The Cure For WIMPs

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This talk is based on

Aboubrahim, WZF, Nath, "*A long-lived stop with freeze-in and freeze-out dark matter in the hidden sector,*" 1910.14092.
Aboubrahim, WZF, Nath, "*Expanding the parameter space of natural supersymmetry,*" 2003.02267.

Aboubrahim, WZF, Nath, Wang, "*Self-interacting hidden sector dark matter, small scale galaxy structure anomalies,*" 2008.00529.
Aboubrahim, WZF, Nath, Wang, "*A multi-temperature universe can allow a sub-MeV dark photon dark matter,*" 2103.15769.
Amin Aboubrahim, WZF, Pran Nath, Zhu-Yao Wang, "*Hidden sectors and a multi-temperature universe,*" 2106.06494.
WZF, Zhang, "*Freeze-in Dark Matter Explanation of the Galactic 511 keV Signal,*" 2405.19431.
WZF, Zhang, 2409.XXXXX.

WZF, Nath, Li, "Cosmologically consistent analysis of gravitational waves from hidden sectors," 2403.09558.

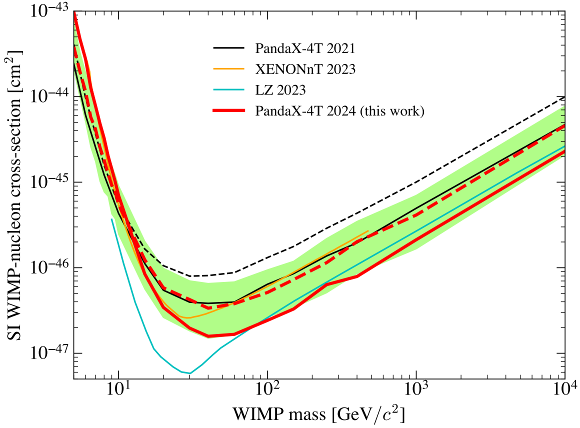
Overview

1. Dark matter from $U(1)$ hidden sectors
   - Explorations into hidden sectorS
   - Recent developments on $U(1)$ hidden sectors
   - Gravitational wave probe of $U(1)$ hidden sectors
2. $U(1)$ hidden sectors rescuing SUSY models
   - Issues of low energy SUSY
   - Freeze-in hidden sectors reconstruct SUSY spectrum
3. Physics of multiple $U(1)$ hidden sectors
   - 100% dark photon dark matter
   - Dark matter explanations of the galactic 511 keV signal
4. The cure for WIMP

Explorations into hidden sectorS

- The null discovery of WIMPs has substantially challenged a large number of traditional dark matter models.
- Direct/indirect detection as well as collider constraints significantly narrow down the parameter space for majority of WIMP dark matter candidates.
- $\Omega h^2 = 0.12$ now becomes a constraint to the dark matter models rather than an ultimate goal to achieve.

Nightmare direct detection constraints on WIMPs



[PandaX, 2024]

Post-WIMP era

- Sub-GeV dark matters (experimental constraints not that strong) Other motivations for sub-GeV
- Quark-phobic type of models (unnatural)
- Resonance models (remain subject to strong constraints from colliders) In many cases, DM and mediators are all pushed to above TeV
- What about the O(1)-O(100)GeV traditonal WIMPs models?
- Should we completely abandon these models?

Traditional WIMP models?

- Should we totally give up almost-excluded traditional WIMP models due to the more stringent constraints?
- In general, what can theorists offer to new physics studies?
- Personal taste from String Pheno studies – Our world is strange and unique.
- Explore more possibilities beyond the Standard Model.

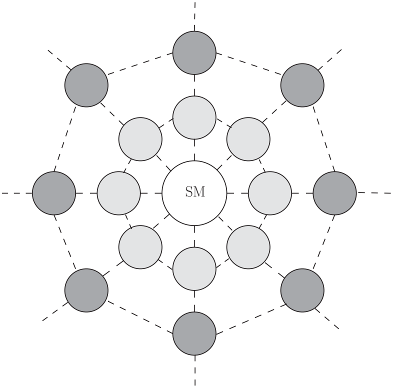
Explore more possibilities beyond the SM

- It is widely accepted that dark matter resides in one or multiple hidden sectors. Since dark matter hasn't been detected other than gravitational observations, it is possible that dark matter undergoes strong interactions within multiple hidden sectors, while only weakly coupled to the Standard Model.
- It is interesting to explore interactions among multiple hidden sectors that contain dark matter candidates.

