Cosmological Models with Freeze-in Baryogenesis

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Hellenic Foundation for Research & Innovation

HEP2023 - 40th Conference on Recent Developments in High Energy Physics and Cosmology, Ioannina

Outline

Based on arxiv:2111.05740 and arxiv:2204.13554

in collaboration with I. Dalianis, A. Goudelis, D. Karamitros, P. Papachristos

- Dark matter and the baryon asymmetry of the Universe
- The freeze-in mechanism
- Infrared “FIMPy baryogenesis”
- Ultraviolet “FIMPy baryogenesis”
- Outlook

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.

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.

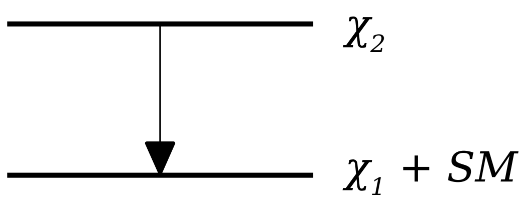
· At some point WIMP annihilations *do* fall out of equilibrium.

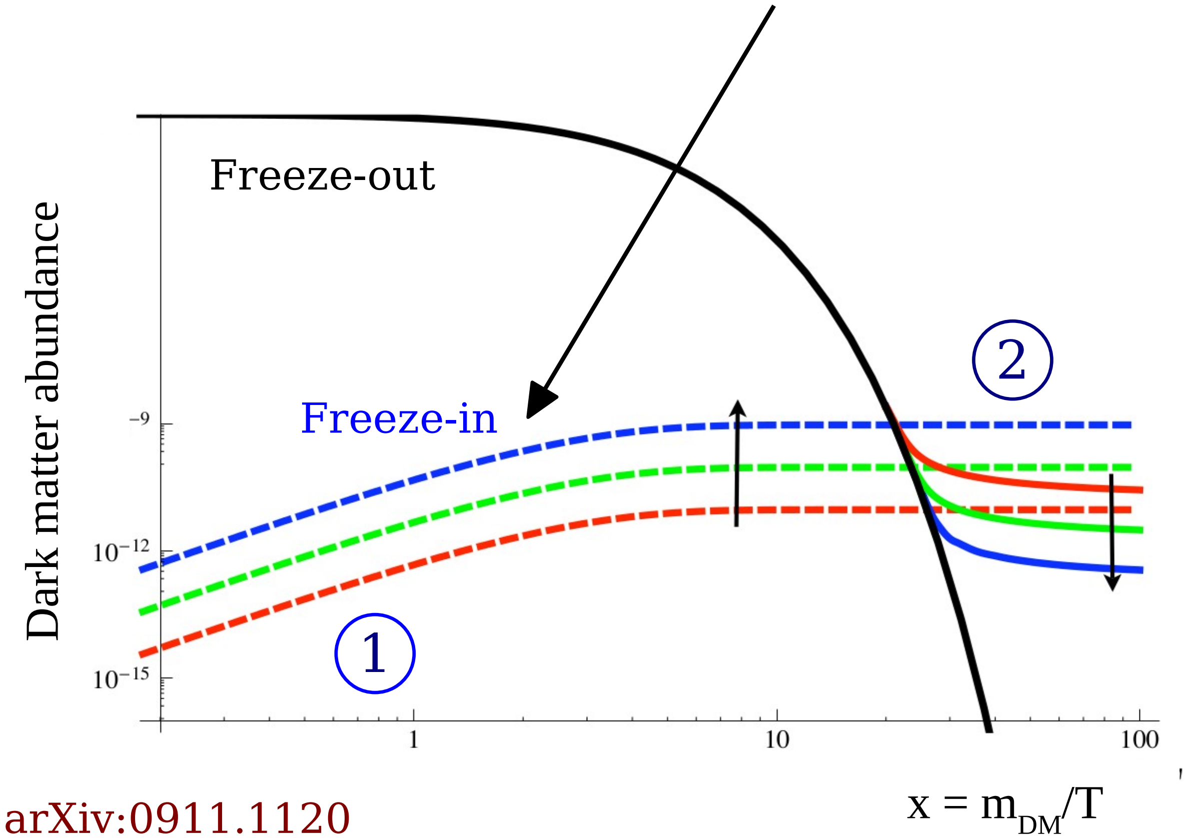
The freeze-in mechanism

arXiv:hep-ph/0106249
arXiv:0911.1120

The freeze-in mechanism 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 cosmologically *e.g.* from the decay of some heavier state or from annihilations of bath particles.





arXiv:0911.1120

Could the same out-of-equilibrium dynamics be exploited in order to achieve succesful baryogenesis?

For the first such proposal, involving asymmetric DM, *cf* arXiv:1010.0245

FIMPy baryogenesis: general idea

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

· 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.

$\boxed{\text{→ All three Sakharov conditions can be satisfied.}}$

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

Naïvely, if denote the measure of *CP* violation by ε_{CP}, we would expect:

$$Y_{\Delta f} \sim \epsilon_{CP} Y_{DM}$$

In practice, and sticking to decays, this limit cannot be achieved due to:

· Washout effects.

· *CPT* and Unitarity, which will force us to introduce multiple decay channels for our heavy particles.

