



# Dark matter and baryogenesis from freeze-in

Based on [arXiv:2111.05740](https://arxiv.org/abs/2111.05740), [arXiv:2204.13554](https://arxiv.org/abs/2204.13554)  
In collaboration with D. Karamitros, P. Papachristou, V. Spanos

Corfu 2022

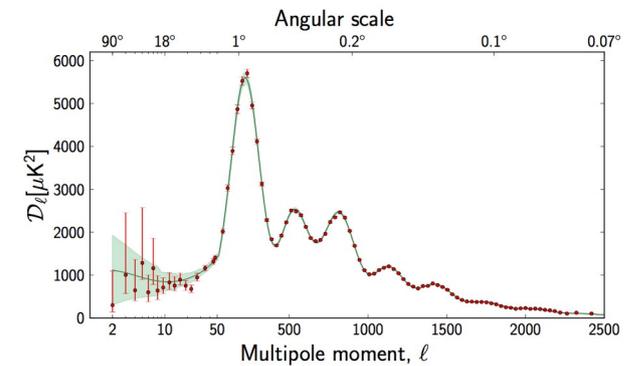
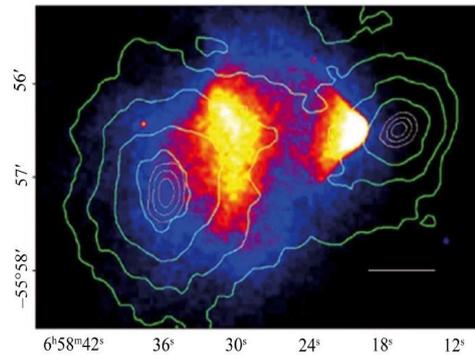
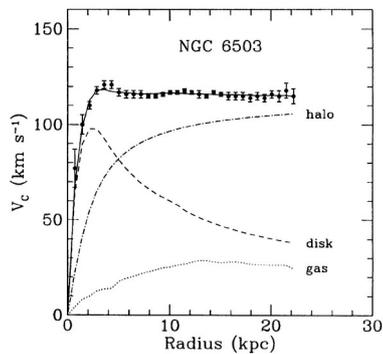


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# Today's topics

## Dark matter

An – as of yet – unidentified form of matter that affects the motion and clustering properties of celestial objects and (assuming  $\Lambda$ CDM) comprises  $\sim 27\%$  of the matter-energy content of the Universe.



## Baryogenesis

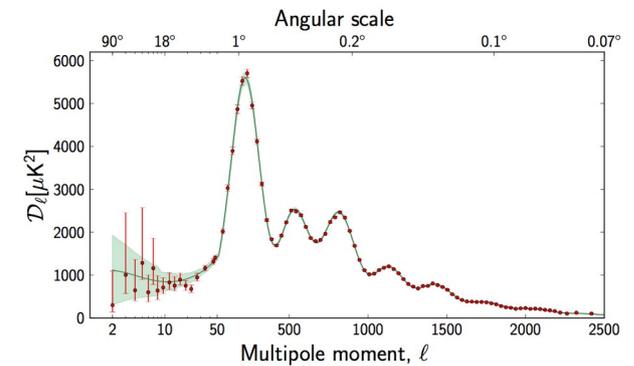
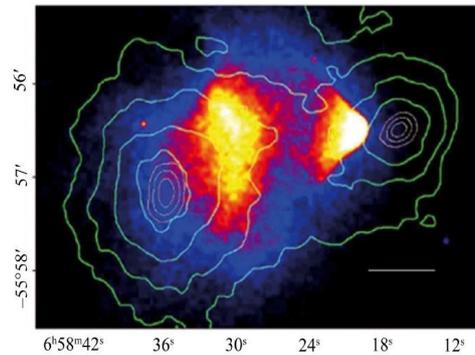
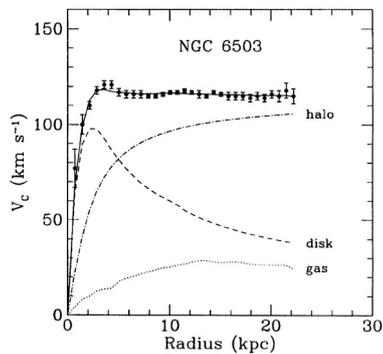
The fact that our Universe appears to be composed of unequal amounts of matter and anti-matter. Sakharov conditions :

- Baryon number violation.
- $C/CP$  violation.
- Interactions out of thermal equilibrium.

