Dark matter and baryogenesis from freeze-in

Based on arXiv:2111.05740, arXiv:2204.13554, arXiv:2304.07345
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Outline

· Dark matter and the baryon asymmetry of the Universe

· The freeze-in mechanism

· Infrared "FIMPy baryogenesis"

· Ultraviolet "FIMPy baryogenesis" and an unconventional cosmological history

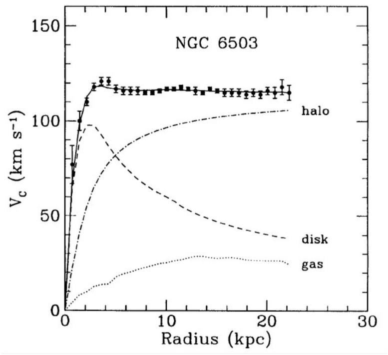
· A possibility for model selection from the CMB ?

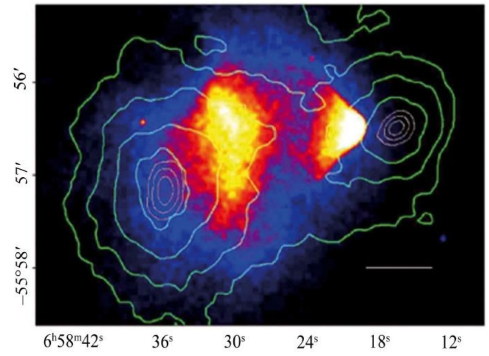
· Outlook

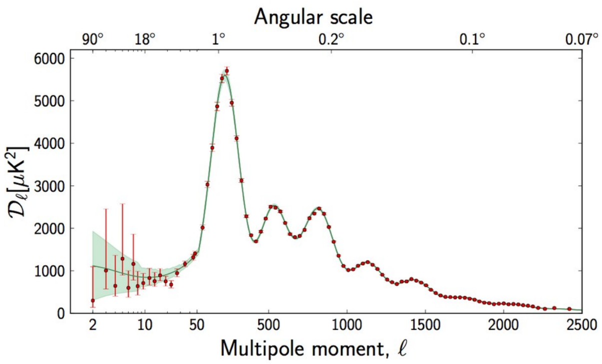
Today's topics

Dark matter

An – as of yet – unidentified form of matter that affects the motion of celestial objects and (assuming ΛCDM) comprises ~27% of the matter-energy content of the Universe.







Baryogenesis

The fact that our Universe appears to be composed of unequal amounts of matter and anti-matter. Sakharov conditions :

· Baryon number violation.
· *C*/*CP* violation.
· Interactions out of thermal equilibrium.

Some introductory comments

Two of the most celebrated questions in contemporary HEP and Cosmology :

The nature and origin of Dark Matter

The origin of the matter – antimatter asymmetry of the Universe

· They require the SM to be extended and placed within a cosmological context.

· They require Cosmology to be analyzed in terms more akin to particle physics.

This shared (rather conceptual) feature doesn't necessarily imply that the two questions are related with each other. There are, of course, groups that work on both, as there are models which actually *do* address both. However :

· Arguably, the first could be partly due to the fact that they share some common formalism and know-how ("particle cosmology").

· The latter is frequently done in a somewhat "disconnected" manner, *i.e.* DM doesn't play much of a role in baryogenesis and vice-versa.

Some introductory comments

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- They require the SM to be extended and placed within a cosmological context.
- They require Cosmology to be analyzed in terms more akin to particle physics.

But what if these two questions *are*, actually, related? Could we imagine a mechanism which could be responsible *both* for the generation of the observed dark matter abundance in the Universe and for the creation of an asymmetry between matter and antimatter in the visible sector?

The answer is *yes*, and different groups have entertained different such possibilities.

Proposals unifying DM and the BAU

Two notable examples :

Asymmetric dark matter

Vast literature, for a review *cf e.g.* arXiv:1305.4939

- Generate an asymmetry in the dark or visible sector (or both, *e.g.* mirror DM).
- If necessary, appropriately transfer it to the other sector.
- Annihilate away the symmetric components.

→ Correlated asymmetries.

WIMPy baryogenesis

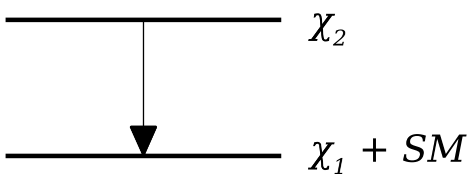
E.g. arXiv:1108.4653, arXiv:1112.2704

- Dark matter could be generated through the usual freeze-out mechanism.
- There is no fundamental reason why WIMP annihilations should respect CP/B.
- At some point WIMP annihilations *do* fall out of equilibrium.

