Freeze-in baryogenesis and early matter domination

Based on arXiv:2111.05740, arXiv:2204.13554, arXiv:2304.07345
In collaboration with I. Dalianis, D. Karamitros, P. Papachristou, V. Spanos

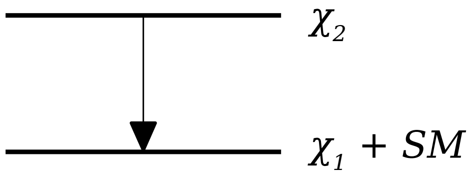
October 2023

Andreas Goudelis
LPC – Clermont Ferrand

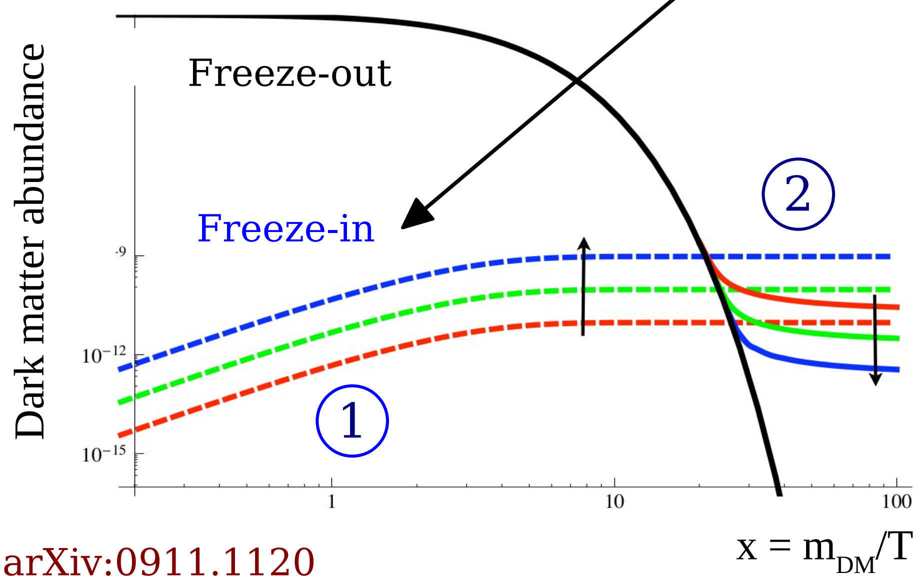
FIMPy baryogenesis: general idea

arXiv:2004.00636, arXiv:2201.11502,
arXiv:2111.05740, arXiv:2204.13554

Freeze-in involves *very* weakly ("feebly") interacting particles (FIMPs) that don't reach thermal equilibrium with the SM thermal bath in the early Universe.



· Such particles can be produced *e.g.* from the decay of some heavier state or from annihilations of bath particles.



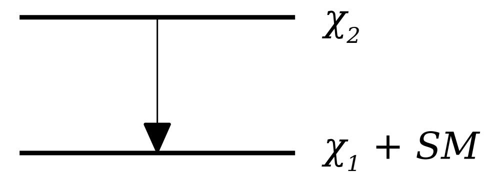
arXiv:0911.1120

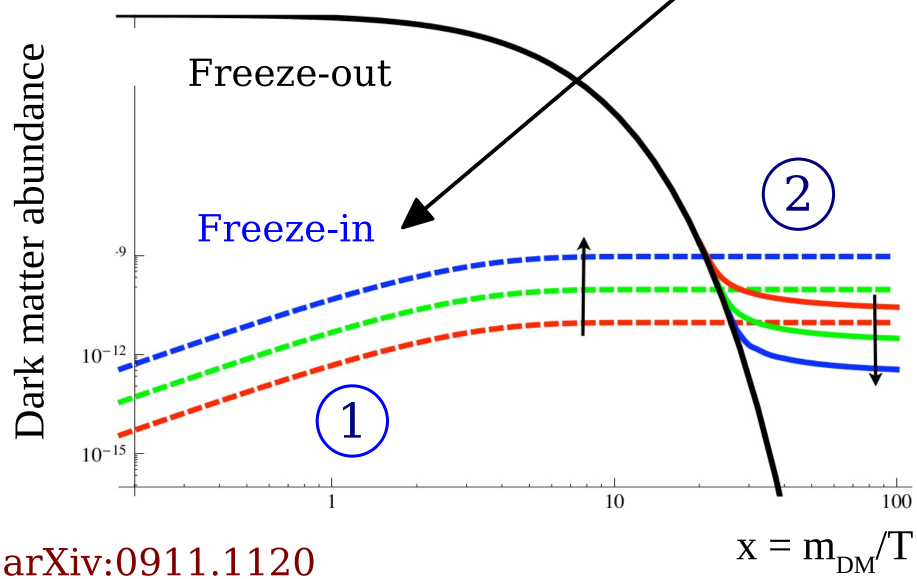
FIMPy baryogenesis: general idea

arXiv:2004.00636, arXiv:2201.11502,
arXiv:2111.05740, arXiv:2204.13554

Freeze-in involves *very* weakly ("feebly") interacting particles (FIMPs) that don't reach thermal equilibrium with the SM thermal bath in the early Universe.

