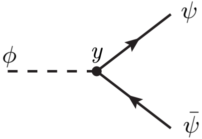
4. Constraints



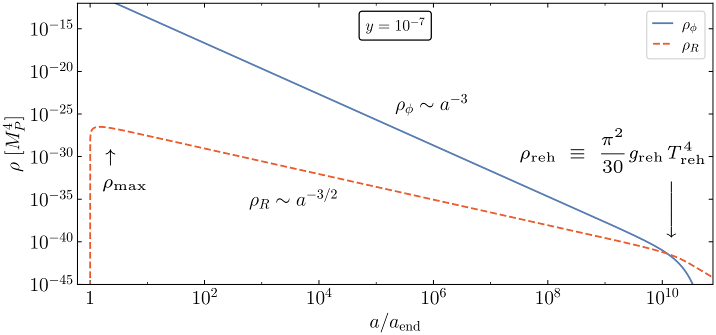
Perturbative decay of the inflaton

Decay into visible sector is assumed to be perturbative

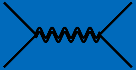
$$\mathcal{L} \supset -y\phi\bar{\psi}\psi$$

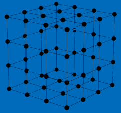


$$\Gamma_\phi = \frac{y^2}{8\pi} m_\phi$$



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



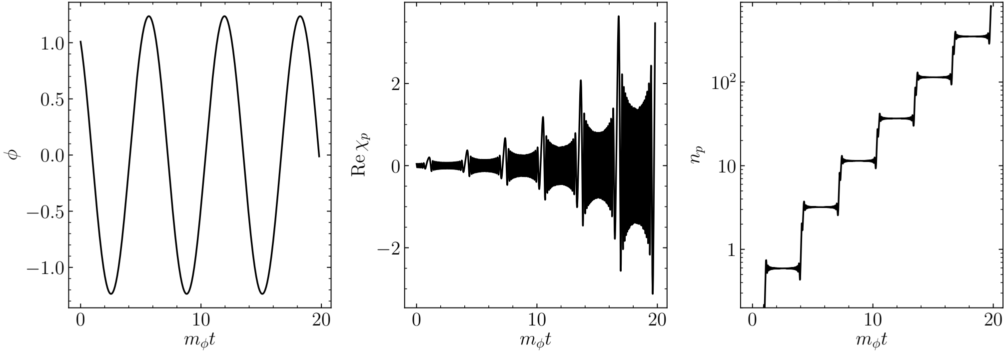


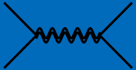
Scalar preheating

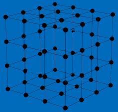
$$\left(\frac{d^2}{dt^2} + 3H\frac{d}{dt} + \frac{p^2}{a^2} + m_\chi^2 + \sigma\phi^2\right)\chi_p \;=\; 0$$

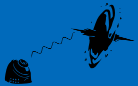
Neglecting expansion,

$$n_p = \frac{1}{2\omega_p}|\omega_p \chi_p - i\dot{\chi}_p|^2$$







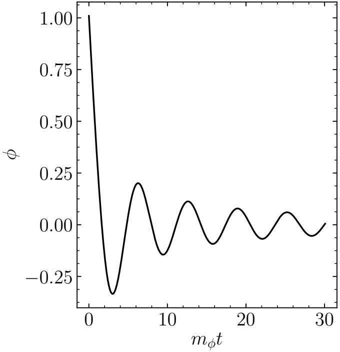


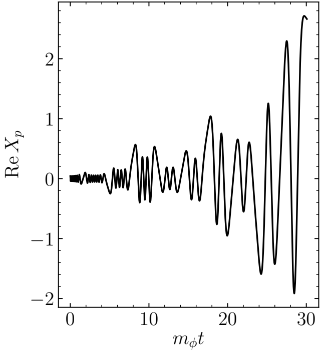
Scalar preheating

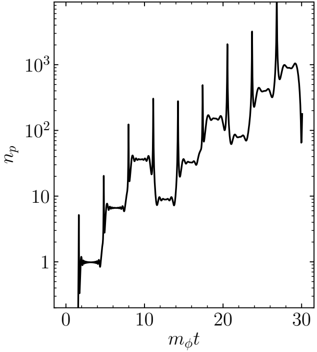
$$\left(\frac{d^2}{dt^2} + 3H\frac{d}{dt} + \frac{p^2}{a^2} + m_\chi^2 + \sigma\phi^2 \right) \chi_p = 0$$

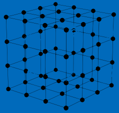
With expansion,

$$X = a\chi \qquad n_p = \frac{1}{2\omega_p}|\omega_p X_p - iX_p'|^2$$









The Boltzmann approximation

Phase space distribution as the solution of the PDE

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

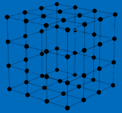
The process is a dissipation of fluctuations of the inflaton *condensate* into χ quanta