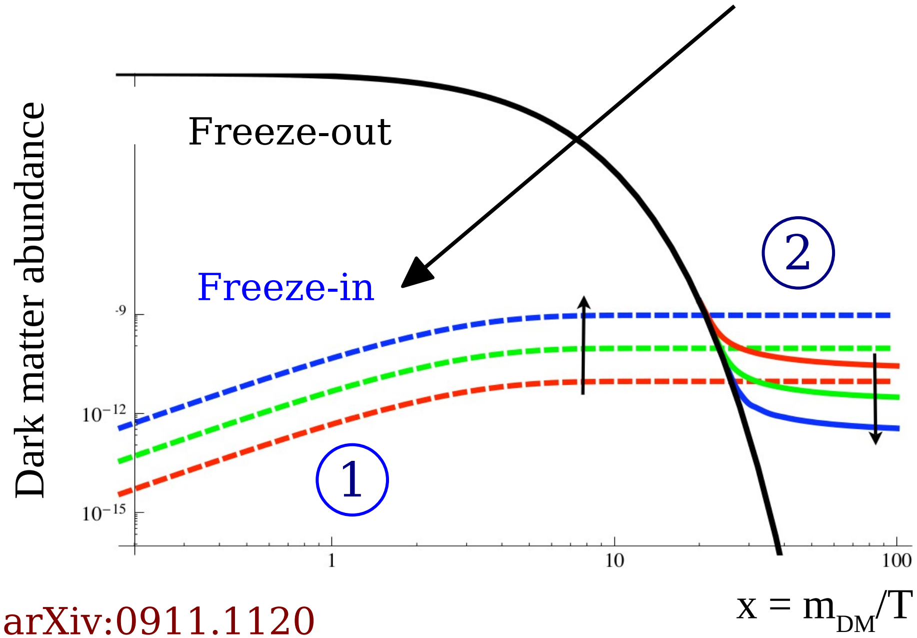
FIMPy baryogenesis: general idea

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

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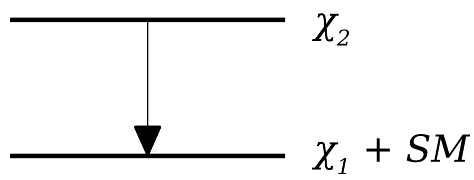

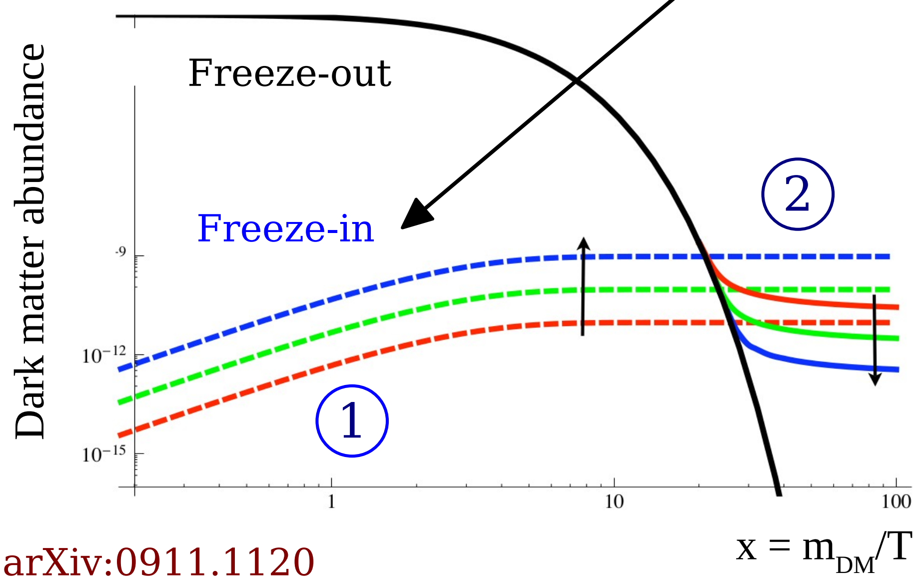

arXiv:0911.1120

· 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

Consider the SM along with a real singlet scalar FIMP S and two charged SU(2)-singlet vector-like fermions F_i, with all exotics odd under a discrete $\mathbf{Z_2}$ symmetry:

arXiv:2111.05740

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \mathcal{L}_S + \mathcal{L}_{SF}$$

$$\mathcal{L}_S = \partial_\mu S\ \partial^\mu S - \frac{\mu_S^2}{2} S^2 + \frac{\lambda_S}{4!} S^4 + \lambda_{Sh} S^2 \left(H^\dagger H\right)$$

$$\mathcal{L}_{SF} = \sum_i \left(\bar{F}_i \left(i\not{D}\right) F_i - M_i \bar{F}_i F_i\right) - \sum_{\alpha,i} \left(\lambda_{\alpha i}\, S\, \bar{F}_i\ e_\alpha + \lambda^*_{\alpha i}\, S\, \bar{e}_\alpha\ F_i\right)$$