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## Baryogenesis

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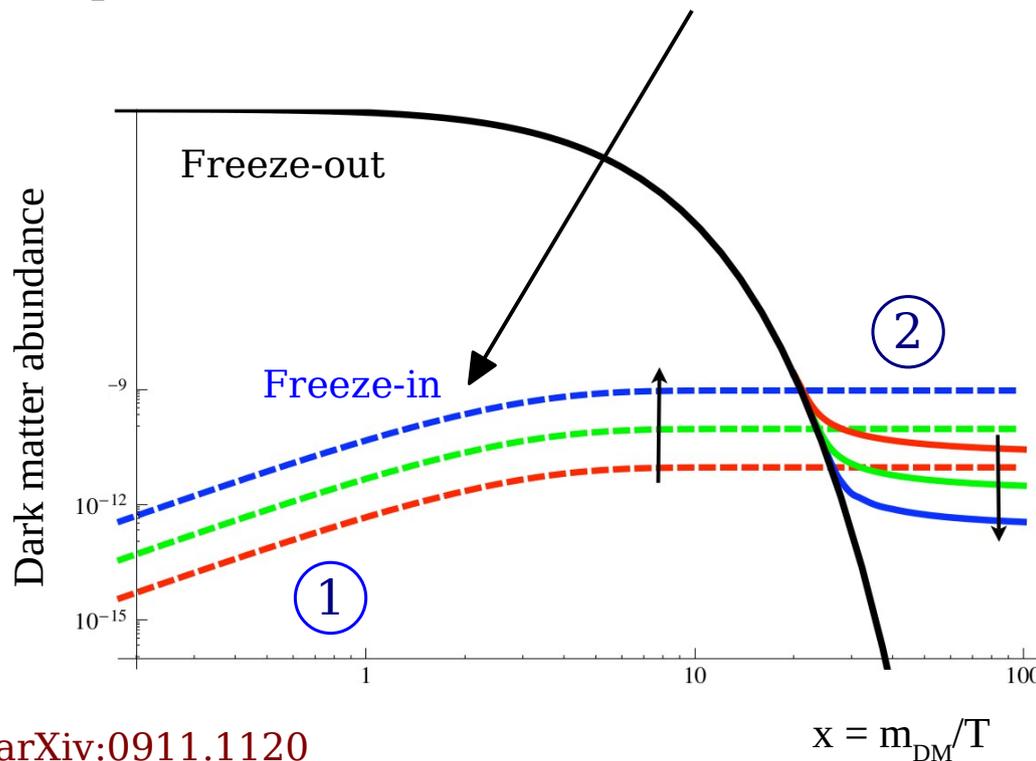
Could these two questions be related ?

# 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.



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

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

arXiv:0911.1120

# 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  $\epsilon_{CP}$ , 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

