Dark matter candidates from multi-temperature $U(1)$ hidden sectors

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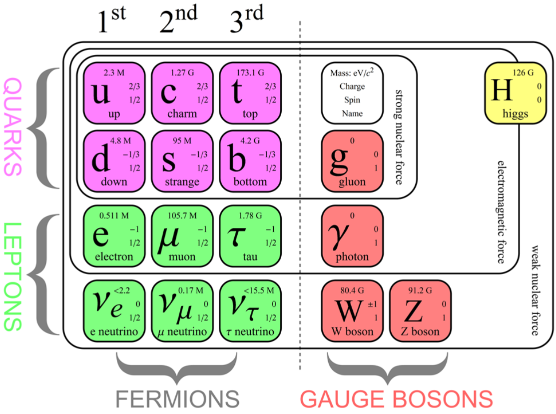
This talk is based on

Amin Aboubrahim, WZF, Pran Nath, 1910.14092
Amin Aboubrahim, WZF, Pran Nath, 2003.02267
Amin Aboubrahim, WZF, Pran Nath, Zhu-Yao Wang, 2008.00529
Amin Aboubrahim, WZF, Pran Nath, Zhu-Yao Wang, 2103.15769

Overview

The Standard Model and beyond

Standard model (SM): By far the most successful and the most accurate theory. No contradiction with all known experiments.



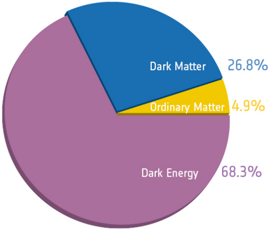
The Standard Model and puzzles beyond

- Theoretical problems: Hierarchy problem. Why the Higgs mass is around the weak scale? ...
- Cannot be explained within the SM framework: Dark matter, dark energy, baryogenesis, ...
- Experimental anomalies: Flavor anomalies, muon $g-2$, ...

Dark matter

Dark matter is an unidentified type of matter comprising approximately 26.8% [Planck 2013] of the mass and energy in the observable Universe. Various puzzles:

- What is dark matter?
- Why the amount of dark matter and visible matter are of the same order?
- How dark matter connects with the SM?



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- Among various works which extend the SM with additional gauge groups, the $U(1)$ extension is the simplest, and is well motivated from the grand unified theory and the string theory.
- The $U(1)$ extension offers dark matter candidates naturally – Dirac fermions charged under $U(1)$.

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- In the R-parity conserving minimal supersymmetric standard model (MSSM) the decay chain always ends up with the LSP along with standard model particles, and thus the LSP is naturally the dark matter candidate.

A brief review of $U(1)$ extensions

$U(1)_v$ 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.
- 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: eg, $U(1)_{L_\mu - L_\tau}, U(1)_{B_1+B_2-2B_3}, \cdots$

Dark sectors from $U(1)_v$ extensions

In these $U(1)_v$ extensions, fermions charged under $U(1)_v$ are automatically dark matter candidates.

- Various experimental constraints for $U(1)_v$ gauge boson. Constraints from LEP II, LHC... It's very likely the $U(1)_v$ gauge bosons are heavy.
- Dark matter could annihilate though the Z' into visible sector particles, one needs to make sure that it can indeed satisfy the observed relic density.
- Could introduce new couplings of the dark particles with SM particles. For example an interaction of $\frac{1}{M} XXLH$ would give rise to asymmetric dark matter.

$U(1)_h$ extensions

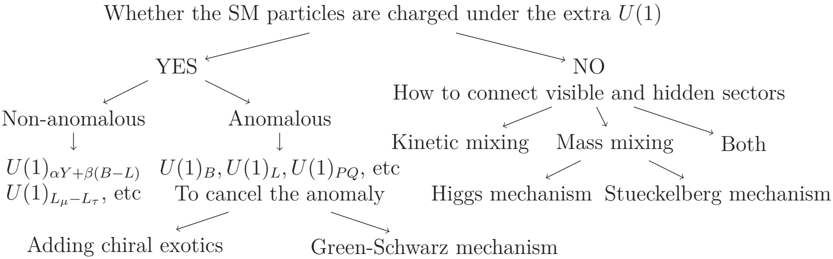
$U(1)_h$ extensions – All of the SM particles are neutral under this $U(1)$. Then one needs to find a mechanism to connect the visible sector and the hidden sector:

1. Kinetic mixing: A term $\sim \frac{\delta}{2} F^Y_{\mu\nu} F^{\mu\nu}_h$ could be induced by loop effects.
2. Mass mixing: A term $\sim m^2_{vh} A_v A_h$ could be induced by either Higgs mechanism or Stueckelberg mechanism.