· Such particles can be produced *e.g.* from the decay of some heavier state or from annihilations of bath particles.





arXiv:0911.1120

· The decays and/or annihilations that are responsible for dark matter production can also violate both the baryon number B (or L) and C/CP.

· But, by construction, in freeze-in these processes are also out-of-equilibrium.

→ All three Sakharov conditions can be satisfied.

NB: in arXiv:2004.00636 and arXiv:2201.11502 *CP* violation is rather due to DM oscillations

A concrete realization: toy model

arXiv:2204.13554

Consider an extension of the SM by a complex scalar field and two vector-like fermions, described by the Lagrangian :

$$\mathcal{L}_{\rm int} = \frac{\lambda_1}{2\Lambda} \left(\bar{e} F_1\right) \varphi^* \varphi^* + \frac{\lambda_2}{2\Lambda} \left(\bar{e} F_2\right) \varphi^* \varphi^* + \frac{\kappa}{\Lambda^2} \left(\bar{e} F_1\right) \left(\bar{F}_2 e\right) + \text{h.c.}$$

· The bulk of dark matter production takes place at the highest considered temperature (in this framework the “reheating temperature” $T_{\rm RH}$) .

· Scattering processes dominate both DM production and baryogenesis.

A concrete realization: toy model

arXiv:2204.13554

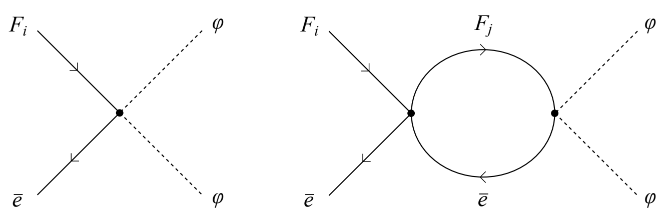
Consider an extension of the SM by a complex scalar field and two vector-like fermions, described by the Lagrangian :

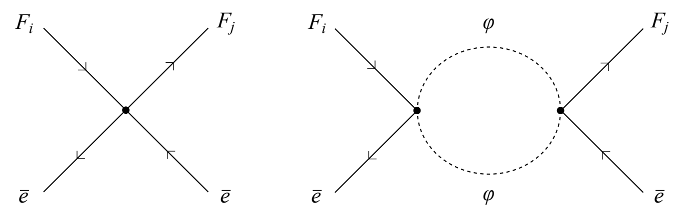
$$\mathcal{L}_{\rm int} = \frac{\lambda_1}{2\Lambda}\left(\bar{e}F_1\right)\varphi^*\varphi^* + \frac{\lambda_2}{2\Lambda}\left(\bar{e}F_2\right)\varphi^*\varphi^* + \frac{\kappa}{\Lambda^2}\left(\bar{e}F_1\right)\left(\bar{F}_2 e\right) + \text{h.c.}$$

· The bulk of dark matter production takes place at the highest considered temperature (in this framework the “reheating temperature” $T_{\rm RH}$) .

· Scattering processes dominate both DM production and baryogenesis.

NB: Qualitatively similar (but quantitatively different) results are obtained if we, instead, assume a fermion DM candidate and operators of higher dimension.





Dark Matter

$$\Omega_{\rm DM}h^2 \approx \frac{2.4\times 10^{23}}{g_{\star s}\sqrt{g_{\star\rho}}}\,\frac{A\,4^n\,n!\,(n+1)!}{2n-1}\,\frac{T_{\rm RH}^{2n-1}\,m_{\rm DM}}{\Lambda^{2n}}$$

Baryogenesis

$$-sHT\frac{\mathrm{d}Y_{\Delta F_i}}{\mathrm{d}T} = -\left[F_i\bar{e}\leftrightarrow\varphi\varphi\right] - \left[F_i\bar{e}\leftrightarrow F_j\bar{e}\right] + (-1)^i\left[F_i\bar{F}_j\leftrightarrow e\bar{e}\right]$$

$$-sHT\frac{\mathrm{d}Y_{B-L_{\rm SM}}}{\mathrm{d}T} = -\sum_i\left[F_i\bar{e}\leftrightarrow\varphi\varphi\right]$$

FIMPy baryogenesis + EMD

arXiv:2304.07345

So far, we have placed ourselves within the simplest of cosmological scenarios : inflation was followed by an uninterrupted period of radiation domination until matter-radiation equality.

