CONSTRAINTS ON SCALAR DARK MATTER PRODUCTION FROM THE INFLATON

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Based on: arXiv:2206.08940, arXiv:2303.07359 w/ M. A.G. Garcia and M. Pierre

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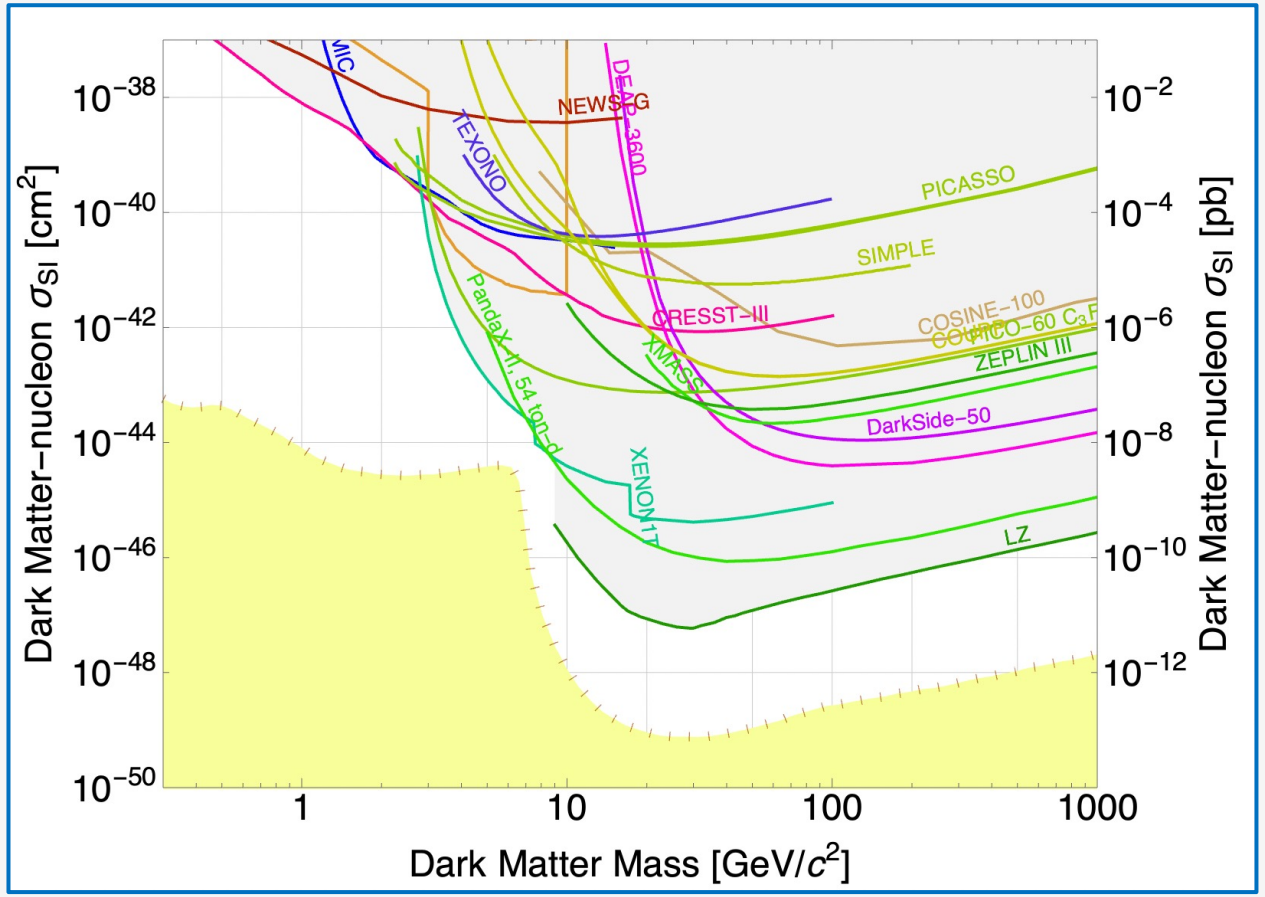
Motivation

WIMPS have not been detected yet!



SuperCDMS Dark Matter Limit Plotter

Consider feebly-interacting massive particles (FIMPs) instead:

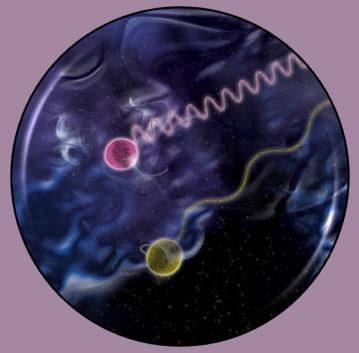
- They are never in thermal equilibrium.
- Production occurs via freeze-in mechanism.
- Avoids direct and indirect detection.
- Depends on the initial conditions of inflation and the reheating mechanism.

In such models, the coupling between the visible and dark sectors is assumed to be sufficiently small to ensure out-of-equilibrium production.

One can consider purely gravitational production of dark matter!

Overview

Particle creation in expanding universes.

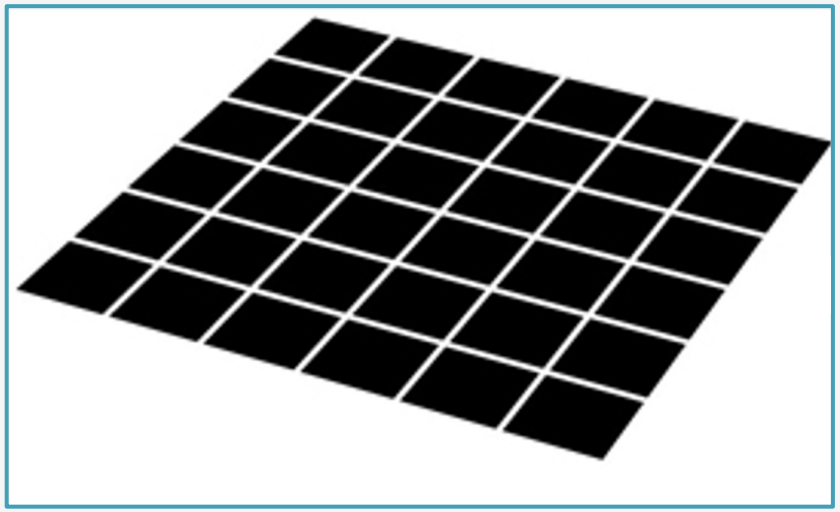


Gravitationally produced scalar dark matter.