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

$$\mathcal{C}[f_\chi(|\boldsymbol{P}|,t)] = \frac{1}{P^0}\sum_{n=1}^{\infty}\int \frac{d^3\boldsymbol{K}}{(2\pi)^3 n_\phi}\frac{d^3\boldsymbol{P}'}{(2\pi)^3 2P'^0}(2\pi)^4\delta^{(4)}(K_n - P - P')|\overline{\mathcal{M}_n}|^2 \times \Big[f_\phi(K)(1+f_\chi(P))(1+f_\chi(P')) - f_\chi(P)f_\chi(P')(1+f_\phi(K))\Big]\,.$$

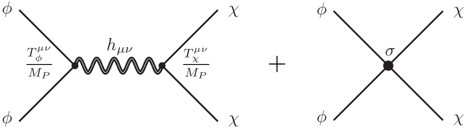
$K_n = (E_n,\boldsymbol{0}) = (nm_\phi,\boldsymbol{0}),\ f_\phi(P,t) = (2\pi)^3 n_\phi(t)\delta^{(3)}(\boldsymbol{P})$ and

$$|\langle\chi\chi|\exp\left(i\int d^4x\mathcal{L}_I\right)|\phi\rangle|^2 = \mathrm{Vol}_4\sum_{n=-\infty}^{\infty}|\mathcal{M}_n|^2(2\pi)^4\delta^{(4)}(p_n - p_A - p_B)\,.$$



The Boltzmann approximation

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

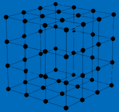


$$\mathcal{M} = -\frac{1}{M_P^2}\left[1 + \frac{2m_{\rm eff}^2}{s}\right] V(\phi) + \sigma\phi^2$$

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 $m_{\rm eff} = 0$



The Boltzmann approximation

With $1 + f_\phi(K) \simeq f_\phi(K)$ and $\beta(t) \equiv \sqrt{1 - \frac{m^2_{\rm eff}(t)}{m^2_\phi}}$

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

Introducing

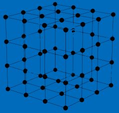
$$f_\chi(|\boldsymbol{P}|, t) \equiv \frac{1}{2}\left[\exp\left(2f^c_\chi(|\boldsymbol{P}|, t)\right) - 1\right]$$

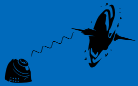
the solution is given by

$$f^c_\chi(|\boldsymbol{P}|,\, t) = \frac{\pi\hat{\sigma}^2\rho^2_\phi(\hat{t})}{16m^7_\phi\beta(\hat{t})^2 H(\hat{t})}\theta(t-\hat{t})\,\theta(\hat{t}-t_{\rm end}), \qquad \frac{a(t)}{a(\hat{t})} = \beta(\hat{t})\frac{m_\phi}{|\boldsymbol{P}|}$$

$$\simeq \frac{\pi\hat{\sigma}^2\rho^2_\phi(t)}{16m^7_\phi H(t)}\left(\frac{m_\phi}{|\boldsymbol{P}|}\right)^{9/2}\theta(m_\phi - |\boldsymbol{P}|)\,\theta\left(|\boldsymbol{P}| - m_\phi\left(\frac{a_{\rm end}}{a(t)}\right)\right)$$

$(t_{\rm end} \ll t \ll t_{\rm reh},\ \beta \simeq 1)$





The Boltzmann approximation

Useful notation: if $f_\chi(P) \equiv f_\chi(P/P_0)$ at decoupling ($t = t_\star$), then for $t > t_\star$

$$f_\chi\left(\frac{P}{P_0}\,\frac{a(t)}{a_\star}\right) = f_\chi\left(\frac{P\,a(t)/a_0}{P_0\,a_\star/a_0}\right) = f_\chi\Bigg(\frac{p}{\underbrace{P_0\,a_\star/a_0}_{T_\star}}\Bigg) \equiv f_\chi(q)$$

C. Ma, E. Bertschinger, Astrophys. J. 455 (1995) 7; D. Blas, J. Lesgourgues, T. Tram, JCAP 07 (2011) 034

Here

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

so that

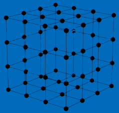
$$n_\chi\left(\frac{a}{a_{\rm end}}\right)^3 = \left(\frac{a}{a_{\rm end}}\right)^3 \int \frac{d^3\boldsymbol{P}}{(2\pi)^3} f_\chi(P,t) = \frac{m_\phi^3}{2\pi^2}\int dq\, q^2 f_\chi(q,t)$$