Multiple hidden sectors beyond the SM

- Hidden sectors generally exist in string theory and GUT models.
- SM extensions with one or more hidden sectors is one possibility of our true world.
- Evolutions of hidden sector particles and hidden sector temperature are important in determining new physics signals, in concordance with various experimental constraints and dark matter relic density constraint.
- YES WE CAN *now* calculate the full evolutions of hidden sector particles as well as hidden sector temperatures.

Multiple hidden sectors beyond the SM



Our SM is in general directly or indirectly connected with multiple hidden sectors, with either weak scale coupling or ultraweak coupling. A hidden sector feebly interacted with the SM will evolve almost independently wrt. the universe, and it possesses its own temperature.

Matters from $U(1)$ hidden sectors

- Minimal setup: Z' (or dark photon γ' for small mass), one or more dark fermion(s), with or without a dark Higgs.
- The dark fermion carrying the extra $U(1)$ charge is a natural dark matter candidate. Light dark photon can also be a dark matter candidate.
- $U(1)$ extension of the Standard Model: $U(1)_v$, $U(1)_h$ (kinetic and/or mass mixing).
- Freeze-out scenarios (dark matter is initially in thermal equilibrium with SM particles) – various problems: direct/indirect detection constraints, collider constraints... It is now *very difficult* to satisfy the relic density together with various experimental constraints.
- Turn to freeze-in (dark matter never achieves thermal equilibrium with SM particles) – one major problem: why there exists such feeble coupling? *Mixings* can just provide such smallness of the coupling constants.

A brief review of $U(1)$ extensions of the SM

$U(1)_v$ extensions – All of or some of the SM particles are charged under this $U(1)$.

1. Anomaly free $U(1)$'s: for example $U(1)_{\alpha Y+\beta(B-L)}$, ...
2. Anomalous $U(1)$'s: for example $U(1)_B$, $U(1)_L$, $U(1)_{PQ}$, ...
    - Adding chiral exotics: making the theory look ugly, also there is no good explanation why these chiral fields are much heavier compared with SM particles, since they haven't been discovered.
    - Green-Schwarz mechanism. The coupling of the $U(1)$ gauge field and the axion is responsible to cancel the anomalies, and at the same time this coupling also give the $U(1)$ gauge boson a Stueckelberg mass.

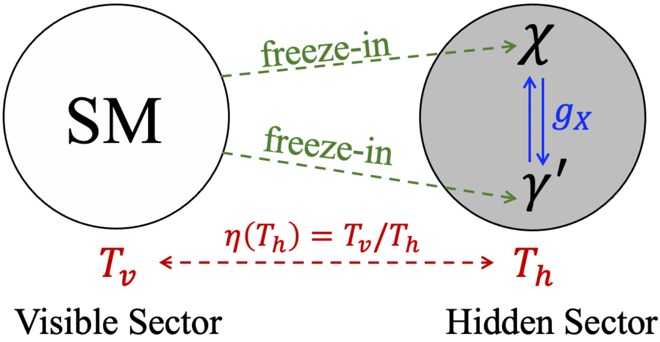
Family-dependent $U(1)_v$ extensions (also anomaly free): for example $U(1)_{L_\mu - L_\tau}$ [WZF, Nath, Peim, 1204.5752], $U(1)_{B_1+B_2-2B_3}$ [Celis, WZF, Vollmann, 1608.03894], ...

$U(1)_h$ extensions – All of the SM particles are neutral under this $U(1)$. Then one needs to find a mechanism to connect the visible sector and the hidden sector:

1. Kinetic mixing: A term $\sim \frac{\delta}{2} F^Y_{\mu\nu} F^{\mu\nu}_h$ can be induced by loop effects.
2. Mass mixing: A term $\sim m^2 A_Y A_h$ can be induced by either Higgs mechanism or Stueckelberg mechanism.
3. Both kinetic mixing and mass mixing. A simultaneous diagonalization is required.

After the diagonalization (either the kinetic terms or the mass terms or both), in the final (physical) eigenbasis $U(1)$'s couple to both hidden sector fields and visible sector fields.

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



A graphic illustration of the freeze-in generation of the simplest $U(1)_X$ hidden sector generated through freeze-in mechanism.

Recent developments on $U(1)$ hidden sectors

- We have developed a formalism to compute the evolution of hidden sector temperature as well as the hidden sector particles produced through freeze-in mechanism [Aboubrahim, WZF, Nath, Wang, 2008.00529].
- The strong interaction among dark matter, which might be the answer to various small scale structure issues, can be addressed in a $U(1)_X$ hidden sector produced via freeze-in beyond the SM.
- This formalism can be applied 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.

