Dark matter in non-standard cosmologies

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Based on: P. Arias, DK, and L. Roszkowski, JCAP **05**, 041 (2021) , [arXiv:2012.07202 [hep-ph]] and P. Arias, N. Bernal, DK, C. Maldonado, L. Roszkowski, and M. Venegas, [arXiv:2107.13588 [hep-ph]].

Outline

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- Theoretical motivation: SUSY, string theory, and other models.
- DM may open a window to the cosmic evolution at higher temperatures.

Cosmological components

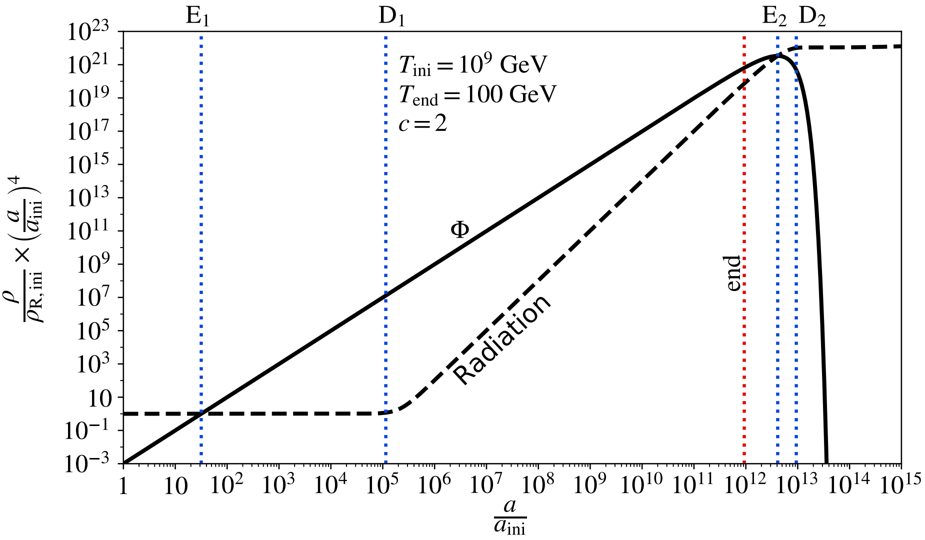
Cosmological components: equations

Assume that there is a fluid (Φ), which at some point dominates the energy density of the Universe, and later deposits energy to plasma with rate Γ_Φ. The equation of state of Φ is $p_\Phi = 1/3\ (c-3)\ \rho_\Phi$ (critical assumption: $c = const.$)

$$\frac{d\rho_\Phi}{dt} = -cH\ \rho_\Phi - \Gamma_\Phi\ \rho_\Phi$$
$$\frac{ds}{dt} = -3H\ s + \frac{\Gamma_\Phi}{T}\ \rho_\Phi$$

The temperature at which Φ decays away in a radiation dominated (RD) Universe ($T_{\rm end}$) can be calculated by $\Gamma_\Phi = H_{\rm R}(T_{\rm end})$. It is more convenient to use this temperature as a free parameter instead of Γ_Φ.

Cosmological components: example



Freeze-in

The Dark Matter particle (χ) is produced via

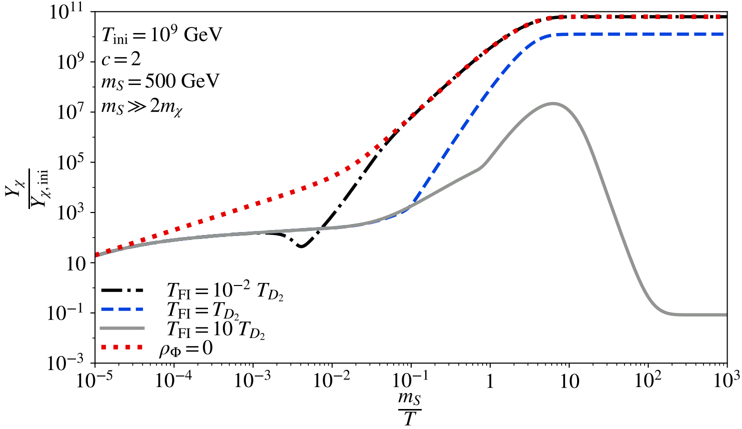
$$\mathcal{L}_{\rm int} = -\frac{y_\chi}{2}\; S\;\left(\chi\chi + \chi^\dagger\chi^\dagger\right)\;,$$