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

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

Assume to be negligible

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

Keep the  $F_i$ 's in equilibrium with the plasma

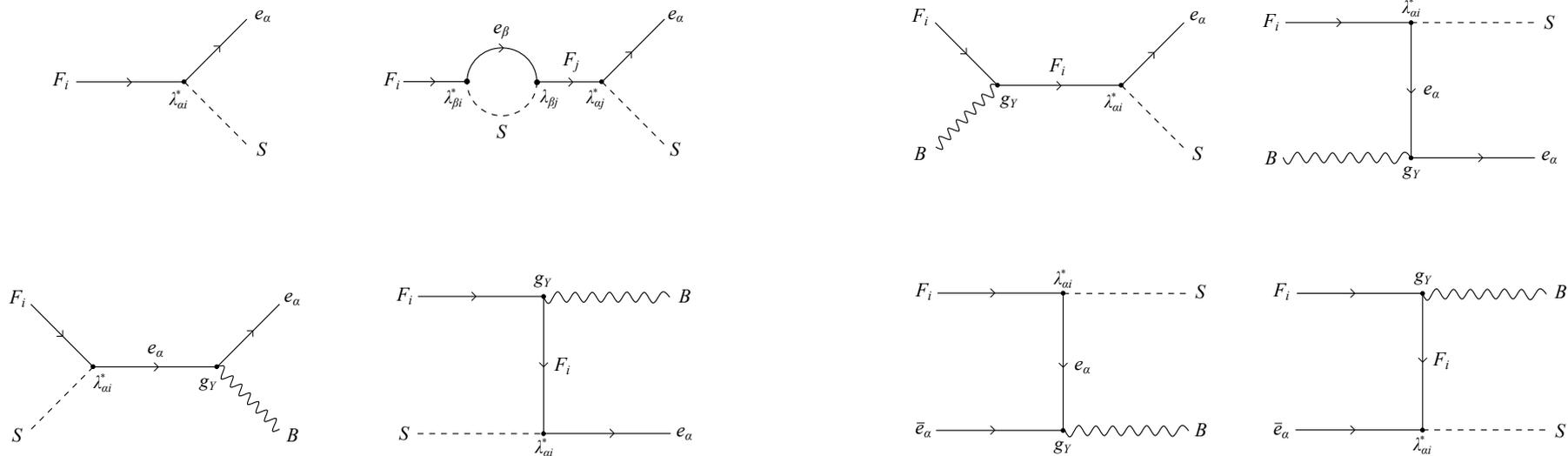
Feeble, complex

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 :  $\left( \sum_{\alpha,i} \gamma_{F_i \rightarrow e_\alpha S} \lesssim H \right) \Big|_{T=M_1}$

# Dark matter production

Generically, the Boltzmann equation reads :

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

➤ Largely suppressed

where :  $\{ab \leftrightarrow cd\} \equiv (ab \leftrightarrow cd) + (\bar{a}\bar{b} \leftrightarrow \bar{c}\bar{d})$

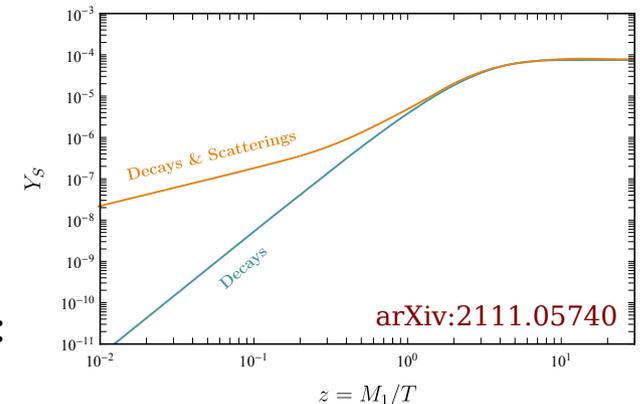
$[ab \leftrightarrow cd] \equiv (ab \leftrightarrow cd) - (\bar{a}\bar{b} \leftrightarrow \bar{c}\bar{d})$

$$(ab \leftrightarrow cd) \equiv \int d\Pi_a d\Pi_b d\Pi_c d\Pi_d (2\pi)^4 \delta^{(4)} \left[ |\mathcal{M}|_{ab \rightarrow cd}^2 f_a f_b (1 \pm f_c) (1 \pm f_d) \right. \\ \left. - |\mathcal{M}|_{cd \rightarrow ab}^2 f_c f_d (1 \pm f_a) (1 \pm f_b) \right]$$