$U(1)$ mixings and the millicharge

1. Without inducing other modifications to the SM, the effective term $\mathcal{L} \sim -\frac{\delta}{2} F^{\rm em}_{\mu\nu} F^{\mu\nu}_X$ is difficult to generated from a renormalized model in UV. Thus considering $\mathcal{L} \sim -\frac{\delta}{2} F^{\rm em}_{\mu\nu} F^{\mu\nu}_X$ 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]. 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.

See [WZF, Zhang, Zhang, 2312.03837] for a comprehensive review.

The destination of the dark photon

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

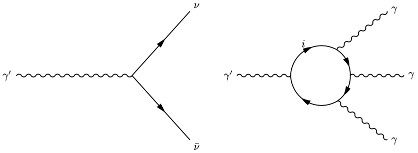


Figure: The coupling of dark photon to neutrinos is suppressed by a factor of $(m^2_{\gamma'}/M^2_Z)$ compared to its coupling to electron-positron pairs. Considering various constraints, the decay of the dark photon to neutrinos due to the mixing effect is always less significant than the decay to the three-photon channel.

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 constraint

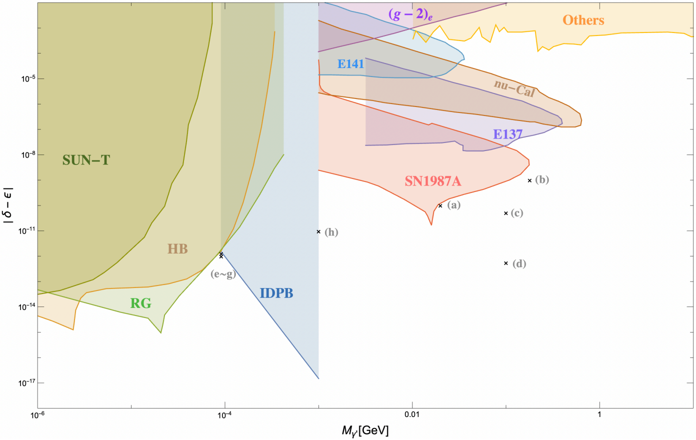


Figure: A display of current constraints (colored regions) on the absolute value of the kinetic mixing parameter minus the mass mixing parameter.

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 observation of gravitational waves in black hole mergers in 2016 opened up a new avenue to explore fundamental physics.

There are various possible sources of gravitational waves

- Compact binary inspiral gravitational waves (LIGO).
- Continuous GW (from spinning neutron stars).
- GWs from Gamma Ray Bursts and possibly from other sources of unknown origin.
- Stochastic GW.

Stochastic GW could reveal fundamental new physics

- Inflation, Big Bang.
- Cosmic strings, primordial black hole evaporation.
- Cosmic phase transitions, specifically the First Order Phase Transition (FOPT).

FOPT: standard model vs experiment

Standard model does not produce a strong enough gravitational wave measurable by current/proposed detectors:

- $\Omega_{\mathrm{GW}} \leq 10^{-28}$ (reach of the Standard Model)
- $\Omega_{\mathrm{GW}} \geq 10^{-20}$ (reach of the proposed detectors)

Hidden sectors could provide much larger gravitational waves possibly in the observational range.

GW provided by the hidden sector

Consider the $U(1)$ extension of the SM

$$\begin{aligned}\Delta\mathcal{L} = &-\frac{1}{4}A_{\mu\nu}A^{\mu\nu} - \left|(\partial_\mu - ig_x A_\mu)\Phi\right|^2 - V^{\rm h}_{\rm eff}(\Phi)\\ &+ \bar{D}(\mathrm{i}\gamma^\mu\partial_\mu - m_D)D - \frac{\delta}{2}A_{\mu\nu}B^{\mu\nu} - g_x Q_D \bar{D}\gamma^\mu D A_\mu\,,\end{aligned}$$

with the temperature dependent potential

$$V^{\rm h}_{\rm eff}(\Phi, T_h) = V_{0h} + V^{(0)}_{1h} + \Delta V^{(T_h)}_{1h} + V^{\rm daisy}_h(T_h)\,.$$

For the one-loop thermal correction we have

$$\Delta V^{(T_h)}_{1h}(\chi_c, T_h) = \frac{{T_h}^4}{2\pi^2}\left[3J_B\left(\frac{m_A}{T_h}\right) + J_B\left(\frac{m_\chi}{T_h}\right) + J_B\left(\frac{m_{G^0_h}}{T_h}\right)\right]$$

where J_i $(i = B, F)$ is defined so that at one loop

$$J_i\left(\frac{m_i}{T_h}\right) = \int_0^\infty \mathrm{d}q\, q^2 \ln\left[1 \mp \exp\left(-\sqrt{q^2 + m_i^2/{T_h}^2}\right)\right],\quad i = (B, F)\,,$$

where (B, F) stand for bosonic and fermionic cases.