and $1 \leq q \leq \dfrac{a(t)}{a_{\rm end}}$

1. Preheating

2. Weak coupling

3. Strong coupling

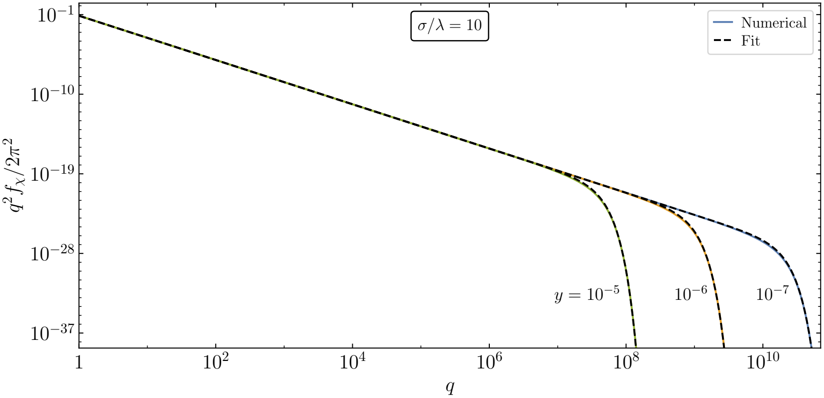


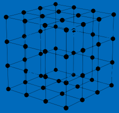
4. Constraints

The Boltzmann approximation

Extending the solution beyond the end of reheating,

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





Non-perturbative particle production

Equation of motion for χ

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

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

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

the equation of motion for the mode functions is

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

with

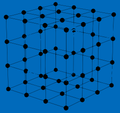
$$\omega_p^2 \;=\; p^2 + a^2 m_{\rm eff}^2 \;=\; p^2 + a^2\left(m_\chi^2 + \sigma\phi^2 + \frac{1}{6}R\right)$$

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

1. Preheating

2. Weak coupling

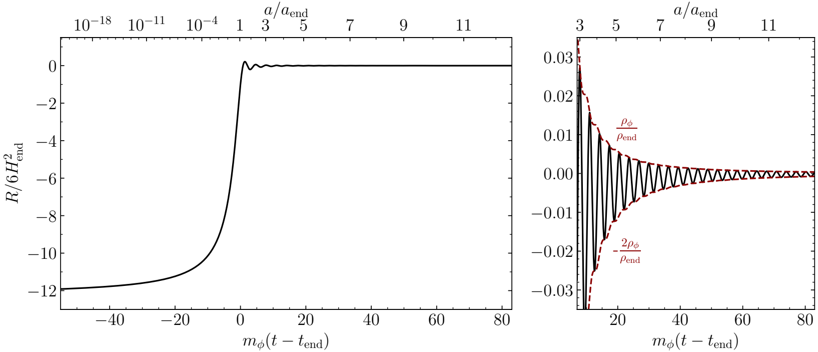
3. Strong coupling



4. Constraints

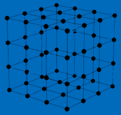
Non-perturbative particle production

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

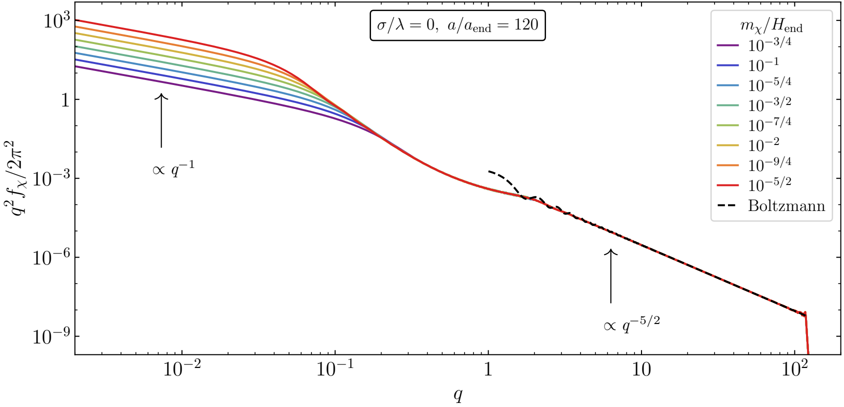


$$\omega_p^2(t_{\rm end}) = p^2 + a_{\rm end}^2\left(m_\chi^2 + \sigma\phi^2 - H_{\rm end}^2\right)$$

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



Pure gravitational production



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

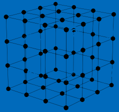
N. Herring, D. Boyanovsky and A. Zentner, PRD 101 (2020) , 083516

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

1. Preheating

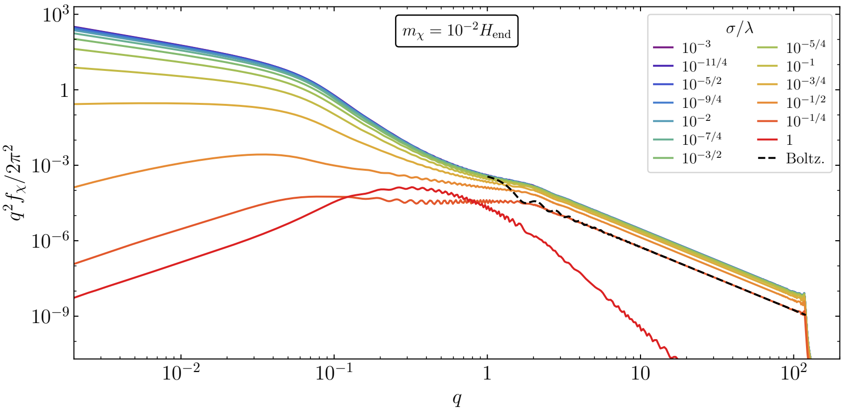
2. Weak coupling

3. Strong coupling

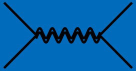


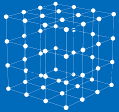
4. Constraints

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 χ can influence the background dynamics