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

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

Assume to be negligible

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

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

Keep the F_i's in equilibrium with the plasma

Feeble, complex

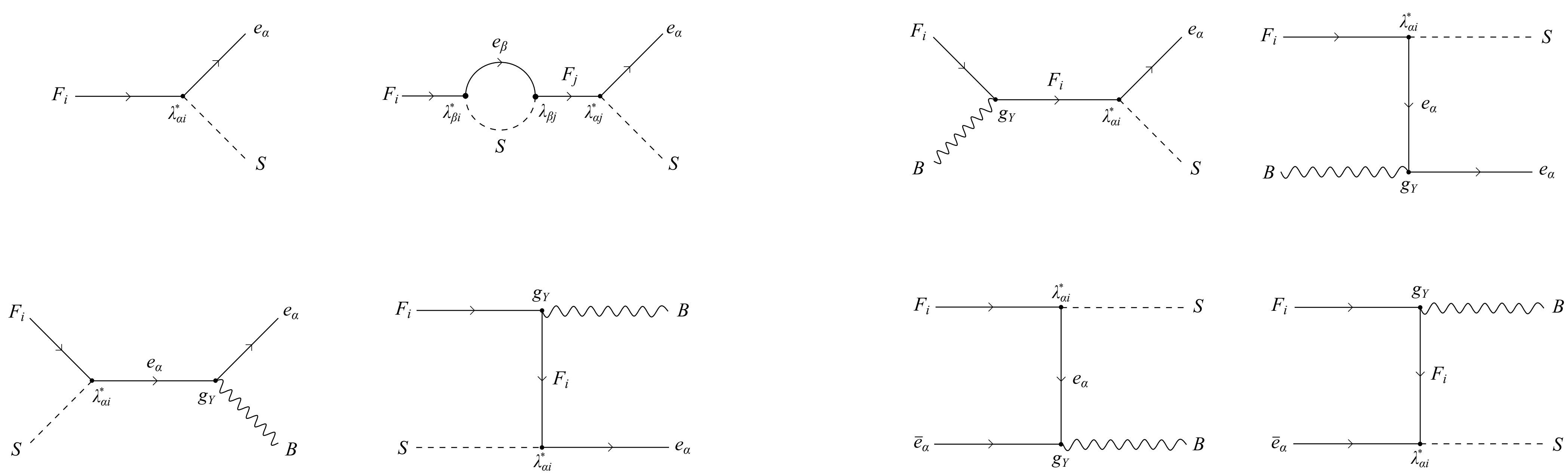
Remarks:

· This Lagrangian does not violate B or (total) L. This will come from sphaleron transitions later on.

· 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 :

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

Largely suppressed

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

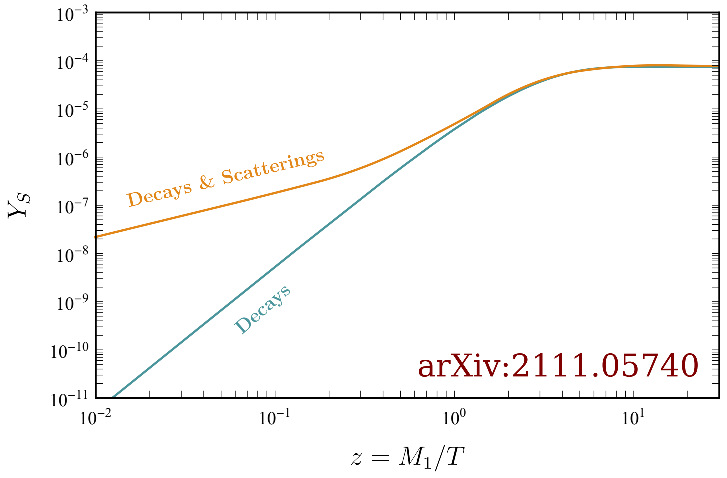
In order to solve this equation :

· 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

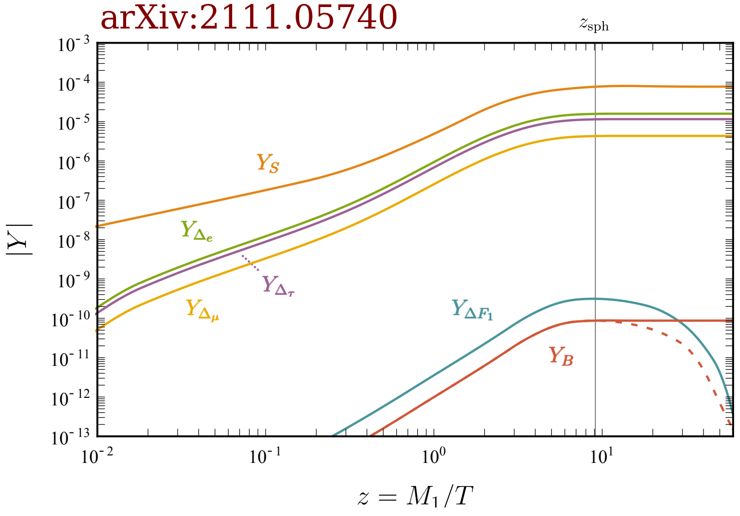
$$
\begin{aligned}
-sHz\frac{\mathrm{d}Y_{\Delta F_i}}{\mathrm{d}z} = {} & \sum_\alpha [F_i \leftrightarrow e_\alpha S] + \sum_\alpha [F_i B \leftrightarrow e_\alpha S] + \sum_\alpha [F_i S \leftrightarrow e_\alpha B] + \sum_\alpha [F_i \bar{e}_\alpha \leftrightarrow SB] \\
& + \sum_{\alpha,\beta,j}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