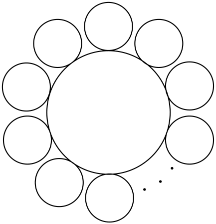
daisy resummation

The daisy loop contributions are only for the longitudinal mode of A and χ and are given for mode $i = A, \chi$ so that

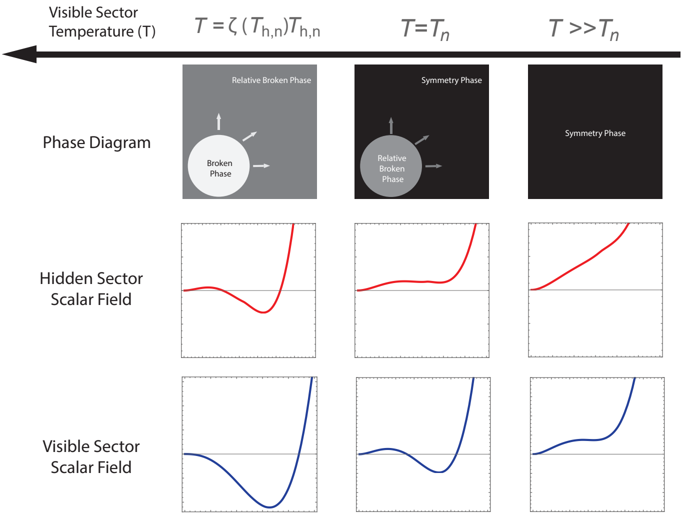
$$V^{\text{daisy}}(i, T_h) = -\frac{T_h}{12\pi}\left\{\left[m_i^2 + \Pi_i(T_h)\right]^{3/2} - m_i^3\right\},$$

where $\Pi_i(T_h)$ is thermal contribution to the zero temperature mass m_i^2. For the longitudinal mode of A and for χ they are given by

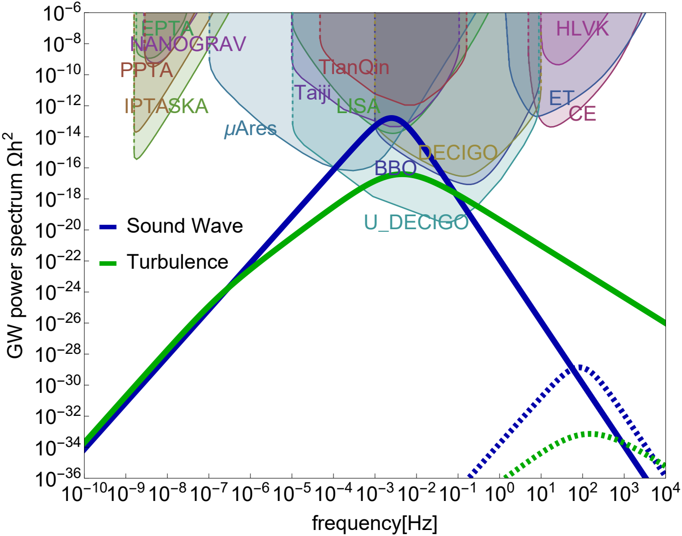
$$\Pi_A(T_h) = \frac{2}{3}g_x^2 {T_h}^2, \quad \Pi_\chi(T_h) = \frac{1}{4}g_x^2 {T_h}^2 + \frac{1}{3}\lambda_h {T_h}^2.$$



Two field tunneling: SM Higgs and hidden scalar



GW signal, SM vs Hidden



Current low energy SUSY status

- SUSY is the natural solution to the hierarchy problem and also offers a natural dark matter candidate – the LSP.
- Sadly there is no signal for supersymmetry (yet). LHC has analyzed up to 139 fb^{-1} of data for each of ATLAS and CMS and the results are consistent with the SM.
- Traditional SUSY signals, such as final states with large missing energy due to a neutralino as the LSP, hard jets arising from the decay of squarks and gluinos, or high momentum leptons coming from the decay of electroweak gauginos are now significantly more constrained.
- From model building point of view, constraints are less severe for more rare processes because of their small production cross-sections. Another search which is still not highly constrained is long-lived particles.