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

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

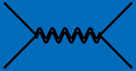
where

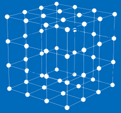
$$\langle\chi^2\rangle = \frac{1}{(2\pi)^3 a^2} \int d^3\boldsymbol{p} \left(|X_p|^2 - \frac{1}{2\omega_p} \right) .$$

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 $\rho_\chi \lesssim 0.1\rho_\phi$

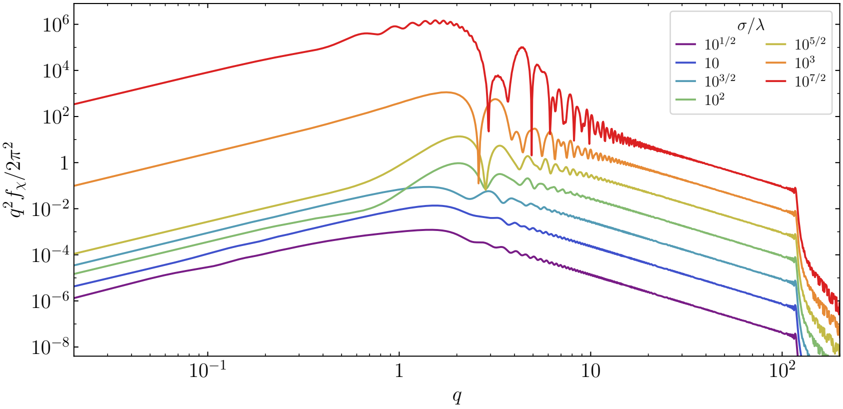


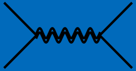


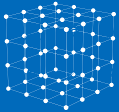
Strong coupling: Hartree

At strong coupling the resonant production of χ 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 χ into ϕ disrupts the inflaton condensate

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

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

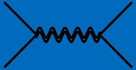
$$
\begin{aligned}
\ddot{\phi} + 3H\dot{\phi} - \frac{\nabla^2\phi}{a^2} + V_{,\phi} &= 0 \\
\ddot{\chi} + 3H\dot{\chi} - \frac{\nabla^2\chi}{a^2} + V_{,\chi} &= 0
\end{aligned}
$$

Software of choice: `CosmoLattice (v1.0)` D. Figueroa, et al., arXiv:2102.01031 [astro-ph.CO]

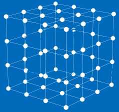
Caveat: no metric perturbations

1. Preheating

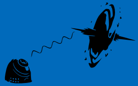
2. Weak coupling



3. Strong coupling



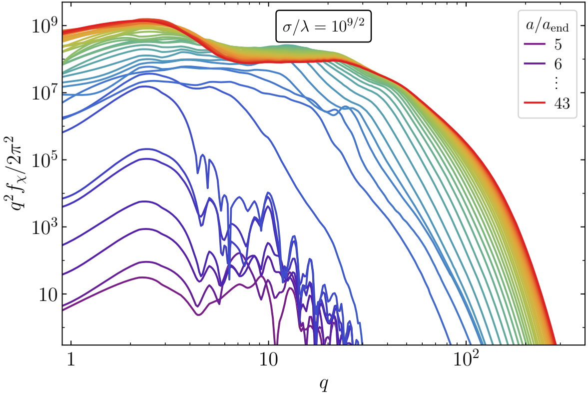
4. Constraints

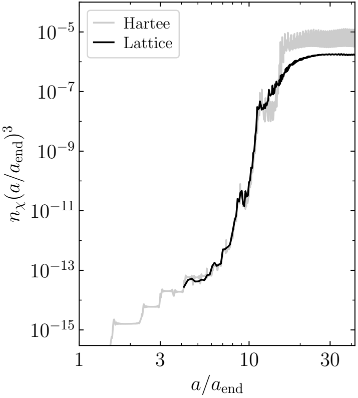


Strong coupling: Lattice

Re-scattering leads to a broadening distribution with pseudo-thermal tail for ϕ and χ

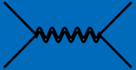
$$f_\chi \sim e^{-\alpha(\sigma/\lambda;t)\,q} \quad \text{in the UV}$$