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

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 : $Y_B = \dfrac{22}{79}\sum_\alpha Y_{\Delta\alpha}$

arXiv:2111.05740



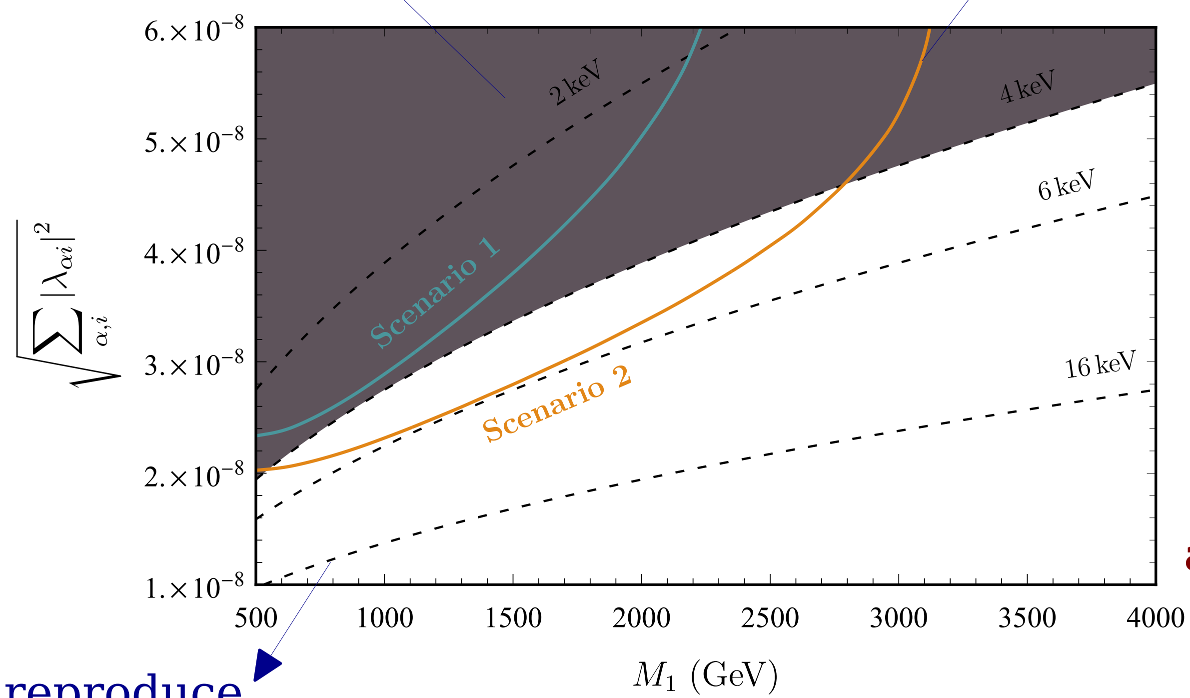
Results

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 (resonant enhancement of CP violation).

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!

A non-renormalizable version

arXiv:2204.13554

What if DM interacts with the SM through non-renormalizable operators?

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

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

which could, *e.g.*, be obtained by integrating out some heavy scalar mediator field. Additional contributions can be forbidden by imposing a $\mathbf{Z_3}$ symmetry as :

Particle	Gauge	$\mathbb{Z}_3$
φ	$(1,1)_0$	ω
φ^*	$(1,1)_0$	ω^{-1}
F_i	$(1,1)_{-1}$	ω^{-1}
$\bar{F}_i$	$(1,1)_1$	ω

In this case it is, rather, scattering processes that dominate both DM production and baryogenesis.

Dark matter: Ultraviolet freeze-in

arXiv:1410.6157

It is known that in such scenarios :

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

· The predicted DM abundance depends on this temperature.

Indeed, if we consider a generic interaction described by an effective operator that scales as $1/\Lambda^n$, by writing down and solving the Boltzman equation for DM production we find :

$$Y_{\rm DM}(T) \approx 2A\,\frac{4^{n+1} n!(n+1)!}{2n-1}\,\frac{45}{1024\times 1.66\,\pi^7 g_{\star s}\sqrt{g_{\star\rho}}}\,\frac{M_{Pl}\,(T_{\rm RH}^{2n-1}-T^{2n-1})}{\Lambda^{2n}}\ ,$$

where A is a coefficient that depends on the underlying model. This leads to the prediction :

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

This general formula can be straightforwardly applied to our scenario.

Baryogenesis - 1

Much like in the previous case, the model provides a source for CP violation whereas the final baryon asymmetry is generated through the interplay with the EW sphalerons.

In this case, the relevant processes are :

+ subleading 3-body decays

and there are three sources of CP asymmetry :

$$\epsilon_i \equiv \frac{\gamma_{F_i \bar{e} \to \varphi\varphi} - \gamma_{\bar{F}_i e \to \varphi^* \varphi^*}}{\gamma_{F_i \bar{e} \to \varphi\varphi} + \gamma_{\bar{F}_i e \to \varphi^* \varphi^*}}$$

$$\epsilon_3 \equiv \frac{\gamma_{F_1 \bar{e} \to F_2 \bar{e}} - \gamma_{\bar{F}_1 e \to \bar{F}_2 e}}{\gamma_{F_1 \bar{e} \to F_2 \bar{e}} + \gamma_{\bar{F}_1 e \to \bar{F}_2 e}}$$

out of which only the first two generate correlated asymmetries in the two sectors.

