Dark matter and baryogenesis from freeze-in

Based on arXiv:2111.05740, arXiv:2204.13554
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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.

→ 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

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

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

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

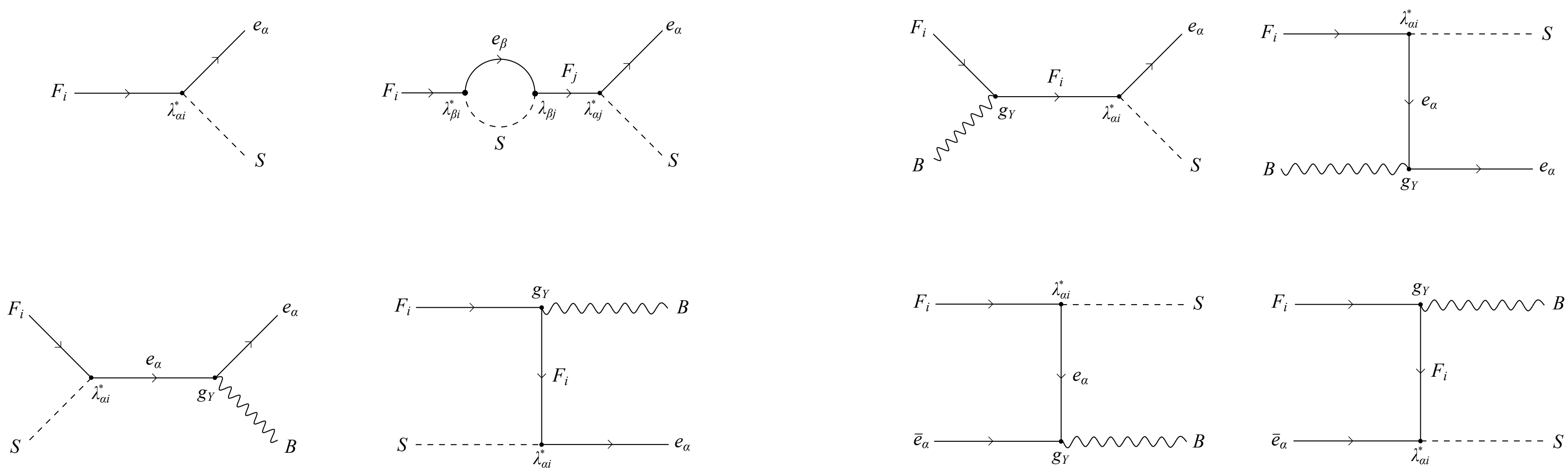
Remarks:

· This 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 :

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

→ Largely suppressed

where :

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

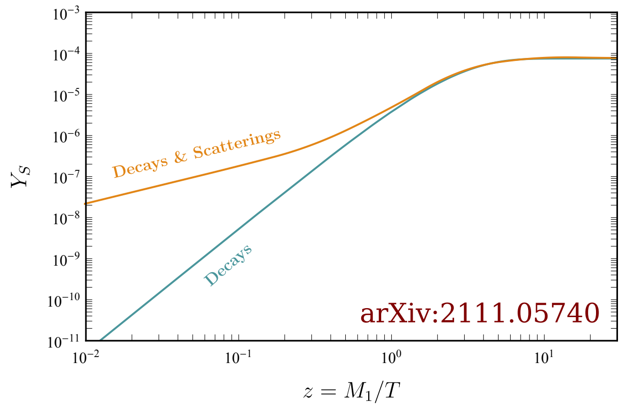
In order to solve this equation :

· 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

$$\epsilon_{\alpha\, i} \equiv \frac{\Gamma\left(F_i \to e_\alpha S\right) - \Gamma\left(\bar{F}_i \to \bar{e}_\alpha S\right)}{\sum_\alpha \Gamma\left(F_i \to e_\alpha S\right) + \Gamma\left(\bar{F}_i \to \bar{e}_\alpha S\right)} = \frac{\Gamma\left(F_i \to e_\alpha S\right) - \Gamma\left(\bar{F}_i \to \bar{e}_\alpha S\right)}{2\,\Gamma_i}$$

$$= -\frac{1}{16\pi} \frac{1 - x_j}{\left(1 - x_j\right)^2 + g_j^2} \frac{|\lambda_{\alpha i}|\,|\lambda_{\alpha j}|}{\left[\lambda^\dagger \lambda\right]_{ii}} \sum_{\beta \neq \alpha} |\lambda_{\beta i}|\,|\lambda_{\beta j}| \sin\left(-\phi_{\alpha i} + \phi_{\alpha j} - \phi_{\beta j} + \phi_{\beta i}\right)$$