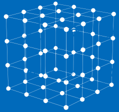


1. Preheating

2. Weak coupling



3. Strong coupling



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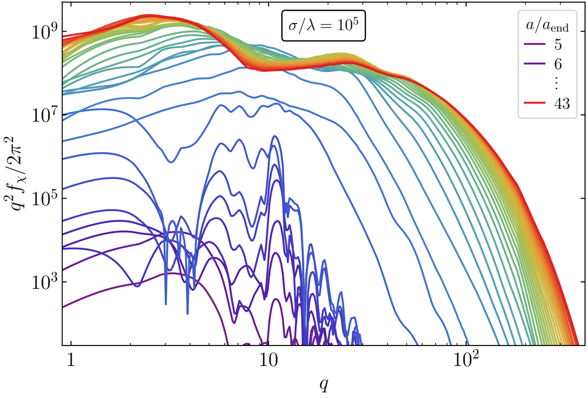
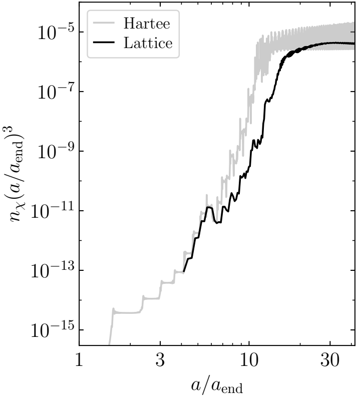
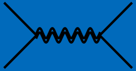
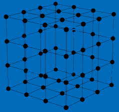
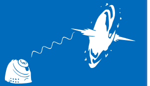




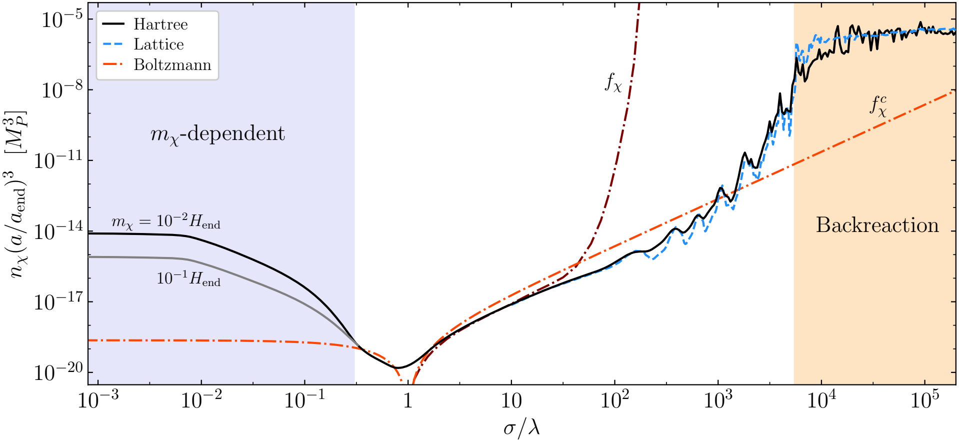


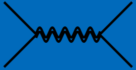


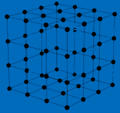


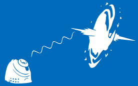
Comoving number densities

Boltzmann has a very limited range of applicability







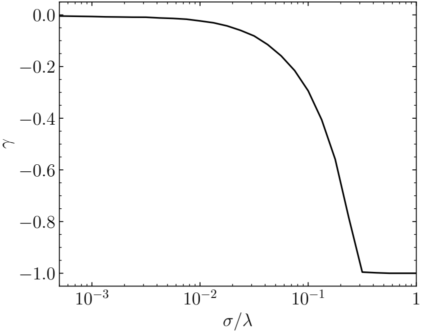


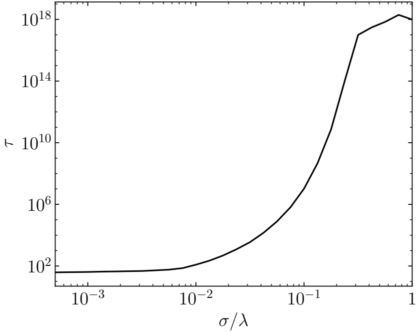
Relic abundance at weak coupling

Saturating the DM relic abundance

$$\Omega_\chi \simeq \frac{m_\chi n_\chi}{\rho_c} = \frac{1}{3 q_0^3} \left(\frac{H_{\rm end} H_0}{M_P^2} \right) \left(\frac{m_\chi}{H_{\rm end}} \right) \frac{1}{2\pi^2} \int_{q_0}^{\infty} dq \, q^2 f_\chi(q, t)$$

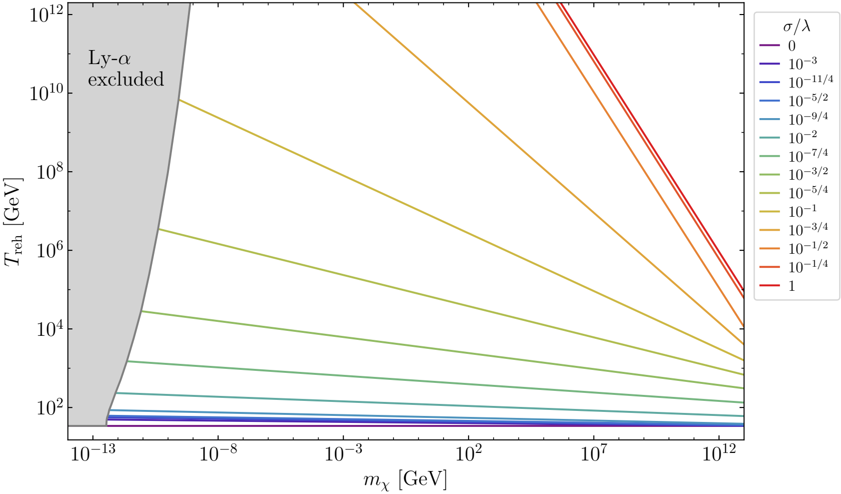
$$\Omega_\chi h^2 = 0.12 \quad \Rightarrow \quad \left(\frac{T_{\rm reh}}{1\,{\rm GeV}} \right) \simeq \tau \left(\frac{m_\chi}{1\,{\rm GeV}} \right)^\gamma$$