Issues of neutralino dark matter

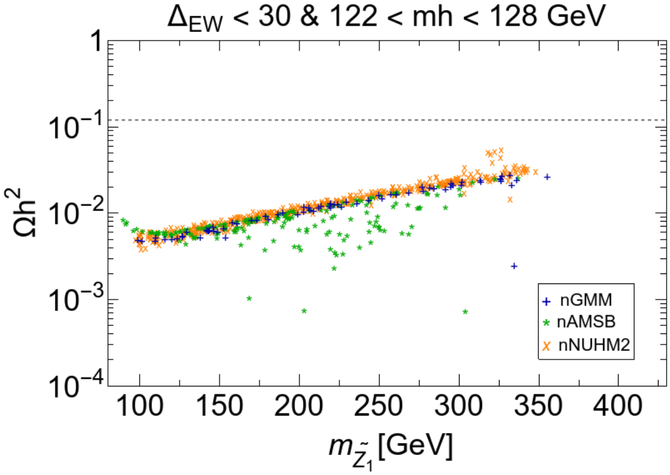
- The measured value of the Higgs boson mass at 126 GeV indicates the size of weak scale supersymmetry lies in the TeV region.
- Direct detection of stop and gluino at the LHC also point to a SUSY breaking scale in the multi-TeV regime.
- Meanwhile, direct searches for relic WIMP dark matter failed to detect the SUSY WIMP.
- Indirect WIMP searches from Fermi-LAT (expecting to detect WIMP annihilation to gamma rays) also place strong limits on SUSY WIMPs.

The requirement of naturalness in SUSY models necessitates light higgsinos not too far from the weak scale. The LSP is expected to be a mainly higgsino-like neutralino with non-negligible gaugino components. The computed thermal WIMP abundance in natural SUSY models is then found to be typically a factor 5-20 below the observed relic density [Baer, Barger, Sengupta, Tata, 2018].

SUSY naturalness

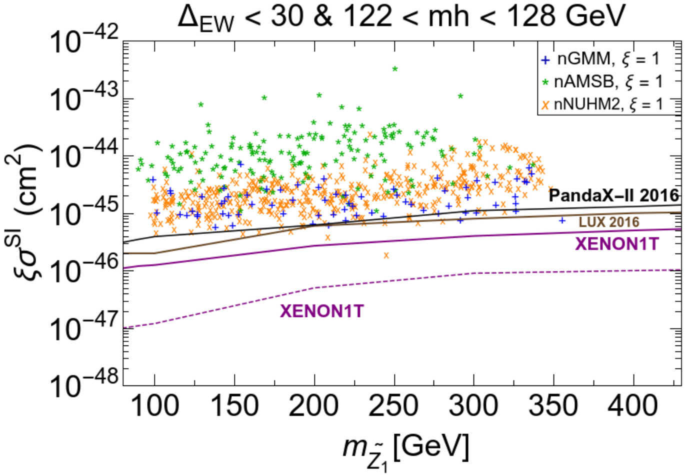
- With various definitions on the SUSY naturalness, typically most natural SUSY models feature a relatively small Higgs mixing parameter μ.
- Small μ leads to a SUSY model with LSP a Higgsino-like neutralino.
- As indicated earlier, higgsino-like neutralino typically leads to a relic density that falls below the experimental value.

Natural SUSY WIMP relic density



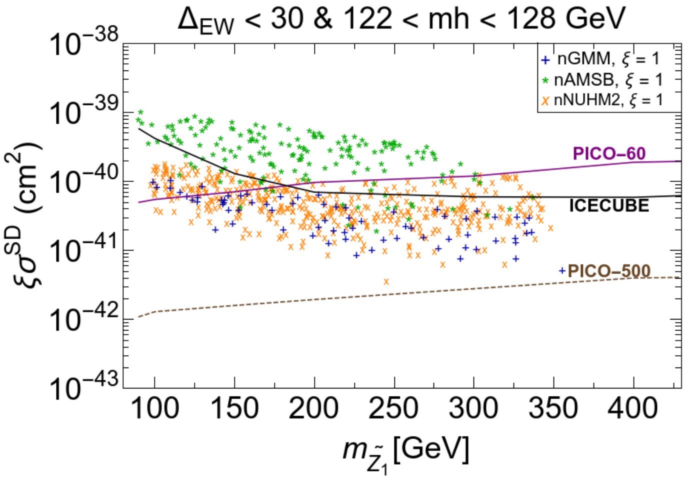
[Baer, Barger, Sengupta, Tata, 2018].

Direct detection bounds



[Baer, Barger, Sengupta, Tata, 2018].

Indirect detection bounds



[Baer, Barger, Sengupta, Tata, 2018].

