

Thermal effects on Dark Matter production during cosmic reheating

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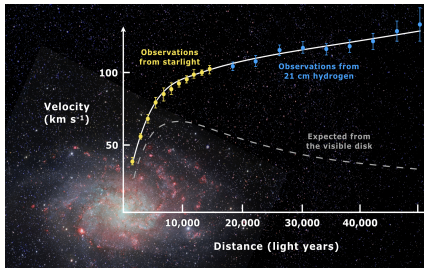
Based on collaboration with M. Drewes, M. Mohammed and S. Zell
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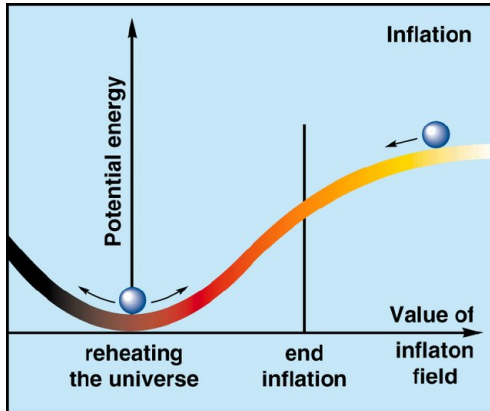


The missing matter content



- Dark Matter presence only inferred from gravitational interactions
- Multitude of DM models: how can we distinguish them/make sure specific scenarios are excluded?
 - Leverage interplay with other cosmological observables.
- Recent interest in models of DM production during reheating.

Inflation & reheating



[Credits: Juan Garcia-Bellido]

- After inflation, inflaton oscillates around the potential minimum and dissipates into radiation, thereby *reheating* the universe

Constraints on the reheating temperature

- Reheating era impacts CMB observables by changing expansion history

$$N_{\text{re}} = \frac{4}{3\tilde{w}_{\text{re}}-1} \left[N_{\text{k}} + \ln \left(\frac{k}{a_0 T_0} \right) + \frac{1}{4} \ln \left(\frac{40}{\pi^2 g_*} \right) + \frac{1}{3} \ln \left(\frac{11g_*}{43} \right) - \frac{1}{2} \ln \left(\frac{\pi^2 m_{\text{Pl}}^2 r A_s}{2\sqrt{\mathcal{V}_{\text{end}}}} \right) \right].$$

- Current and future experiments already constraint the reheating temperature

$\rho_R(T_{\text{re}}) = \rho_\phi(T_{\text{re}})$

benchmark	model	α	$\bar{n}_s$	σ_{n_s}	$\bar{r}$	σ_r	$\log_{10} \left(\frac{T_{\text{re}}}{\text{GeV}} \right)$
A	α -T	2	0.9651	0.002	0.00696	0.001	$13.7^{+1.2}_{-2.0}$
B	RGI	20	0.9607	0.002	0.0265	0.00175	$-0.8^{+1.5}_{-1.0}$
C	MHI	2	0.9623	0.002	0.00947	0.0013	$6.8^{+3.0}_{-2.7}$

Projected LiteBIRD 1σ sensitivity.

DM during reheating

System described by set of 3 coupled equations

1. Inflaton condensate decay

$$\dot{\rho}_{\phi} + (3H + \Gamma_{\phi})(\rho_{\phi} + P_{\phi}) = 0$$

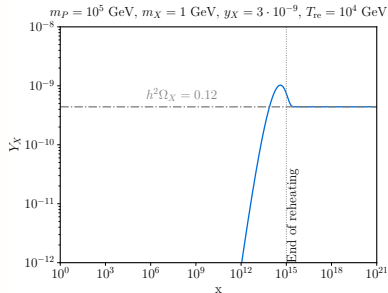
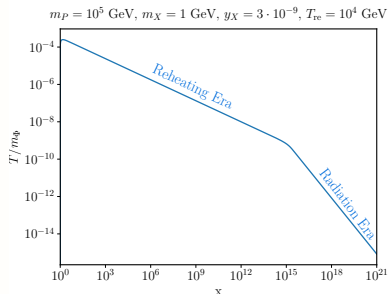
2. Production of radiation degrees of freedom ($g_{\star} = 106.75$)