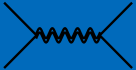


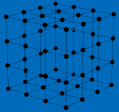


Relic abundance at weak coupling

Saturating the DM relic abundance







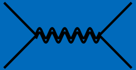
Relic abundance at strong coupling

Saturating the DM relic abundance

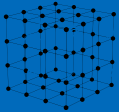
$$\Omega_\chi h^2 \simeq 0.12 \left(\frac{2.05 \times 10^{-11}}{\lambda}\right) \left(\frac{n_\chi (a/a_{\rm end})^3}{1.8 \times 10^{-12}\, M_P^3}\right) \left(\frac{m_\chi}{1\ \mathrm{GeV}}\right) \left(\frac{T_{\rm reh}}{10^{10}\ \mathrm{GeV}}\right)$$

1. Preheating

2. Weak coupling



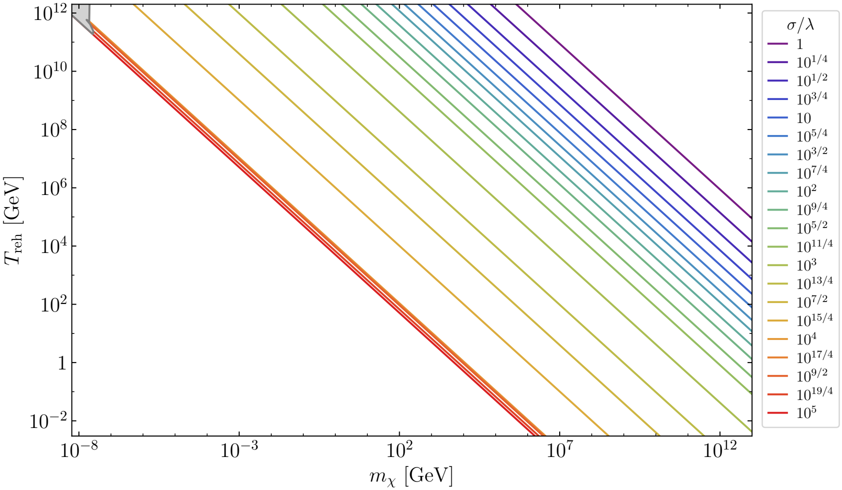
3. Strong coupling



4. Constraints

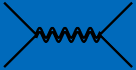
Relic abundance at strong coupling

Saturating the DM relic abundance

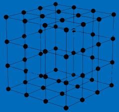


1. Preheating

2. Weak coupling

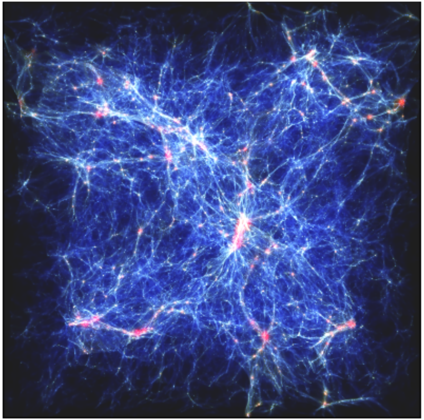


3. Strong coupling

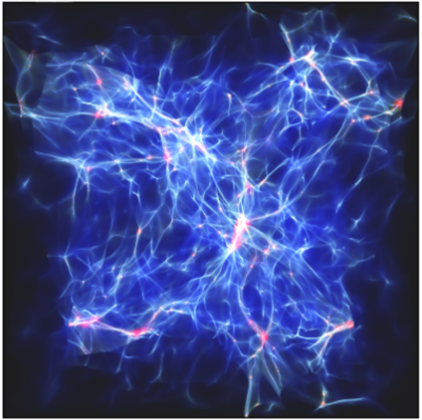


4. Constraints

Light dark relics from reheating



CDM

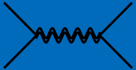


WDM (0.5 keV)

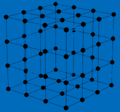
J. Baur et al., JCAP 08 (2016), 012

1. Preheating

2. Weak coupling

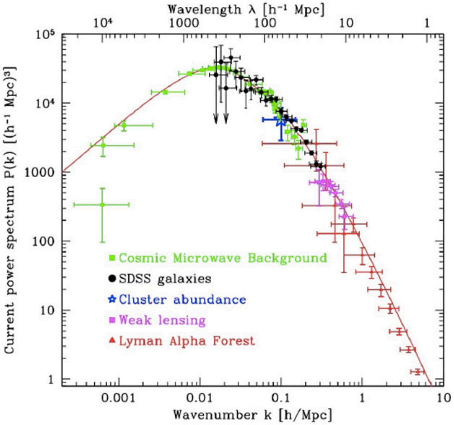


3. Strong coupling

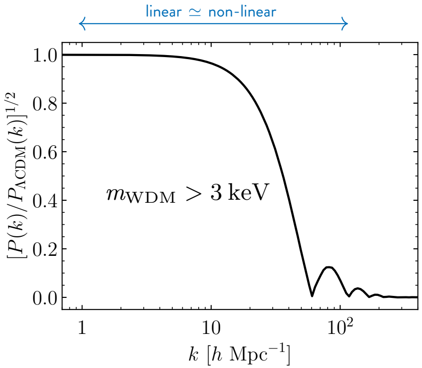


4. Constraints

How warm is out-of-equilibrium dark matter?



