Freeze-in hidden sectors with internal interactions

Wan-Zhe FENG

Center for Joint Quantum Studies and Department of Physics, Tianjin University

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This talk is based on

Amin Aboubrahim, WZF, Pran Nath, Zhu-Yao Wang, 2008.00529

Amin Aboubrahim, WZF, Pran Nath, Zhu-Yao Wang, 2103.15769

Amin Aboubrahim, WZF, Pran Nath, Zhu-Yao Wang, 2106.06494

Kai-Yu Zhang, WZF, 2204.08067

WZF, Zi-Hui Zhang, Kai-Yu Zhang, 2312.03837

WZF, Zi-Hui Zhang, 2405.19431

Overview

1. Dark matter from $U(1)$ hidden sectors
   - General discussions
   - Difficulties in the calculation
   - Evolution of the hidden sector temperature
2. $U(1)$ mixings and the millicharge
   - The generation of millicharge
   - The full evolution of sub-GeV millicharge dark matter
3. Dark matter explanations of the galactic 511 keV signal
   - Galactic 511 keV signal
   - Dark matter interpretations
   - Decaying dark photon dark matter from freeze-in

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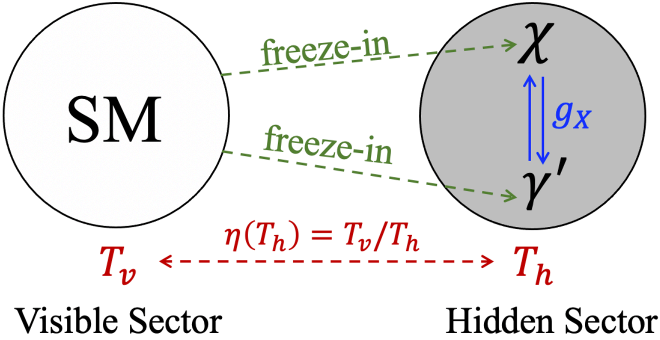
- Turn to freeze-in – one major problem: why there exists such feeble coupling? *Mixings* can just provide such smallness of the coupling constants.

Explorations into hidden sectors

- Hidden sectors generally exist in string theory and various GUT models.
- Evolutions of hidden sector particles and hidden sector temperature are important in determining new physics signals.
- SM extensions with one or more hidden sectors is one possibility of our true world.

A graphic illustration of the simplest $U(1)_X$ model



A graphic illustration of the freeze-in generation of the simplest $U(1)_X$ model.

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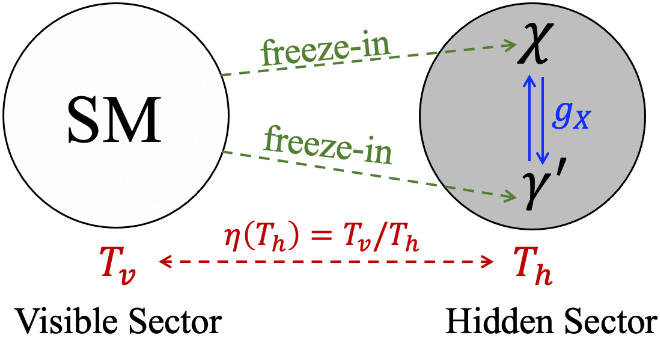

Because of the self-interaction inside the hidden sector, this simplest setup is difficult to calculate.

Why difficult?

- Indeed, *previously*, the evolution of *any* models with a freeze-in produced hidden sector involving hidden sector self-interactions, cannot be computed accurately.

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- The thermal averaged cross-section of hidden sector interactions depend on the hidden sector temperature. We have no clue what the hidden sector temperature is.
- How to setup a connection between the hidden sector temperature and the visible sector (SM) temperature.

Solution

In [Aboubrahim, WZF, Nath, Wang, 2008.005299], a general formalism was established to compute the *complete* evolution of the hidden sector (produced through freeze-in) particle number densities as well as the hidden sector temperature.

For a general hidden sector feebly coupled to the visible sector, its temperature T_h is linked to the visible sector temperature (the temperature of the observed Universe) T by a function $\eta(T_h) = T/T_h$.

The continuity equation derived from Friedmann equations is now modified to be

$$\frac{\mathrm{d}\rho_h}{\mathrm{d}t} + 3H\left(\rho_h + p_h\right) = j_h\,,$$
$$\frac{\mathrm{d}\rho_v}{\mathrm{d}t} + 3H\left(\rho_v + p_v\right) = -j_h\,,$$

where j_h is the source term arising from the freeze-in.

Temperature dependence

One can further deduce

$$\rho \frac{\mathrm{d}\rho_h}{\mathrm{d}T_h} = \left(\frac{\zeta_h}{\zeta} \rho_h - \frac{j_h}{4H\zeta} \right) \frac{\mathrm{d}\rho}{\mathrm{d}T_h} \, ,$$

$\zeta_h = \frac{3}{4}(1 + p_h/\rho_h)$ and $\zeta_h = 1$ for radiation dominated hidden sector.