with S being in equilibrium with the plasma. [1]
The BE in terms of the DM yield, $Y_\chi \equiv n_\chi/s$, is expressed as

$$\frac{d\log Y_\chi}{d\log\frac{T_{\rm ini}}{T}} = \quad \delta_h \frac{\{S\to\chi\chi\} + \{SS\to\chi\chi\}}{H_{\rm R} n_\chi} \times \overbrace{\frac{H_{\rm R}}{H}}^{0<\mathcal{F}_1\leq 1} \underbrace{\left(1-\frac{\Gamma_\Phi}{H}\frac{\rho_\Phi}{3s\;T}\right)^{-1}}_{1\leq\mathcal{F}_2\lesssim 8/c} \underbrace{\left[1-\frac{d\log S}{d\log\frac{T_{\rm ini}}{T}}\left(\frac{d\log N_\chi}{d\log\frac{T_{\rm ini}}{T}}\right)^{-1}\right]}_{\mathcal{F}_3\leq 1}.$$

[1] There is an extensive discussion on freeze-in production in NSCs, such as . J. H. Chung, E. W. Kolb and A. Riotto, Phys. Rev. D **60** (1999) 063504[hep-ph/9809453], M. Drees and F. Hajkarim, JCAP **1802**, 057 (2018) [arXiv:1711.05007]., F. D'Eramo, N. Fernandez and S. Profumo, JCAP **1802**, 046 (2018) [arXiv:1712.07453], N. Bernal, F. Elahi, C. Maldonado and J. Unwin, [arXiv:1909.07992], and many others.

Dark matter production: example



- Φ significantly alters the DM production.
- If $T_{\rm FI} < T_{\rm D_2}$, the final result is the same as in RD (consequence of infrared freeze-in).
- The maximum relic is obtained for RD, despite $\mathcal{F}_{1,2}$.
- The change of the sign of $\mathcal{F}_3$ causes minima and maxima, which affect DM thermalization.

Dark matter momentum: qualitative description

Matching today's DM momentum with the WDM scenario, [2] DM mass has to obey

$$m_\chi > \frac{\langle p_{\chi,0}\rangle}{1.2\times 10^{-7}}\left(\frac{m_{\rm WDM}}{\rm keV}\right)^{4/3} .$$

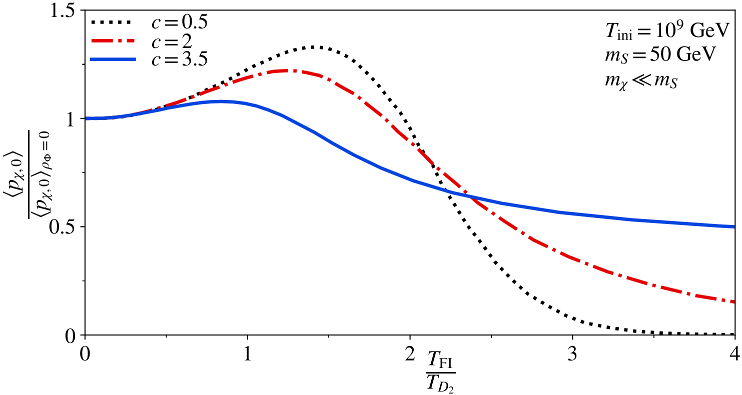
Generally one has to slove the Boltzmann equation for the phase-space distribution of χ. [3] However, assuming that the distribution of S is sharp (*i.e.* the variance of the energy of S is small), we derive an equation for the DM mean momentum. For $T > T_{\rm EW} \sim 150$ GeV and $m_\chi \ll T$, this equation can be written as

$$\frac{d\log\frac{\langle p_\chi\rangle}{T}}{d\log\frac{T_{\rm ini}}{T}} = \underbrace{1-\left(1-\frac{\Gamma_\Phi}{H}\frac{\rho_\Phi}{3s\,T}\right)^{-1}}_{1-\frac{8}{c}\lesssim\mathcal{T}_1\leq 0} + \overbrace{\left(\frac{1}{2}\frac{\langle E_S\rangle}{T}\frac{T}{\langle p_\chi\rangle}-1\right)\frac{d\log N_\chi}{d\log\frac{T_{\rm ini}}{T}}}^{\mathcal{T}_2\geq 0} .$$