What if the history of the Universe involved additional epochs ?

Consider the case in which, at some point after inflation (*and* freeze-in), the Universe became temporarily dominated by some fluid X behaving as matter, which subsequently decayed (symmetrically) into SM particles.

Upon the decay of X, entropy is injected in the plasma and all quantities become diluted

Note also that :

· In the case of scalar DM, $Y_{\rm DM} \sim T_{\rm RH}/\Lambda$, whereas $Y_{\rm B\text{-}LSM} \sim T_{\rm RH}^4/\Lambda^6$

· In the case of fermion DM, $Y_{\rm DM} \sim T_{\rm RH}^3/\Lambda^4$, whereas $Y_{\rm B\text{-}LSM} \sim T_{\rm RH}^8/\Lambda^{10}$

→ The dilution process may impact dark matter and baryogenesis in different ways

The radiation – condensate system

Once the scalar condensate decays, the relativistic degrees of freedom that are present in the Universe are diluted by

$$\Delta_{\rm EMD} \equiv \frac{S_{\rm final}}{S_{\rm initial}} \approx \frac{T_{{\rm dom},X}}{T_{{\rm dec},X}}$$

where S are the comoving entropies of the Universe at times well before and well after the decay of X.

The evolution of the cosmological background is, in this case, described by the system of equations

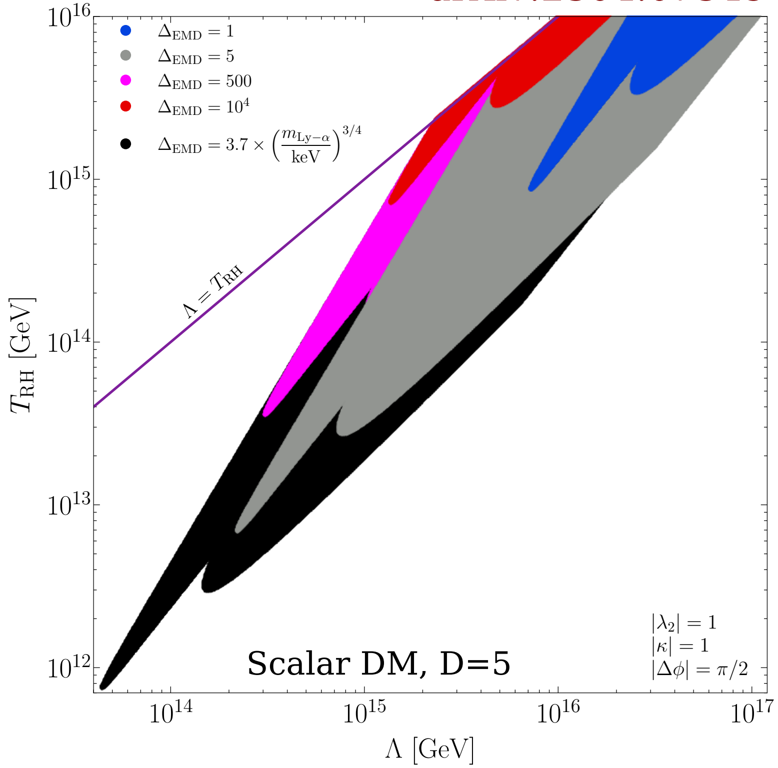
$$\begin{aligned}
\frac{d\rho_X}{d\tilde{N}} &= -3\rho_X - \frac{\Gamma_X}{H}\rho_X \\
\frac{d\rho_{\rm rad}}{d\tilde{N}} &= -4\rho_{\rm rad} + (1-{\rm B}_{\rm DM})\frac{\Gamma_X}{H}\rho_X \\
\frac{d\rho_{\rm DM}}{d\tilde{N}} &= -4\rho_{\rm DM} + {\rm B}_{\rm DM}\frac{\Gamma_X}{H}\rho_X \\
\frac{dH}{d\tilde{N}} &= -\frac{1}{2HM_{\rm Pl}^2}\left(\rho_X + \frac{4}{3}\rho_{\rm DM} + \frac{4}{3}\rho_{\rm rad}\right)
\end{aligned}$$

where $dN = d(\ln a) = Hdt$, and we assume $\mathrm{B}_{\rm DM} = 0$ (*i.e.* no X decays into DM).