Baryogenesis - 2

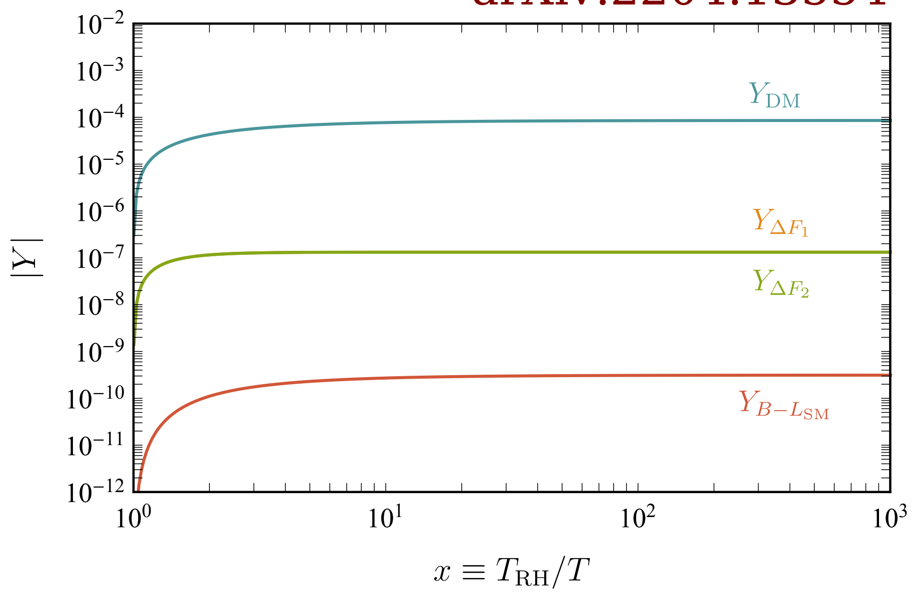
The relevant Boltzmann equations in this case read :

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

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

arXiv:2204.13554

with numerical solutions resembling as :



Given the temperatures that are the most relevant for our parameter space, the final baryon asymmetry in this case is found to be given by :

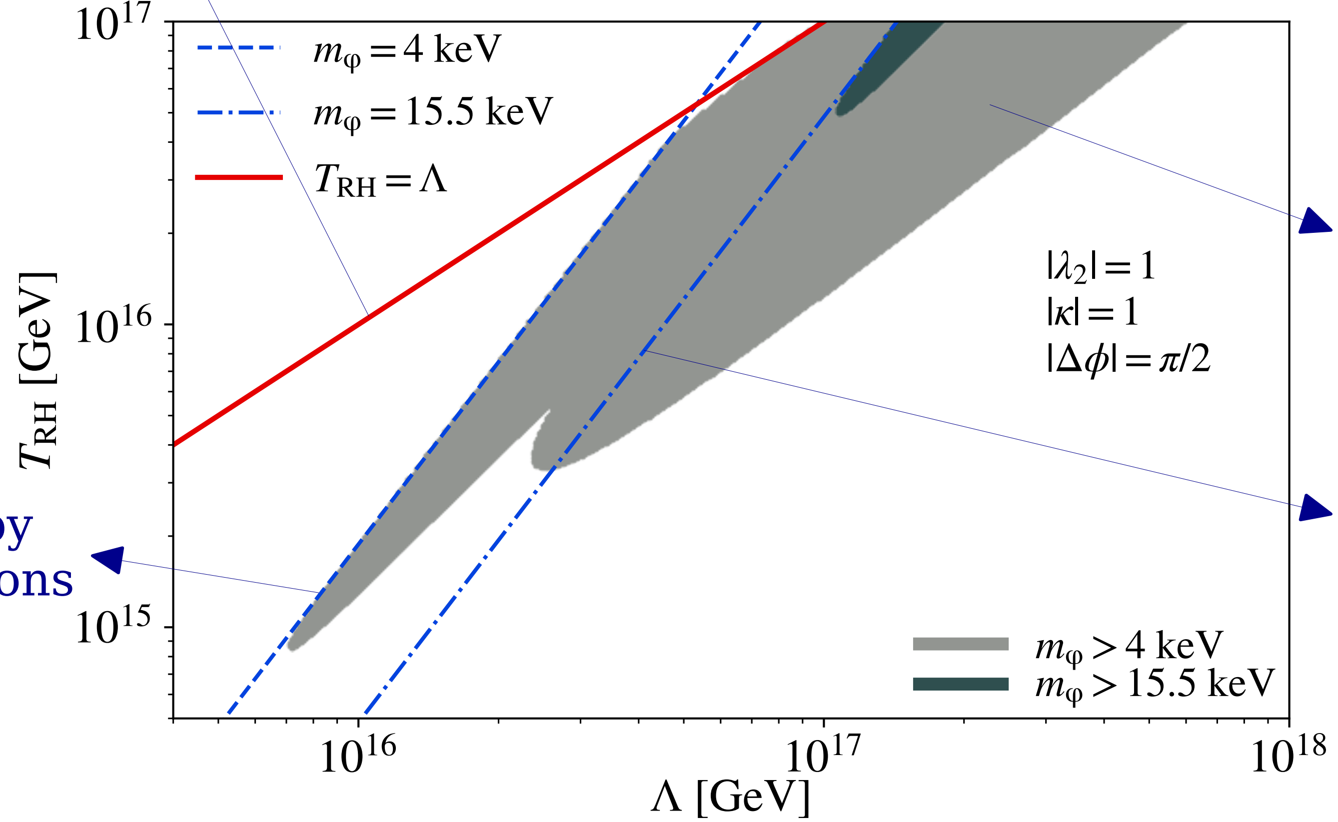
$$Y_B = \frac{22}{79}Y_{B-L_{\mathrm{SM}}}$$

Results: scalar DM

Once again, the mechanism works! Dark matter production and baryogenesis can be simultaneously achieved and, again, DM is predicted to be relatively light.