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Assume to be negligible

$$\mathcal{L}_{SF} = \sum_i \left(\bar{F}_i \left(i\not{D}\right) F_i - M_i \bar{F}_i F_i\right) - \sum_{\alpha,i} \left(\lambda_{\alpha i}\, S\, \bar{F}_i\ e_\alpha + \lambda^*_{\alpha i}\, S\, \bar{e}_\alpha\ F_i\right)$$

Keep the F_i's in equilibrium with the plasma

Feeble, complex

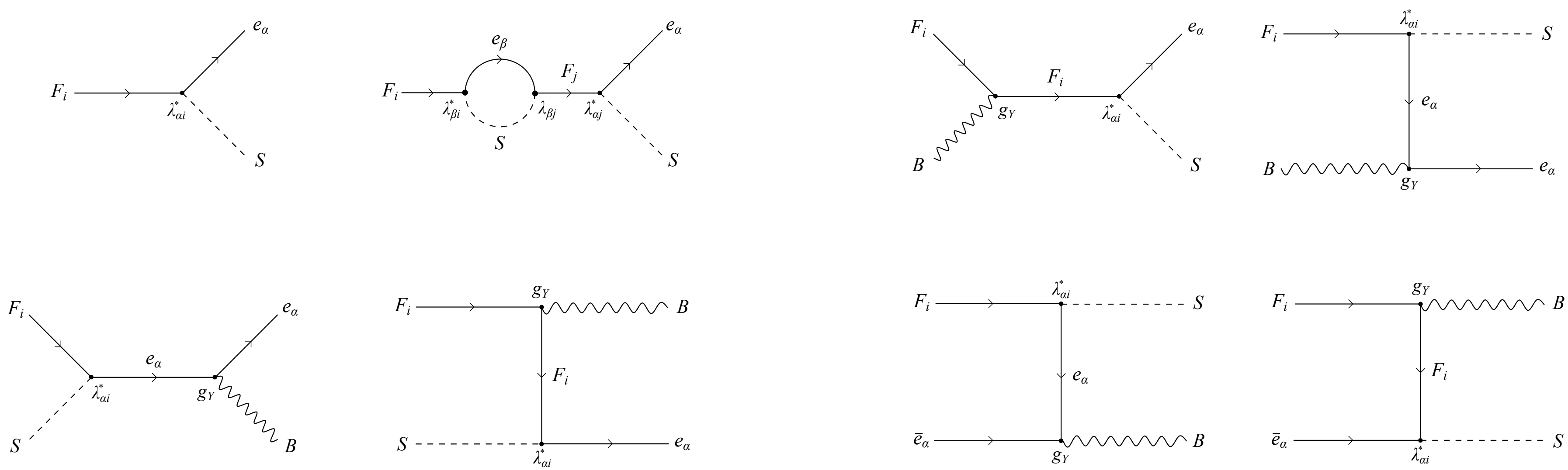
Remarks:

· This specific Lagrangian does not violate B or (total) L. This will come from sphaleron transitions later on. This is a model-dependent issue.

· It does, however, contain an additional source of CP violation with respect to the SM, due to the complex nature of the $\lambda_{\alpha i}$ couplings.

A concrete realization: physics

Processes that contribute to the generation of dark matter and of a *CP* asymmetry:



· The decays are the leading process. Scattering processes essentially just tend to wash out the generated asymmetry.

· In order to maximize *CP* violation, we will set $M_{F1} \sim M_{F2}$.

· Most of the action takes place at temperatures $T \sim M_F$.