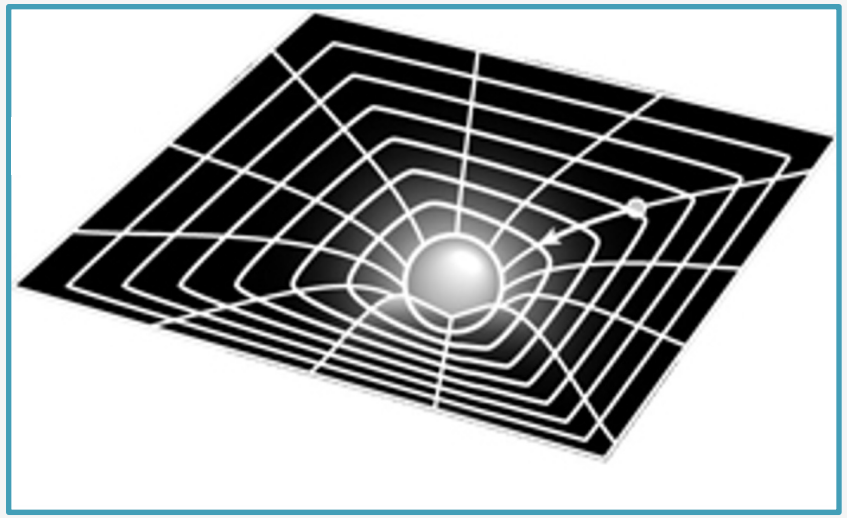
Dark matter creation during inflation and reheating.

Quantization in Curved Spacetime

Our starting point: QFT in curved spacetime.



Flat spacetime



Curved spacetime

- Massive scalar field action in curved spacetime:

$$\mathcal{S} = \int d^4x \sqrt{-g}\left[\frac{1}{2}(\partial_\mu\phi)^2 + \frac{1}{2}(\partial_\mu\chi)^2 - V(\phi) - \frac{1}{2}\left(m_\chi^2 + \sigma\phi^2\right)\chi^2 + \mathcal{L}_{\phi-\mathrm{SM}}\right]$$

$g \equiv \det(g_{\mu\nu})$ is the metric determinant

$M_P = 1/\sqrt{8\pi G_N} \simeq 2.435 \times 10^{18}\ \mathrm{GeV}$

R is the Ricci curvature

Inflationary Potential

Direct Coupling

Inflaton to SM Coupling

Non-Perturbative Production of Dark Matter

We introduce a scalar dark matter field, χ,

$$V_\chi = \frac{1}{2} m^2 \chi^2$$

Dark matter action

$$\mathcal{S} = \int d^4x \sqrt{-g} \left[\frac{1}{2} (\partial_\mu \chi)^2 - \frac{1}{2} m_\chi^2 \chi^2 + \sigma \phi^2 \chi^2 \right]$$

Minimal Coupling

$$\xi = 0$$

Models with non-minimal coupling: M. A. G. Garcia, M. Pierre, S. Verner; to appear this week

It leads to :

$$\left[\frac{d^2}{d\tau^2} - \nabla^2 - \frac{a''}{a} + a^2 m_\chi^2 + \sigma a^2 \phi^2 \right] X(\tau, \mathbf{x}) = 0$$

Introduced a rescaled field : $X \equiv a\chi$

V. Mukhanov and S. Winitzki "Quantum Effects in gravity"

Conformal time

$$dt/d\tau = a$$

$$' \equiv d/d\tau$$

The momentum modes of the field X

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

where $\mathbf{k}$ is the comoving momentum and $\hat{a}^\dagger_\mathbf{k}$ and $\hat{a}_\mathbf{k}$ are the creation and annihilation operators

Non-Perturbative Production of Dark Matter

We impose the Wronskian condition

$$X_k X_k^{*\prime} - X_k^* X_k' = i$$

To solve the mode equations, we choose the positive frequency of the Bunch-Davies vacuum:

$$X_k(\tau_0) = \frac{1}{\sqrt{2\omega_k}}, \qquad X_k'(\tau_0) = -\frac{i\omega_k}{\sqrt{2\omega_k}}$$

T.S Bunch and P.C. W. Davies, 1977

These initial conditions correspond to the zero-particle initial state.

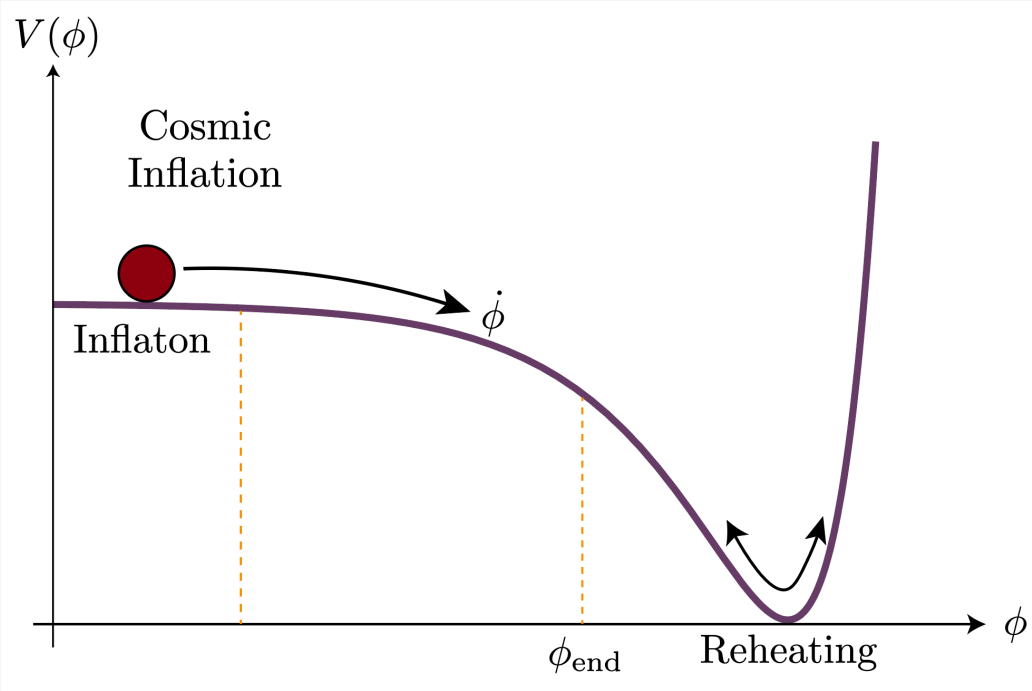
We find the mode equations:

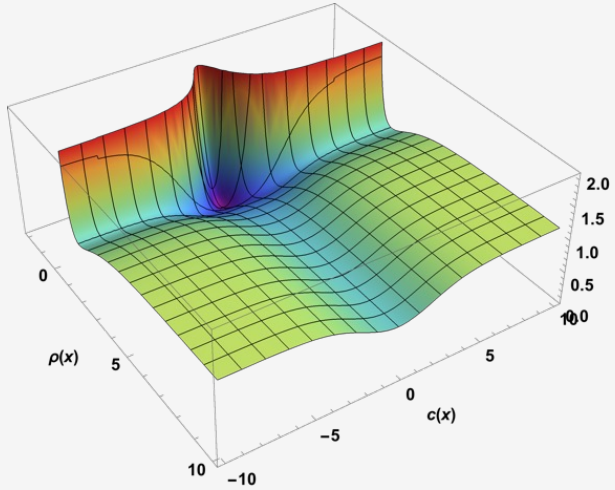
$$\omega_k^2 = k^2 + a^2 m_{\rm eff}^2 \longrightarrow m_{\rm eff}^2 \equiv m_\chi^2 + \sigma\phi^2 - \left(\frac{1-3w}{2}\right) H^2$$

For low momentum (IR) modes, the mode frequency squared may become negative during inflation if $k^2 < a^2|m_{\rm eff}^2|$, leading to a fast mode growth during inflation due to the tachyonic instability

$$m_\chi \ll H \qquad k^2 \lesssim a^2\left(\frac{1-3w}{2}H^2 - \sigma\phi^2\right)$$

Dark Matter Production During Inflation





$$\omega_k^2 \equiv k^2 + a^2\left(\frac{R}{6} + m_\chi^2 + \sigma\phi^2\right)$$

Since the scale factor a grows, the mode frequency increases
This leads to the growth of n_k.

End of inflation, when $V_{\rm end} = \dot{\phi}_{\rm end}^2$ and $H_{\rm end}^2 M_P^2 = V_{\rm end}/2$

Tachyonic growth for the low momentum (IR) modes

$$\sigma \lesssim \left(\frac{1-3w}{2}\right)\frac{H^2}{M_P^2}$$

T-Model and Starobinsky Model Constraints

Starobinsky Model of Inflation

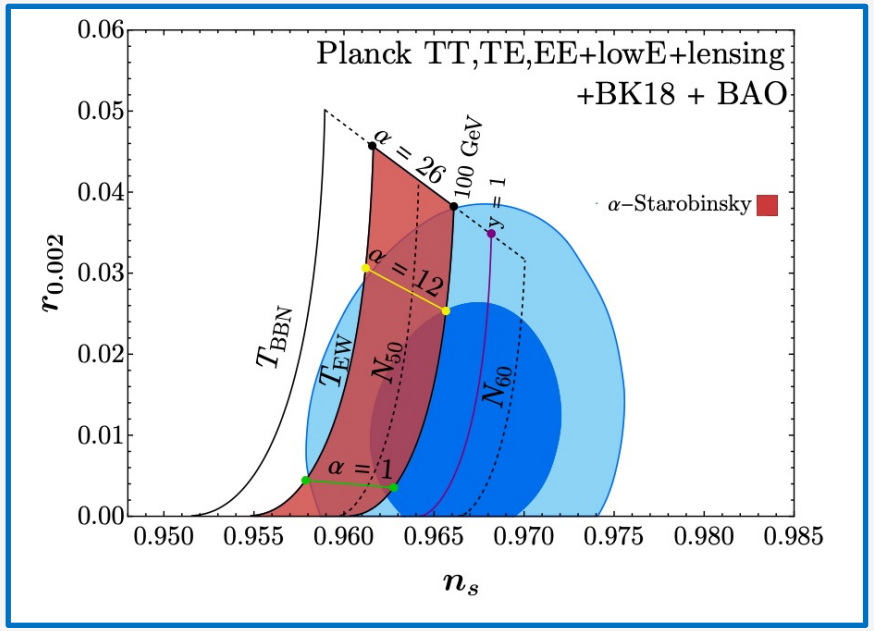
$$V(\phi) = \frac{3}{2}\lambda M_P^4 \left[1 - e^{-\sqrt{\frac{2}{3}}\frac{\phi}{M_P}}\right]^2$$

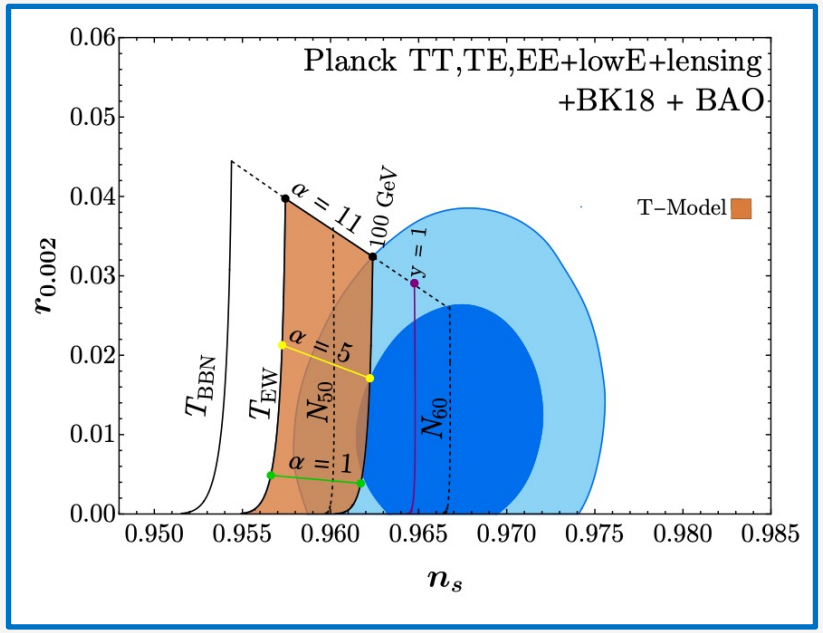
$\lambda \simeq 8 \times 10^{-11}$ $H_{\rm end} \simeq 7 \times 10^{12}\,{\rm GeV}$

T-model of Inflation

$$V(\phi) = \lambda M_P^4 \left[\sqrt{6}\tanh\left(\frac{\phi}{\sqrt{6}M_P}\right)\right]^2$$

$\lambda \simeq 2 \times 10^{-11}$ $H_{\rm end} \simeq 6 \times 10^{12}\,{\rm GeV}$