Small-x behaviour regulated as in arXiv:hep-ph/9812256

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

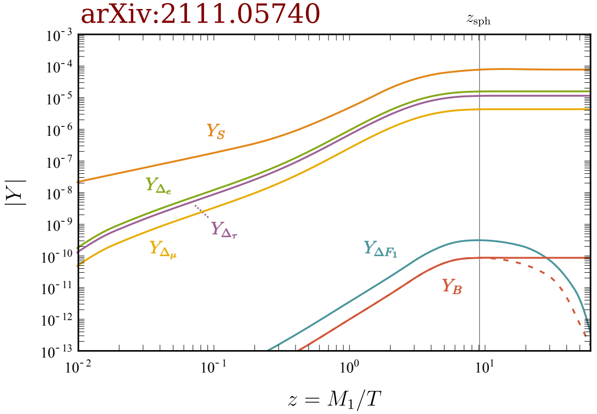
$$
\begin{aligned}
-sHz\frac{\mathrm{d}Y_{\Delta F_i}}{\mathrm{d}z} = & \sum_\alpha [F_i \leftrightarrow e_\alpha S] + \sum_\alpha [F_i B \leftrightarrow e_\alpha S] + \sum_\alpha [F_i S \leftrightarrow e_\alpha B] + \sum_\alpha [F_i \bar{e}_\alpha \leftrightarrow SB] \\
& + \sum_{\alpha,\beta,j} [F_i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

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

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

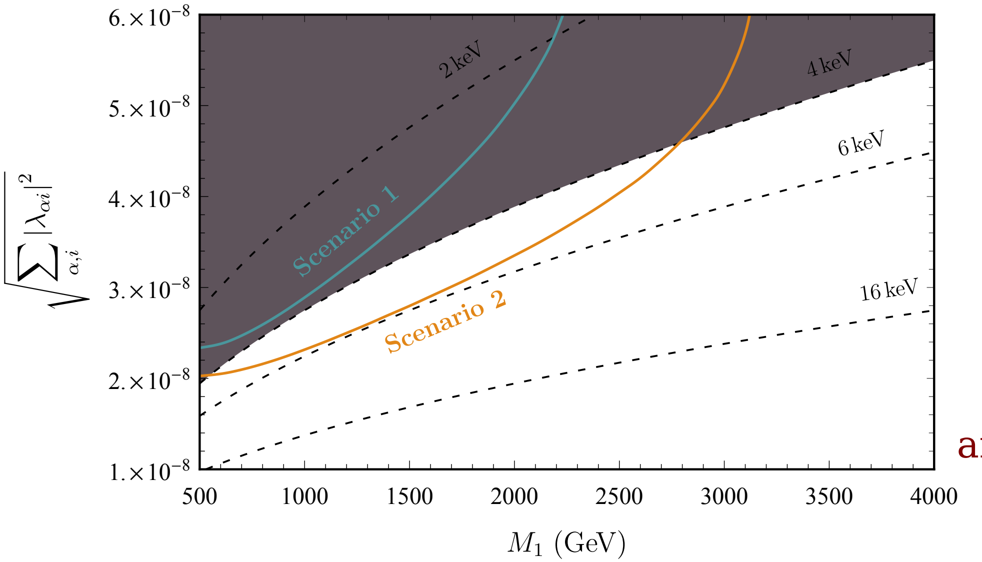
The baryon asymmetry is simply given by : $Y_B = \dfrac{22}{79}\sum_\alpha Y_{\Delta\alpha}$

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 (resonnant enhancement of CP violation).



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Results

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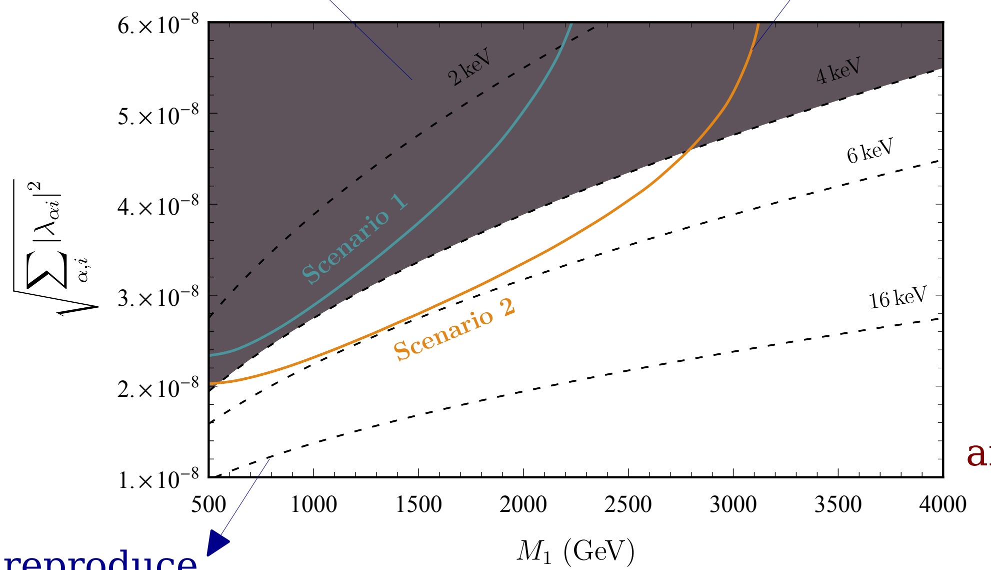
Excluded by Lyman-α forest observations