- After the diagonalization (either the kinetic terms or the mass terms or both), in the final (physical) eigenbasis the $U(1)$'s would couple to both hidden sector fields and visible sector fields.
- In most of these models, the Z' carries a small fraction of Z boson. Due to the $Z - Z'$ mixing constraint, Z' could interact with the SM particles with only small or feeble couplings.

Summary

Here we summarize all above different scenarios in the following chart:



Whether the SM particles are charged under the extra $U(1)$

YES

Non-anomalous

$U(1)_{\alpha Y+\beta(B-L)}$

$U(1)_{L_\mu - L_\tau}$, etc

Anomalous

$U(1)_B, U(1)_L, U(1)_{PQ}$, etc

To cancel the anomaly

Adding chiral exotics

Green-Schwarz mechanism

NO

How to connect visible and hidden sectors

Kinetic mixing

Mass mixing

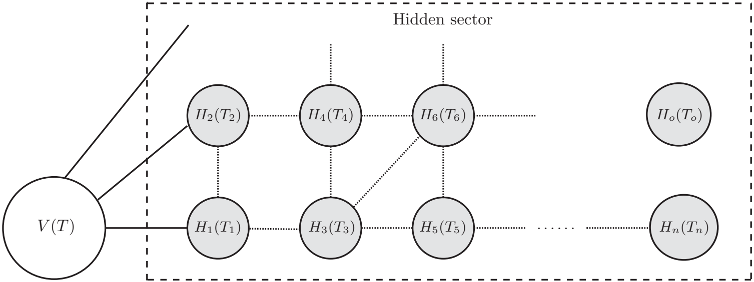
Higgs mechanism

Stueckelberg mechanism

Both

Hidden sector in general

In general there can be multiple hidden sectors. The visible sector may have direct couplings with some of the dark sectors, or indirect couplings with others via interactions among the entire hidden sector.



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- 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.
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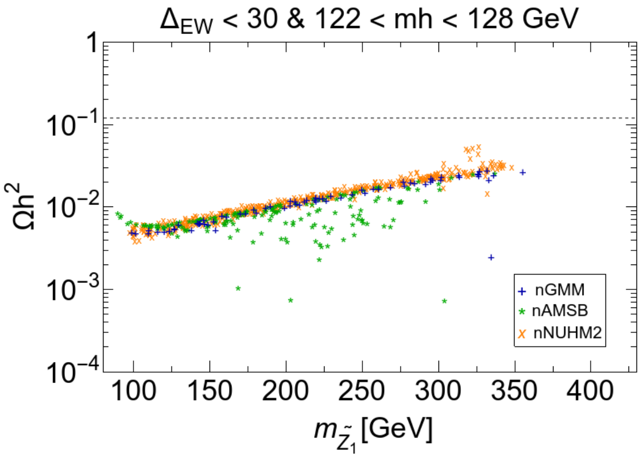
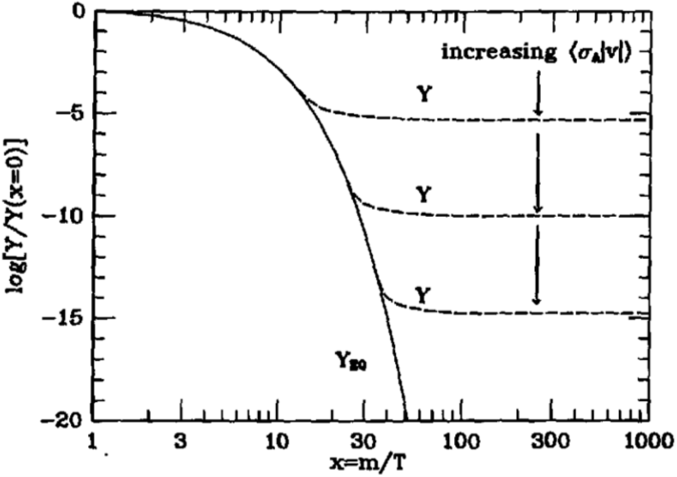
Natural SUSY WIMP relic density