· Non-equilibration is ensured by imposing : $\left(\sum_{\alpha,i} \gamma_{F_i \to e_\alpha S} \lesssim H \right)\Big|_{T=M_1}$

Dark matter production

Generically, the Boltzmann equation reads :

$$s\,\frac{\mathrm{d}Y_S}{\mathrm{d}t} = \sum_{\alpha,i}\{F_i \leftrightarrow e_\alpha S\} + \sum_{\alpha,i}\{F_i B \leftrightarrow e_\alpha S\} - \sum_{\alpha,i}\{F_i S \leftrightarrow e_\alpha B\} + \sum_{\alpha,i}\{F_i \bar{e}_\alpha \leftrightarrow S B\}$$
$$+\, 2\sum_{i,j}\{F_i \bar{F}_j \leftrightarrow SS\} + 2\sum_{\alpha,\beta}\{\bar{e}_\alpha e_\beta \leftrightarrow SS\}$$

→ Largely suppressed

where :

$$\{a\,b \leftrightarrow c\,d\} \equiv (a\,b \leftrightarrow c\,d) + (\bar{a}\,\bar{b} \leftrightarrow \bar{c}\,\bar{d})$$
$$[a\,b \leftrightarrow c\,d] \equiv (a\,b \leftrightarrow c\,d) - (\bar{a}\,\bar{b} \leftrightarrow \bar{c}\,\bar{d})$$
$$(a\,b \leftrightarrow c\,d) \equiv \int \mathrm{d}\Pi_a \mathrm{d}\Pi_b \mathrm{d}\Pi_c \mathrm{d}\Pi_d\,(2\pi)^4\,\delta^{(4)}\Big[\,|\mathcal{M}|^2_{ab\to cd}\, f_a f_b\,(1\pm f_c)\,(1\pm f_d) - |\mathcal{M}|^2_{cd\to ab}\, f_c f_d\,(1\pm f_a)\,(1\pm f_b)\Big]$$

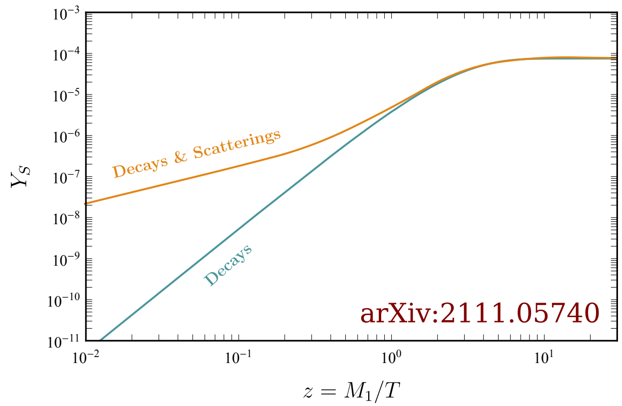
In order to solve this equation :

· Assume radiation domination.

· Neglect backreactions.

· Assume MB distributions.

→ In practice, decays dominate :



Baryogenesis - 1

· The decay processes in our model are the leading source of *CP* violation

$$\epsilon_{\alpha\, i} \equiv \frac{\Gamma\left(F_i \to e_\alpha S\right) - \Gamma\left(\bar{F}_i \to \bar{e}_\alpha S\right)}{\sum_\alpha \Gamma\left(F_i \to e_\alpha S\right) + \Gamma\left(\bar{F}_i \to \bar{e}_\alpha S\right)} = \frac{\Gamma\left(F_i \to e_\alpha S\right) - \Gamma\left(\bar{F}_i \to \bar{e}_\alpha S\right)}{2\,\Gamma_i}$$
$$= -\frac{1}{16\pi} \frac{1 - x_j}{\left(1 - x_j\right)^2 + g_j^2} \frac{|\lambda_{\alpha i}|\,|\lambda_{\alpha j}|}{\left[\lambda^\dagger \lambda\right]_{ii}} \sum_{\beta \neq \alpha} |\lambda_{\beta i}|\,|\lambda_{\beta j}| \sin\left(-\,\phi_{\alpha i} + \phi_{\alpha j} - \phi_{\beta j} + \phi_{\beta i}\right)$$

General logic:

· The F_i's carry the same lepton number as the SM leptons. Define: $Y_L = Y_{LSM} + Y_{LF}$.

· All processes (incl. sphaleron transitions) conserve $Y_{B-L} \equiv Y_B - Y_{LSM} - Y_{LF}$.

· All processes conserve Y_L *except for sphaleron transitions* : the latter are insensitive to Y_{LF} (the F_i's are SU(2)-singlets), but they can convert a non-zero lepton asymmetry stored in the SM sector into a baryon one.

· Then, if sphalerons decouple before all of the F_i's decay away, a net baryon asymmetry can be generated and survive to the present day.