Solution

- Models where the WIMP relic density (taken to be its thermal value) forms just $\sim 5-20\%$ of the measured CDM density survive the combined constraints from LHC as well as from direct and indirect searches.
- To gain concordance with observations, either additional DM particles must be present or additional non-thermal mechanisms must augment the neutralino abundance.
- Freeze-in $U(1)$ hidden sectors allow us to reconstruct the MSSM spectrum, and gives us more choices for the SUSY parameter space.
- Thus hidden sectors provide more possibilities in constructing particle physics models to explain various unknown problems.

$U(1)$ extension of the SUSY model

- Consider an MSSM/SUGRA model extended by an $U(1)$ sector feebly interacted with the MSSM.
- The model contains additional chiral scalar superfields S and $\bar{S}$ and a vector superfield C. The fermionic component of S and $\bar{S}$ and the gaugino components of C mix with the MSSM neutralino fields producing a 6×6 neutralino mass matrix.
- Two different neutralino mass hierarchies:
  1. the real LSP is the dark neutralino,
  2. the real LSP is the MSSM neutralino,

  which will be the dark matter candidate of the model.

Case 1: The real LSP is the dark neutralino

In the neutralino sector, we label the mass eigenstates as

$$\tilde{\xi}_1^0,\ \mathrm{MSSM\,LSP},\ \tilde{\xi}_2^0,\ \tilde{\chi}_1^0,\ \tilde{\chi}_2^0,\ \tilde{\chi}_3^0, \tilde{\chi}_4^0.$$

Since the mixing parameter δ is small, $\tilde{\xi}_1^0$ and $\tilde{\xi}_2^0$ are mostly the dark neutralinos while the remaining four $\tilde{\chi}_i^0$ $(i = 1 \cdots 4)$ are mostly MSSM neutralinos.

In this case, the real $\tilde{\xi}_1^0$ is the DM candidate and the MSSM LSP can be long-lived squarks or sleptons.

Long-lived particles

- If the particle is charged and stable over detector length it can be identified by the track it leaves in the inner tracker and in the muon spectrometer. Other signatures are possible such as a disappearing track where a charged particle can decay into very soft final states which escape the trigger threshold.
- ATLAS and CMS were not designed to look for long-lived particles and part of the upcoming upgrade is to further their capabilities to become more sensitive to such searches.
- Most long-lived particle searches at the LHC consider an NLSP very close in mass to the LSP ($\Delta m \sim$ few GeV down to MeV) resulting in a highly suppressed phase space. This leads to a small decay width for the NLSP and thus a long-lived particle.
- Long-lived particles can also arise in SUSY models with a hidden sector if the hidden sector has ultraweak interactions with the visible sector and the LSP of the visible sector decays into the hidden sector.

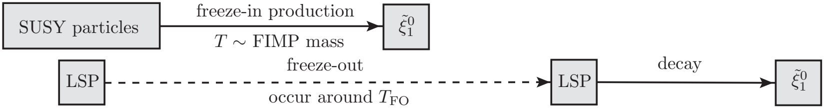
Case 2: The real LSP is the MSSM neutralino

With the freeze-in $U(1)$ hidden sector, the mass hierarchy in this setup is:

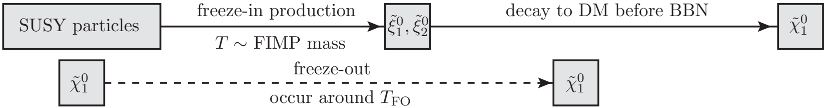
$$\tilde{\chi}_1^0,\ \tilde{\xi}_1^0,\ \tilde{\xi}_2^0,\ \tilde{\chi}_2^0,\ \tilde{\chi}_3^0,\ \tilde{\chi}_4^0.$$

In this case $\tilde{\chi}_1^0$ is the real LSP among the entire SUSY sector and is thus the dark matter candidate.

Reconstruct SUSY models with FIMPs

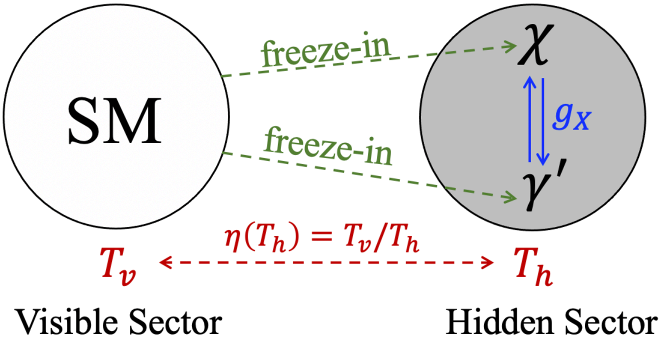


[Aboubrahim, WZF, Nath, 1910.14092].