Computing what happens if $T_{\mathrm{RH}} > \Lambda$ would require knowledge of the underlying theory

arXiv:2204.13554



Both baryogenesis and DM viable, the latter with appropriate choice of the DM mass

Maximal value of T_{RH} for which the observed DM abundance can be reproduced for given mass limit

Lower masses excluded by Lyman-α forest observations

arXiv:2011.13458

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

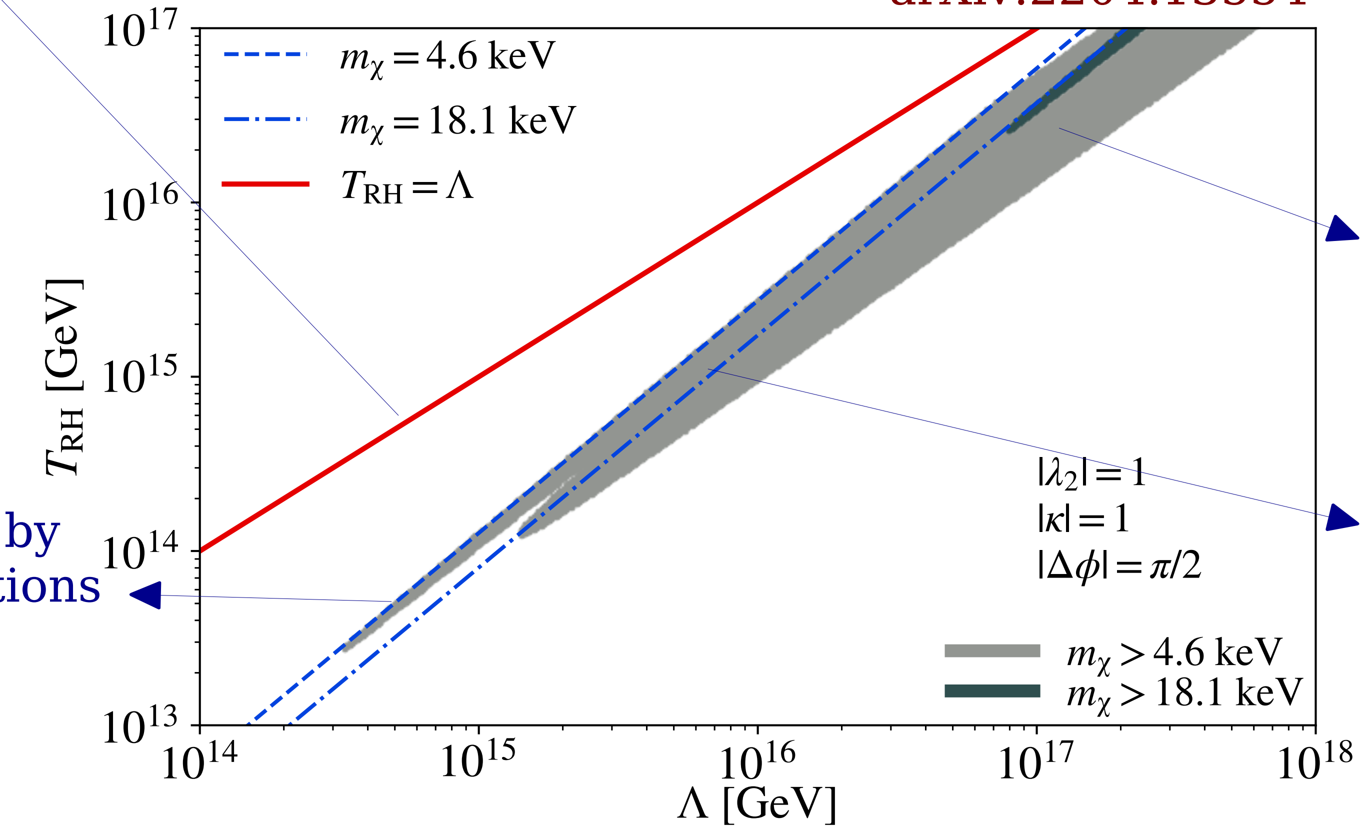
· Although our parameter space is viable, one might be troubled by such high values for T_{RH}. Can we do better?

Results: fermion DM

One straightforward way to achieve lower values for T_{RH} is by considering, rather, Dirac fermion DM.

Computing what happens if $T_{\mathrm{RH}} > \Lambda$ would require knowledge of the underlying theory

arXiv:2204.13554



Both baryogenesis and DM viable, the latter with appropriate choice of the DM mass

Lower masses excluded by Lyman-α forest observations

arXiv:2011.13458

Maximal value of T_{RH} for which the observed DM abundance can be reproduced for given mass limit

· In this case the relevant interaction is of mass dimension 6.

· Very similar mechanism as in the scalar case, but stronger temperature dependence → Can live with lower T_{RH}.