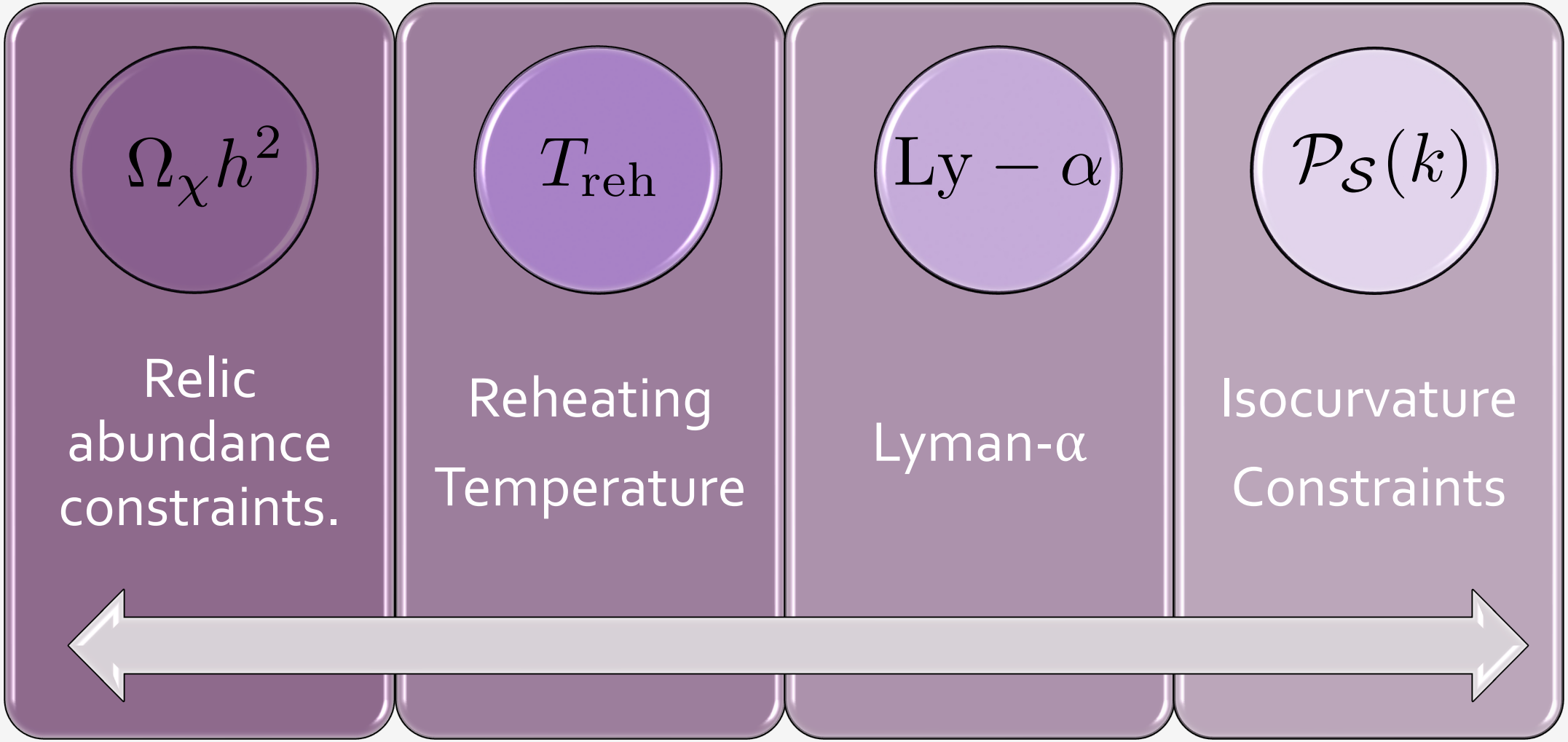




BICEP/Keck constraints on Starobinsky models (left) and T-models (right). The panel compares the 68% and 95% C. L. constraints in the (n_s, r) plane with the model predictions for different number of e-folds N_{50} and N_{60}.

J. Ellis, M. Garcia, D. Nanopoulos, K. Olive, S. Verner, 2021

Overview


$\Omega_\chi h^2$
Relic abundance constraints.
$T_{\rm reh}$
Reheating Temperature
$\mathrm{Ly}-\alpha$
Lyman-α
$\mathcal{P}_{\mathcal{S}}(k)$
Isocurvature Constraints

Dark Matter Production During Inflation and Reheating

Re-scaled dimensionless comoving momentum

$$q \equiv \frac{K}{m_\phi}\left(\frac{a}{a_{\rm end}}\right)$$

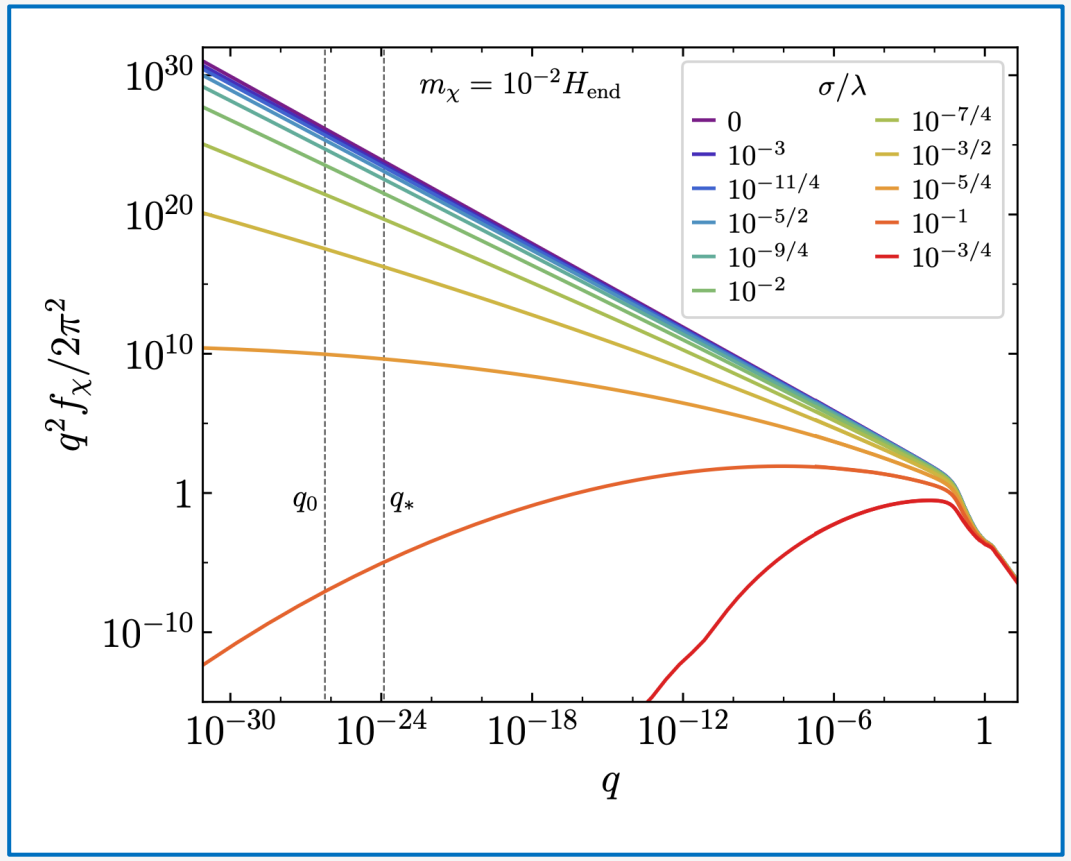
K is the physical momentum
m_ϕ is the inflaton mass