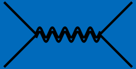
R. Murgia, V. Iršič and M. Viel, PRD 98 (2018), 083540



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

1. Preheating

2. Weak coupling



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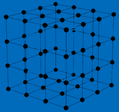


4. Constraints

How warm is out-of-equilibrium dark matter?

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

$$\downarrow$$

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

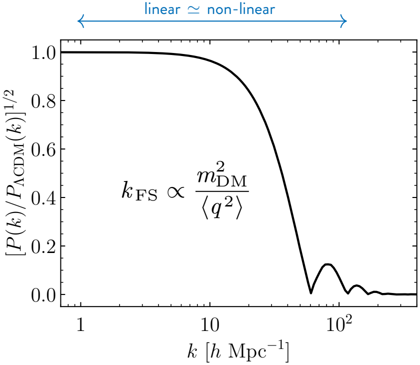
$$k^2_{\rm FS}(a) = \frac{9}{10}\,\frac{\mathcal{H}^2}{w}$$

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

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

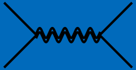
$$w(m_{\rm DM}) = w_{\rm WDM}(m_{\rm WDM}) \longrightarrow$$

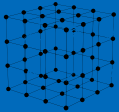
R. Murgia, V. Iršič and M. Viel, PRD 98 (2018), 083540



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-α constraint

From Boltzmann f_χ^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

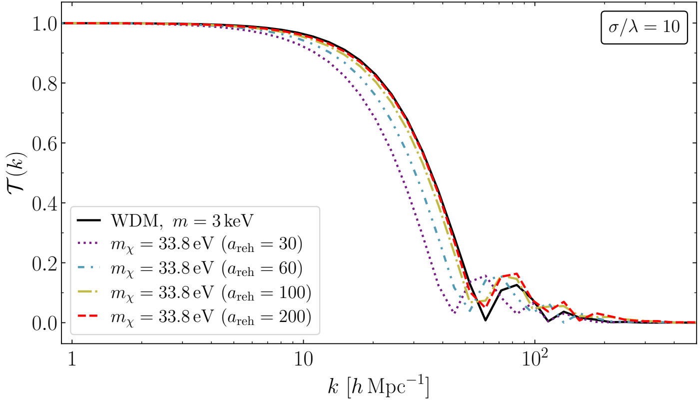
$$\begin{aligned} m_{\rm DM} &> 15.78\,{\rm keV}\left(\frac{m_{\rm WDM}}{3\,{\rm keV}}\right)^{4/3} m_\phi\, \rho_{\rm end}^{-1/4}\, g_{\rm reh}^{-1/12} \\ &\simeq 32.4\,{\rm eV}\left(\frac{m_{\rm WDM}}{3\,{\rm keV}}\right)^{4/3}\left(\frac{\lambda}{2.05\times 10^{-11}}\right)^{1/4}\left(\frac{427/4}{g_{\rm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

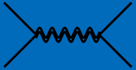
Weaker than WDM one, and without dependence on duration of reheating!

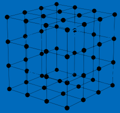
Lyman-α constraint

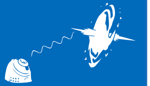
For all non-lattice, $\sigma \neq \lambda$ cases, the perturbative tail is present

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





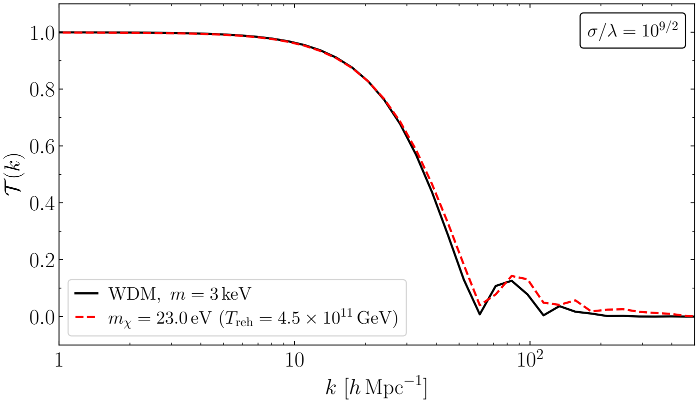




Lyman-α constraint

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

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



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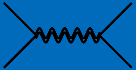
2. Weak coupling