Using the fact $\rho = \rho_v + \rho_h$, and the total entropy of Universe is conserved and the Hubble parameter is given by

$$H^2 = \frac{8\pi G_N}{3} \left[\rho_v(T) + \rho_h(T_h) \right] ,$$

one can finally obtain

$$\frac{\mathrm{d}\eta}{\mathrm{d}T_h} = -\frac{A_v}{B_v} + \frac{\zeta\rho_v + \rho_h(\zeta - \zeta_h) + j_h/(4H)}{B_v[\zeta_h \rho_h - j_h/(4H)]} \frac{\mathrm{d}\rho_h}{\mathrm{d}T_h} \, ,$$

with A_v, B_v functions of T_h and g_{eff}.

The complete coupled Boltzmann equations for $U(1)_X$

$$
\begin{aligned}
\frac{\mathrm{d}Y_\chi}{\mathrm{d}T_h} =& -\frac{s}{H}\frac{\mathrm{d}\rho_h/\mathrm{d}T_h}{4\rho_h - j_h/H}\sum_{i\in\mathrm{SM}}\Big\{(Y_\chi^{\mathrm{eq}})^2\langle\sigma v\rangle^{T_h\eta}_{\chi\bar\chi\to i\bar i} + \frac{1}{s}Y_{\gamma^*}\langle\Gamma\rangle^{T_h\eta}_{\gamma^*\to\chi\bar\chi} \\
&+\theta(M_{\gamma'}-2m_\chi)\big[-Y_\chi^2\langle\sigma v\rangle^{T_h}_{\bar\chi\chi\to\gamma'} + \frac{1}{s}Y_{\gamma'}\langle\Gamma\rangle^{T_h}_{\gamma'\to\chi\bar\chi}\big] \\
&-Y_\chi^2\langle\sigma v\rangle^{T_h}_{\chi\bar\chi\to\gamma'\gamma'} + Y_{\gamma'}^2\langle\sigma v\rangle^{T_h}_{\gamma'\gamma'\to\chi\bar\chi}\Big\}, \\
\frac{\mathrm{d}Y_{\gamma'}}{\mathrm{d}T_h} =& -\frac{s}{H}\frac{\mathrm{d}\rho_h/\mathrm{d}T_h}{4\rho_h - j_h/H}\sum_{i\in\mathrm{SM}}\Big\{Y_\chi^2\langle\sigma v\rangle^{T_h}_{\chi\bar\chi\to\gamma'\gamma'} - Y_{\gamma'}^2\langle\sigma v\rangle^{T_h}_{\gamma'\gamma'\to\chi\bar\chi} \\
&+\theta(M_{\gamma'}-2m_\chi)\big[Y_\chi^2\langle\sigma v\rangle^{T_h}_{\bar\chi\chi\to\gamma'} - \frac{1}{s}Y_{\gamma'}\langle\Gamma\rangle^{T_h}_{\gamma'\to\chi\bar\chi}\big] \\
&+\theta(M_{\gamma'}-2m_i)\big[Y_i^2\langle\sigma v\rangle^{T_h\eta}_{i\bar i\to\gamma'} - \frac{1}{s}Y_{\gamma'}\langle\Gamma\rangle^{T_h}_{\gamma'\to i\bar i}\big] \\
&+Y_i^2\langle\sigma v\rangle^{T_h\eta}_{i\bar i\to\gamma'\gamma} + 2Y_iY_{\gamma'}^{\mathrm{eq}}\langle\sigma v\rangle^{T_h\eta}_{i\gamma'\to i\gamma}\Big\}.
\end{aligned}
$$

Turn back to the $U(1)_X$ beyond the SM

- This formalism can apply to any models with a freeze-in produced hidden sector involving hidden sector self-interactions, and compute the complete evolution of the hidden sector particles.

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- This formalism can apply to any models with a freeze-in produced hidden sector involving hidden sector self-interactions, and compute the complete evolution of the hidden sector particles.
- We focus on a $U(1)_X$ beyond the SM, where all SM particles are not charged under the $U(1)_X$.
- To setup the connection, kinetic mixing and/or mass mixing will be evoked.

History of kinetic mixing and millicharge dark matter

- Holdom 1986: The kinetic mixing between two massless $U(1)$'s can generate a millicharge.
- Goldberg and Hall 1986: millicharge dark matter.
- Feldman, Liu and Nath 2007: a kinetic mixing cannot generate a millicharge considering the extra $U(1)$ mixed with the full electroweak theory. Mass mixing can be the only source.
- [WZF, Zhang, Zhang, 2312.03837] provides a comprehensive review on this subject.