Cf also "Dirac leptogenesis", arXiv:hep-ph/9907562

Baryogenesis - 2

The Boltzmann equations for the various asymmetries read

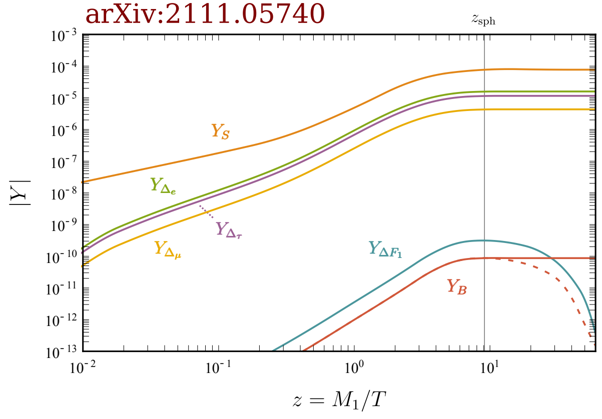
$$
\begin{aligned}
-sHz\frac{\mathrm{d}Y_{\Delta F_i}}{\mathrm{d}z} =& \sum_\alpha [F_i \leftrightarrow e_\alpha S] + \sum_\alpha [F_i B \leftrightarrow e_\alpha S] + \sum_\alpha [F_i S \leftrightarrow e_\alpha B] + \sum_\alpha [F_i \bar{e}_\alpha \leftrightarrow SB] \\
&+ \sum_{\alpha,\beta,j} [F_i \bar{e}_\alpha \leftrightarrow \bar{F}_j e_\beta] + \sum_{\alpha,\beta} [F_i \bar{e}_\alpha \leftrightarrow F_j \bar{e}_\beta] + \sum_{\alpha,\beta} [F_i e_\beta \leftrightarrow F_j e_\alpha] \\
&+ \sum_{\alpha,\beta} [F_i \bar{F}_{j\neq i} \leftrightarrow e_\alpha \bar{e}_\beta] + [F_i \bar{F}_{j\neq i} \leftrightarrow SS] + \sum_{\alpha,\beta,j} [F_i F_j \leftrightarrow e_\alpha e_\beta] \\
&+ [F_i S \leftrightarrow F_{j\neq i} S]
\end{aligned}
$$

$$
\begin{aligned}
-sHz\frac{\mathrm{d}Y_{\Delta_\alpha}}{\mathrm{d}z} =& \sum_i [F_i \leftrightarrow e_\alpha S] + \sum_i [F_i B \leftrightarrow e_\alpha S] + \sum_i [F_i S \leftrightarrow e_\alpha B] + \sum_i [F_i \bar{e}_\alpha \leftrightarrow SB] \\
&+ \sum_{i,j,\beta} [F_i \bar{e}_\alpha \leftrightarrow \bar{F}_j e_\beta] + \sum_{i,j,\beta\neq\alpha} [F_i \bar{e}_\alpha \leftrightarrow F_j \bar{e}_\beta] + \sum_{i,j,\beta\neq\alpha} [F_i e_\beta \leftrightarrow F_j e_\alpha] \\
&+ \sum_{i,j,\beta\neq\alpha} [F_i \bar{F}_j \leftrightarrow e_\alpha \bar{e}_\beta] + \sum_{\beta\neq\alpha} [\bar{e}_\alpha e_\beta \leftrightarrow SS] + \sum_{i,j,\beta} [F_i F_j \leftrightarrow e_\alpha e_\beta] \\
&+ \sum_{\beta\neq\alpha} [e_\beta S \leftrightarrow e_\alpha S]'
\end{aligned}
$$

where : $Y_{\Delta F_i} \equiv Y_{F_i} - Y_{\bar{F}_i},\ Y_{\Delta_\alpha} \equiv Y_B/3 - Y_{L_{\mathrm{SM}\alpha}}$