With an additional component

The starting point assumption is that the DM particle species only interacts feebly with the bath particles through an effective operator $\hat{\mathcal{O}}_{(n)}$ of mass dimension $(n+4)$

$$\mathcal{L} \supset \frac{1}{\Lambda^n}\,\hat{\mathcal{O}}_{(n)}$$

Let us call X a scalar field

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

$d\tilde{N} = d(\ln a) = H dt$ $\qquad$ $\mathrm{B}_{\rm DM} \equiv \mathrm{Br}(X \to \mathrm{DM})$, is vanishing

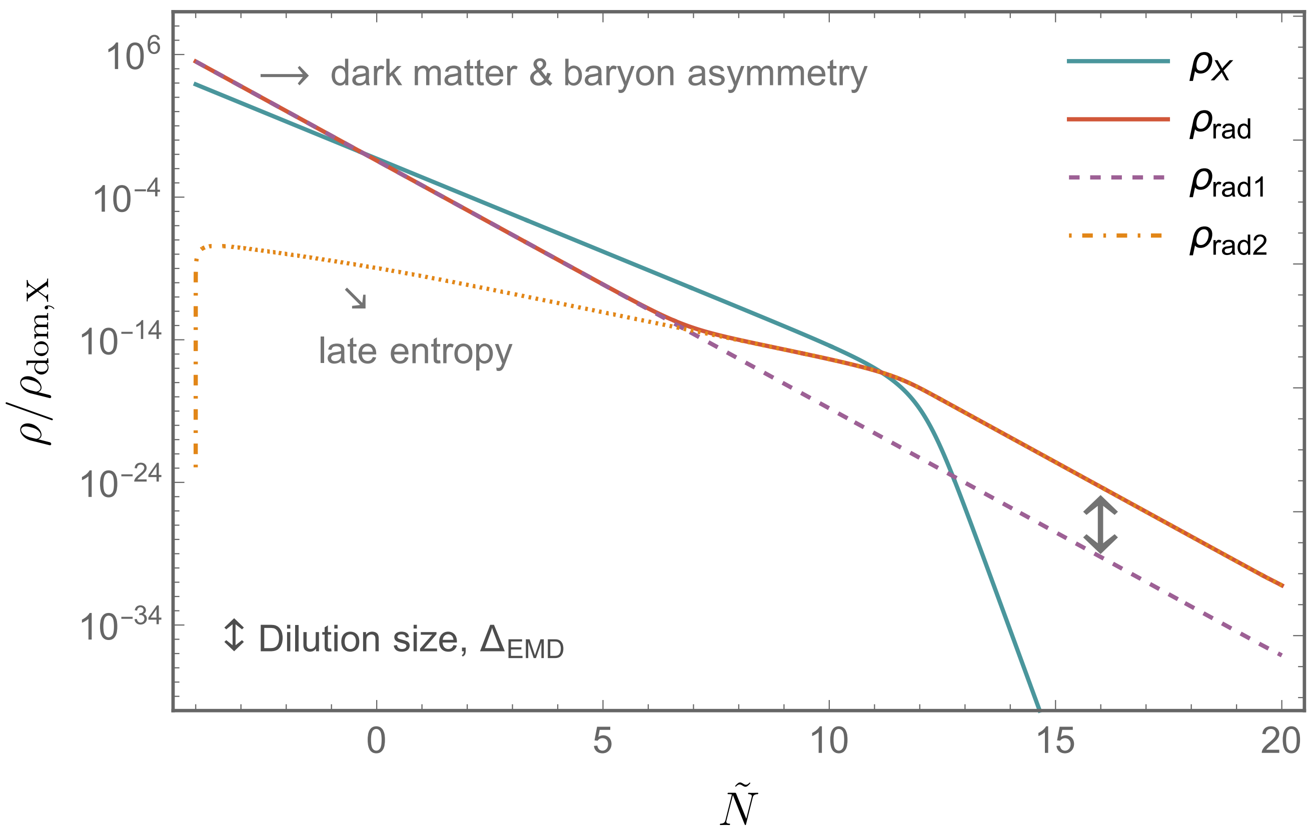
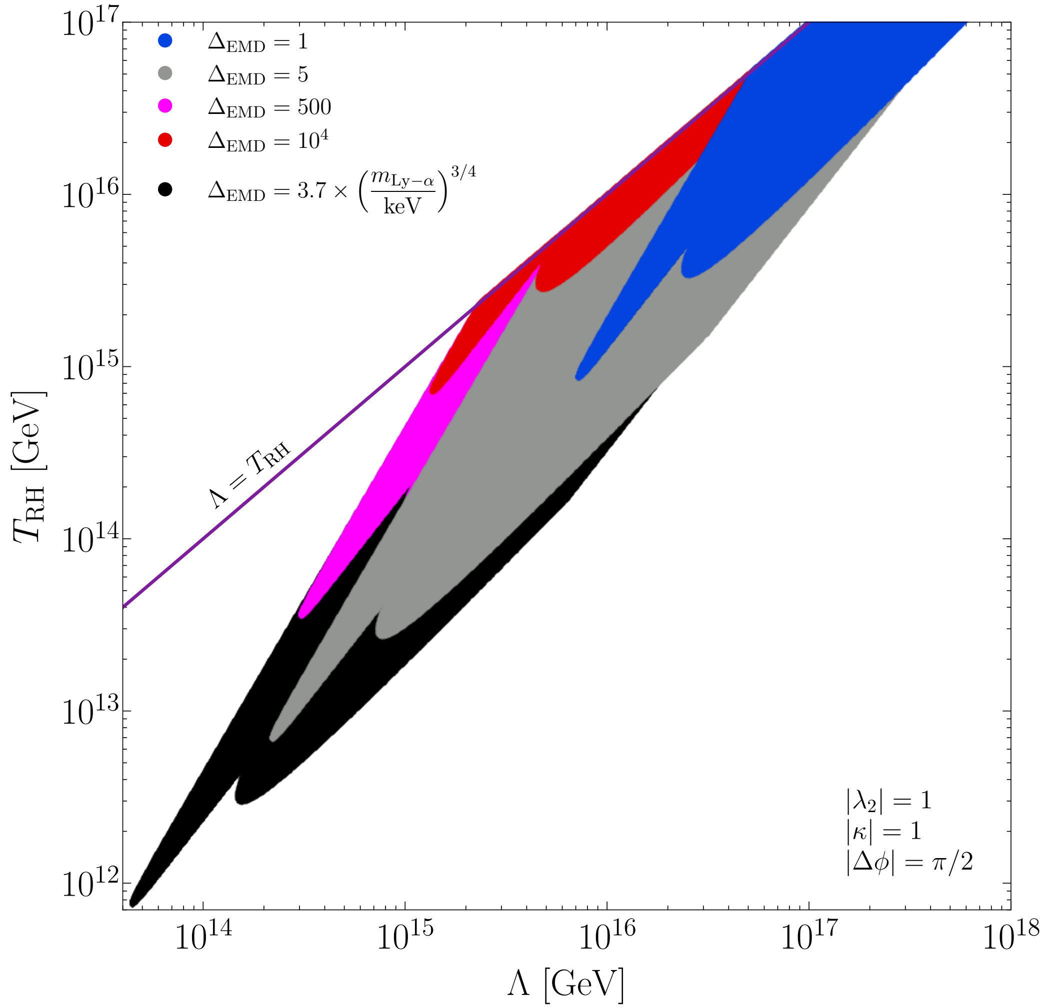