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

$$f_\chi \propto q^{-2\nu}$$

$$\nu = \sqrt{9/4 - m_{\rm eff}^2/H^2}$$

$$m_{\rm eff}^2 \equiv m_\chi^2 + \sigma\phi^2 - \left(\frac{1-3w}{2}\right)H^2$$



Phase space distribution (PSD) of a gravitationally excited scalar field (evaluated at a/a_{end} = 120) for a range of dark matter masses, coded by color (T-model).

$$f_\chi \propto 1/q^3$$

$\sigma = 0, \quad m_\chi \ll H$

$q \ll 1$

$p \ll H_{\rm end}$

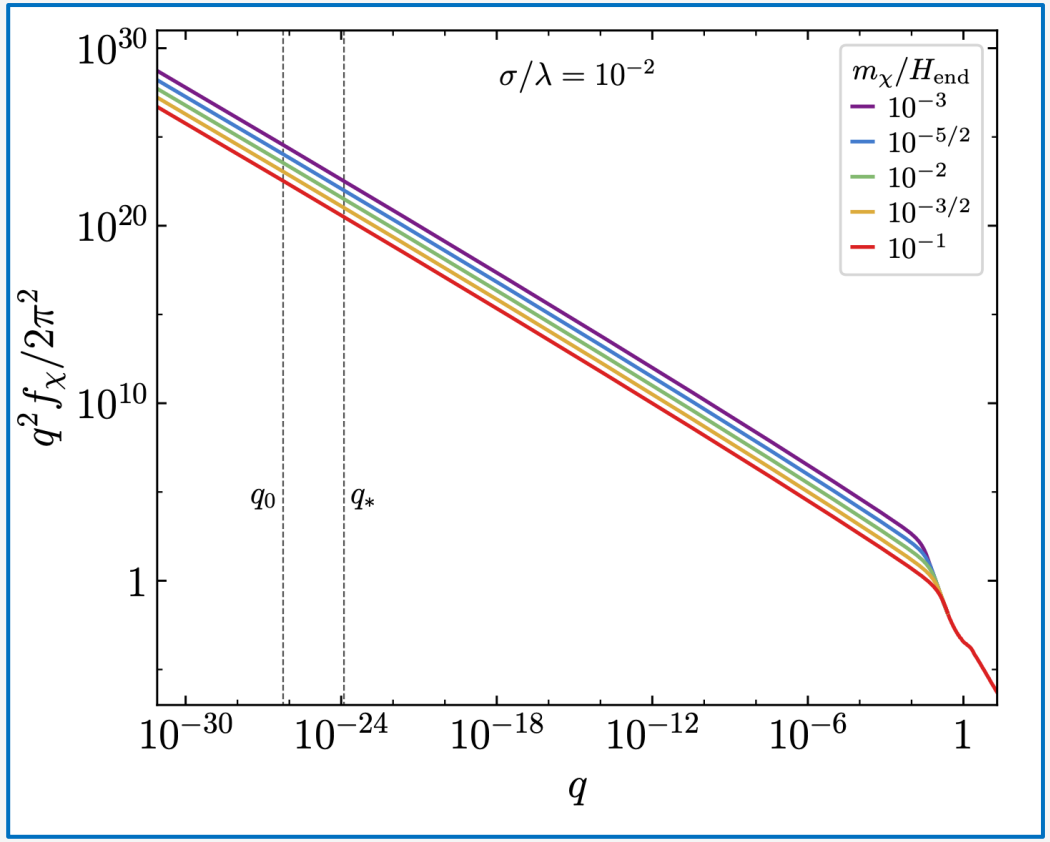
Dark Matter Production During Inflation and Reheating

$$f_\chi \propto q^{-2\nu}$$

$$\nu = \sqrt{9/4 - m_{\rm eff}^2/H^2}$$

$$m_{\rm eff}^2 \equiv m_\chi^2 + \sigma\phi^2 - \left(\frac{1-3w}{2}\right) H^2$$

Therefore, the corresponding number density diverges logarithmically in the IR in the absence of a cutoff scale if



Phase space distribution (PSD) of a gravitationally excited scalar field (evaluated at a/a_{end} = 120) for a range of dark matter masses, coded by color (T-model).

A. Starobinsky and J. Yokoyama, 1994

"The lower cut-off is constant in the momentum space because it is determined by the moment when the de Sitter expansion begins"

