Freeze-out and freeze-in in the dark axion portal

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Portals to the dark sector

1. Axion portal: $(\phi/f_\phi)F_{\mu\nu}\tilde{F}^{\mu\nu}$. ALP: Axion-like particle.
2. Vector portal: $F_{\mu\nu}F'^{\mu\nu}$. DP: Dark photon.

A portal which contain ϕ and γ'?: Dark axion portal.

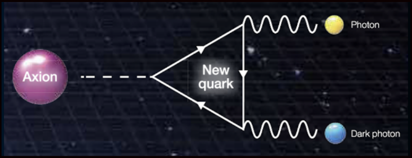


Figura 1: Dark axion portal.

Outline

1. Model.
2. Freeze-out and long-lived particles.
3. Freeze-in, low T_{RH} and collider constraints.
4. Conclusions

Lagrangian

Let us add a $U(1)$ gauge symmetry to the SM plus a singlet pseudo-scalar. Assuming a dark-CP symmetry $(A', \phi) \to -(A', \phi)$, the Lagrangian is:

$$\mathcal{L} \supset -\frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} - \frac{1}{2}m^2_{\gamma'}A'^2_{\mu} + \frac{1}{2}(\partial_\mu\phi)^2 - \frac{1}{2}m^2_\phi\phi^2 - \lambda_{HS}\phi^2|H|^2$$

with $F'_{\mu\nu}$ the $U(1)$ dark photon field strength, and H the Higgs doublet.

No vev for ϕ.

darkCP: **no kinetic mixing between SM gauge bosons and the new vector boson**.

Lagrangian

A five-dimensional operator is allowed (Kaneta et al 2016, PLR):

$$\mathcal{L}_A = \frac{g_D}{4}\phi F'_{\mu\nu}\tilde{F}^{\mu\nu},$$

where the dual field strength defined as $\tilde{F}^{\mu\nu} = \frac{1}{2}\epsilon^{\mu\nu\alpha\beta}F_{\alpha\beta}$.

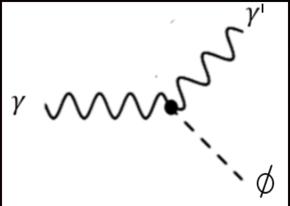


Figura 2: Feynman rule.

Four free parameters:

$$m_{\gamma'}, m_\phi, g_D, \lambda_{HS}$$

Literature

Various studies:

1. Freeze-in: high T_{RH} and dark Primakoff (Kaneta et al 2017).
2. Supernova constraints (A. Hook et al, 2021).
3. CMB (A. Hook et al, 2023).
4. N_{eff} (H. Hong et al 2024)
5. Collider: FASER2, MATHUSLA, B-factories (Jodlowski 2023, de Niverville et al. 2018)
6. more ...

Freeze-out

Thermal dark photon DM

1. Mass focus GeV $\lesssim (m_{\gamma'}, m_\phi) \lesssim$ TeV, with $m_{\gamma'} < m_\phi$.
2. Chemical equilibrium (CE) **within the dark sector**

$$\Gamma(\gamma' + SM \leftrightarrow \phi + SM) \gg H$$

3. Not CE during freeze-out (Garny et al PRD 2017, D'Agnolo et al 2017 PRL).

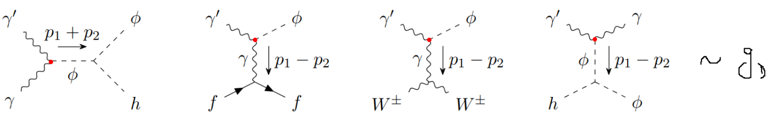


Figura 3: Feynman diagrams relevant for $\Gamma_{\gamma' \to \phi}$ conversions.