$$\dot{\rho}_R + 4H\rho_R - \Gamma_{\phi}(\rho_{\phi} + P_{\phi}) = 0$$

3. Dark Matter production from the thermal bath

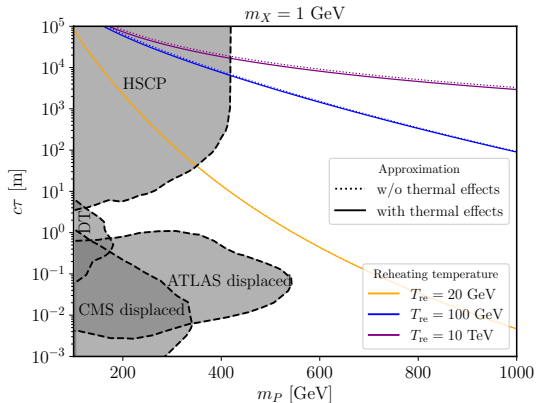
$$\dot{n}_X + 3Hn_X = \mathcal{C}_X$$

DM collision integral



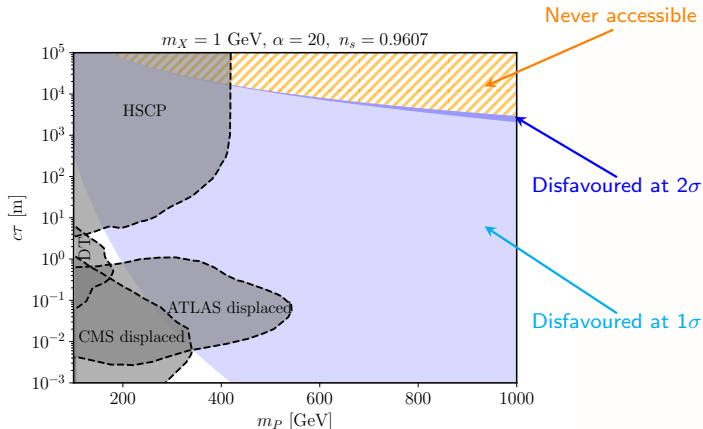
Interplay cosmology-colliders

- Low reheating temperature modify expected predictions for colliders by diluting the DM content
- Example of constraint for muophilic DM candidate X ($\mathcal{L} \propto P\bar{X}\mu_R$):



Interplay cosmology-colliders

- LiteBIRD could exclude sizeable part of collider-accessible parameter space (depends on inflationary scenarios)

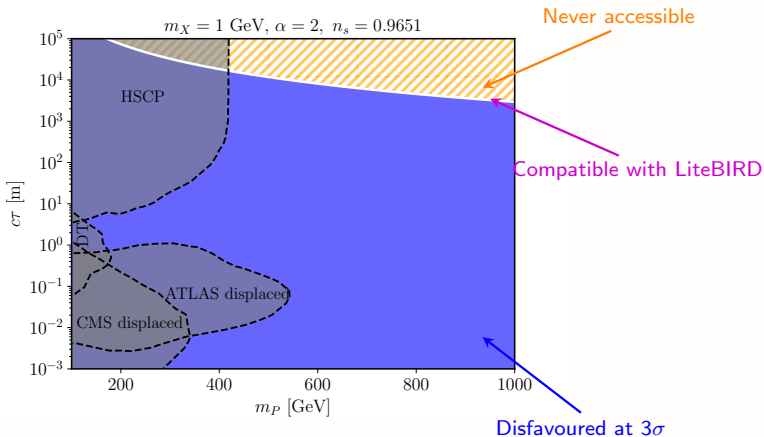


Radion Gauge Inflation

$$\mathcal{V}(\phi) = M^4 \left[\frac{(\phi/m_{\text{Pl}})^2}{\alpha + (\phi/m_{\text{Pl}})^2} \right]$$

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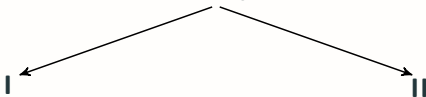