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

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

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

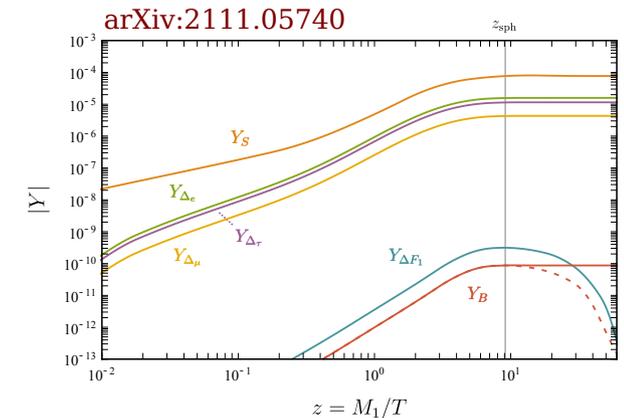
The Boltzmann equations for the various asymmetries read

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

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

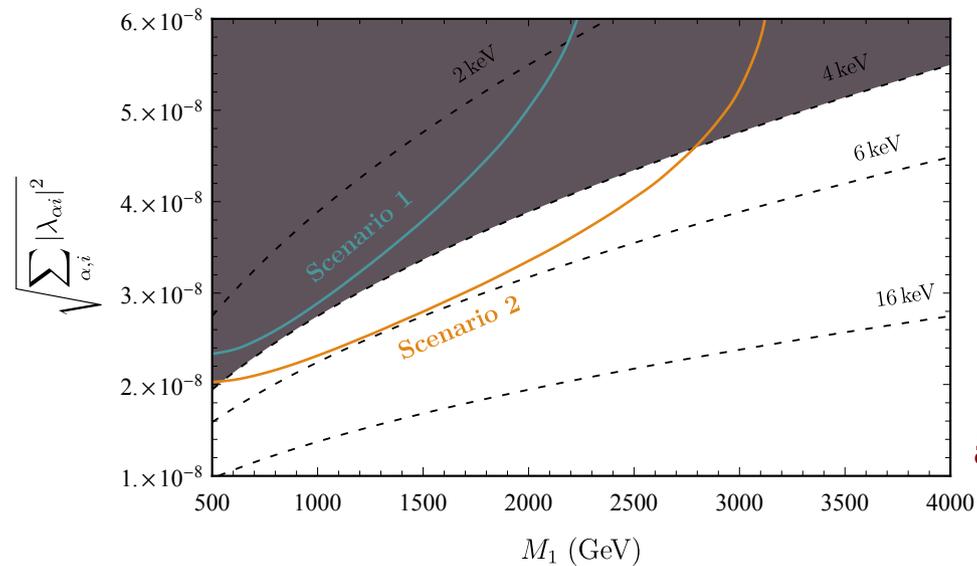
where :  $Y_{\Delta F_i} \equiv Y_{F_i} - Y_{\bar{F}_i}$ ,  $Y_{\Delta \alpha} \equiv Y_B/3 - Y_{L_{SM\alpha}}$