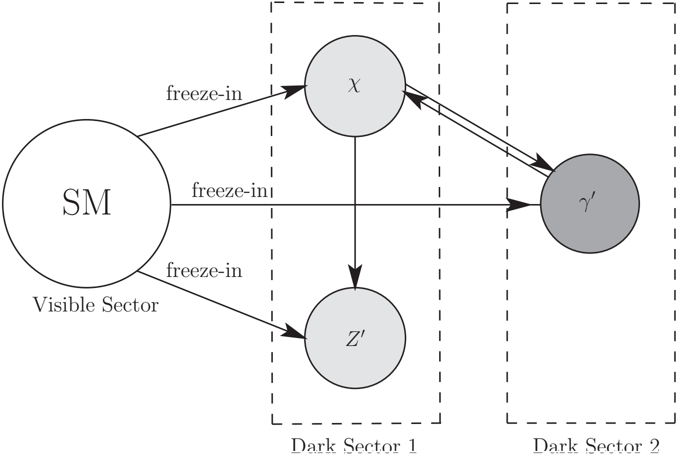
[Aboubrahim, WZF, Nath, 2003.02267].

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



For a single $U(1)$ extension, a dark photon dark matter can occupy at most $\sim 5\%$ of the total dark matter relic density.
$\Longrightarrow$ Extension with more $U(1)$'s.

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



[Aboubrahim, WZF, Nath, Wang, 2103.15769]: dark photon dark matter from two $U(1)$'s can occupy almost 100% of the relic density.

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

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

The dark matter interpretation

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

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

$$\dot{n}_{e^+}^{\mathrm{dec}} = f_X \frac{\rho(r)}{m_X} \Gamma_{X\to e^+e^-} \mathrm{Br}(X \to e^+e^-) \, ,$$

Two types of dark matter density profiles widely adopted:

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

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

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

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

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.

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

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

[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, Boehm, McCabe, 2016][Ema, Sala, Sato, 2020][Boehm, Chu, Kuo, Pradler, 2020][Drees, Zhao, 2021][De la Torre Luque, Balaji, Silk, 2021]

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].

Dark matter decay

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

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

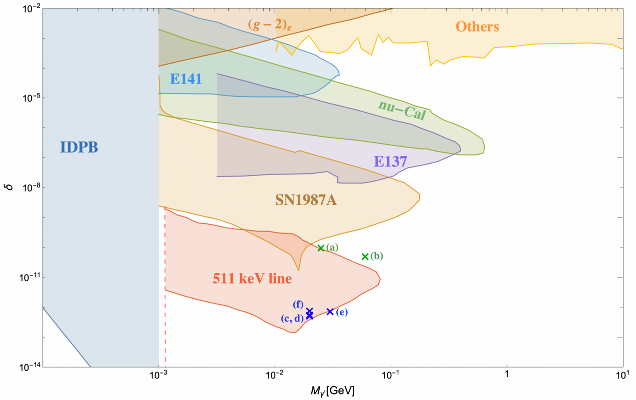
which can be also written as

$$g^2 \times f_X \times \text{Br}(X \to e^+e^-) \sim 10^{-50} - 10^{-47}\,,$$
$$\Longrightarrow g \lesssim 10^{-16}$$

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 $\text{Br}(X \to e^+e^-)$ is the branching fraction of X decay to e^+e^-. The coupling g is soooooo small even for the freeze-in production.

[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]

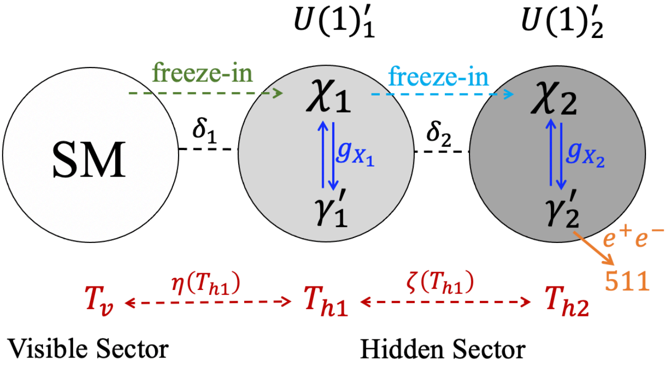
Two types of benchmark models



[WZF, Zhang, 2405.19431]