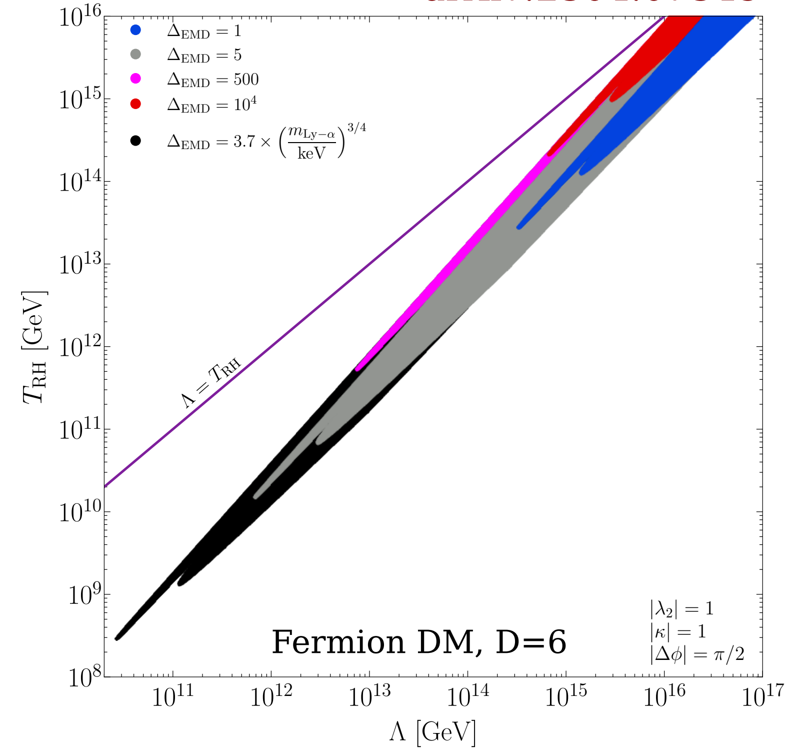
Results

All in all, the mechanism works! Dark matter production and baryogenesis can be simultaneously achieved.

arXiv:2304.07345



arXiv:2304.07345



· Depending on dilution size, can live with a wide range of reheating temperatures.

· In the zero-dilution case, DM again predicted to be close to the Lyman-α bound, but can reach the multi-MeV range in the presence of dilution.

· However, this scenario is extremely challenging phenomenologically...

EFTs, dilution and inflation

A modified cosmological history could have an impact on inflationary observables, most notably the spectral index n_s and the tensor-to-scalar ratio r. We will focus on the former. The general idea goes as follows :

· Each of the microscopic toy models that we have considered favours, for a given dilution size, a region of the (Λ, $T_{\rm RH}$, $m_{\rm DM}$) parameter space.

· All of these quantities allow us to compute the observable number of e-folds N_*

$$N_* \equiv \int_{t_*}^{t_{\rm end}} {\rm d}t H = \ln(a_{\rm end}/a_*) \,,$$

Which, in presence of and EMD phase is shifted wrt its “thermal” value as

$$N_* = N^{(\rm th)} - \delta N_* \,\approx\, N^{(\rm th)} - \frac{1}{3}\ln(\Delta_{\rm EMD})$$

which means that our viable parameter space can be recasted in terms of N_*.

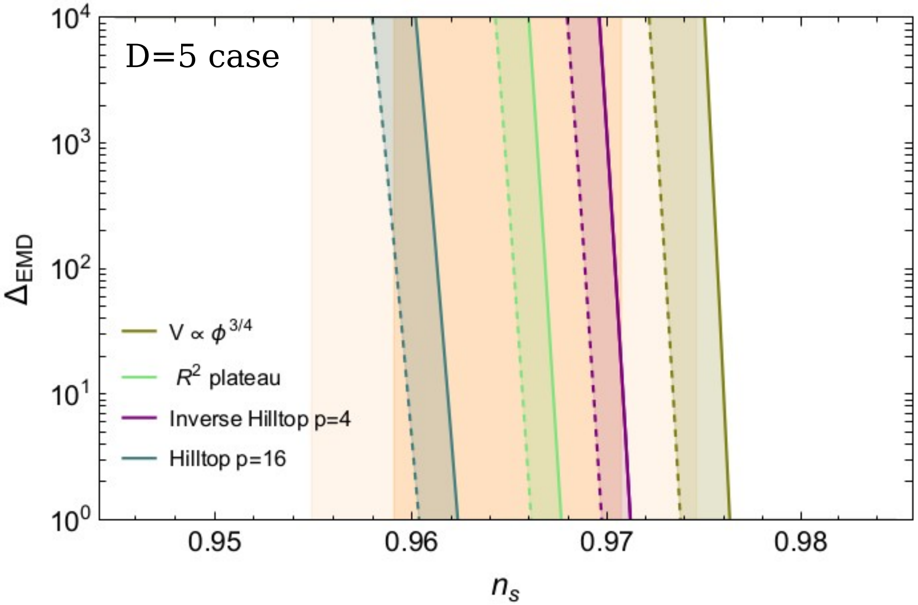
· Lastly, N_* can be related, within specific models of inflation, with the spectral index through a relation of the type $n_s = n_s(N)$.