$U(1)$ mixings and the millicharge

1. Without inducing other modifications to the SM, the effective term $\mathcal{L} \sim -\frac{\delta}{2} F^{\text{em}}_{\mu\nu} F^{\mu\nu}_X$ is difficult to generated from a renormalized model in UV. Thus considering $\mathcal{L} \sim -\frac{\delta}{2} F^{\text{em}}_{\mu\nu} F^{\mu\nu}_X$ is not appropriate, especially from the theoretical perspective.
2. Even one consider such mixing term, the millicharge cannot be generated if the extra $U(1)_X$ is massive.
3. The millicharge can be only generated in three ways:
   1. The dark particle carries a tiny amount of hypercharge as a prior.
   2. A kinetic mixing between a *massless* $U(1)$ and the hypercharge gauge field, and the generated millicharge is proportional to the kinetic mixing parameter.
   3. The mass mixing between a *massive* $U(1)$ and the hypercharge gauge field, and the generated millicharge is proportional to the mass mixing parameter [Cheng and Yuan 2007, Feldman, Liu and Nath 2007].

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    3. The mass mixing between a *massive* $U(1)$ and the hypercharge gauge field, and the generated millicharge is proportional to the mass mixing parameter [Cheng and Yuan 2007, Feldman, Liu and Nath 2007]. In this case the kinetic mixing does not play any role in generating the millicharge, and the millicharge generated is proportional to the mass mixing parameter.

The destination of the dark photon

Decay channels of the dark photon for $M_{\gamma'} < 2m_e$: to neutrinos, and to three photons

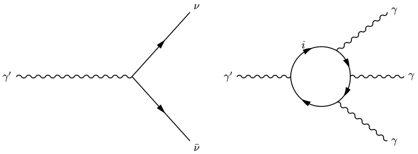

Figure: Dark photon decay channels for $M_{\gamma'} < 2m_e$, including the decay to pairs of neutrino, and to three photons. Considering various constraints, the decay of the dark photon to neutrinos due to the mixing effect is always suppressed compared to the three-photon decay channel.

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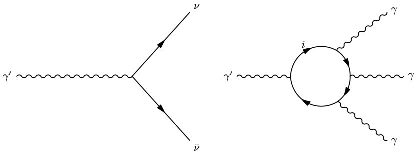

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Although the dark photon's lifetime is extended beyond the age of the Universe, it can still undergo decay, even in minuscule amounts. This decay contributes to the isotropic diffuse photon background (IDPB), and thus the model suffer even more stringent constraints.

IDPB

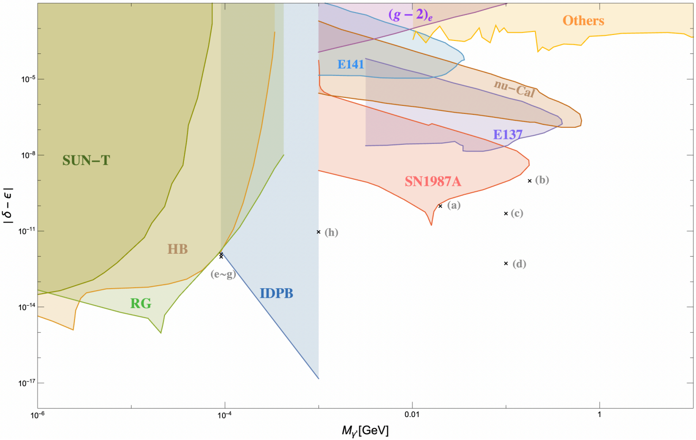

Figure: A display of current constraints (colored regions) on the absolute value of the kinetic mixing parameter minus the mass mixing parameter.

Sub-GeV millicharge dark matter

Focus on sub-GeV mass region of dark matter, we consider six different cases, which have very distinct evolution details:

Case		Model	$M_{\gamma'}$	m_χ	g_X	δ	ϵ	ε	$\Omega_\chi h^2$	$\Omega_{\gamma'} h^2$	$\tau_{\gamma'}$
1	$m_\chi > M_{\gamma'} > 2m_e$	a	20	100	0.0054	1×10^{-13}	1×10^{-10}	1.57×10^{-12}	0.120	0	0.616
		b	180	250	0.015	1×10^{-12}	1×10^{-9}	4.36×10^{-11}	0.120	0	6.82×10^{-4}
2	$2m_\chi > M_{\gamma'} > m_\chi > 2m_e$	c	100	60	1.59×10^{-5}	1×10^{-14}	5×10^{-11}	2.29×10^{-15}	0.120	0	0.491
3	$M_{\gamma'} > 2m_\chi > 2m_e$	d	100	10	0.01	1×10^{-14}	5.6×10^{-13}	1.62×10^{-14}	0.120	0	2.48×10^{-19}
4	$2m_e > m_\chi > M_{\gamma'}$	e	0.09	1	0.20	1×10^{-14}	1.27×10^{-12}	7.34×10^{-13}	7.42×10^{-12}	4.43×10^{-3}	2.67×10^{30}
5	$2m_e > 2m_\chi > M_{\gamma'} > m_\chi$	f	0.09	0.06	0.01	1×10^{-14}	1.27×10^{-12}	3.67×10^{-14}	5.94×10^{-3}	2.58×10^{-9}	2.67×10^{30}
		g	0.09	0.06	1.5×10^{-4}	1×10^{-14}	1.27×10^{-12}	5.50×10^{-16}	1.85×10^{-3}	3.03×10^{-3}	2.67×10^{30}
6	$2m_e > M_{\gamma'} > 2m_\chi$	h	1	0.05	0.001	4×10^{-13}	1×10^{-11}	2.9×10^{-14}	0.120	0	6.20×10^{-18}