Baryon asymmetry OK

arXiv:2011.13458



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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

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 :

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

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

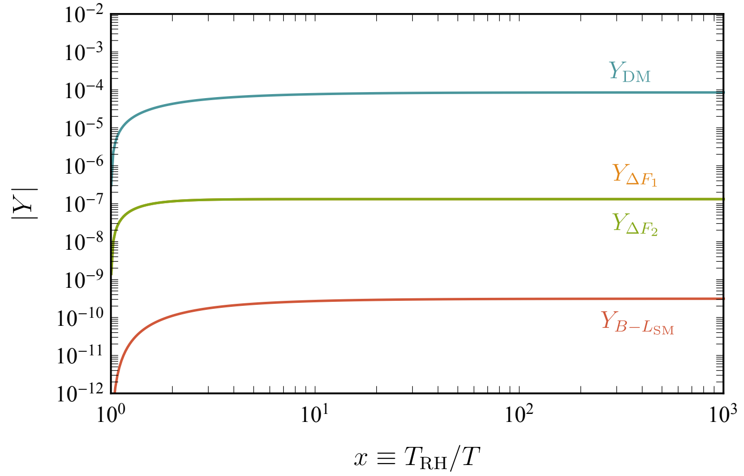
The relevant Boltzmann equations in this case read :

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

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

with numerical solutions resembling as :

arXiv:2204.13554



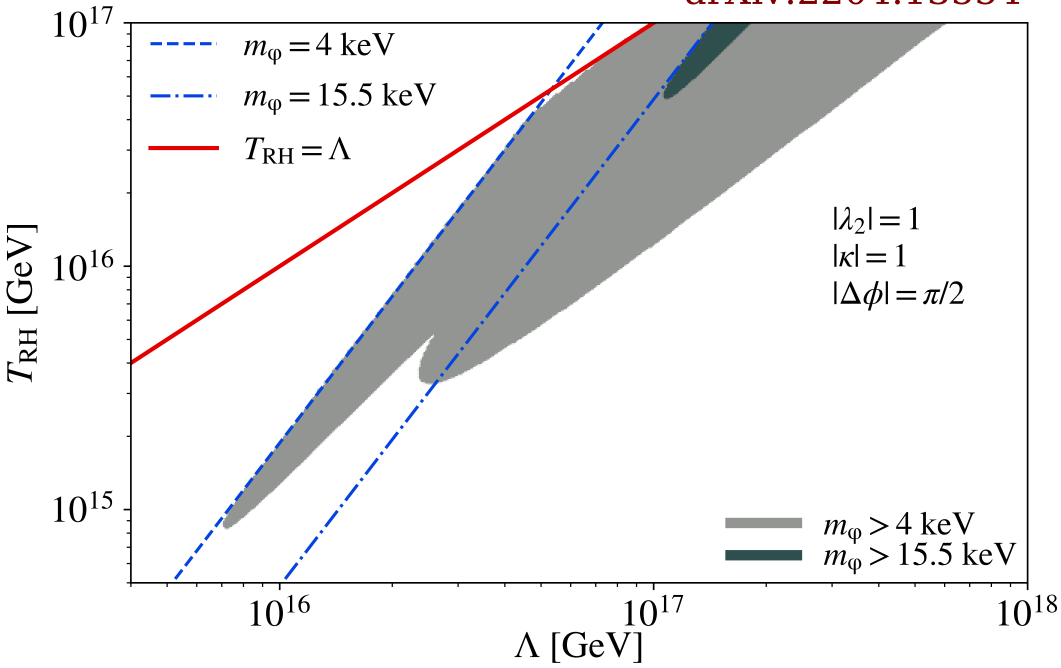
Given the temperatures that are the most relevant for our parameter space, the final baryon asymmetry in this case is found to be given by :