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



# 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).



arXiv:2111.05740

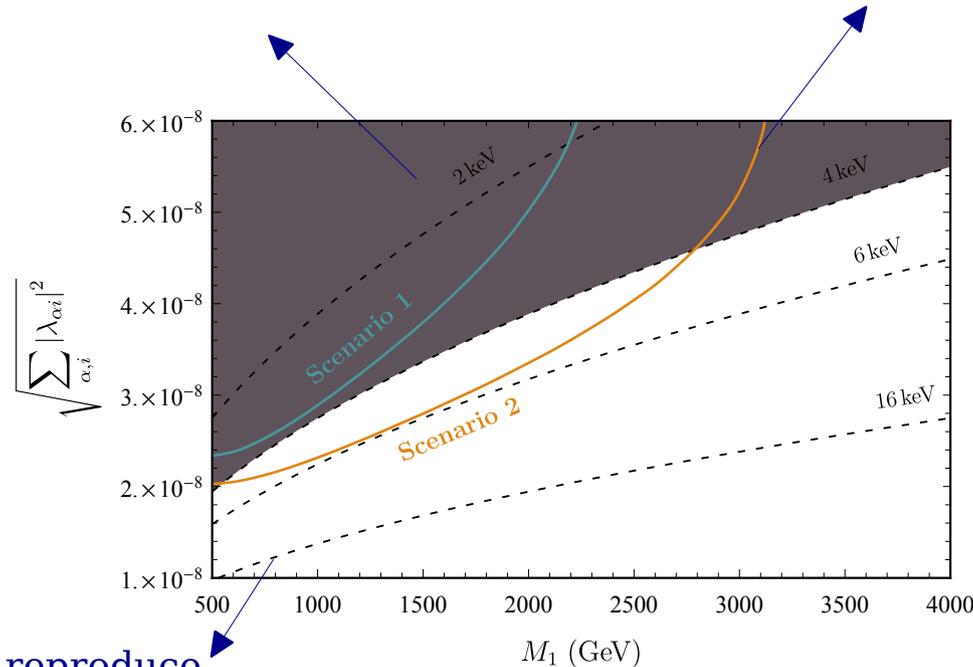
# Results

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Excluded by Lyman- $\alpha$  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

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 :

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

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	$\mathbb{Z}_3$
$\varphi$	$(1, 1)_0$	$\omega$
$\varphi^*$	$(1, 1)_0$	$\omega^{-1}$
$F_i$	$(1, 1)_{-1}$	$\omega^{-1}$
$\bar{F}_i$	$(1, 1)_1$	$\omega$

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”  $T_{\text{RH}}$ ).
- 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 :

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

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

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

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 :

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

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

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

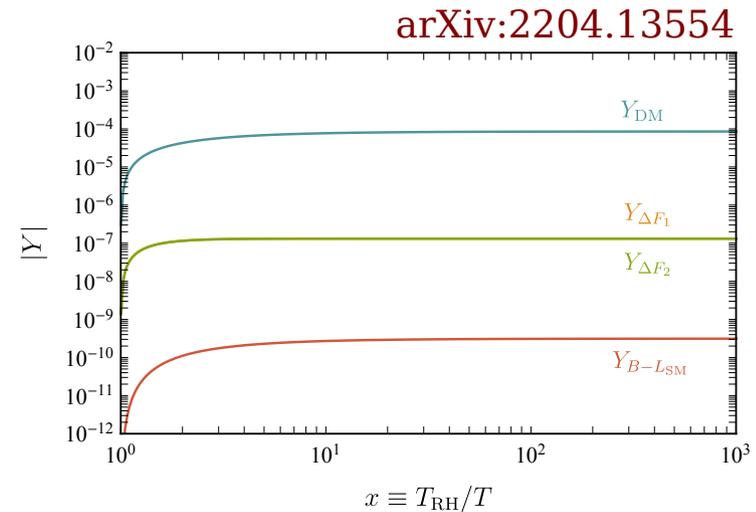
# Baryogenesis - 2

The relevant Boltzmann equations in this case read :

$$-sHT \frac{dY_{\Delta F_i}}{dT} = -[F_i \bar{e} \leftrightarrow \varphi \varphi] - [F_i \bar{e} \leftrightarrow F_j \bar{e}] + (-1)^i [F_i \bar{F}_j \leftrightarrow e \bar{e}]$$

$$-sHT \frac{dY_{B-L_{SM}}}{dT} = -\sum_i [F_i \bar{e} \leftrightarrow \varphi \varphi]$$

with numerical solutions resembling as :