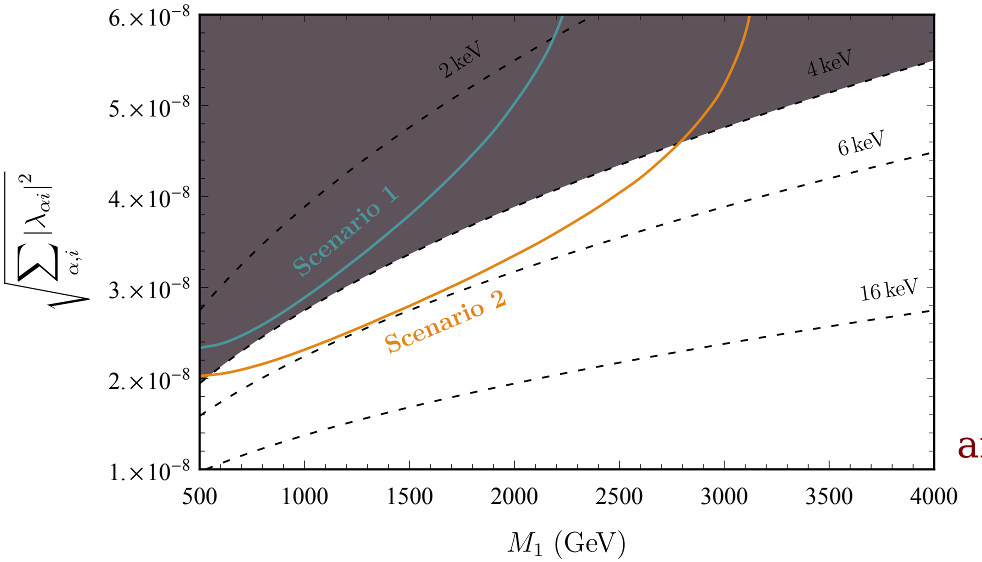
The baryon asymmetry is simply given by : $Y_B = \frac{22}{79}\sum_\alpha Y_{\Delta\alpha}$

arXiv:2111.05740



Results

All in all : a viable baryon asymmetry can be obtained along with the observed DM abundance in the Universe, as long as DM is quite light and the F_i's are close in mass (resonnant enhancement of CP violation).



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Results

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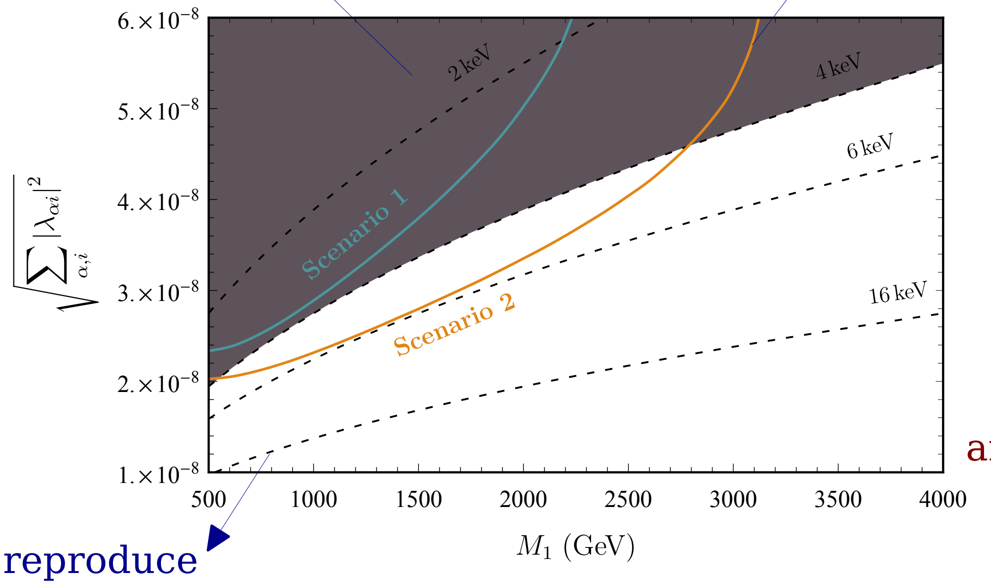
Excluded by Lyman-α forest observations

Baryon asymmetry OK

arXiv:2011.13458



arXiv:2111.05740

Required DM mass to reproduce Planck observations

· The F_i's cannot be too heavy, otherwise they decay before sphaleron decoupling → the baryon asymmetry would be completely washed out.

→ The scenario can be partly probed at the LHC

Cf also arXiv:1811.05478

A non-renormalizable version

arXiv:2204.13554

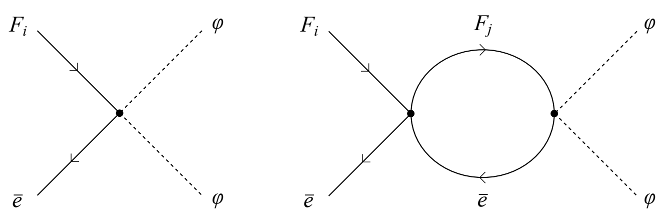
Consider a similar extension of the SM by a complex scalar field and two vector-like fermions, described by the Lagrangian :