In other words, given an inflationary model, we can draw conclusions on the microscopic scenarios which are favoured and vice-versa

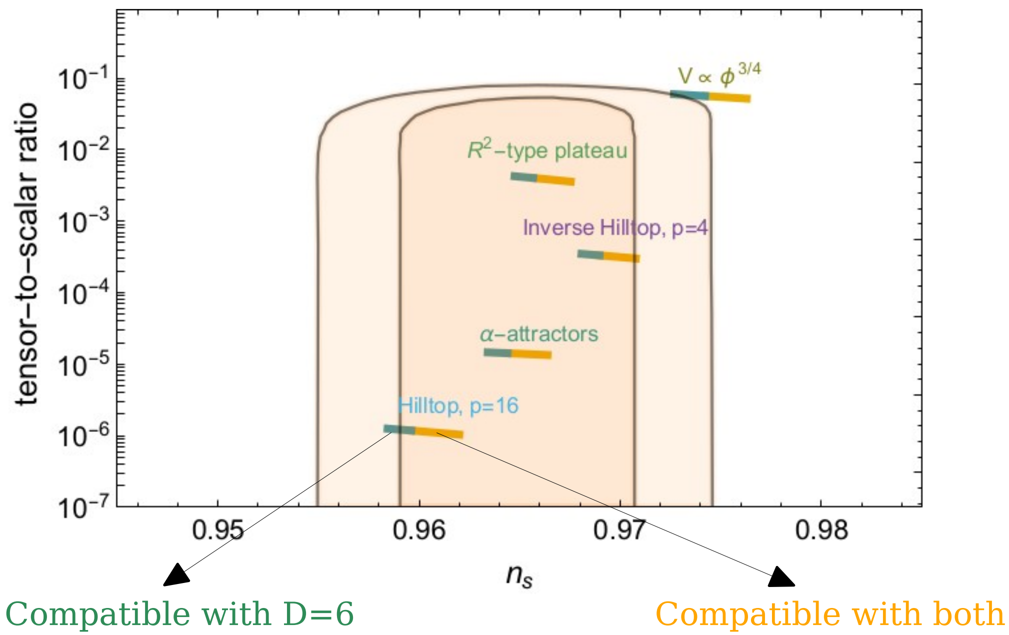
Potential imprints on the CMB ?

A dedicated analysis for a set of representative inflationary models yields the following results

arXiv:2304.07345



arXiv:2304.07345



· EUCLID/21-cm surveys could reach a 10^{-3} precision in the measurement of n_s.

· CMB Stage-4 experiments could detect r > 0.003.

· Is it possible to fully test the UV FIMPy baryogenesis scenario ? → No

→ But it may become possible to use CMB observables for model selection.

Summary and outlook

· There is no *a priori* reason why the observed dark matter abundance and the matter-antimatter asymmetry of the Universe should admit a common explanation.

· However, it *is* a possibility. And a much welcome one! This is the reason why such an option has been entertained since quite a few years and in the context of different DM generation mechanisms (asymmetric DM, freeze-out, freeze-in).

· Freeze-in production of DM, in particular, constitutes an interesting playground for baryogenesis, since it incorporates from the start one of the three Sakharov conditions: out-of-equilibrium dynamics.

· "Freeze-in baryogenesis" can work in wildly different contexts: asymmetric dark matter, symmetric dark matter that is mostly produced in the IR, UV freeze-in. It can give rise to interesting signals at the LHC and Cosmology.

· Once embedded within concrete inflationary scenarios, models which are otherwise extremely hard to test can give rise to observable predictions.

Thank you!