The benchmark models we consider in this work for six different types of models. The lifetimes (in the unit of seconds) of the dark photon for each model are listed in the last column. $M_{\gamma'}$ and m_χ are in MeVs.

Case 2, model c: $M_{\gamma'} = 100\text{MeV}, M_\chi = 60\text{MeV}$

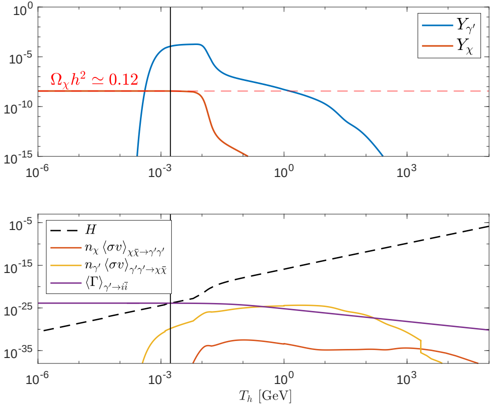

Figure: In this case we choose a rather small $g_X \sim 10^{-5}$, thus hidden sector interactions never reach equilibrium inside the hidden sector. However, these ultraweak interactions still play significant role.

Case 2, model c: $M_{\gamma'} = 100\text{MeV}, M_\chi = 60\text{MeV}$

Comparison of different calculations	$\Omega_\chi h^2$
All freeze-in processes included	0.1195
Plasmon decay process excluded	0.1195
Four-point γ' freeze-in processes excluded	0.0643
Pure freeze-in for χ	10^{-9}

Table: A comparison of different calculations of the dark matter relic density for the benchmark model c. There is no such limit called "pure freeze-in".

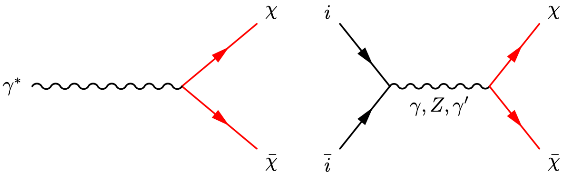

Figure: Freeze-in processes for the dark fermion χ.

Dark photon freeze-in

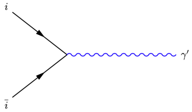

Figure: Three-point freeze-in processes for the dark photon γ'.

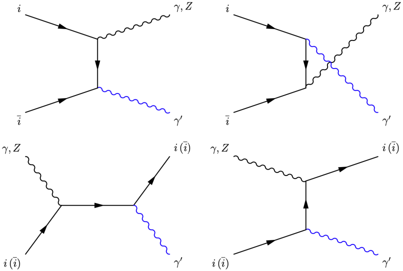

Figure: Four-point freeze-in processes for the dark photon γ'.

General discoveries from $U(1)$ sector freeze-in

In [Aboubrahim, WZF, Nath, Wang, 2008.00529], a general formalism was established to compute the *complete* evolution of the hidden sector (produced through freeze-in) particle number densities as well as the hidden sector temperature.

In [WZF, Zhang, Zhang, 2312.03837] we find some general results which may apply to general freeze-in scenarios:

1. The hidden sector interactions never reach equilibrium, does not indicate such interactions don't occur. On the contrary, these interactions inside the hidden sector play significant role in determining the dark particle number densities.
2. The hidden sector interactions (even ultraweak) must be taken into account at all times. There is no such limit called "pure freeze-in".
3. Four-point freeze-in processes must be kept at all times, even the three-point freeze-in production channels are present for the same freeze-in particle.

The 511 keV photon signal

Longstanding discovery and seen from many collaborations:

The galactic 511 keV photon line emission has been firstly observed for more than 50 years [Johnson, Harnden, Haymes, 1972], and confirmed by recent measurements including the SPI spectrometer on the INTEGRAL observatory [astro-ph/0309442, ...] and COSI balloon telescope [arXiv:1912.00110], see [arXiv:1009.4620] for an early review.

Basic interpretation

Low-energy positrons can annihilate with electrons and produce two 511 keV photons directly in a small fraction (faction $(1 - f_p)$), or form a bound state known as positronium (fraction f_p) with two possible states.