Equations

The coupled Boltzmann equations (cBE) for the yields are given by

$$\frac{dY_{\gamma'}}{dx} = \frac{1}{3H}\frac{ds}{dx}\Bigg[\langle\sigma_{\gamma'\gamma'00}v\rangle\left(Y_{\gamma'}^2 - Y_{\gamma',e}^2\right) + \langle\sigma_{\gamma'\phi00}v\rangle\left(Y_{\gamma'}Y_\phi - Y_{\gamma'e}Y_{\phi,e}\right) + \frac{\Gamma_{\gamma'\to\phi}}{s}\left(Y_{\gamma'} - Y_\phi\frac{Y_{\gamma'e}}{Y_{\phi e}}\right) + \frac{\Gamma_\phi}{s}\left(Y_\phi - Y_{\gamma'}\frac{Y_{\phi e}}{Y_{\gamma'e}}\right)\Bigg]$$

$$\frac{dY_{\phi}}{dx} = \frac{1}{3H}\frac{ds}{dx}\Bigg[\langle\sigma_{\phi\phi00}v\rangle\left(Y_{\phi}^2 - Y_{\phi,e}^2\right) + \langle\sigma_{\gamma'\phi00}v\rangle\left(Y_{\gamma'}Y_\phi - Y_{\gamma'e}Y_{\phi,e}\right) - \frac{\Gamma_{\gamma'\to\phi}}{s}\left(Y_{\gamma'} - Y_\phi\frac{Y_{\gamma'e}}{Y_{\phi,e}}\right) - \frac{\Gamma_\phi}{s}\left(Y_\phi - Y_{\gamma'}\frac{Y_{\phi,e}}{Y_{\gamma'e}}\right)\Bigg]$$

with 0 indicating a SM state, and $Y_{\gamma' e}$ and $Y_{\phi e}$ the equilibrium yields. The rate of particle conversions per DM particle is given by

$$\Gamma_{\gamma'\to\phi} = \sum_{k,l}\langle\sigma_{\gamma' k\to\phi l}v\rangle\, n_{k,e}, \qquad (1)$$

with k, l a SM state. Here $n_{k,e} \propto T^3$.

Equations

Implementation: `LanHEP` → `micrOMEGAs` 5.3.41. Two methods:

1. `darkOmega` : It assumes **chemical equilibrium (CE) within the dark sector for all** T. This is:

$$\frac{dY_{DM}}{dx} = \frac{s\langle\sigma v_{\rm eff}\rangle}{Hx}\left(Y_{DM}^2 - Y_{DM,eq}^2\right)$$

$$\langle\sigma v_{\rm eff}\rangle \simeq \frac{1}{g_{\rm eff}^2}\sum_{ij} r_i r_j \langle\sigma v\rangle_{ij} \quad \text{with} \quad g_{\rm eff} = \sum_i r_i$$

$$\text{and} \quad r_i = g_i(1+\Delta_i)^{3/2}\exp(-x_f\Delta_i)\,.$$

   where it was assumed that $Y_{\gamma'}/Y_{\gamma',e} = Y_\phi/Y_{\phi,e}$.

2. `darkOmegaN` : No CE assumption, then it solves the cBE.

LanHEP software package

MicrOMEGAs: a code for the calculation of Dark Matter Properties including the **relic density**, direct and **indirect rates** in a general supersymmetric model and other models of New Physics

Results: relic abundance

Coscattering (or CFO), mediator FO, and (co)annihilations.

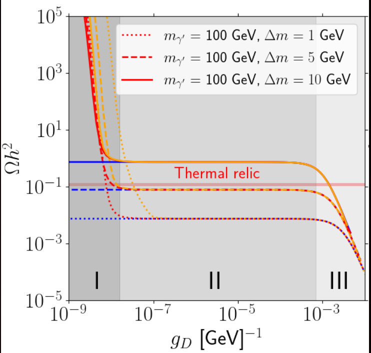


Figura 4: Relic abundance as a function of g_D. The red curves are obtained with darkOmegaN, the blue ones with darkOmega, and the orange ones without considering processes 1020. The regions shown in each plot as I, II and III, correspond to the case of $\Delta = 5$ GeV. For all the cases $\lambda_{HS} = 1$.

Results: Long-lived particles (LLP)

1. Pair production of ALPs: $pp \to \phi\phi$.
2. Displaced vertex $2\gamma + \not{E}$.

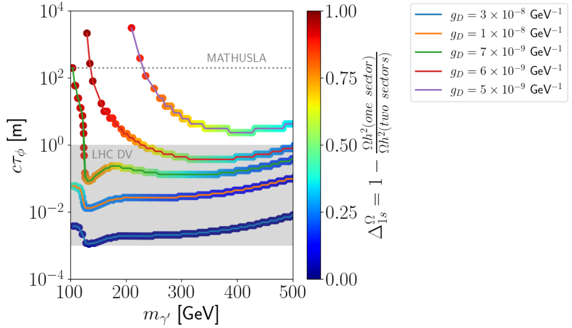


Figura 5: Expected $c\tau$ distance for ϕ from the proton-proton colliding point, and the region expected for displace vertex (DV) in the detectors at the LHC. $\lambda_{HS} = 1$.