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

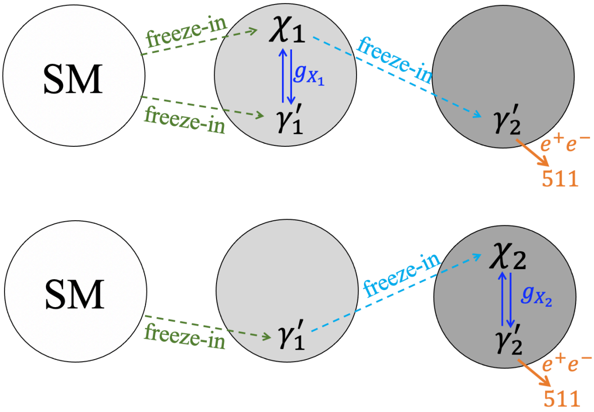
A two-$U(1)$ model



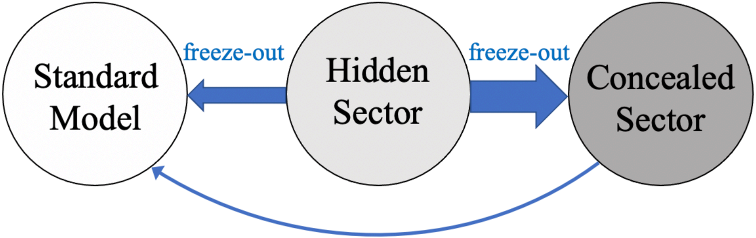
Full Boltzmann equations

$$
\begin{aligned}
\frac{\mathrm{d}Y_{\chi_1}}{\mathrm{d}T_{h_1}} = &- s\,\frac{\mathrm{d}\rho/\mathrm{d}T_{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{\mathrm{d}Y_{\gamma'_1}}{\mathrm{d}T_{h_1}} = &- s\,\frac{\mathrm{d}\rho/\mathrm{d}T_{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_i^2\,\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{\mathrm{d}Y_{\chi_2}}{\mathrm{d}T_{h_1}} = &- s\,\frac{\mathrm{d}\rho/\mathrm{d}T_{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{\mathrm{d}Y_{\gamma'_2}}{\mathrm{d}T_{h_1}} = &- s\,\frac{\mathrm{d}\rho/\mathrm{d}T_{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], \\
\frac{\mathrm{d}\eta}{\mathrm{d}T_{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{\mathrm{d}\rho_{h_1}/\mathrm{d}T_{h_1}}{\mathrm{d}\rho_v/\mathrm{d}T_v}\,, \quad \frac{\mathrm{d}\zeta}{\mathrm{d}T_{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{\mathrm{d}\rho_{h_1}/\mathrm{d}T_{h_1}}{\mathrm{d}\rho_{h_2}/\mathrm{d}T_{h_2}}\,,
\end{aligned}
$$

Two types of benchmark models

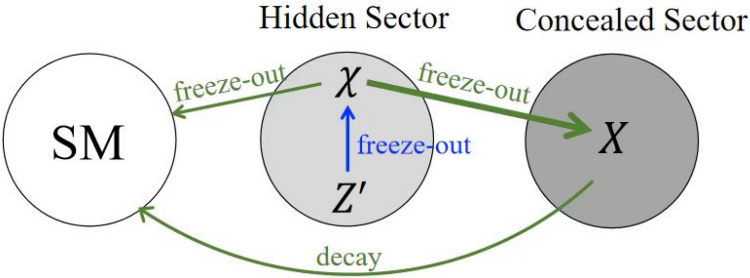


The cure for WIMP



WZF, Zhang, 2409.XXXXX.

Rescuing $U(1)$ WIMPs



WZF, Zhang, 2409.XXXXX.

Comment: for $U(1)_{B-L}$ types of models, which are subject to stringent constraints from dark matter direct and indirect detections as well as colliders, the gauge coupling of such $U(1)$ MUST BE ULTRAWEAK. "Secluded" method does not work.

Conclusion

- Recent developments of $U(1)$ hidden sectors are reviewed:
  1. A general method of computing freeze-in production of hidden sector which involves inner interactions given by [Aboubrahim, WZF, Nath, Wang, 2008.00529].
  2. 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.
  3. Freeze-in $U(1)$ hidden sectors reconstructing low energy SUSY spectrum is discussed. [Aboubrahim, WZF, Nath, 1910.14092, 2003.02267].
  4. The power of multiple $U(1)$ hidden sectors are shown [Aboubrahim, WZF, Nath, Wang, 2103.15769][WZF, Zhang, 2405.19431].
  5. Study of gravitational waves opens up a new avenue for the exploration of hidden sector physics [WZF, Nath, Li, 2403.09558].
- A possible explanation of the null discovery of WIMP is presented [WZF, Zhang, 2409.XXXXX].