The singlet state (para-positronium/p-Ps) with a zero total spin angular momentum $s = 0$, which occupies $1/4$ of the fraction of the total positronium can annihilate into two photons with energies equal to 511 keV.

Thus the total production rate of 511 keV photons is given by

$$\dot{n}_\gamma = 2\Big[\big(1 - f_p\big) + \frac{1}{4} f_p\Big]\dot{n}_{e^+} = 2\Big(1 - \frac{3}{4} f_p\Big)\dot{n}_{e^+}\,.$$

The dark matter interpretation

The positron production rates in the case of annihilation and decays are given by ($\rho\left(r\right)$ is the dark matter density)

$$\dot{n}_{e^+}^{\rm ann} = f_X \frac{\rho^2\left(r\right)}{4m_X^2} \left\langle \sigma v \right\rangle_{X\bar{X}\to e^+e^-} \ ,$$
$$\dot{n}_{e^+}^{\rm dec} = f_X \frac{\rho\left(r\right)}{m_X} \Gamma_{X\to e^+e^-} {\rm Br}(X \to e^+e^-)\,,$$

Two types of dark matter density profiles widely adopted:

1. The Navarro-Frenk-White (NFW) profile [Navarro, Frenk, White 1996]

$$\rho_{\rm NFW}\left(r\right) = \rho_s \left(\frac{r}{r_s}\right)^{-\gamma}\left(1+\frac{r}{r_s}\right)^{\gamma-3}.$$

2. The Einasto profile [Einasto, arXiv:0901.0632]

$$\rho_{\rm Einasto}\left(r\right) = \rho_s \exp\left\{-\left[\frac{2}{\alpha}\left(\frac{r}{r_s}\right)^{\alpha} - 1\right]\right\}.$$

Constraints on dark matter responsible for 511

- Internal bremsstrahlung $\chi\bar{\chi} \to e^+e^-\gamma$, constrains the dark matter mass $\lesssim 20$ MeV [Beacom, Bell, Bertone, 2004].
- Positron in-flight annihilation [Beacom, Yuksel, 2005]. Small fraction of energetic positrons will annihilate with electrons during their energy-loss, which sets constraint on annihilation dark matter mass $\lesssim 3$ MeV, and decaying dark matter mass $\lesssim 6$ MeV.
- Additional constraints on feebly interacting particles from supernova [Calore, Carenza, Giannotti, Jaeckel, Lucente, Mastrototaro, Mirizzi, 2021].

Dark matter annihilation

The light WIMP achieved their final relic abundance through the freeze-out mechanism with the (total) annihilation cross-section

$$\langle \sigma v \rangle_{\rm ann} \simeq 3 \times 10^{-26} \left(\frac{m_{\rm DM}}{\rm MeV} \right)^2 \ {\rm cm}^3/{\rm s}$$

at the freeze-out.

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at the freeze-out.

To explain the 511 keV signal the annihilation of dark matter at late times needs to be

$$\langle \sigma v \rangle^{511}_{e^+e^-} \simeq 5 \times 10^{-31} \left(\frac{m_{\text{DM}}}{\text{MeV}} \right)^2 \text{ cm}^3/\text{s}\,.$$

[Boehm, Hooper, Silk, Casse, Paul, 2003][Ascasibar, Jean, Boehm, Knoedlseder, 2005][Gunion, Hooper McElrath, 2005][Huh, Kim, Park, Park, 2007][Vincent, Martin Cline, 2012][Wilkinson, Vincent, B?hm, McCabe, 2016][Ema, Sala, Sato, 2020][Boehm, Chu, Kuo, Pradler, 2020][Drees, Zhao, 2021][De la Torre Luque, Balaji, Silk, 2021]...

Dark matter decay

To explain the 511 keV signal, based on the dark matter profiles widely adopted, one needs

$$\frac{\tau_{X\to e^+e^-}(\mathrm{sec}) \times M_X(\mathrm{MeV})}{f_X \times \mathrm{Br}(X \to e^+e^-)} \sim 10^{26} - 10^{29}\,,$$

which can be also written as

$$g^2 \times f_X \times \mathrm{Br}(X \to e^+e^-) \sim 10^{-50} - 10^{-47}\,,$$

where g is the coupling of X with e^+e^-, f_X is the fraction of X in the total dark matter relic density, and $\mathrm{Br}(X \to e^+e^-)$ is the branching fraction of X decay to e^+e^-.

[Picciotto, Pospelov, 2004][Hooper, Wang, 2004][Takahashi, Yanagida, 2005][Finkbeiner, Weiner, 2007][Pospelov, Ritz, 2007][Cembranos, Strigari, 2008][Vincent, Martin Cline, 2012][Cai, Ding, Yang, Zhou, 2020][Lin, Yanagida, 2022][Cappiello, Jafs, Vincent, 2023][Cheng, Lin, Sheng, Yanagida, 2023]

Perspective as a BSM model builder

[WZF, Lust, Schlotterer, Stieberger, Taylor, 2010]
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$\Omega h^2 = 0.12$ now becomes a constraint to the dark matter model rather than a ultimate goal to achieve.