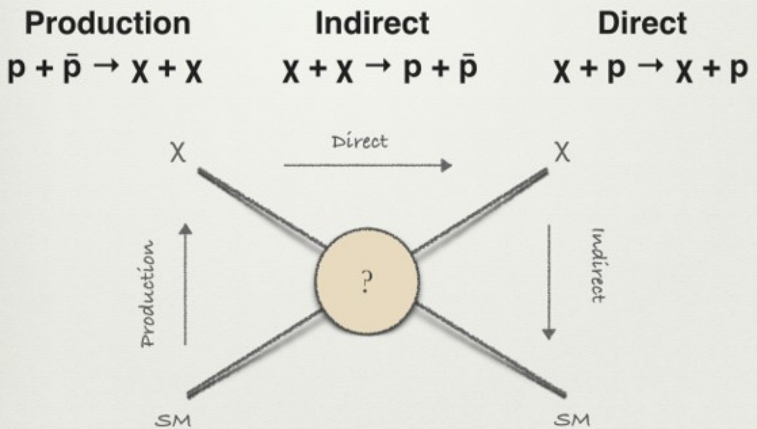


Dark matter freeze-out

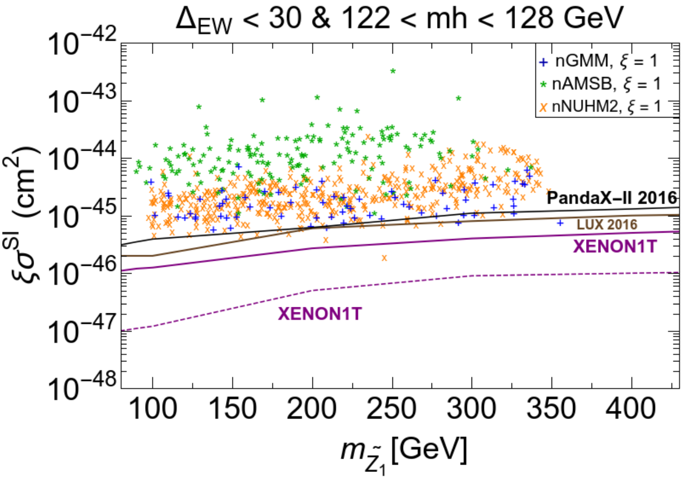
Dark matter annihilation: $X + \bar{X} \rightarrow f + \bar{f}$



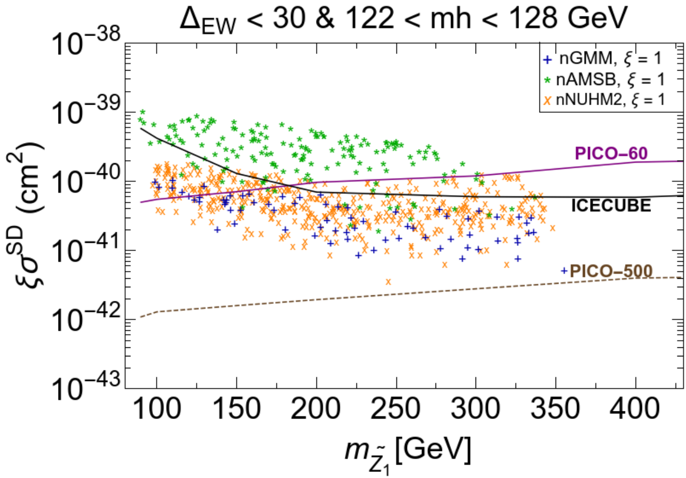
Dark matter detections



Direct detection bounds



Indirect detection bounds



Solution

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Freeze-in mechanism

- The feebly interacting massive particle (FIMP) as dark matter candidate can be created by the ultraweak renormaizable interaction [Hall Jedamzik March-Russell West, 2009].
- These particles never achieved thermal equilibrium in the thermal bath.
- Although the interactions are feeble they still lead to some FIMP production.
- Dominant production of FIMP occurs at $T \sim M_{\text{FIMP}}$.
- Increasing the interaction strength increases the dark matter number density, opposite to the freeze-out case.

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Visible sector particles (including SM or MSSM particles, and any other hypothetical particles which are in thermal equilibrium)

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Different ways of getting FIMP: bath particles decay; bath particles combination; 2→2 processes.

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.
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- 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.

Models with long-lived particles

- Consider an MSSM/SUGRA model extended by an extra $U(1)_X$ gauge group with a gauge kinetic mixing [Holdom 1985] and Stueckelberg mass mixing [Kors and Nath 2005] between the $U(1)_X$ and the SM hypercharge $U(1)_Y$.
- 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. The input mass hierarchy of the neutralino sector allows us to have the hidden neutralino as the real LSP of our model.
- The decay of the NLSP and any other heavier MSSM field into the hidden sector LSP is highly suppressed by the mixing parameters, and the LSP will be produced out of equilibrium in the early universe.

