Thermal effects on Dark Matter production during cosmic reheating

Yannis Georis (ヤニス・ジョリス)
Based on collaboration with M. Drewes, M.A.S. Mohammed and S. Zell
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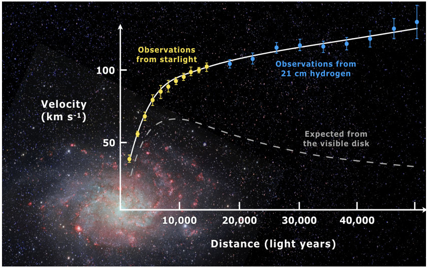
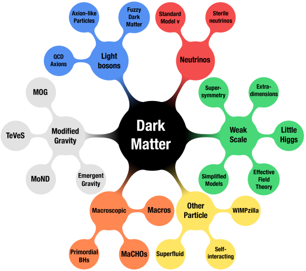
The missing matter content



[Credits: M. De Leo]



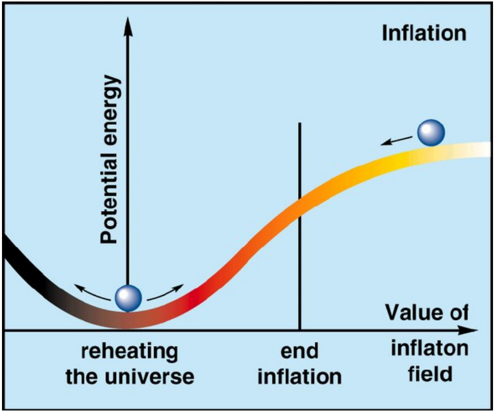
[Credits: G. Bertone and T. Tait]

- Dark Matter presence only inferred from gravitational interactions
- Multitude of DM models:
    - How to distinguish them?
    - How to make sure specific scenarios are excluded?

$\longrightarrow$ 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

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

- Current and future experiments already constraint the reheating temperature

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

benchmark	model	α	$\bar{n}_s$	σ_{n_s}	$\bar{r}$	σ_r	$\log_{10}(\frac{T_{\rm re}}{\rm GeV})$
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

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

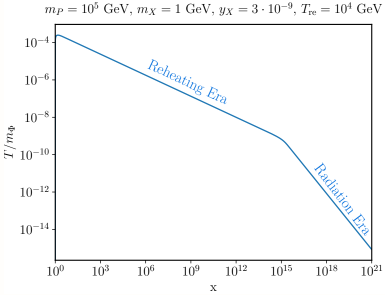
2. Production of radiation degrees of freedom ($g_\star = 106.75$)

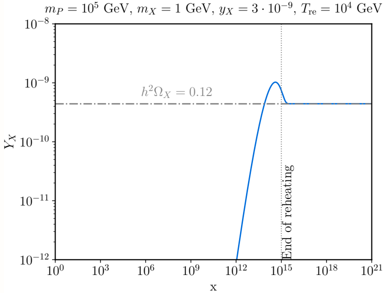
$$\dot{\rho}_R + 4H\rho_R - \Gamma_\phi\,(\rho_\phi + P_\phi) = 0$$