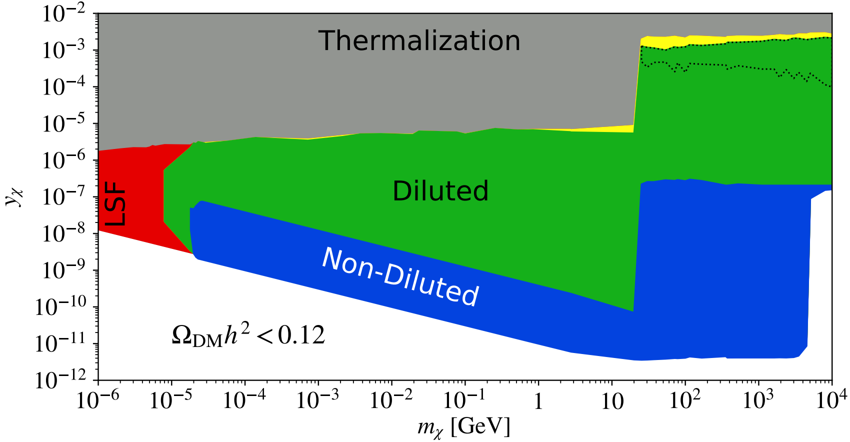
2 Similarly to R. Huo, Phys. Lett. B **802** (2020), 135251 [arXiv:1907.02454].

3 Also see Alessandro's presentation.

Dark matter momentum: example



- Φ changes the evolution of DM momentum.
- If $T_{\rm FI} < T_{\rm D_2}$, the final result is the same as in RD.
- For $T_{\rm FI} > T_{\rm D_2}$, $\langle p_\chi \rangle$ redshifts faster than T.
- If $T_{\rm FI} \approx T_{\rm D_2}$, $\langle p_\chi \rangle$ is slightly enhanced.


Thermalization
Diluted
LSF
Non-Diluted
$\Omega_{DM}h^2 < 0.12$
y_χ
m_χ [GeV]
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-6}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
10
10^{2}
10^{3}
10^{4}

Axion dark matter

Axion DM production: misalignment mechanism

The (zero-mode) axion equation of motion is

$$\frac{d^2\theta}{du^2} + \left[\frac{1}{2}\frac{d\log H^2}{du} + 3\right]\frac{d\theta}{du} + \left(\frac{\tilde{m}_a}{H}\right)^2 \sin\theta = 0 \ ,$$

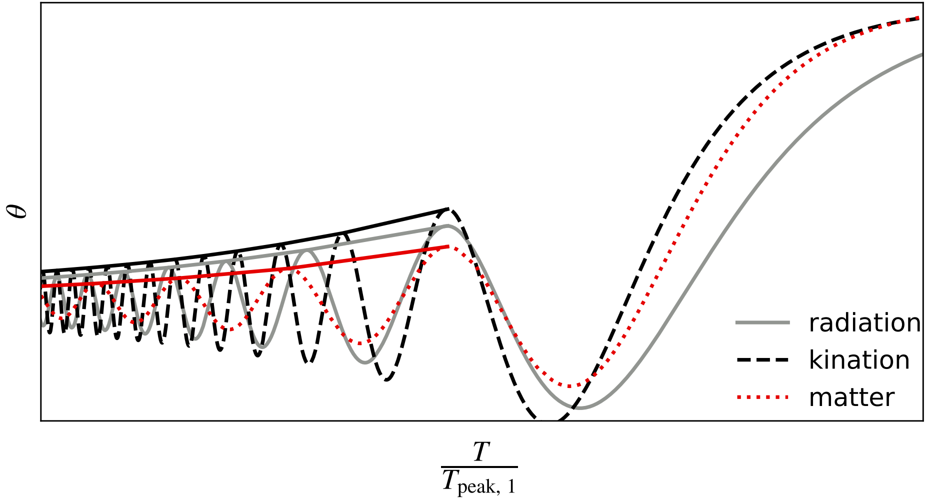
with $\tilde{m}_a$ the temperature-dependent axion mass, and $u = \log\frac{R}{R_{\rm ini}}$.

- Oscillation temperature, $T_{\rm osc}$, at $\tilde{m}_a = 3H$.
- For $T \gg T_{\rm osc}$, $\theta \approx \theta_{\rm ini} = const$.
- For $T \approx T_{\rm osc}$, time-dependent pendulum with time-dependent friction.
- For $T \ll T_{\rm osc}$, adiabatic evolution.