The dark neutralino

In the neutralino sector, we label the mass eigenstates as

$$\tilde{\xi}_1^0,\ (\tilde{t}_1);\ \tilde{\xi}_2^0,\ \tilde{\chi}_1^0,\ \tilde{\chi}_2^0,\ \tilde{\chi}_3^0,\ \tilde{\chi}_4^0\,.$$

Since the mixing parameter δ is very small, the first two neutralinos $\tilde{\xi}_1^0$ and $\tilde{\xi}_2^0$ reside mostly in the hidden sector while the remaining four $\tilde{\chi}_i^0$ $(i = 1 \cdots 4)$ reside mostly in the MSSM sector.

For the case when the lighter hidden neutralino $\tilde{\xi}_1^0$ is the least massive of all sparticles in the $U(1)_X$-extended SUGRA model, $\tilde{\xi}_1^0$ is the real LSP and thus the dark matter candidate.

Neutral gauge bosons

- For the charge-neutral gauge vector boson sector, the 2×2 mass-squared matrix of the standard model is enlarged to become a 3×3 mass-squared matrix in the $U(1)_X$-extended SUGRA model.
- After spontaneous electroweak symmetry breaking and the Stueckelberg mass growth the 3×3 mass-squared matrix of neutral vector bosons in the basis (A_μ^3, B_μ, C_μ). After diagonalization of the 3×3 mass-squared matrix, one then arrives the physical mass eigenbasis (γ, Z, Z').

The sources for relic density

- For MSSM coupled to the hidden sector by ultraweak interactions, the LSP relic density cannot be satisfied by the usual freeze-out mechanism. Indeed, its freeze-out relic density arising from its pair annihilation would be negligible because of the ultraweak coupling.
- Yet the observed relic density can be achieved by a combination of the freeze-in and freeze-out mechanisms.

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- Yet the observed relic density can be achieved by a combination of the freeze-in and freeze-out mechanisms.
- Here the freeze-out contribution arises from the decay of the NLSP (in our case, stop) after it freezes out. Despite the tiny decay widths of all heavier MSSM sparticles into the LSP, this decay will eventually happen over a period of time thus producing the desired contribution to the dark matter relic abundance.

Freeze-in contribution

- We assume hidden sector particles having negligible abundance in the early universe.
- Since the lighter hidden neutralino $\tilde{\xi}_1^0$ is the lightest particle in the thermal bath, all the heavier R-parity odd particles, though ultraweakly coupled to $\tilde{\xi}_1^0$, will eventually decay into it.

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- Since the lighter hidden neutralino $\tilde{\xi}_1^0$ is the lightest particle in the thermal bath, all the heavier R-parity odd particles, though ultraweakly coupled to $\tilde{\xi}_1^0$, will eventually decay into it.
- This implies that the abundance of $\tilde{\xi}_1^0$ will rise as the temperature T drops until the decaying particles run out leading to a saturation in the abundance of $\tilde{\xi}_1^0$.
- As a general feature of freeze-in dark matter, for a decaying particle of mass M the dominant production of $\tilde{\xi}_1^0$ occurs at $T \sim M$.
- In summary the freeze-in contribution is given by

$$(\Omega h^2)_{\rm FI} = \sum_{\text{all heavy sparticles}} (\Omega h^2)_{\rm FI} \,.$$

Benchmark models

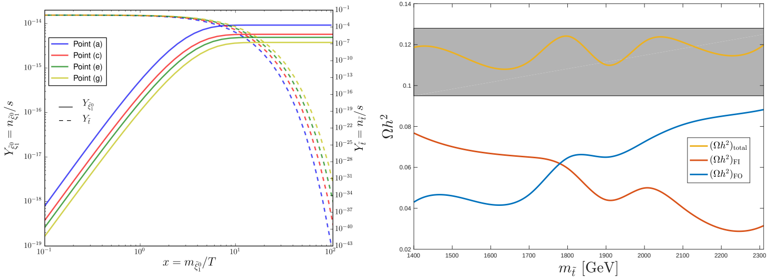
The input parameters of the $U(1)_X$-extended non-universal SUGRA model with parameters as below (at the GUT scale)

$$m_0, \quad A_0, \quad m_1, \quad m_2, \quad m_3, \quad M_1, \quad M_{XY}, \quad \delta, \quad \tan\beta, \quad \text{sgn}(\mu).$$

where $m_0,\ A_0,\ m_1,\ m_2,\ m_3,\ \tan\beta$ and $\text{sgn}(\mu)$ are the soft parameters in the MSSM sector, and M_1 and M_{XY} are hidden sector mass parameters. We select ten benchmarks satisfying all the previous constraints and are displayed in the following Table