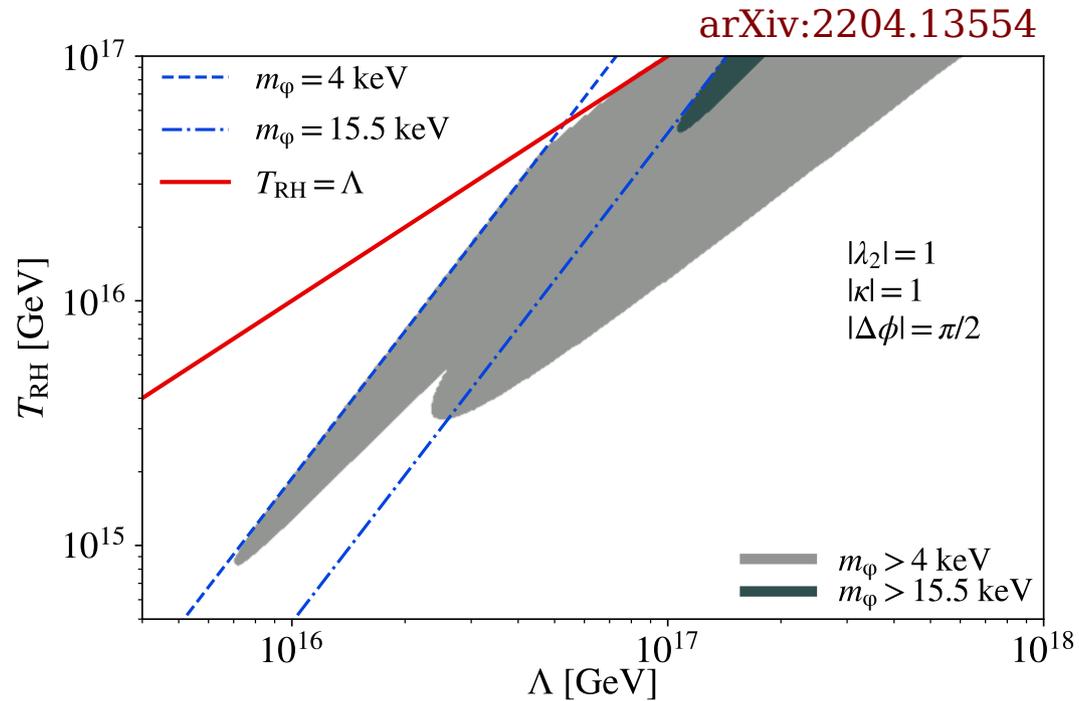


Given the temperatures that are the most relevant for our parameter space, the final baryon asymmetry in this case is found to be given by :

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

# Results

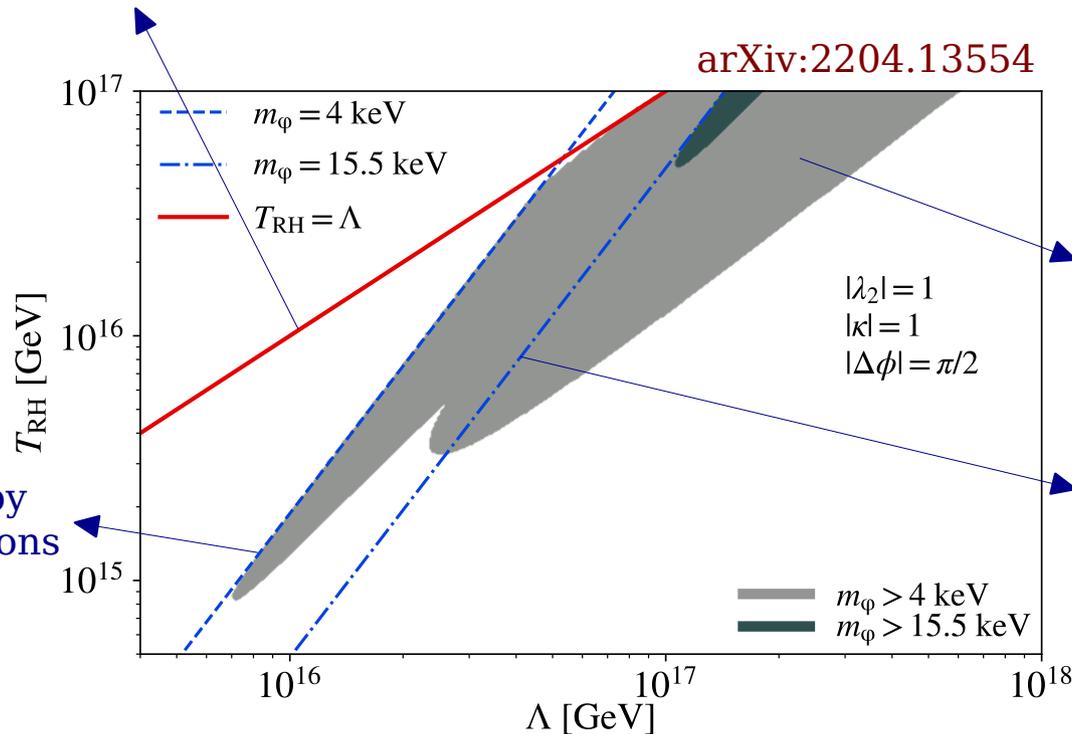
Once again, the mechanism works! Dark matter production and baryogenesis can be simultaneously achieved and, again, DM is predicted to be relatively light.