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

Results

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

arXiv:2204.13554

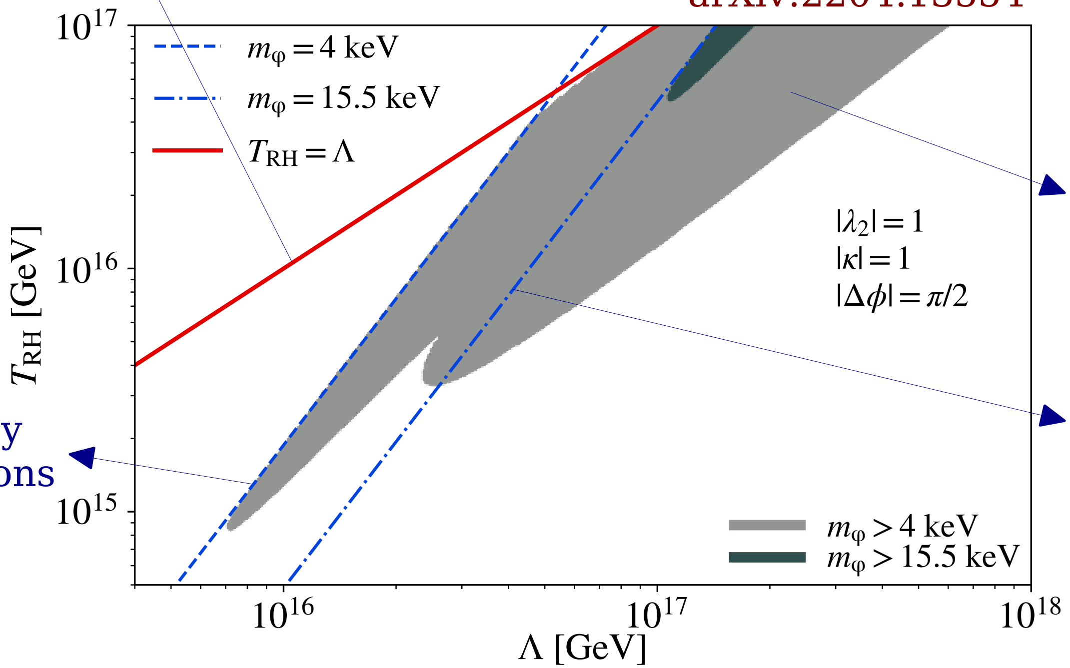


Results: scalar DM

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 $T_{RH} > \Lambda$ 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

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

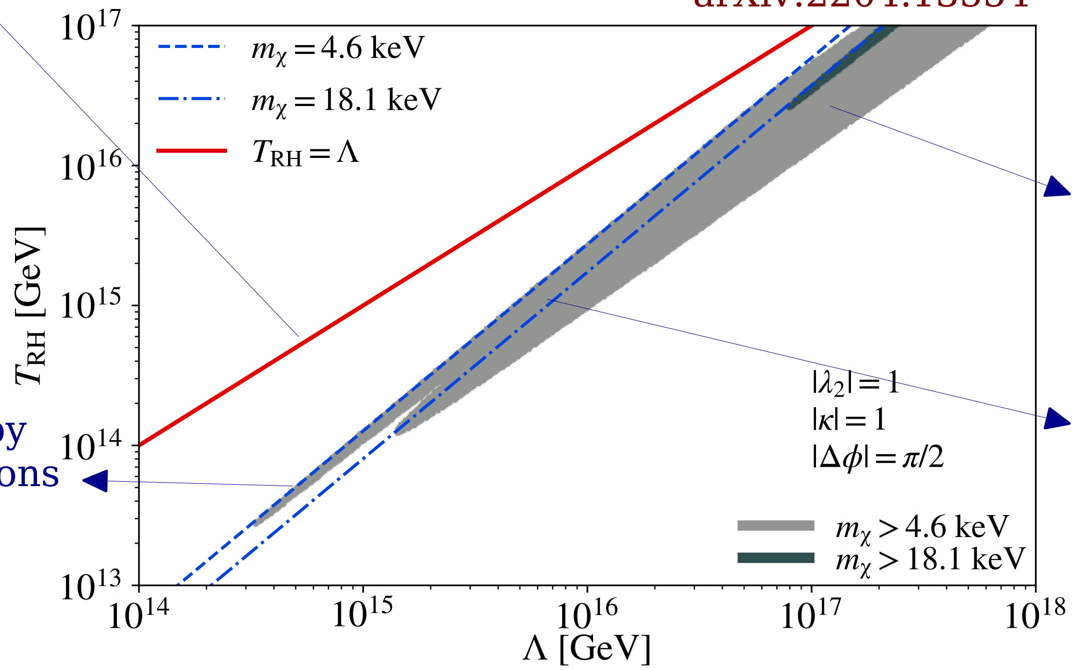
· Although our parameter space is viable, one might be troubled by such high values for T_{RH}. Can we do better?

Results: fermion DM

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

Computing what happens if $T_{RH} > \Lambda$ 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

· 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}.

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, WIMPy baryogenesis...).

· 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 ?

Thank you!