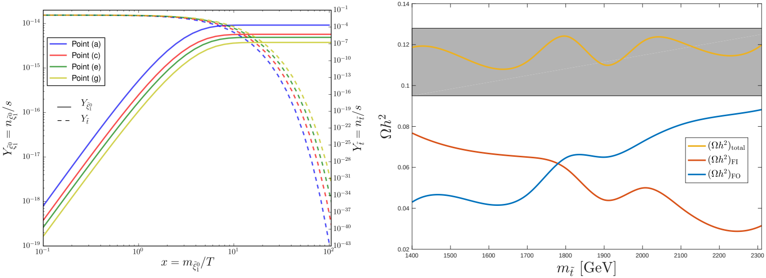
Model	h^0	μ	$\tilde{\chi}_1^0$	$\tilde{\chi}_1^\pm$	$\tilde{\xi}_1^0$	$\tilde{t}$	$\tilde{g}$	$(\Omega h^2)_{\rm FO}$	$(\Omega h^2)_{\rm FI}$	Ωh^2	τ_0
(a)	124.2	3122	1416	1759	1129	1409	3218	0.044	0.076	0.119	0.79
(b)	125.5	3168	1529	2218	1223	1502	2709	0.046	0.070	0.116	0.81
(c)	124.4	2324	1678	1727	1355	1618	2821	0.038	0.089	0.127	0.97
(d)	125.6	3665	1907	2587	1314	1702	2817	0.047	0.065	0.112	0.43
(e)	125.5	3556	1836	2310	1484	1804	3737	0.065	0.059	0.124	0.91
(f)	125.4	2763	2085	2773	1525	1903	2575	0.065	0.044	0.110	0.84
(g)	125.8	2900	2254	2737	1649	2005	3224	0.073	0.050	0.122	0.96
(h)	125.6	3513	3461	3519	1722	2102	3284	0.081	0.040	0.121	0.92
(i)	126.8	3444	2316	3465	1673	2201	3033	0.085	0.030	0.115	0.66
(j)	123.7	4454	3034	4360	1742	2304	3460	0.088	0.031	0.119	0.55

Relic density



Left panel: a plot of the comoving number density $Y_{\tilde{\xi}_1^0}$ and $Y_{\tilde{t}}$ versus $x \equiv m_{\tilde{\xi}_1^0}/T$ for four illustrative benchmarks (a), (c), (e) and (g) for the freeze-in situation.

Relic density



Left panel: a plot of the comoving number density $Y_{\tilde{\xi}_1^0}$ and $Y_{\tilde{t}}$ versus $x \equiv m_{\tilde{\xi}_1^0}/T$ for four illustrative benchmarks (a), (c), (e) and (g) for the freeze-in situation. Right panel: A plot of the relic density versus the stop mass for all the benchmark models. The FI and FO contributions are shown along with their sum which lies inside the grey patch shows the allowed region of the relic density taking theoretical uncertainties into account.

Stop R-hardrons as the collider signature

- Long-lived stops (with a decay width $\lesssim 0.2$ GeV) immediately hadronize forming color-neutral R-hadrons, $R_{\tilde{t}}$, which can be thought of as a stop surrounded by a "cloud" of light quarks. Around 93% of $R_{\tilde{t}}$ formed are R-mesons $\tilde{t}\bar{q}$ and the rest are R-baryons $\tilde{t}qq$.
- Then most of the $R_{\tilde{t}}$ transform from mesons to baryons. This transition leads to charge flipping where an R-hadron can go from being electrically charged to neutral and vice-versa.
- On the average, almost half of the R-hadrons end up flipping sign [Hohansen, 2006] as they travel the detector length and will therefore, leave a track in the inner detector tracker (ID) and in the muon spectrometer (MS).
- Due to the charge flipping property, tracks may suddenly disappear or appear which is a feature used by experimental collaborations to look for R-hadrons.

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.

The setup

With a similar setup to the previous case, an extra $U(1)$ was introduced and in addition to the gauge boson mixing we shall again have six neutralinos, but with a different mass hierarchy

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

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

The relic density of $\tilde{\chi}_1^0$

The relic density of the lightest neutralino $\tilde{\chi}_1^0$ arises from two sources:

- The usual freeze-out contribution.
- Decay from the freeze-in production of the dark neutralinos.