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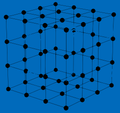
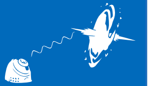
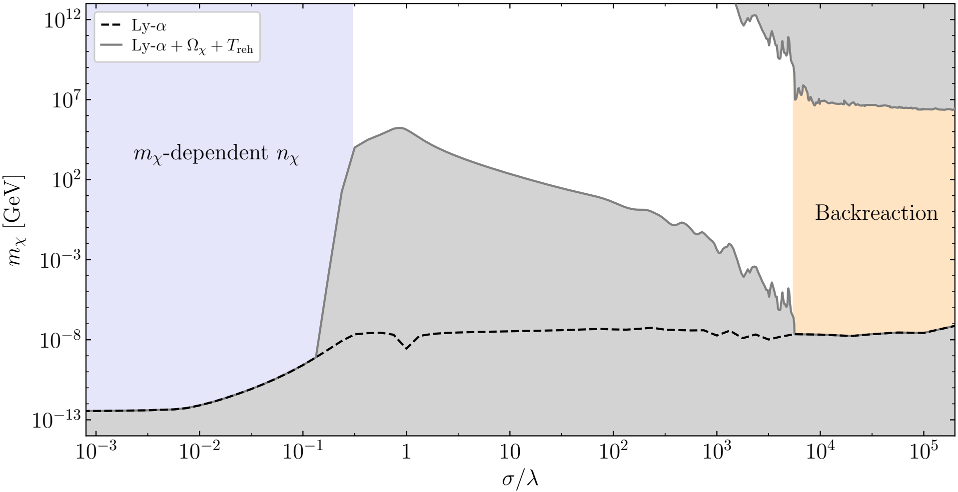


4. Constraints



The allowed parameter space



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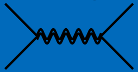
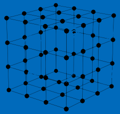
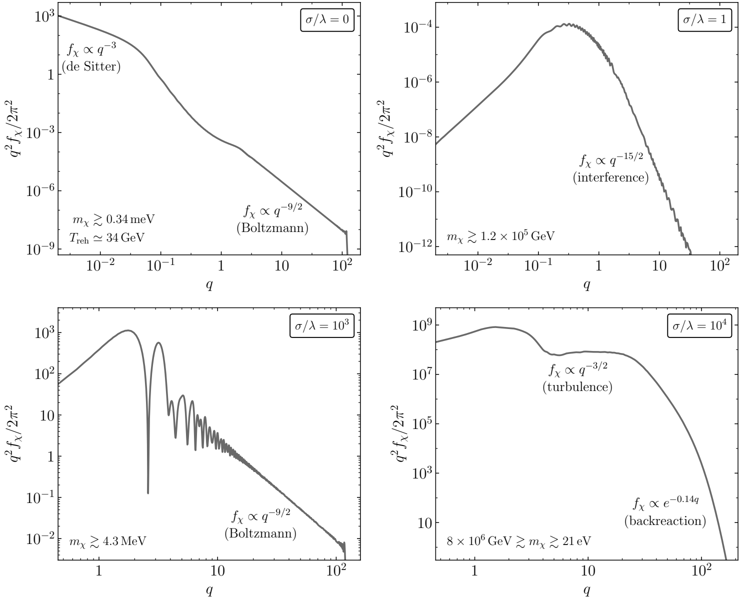


3. Strong coupling



4. Constraints

Summary



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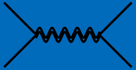

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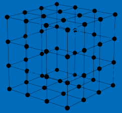
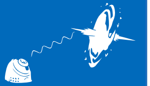
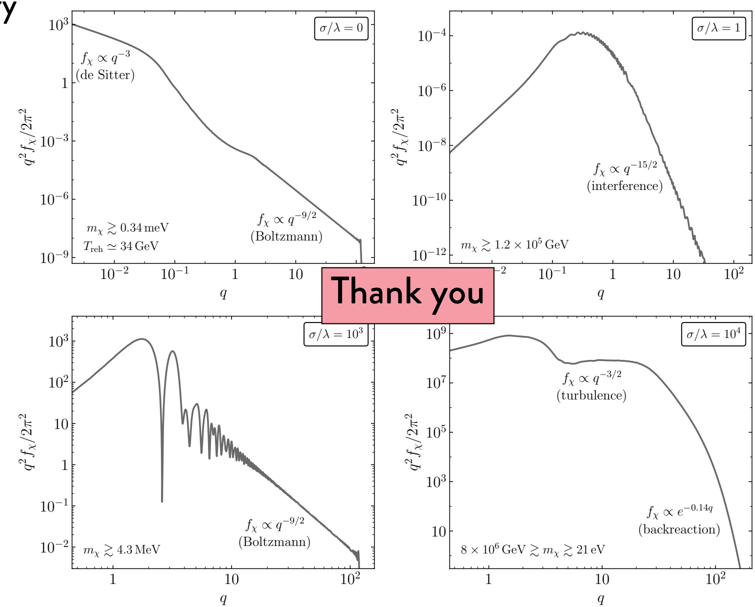


4. Constraints



Summary



Thank you