$$f_\chi \propto 1/q^3$$

$$\sigma = 0, \quad m_\chi \ll H$$

$$q \ll 1$$

$$p \ll H_{\rm end}$$

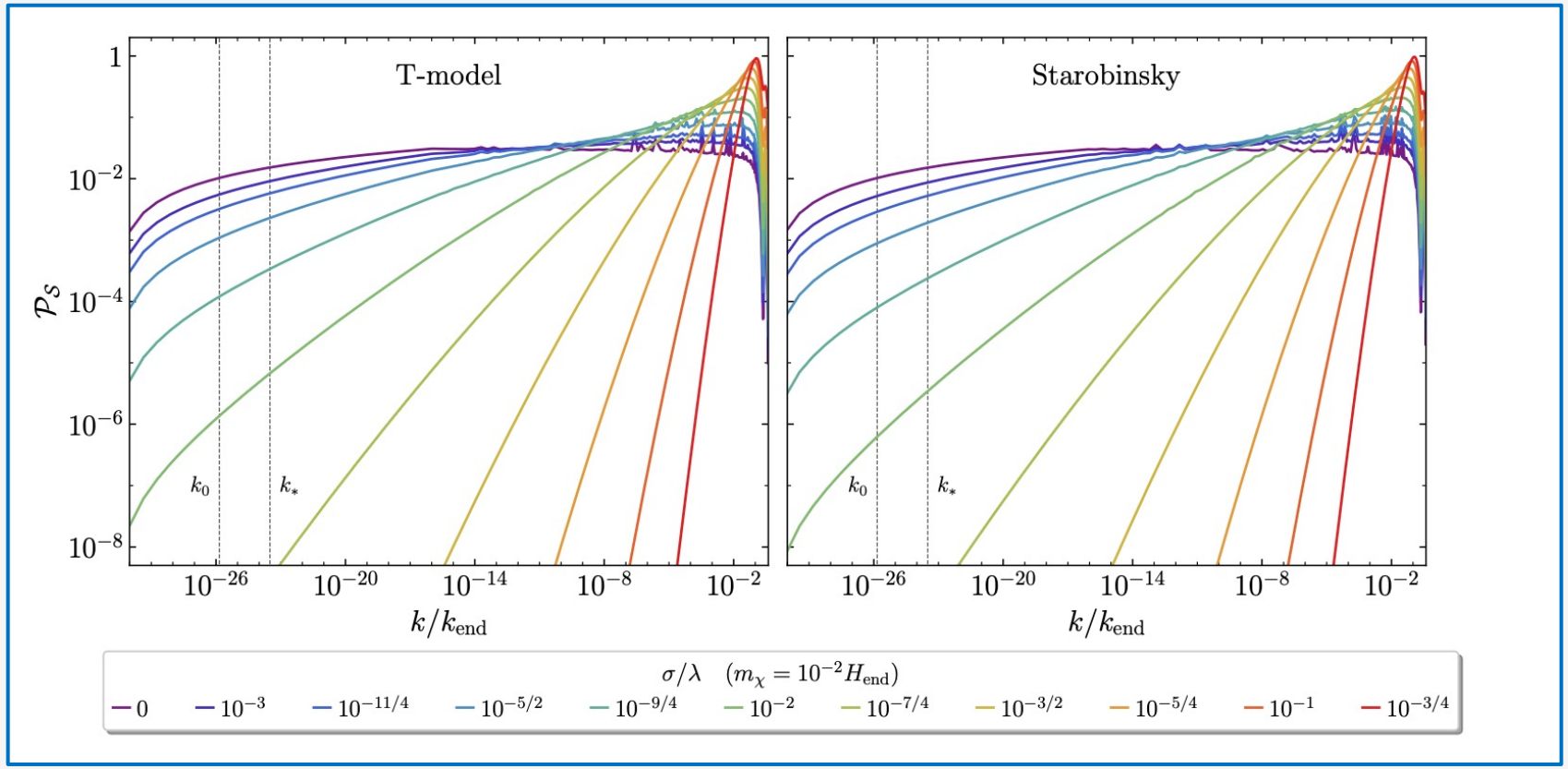
The present-horizon cutoff:

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

$$R_{\rm rad} \equiv \frac{a_{\rm end}}{a_{\rm rad}} \left(\frac{\rho_{\rm end}}{\rho_{\rm rad}}\right)^{1/4} \simeq \left(\frac{\Gamma_\phi}{H_{\rm end}}\right)^{1/6}$$

J. Martin and C. Ringeval, 2010

Isocurvature Constraints



DM isocurvature power spectrum for different inflaton-DM couplings, with each coupling represented by a different color. The vertical lines indicate the present horizon scale and the Planck pivot scale.

$$\mathcal{P}_{\mathcal{S}}(k) = \frac{k^3}{2\pi^2 \rho_\chi^2} \int d^3\mathbf{x} \, \langle \delta\rho_\chi(\mathbf{x}) \delta\rho_\chi(0) \rangle e^{-i\mathbf{k}\cdot\mathbf{x}}$$

where ρ_χ and $\delta\rho_\chi$ denote the DM energy density and its fluctuation

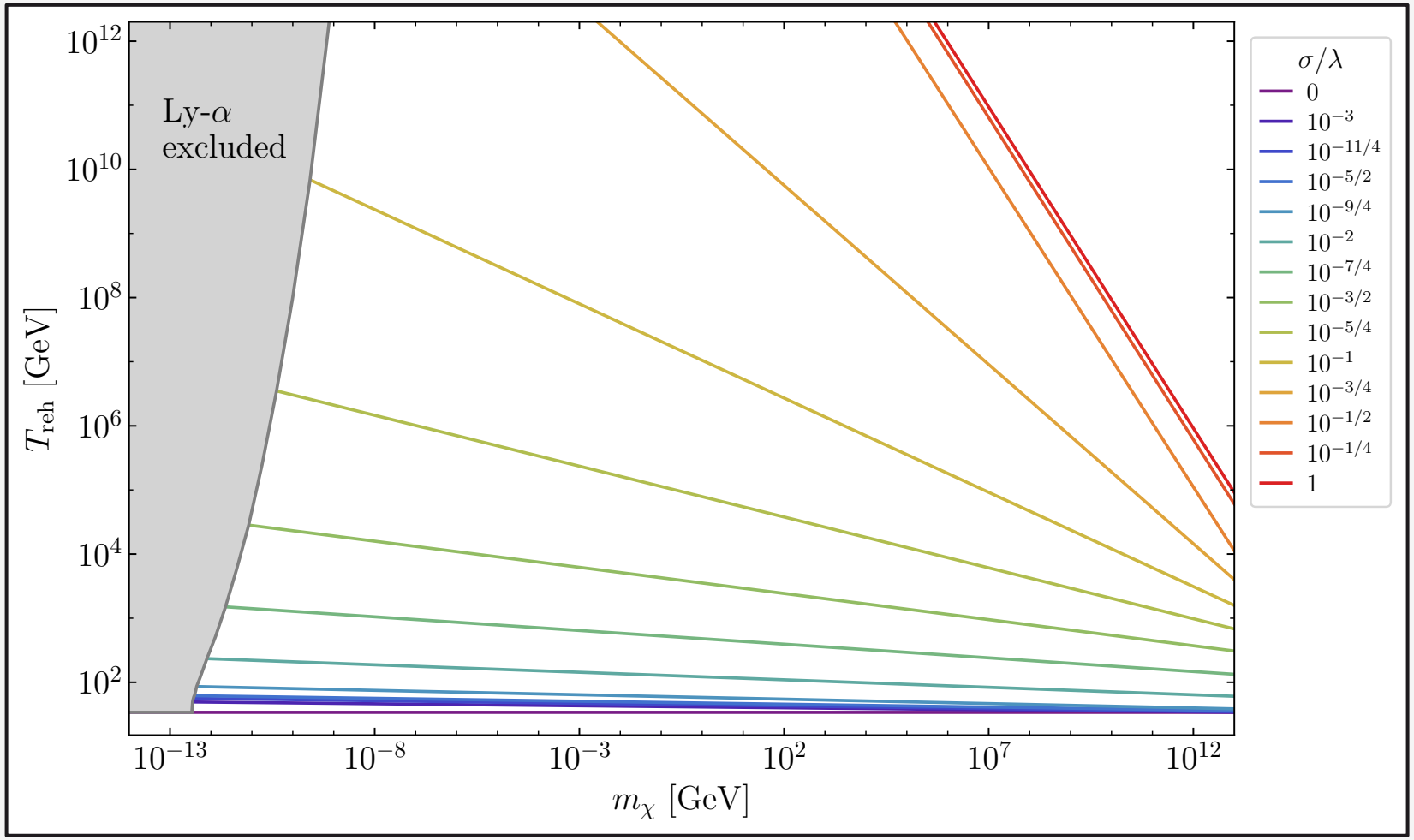
$$\mathcal{P}_{\mathcal{S}}(k_*) \lesssim 8.3 \times 10^{-11}$$