BSM model builder's creed: ONE more beyond the SM

Annihilation DM from freeze-in is highly implausible

To explain the 511 keV signal, the effective coupling between $\chi\bar{\chi}$ and e^+e^- is too large for the freeze-in production (overproduction of the dark matter from freeze-in).

One can introduce mediators (which can decay or annihilate into SM completely)

$$\chi\bar{\chi} \xrightarrow{\text{scalar } S, \text{dark photon } \gamma' \cdots} e^+e^-$$

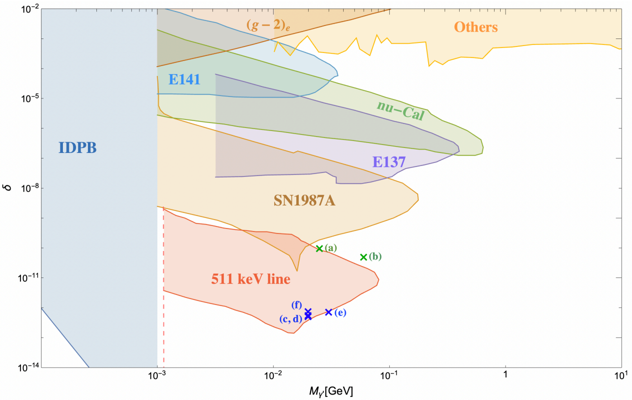
such that one can arrange the interactions among the hidden sector

$$\chi\bar{\chi} \to SS,\ \gamma'\gamma' \to e^+e^- \text{ before BBN}$$

such that the overproduction of the dark matter χ can be depleted.

But now the mediators will receive stringent constraints from experiments and thus are already ruled out [Calore, Carenza, Giannotti, Jaeckel, Lucente, Mastrototaro, Mirizzi, 2021].

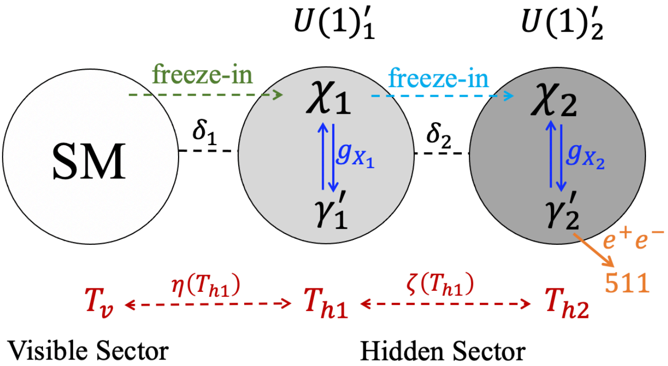
Two types of benchmark models



[WZF, Zhang, 2405.19431]

511 constraints for feebly interacting particles: [Calore, Carenza, Giannotti, Jaeckel, Lucente, Mastrototaro, Mirizzi, 2021]