α -attractor T-model inflation

$$\mathcal{V}(\phi) = M^4 \tanh^2 \left[\frac{\phi}{\sqrt{6\alpha} m_{\text{Pl}}} \right]$$

Impact of thermal effects on DM yield

Thermal effects can impact DM abundance in 2 ways



Modifying the **DM production rate** Modifying the **temperature evolution**
through the inflaton decay rate

Quantum statistical effects

$$\begin{array}{ccc}
 f_{\text{F/B}}, 1 \pm f_{\text{F/B}}, M(T) & \Gamma_\phi = \frac{y_\phi^2}{8\pi} M_\phi \left(1 - 2 \left(\frac{M_\psi}{M_\phi} \right)^2 \right)^{1/2} (1 - 2 f_{\text{F}}(M_\phi/2)) & \\
 \updownarrow & \updownarrow & \\
 e^{-E/T}, 1, m & \Gamma_\phi = \frac{y_\phi^2}{8\pi} m_\phi \left(1 - 2 \left(\frac{m_\psi}{m_\phi} \right)^2 \right)^{1/2} &
 \end{array}$$

Thermal masses

Thermal effects on DM production rates

- Standard freeze-in happens at

$$m_P/T_{\text{FI}} \sim \mathcal{O}(2 - 5)$$

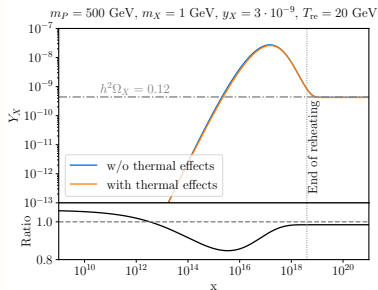
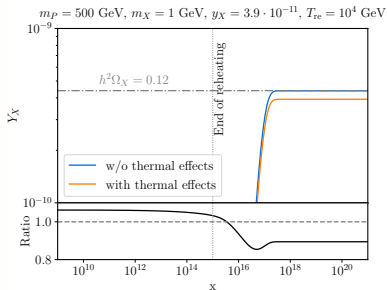
→ $\mathcal{O}(10 - 20\%)$ change in DM yield due to thermal corrections.

See e.g. Becker et al, '23 for detailed comparison

- Late-time inflaton decay pushes freeze-in to

$$m_P/T_{\text{FI}} \gg \mathcal{O}(2 - 5)$$

→ Lesser impact of finite-temperature effects!



Impact of thermally-corrected inflaton decay on DM abundance

Sensitivity of DM abundance to thermal effects on inflaton decay rate conditioned by:

1. **Maximal temperature** of universe **larger than inflaton mass**

$T_{\text{max}} > m_\phi$. Parametrising $\Gamma_\phi = g^2 m_\phi / c$, leads to

$$g \gtrsim 1.5 \cdot 10^{-4} \left(\frac{m_\phi}{10^{13} \text{ GeV}} \right)^{3/2}$$

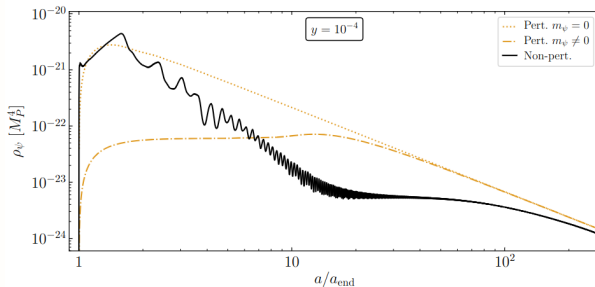
For two-parameter plateau models, $m_\phi \gtrsim 10^{13} \text{ GeV}$ such that $g \gtrsim 1.5 \cdot 10^{-4}$.