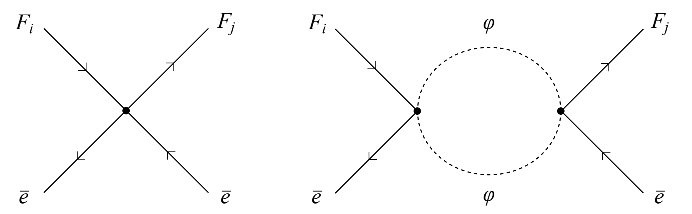
$$\mathcal{L}_{\rm int} = \frac{\lambda_1}{2\Lambda}\left(\bar{e}F_1\right)\varphi^*\varphi^* + \frac{\lambda_2}{2\Lambda}\left(\bar{e}F_2\right)\varphi^*\varphi^* + \frac{\kappa}{\Lambda^2}\left(\bar{e}F_1\right)\left(\bar{F}_2 e\right) + {\rm h.c.}$$

· 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

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

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

A non-renormalizable version + 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.

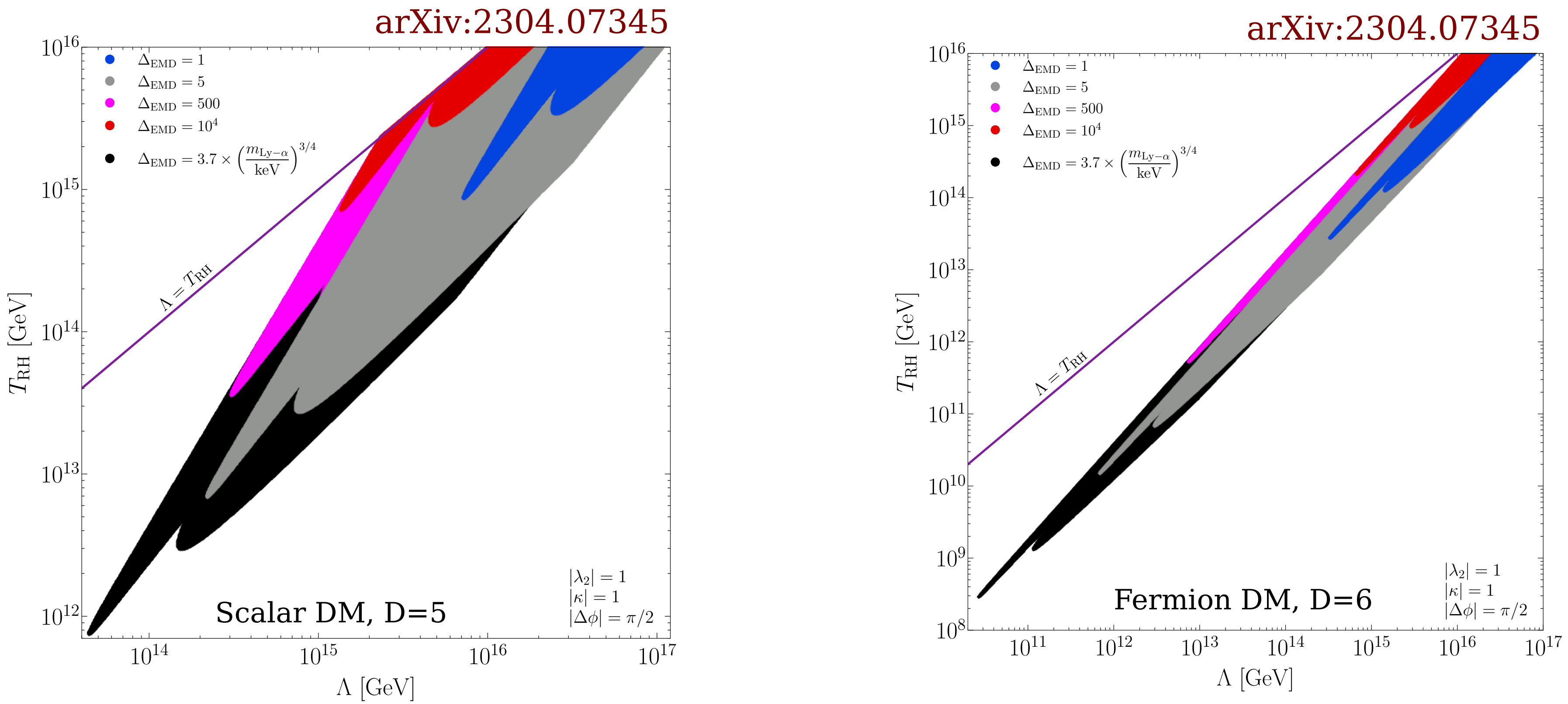
The evolution of the cosmological background is, in this case, described by the system of equations

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

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

Results

Once again, the mechanism works! Dark matter production and baryogenesis can be simultaneously achieved.