A two-$U(1)$ model



Full Boltzmann equations

$$
\begin{aligned}
\frac{dY_{\chi_1}}{dT_{h_1}} = -\, s\,\frac{d\rho/dT_{h_1}}{4\rho H}\sum_{i\in\mathrm{SM}}\Big\{ & (Y^{\rm eq}_{\chi_1})^2\,\langle\sigma v\rangle^{T_{h_1}\eta}_{\chi_1\bar\chi_1\to i\bar i} - Y^2_{\chi_1}\,\langle\sigma v\rangle^{T_{h_1}}_{\chi_1\bar\chi_1\to\chi_2\bar\chi_2} \\
& - Y^2_{\chi_1}\,\langle\sigma v\rangle^{T_{h_1}}_{\chi_1\bar\chi_1\to\gamma'_1\gamma'_1} + Y^2_{\gamma'_1}\,\langle\sigma v\rangle^{T_{h_1}}_{\gamma'_1\gamma'_1\to\chi_1\bar\chi_1} - Y^2_{\chi_1}\,\langle\sigma v\rangle^{T_{h_1}}_{\chi_1\bar\chi_1\to\gamma'_1\gamma'_2} \\
& + \theta(M_{\gamma'_1} - 2m_{\chi_1})\big[-Y^2_{\chi_1}\,\langle\sigma v\rangle^{T_{h_1}}_{\chi_1\bar\chi_1\to\gamma'_1} + \frac{1}{s}Y_{\gamma'_1}\langle\Gamma\rangle^{T_{h_1}}_{\gamma'_1\to\chi_1\bar\chi_1}\big]\Big\}, \\
\frac{dY_{\gamma'_1}}{dT_{h_1}} = -\, s\,\frac{d\rho/dT_{h_1}}{4\rho H}\sum_{i\in\mathrm{SM}}\Big\{ & Y^2_{\chi_1}\,\langle\sigma v\rangle^{T_{h_1}}_{\chi_1\bar\chi_1\to\gamma'_1\gamma'_1} - Y^2_{\gamma'_1}\,\langle\sigma v\rangle^{T_{h_1}}_{\gamma'_1\gamma'_1\to\chi_1\bar\chi_1} + Y^2_{\chi_1}\,\langle\sigma v\rangle^{T_{h_1}}_{\chi_1\bar\chi_1\to\gamma'_1\gamma'_2} \\
& - Y^2_{\gamma'_1}\,\langle\sigma v\rangle^{T_{h_1}}_{\gamma'_1\gamma'_1\to\chi_2\bar\chi_2} + \theta(M_{\gamma'_1} - 2m_i)\big[Y^2_i\,\langle\sigma v\rangle^{T_{h_1}\eta}_{i\bar i\to\gamma'_1} - \frac{1}{s}Y_{\gamma'_1}\langle\Gamma\rangle^{T_{h_1}}_{\gamma'_1\to i\bar i}\big] \\
& + \theta(M_{\gamma'_1} - 2m_{\chi_1})\big[Y^2_{\chi_1}\,\langle\sigma v\rangle^{T_{h_1}}_{\chi_1\bar\chi_1\to\gamma'_1} - \frac{1}{s}Y_{\gamma'_1}\langle\Gamma\rangle^{T_{h_1}}_{\gamma'_1\to\chi_1\bar\chi_1}\big] \\
& + \theta(M_{\gamma'_1} - 2m_{\chi_2})\big[Y^2_{\chi_2}\,\langle\sigma v\rangle^{T_{h_1}\zeta}_{\chi_2\bar\chi_2\to\gamma'_1} - \frac{1}{s}Y_{\gamma'_1}\langle\Gamma\rangle^{T_{h_1}}_{\gamma'_1\to\chi_2\bar\chi_2}\big]\Big\}, \\
\frac{dY_{\chi_2}}{dT_{h_1}} = -\, s\,\frac{d\rho/dT_{h_1}}{4\rho H}\sum_{i\in\mathrm{SM}}\Big\{ & Y^2_{\gamma'_1}\,\langle\sigma v\rangle^{T_{h_1}}_{\gamma'_1\gamma'_1\to\chi_2\bar\chi_2} + Y^2_{\chi_1}\,\langle\sigma v\rangle^{T_{h_1}}_{\chi_1\bar\chi_1\to\chi_2\bar\chi_2} - Y^2_{\chi_2}\,\langle\sigma v\rangle^{T_{h_1}\zeta}_{\chi_2\bar\chi_2\to\gamma'_2\gamma'_2} \\
& + Y^2_{\gamma'_2}\,\langle\sigma v\rangle^{T_{h_1}\zeta}_{\gamma'_2\gamma'_2\to\chi_2\bar\chi_2} + \theta(M_{\gamma'_1} - 2m_{\chi_2})\big[-Y^2_{\chi_2}\,\langle\sigma v\rangle^{T_{h_1}\zeta}_{\chi_2\bar\chi_2\to\gamma'_1} + \frac{1}{s}Y_{\gamma'_1}\langle\Gamma\rangle^{T_{h_1}}_{\gamma'_1\to\chi_2\bar\chi_2}\big]\Big\}, \\
\frac{dY_{\gamma'_2}}{dT_{h_1}} = -\, s\,\frac{d\rho/dT_{h_1}}{4\rho H}\sum_{i\in\mathrm{SM}}\Big[& Y^2_{\chi_1}\,\langle\sigma v\rangle^{T_{h_1}}_{\chi_1\bar\chi_1\to\gamma'_1\gamma'_2} + Y^2_{\chi_2}\,\langle\sigma v\rangle^{T_{h_1}\zeta}_{\chi_2\bar\chi_2\to\gamma'_2\gamma'_2} - Y^2_{\gamma'_2}\,\langle\sigma v\rangle^{T_{h_1}\zeta}_{\gamma'_2\gamma'_2\to\chi_2\bar\chi_2}\Big],
\end{aligned}
$$

$$
\frac{d\eta}{dT_{h_1}} = -\frac{\eta}{T_{h_1}} + \frac{1}{T_{h_1}}\left(\frac{4H\rho_v + j_{h_1} + j_{h_2}}{4H\rho_{h_1} - j_{h_1}}\right)\frac{d\rho_{h_1}/dT_{h_1}}{d\rho_v/dT_v}\,, \quad \frac{d\zeta}{dT_{h_1}} = -\frac{\zeta}{T_{h_1}} + \frac{1}{T_{h_1}}\left(\frac{4H\rho_{h_2} - j_{h_2}}{4H\rho_{h_1} - j_{h_1}}\right)\frac{d\rho_{h_1}/dT_{h_1}}{d\rho_{h_2}/dT_{h_2}}\,,
$$