Conclusions freeze-out

1. The freeze-out regime fulfill the correct relic abundance: coscatterg, mediator FO, and (co)annihilations.
2. ALP may become a neutral LLP (striking signature). Lifetime for ϕ in the reach of LHC displaced vertex.

Freeze-in

Freeze-in scenarios

Two ways of producing the DM:

1. DP as the DM. The ALP in thermal equilibrium due to sizable Higgs portal couplings, and involved in the process of production of DPs (BDS, J. Jonas, L. Duarte).
2. Either DP or ALP as the DM. Negligible Higgs portal (BDS, P. Arias, J. Jaeckel, A. Arza).

Freeze-in: high T_{RH}

Let us consider

1. $m_\phi < m_{\gamma'}$ and negligible yields for (ϕ, γ') for $T > T_{RH}$.
2. $f\bar{f} \to \phi\gamma'$ the leading process.

After solving the Boltzmann equation one obtains

$$Y_{\phi,R} = \frac{45\zeta(3)^2 g_f^2 M_P}{2\pi^7 g_{*s}} \sqrt{\frac{90}{g_{*s}}} \langle \sigma v \rangle \, T_{RH}$$

with g_f the internal dof of the fermions, and

$$\langle \sigma v \rangle = \frac{e^2 g_D^2}{96\pi m_W^2 m_Z^2} \left[8m_W^4 - 4m_W^2 m_Z^2(-3 + 4c_w^2) + m_Z^4(5 - 12c_w^2 + 8c_w^4) \right] \quad (2)$$

Freeze-in: low T_{RH}

1. At low T_{RH} (e.g. $m_e < T_{RH} \lesssim m_\phi$), Boltzmann suppression on the cross section:

$$\langle \sigma v \rangle_{f\bar{f}\to\phi\gamma'} \propto \int d^3p_1 d^3p_2 e^{-E_1/T} e^{-E_2/T} (\sigma v)_{f\bar{f}\to\phi\gamma'}$$

2. High g_D couplings makes $\gamma\gamma \to \phi\phi$ sizable, becoming the leading process in certain regions of the parameter space.

Freeze-in

1. $\mathcal{L}_B = \frac{g_D}{4}\phi F'_{\mu\nu}\tilde{B}^{\mu\nu}$.
2. Relic abundance strongly dependent on T_{RH}.

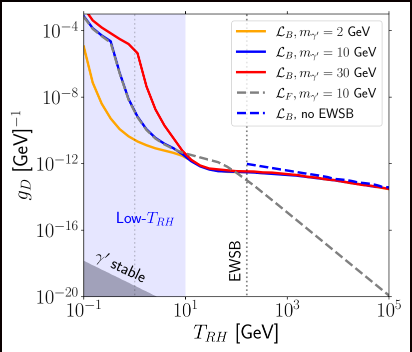
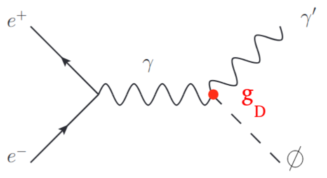


Figura 6: Freeze-in for $m_\phi = 1$ GeV. The solid colorful lines are obtained fulfilling the correct relic abundance using the operator $\mathcal{L}_B$. The dashed blue line considers the symmetric SM Lagrangian, i.e. before EWSB, whereas the dashed grey the calculation using $\mathcal{L}_F$. Results obtained with `micrOMEGAs`.

Freeze-in: no Higgs portal

1. Dark axion portal at low T_{RH} could be tested at B-factories!.



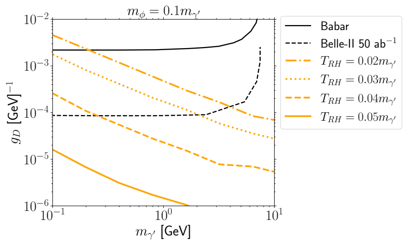


Figura 7: (left) Process at B-factories. (right) Orange contours giving the correct relic abundance via freeze-in. The black lines correspond to upper limits (deNiverville et al 2018).