Subtlety: the second contribution should take place after the neutralino freeze-out processes.

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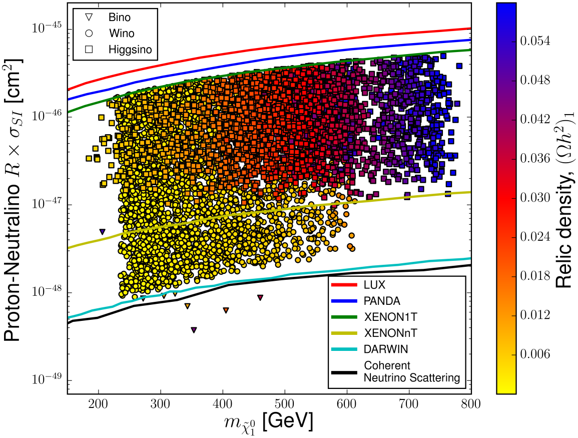
Using the definition of the Hubble parameter and the Friedman equation, one has the relation

$$t \approx \frac{M_{\mathrm{Pl}}^2}{3.32^2 g_*} \frac{1}{T^2} \,.$$

One can estimate that for temperature greater than 20 GeV, corresponds to the time less than 10^{-9} sec, however, the lifetime of the hidden sector neutralino is around 0.1-1 sec, and thus they will decay after the LSP freeze-out but before BBN.

Figures



[Amin Aboubrahimb, WZF and Pran Nath, 2003.02267]

Dark matter small scale problems

Compare with DM-only simulations, four main discrepancies between CDM predictions and observations are

- Core-cusp problem
- Diversity problem
- Missing satellites problem
- Too-big-to-fail problem

Can be explained by self-interacting dark matter [Spergel, Steinhardt, 1999] with velocity-dependence on the self-interaction cross-sections.

$U(1)$ extension and the dark freeze-out

The relevant part of the Lagrangian of the extended model is

$$\begin{aligned}\mathcal{L} = & -\frac{1}{4}C^{\mu\nu}C_{\mu\nu} - g_X\bar{D}\gamma^\mu DC_\mu + m_D\bar{D}D \\ & -\frac{\delta}{2}C^{\mu\nu}B_{\mu\nu} - \frac{1}{2}(M_1C_\mu + M_2B_\mu + \partial_\mu\sigma)^2,\end{aligned}$$

where C_μ is the gauge field of $U(1)_X$, B_μ is the gauge field for the $U(1)_Y$, σ is an axion field which gives mass to C_μ and is absorbed in the unitary gauge, D is a Dirac fermion which is charged under $U(1)_X$, δ is the kinetic mixing parameter, M_1 and M_2 are the mass parameters in the Stueckelberg mass mixing.

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The diagonalization of the gauge boson mass matrix along with the mass matrix arising from the spontaneous breaking of the Higgs boson in $SU(2) \times U(1)_Y$ gives the following mass eigenstates: the photon (γ), the Z boson, and $Z'(\gamma')$.

The dark freeze-out

- Freeze-in production of the dark fermion D and dark photon γ'.
- Freeze-out process in the hidden sector $D\bar{D} \to \gamma'\gamma'$.
- The two above processes take place at the same time, thus one needs to solve a series of coupled Boltzmann equations.

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Subtleties:

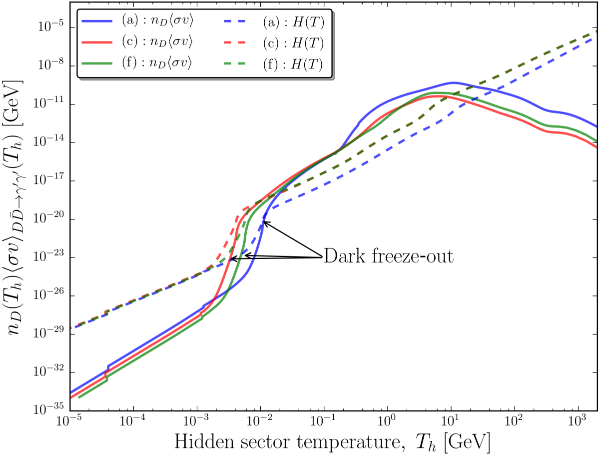
- The dark freeze-out did happen.
- The dark matter self-interaction did happen.
- Influence on the initial input of hidden sector temperature.