from *Planck*

$$m_\chi \gtrsim 0.54\, H_* \,, \qquad [\sigma = 0]$$

$$\sigma \gtrsim (0.01 - 0.02) \left(\frac{H_*}{M_P} \right)^2$$

Structure Formation Constraints



Parameter space for light scalar dark matter ($m_\chi < m_\phi$) with a weak coupling to the inflaton, $\sigma/\lambda < 1$. Each line corresponds to the observed dark matter abundance $\Omega_\chi h^2 = 0.12$. The gray shaded region shows the excluded parameter space by the Lyman-α measurement of the matter power spectrum.

For out-of-equilibrium DM production mechanisms, the Lyman-α bound is dependent on the details of the production and decoupling of the dark particles

$$m_\chi^{\text{Ly-}\alpha} = m_{\rm WDM}^{\text{Ly-}\alpha}\left(\frac{T_\star}{T_{\rm WDM,0}}\right)\sqrt{\frac{\langle q^2\rangle}{\langle q^2\rangle_{\rm WDM}}}$$

$T_{\rm WDM,0}$ is the WDM temperature

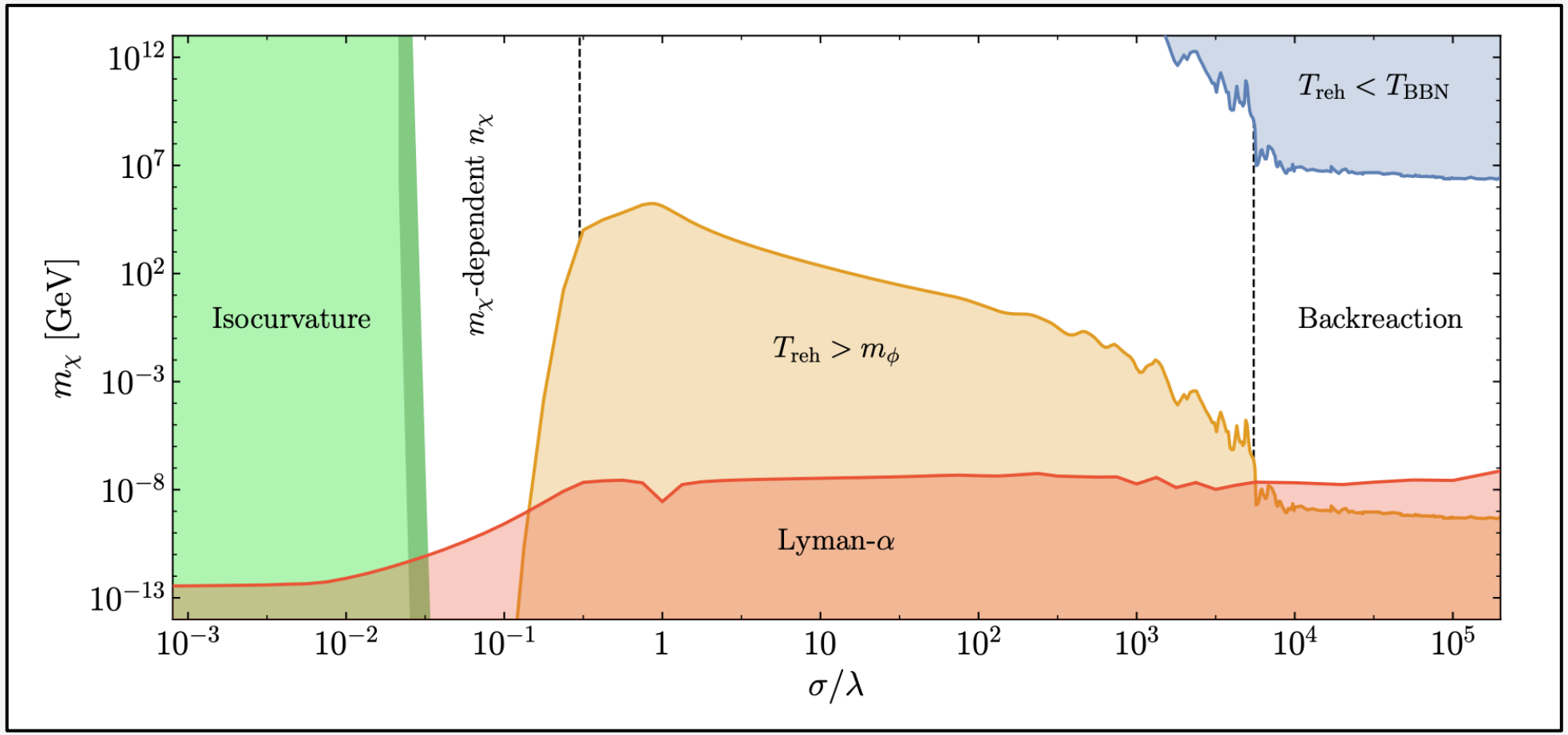
$T_\star$ is the characteristic energy scale of the produced DM,

$$T_\star = m_\phi(a_{\rm end}/a_0)$$

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

$$\langle q^2\rangle_{\rm WDM} \simeq 12.93$$

Combined Constraints



The allowed parameter space (white) for the DM mass and its coupling to the inflaton, in which the relic abundance constraint can be saturated. Forbidden regions correspond to the overproduction of isocurvature (green), the oversuppression of small structure (red), the constraint for a reheating temperature below that required for successful Big Bang Nucleosynthesis (blue), or the constraint for a reheating temperature above what is allowed by perturbative reheating (orange). The width of the boundary of the isocurvature constraint corresponds to a number of e-folds $47 < N_* < 55$. The leftmost part of the allowed space corresponds to a region where the power spectrum is sensitive to the DM mass, while the rightmost region corresponds to particle production via broad resonance.