Conclusions

1. Dark axion portal: ALPs and DP.
2. In **freeze-out**, existence of LLP: **coscattering regime** and **mediator FO**.
3. **Freeze-in** realized in different ways. Low T_{RH} increases the couplings to reach sensitivities of B-factories.
4. Future: advanced collider analysis, soft connection between freeze-in and coscattering, etc...

Danke!.

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Appendix

Relic abundance as a function of g_D

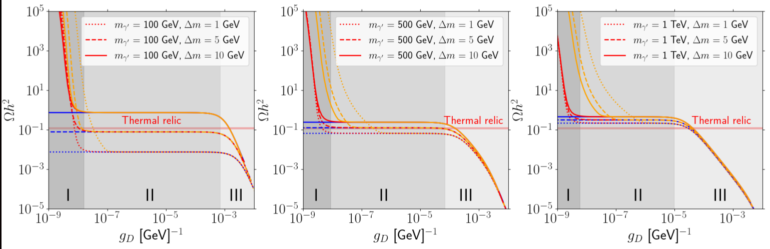

Figura 8: Relic abundance. The red curves are obtained with `darkOmegaN`, the blue ones with `darkOmega`, and the orange ones without considering the process 1020. The regions shown in each plot as I, II and III, correspond to the case of $\Delta = 5$ GeV. In all the plots we have set $\lambda_{HS} = 1$.

Results: $\Delta m \gtrsim 1$ GeV

1. Viable DM masses from ∼50 GeV.

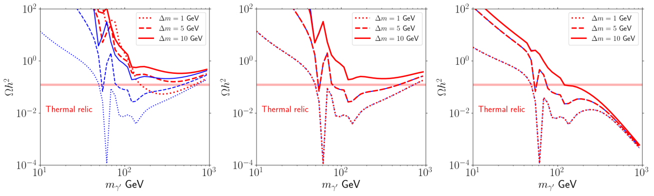

Figura 9: (top) Relic abundance as a function of $m_{\gamma'}$. In the left, middle and right columns we consider $g_D = 6 \times 10^{-9}$ GeV^{-1}, 10^{-5} GeV^{-1} and 10^{-3} GeV^{-1}, respectively. The red and blue lines are obtained with `darkOmegaN` and `darkOmega`, respectively. Here we set $\lambda_{HS} = 1$. (bottom) Relic abundance as a function of λ_{HS}, for $m_{\gamma'} = 500$ GeV. The values of g_D follows the same order than the top row of plots.

Results: $\Delta m \leq 1$ GeV

1. Viable DM masses from ∼30 GeV.

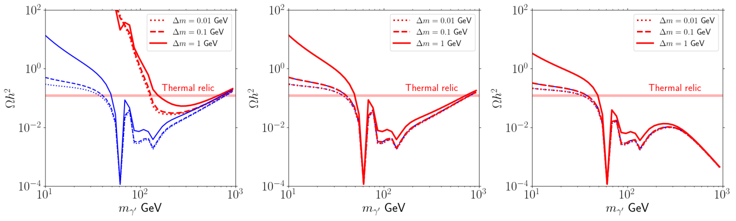

Figura 10: Same than before but in the small mass shift scenario.

Long-lived particles (LLP)

1. In collider environments: particles that decay far from the interaction vertex ("long" lifetimes).
2. In the SM we have some LLP.
3. Different experiments to search for new LLP: ATLAS, CMS, FASER, MATUSHLA, etc...

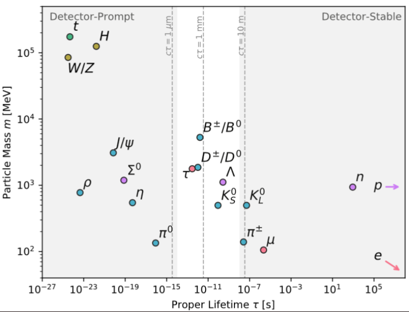

Figura 11: Lifetime of some SM particles.