2. **Reheating** should remain **perturbative**: $g \lesssim 10^{-4}$. Can be relaxed if only asked that reheating temperature is not modified.
3. **DM production** needs to **peak in the UV**. In the ultra-relativistic regime, only possible for operators of dimension

$$d \geq \frac{4(2 + \bar{w}_{\text{re}})}{1 + \bar{w}_{\text{re}}}, \quad \bar{w}_{\text{re}} = \frac{j - 2}{j + 2} \text{ for } \mathcal{V}(\phi) \propto \phi^j.$$

due to additional dilution from inflaton decay.

Going beyond the perturbative regime



[Garcia/Kaneta/Mambrini/Olive/Verner '21]

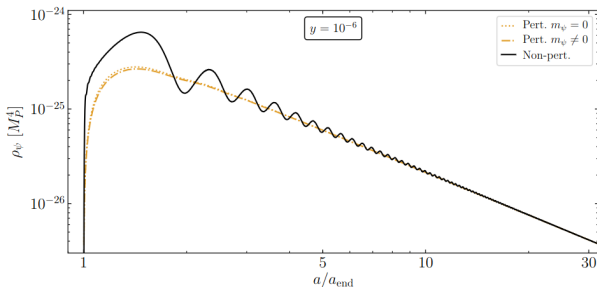
- During fermionic reheating, time-dependent fermion mass $m_{\text{eff}}(t) = m_\psi + y\phi(t)$ and evolution can become non-adiabatic

$$\left| \frac{\dot{w}_k}{w_k^2} \right| \gg 1$$

- Relevance of ϕ -induced mass partially captured by suppression factor

$$\mathcal{R} = \left(\frac{m_{\text{eff}}(t_0)}{m_\phi} \right)^2$$

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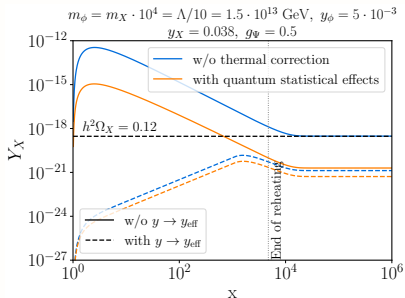
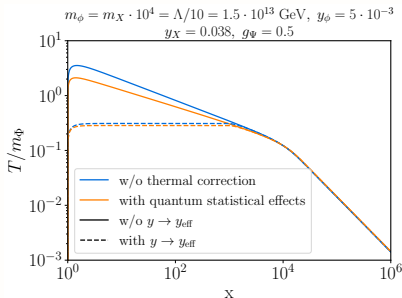
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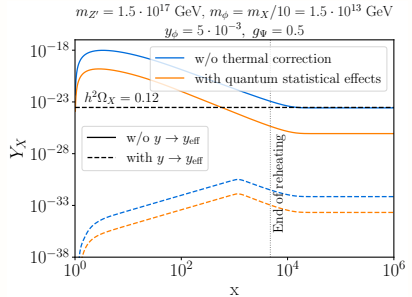
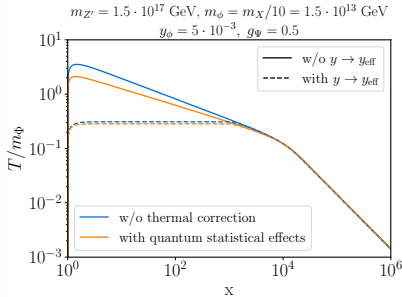
Counter-example 1: UV-dominated freeze-in from a dimension-9 operator

- For UV-dominated freeze-in, precise modelling of inflaton decay can have order of magnitude impact on the DM abundance.



Counter-example 2: UV-dominated freeze-in due to Boltzmann suppression

- For UV-dominated freeze-in, precise modelling of inflaton decay can have order of magnitude impact on the DM abundance.



Conclusion

- Dark Matter production during reheating impact phenomenology of simple models
- Future CMB experiments such as LiteBIRD or Simons Observatory can put constraints on DM parameter space
- Finite-temperature effects on DM production rate typically smaller for reheating-dominated scenarios
- Finite-temperature effects on (perturbative) inflaton decay typically do not sizeably impact DM abundance for simple 2-parameter models except in "extreme" cases
- Precise modelling of reheating necessary for UV-dominated freeze-in