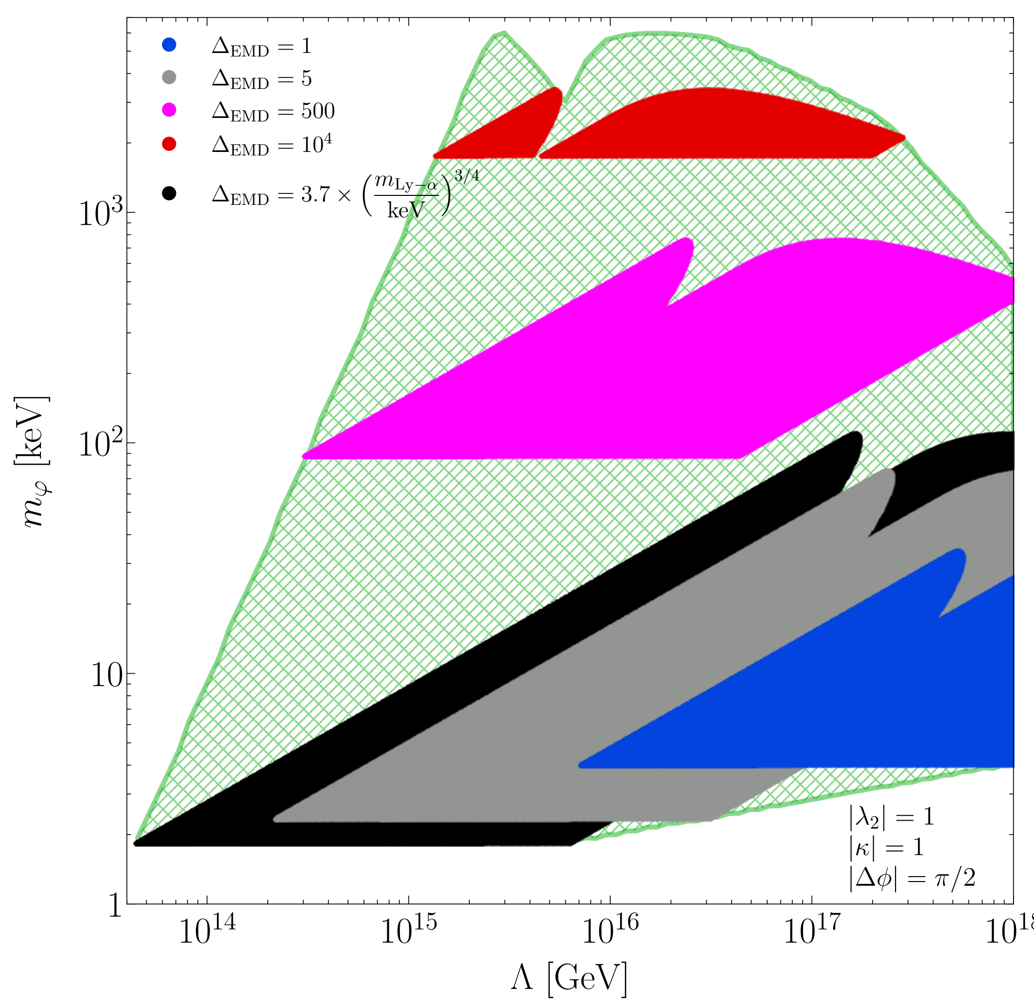
Figure 2: The evolution of the energy densities of two interacting fluids, radiation (red) and a scalar field X (blue), with respect to the e-folds number $\tilde{N}$, normalized by the energy density at the moment of X domination ($\tilde{N} = 0$). With a dashed line we depict the evolution of the radiation energy density in the absence of X decays and with a dot-dashed the radiation component produced from the out of equilibrium X-decay. The Figure illustrates a scenario where the scalar condensate domination lasts $\tilde{N}_{\rm EMD} \sim 12$ e-folds and realizes a dilution of size $\Delta_{\rm EMD} \sim 10^4$.