Coupled Boltzmann equations

$$\begin{aligned}\frac{dn_D}{dt}+3Hn_D=&\Big[\langle\sigma v\rangle_{D\bar{D}\to i\bar{i}}(T)n_D^{\rm eq}(T)^2\\&-\langle\sigma v\rangle_{D\bar{D}\to\gamma'\gamma'}(T_h)n_D(T_h)^2\\&+\langle\sigma v\rangle_{\gamma'\gamma'\to D\bar{D}}(T_h)n_{\gamma'}(T_h)^2\Big].\end{aligned}$$

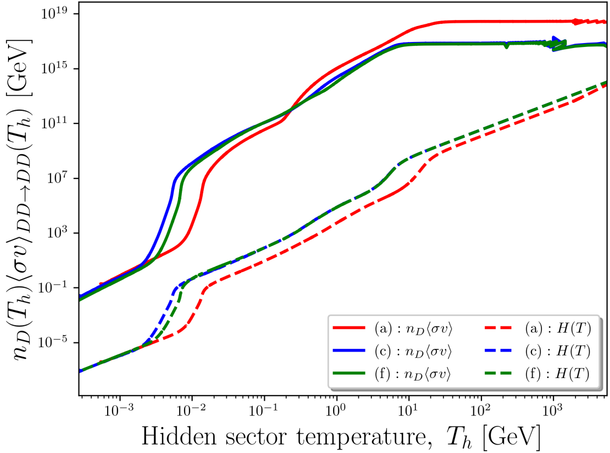
$$\begin{aligned}\frac{dn_{\gamma'}}{dt}+3Hn_{\gamma'}=&\Big[\langle\sigma v\rangle_{D\bar{D}\to\gamma'\gamma'}(T_h)n_D(T_h)^2\\&-\langle\sigma v\rangle_{\gamma'\gamma'\to D\bar{D}}(T_h)n_{\gamma'}(T_h)^2\\&+\langle\sigma v\rangle_{i\bar{i}\to\gamma'}(T)n_i^{\rm eq}(T)^2\\&-\langle\Gamma_{\gamma'\to i\bar{i}}(T_h)\rangle n_{\gamma'}(T_h)\Big].\end{aligned}$$

Figures



[Aboubrahimb, WZF, Nath, Wang, arXiv:2008.00529]

Figures



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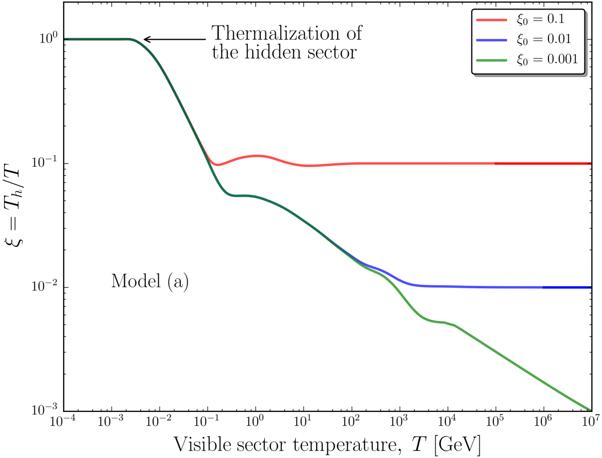

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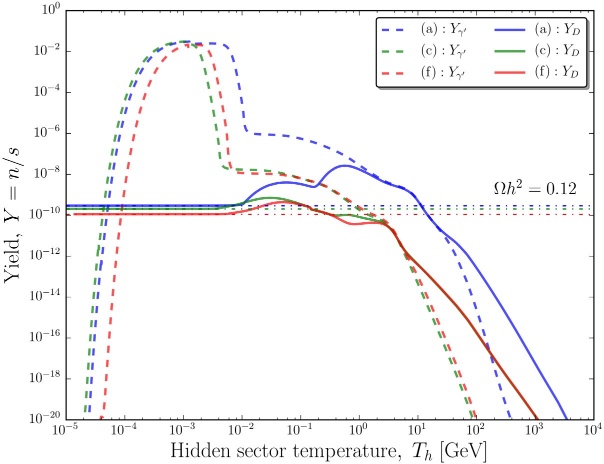