3. Dark Matter production from the thermal bath

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

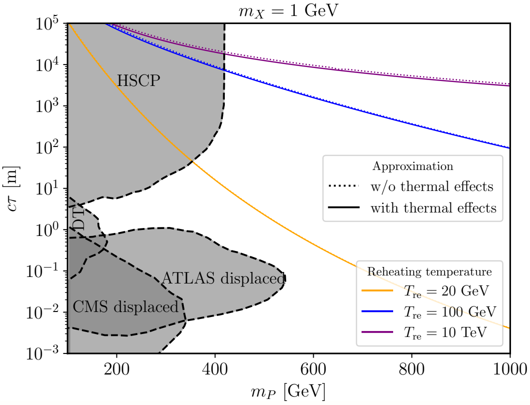
DM collision integral





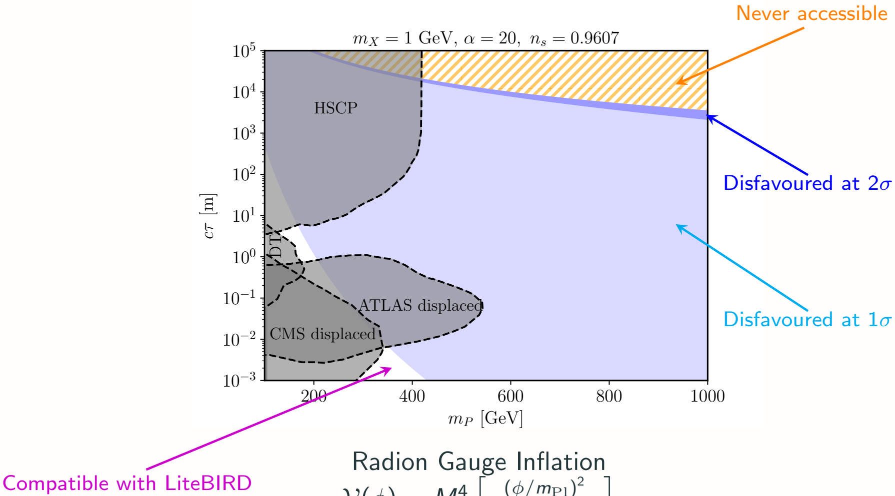
Interplay cosmology-colliders

- 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

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

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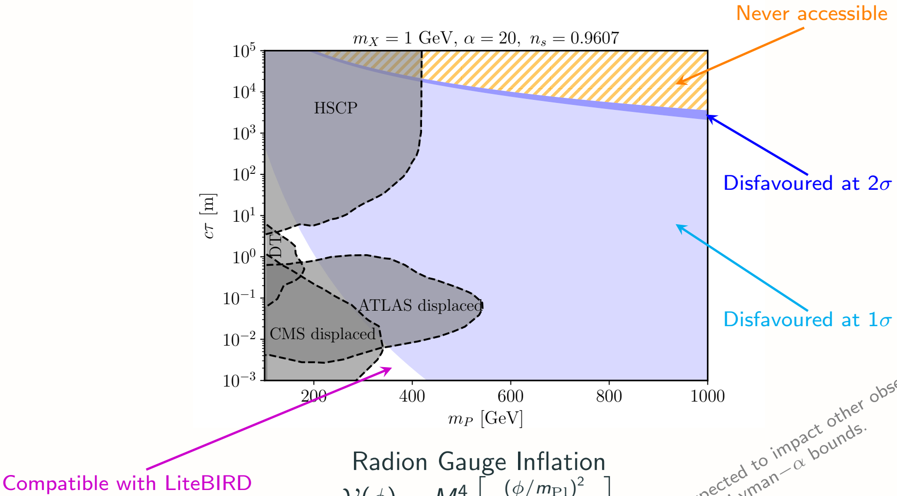

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Reheating expected to impact other observables, e.g. Lyman−α bounds.

Impact of thermal effects on DM yield

Thermal effects can impact DM abundance in 2 ways

I

Modifying the DM production rate

Quantum statistical effects

$$f_{\mathrm{F/B}},\ 1 \pm f_{\mathrm{F/B}},\ M(T)$$

Thermal masses

$$\updownarrow$$

$$e^{-E/T}, \quad 1, \quad m$$

II

Modifying the temperature evolution through the inflaton decay rate

$$\Gamma_\phi = \frac{y_\phi^2}{8\pi} M_\phi \left(1 - 2\left(\frac{M_\Psi}{M_\phi}\right)^2\right)^{1/2} (1 - 2 f_{\mathrm{F}}(M_\phi/2))$$

$$\updownarrow$$

$$\Gamma_\phi = \frac{y_\phi^2}{8\pi} m_\phi \left(1 - 2\left(\frac{m_\psi}{m_\phi}\right)^2\right)^{1/2}$$

Thermal effects on DM production rates

- Standard freeze-in happens at

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

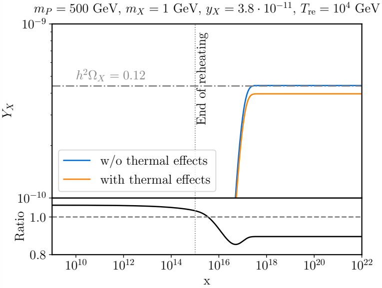
$\longrightarrow \mathcal{O}(10-20\%)$ change in DM yield due to thermal corrections.

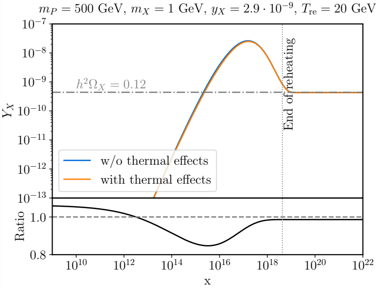
See e.g. Becker et al, '23 for detailed comparison

- Late-time inflaton decay pushes freeze-in to

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

$\longrightarrow$ Lesser impact of finite-temperature effects!