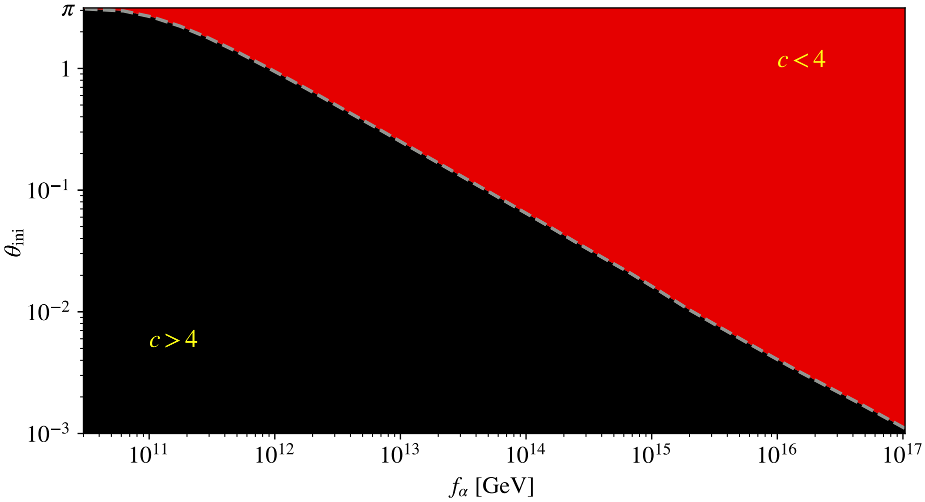
Assuming entropy is increased by γ (after adiabatic evolution starts), the WKB estimate is

$$\rho_{a,0} = \gamma^{-1}\frac{s_0}{s_{\rm osc}}\ \frac{1}{2}\ {f_a}^2\ m_a\ \tilde{m}_{a,\rm osc}\ \theta_{\rm ini}^2 \ ,$$

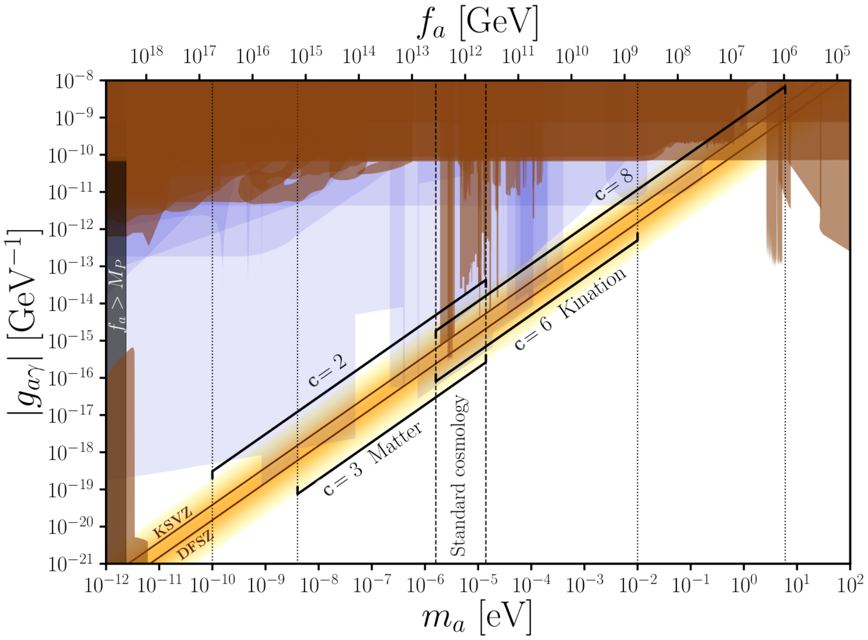
Axion DM production: example



Parameter space



NSC vs axion detection



Summary

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What we did:

- Detailed treatment of freeze-in in NSC scenarios.
- Detailed analysis of axion DM in NSC scenarios.

What we saw:

- Possibility for larger couplings without over-closing the Universe, with interesting DM momentum behaviour.
- Distinct "natural" axion window that depends on the type of NSC, *i.e.* depending on whether $c > 4$ or $c < 4$.

What we want to see:

- Potential detection of FIMPs?
- Detection of axions can exclude or probe NSC scenarios?

Thank you!