Long-lived particles (LLP)

At the LHC, we may pair produce ALPs as **displaced vertex** from

$$p + p \to \phi + \phi, \qquad \phi \to \gamma' + \gamma$$

1. $\sigma(p + p \to \phi + \phi) \propto \lambda_{HS}^2$.
2. $\Gamma(\phi \to \gamma' + \gamma) \propto g_D^2$, then $c\tau \propto \frac{1}{g_D^2}$. $(\mathrm{Br}_{\phi \to \gamma'\gamma} = 1)$.

Remember that the thermal dark-axion scenario gives the correct relic abundance for EW masses of the new states and for $\lambda_{HS} = 1$ and $g_D \ll 1$!.

Prospects of LLP at detectors

1. Small g_D: region I and II (coscattering and mediator FO, respectively).
2. Displacement vertex in the distance reach of LHC and MATUSHLA.

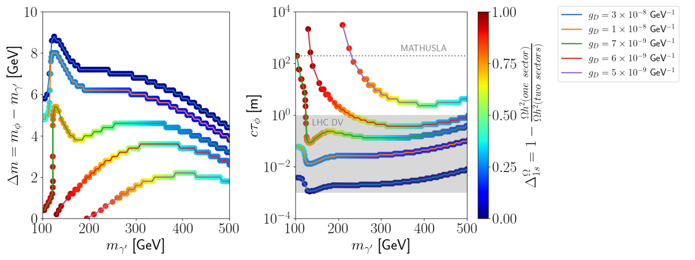

Figura 12: Points fulfilling the correct relic abundance. The color of each point represents Δ^Ω_{1s}. Here we have set $\lambda_{HS} = 1$. In the plot in the right, we highlight the expected distance of MATHSULA from the proton-proton colliding point, and the region expected for displace vertex (DV) in the detectors at the LHC.

App: Supernova constraints

The core collapse supernova SN1987A continues providing valuable constraints on new physics. For $(m_\phi, m_{\gamma'}) < T_{BBN}$, it is required that

$$n_e \langle v\sigma_{e^+e^- \to \phi\gamma'} \rangle < H(T_{BBN}) \tag{3}$$

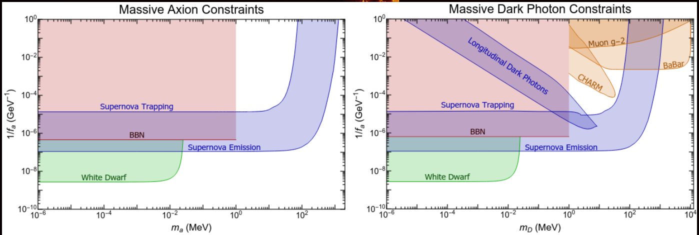

Figura 13: Constraints on light dark states.

App: BBN

1. If the new degrees of freedom are thermal and light, they can affect the BBN processes. Even more, in Hong et al 2023, they show that even if the new daark states are not thermalized at BBN, they may had thermalized at higher temperatures and that affect the N_{eff} at the time of CMB (since $\Gamma \propto T^3$ and $H \propto T^2$).
2. If they are light degrees of freedom non-thermal, do they affect BBN?. I guess that in principle they could, because they are radiation that could in principle dominate the energy density of the universe, and then affect H, which in turn affects BBN.

However, in my case I need to see whether they are relativistic at BBN or not.

DM candidates

$U(1)_X$ and $U(1)_{PQ}$ different, one gauge and the other global. Assume heavy fermions:

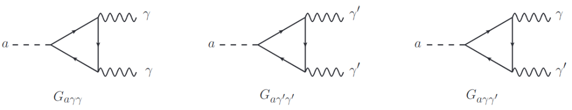

Figura 14: Vertex.

1. The DP can be produced from freeze-out or freeze-in.
2. Question: is it possible to have DM (with one of the dark states), at the MeV - GeV scale with freeze-out or freeze-in with high T_{RH}.
3. For lighter than keV, one needs to consider non-thermal production. E.g., The dark matter abundance is initially stored in an axion which is misaligned from its minimum. When the axion starts oscillating, it efficiently transfers its energy into dark photons via a tachyonic instability (Agrawal et al 2018).