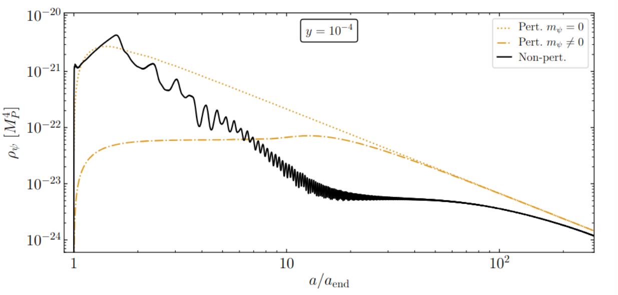


Impact of thermally-corrected inflaton decay on DM abundance

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

1. Maximal temperature of universe larger than inflaton mass $T_{\rm max} \gtrsim m_\phi$. Parametrising $\Gamma_\phi = \mathrm{g}^2 m_\phi/\mathrm{c}$, leads to
$$\mathrm{g} \gtrsim 1.5 \cdot 10^{-4} \left(\frac{m_\phi}{10^{13}\ \mathrm{GeV}}\right)^{3/2}$$
For two-parameter plateau models, $m_\phi \gtrsim 10^{13}$ GeV such that $\mathrm{g} \gtrsim 1.5 \cdot 10^{-4}$.
2. Reheating should remain perturbative: $\mathrm{g} \lesssim 10^{-4}$. 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
$$d \geq \frac{4(2+\bar{w}_{\rm re})}{1+\bar{w}_{\rm re}},\ \ \bar{w}_{\rm re} = \frac{j-2}{j+2} \text{ for } \mathcal{V}(\phi) \propto \phi^j\ .$$
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 $m_{\rm eff}(t) = m_\Psi + y\phi(t)$ 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

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

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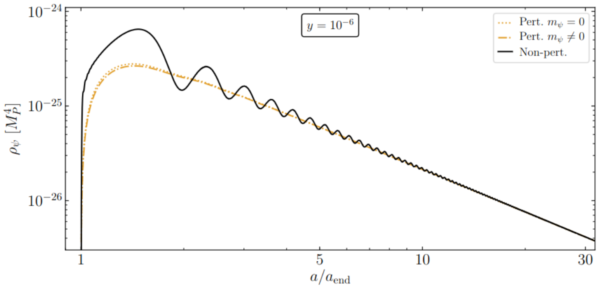

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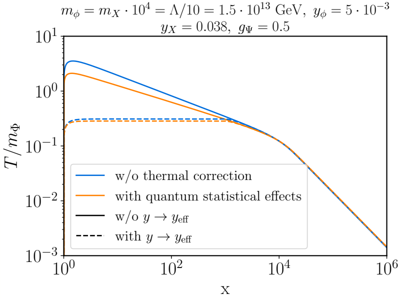
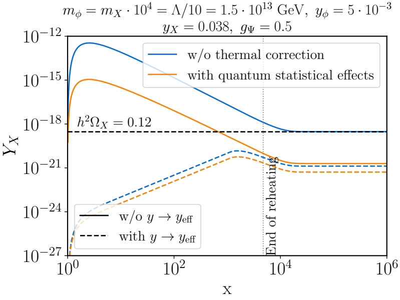
Counter-example 1: UV-dominated freeze-in from a dimension-9 operator

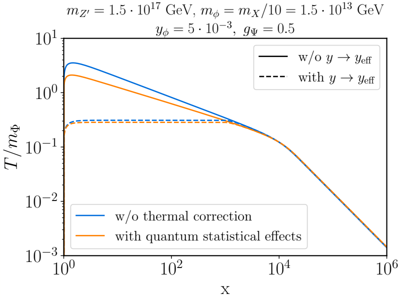
- For UV-dominated freeze-in, precise modelling of inflaton decay can have order of magnitude impact on the DM abundance.

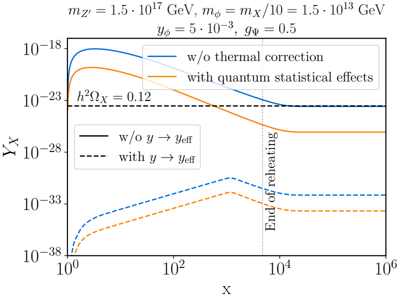




Counter-example 2: UV-dominated freeze-in due to Boltzmann suppression

- 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

Thanks for your attention!
ご清聴ありがとうございました。