· 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.

· Less obvious connection with LHC physics, but possibilities do exist.

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 $(\Lambda, T_{\rm RH}, m_{\rm DM})$ 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_*.

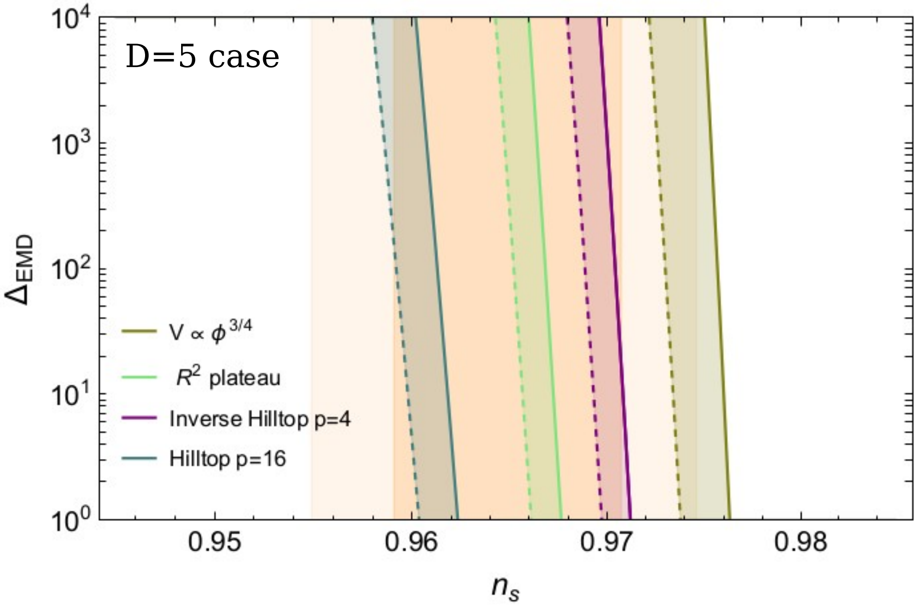
· Lastly, N_* can be related, within specific models of inflation, with the spectral index through a relation of the type $n_s = n_s(N)$.

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

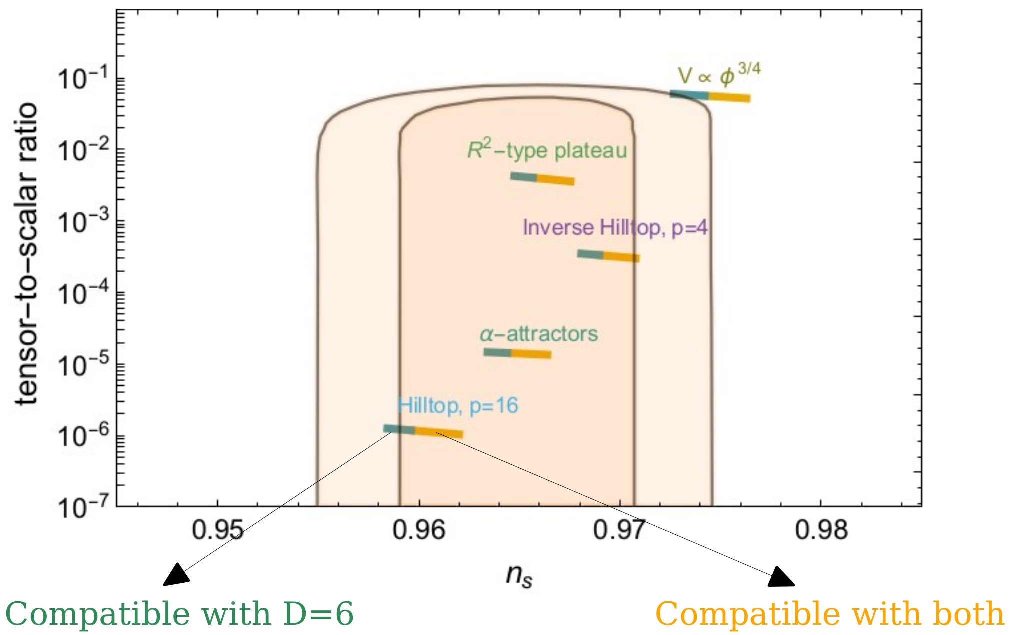
Potential imprints on the CMB ?

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!