# 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



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- $\alpha$  forest observations

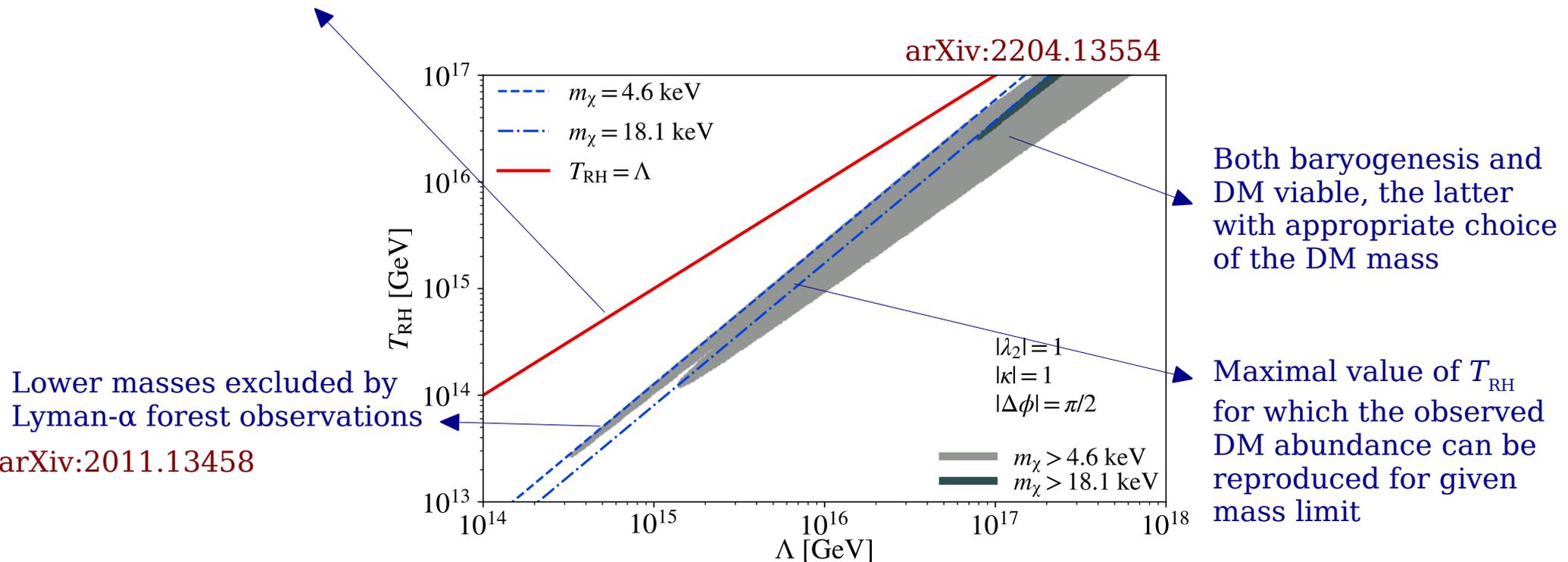
arXiv:2011.13458

- 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  $T_{RH} > \Lambda$  would require knowledge of the underlying theory



- In this case the relevant interaction is of mass dimension 6.
- Very similar mechanism as in the scalar case, but stronger temperature dependence  $\rightarrow$  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!