d=5 case



$\Delta_{\rm EMD} = 1$
$\Delta_{\rm EMD} = 5$
$\Delta_{\rm EMD} = 500$
$\Delta_{\rm EMD} = 10^4$
$\Delta_{\rm EMD} = 3.7 \times \left(\frac{m_{\rm Ly-\alpha}}{\rm keV}\right)^{3/4}$
$\Lambda = T_{\rm RH}$
$|\lambda_2| = 1$
$|\kappa| = 1$
$|\Delta\phi| = \pi/2$
$T_{\rm RH}$ [GeV]
Λ [GeV]

(a)



$\Delta_{\rm EMD} = 1$
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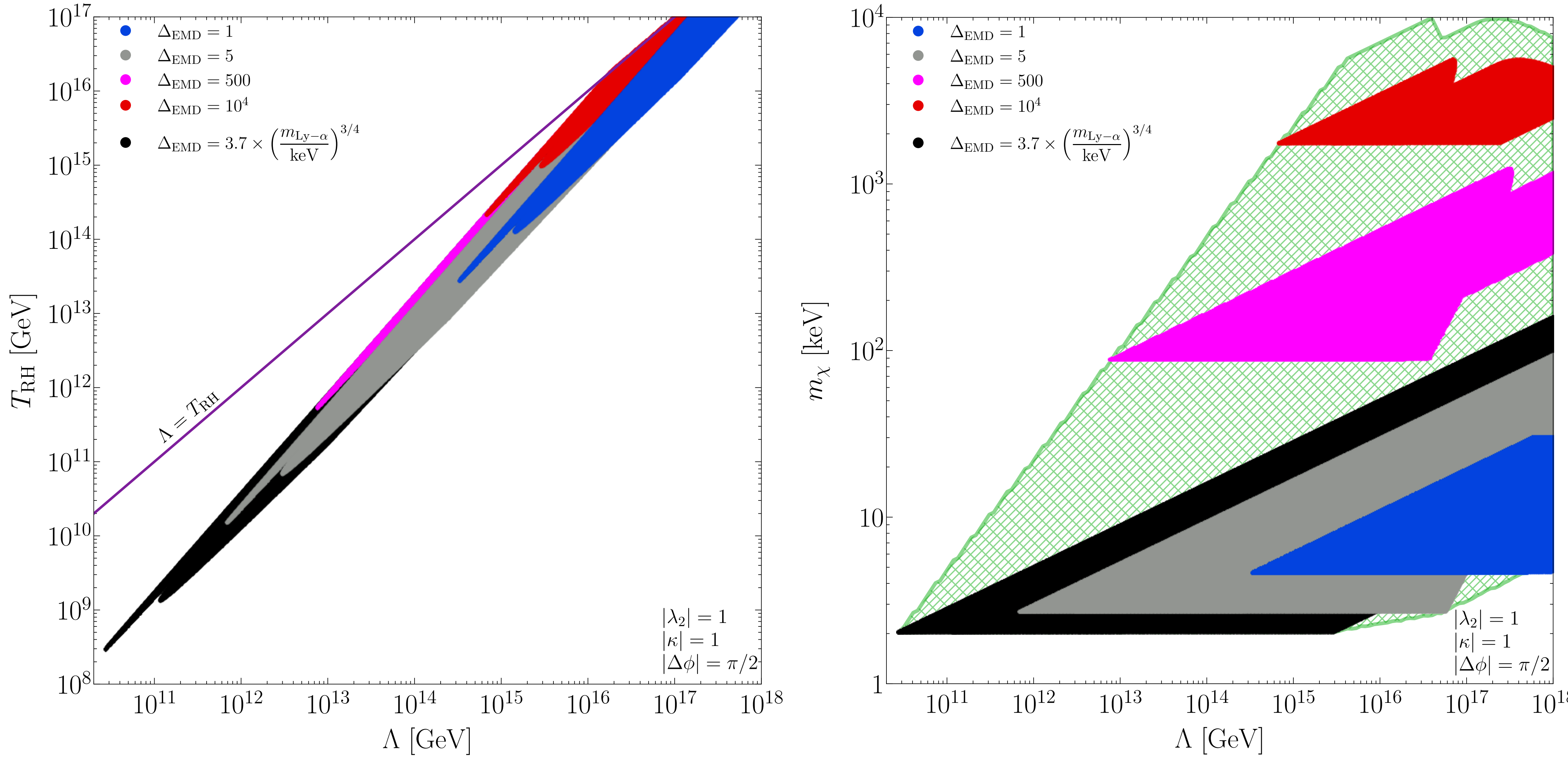
$|\lambda_2| = 1$
$|\kappa| = 1$
$|\Delta\phi| = \pi/2$
m_φ [keV]
Λ [GeV]

(b)

d=6 case



$\Delta_{\rm EMD} = 1$
$\Delta_{\rm EMD} = 5$
$\Delta_{\rm EMD} = 500$
$\Delta_{\rm EMD} = 10^4$
$\Delta_{\rm EMD} = 3.7 \times \left(\frac{m_{\rm Ly-\alpha}}{\rm keV}\right)^{3/4}$
$\Lambda = T_{\rm RH}$
$T_{\rm RH}$ [GeV]
Λ [GeV]
m_χ [keV]
$|\lambda_2| = 1$
$|\kappa| = 1$
$|\Delta\phi| = \pi/2$

(a) **(b)**

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) and it can give rise to interesting signals at the LHC.

· Interesting question: symmetric dark matter freeze-in baryogenesis scenarios seem to predict rather light DM. How generic is this feature ?