Conclusions

- In the absence of a direct inflaton-dark matter coupling, i.e. σ = 0, the isocurvature power spectrum is nearly scale-invariant and must satisfy the constraint:

$$m_\chi \gtrsim 0.54\, H_* \,, \qquad [\sigma = 0]$$

- In the limit where the bare dark matter mass is much smaller than the Hubble scale, the isocurvature constraint is satisfied when:

$$\sigma \gtrsim (0.01 - 0.02) \left(\frac{H_*}{M_P}\right)^2$$

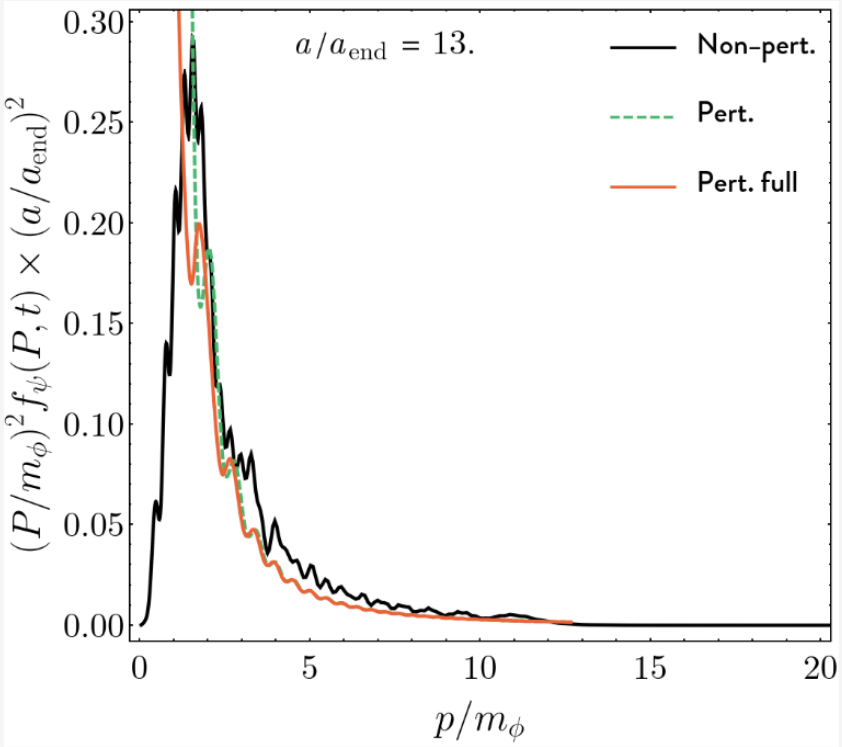
- The Lyman-α constraint excludes masses lighter that 0.34 meV for pure gravitational production.

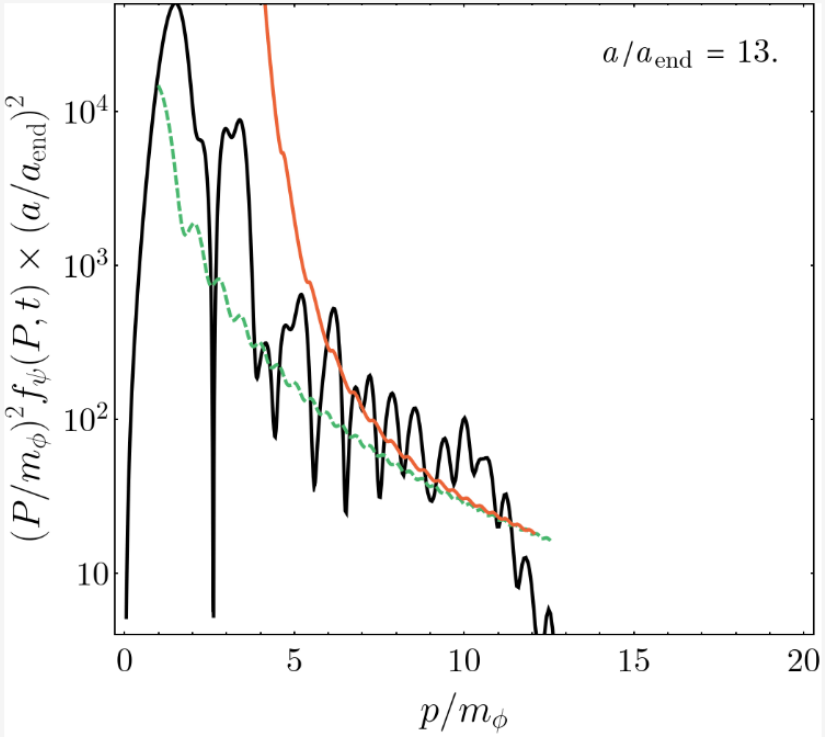
- The combination of Ly-α and isocurvature limits result in the lightest allowed mass:

$$m_\chi \simeq 5\,\mathrm{meV} \qquad \sigma/\lambda \simeq 0.024$$

- CMB-S4 and LiteBIRD experiments could detect the B-modes or the isocurvature modes in the CMB narrowing down the gravitational particle production models.

Thank you!


$a/a_{\rm end} = 13.$
Non-pert.
Pert.
Pert. full
$(P/m_\phi)^2 f_\psi(P,t) \times (a/a_{\rm end})^2$
p/m_ϕ
0.30
0.25
0.20
0.15
0.10
0.05
0.00
0
5
10
15
20


$a/a_{\rm end} = 13.$
$(P/m_\phi)^2 f_\psi(P,t) \times (a/a_{\rm end})^2$
p/m_ϕ
10^4
10^3
10^2
10
0
5
10
15
20