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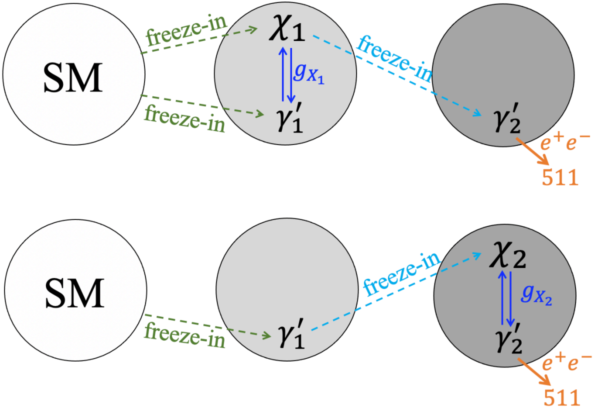
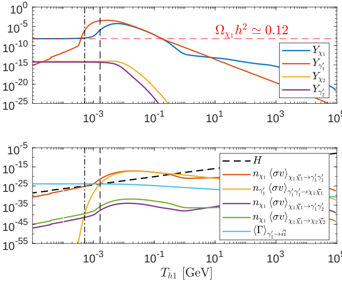
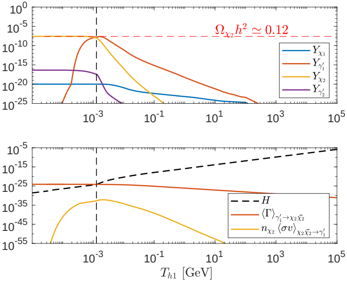


Evolution of the two models





Dark photon dark matter explanation of the 511 signal

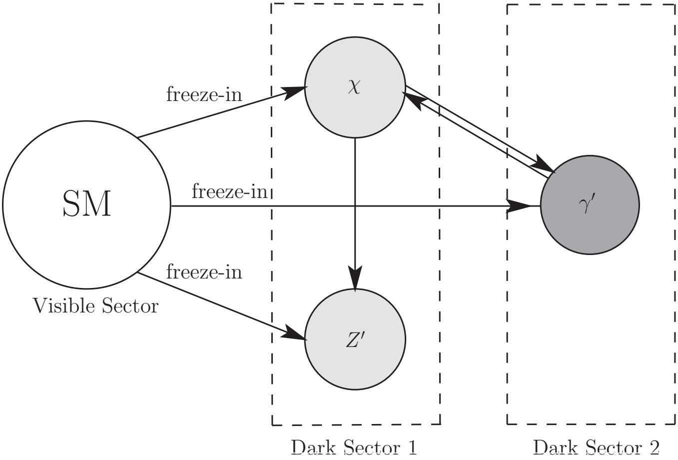
The 511 keV photon flux generated by the decay of the dark photon γ'_2 is computed to be

$$\Phi_{511} = \frac{f_{\gamma'_2}}{8\pi} \int d\Omega \int_{\mathrm{l.o.s}} \frac{\rho(r)}{M_{\gamma'_2}} \Gamma_{\gamma'_2 \to e^+e^-} ds \,.$$

The bulge flux	$\Phi_{511}^{\mathrm{NFW}}$	$\Phi_{511}^{\mathrm{Einasto}}$
$\lvert l\rvert \lesssim 30°$, $\lvert b\rvert \lesssim 15°$	8.3	9.7
FWHM $\simeq 20.55°$	4.8	6.0

The results of bulge flux for benchmark model a using different integral range for the two dark matter density profile we consider. All fluxes are in units of $10^{-4}\ \mathrm{ph\,cm^{-2}\,s^{-1}}$, which are consistent with the measured bulge flux ~ 9.6 [Siegert, Diehl, Khachatryan, Krause, Guglielmetti, Greiner, Strong, Zhang, 2016].

Dark photon dark matter from $U(1)$ mixings



[Aboubrahim, WZF, Nath, Wang, 2021]

Conclusion

- A general method of computing freeze-in production of hidden sector which involves inner interactions given by [Aboubrahim, WZF, Nath, Wang, 2008.00529] is reviewed.
- A general discussion of the $U(1)$ mixings as well as the most comprehensive study of the sub-GeV freeze-in millicharge dark matter [WZF, Zhang, Zhang, 2312.03837] is presented.
- The dark matter interpretation of the 511 keV signal is discussed. In the models we study, the freeze-in mechanism generates the entire dark matter relic density, and thus any types of additional dark matter components produced from other sources are unnecessary. The two-$U(1)$ model remains a strong candidate for explaining the 511 keV signal consistent with various dark matter density profiles [WZF, Zhang, 2405.19431].