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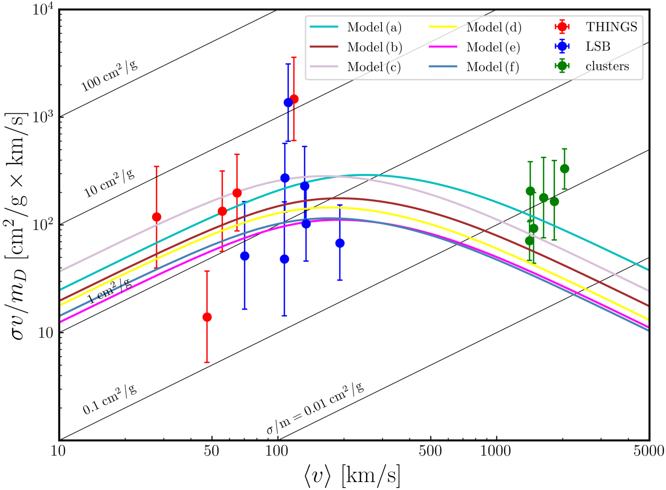

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Models with two $U(1)$'s

- An intriguing possibility is that dark matter is made up of very light dark photons from hidden sectors.
- However, dark photon dark matter with mass range around sub-MeV appears difficult to realize.
- The problem arises in part because with the visible sector interacting with a hidden sector via kinetic mixing, the twin constraints that the dark photon has a lifetime larger than the age of the Universe, and also produce a sufficient amount of dark matter to populate the universe are difficult to satisfy.

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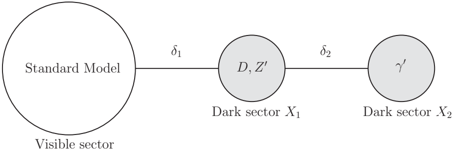
- The problem arises in part because with the visible sector interacting with a hidden sector via kinetic mixing, the twin constraints that the dark photon has a lifetime larger than the age of the Universe, and also produce a sufficient amount of dark matter to populate the universe are difficult to satisfy.
- To encounter this problem, we propose a SM extension with two $U(1)$'s.



[Amin Aboubrahimb, WZF, Pran Nath, Zhu-Yao Wang, arXiv:2103.15769]

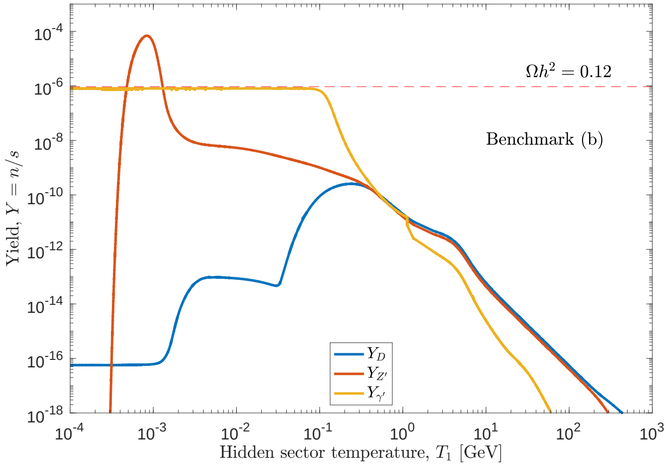
The model

In the gauge eigenbasis $V^T = (D, C, B, A_3)$ the mixing matrices can be written as

$$\begin{pmatrix} 1 & \delta_2 & 0 & 0 \\ \delta_2 & 1 & \delta_1 & 0 \\ 0 & \delta_1 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} M_4^2 & M_3 M_4 & 0 & 0 \\ M_3 M_4 & M_1^2 + M_3^2 & M_1 M_2 & 0 \\ 0 & M_1 M_2 & \frac{1}{4} v^2 g_Y^2 + M_2^2 & -\frac{1}{4} v^2 g_2 g_Y \\ 0 & 0 & -\frac{1}{4} v^2 g_2 g_Y & \frac{1}{4} v^2 g_2^2 \end{pmatrix}$$

These two matrices cannot be analytically diagonolized simultaneously, thus a perturbation methods is used as an approximation

Figures



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Conclusion

1. The SUSY WIMP is highly constrained by the combined results from LHC as well as from direct and indirect searches.
2. The ultraweak interactions generated freeze-in dark matter allow us to reconstruct the MSSM spectrum, and gives us more choices for the SUSY parameter space.
3. Freeze-in mechanism with feeble couplings also provides us more possibilities in constructing particle physics models to explain various unknown problems..
4. Multi-hidden sector extension of the SM is general. In the multi-temperature sector Universe, we have developed a method to keep track of both the temperatures as well as the yields of particles in each sectors.

Thank You!